Climatological Bulletin

Volume 18, Number 1, April 1984

Canadian Meteorological
and Oceanographic
Society

La Société Canadienne
de Météorologie et
d' Océanographie

Information for Contributors and Subscribers

As a publication of the Canadian Meteorological and Oceanographic Society, the Climatological Bulletin provides a medium of information on climatology. The editorial board gives special encouragement to the submission of manuscripts on applied climatology, e.g., agriculture, climatic change and variability, climate impact assessment, data bases, energy, environment, forestry, health, measurement, recreation, and transportation. Several formats are provided, including the formally reviewed "Articles", and the less formal "Notes" section. The latter consists of shorter contributions, such as research notes, surveys, overviews, and book reviews. Submissions from students through their professors are encouraged. News items are welcome, and are placed in a separate "News" section.

Authors, including students, may choose to submit their scripts to formal review, or Notes. This should be indicated in the cover letter accompanying the manuscript. Research articles are independently reviewed by at least two anonymous referees. Notes are reviewed by the editor in consultation with the editorial board. Articles are accepted in either English or French. An abstract is required preferably in both English and French.

Contributors should submit manuscripts to Stewart J. Cohen, Editor, Climatological Bulletin, Dept. of Geography, York University, 4700 Keele Street, Downsview, Ontario, Canada, M3J 1P3. All manuscripts should be typed double spaced on one side of good quality white paper, 28 cm × 21.5 cm or its nearest equivalent. The abstract, list of references, tables, and a list of figure captions should be typed double spaced on separate sheets. The total length of research manuscripts should not exceed 5,000 words, exclusive of illustrative material. Comments, reviews, opinions, and news items should not exceed 1,500 words. Furnish an original and three copies if possible, in the order listed below.

TITLE PAGE should include the full names of authors, and professional affiliations.

The ABSTRACT should be less than 250 words, and typed on a separate page.

The TEXT of longer contributions should be typed double spaced on numbered pages, and divided into sections, each with a separate heading and numbered consecutively. The section heading should be typed on a separate line.

ACKNOWLEDGEMENTS are typed on a separate sheet immediately following the text.

If FOOTNOTES are required, they should be typed, double spaced, on a separate sheet under the heading "Notes" at the end of the text.

REFERENCES should be arranged alphabetically by senior author's last name. The text citation should consist of name(s) of the author(s) and the year of publication, for example Jones (1975) or (Jones, 1975). When there are two or more cited publications by the same author in the same year, distinguishing letters a, b, etc., should be added to the year. A reference to "in press" implies that the paper has been accepted for publication. Titles of periodicals should be given in full.

FIGURE LEGENDS must be provided for each figure, and should be typed together, double spaced, on a separate sheet.

ILLUSTRATIONS should be numbered sequentially. Original drawings, lettering, and symbols should be large enough so that after reduction, the smallest character will be at least 1.5 mm high.

Each TABLE should be numbered sequentially. Type all tables double spaced on separate sheets.

Authors should use the International System of units, but may show other units in parentheses. Authors should provide instructions in the margin for any special type required (Greek letters, capitals, bold face, etc.).

Page charges are not levied against the author. Authors of research articles will receive 10 reprints. Notes authors will receive 2 reprints.

Correspondence regarding Society affairs, membership, Institutional subscriptions and back issues of the journal should be directed to the Corresponding Secretary, Canadian Meteorological and Oceanographic Society, Suite 805, 151 Slater Street, Ottawa, Ontario K1P 5H3. Telephone (613) 237-3392.

Renseignements pour les collaborateurs et les abonnés

Publication de la Société canadienne de météorologie et d'océanographie, le Bulletin climatologique offre un moyen d'information sur la climatologie. Le comité de rédaction encourage en particulier la soumission de manuscrits sur la climatologie appliquée, comme l'agriculture, les changements et la variabilité du climat, la prospective climatologique, les bases de données, l'énergie, l'environnement, la sylviculture, la santé, les mesures, les loisirs et les transports. Cette publication compte plusieurs catégories d'articles, dont les "Articles", officiellement évalués, et la partie plus libre des "Notes", qui se compose d'articles plus courts, comme les notes de recherche, les études, les vues d'ensemble et les critiques de livres. On incite les étudiants à présenter des articles par l'intermédiaire de leurs professeurs. Nous faisons bon accueil aux informations, qu'on publie à part dans la partie des "Nouvelles".

Les auteurs, y compris les étudiants, peuvent choisir de soumettre leurs manuscrits à l'appréciation officielle ou aux "Notes". Ils doivent l'indiquer sur la lettre d'accompagnement du manuscrit. Les articles de recherche sont indépendamment soumis à l'examen d'au moins deux appréciateurs anonymes. Le rédacteur en chef examine les "Notes" conjointement avec le comité de rédaction. On accepte les articles soit en français, soit en anglais. Il faut envoyer un résumé, de préférence en français et en anglais.

Les collaborateurs sont priés de soumettre leurs manuscrits à Stewart J. Cohen, rédacteur en chef, Bulletin climatologique, département de géographie, université York, 4700, rue Keele, Downsview, Ontario, Canada M3J 1P3. Il faut dactylographier tous les manuscrits à double interligne, sur un côté d'un papier blanc de bonne qualité, de 28 sur 21,5 cm ou des dimensions les plus rapprochées. Il faut dactylographier à double interligne, sur des feuilles à part, le résumé, la liste des références, les tableaux et la liste des légendes. La longueur totale des manuscrits de recherche ne devrait pas dépasser 5 000 mots, illustrations non comprises. Les commentaires, les critiques, les opinions et les informations ne doivent pas dépasser 1 500 mots. Fournir l'original et, si possible, trois copies, selon la disposition suivante:

LA PAGE DE TITRE doit comprendre: nom, prénoms des auteurs, ainsi que les affiliations professionnelles.
LE RÉSUMÉ, dactylographié sur une page à part, ne doit pas compter plus de 250 mots.
LE TEXTE. Il faut taper à double interligne, sur des pages numérotées, le texte des articles plus longs et le diviser en sections, chacune dotée d'une en-tête à part et numérotée dans l'ordre. Il faut dactylographier l'en-tête de section sur une ligne à part.
LES REMERCIEMENTS doivent être dactylographiés sur une page à part, après le texte.
LES NOTES DE BAS DE PAGE doivent être dactylographiées à double interligne, sur une feuille à part, au-dessous de l'en-tête "Notes", à la fin du texte.
LES RÉFÉRENCES doivent être disposées dans l'ordre alphabétique, d'après le nom de l'auteur principal. Les citations doivent comprendre le ou les noms du ou des auteurs et l'année de publication, comme Jones (1975) ou (Jones, 1975). Si l'on cite deux ou plusieurs publications du même auteur pendant la même année, il faut ajouter à l'année des lettres qui permettent de les différencier, comme a, b, etc. La mention "à l'impression" implique qu'on a accepté de publier la communication. Il faut indiquer les titres des périodiques en entier.
LES LÉGENDES: elles sont requises pour chaque figure. On dactylographiera ces légendes ensemble, à double interligne, sur une feuille à part.
LES ILLUSTRATIONS doivent être numérotées dans l'ordre. L'original des dessins, des caractères et des symboles doit être assez grand pour que, après réduction, le caractère le plus petit mesure au moins 1,5 mm de haut.
LES TABLEAUX doivent être numérotés dans l'ordre. La dactylographie pour tous les tableaux doit être à double interligne sur des feuilles à part.

Les auteurs doivent utiliser le système international de mesure, mais ils peuvent indiquer d'autres mesures entre parenthèses. Les auteurs doivent porter dans la marge des instructions pour tout caractère spécial voulu (lettres grecques, majuscules, caractères gras, etc.).

On ne fait pas payer de pages à l'auteur. L'auteur d'un article de recherche reçoit dix tirés à part et les auteurs des notes deux.

La correspondance concernant les activités de la Société, les souscriptions des membres et des institutions et les numéros déjà parus, devrait être adressée au Secrétaire-correspondant, Société canadienne de météorologie et d'océanographie, Suite n° 805, 151 rue Slater, Ottawa (ONT.) K1P 5H3. Téléphone: (613)-237-3392.

Climatological Bulletin

Vol. 18, No. 1, April 1984

Foreword

As we learn more about carbon dioxide and the "Greenhouse Effect", additional concerns are raised, regarding potential side effects of increased CO_2 on the environment and the economy. One area of widespread interest is agriculture. Although considerable uncertainty remains when attempting to predict changes in the climate of specific regions, plausible scenarios do exist, which permit us to explore potential impacts on food production. The article by Stewart addresses both the direct effects of increased CO_2 on plant growth, as well as the indirect effects on Canadian agriculture of CO_2-induced climatic change.

Agriculture is also the focus of the article by Brown and Wyllie, and the note by Bootsma. Brown and Wyllie examine the spatial and temporal aspects of summer dry spells in Southern Ontario, a region with a humid climate, but where dry spells of 2 weeks or longer are a frequent occurrence. June and July, 1983, will long be remembered in the Toronto area as one of the warmest and driest periods in recent memory. In Bootsma's note, temperature is examined, particularly the accumulation of heat units or "degree days". The author presents a simple statistical model for determining the dates of threshold accumulations of growing degree days.

The October 1983 issue included Idso's note which presented an alternative scenario of CO_2-induced climate change, one which postulates a possible cooling trend. This led to a comment by Hamilton which appears in News and Comments, immediately followed by Idso's reply.

Stewart J. Cohen

Atmospheric carbon dioxide and Canadian Agriculture

D.W. Stewart

The concentration of atmospheric CO_2 has increased by 50-75 ppm since the middle of the last century due to burning of fossil fuel and the clearing of land for agriculture. It will continue to increase and may double from pre-industrial levels sometime in the next century depending on future consumption of fossil fuel. This increase will affect agriculture in two ways: directly through a CO_2 effect on photosynthesis and plant growth; and indirectly through the effect of CO_2 on the earth's climate. There are grounds for optimism that increased atmospheric CO_2 should lead to increased plant growth rates and larger water use efficiencies of agricultural crops. The CO_2 effect on climate is to increase surface temperatures and, in some regions, precipitation. Longer growing seasons and more favourable temperatures for plant growth should help Canada's agriculture although risks of droughts in some areas will increase. It is important to quantify these effects of CO_2 so that the continued use of fossil fuel can be fully evaluated.

La concentration de CO_2 atmosphérique a augmenté de 50-75 ppm depuis le milieu de siècle dernier dû à l'utilisation du combustible fossile et au déboisement des terres pour l'agriculture. Elle continuera de croître et pourra même doubler les niveaux de la période pré-industrielle tôt ou tard au cours du prochain siècle dépendant de la consommation future du combustible fossile. Cet accroissement affectera l'agriculture de deux façons: directement par un effet du CO_2 sur la photosynthèse et la croissance des plantes; et indirectement par l'effet du CO_2 sur le climat de la terre. Il y a lieu d'espérer que l'augmentation du CO_2 atmosphérique conduira à une augmentation des taux de croissance des plantes et à une plus grande efficacité dans l'utilisation de l'eau par les plantes cultivées. L'effet du CO_2 sur le climat se traduit par une augmentation des températures de surface et, dans certains régions, des précipitations. Des saisons de croissance plus longues et des températures plus favorables à la croissance des plantes devraient aider l'agriculture canadienne bien que les risques de sécheresse augmenteront dans certaines régions. Il est important de quantifier ces effets du CO_2 de façon à ce que l'utilisation continue du combustible fossile puisse être plainement évaluée.

Agrometeorology Section,
Land Resource Research Institute,
Research Branch, Agriculture Canada, Ottawa, Ontario
(LRRI Contribution No. 83-53)
Please address correspondence and reprint requests to D.W. Stewart.

INTRODUCTION

The atmospheric carbon dioxide concentration has been increasing steadily at about 1 ppm per year since accurate measurements started at Mauna Loa, Hawaii in 1958 (Keeling et al., 1976) and it is now about 340 ppm (Hecht, 1981; Gates, 1983). Pre-industrial levels are estimated to have been between 265 and 290 ppm (Stuiver, 1978; Hecht, 1981). Therefore, a rise of 50 to 75 ppm has taken place within the past 150 years. Stuiver (1978) has attributed about one-half of this increase to biospheric sources, mainly clearing of forests and the cultivation of new lands for agriculture that released carbon stored in woody tissue and soil organic matter. The other half has come from the burning of fossil fuel.

There are numerous projections of future CO_2 increases (Broecker, 1975; Woodwell, 1978). Assuming an exponential type increase, CO_2 could double in concentration by the middle of the next century. If we simply project the average increase over the last 20 years, the atmospheric CO_2 would be about 410 ppm by the middle of the next century. Such projections depend on a multitude of complex functions such as the future per capita use of fossil fuels, the contribution of atmospheric CO_2 from the biosphere and future population growth, none of which can be predicted with accuracy. Although only trace amounts of this gas are present in the atmosphere, it has, and will have, profound effects on many aspects of life on this planet. In this article I will discuss first how agriculture has contributed to the CO_2 increase, and more importantly, how it will be affected by future increases.

CAUSES OF THE CO_2 INCREASE

A natural ecosystem slowly removes CO_2 from the atmosphere and stores it in living plant material and soil organic matter. Some ecosystems store more carbon than others. The short grass prairie of southwestern Saskatchewan, with its hot dry growing conditions, has less soil organic matter than the long grass prairies to the north and east where cooler more humid conditions produce a soil with a deep, black surface horizon. Anaerobic conditions in bogs favour an even greater build-up of soil organic matter.

Ecosystems also differ in where they store their carbon. Most of the carbon in a prairie ecosystem is in soil organic matter while forests, especially tropical forests, store most of their carbon in above ground woody tissue. In Table 1, values for above ground carbon (kg/m^2) for various ecosystems (Woodwell, 1978) and weighted averages of soil organic carbon (kg/m^2) for North America, South America and Eurasia, Africa and Oceania (Bohn, 1976) are tabulated. As well, for comparison purposes, I have calculated the amount of carbon in the atmosphere (kg/m^2). It is clear from this table that substantial amounts of carbon are stored in forests and soil organic matter and that clearing forests and cultivating land, thereby oxidizing a substantial fraction of such car-

TABLE 1 Amount of carbon in above ground vegetation, soil organic matter and the atmosphere

Biomass[1]	*kg/m*^{2}
Forests: Tropical	3.0 – 36.0
Temperate	3.0 – 90.0
Boreal	3.0 – 18.0
Savannas	0.1 – 7.0
Grasslands	0.1 – 2.3
Cultivated Lands	0.2 – 5.4
Soil Organic Matter[2]	
North America	32.8
South America	16.5
Asia, Africa, Europe and Oceania	23.7
Atmosphere	1.5

[1] Woodwell (1978)
[2] Bohn (1976)

bon, can lead to significant additions to atmospheric CO_2.

In Canada, soil organic losses, particularly in the prairies has been of concern for some time. Losses of nitrogen, which are usually proportional to organic matter, of 18 to 33 percent have been reported for periods of 14 to 22 years of cultivation in the prairie provinces (Soper and Racz, 1967; Doughty, Cook and Wardner, 1954; Newton, Wyath and Brown, 1945). The practice of summerfallow (leaving a field fallow for one growing season) has been identified as a main factor for continued decrease of organic matter with cultivation (Campbell and Souster, 1982; McGill et al., 1981).

Measurements by Stuiver (1978) and Wilson (1978) indicate that one half of the modern day CO_2 increase comes from deforestation and cultivation of land. Most of this biospheric release came between 1860 and 1900 when 'new lands' were cleared and cultivated in North America, Eastern Europe, New Zealand, Australia and South Africa. This is important for two reasons. It means the current increase in atmospheric CO_2 began over one hundred years ago. Secondly, if agriculture and deforestation have been major contributors to the increase, then perhaps, as suggested by Wilson (1978), the increase could be moderated to some extent by agricultural practices.

These same studies of carbon isotopes from tree rings suggest that fossil fuel has become the major source of CO_2 in the last three decades. Broecker et al. (1979) show that during this time approximately one half of the

CO_2 released has remained in the atmosphere; the ocean has absorbed about 40% of the remainder. The rest is assumed taken up by the biosphere. However, Woodwell (1978) and Baumgartner (1978) argue that present destruction of tropical forests in developing countries would make the biosphere a net source rather than a net sink of CO_2. This makes the world carbon balance a puzzle since there is no explanation as to where this extra carbon is going. Here again, this is important for both future predictions of CO_2 and for possible solutions to the CO_2 increase.

PLANT RESPONSE TO THE CO_2 INCREASE

An increase in atmospheric CO_2 has a direct effect on plant growth mainly through the process of photosynthesis. This process can be expressed as:

$$CO_2 + 2H_2O \xrightarrow{\eta\nu} (CH_2O) + H_2O + O_2$$

CH_2O and $\eta\nu$ represent carbohydrate and solar radiation ($0.4 - 0.7\ \mu$), respectively. Plants and some bacteria have the ability to combine CO_2 with water to form carbohydrates which are essential to all forms of life on this planet. Carbohydrates are both a building material and a source of energy for plants (and higher forms of life as well). Energy is needed for growth and maintaining existing tissue. Energy becomes available via respiration expressed as:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

Thus, a plant can both absorb and release CO_2 depending on which process is dominant at a given time. In light, the plant is a sink, and in darkness, a source of CO_2. As the plant matures, respiration rates tend to approach those of photosynthesis as increasing amounts of energy are needed for maintenance purposes.

Light capture for the photosynthesis process takes place at the chloroplasts situated mainly in leaf mesophyll and pallisade cells. Thus CO_2 used in photosynthesis has to diffuse through the epidermal layer of the plant via special valve-like structures called stomates, through the intercellular spaces and into plant cells. This process can be expressed as:

$$P = (C_a - C_o) / (r_a + r_s + r_m)$$

where C_a and C_o are CO_2 concentrations in the ambient air and at the chloroplasts respectively, and r_a, r_s and r_m are boundary layer resistance, the stomatal resistance and the mesophyll resistance respectively. The boundary layer resistance is usually small compared to r_s and r_m. While r_m can be increased by water stress, the main controlling resistance is r_s, a complex function of incident light flux density, water stress and concentration of CO_2 in the intercellular spaces (C_i) (Rashke, 1975).

For a plant to function effectively, water has to be present in the plant tissue. Most cultivated species are 80-90% water. A 20 to 25% loss in turgidity closes the stomates and stops photosynthesis. Leaf expansion stops with even smaller losses in turgidity. To maintain turgidity water lost through open stomates (transpiration) is replaced by soil water via the root system. Water stress develops when available soil water cannot replenish water lost due to transpiration. When this happens rate of dry matter production decreases.

Stomates respond to intercellular CO_2 as well as water stress. This response varies with the type of plant. Cultivated species can be divided into C_4 (e.g. corn, sorghum, millet and sugarcane) and C_3 types (almost all other cultivated species). The main exception is pineapple which belongs to a third smaller group (CAM). These groups are differentiated by different chemical pathways to accomplish the photosynthetic process. In general the stomates of C_4 plants are much more sensitive to increases in C_i than C_3 plants (Aketa and Moss, 1972; Goudrian and van Laar, 1978; Rosenberg, 1981). The measurements of Aketa and Moss (1972) for example, show that transpiration declined 50% for C_4 plants when C_a was increased from 0 to 800 ppm and only 20% for C_3 plants. This means that as C_a increases for C_4 plants, the increase in the difference between C_a and C_o is offset by an increase in r_s so that P remains relatively constant. For C_3 plants the increase in r_s does not offset the gradient and P increases. In both cases, water use efficiency (mg of CH_2O fixed per mg of water transpired) increases, which is good news for arid and semi-arid regions. Even in humid regions such as Ontario, summer droughts are relatively common.

There is no doubt that all plants benefit to some extent from an enriched CO_2 atmosphere. Certainly CO_2 fertilization is relatively common in the greenhouse industry (Wittwer, 1970). As well, growth room studies such as those by Sionet et al. (1980, 1981) indicate increased yields, at least for C_3 plants. However, Kramer (1981) and Lemon (1981) have cautioned against extrapolating growth room and greenhouse studies to the natural environment. CO_2 fertilization is extremely difficult in field situations (Allen, 1973, 1979). Thus, there is little or no data to guide our thinking in this situation.

One reason for caution here is that studies by Aoki and Yakaki (1978) have shown that at high CO_2 levels photosynthesis rates decrease with time. This seems to be caused by high concentrations of starch forming in leaf cells at very high rates of photosynthesis (Kramer, 1981). Nafziger and Koller (1976) were able to demonstrate a negative correlation between photosynthesis and starch accumulation for soybeans. However, Mauney et al. (1979) were able to demonstrate a significant negative correlation for cotton only at 330 ppm CO_2. Photosynthesis rates for cotton at 660 ppm and soybeans, sunflower and sorghum at both 330 and 660 ppm were not significantly correlated with starch accumulation. The main difference between these studies is that the daily photosynthate accumulation found by Nafziger and Koller (1976) was much higher than that found by Mauney et al. (1979) due to higher light flux densities and longer daylengths. Thus, Nafziger and Koller's starch accumulations were high enough to inhibit photosynthesis. A key question is what levels of CO_2 in the natural environment would cause starch accumulation in the leaves to inhibit photosynthesis – a question which deserves much more research.

Trying to assess the effects of CO_2 increase on plant growth in the natural environment will not be easy. The plant growth system is extremely complex and varies among species. Therefore, to assess responses for a number of species in a natural ecosystem will be even more difficult. As well, photosynthesis is just one process involved in plant growth. Leaf expansion, flowering and translocation will affect the final economic yield and may decrease the effect of increased rates of photosynthesis. However, there are grounds for optimism. Photosynthesis is such a basic process in plant growth that increasing it should have some effect, particularly on agricultural crops, which are geared to maximizing dry matter. Although it will be difficult to quantify this effect, it is necessary since we must be able to determine how the direct effect of rising atmospheric CO_2 will offset any of the negative aspects of climatic change which will be discussed next.

CLIMATIC CHANGE

Many scientists, with at least one exception (Idso, 1980), agree that increasing atmospheric CO_2 concentrations should lead to an increase in the earth's surface temperature. The best evidence for this comes from three-dimensional general circulation models of the earth's atmosphere. Recent reviews of these models (Charney et al., 1979) concluded that best estimates of the CO_2 effect predict an average global warming of $3.0 \pm 1.5°C$ with a doubling of present levels of CO_2. These same models predict an enhancement of the effect with latitude. However, there is difficulty in discussing the effect such a change would have on agriculture due to the rather large uncertainty in predicting future climate – not only mean annual temperatures, but also precipitation and the seasonal distribution of each. Therefore, the possible effects will be covered here in relatively general terms.

At first glance, a warming trend should be beneficial for Canada as agricultural regions would be extended northward. However, for much of Canada, this northward extension is blocked by the Canadian Shield. Major exceptions are the clay belts of northern Ontario and Quebec, the Peace River area of northern Alberta and British Columbia and river valleys in the Yukon and North West Territories.

The main climate restriction in the clay belt at present is temperature. Growing season precipitation is 400-500 mm compared to 350-400 mm for southern Ontario. Thus, a warming trend, even if not accompanied by a corresponding precipitation increase would markedly improve the agricultural potential of this region. A 1.5 and 3.0°C rise at Kapuskasing would increase the frost free period from 90 to 110 and 135 days, respectively. Ottawa has an average frost free period of 130 days. Similarly, degree days (base temperature of 0°C) would increase from 1430 to 1870 and 2350, respectively. Ottawa has 2370 degree days (D.W. Stewart, unpublished data). The main problem with this area is lack of surface drainage. Today, tile drains for most fields in the clay belts are a prerequisite of successful crop production. If large acreages, particularly in the

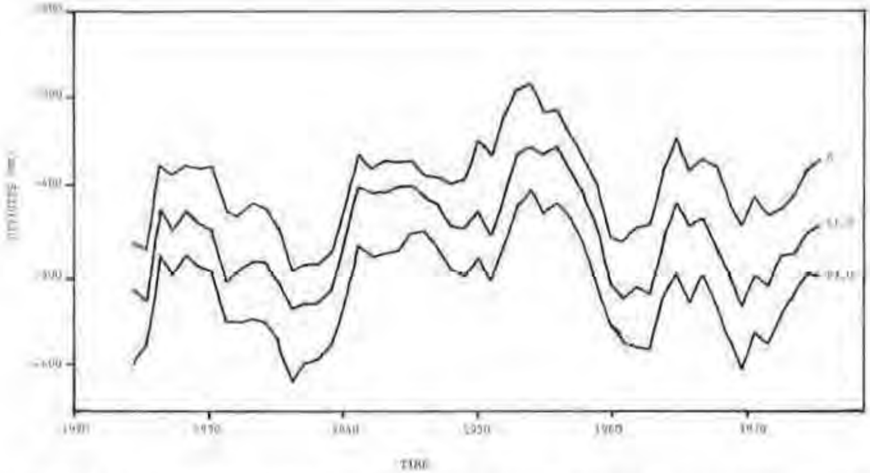


FIGURE 1 The variation of precipitation deficits (precipitation-potential evaporation) with time at Medicine Hat, Alberta using actual temperatures, temperatures plus 1.5°C and temperatures plus 3°C

northern parts of the clay belt, are to be cultivated, surface drainage action will have to be undertaken on a regional basis.

The Peace River area has a much lower annual precipitation rate (350 to 400 mm annually). This compares with 300 mm at Swift Current. Growing season precipitation is very uniform over most of the Canadian Prairies including the Peace River District at 200-250 mm (Chapman and Brown, 1978). A 1.5 and 3.0°C rise in average temperature would increase the frost free period from 105 to 130 and 155 days, respectively, at Beaverlodge. Degree days would increase from 1080 to 1620 and 2200 respectively, at Fort Vermilion. Swift Current has a frost free period of 110 days, and 1820 degree days (D.W. Stewart, unpublished calculations). Thus, with these warming trends, wheat growing areas could extend into the northern Peace River District. However, without an increase in precipitation, wheat production could easily decrease in the south west as temperatures rise. Gains in wheat growing areas in the north could be negated by loss of production in the south due to drought. At the same time, rape, Canada's second most important export crop, would be limited to northern fringes of cultivable land.

The area which would be most affected by a warming trend with no increase in precipitation is the Palliser triangle of southern Saskatchewan and southeastern Alberta. Fig. 1 shows water deficits (precipitation-potential evapotranspiration) of frost free periods for Medicine Hat in southeastern Alberta from 1922 to 1978 (D.W. Stewart, unpublished data). Five-year running means were used to reduce the variance. Potential evapotranspiration was calculated using the equations of Baier and Robertson (1965) and Baier (1971). No direct effect of CO_2 on transpiration was considered. Water deficits were calculated for actual temperatures, actual temperatures plus 1.5°C and actual temperatures plus 3.0°C. Note the extended dry period from 1930-1940. Other periods around 1960 and 1970 approached the conditions of the thirties but for shorter time intervals. The thirties, of course, are well known for the havoc weather conditions created for western Canadian grain farmers, particularly those in the Palliser triangle. One can see from Figure 1 that a 3°C increase would result in average growing conditions being worse than what actually existed in the thirties. While technological advances have improved farmers' ability to farm in this area, they would be severely tested by warming trends.

The potential for increased drought and wind erosion in the Palliser triangle are the main negative aspect to be anticipated with a warming trend. There are some very positive aspects. For example, fruit and vegetable production in Canada should increase thereby decreasing imports. In Eastern Canada corn and soybean acreages would increase, as well as yields. Northern limits of winter wheat which currently run through Montana and North Dakota would migrate north into Alberta, Saskatchewan and Manitoba. On the whole, Canada would be one of the few countries in the world to benefit from a warming trend.

PLANNING FOR THE CO_2 EFFECT

I am sometimes asked what agriculture is doing in anticipation of a CO_2 effect. For example, is now the time to start establishing peach orchards in the Ottawa Valley of Eastern Ontario? (This was suggested to me by a science reporter for an Ottawa newspaper.) The answer is an emphatic no. The CO_2 effect of 3°C has a rather large estimated error of ±1.5°C. Also, despite the effort put into modelling the earth's very complex weather system, no one has satisfactorily explained why the earth's surface has been cooling slightly since 1940 despite the increased combustion of fossil fuel (MacCracken and Moses, 1982). In this same time period surface temperatures in southern Canada have cooled about 0.5°C (Phillips, 1981). Whether warming will resume in the next 20 years (the earth was warming between 1880 and 1940) will depend on whether the CO_2 effect offsets other factors. An analysis of 0^{16} from ice cores on Denn Island has projected a cooling trend for the next 50 years (Koerner and Fisher 1980). Uncertainty about the models themselves, plus our inadequate understanding of long term climatic cycles, make predicting climatic trends for the next 20-50 years very hazardous. However, there is little doubt that if we keep burning fossil fuels at current rates the atmospheric CO_2 concentration will continue to rise, and that this will result in a warmer climate than would be present if this CO_2 increase had not been present. Other trace gases such as nitrous oxide, methane and chlorofluorocarbons will also increase in concentration and add to the warming effect because of their ability to absorb infra-red radiation.

Therefore, I think current planning should be general rather than specific and oriented towards research. The possible exception is the Palliser triangle where warming could have its most serious negative affect. In this case, research is already being directed towards stabilizing the soil structure of the area. It has been recognized that the crop-summerfallow rotation of spring wheat in Western Canada has contributed to a decline in soil organic matter. As well, the soil after summerfallow and before spring seeding is very susceptible to wind erosion. Thus, emphasis in research is being placed on reducing summerfallow and minimizing tillage. This not only increases soil organic matter and soil stability but also leaves more wheat stubble on the ground surface to combat wind erosion. Possible changes that could take place with a definite warming trend would be introduction of winter wheat on better drained lands and the conversion of cash crops to permanent grass on sandier soils.

Minimum tillage is also becoming important in the more humid areas. Row crops such as corn and soybeans, planted year after year, also contribute to declining soil organic matter. This leads to soil compaction and more water erosion. The practice of minimum tillage together with grain-crop-forage rotations are therefore gaining popularity. This, in effect, takes CO_2 from the atmosphere and adds carbon to the soil; while it may have little effect on reducing increases in atmospheric CO_2, at least it is not contributing to the problem.

There are, of course, on-going research programs designed to produce and test new crop varieties and agronomic production techniques. Most breeding programs produce new varieties within ten years. Unless there is a very abrupt change in climate, these on-going programs, with possibly more emphasis in quantifying factors contributing to yield, should take care of necessary crop adaptations to both CO_2 increases and climate changes. The modern farming community adopt new varieties relatively quickly. For example, the development of early maturing varieties of, first corn, and more recently, soybeans, have led to substantial increases in acreages of these crops in Eastern Ontario and Quebec within the past twenty years.

Another program has the potential of making a significant contribution to our understanding of the earth's carbon balance. Desjardins et al. (1981) have developed a method of measuring vertical fluxes of CO_2 over large areas. Accurate measurements of these fluxes, particularly over natural ecosystems and oceans, should lead to better estimates of world-wide sources and sinks of CO_2. These estimates are necessary if we are to understand where the CO_2 from burned fossil fuel is going, and whether the biosphere is a net source or sink of CO_2.

This leads to the question of future use of fossil fuels. Should we continue to burn coal and oil? If the CO_2 effects on climate are large (3°C for a doubling of CO_2, for example) with oceans buffering any obvious increase in surface temperature, then these effects will linger long after a decision is made to convert to an alternative energy source. In this situation, a decision to convert should be made as soon as possible. However, such a decision would be extremely difficult to make for the following reasons: (a) some countries such as Canada and the USSR would probably benefit from increased surface temperatures even if most of the world would be net losers; (b) western industrialized countries are heavily structured to use fossil fuels, and changing to an alternate fuel would be expensive; (c) the evidence for surface warming can be questioned, and even the most recent general circulation models are crude representations of the real world; (d) there are positive effects of the increased atmospheric CO_2 concentration on plant growth and these are difficult to quantify. Thus CO_2 will almost certainly continue to increase in the near future at least. Improving our knowledge on all aspects of atmospheric CO_2 is essential.

REFERENCES

Aketa, S. and D.N. Moss, 1972. Differential stomatal response between C_3 and C_4 species to atmospheric CO_2 concentration and Light. *Crop Sci. 12:* 789-793.

Allen, L.H. Jr., 1973. *Crop micrometeorology:* A. Wide-row light penetration; B. Carbon-dioxide enrichment and diffusion. Ph.D Thesis, Cornell University, Ithaca, N.Y. 366pp. Univ. Microfilm Diss. Abstr. No. 73-14,716.

Allen, L.H. Jr., 1979. Potential for CO_2 enrichment. In: Modification of the Aerial Environment of Crops. Agr. Eng. Mono. No. 2. American Soc. of Agr. Eng.

Aoki, M. and K. Yabuki, 1977. Studies on the carbon dioxide enrichment for plant growth. VII. Changes in dry matter production and photosynthetic rate of cucumber during carbon dioxide enrichment. *Agr. Meteor.* 18:475-485.

Baier, W. and G.W. Robertson, 1965. Estimation of latent evaporation from simple weather observations. *Can. J. Plant Sci.* 45:276-284.

Baier, W., 1971. Evaluations of latent evaporation estimates and their conversion to potential evaporation. *Can. J. Plant Sci.* 51:255-266.

Baumgartner, A., 1979. Forest and the global carbon dioxide balance. In: Symposium on Forest Meteorology. WMO Bulletin No. 527. p57-78.

Bohn, H.L., 1976. Estimate of organic carbon in world soils. *Soil Sci. Soc. Am. J.* 40:468-470.

Brocker, W.S., 1975. Climatic change: Are we on the brink of a pronounced global warming. *Science* 189:460-463.

Brocker, W.S., T. Takahasi, H.J. Simpson and T.H. Peng, 1979. Fate of fossil fuel CO_2 and the global carbon budget. *Science* 206:409-418.

Campbell, C.A. and W. Souster, 1982. Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping. *Can. J. Soil Sci.* 62:651-656.

Chapman, L.J. and D.M. Brown, 1978. The climates of Canada for agriculture. Canadian Land Inventory. Report No. 3, 1966, revised 1978, Environment Canada.

Charney, J.G., 1979. Carbon dioxide and climate: A scientific assessment. Report by the ad hoc study group on CO_2 and climate to the Climate Research Board, Assembly of Mathematical and Physical Sciences, National Research Council, National Academy of Sciences, Washington, D.C.

Desjardins, R.L., E.J. Brach, P. Alvo and P.H. Schuepp, 1981. Aircraft monitoring of surface carbon dioxide exchange. *Science* 216:733-735.

Doughty, J.L., F.D. Cook and F.G. Warder, 1954. Effect of cultivation on the organic matter and nitrogen of brown soils. *Can. J. Agr. Sci.* 34:406-411.

Gates, D.M., 1983. An overview. In: "CO_2in Plants: The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide", ed. by E.R. Lemon, AAAS Selected Symposium Series No. 84.

Goudriaan, J. and H.H. van Laar, 1978. Relations between leaf resistance, CO_2 concentration and CO_2 assimilation in maize, beans, lalang grass and sunflower. *Photosynthetica* 12:241-249.

Hecht, A.D., 1981. The challenge of climate to man. *EOS* 62:1193-1197.

Idso, S.B., 1980. The climatological significance of a doubling of earth's atmospheric carbon dioxide concentration. *Science* 207:1462-1463.

Keeling, C.D., R.B. Bacastow, A.E. Bainbridge, C.A. Ekdahl Jr., P.S. Gukenther, L.S. Waterman and J.F.S. Chin, 1976. Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. *Tellus* 28:538-551.

Koerner, R.M. and D.A. Fisher, 1980. Liquified natural gas tanker transport through Parry Channel and climatic change. Report Polar Continental Shelf Project, Energy, Mines and Resources, Ottawa, Canada.

Kramer, P.J., 1981. Carbon dioxide concentration, photosynthesis and dry matter production. *Bioscience* 31:29-33.

Lemon, E.R., 1977. The land's response to more carbon dioxide. In: The Fate of Fossil Fuel CO_2 in the Oceans. N.R. Anderson and A. Malahoff (eds.), Plenum Press, N.Y. p97-130.

Mauney, J.R., G. Guinn, K.E. Fry and J.D. Hesketh, 1979. Correlation of photosynthetic carbon dioxide uptake and carbohydrate accumulation in cotton, soybean, sunflower and sorghum. *Photosynthetica* 13:260-266.

McCracken, M.C. and H. Moses, 1982. The first detection of carbon dioxide effects. Workshop summary, 8-10 June 1981, Harpers Ferry, W. Va. Bull. *Am. Met. Soc.* 63:1164-1178.

McGill, W.B., C.A. Campbell, J.F. Dormaar, E.A. Paul and D.W. Anderson, 1981. Soil organic matter losses. In: Agricultural Land: Our Disappearing heritage – A Symposium. Proc. 18th Ann. Alta. Soil Sci. Workshop, Edmonton, Alta.

Nafziger, E.D. and H.R. Koller, 1976. Influence of leaf starch concentration on CO_2 assimilation in soybean. *Plant Physiol.* 57:560-563.

Newton, J.D., F.A. Wyatt and A.L. Brown, 1945. Effects of cultivation and cropping on the chemical composition of some Western Canada prairie soils. Part III. *Sci. Agr.* 25:718-737.

Phillips, D.W., 1981. The Canadian climate in '80. A year of remarkable extremes and costly impacts. In: Canadian Climate in Review. D.W. Phillips and G.A. McKay (eds.). Environment Canada p8-19.

Rashke, K., 1975. Stomatal action. *Ann. Rev. Plant Physiol.* 26:309-340.

Rosenberg, N.J., 1981. The increasing CO_2 concentration in the atmosphere and its implication on agricultural productivity. I. Effects on photosynthesis, transpiration and water use efficiency: *Climate Change* 3:265-279.

Sionit, N., H. Hellmers and B.R. Strain, 1980. Growth and Yield of wheat under CO_2 enrichment and different levels of mineral nutrition. *Agron. J.* 73:1023-1027.

Soper, R.J. and G.J. Racz, 1967. Chemical factors of soil. In: Proceedings of the Canadian Centennial Wheat Symposium, ed. by K.F. Nielson, Modern Press, Saskatoon, Canada.

Stuiver, M., 1978. Atmospheric carbon dioxide and carbon reservoir changes. *Science* 199:253-258.

Wilson, A.C., 1978. Pioneer agriculture explosion and CO_2 levels in the atmosphere. *Nature* 273:40-41.

Wittwer, S.H., 1970. Aspects of CO_2 enrichment for crop production. *Transactions of the ASAE No. 68.* 315:249-251,256.

Woodwell, G.M., 1978. The carbon dioxide question. *Sci. Am.* 238:34-43.

Growing season dry spells in southern Ontario[1]

D. Murray Brown[2] and William D. Wyllie[3]

An analysis of the frequency and distribution of growing season dry spells from 1957 to 1979 indicated that short-period (10-to-20 day) spells occur at some time every year in southern Ontario. Dry spells of longer duration (four weeks or more) occur about once every three years. Two criteria were used in defining the dry spells. These criteria were based on nil or small precipitation amounts and the percent of stations receiving less than the given amount in a specific area. By dividing the region into five areas it was shown that one or two districts may be dry in one period of the growing season and others in another period or the dry spells may extend over the whole region at the same time, e.g. 1966. Apparently the average dry spell is of longer duration in the southwestern and central areas of southern Ontario than in the area east from Georgian Bay to the Ottawa River and the St. Lawrence-Ottawa lowlands of eastern Ontario. Rainfall during five of the longest and most extensive dry spells was accumulated and mapped to show the driest areas during such periods. There were no patterns that indicated that some areas could expect to receive more rainfall during dry spells than others.

Une analyse de la fréquence et de la distribution des périodes de déficits hydriques durant les périodes de croissance depuis 1957 jusqu'a 1979 a démontré que de courtes périodes de déficits hydriques (de 10 à 20 jours) ont lieu chaque année au sud de l'Ontario. Des déficits hydriques d'une plus longue durée (c'est-à-dire de quatre semaines ou plus) ont lieu environ une fois à tous les trois ans. On a utilisé deux critères afin de definir les déficits hydriques. Ces critères sont basés sur la hauteur minimale (ou inexistante) de la pluie

[1] This study is part of Project 657 of the University of Guelph, Ontario Ministry of Agriculture and Food Program 35, Agricultural Meteorology, and was undertaken in cooperation with the Ontario Region, Atmospheric Environment Service, Environment Canada, Toronto. Both the provincial Experience and the federal Employment Incentives program funds were used to provide assistants for the original data assembly.

[2] Professor, Agricultural Meteorology, Department of Land Resource Science, O.A.C., University of Guelph, GUELPH, Ontario. N1G 2W1.

[3] Retired. Former Scientific Liaison Officer, Ontario Region, Atmospheric Environment Service, TORONTO, Ontario.

et sur le pourcentage de stations recevant moins qu'une certaine hauteur de pluie dans une certaine région. En divisant la région du sud de l'Ontario en cinq zones, on a démontré qu'une ou deux de ces zones souffrent de déficits hydriques à un moment ou à un autre durant la période de croissance; quelquefois, les déficits hydriques s'étendent à la région entière en même temps comme on a constaté en 1966. Il semble que la durée d'un déficit hydrique moyen soit plus longue dans le sud-ouest et au coeur du sud de l'Ontario que dans la région s'étendant de l'est de la baie Georgienne jusqu'à la rivière Outaouais et les basses terres de la région Outaouais-St-Laurent de l'est de l'Ontario. La hauteur de la pluie durant cinq des déficits hydriques les plus longs et les plus étendus a été enregistré et des documents cartographiques ont été préparés afin d'indiquer les régions les plus sèches durant ces périodes. On n'a noté aucun lien entre les différentes régions étudiées et la hauteur des précipitations durant les périodes de déficits hydriques.

Short dry periods of between three days and two weeks are characteristic of subhumid and humid regions as a result of the pattern of passage of weather fronts and storm centres. Periodically dry periods extend as long as four to six weeks in some areas before a general rainfall occurs. Thunderstorm activity usually brings rainfall to some localities in these regions during the extended dry periods. Southern Ontario is typical of these patterns due to its location relative to the changing position of the 'polar front'. This paper presents the results of a study of the frequency of occurrence of dry spells over a period of 23 years and distribution of rainfall during five extended dry periods in southern Ontario.

Precipitation is usually expressed in terms of the average or 'normal' amount per month, although recently the standard deviation and extremes are also included (AES/CCP, 1982). On average most areas of southern Ontario receive between 60 and 80 mm of precipitation per month (rainfall + water equivalent of snowfall). In the May through September period between 300 and 400 mm of rain can be expected. Another precipitation statistic sometimes used is the return period (in years) of large rainfalls (Bruce, 1968). The frequency of occurrence of specified precipitation amounts and the extreme amount in each 10-day period of the year were summarized by Brown et al. (1969) for several Ontario sites. However, such statistics alone are not adequate when considering the need to supply water for irrigation and the agricultural production potential for a region.

Prolonged periods with little or no rain during the growing season cause dry soils, crop stress and reduced yields. The effects of such dry spells depend on their duration, time of occurrence, evaporative demand and the amount of rain during the period. Short dry spells in spring can be beneficial for seeding and warming the soil so that newly seeded crops emerge quickly and develop a good primary root system. Dry weather in autumn can also be beneficial for harvest operations. On the other hand, dry spells in summer are usually detrimental to crop production particularly if accompanied by very high evaporative demand days. Some studies have calculated seasonal moisture deficiencies (Sanderson, 1950) and the occurrence of both short duration and extended dry periods (brown et al., 1968) for a few locations across the region. The average annual seasonal water deficit also has been mapped in several studies (Sanderson, 1950; Brown et al., 1968; Agriculture Canada, 1977). The present study concentrates on the occurrence and duration of dry spells between extensive rainfalls across the region. The objectives were: (a) to compare the occurrences of such dry spells for different regions in southern Ontario; and (b) to map the distribution of rainfall during the longest and most wide-spread dry periods that have occurred over the 23 years from 1957 to 1979.

DEFINITION OF DRY SPELLS

Both temporal and spatial variations are typical of precipitation events, especially during the summer season when much of the rainfall results from thunderstorms. Thus dry spells, too, vary in length and geographic extent. This makes it difficult to be specific in defining a dry spell because two or three separate thunderstorms may occur in one locality and completely miss a neighbouring area. The latter area would have a dry spell. Numerous definitions and criteria have been used to define droughts (long dry spells) in humid and semi-humid regions (W.M.O., 1975) and their effect on agriculture (Gibbs, 1975). For this study two quite different criteria were used to determine if comparable dry periods would result from the analysis of rainfall data for a defined area. These are referred to as the 60% and 80% criteria. *60% criterion* – a day at an observing station was considered dry if the rainfall was less than 7.6 mm (0.3") and for an area to be considered dry 60% of the stations in the area had to experience several days of 'dry' weather; *80% criterion* – a day at any station was considered dry if no measurable rain fell and an area was considered dry if more than 80% of the stations in the area had no rain.

AREA DIVISIONS OF SOUTHERN ONTARIO

The precipitation records examined in this study were abstracted from copies of the Monthly Record of Meteorological Observations in Canada. Over two thirds of these records for the years 1957 to 1979 were reported in groups of counties such as the Lake Erie and Niagara Counties. In dividing up southern Ontario into fairly uniform geographic areas for this study, it was decided to use these county grouping as much as possible. As a consequence, southern Ontario was divided into five areas as shown in Figure 1.

CLIMATIC STATIONS USED IN THE STUDY

Climatic stations used in the analysis for Objective (a) were selected to give as uniform as possible a distribution of data across each area, thus, preventing a large number of stations in one sector from dominating the analysis for an area.

FIGURE 1 Areas of southern Ontario with locations of Climatological Stations used in study of occurrences of dry spells. (Numerical listing and names of Stations are in Appendix A).

TABLE 1 Average length and range in length of longest dry spells for each area considering each year in the 1957 to 1979 period based on the 80% criterion (top) and the 60% criterion (bottom).

Area	Range of Longest Dry Spells	Average Length Longest Dry Spells
(a) *80% criterion*		
1	12-41	23.3
2	12-47	26.0
3	12-47	24.7
4	10-31	17.4
5	10-21	17.3
(b) *60% criterion*		
1	29-67	46.6
2	25-102	48.8
3	32-73	48.8
4	23-56	40.7
5	20-54	37.4

Stations were selected which could provide data for the full 23-year period of the study from 1957 to 1979. When a station had missing data for any month, it was substituted for by a nearby station as shown in Appendix A. Areas 1, 2 and 4 had sufficient stations available to achieve a uniform distribution. However, in Areas 3 and 5, a uniform distribution was not possible due to data being unavailable in certain sectors. Rainfall data for all sites with a complete record were used for mapping purposes to satisfy Objective (b).

COMPARISON OF DRY SPELLS OCCURRENCES BASED ON THE TWO CRITERIA

Daily precipitation records for the period May 1st to September 15th from 1957 to 1979 were examined so as to determine the percentage of stations in each area which satisfied the criterion of no measurable rain, or of less than 7.6 mm of rainfall. From these data, the length of dry spells satisfying the 60% and the 80% criteria were determined. The periods with the longest dry spells based on each criterion in each year and in each area were selected for evaluation. The 80% criterion yielded shorter dry spells than the 60% criterion. The *average* lengths of the longest dry spells for the 23 years based on the 80% criterion ranged from 17 days for Area 5 to 26 days for Area 2 (Table 1a) compared to 37 to 49 days based on the 60% criterion (Table 1b). A comparison of the length and time of occurrence of the longest dry spells using the 60% and 80% criteria is shown for four example years in Figure 2. The differences among Areas in timing of the dry spells based on the two criteria are shown by the occurrences in 1958, 1967 and 1976. This lack of consistency occurred in most years. The most obvious consistency among Areas, particularly Areas 1 to 3, occurred in 1966. This dry spell lasted from mid-June to late July across most of southern Ontario. Other years in which both criteria showed uniformity in timing among dry spells across at least three of the Areas were 1957, 1963, 1974, 1977, 1978 and 1979. Since there was a lack of consistency in timing among dry spells between the two criteria in most of the 23 years, it was decided to use the 80% criterion to illustrate the timing of the longest dry spells for each of the five areas in the 23 years of the study. This was the obvious choice since it provided the truest picture of dry spells across the region.

LENGTHS OF DRY SPELLS IN EACH AREA OVER THE 23 YEARS

The timing of the longest dry spells based on the 80% criterion is illustrated in Fig. 3 for each Area in each year used in the study. In the 23 year period there were seven years that had fairly long and extensive dry spells in mid-summer (between June 15 and Aug. 15). Two of these (1966 and 1978) covered all of southwestern and central Ontario (Areas, 1, 2 and 3) and lasted for a 30 to 47 day period from mid-June to the latter part of July. Another extensive spell occurred in 1963 and lasted over 30 days in Areas 1, 2 and 3, but ended before

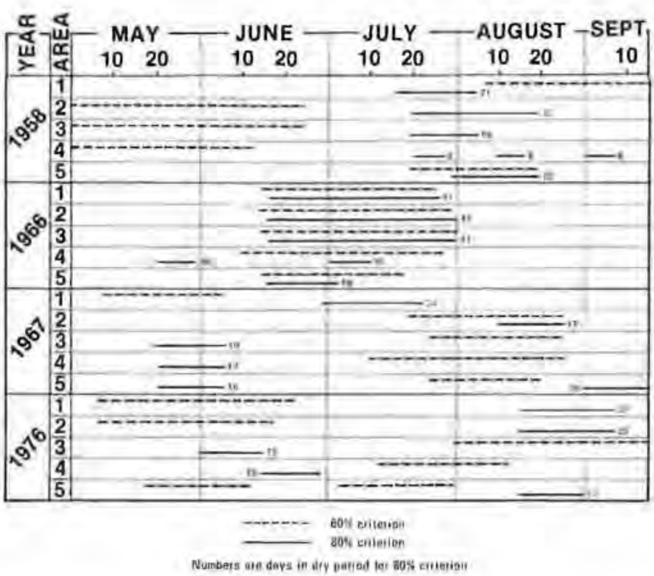


FIGURE 2 A comparison of the length and time of occurrence of the longest dry spells in each of four years using the 60% and 80% criteria for five areas.

mid-July. This was the long dry spell that reduced hay and pasture yields in eastern Ontario (Area 4). It does not show up as very severe based on the 80% criterion, but was more apparent when the 60% criterion was used. This was the first year of a series of 4 years, from 1963 to 1966, when a lack of precipitation in the early to mid-part of the growing season affected yields of many crops in southern Ontario. Parts of eastern Ontario received less than 60 mm of rainfall in June and July, 1963. The 'normal' for the two months is over 150 mm. This area was also fairly dry in June, July and August 1964, when a large part of the region received less than 100 mm. In 1965, the dry weather occurred earlier as much of eastern Ontario received less than 50 mm in May and June. Considerable hay was hauled into the region from western Ontario, Quebec and New York state in order to sustain dairy herds through the following winter. Dry weather prevailed in much of southern Ontario from early June to early August, 1966 as depicted in Figures 2, 3 and 4.

The dry spell in 1979 lasted just over three weeks in July mainly in Areas 3, 4 and 5. In 1957, 1958 and 1970, mid-summer dry spells occurred after mid-July and into August. These latter spells were a benefit to spring grain harvest, but slowed seed filling rates in crops such as corn, soybeans, and white beans. The dry spells that occurred in May 1971, 1975 and 1977 were a benefit to corn and soybean planting operations but could have caused problems with seed germination had they lasted longer.

The late growing season dry spells, based on 80% criterion (Fig. 3) are most evident in 1969 (all 5 Areas), 1973 (Areas 1, 2 and 3) and 1976 (Areas 1

FIGURE 3 Dry spells based on 80% criterion for growing seasons from 1957 to 1979 for the five Areas.

and 2). There was evidence of late season dry spells in the same years based on the 60% criterion.

It is apparent from Figure 3 and Table 1 that dry spells last longer in southwestern and central Ontario (Areas 1, 2 and 3) than in eastern Ontario and the Algonquin highlands (Areas 4 and 5). This pattern is very important from an agricultural standpoint as over 90% of the farm cash receipts in southern Ontario go to farmers in Areas 1, 2 and 3.

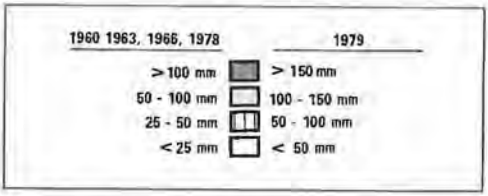
DISTRIBUTION OF RAINFALL DURING SELECTED SEVERE DRY SPELLS

Five significant dry periods in terms of duration and extent were selected for mapping the distribution of rainfall across the whole of southern Ontario. These dry periods occurred between July 19 and August 28, 1960; May 23 and July 12, 1963; June 16 and July 26, 1966; June 13 and July 25, 1978; and June 11 and August 8, 1979. Rainfall data for all sites with a complete record, as published, were used for each period rather than the limited number of stations used in the original survey study (Objective a). Thus just over 200 sites were used for this part of the study, except in 1960, when about 175 sites recorded usable rainfall data. Unfortunately, these sites were not uniformly distributed across the region. The greatest concentration of sites occurs in the southwest part of Area 3 and the sparsest in Area 5. As a result of the sparseness of sites in parts of some Areas, it is likely that some thunderstorm events went unrecorded during these dry spells. Nevertheless maps of the rainfall distribution based on the 'official' recording sites should provide useful information on the approximate extent of the driest areas for agricultural water management planning in the future.

The dry spell in 1966 was the severest and most widespread in the 23 years studied. The rainfall pattern for this dry spell is illustrated in Figure 4. Most of southern Ontario received less than 25 mm of rainfall (<24% of normal) in the 41-day period from June 16 to July 26, and a large part of Areas 1, 2 and 3 received less than 15 mm. Normally, rainfalls from mid-June to July 26th average just over 100 mm. The southwest part of Area 1 was the only part of southern Ontario to receive near or above normal rainfall during this period in 1966. Isolated localities received in excess of 50 mm. The rest of southern Ontario was very dry during this critical mid-summer period with widespread areas from the Lake Huron/Georgian Bay to Lake Ontario receiving less than 15% of normal rainfall.

The next most severe dry spell in this 23-year period occurred in 1978 during a period similar to that in 1966. It lasted 43 days from June 13 to July 25 (Fig. 5). The driest parts with less than 25 mm (<23% of normal) occurred in narrow bands - one from near southern Lake Huron to northern Lake Erie; another north of the western end of Lake Ontario and extending to southern Lake Simcoe; and a third on the north shore of Lake Ontario at the eastern end. Most of the remainder of southern Ontario received less than 50 mm, which is still quite dry when one considers that the evapotranspiration from well-watered crops could have exceeded 200 mm (based on Thornthwaite, 1948 method) during this 43-day period. The only parts that exceeded 100 mm were in the northern and eastern sections of the region.

A more recent mid-summer dry spell in 1979 (Fig. 6) started about the same time as those in 1966 and 1978, but lasted into August for a total of 59 days. This dry spell was less severe than the other two as most parts received in excess of 100 mm of rainfall (>66% of normal) and some isolated parts received



Legend for Rainfall Maps (Figures 4-8)

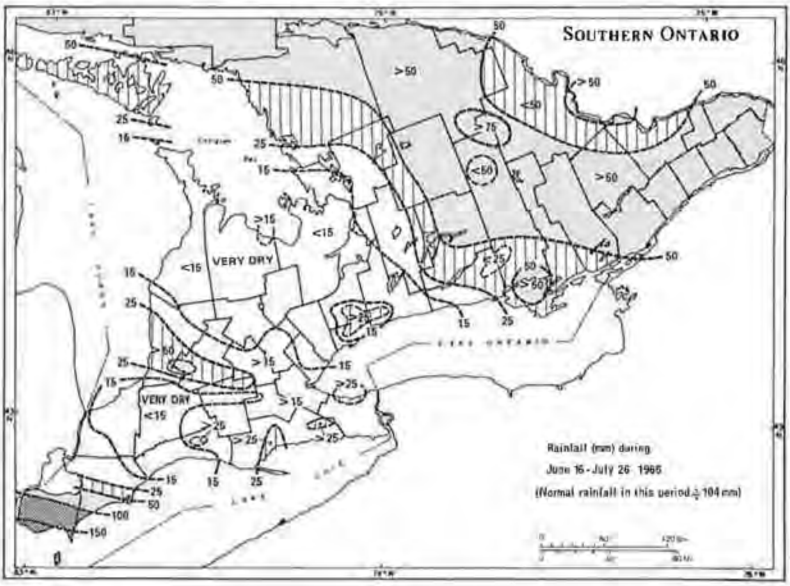


FIGURE 4 Approximate distribution of rainfall over southern Ontario during a 41-day dry period in June-July, 1966.

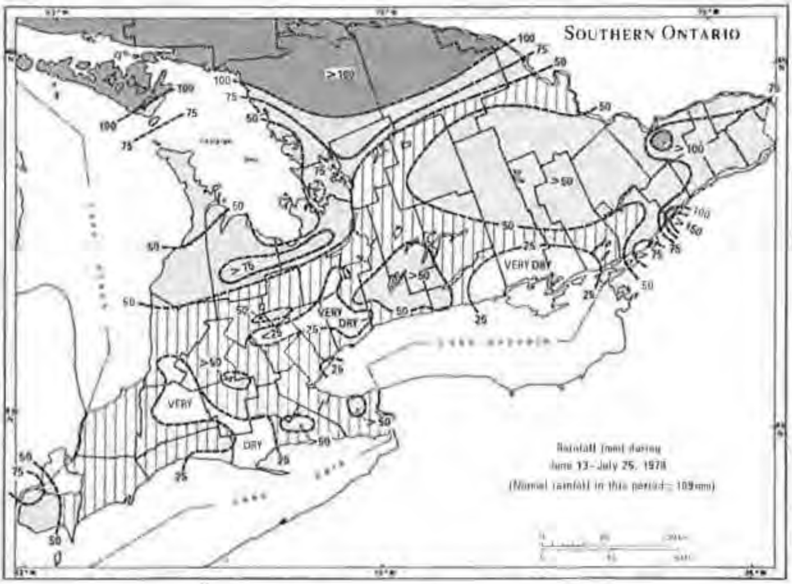


FIGURE 5 Approximate distribution of rainfall over southern Ontario during a 43-day dry period in June-July, 1978.

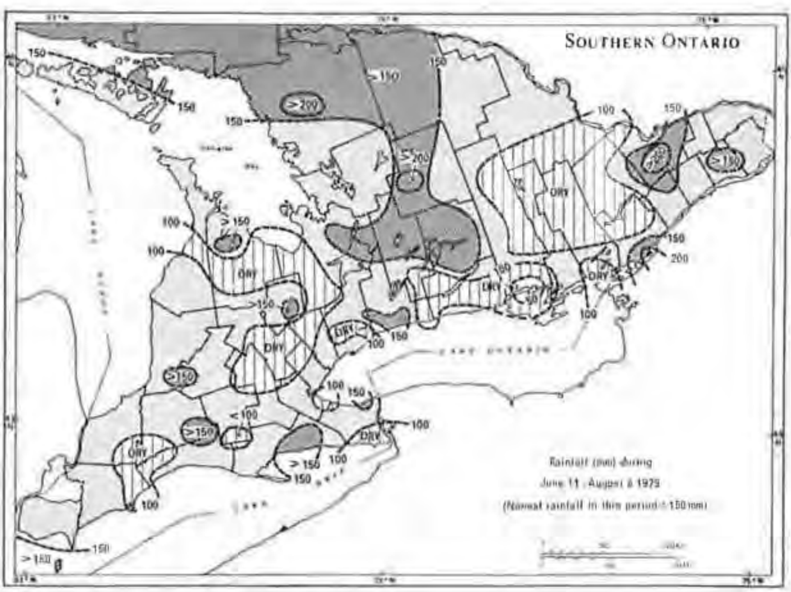


FIGURE 6 Approximate distribution of rainfall over southern Ontario during a 59-day dry period in June-July-August, 1979.

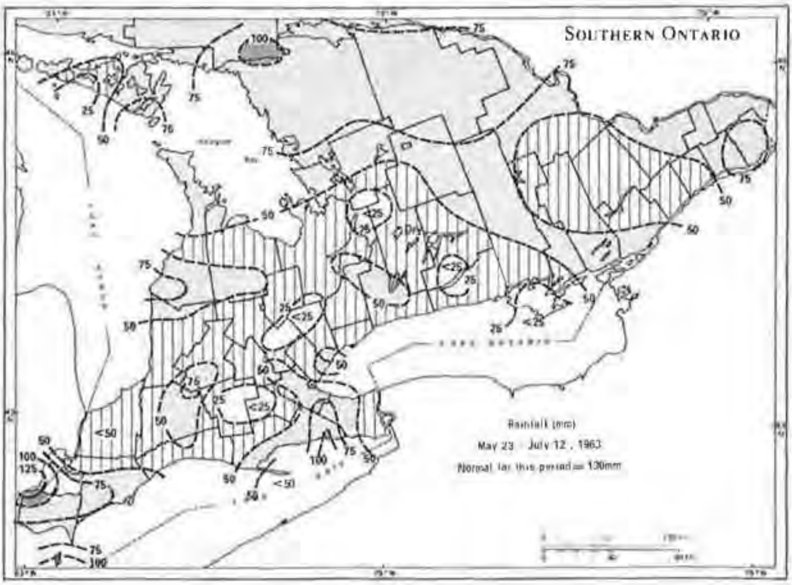


FIGURE 7 Approximate distribution of rainfall over southern Ontario during a 51-day dry period from late May to early July, 1963.

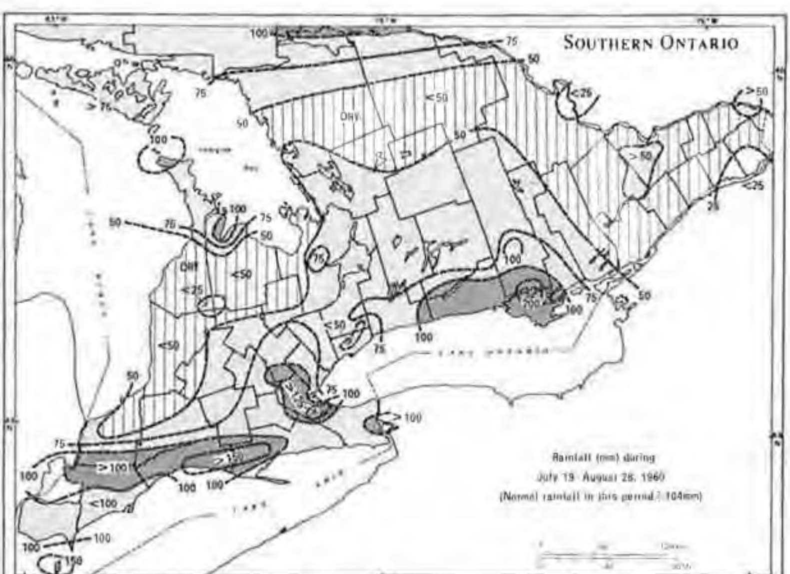


FIGURE 8 Approximate distribution of rainfall over southern Ontario during a 41-day dry period in July-August, 1960.

in excess of normal (150 mm). The driest parts with less than 100 mm are fairly widely scattered across the region. The largest dry areas occurred south of Georgian Bay and in eastern Ontario. The driest spot with <50 mm of rainfall occurred in the Belleville area (station 28 in Fig. 1). An indication of the severity of this dry spell can be gained from the fact that the evapotranspiration from well-watered crops could have exceeded 270 mm in this 59-day period.

The 1963 dry period occurred earliest in the season of the five major dry spells studied, starting in late May and lasting to mid-July (Fig. 7). It was the first of the four mid-sixties dry seasons to severely affect crop production in southern Ontario. The large area in eastern Ontario that received less than 50 mm of rain in the 51-day period illustrates why hay and pasture crops were so severely affected that year. No doubt new seedings of hay were also affected and resulted in lower yielding hay crops in subsequent years.

In 1960 the main dry area occurred east of Lake Huron, and east from Georgian Bay including all of the eastern counties (Fig. 8). This dry period occurred later than the others, July 19 to August 28. The normal rainfall in this period would be just over 100 mm, and less than 50 mm fell in most of Areas 2, 4 and 5. Areas along the north shores of Lakes Erie and Ontario received the most rainfall with a few parts exceeding 150 mm and over 200 mm in the Belleville area (station 28 in Fig. 1). This was the centre of one of the driest areas in both 1978 and 1979.

A comparison of the five maps shows there is little consistency in the spatial distribution of dry periods across southern Ontario. There appeared to be a tendency for areas near the Great Lakes to be slightly more prone to dry spells. However, the small encircled localities with rainfall greater than the surrounding areas occurred just as frequently near the Lakes as further inland. These circles indicate thunderstorm events at the measurement sites and may not represent a large enough area due to the sparsity of sites. This is especially true for Areas 4 and 5. On the other hand, very scattered storms, such as are common in dry spells, may give an exaggerated impression of the extent of rainfall when caught by two or more stations in an area. Radar mapping could assist in determining the extent of such rainfalls.

SUMMARY AND CONCLUSIONS

An attempt was made to depict the frequency and distribution of dry spells during the growing season across southern Ontario. Two criteria were used to determine their frequency of occurrence from historical rainfall records. The region was divided into five areas (Fig. 1) and the criteria applied to each. When only 60% of the chosen recording sites in an Area and a small amount of daily rainfall were used to assess the length of dry spells it was apparent that this criterion resulted in periods which were too long to be representative. When 80% of chosen sites and no rainfall was used as the criterion, it appeared slightly too restrictive. The average length of the longest dry spell for the 23 years ranged from 37 to 49 days based on the 60% criterion and from 17 to 26 days from the 80% criterion (Table 1). Figure 2 shows examples based on both criteria. In some cases the dry spells based on the two criteria coincide and in other cases the one criterion occurs at one time of the growing season and the other at another time.

Five of the most severe dry spells, in duration and geographic extent were chosen for mapping. The total rainfall recorded during each of these dry spells at all measurement sites was mapped to provide an indication of the real distribution of the driest areas (Figs. 4 to 8). Three of these spells occurred between mid-June and the latter part of July or early August, when temperatures and evaporative demand are usually the highest. There was no consistency in the spatial distribution of dry periods across the region.

A study of this nature, once the dry spells have been established, could be assisted considerably by integrating the computer-derived SCEPTER radar rainfall maps during the dry spell. This would help to put limits on the isolated thunderstorm downpours and likely pick up a few that go unrecorded at the official rainfall measurement sites. As the need for more careful planning of our water resources increases, and to be sure that agriculture gets its share, the benefits of such a study using the SCEPTER maps will be more apparent.

ACKNOWLEDGEMENTS

A study of this nature requires input from many people. First, the volunteer weather observers and those at airport, city and agricultural experiment stations, recorded the precipitation. Then, there were the students who helped compile the data and put it on maps and the cartographer who made the final versions of the maps. Finally, the reviewers of an original manuscript made many useful suggestions.

Unfortunately, we cannot thank all of the weather observers individually, but we do thank them collectively. The students who contributed were Marie Ridder and Agnes O'Hannesin, whose efforts were much appreciated. We would also like to thank our cartographer Andy McLennan, our typist Sheree Henry and our reviewers – Terry Allsopp, Andy Bootsma, Bruce Findlay and Robert Hughes.

Financial support from the Ontario Ministry of Agriculture and Food and the Atmospheric Environment Service, Environment Canada, is gratefully acknowledged.

AES/CCP. 1982. *Canadian Climate Normals* - Temperature and Precipitation 1951-1980 Ontario. Environment Canada, Atmospheric Environment Service. Downsview. A Publication of the Canadian Climate Program. 254 pp.

Agriculture Canada, 1977. Agroclimatic Atlas. Agrometeorology Section, Research Branch, Agriculture Canada, Ottawa, Ontario. 17 maps.

Brown, D.M., G.A. McKay and L.J. Chapman. 1968. The Climate of Southern Ontario. Climatological Studies Number 5. Atmospheric Environment Service. Environment Canada. Downsview. Reprinted, 1980.

Brown, D.M., J. Rogalsky and G.A. McKay. 1969. *Daily Temperature and Precipitation Frequencies in Ontario.* Climatological Studies Number 7. Meteorological Branch, Canada Dept. of Transport. Toronto. 100 pp.

Bruce, J.P. 1968. Atlas of Rainfall Intensity-Duration Frequency Data for Canada. Climatological Studies Number 8. Meteorological Branch, Canada Dept. of Transport. Toronto. 2pp. 31 figs.

Environment Canada. Monthly Record of Meteorological Observations in Canada. Atmospheric Environment Service, Environment Canada.

Gibbs, W.J. 1975. Drought - Its Definition, Delineation and Effects. In World Meteorological Organization Special Environmental Report No. 5, Drought (WMO. - No. 403) 1-39. Secretariat of W.M.O. - Geneva - Switzerland.

Sanderson, Marie, 1950. Moisture relationships in southern Ontario. *Sci. Agric.* 30: 235-255.

Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. *Geogr. Rev.* 38: 55-94.

W.M.O. 1975. *Drought and Agriculture.* Report of Working Group on the Assessment of Drought. World Meteorological Organization. Technical Note No. 138 (WMO - No. 392) 127 pp. Secretariat of W.M.O. - Geneva - Switzerland.

Area 1

1	Chatham	7	Sarnia
2	Hamilton	8	Simcoe
3	Harrow	9	Vineland Station
4	London A	10	Welland
5	Ridgetown	11	Windsor
6	St. Thomas	12	Woodstock

Area 2

13	Blyth (13a Clinton)	20	Kitchener
14	Brucefield	21	Lucknow
15	Chatsworth	22	Orangeville
16	Durham	23	Paisley
17	Fergus Shand Dam	24	Redickville
18	Goderich	25	Stratford
19	Guelph OAC	26	Wiarton

Area 3

27	Albion	37	Midhurst
28	Belleville	38	Midland
29	Bloomfield	39	Orillia
30	Bradford (30a Newmarket)	40	Orono
31	Brampton	41	Peterborough
32	Burlington	42	Pickering (42a Oshawa)
33	Campbellford	43	Port Hope (43a Cobourg)
34	Collingwood	44	Toronto
35	Kingston	45	Toronto Int'l Airport
36	Lindsay	46	Trenton

Area 4

47	Apple Hill (47a Dalkeith)	54	Hawkesbury
48	Arnprior (48a Chat's Falls)	55	Kemptville
49	Brockville	56	Metcalf (56a Ottawa NRC)
50	Carelton Place (50a Almonte)	57	Morrisburg
51	Carp	58	Ottawa
52	Cornwall	59	Port Elmley
53	Glen Gordon (53a Lancaster)	60	St. Elmo (60a Russel)

61	Bancroft	69	Minden
62	Chalk River	70	Muskoka A
63	Chenaux	71	North Bay
64	Combermere	72	Parry Sound
65	Des Joachims (65a Rolphton)	73	Pembroke (73a Petawawa)
66	Haliburton	74	Powassen (74a Magnetawan)
67	Huntsville	75	Scotia (75a Burkes Falls)
68	Killaloe (68a Madawaska)		

A simple procedure used to estimate selected growing degree-day summations in spring and autumn in the Atlantic region

A. Bootsma

Simple regression equations were developed which accurately estimate the average date when 350 and 450 growing degree-days above 5°C (GDD_5) have accumulated in spring and when 450 GDD_5 are remaining in autumn in the Atlantic region of Canada. Monthly normal temperatures were used as predictors in the equations. Coefficients of determination (r^2) were high ($\geq$0.98) and standard errors of estimate were near 1 day.

On a établi des équations à régression simple permettant d'évaluer avec précision la date moyenne à laquelle 350 ou 450 degrés-jours au-dessus de 5°C (GDD_5) se sont accumulés au printemps et celle à laquelle il reste 450 GDD_5 en automne dans la rétion de l'Atlantique du Canada. Les normales mensuelles de température servent d'indices dans les équations. Les coefficients de détermination (r^2) pour ces équations sont élevés ($\geq$0,98) et l'erreur-type des estimations ne dépasse pas un jour.

Growing degree-days (GDD) above selected base temperatures are commonly used in agricultural applications as an indicator of crop development and for classifying agroclimates of regions. Normal GDD values can be calculated from temperature normals, although corrections must be made for periods when daily mean temperatures can fall below the base value. Thom (1966) developed a method of estimating the required correction based on the standard deviation of the mean monthly air temperature. A more direct method is to use daily mean temperatures to calculate GDD and then take the average for the required period of years.

Average dates when selected summations of GDD above 5°C (GDD_5) were reached in spring and remained in autumn were required to formulate general cutting management guidelines for forage crop production in the Atlantic region of Canada. Summations of 350 and 450 GDD_5 in spring were chosen for this purpose since these summations corresponded closely with the GDD_5 required to reach the optimum stage of development for the first harvest of several forage cultivars recommended for production in the region (Bootsma,

Agrometeorology Section, Land Resource Research Institute, Research Branch, Agriculture Canada, Ottawa, Ontario K1A 0C6.

Land Resource Research Institute Contribution No. 83-16

1984). The average date when 350 GDD_5 have accumulated in spring was applicable to early timothy cultivars such as Clair, while the 450 GDD_5 date applied to alfalfa, red clover and timothy cultivars which reach optimum maturity for harvest at about the same time as Climax timothy. The 5°C temperature base has also been used by other workers to estimate the development stage in alfalfa (Selirio and Brown, 1979). The average date when 450 GDD_5 remain in autumn was required as an indicator of the start of the autumn period during which alfalfa should not be harvested for plants to gain winter hardiness (Bootsma and Suzuki, 1983).

The methods described above for calculating GDD normals are not particularly well suited for calculating dates when the required GDD summations are reached. Thom's method is used only for calculating monthly normals. Published GDD normals are generally for monthly values (Environment Canada, 1982) or sometimes weekly for selected climate stations (Treidl, 1979). Consequently, the required data for all climate stations in the Atlantic region were not readily available from published sources. Possibly the best procedure for calculating average dates of the selected GDD summations would be to use daily temperature records, but this also has several drawbacks, namely:

i) daily temperature records for all climate stations in the region would need to be readily available to the user;
ii) dates calculated from short term stations would need to be adjusted to the long term normal;
iii) the proper starting date for accumulating GDD may be difficult to determine in years when GDD begin to accumulate before growth of forages begins.

To overcome the above limitations, a simple method was developed which estimates average dates of selected summations of GDD_5 from monthly normals of average mean daily air temperature. Regression and correlation analyses were used to determine the relationship between these dates and air temperature. Normal rather than yearly data were used throughout this study because the intent was to determine spatial but not temporal variation in the date of selected GDD_5 summations in the Atlantic region for zonation purposes (Bootsma, 1984).

DEVELOPMENT OF REGRESSION EQUATIONS

Regression equations were determined using climate data for the 1941-1970 normal period from 68 selected stations in the provinces of New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland (Environment Canada, 1971).

For the spring period, the equations determined using 68 cases (stations) were:

$$S_{350} = 126.72 - 12.527\,T_1 + 0.3077\,T_1^2 \quad (1)$$

$$S_{450} = 140.11 - 13.201\,T_1 + 0.3354\,T_1^2 \quad (2)$$

where S_{350} and S_{450} are the average dates (1941-1970 normals) when 350 and 450 GDD_5, respectfully, have accumulated in spring (June 1=1): T_1 is the normal average mean daily temperature for May and June, i.e. $\frac{T(May) + T(June)}{2}$, (°C)

Equations (1) and (2) had coefficients of determination (r^2) of 0.99 and standard errors of estimate (s.e.e.) of 0.90 days. Including the quadratic term (T_1^2) in addition to T_1 in the regressions increased the explained variances significantly ($P \leq 0.01$) and reduced the s.e.e. from 1.5 days to 0.9 days.

For the autumn period, the following equation was determined using 68 cases (stations):

$$F_{450} = -43.34 + 6.317\ T_2 \quad (3)$$

where F_{450} is the average date when 450 GDD_5 remain in autumn (August 1=1); T_2 is the average mean daily air temperature for September and October, i.e. $\frac{T(September) + T(October)}{2}$, (°C)

Equation (3) had an r^2 value of 0.98 and a s.e.e. of 1 day. Including a quadratic term (T_2^2) in the regression did not increase the explained variance significantly ($P \leq 0.05$).

The dependent variables in regression (S_{350}, S_{450}) were calculated by accumulating daily values of GDD_5 from normal temperature graphs plotted using monthly air temperature normals for the 1941-1970 period. Slight corrections (less than 25 GDD_5) were applied to monthly GDD summations for months in which daily mean air temperatures could drop below the 5°C base temperature in some years. Corrections were based on a comparison between monthly GDD_5 sums calculated from the normal temperature graph and those calculated from daily maximum and minimum air temperatures by Environment Canada. The corrections have been described in more detail elsewhere (Bootsma, 1984).

The independent parameters T_1 and T_2 were selected because (i) GDD_5 are derived from temperatures, (ii) the period when selected GDD sums accumulate in the Atlantic region coincided closely with the period over which T_1 and T_2 were averaged, and (iii) these variables were readily available for most short and long term climate stations in the Atlantic region.

Values for S_{350}, S_{450} and F_{450} determined from normal temperature graphs, with corrections applied, were compared with dates determined by interpolating weekly GDD_5 summations published by Environment Canada (Treidl, 1979) for 36 locations, using linear regression and correlation analyses. The dates determined using these two methods were highly correlated ($r \geq 0.98$). Regression coefficients for the spring dates (S_{350} and S_{450}) were not significantly different from the 1:1 relationship ($P \leq 0.05$). The s.e.e. was 1.2 days for both dates. The slope of the regression line for the autumn date (F_{450}) was not significantly different from 1.0 ($P \leq 0.05$) but the constant in the regression equation was significantly different from 0.0. The dates obtained using the graph method were consistently 2 to 3 days earlier than those obtained from Environment Canada data. Reasons for this bias were not immediately apparent. For agricultural purposes, the differences were relatively insignificant and could be readily adjusted for if needed. The s.e.e. for the autumn regression was 1.27 days.

DISCUSSION

The regression equations which have been developed here can provide estimates of average dates when the selected GDD_5 summations have accumulated in spring or remain in autumn in the Atlantic region from long-term temperature normals or from short term temperature data adjusted to the 30-year normal period. The accuracy of these estimates is more than sufficient for the agricultural applications which have been presented. Dates can be readily computed for new 30-year normal periods without recalculating the regression coefficients. However, the relationships should not be used outside the Atlantic region without further testing. Although the method used may be applicable to other regions, the regression coefficients and the independent parameters T_1 and T_2 may differ. For example, in regions with earlier springs it may be desirable to include the mean temperature for April in the parameter T_1.

The regression equations were developed for specific GDD summations using a base temperature of 5°C. Equations could be developed for applications requiring different base temperatures or GDD summations. It would be useful to test the validity of using these equations for individual seasons so that expected dates of selected GDD sums could be readily calculated from long range temperature anomaly forecasts, should these become sufficiently reliable.

REFERENCES

Bootsma, A. 1984. Climatic zonation for forage crops in the Atlantic region. Agric. Can., Land Resource Res. Inst., Ottawa (in press).

Bootsma, A. and Suzuki, M. 1983. Critical fall rest period for alfalfa in the Atlantic region. Agriculture Canada, Canadex 121.07, 2pp.

Environment Canada. 1971. *Temperature and precipitation 1941-1970, Atlantic provinces.* Atmospheric Environment Service, Downsview, Ont., 55pp.

Environment Canada. 1982. *Canadian climate normals, volume 4, degree days 1951-1980.* Atmospheric Environment Service, Downsview, Ont., 280pp.

Selirio, I.S. and Brown, D.M. 1979. Soil moisture-based simulation of forage yield. *Agric. Meteorol.* 20:99-114.

Thom, H.C.S. 1966. Normal degree days above any base by the universal truncation coefficient. *Monthly Weather Review* 94(7):461-465.

Treidl, R.A. (ed.) 1979. Handbook on agricultural and forest meteorology. Part II. Atmospheric Environment Service, Downsview, Ont., Table 5.

Comments on "Do increases in atmospheric CO_2 have a cooling effect on surface air temperature?"

Kevin Hamilton

In a recent paper Idso (1983) makes some very misleading remarks about the possible effect of H_2O continuum absorption on the predicted sensitivity of surface temperature to changes in atmospheric CO_2 concentrations. He correctly points out that the widely quoted estimates of the warming expected to accompany increased CO_2 levels (e.g., Manabe and Wetherald, 1980) are based on models that do not include H_2O continuum absorption in the 12-18 micron region of the spectrum. He then notes that recently Kiehl and Ramanathan (1982) have incorporated this extra source of infrared opacity in a radiative transfer model of the atmosphere. In their paper Kiehl and Ramanathan (KR) determined the change in the calculated infrared flux resulting from a doubling of CO_2 concentration (using *fixed* tropospheric temperatures for the comparison). Idso remarks that KR found the change in their downward infrared flux at the ground was reduced by a factor of three when H_2O continuum absorption was included in the model. Idso clearly means to imply that current estimates of the surface temperature response to CO_2 variations must thus be too large by a factor of three.

In reality the earth's surface temperature and the atmospheric temperatures throughout the depth of the troposphere are strongly coupled through dynamical mechanisms such as small scale convection and vertical heat transports by baroclinic waves. Thus, *as KR themselves rather emphatically state*, the total radiative heating of the earth plus troposphere system is a much more suitable quantity to employ when judging the possible effects of a change in the radiative transfer algorithms on calculated climate sensitivity. KR also computed this quantity and found that the sensitivity of the total earth-tropospheric heating to a doubling of CO_2 is altered by only 4.5% when H_2O continuum absorption is included. Thus one can be fairly confident that consideration of H_2O continuum effects will make only very modest changes in model estimates of climate sensitivity.

Department of Oceanography
University of British Columbia
Vancouver, B.C. V6T 1W5

REFERENCES

Idso, S.B., 1983: Do increases in atmospheric CO_2 have a cooling effect on surface air temperature? *Climatological Bulletin, 17*, No. 2, 22-26.

Kiehl, J.T. and V. Ramanathan, 1982: Radiative heating due to increased CO_2: The role of H_2O continuum absorption in the 12-18 micron region. *Journal of the Atmospheric Sciences, 39*, 2923-2926.

Manabe, S. and R.T. Wetherald, 1980: On the distribution of climate change resulting from an increase in CO_2 content of the atmosphere. *Journal of the Atmospheric Sciences, 37*, 99-118.

The impetus for CO_2-induced climatic change: a reply to comments of Dr. Kevin Hamilton

Sherwood B. Idso

Kevin Hamilton's comments cut to the very core of a key question of the CO_2-climate controversy: What is the proper impetus or driving force for surface air temperature change? In the short note of mine which he challenges (Idso, 1983), I imply that this driving force is the CO_2-induced change in total radiant energy absorbed at the Earth's surface. Dr. Hamilton disagrees, joining with Kiehl and Ramanathan (1982) to "emphatically state" that the total CO_2-induced radiative heating of the Earth-troposphere system is "much more appropriate."

The manner in which this latter philosophy is posited by both Dr. Hamilton and Kiehl and Ramanathan is a prime example of what I have called "science by decree" in my recent book (Idso, 1982a). It is the unqualified declaration that something is proper or improper, enlightening or misleading, true or false, presented without any evidence to substantiate it. In fact, the statement is generally made so matter-of-factly that it has almost the ring of a natural law.

Contrast this approach with that taken in my short note relative to the ultimate climatic consequences of the rapidly rising CO_2 content of Earth's atmosphere. Actual data from the real world are presented, possible inferences are drawn, and tentative conclusions reached. I then state that the exercise in question merely *indicates* something and close with the caution that it by no means *proves* it. Indeed, even the title of my paper is followed by a question mark.

But let us return to the key point raised by Dr. Hamilton, the question of what is the proper impetus for CO_2-induced climatic change. It is surely true, as he implies, that the surface of the Earth is coupled to the troposphere above it, and that they in some way function as a system. But what is the physics of that interrelationship? Is the linkage of such a nature that a change in the energy content of the total system results in a unique change in the temperature of its lower boundary? Or, are there multiple solutions to the problem, such that different *distributions* of the total energy content of the system may result in different boundary conditions at its lower surface?

U.S. Water Conservation Laboratory
4331 E. Broadway Rd.
Phoenix, AZ 85040, U.S.A.

Irrespective of what the correct answers to these questions may be, it seems reasonable to believe that the temperature of the lower boundary of the system will be determined in large measure by something happening in the vicinity of that boundary; and a not-illogical choice for that "something" is a perturbation of the downward flux of radiant energy to the Earth's surface, for this phenomenon-process would seem to qualify as a good mechanism by which information about what is happening in the troposphere above may be transmitted to the surface below. Consequently, this *hunch*, as it were, allows us to formulate a *testable hypothesis*, which is that planet Earth has a *unique* "surface air temperature response function," defined as the change in surface air temperature brought about by a change in radiant energy absorbed at the surface. And if this hypothesis can be proven, it follows as a logical consequence that the proper impetus for surface air temperature change within the context of the CO_2-climate question is indeed the CO_2-induced change in total radiant energy absorbed *at the Earth's surface.*

Now the first evaluation of a surface air temperature response function for Earth's atmosphere to be made by empirical means within the context of the CO_2-climate question was that of Newell and Dopplick (1979), who inferred from a variety of experimental observations that an appropriate mean value for the globe as a whole was $0.1°K\ (Wm^{-2})^{-1}$. Can this number be obtained by any other empirical means?

Consider the Earth as it presently exists. It currently has a mean surface air temperature of 288°K. Imagine next that the entire atmosphere were somehow removed, but that the absorption of solar radiation at the surface remained unaltered. The mean surface temperature of the globe in this situation would ultimately decline to about 254.4°K. This 33.6°K decrease in surface temperature comes about as a result of a 348 Wm^{-2} reduction in atmospheric thermal radiation to the surface (Idso, 1982b,c). Consequently, the *total equilibrium* surface air temperature response function of Earth's atmosphere is derived from this "thought experiment" to be $33.6°K/348\ Wm^{-2}$ or about $0.1°K\ (Wm^{-2})^{-1}$, precisely the same value as that derived by Newell and Dopplick.

Consider once again the Earth as it presently exists, with its mean annual equator-to-pole surface air temperature gradient sustained by the mean annual equator-to-pole gradient of total surface-absorbed radiant energy. If the former parameter is plotted as a function of the latter parameter, two distinct linear relationships result, one of slope $0.196°K\ (Wm^{-2})^{-1}$ between the poles and 63° N,S latitude, and one of slope $0.090°K\ (Wm^{-2})^{-1}$ between 63° N,S latitude and the equator (Idso, 1984a,b). Weighting these results for the proper percentages of Earth's surface area to which they apply (12% and 88%, respectively), a *total equilibrium* surface air temperature response function of $0.1°K\ (Wm^{-2})^{-1}$ is again obtained for the globe as a whole.

These examples illustrate the fact that there are at least three separate and independent ways of empirically deriving an identical result for the surface air temperature response function of Earth's atmosphere. All of these "natural experiments," as I like to call them, involve indisputable equilibrium transitions, and they all apply to the globe as a whole, thus satisfying the two criteria which are essential for a proper derivation of this unique number-concept. Consequently, there is compelling evidence to indicate that this number-concept will successfully predict the ultimate surface air temperature consequences of *any* atmospheric perturbation which results in a change in surface-absorbed radiation. Give me the value of the initial or primary change in radiative energy absorbed at the Earth's surface due to any phenomenon whatsoever, plus the value of any feedback-induced change in radiation absorbed there, and I will give you the ultimate change in mean global surface air temperature to be expected when equilibrium is finally achieved, merely by multiplying the sum of those two flux changes by $0.1^{\circ}K\ (Wm^{-2})^{-1}$. The three examples just cited demonstrate that *this procedure works*; and as the old adage goes, the proof of the pudding is in the eating.

REFERENCES

Idso, S.B. 1982a. *Carbon Dioxide: Friend or Foe?* An inquiry into the climatic and agricultural consequences of the rapidly rising CO_2 content of Earth's atmosphere. IBR Press, 631 E. Laguna Dr., Tempe, AZ 85282, 92 p.

Idso, S.B. 1982b. An empirical evaluation of Earth's surface air temperature response to an increase in atmospheric carbon dioxide concentration. *In* AIP Conf. Proc. No. 82: Interpretation of climate and photochemical models, ozone and temperature measurements, R.A. Reck and J.R. Hummel, eds., Amer. Inst. of Physics, New York, pp. 119-134.

Idso, S.B. 1982c. A surface air temperature response function for earth's atmosphere. *Boundary-Layer Meteorol.* 22:227-232.

Idso, S.B. 1983. Do increases in atmospheric CO_2 have a *cooling* effect on surface air temperature? *Climatol. Bull.* 17(2):22-26.

Idso, S.B. 1984a. The CO_2 greenhouse effect: Climatic or biological? Proc. Ann. Meeting of the Irrigation Association. In press.

Idso, S.B. 1984b. An empirical evaluation of earth's surface air temperature response to radiative forcing, including feedback, as applied to the CO_2-climate problem. In review.

Kiehl, J.T. and V. Ramanathan. 1982. Radiative heating due to increased CO_2: The role of H_2O continuum absorption in the 12-18 μm region. *J. Atmos. Sci.* 39:2923-2926.

Newell, R.E. and T.G. Dopplick, 1979. Questions concerning the possible influence of atmospheric CO_2 on atmospheric temperature. *J. Appl. Meteorol.* 18:822-825.