# Climatological Bulletin

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# Bulletin climatologique

Canadian Meteorological and Oceanographic Society

La Société Canadienne de Météorologie et d'Océanographie

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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, commerce, energy, environment, fisheries, forestry, health, recreation, transportation, and water resources), climatic change and variability, climate impact studies, climate model applications (including physical climatology), and regional studies (including ocean areas). It is published with the aid of a grant from the Government of Canada through the Natural Sciences and Engineering Research Council.

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Contributors should submit manuscripts to Alexander H. Paul, editor, CLIMATOLOGICAL BULLETIN, Department of Geography, University of Regina, Regina, Saskatchewan, S4S 0A2. All manuscripts should be typed double spaced on one side of good quality white paper, 28 cm x 21.5 cm, or its nearest equivalent. The abstract, list of references, tables, and a list of figure captions should be typed doubled spaced on separate sheets. Comments (including book reviews and opinions) and news items should not exceed 1 500 words. Furnish an original and three copies if possible, in the order listed below.

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

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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, le commerce, l'énergie, l'environnement, la pêcherie, la sylviculture, la santé, les loisirs, les transports, et les ressources en eau), les changements et la variabilité du climat, la prospective climatologique, les applications des modèles du climat (inclus la climatologie physique), et les études régional (inclus les océans). Il est publié grâce à une subvention accordée par le gouvernement canadien par l'intermédiare du Conseil de recherches en sciences naturelles et en génie.

Les auteurs peuvent choisir de soumettre leurs manuscrits aux "Articles", "Notes de Recherches", ou "Nouvelles et Commentaires". Ils doivent l'indiquer sur la lettre d'accompagnement du manuscrit. Les articles de recherche et les "Notes" sont indépendamment soumis à l'examen d'au moins deux appréciateurs anonymes. Le rédacteur en chef examine les "Nouvelles et Commentaires" 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 Alexander H. Paul, rédacteur en chef, BULLETIN CLIMATOLOGIQUE, Département de geographie, Université Regina, Regina, Saskatchewan, S4S 0A2. 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. 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.

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# Foreword / Avant-Propos

This is my first issue as editor, and I hope to continue the good work that has gone before. In particular I would like to acknowledge Stewart Cohen's contribution to the development of *Climatological Bulletin* over the past few years. He also did much of the work on this issue.

Without manuscripts no journal can flourish. We encourage all involved in climatological research to consider the *Bulletin* as a potential outlet for their work. We welcome submissions, of news items as well as notes or full-length manuscripts.

*Alec H. Paul*

# Severe Storms Over Canada's Ocean Waters: 1957-1983

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ABSTRACT

Four regional catalogue summaries have been prepared describing a total of 450 extreme wind storms which occurred over Canadian ocean waters during the 27-year period 1957-1983. The catalogues synthesize in a standard format large amounts of meteorological and oceanographic data on severe Canadian maritime storms. The four regions considered were Canada's East Coast, West Coast, Western High Arctic, and Hudson Bay-Foxe Basin; together these regions cover almost all of Canada's ocean waters. Data sources included marine weather reports from ships of opportunity, ocean weather ships, and offshore drilling platforms, observations from drifting buoys, coastal and island weather stations, surface wind hindcasts, and surface weather maps. A standardized methodology was used to identify, select, and describe the individual storms. This paper gives an overview of the preparation and contents of the catalogues. It also presents a compilation of selected results, including regional and overall annual storm frequency, monthly storm distributions and composite storm track maps for the decade 1967-1976.

RÉSUMÉ

Quatre catalogues récemment préparés décrivent un total de 450 tempêtes de vents violents survenues au-dessus des eaux océaniques canadiennes entre 1957 et 1983. Présentés dans un format standard, ces catalogues rassemblent plusieurs données météorologiques et océanographiques provenant de violentes tempêtes maritimes au

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Canada. Les quatre régions analysées sont la Côte Est canadienne, la Côte Ouest canadienne, la partie ouest de l'Arctique, et la Baie d'Hudson-le Bassin de Foxe. Regroupées, ces régions couvrent presque la totalité des eaux océaniques canadiennes. Les sources d'informations utilisées dans l'élaboration de ces catalogues comprennent des rapports sur les conditions atmosphériques provenant de plates-formes de forage, de navires météorologiques ou de navires opportunistes; des observations provenant de balises flottantes et de stations météorologiques sur des côtes ou des îles ainsi que des "*surface wind hindcasts and surface weather maps*". Une méthode standardisée a été utilisée pour identifier, sélectionner et décrire chaque tempête. Cet article donne un aperçu de la préparation et du contenu des catalogues et présente également une compilation de résultats sélectionnés incluant la fréquence annuelle des tempêtes: totale et par région, la distribution mensuelle des tempêtes ainsi que des cartes géographiques combinées montrant la trajectoire des tempêtes survenues au cours de la décennie 1967-1976.

## 1. INTRODUCTION

The shipping and fishing industries have always been an important sector of the Canadian economy. More recently, the advent of offshore oil, gas and mineral exploration and production has greatly increased the economic importance of Canada's ocean waters. The need for a better understanding of the meteorology and climatology of these ocean areas for design, planning and operational purposes fortunately has been appreciated by both industry and government. For example, while a ship's manoeuverability may enable the captain to avoid the worst conditions in a storm, stationary production platforms or drilling vessels have to be designed to withstand the most extreme conditions likely to be encountered. The Ocean Ranger tragedy in 1982 is a case in point.

In order to collect and synthesize available extreme meteorological and oceanographic observations, catalogue summaries of severe storms have been produced for Canada's ocean waters on the East Coast (Lewis and Moran, 1984), the West Coast (Lewis and Moran, 1985), Hudson Bay-Foxe Basin (Lewis, 1986) and the Western High Arctic region (Lewis, 1987a), hereinafter referred to as EC, WC, HF, and WA, respectively (Figure 1). Together they cover almost all of Canada's coastal waters. A similar catalogue of storms over the Great Lakes has now also been completed (Lewis, 1987b) but is not reviewed here.

The meteorological parameter used in the four storm catalogues to define a "severe" storm was extreme observed wind speed. Wind is a critical meteorological parameter. Apart from the damage caused by wind stress to offshore or coastal structures, strong winds can generate damaging waves. In the relevant regions/seasons, these may force movement of the ice pack which in turn may close channels, endanger offshore structures, and cause coastal damage by driving ice onshore. When combined with low temperatures, strong

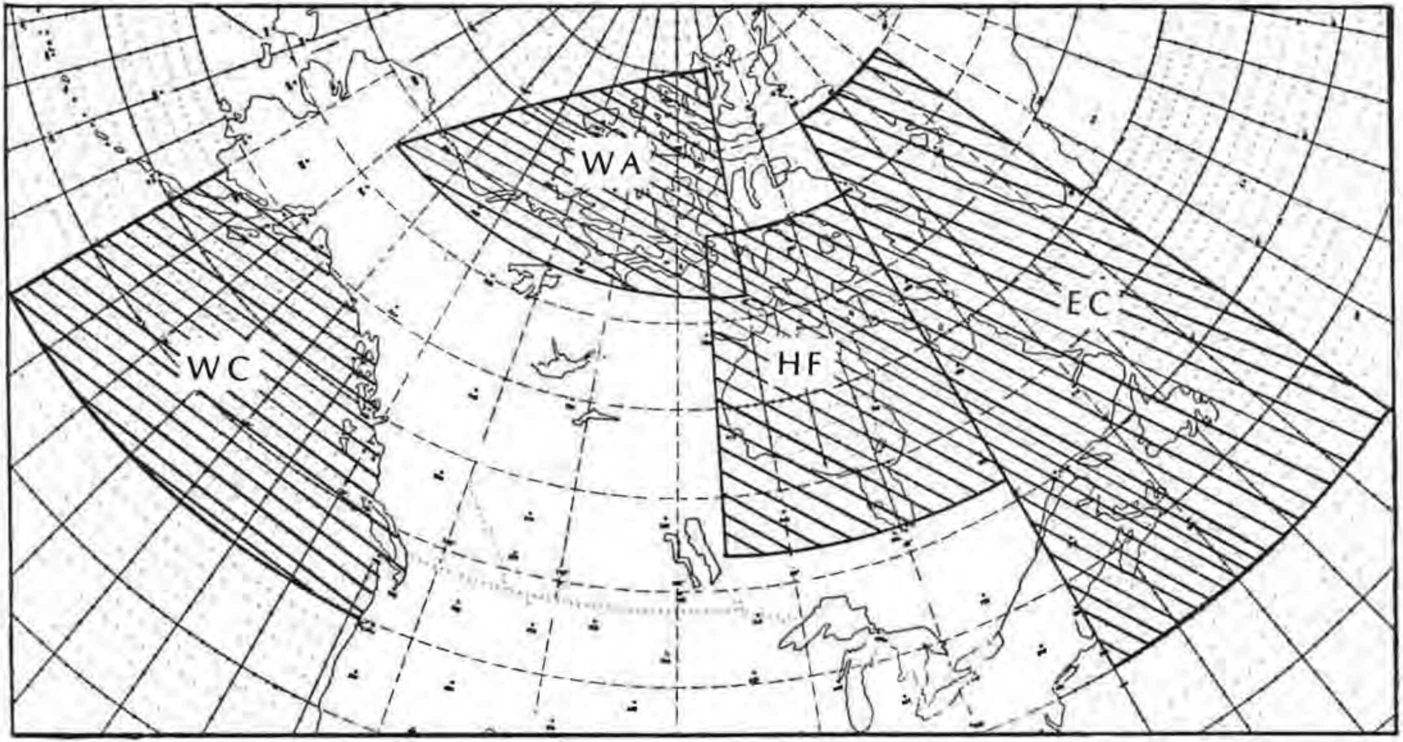



FIGURE 1. The locations of the four study areas. EC = East Coast WC = West Coast, HF = Hudson Bay-Foxe Basin, WA = Western High Arctic.

winds produce severe windchill, freezing spray and blizzard conditions. Human and mechanical activity is severely restricted under such conditions. As discussed in Section 2, extreme sustained wind speed was chosen instead of extreme gust speed.

Each storm catalogue contains descriptive summaries of a representative sample of the worst storms (125 for EC and WC, 100 for HF and WA), as defined by extreme observed wind speed, which occurred in each study area during the 27-year period 1957–1983. This format not only provides an understanding of the climatology of extreme storms for each region but also gives the reader a greater appreciation of the *actual* conditions which can occur in such storms than may be obtained from purely statistical studies based on limited amounts of data.

No other studies of similar scope or using a similar methodology have been identified in the literature. However, some other studies were useful in preparing the storm catalogues. Brown et al. (1986) compiled a climatology of severe storms which affected coastal areas of eastern Canada, based upon extreme wave height. This study did not include descriptive details of individual storms. Since 1960, the Mariners Weather Log has given brief descriptions of the worst North Atlantic and North Pacific storms which occurred each month; it also contains monthly storm track summaries for the North Atlantic and North Pacific. The annual reports of the Atmospheric Environment Service (AES) Beaufort Weather and Ice Office (in operation from 1976-1985) have, since 1980, contained brief summaries of a few of the worst storms which occurred during the Beaufort Sea drilling season; however, only three of these storms were severe enough to be included in WA. The comprehensive climatologies of Maxwell (1980, 1982a) for the Canadian Arctic Islands and adjacent waters and Burns (1973, 1974) for the Mackenzie Valley and Beaufort Sea contain some case studies of typical storms in those areas. Case studies of individual severe storms, not surprisingly, were found to be more numerous in the literature for the EC and WC than for HF and WA. These studies have been referenced in the individual storm descriptions where appropriate. Available climatologies of cyclone tracks include those by Maxwell (1982b) for Canada's northern and eastern coastal zones, Reitan (1979) and Zishka and Smith (1980) for North America and surrounding waters, and Klein (1957) and Whittaker and Horn (1982) for the Northern Hemisphere.

The intent of this paper is to outline the information contained in these four storm catalogues and to describe the methodology employed in their production. Copies of the individual catalogues may be obtained from the Canadian Climate Centre (see References).

Meteorological and climatological data sources used in the preparation of the catalogues are outlined in the following section. The common methodology employed in their production is then described, followed by some selected climatological analyses based on all four catalogues.

## 2. SOURCES OF DATA

Most of the extreme wind data used for storm identification and selection were obtained from digitized climatological data sets which were accessed using the AES MAST/LAST software packages (see Section 3a). Additional sources of information included Canadian Meteorological Centre (CMC) surface pressure analyses and some individual case studies pertinent to each study area. Especially useful for the EC and WC were the brief storm descriptions and monthly storm track maps for the North Pacific and North Atlantic published in the Mariners Weather Log. Table 1 provides a summary of the digitized data sets used in the production of all four catalogues. A brief description of each of the major data sources is given below.

### a) *Marine Observations*

Since the storm catalogues were concerned primarily with the maritime environment, emphasis was placed on available marine weather observations. At the time of preparation of the HF and WA catalogues, a copy of the COADS (Comprehensive Ocean-Atmosphere Data Set) was available at AES. This is a very large marine data set which contains 53 million ship reports for the period 1854–1969 and 18 million for the period 1970–1979 (Slutz et al., 1985). For the earlier EC and WC catalogues a slightly less complete marine data set compiled by the U.S. National Climate Data Center (NCDC) was available. For the period 1980–1983, a separate marine data set which contained observations from Canadian ships alone (i.e., those vessels which submit their logs to Canadian port authorities) was used for all four catalogues.

The majority of the observations contained in these data sets have been taken from merchant ship weather reports, either by manual extraction from the ship's weather log or by archiving ship reports which have entered the Global Weather Telecommunication System (GTS) via radio-telegraph transmission to shore. The other observations were contributed by naval vessels, instrumented buoys, research vessels, ocean weather ships and oil rigs/drill ships.

Each marine report may contain up to 20 meteorological and oceanographical parameters. Values of other parameters (besides wind speed) such as mean sea-level pressure, present weather, and wave heights were used as an aid in the quality control of suspect extreme wind values. The wind speed reported from ships is defined as the one-minute mean wind speed observed at the hour of observation (AES, 1982). No information on gusts is included in these marine reports.

Problems inherent in using marine observations include: 1) marked temporal and spatial variations in the frequency of ship reports due to such factors as length of shipping season and location of sea lanes; 2) low-wind-speed bias due to sparse data, i.e., a rare event such as an extreme wind is likely to be missed, and fair-weather bias caused by a ship captain's

TABLE 1. Digitized data sets used in preparing the storm catalogues.

| Catalogue | Data Set: Marine Data[*] No. of Observations >48 kn (1957-1983) | Coastal and Island Stations No. of Stations Used | Surface Geostrophic Winds No. of Grid Points within Area | NEDN Surface Winds No. of Grid Points within Area | Others |
|---|---|---|---|---|---|
| East Coast | 11,868 | 6 | 25 | not used | • OWS 'Bravo' |
| West Coast | 5,571 | 19 | 28 | not used | • Oceanographic data buoys, (5 buoys, 1973-1982) • OWS 'Papa' data 1957-1981 (June) • Lighthouse data set (5 stations, 1964-1983) |
| Hudson Bay-Foxe Basin | 91[#] | 15[†] | 16 | 17 | |
| Western High Arctic | 124[*] | 24 | 13 | 12 | • Dome Petroleum drillsite data (1976-1982) • Panarctic Oil drillsite data (1973-1982) • Polar Continental Shelf Project research stations (1973-1983) |

[*] NCDC marine database for EC and WC, 1957-1979; COADS for HF and WA, 1957-1979; Canadian ships only for all areas, 1980-1983.
[#] 10 rejected as erroneous.
[†] 4 just outside area.
[*] 67 rejected as erroneous.

predisposition to avoid the worst conditions in a storm; and 3) observer errors. According to Cardone et al. (1980) only 10% of ship reports are from direct measurements; the remainder are estimated using the Beaufort Scale, then converted into knots (with the result that the maximum possible value in most cases is 68 knots, i.e., force 12 on the Beaufort Scale). Inexperienced observers, poor siting of the anemometers relative to the ship's superstructure, and errors during radio transmission can also be included in this last category. Many obviously erroneous wind speed values were identified in the marine data sets used for all four catalogues.

b) *Coastal and Island Meteorological Stations*

Station records from the hourly data archive of the Canadian Climate Centre are available in digital format from 1953 onwards. Extreme wind reports from selected coastal and island stations were used in all four catalogues for storm identification and selection, but to varying degrees depending mainly upon the availability of marine data.

Land stations have the advantage of a long and regular observation record of generally high quality at a fixed location. However, meteorological conditions including surface wind speed are often different between land and open water or ice pack. Various studies have been carried out to investigate whether coastal winds, with or without some adjustment factor, may be used to represent marine/ice pack winds. These include studies by Raynor (1968), Savdie and Berry (1976), Parker and Alexander (1983) and Olson (1986). In general it appears that land-based winds underestimate winds over open water but overestimate winds over the marine ice pack.

Station elevation and local channelling effects can also have a strong influence on wind speed. No attempt was made to reduce the land station wind to a common elevation. This decision can be partly justified, especially for the WA and HF where many of the stations are located at airstrips, because it is the actual surface wind which will be the limiting factor in ground operations. However, some geographical bias was exerted against wind reports from a few stations, such as Cape St. James (WC) and Mackar Inlet and Pelly Bay (HF), in order to avoid selecting an excessive number of storms based solely on observations from one high-elevation station where local effects are likely very important.

c) *Surface Geostrophic Winds and NEDN Surface Winds*

A hindcast surface geostrophic wind data set which contains 6-hourly gridded values (381-km grid spacing true at 60° N) for Canadian marine areas for the period 1946–1978 has been developed by AES. It uses a subset of the U.S. Fleet Numerical Oceanographic Centre (FNOC) gridded hemispheric surface pressure analyses (e.g., Swail, 1985). Like the land station records, the gridded hindcast wind data set contains an unbroken, regularly-spaced time series of winds at fixed locations. The ability of geostrophic winds to estimate true surface winds has been the subject of much discussion in the literature, but consensus appears to be that geostrophic winds overestimate true surface winds, even over the ocean. However, a sparse surface observational network (especially true for HF and WA) together with the coarse grid spacing (381 km) can result in significant underestimate of actual surface pressure gradients in storm regions, thus giving geostrophic wind speeds which are *less* than observed surface wind speeds. For example, Swail et al. (1984) found good agreement between extreme observed wind speeds at Ocean Weather Station 'Bravo' and the corresponding surface geostrophic winds. This was confirmed in the EC catalogue, where 52 of the 102 storms for which surface geostrophic wind data were available had differences of less than 10 knots between the maximum observed and maximum geostrophic value. Of the remaining 50 storms, 29 had higher geostrophic than observed winds while the other 21 had higher observed winds.

As hindcast wind values constituted the major data source in storm identification and selection for the HF catalogue, the U.S. National Environmental Data Network (NEDN) data set, which also contains gridded surface winds based on the FNOC gridded surface pressure data, was accessed to cover the 5-year period 1979–1983 for which no surface geostrophic winds were available in the AES data set. NEDN surface winds are a blend between "first guess" geostrophic winds derived from the sea level pressure field and actual observed winds (Kelresearch, 1985). Olson (1986) found reasonable agreement between NEDN surface winds and surface geostrophic winds at locations around Hudson Bay, Hudson Strait and Foxe Basin. NEDN winds were also used as an aid in storm identification (but not selection) for the WA catalogue.

#### d) *CMC Surface Analyses*

The principal tool used in the synoptic analysis of all 450 severe storms described in the four catalogues was the microfilm archive of Canadian Meteorological Centre (CMC) weather maps. Six-hourly surface charts are available for the years 1957–1983. These were used to produce the storm track maps included for each storm (through location of storm centres), to determine storm size, and to obtain minimum central pressures.

### 3. METHODOLOGY

#### a) *Storm Identification and Selection*

The underlying aim in developing the methodology for storm selection was to ensure that a representative sample of the worst storms (as determined by extreme wind speed) which occurred during the study period 1957–1983 was selected for description. However, there was an added proviso that at least two storms be included for each calendar month. This was done to emphasize the fact that severe storms can occur throughout the year. Storms producing storm-force winds (defined as 48 knots or more) during the summer months may in fact be regarded as more hazardous than stronger winter storms simply because they are less expected at that time of year. Systems which produced winds of storm force were identified for all calendar months in all four study areas.

The first step in the storm identification/selection process was to produce chronological listings of all periods of storm-force winds from all of the available data sources for a study area. This could be done for all of the digital data sets by accessing the AES data archive using a powerful software package called MAST (*MA*rine *ST*atistics) which was developed at AES (see AES, 1985; Swail et al., 1983). For land stations the hourly data records were first converted into MAST format using a companion software package called LAST (*LA*nd *ST*atistics).

These computer listings of storm-force winds were then divided by hand into "storm periods". Storm information from other sources, especially the Mariners Weather Log (for the EC and WC catalogues), was compiled manually into a chronological listing. Note that at this stage it was not always possible to identify individual storms since there were not always periods of calm between storm systems. Appendices to all four catalogues include: separate listings of all periods of storm-force winds for the marine (1946–1983) and land station (1953–1983) data sets; tables of the annual distributions of the maximum wind speeds reported during each storm period by wind speed category; and, for the HF and WA catalogues only, additional listings and tables of storm-force geostrophic (1946–1978) and NEDN surface winds (1979–1983).

The next step was to try to meld together the extreme wind speed data from all of the chronological listings and to identify the worst storms. Owing to the greatly varying amounts and types of data available for the different study areas, the final storm selection processes for the four catalogues differed as follows:

*East Coast (EC):* Due to the large number of marine observations of storm-force winds during the study period (> 10,000), it was possible to use extreme observed marine winds as the main criterion for selecting the 125 storms. The maximum observed wind reported during each of the EC 125 storms was in fact a marine observation.

*West Coast (WC):* Here there was a smaller number of marine reports of storm-force winds during the study period (< 6000), many of which were from the extreme northwest of the study area. But there was a large number of extreme wind reports from coastal, island and lighthouse stations, many of them not supported by marine observations of storm-force winds. Thus it was decided to include some storms based solely on observations of extreme winds from land stations.

*Hudson Bay-Foxe Basin (HF):* Because of the virtual absence of any observed data from the vast central area of Hudson Bay, it was decided to use derived surface geostrophic and NEDN winds in the storm-selection process. However, no storm was selected based *solely* on a derived wind value unless that value was ⩾64 knots. There were only 81 valid storm-force wind observations from marine sources; so for most of the storms selected on the basis of actual observations of storm-force wind, the reports were from coastal or island stations.

*Western High Arctic (WA):* Again there were very few (only 57) valid storm-force wind reports from marine sources, and most of the storms were selected based on observations from coastal or island stations. It was decided not to include any storms based solely on derived wind values in this catalogue, and in any case there were no storms in the study area for which a derived wind value of ⩾64 kt was not supported by at least one report of observed storm-force wind.

For the EC and WC catalogues the storms were selected in groups based on the maximum reported wind speed, starting with the highest values (⩾70 kt) and then working down with intervals of 5 kt (i.e., ⩾65 kt, ⩾60 kt, etc.). The CMC surface analyses were obtained for each storm and checked, together with other meteorological parameters reported concurrently with the extreme winds, to establish the likely validity of the reported wind speeds. Taking into account the requirement for the inclusion of at least two storms for each calendar month, and some geographical and temporal biases, the maximum reported wind speed for selection was lowered until 125 storms had been chosen. For the WA and HF, storm "selection categories" were defined based on the maximum wind speed observed/hindcast and the number and type of observations/hindcasts. The categories were then subjectively ranked in order of severity and the storms selected by category in descending order of severity until 100 storms had been selected (see Lewis: 1986, 1987 for more details). However, the greatly reduced number of storm-force wind reports/hindcasts as compared to the EC and WC resulted in most of those storm periods with at least two reported storm-force winds being investigated for possible inclusion in the catalogues. In contrast, storms with observed winds as high as 60 kt were passed over in the EC and WC selection process.

b) *Storm Descriptions*

Storms are arranged in chronological order in each catalogue. Each storm description consists of a 7- or 8-line point-form summary of representative storm characteristics, followed by a brief narrative describing the storm's synoptic history and expanding on the information included in the point-form summary. A storm track map and one surface pressure chart for a time considered to be within 12 hours of the storm's maximum influence over the study area are also included. Apart from some small differences in the items included in the point-form storm summaries, a consistent format has been used in all four catalogues to describe individual storms.

The point-form storm summary which precedes each storm description is intended to be useful for quick reference and comparison purposes. The headings used are defined as follows:

i) *Storm Period/Duration*: The storm period is the date range (GMT) between the first and last observation of a storm-force wind within the study area attributed to the storm. For HF only, derived winds as well as observed winds are included in the storm period evaluation. The storm duration is the length of time (hours) between the first and last observations (and/or hindcasts for HF) of a storm-force wind within the study area.

ii) *Maximum Observed Wind*: This is the maximum sustained wind speed (knots) reported during the storm. Information on the type of observation (e.g., land vs. marine) and the location of the report relative to the storm centre is also given in abbreviated form under this heading.

iii) *Maximum Derived Wind*: For all catalogues for the years 1957–1978 this heading gives the highest computed surface geostrophic wind (knots) within the study area during the storm period. For HF and WA, in the case of the remaining five years of the study period, 1979–1983, the highest NEDN surface wind (knots) evaluated within the study area and storm period is given. For HF only, the position of the highest wind evaluated relative to the storm centre is also given.

iv) *Maximum Radial Extent*: This is a rough estimate of the radius (km) within which storm-force winds may be expected. It was obtained by considering first, the pressure gradient on the CMC surface analyses; and second, the location of the storm-force wind reports/evaluations at the synoptic reporting time closest to the time of the storm's presumed maximum influence over the study area. Obviously, this is a very rough subjective estimate of storm size, but it does allow a small, intense mesoscale system to be distinguished from a well-developed North Atlantic or North Pacific extratropical low.

v) *Lowest Central Pressure*: This is the lowest central pressure (kiloPascals) reached by the storm at a synoptic observing time during the storm period.

vi) *Source Region/Type*: For EC and HF the source region is the approximate area of cyclogenesis of the storm. For the WC and WA, because the areas of cyclogenesis were normally well removed from the study area both in space and time, the source region has been defined as the direction from which the storm approached the study area. The type classification differed between all four catalogues and ranged from a simple differentiation between frontal lows or cold lows (which covered the majority of WC storms) to attempts to identify sets of storms with similar characteristics in terms of formation and movement relative to the study areas.

vi) *Notable Effects*: This heading was used only for the EC and WC, where other information related to many of the storms, such as wave or swell heights or damage caused by the storm, was available from sources such as the Mariners Weather Log.

## 4. SELECTED RESULTS

Although the emphasis of the catalogues was on the presentation of synthesized information on the selected severe storms rather than on the climatological analysis of that information, some basic analyses were carried out which are summarized here.

### a) *Annual Frequency of Severe Storms*

Figure 2 shows the annual frequency of severe storms for the four study areas over the 27-year study period. Although some effort was made to allow for the temporal variation in the availability of data, attempts to infer climatological variability in the distribution of severe storms in each area should be

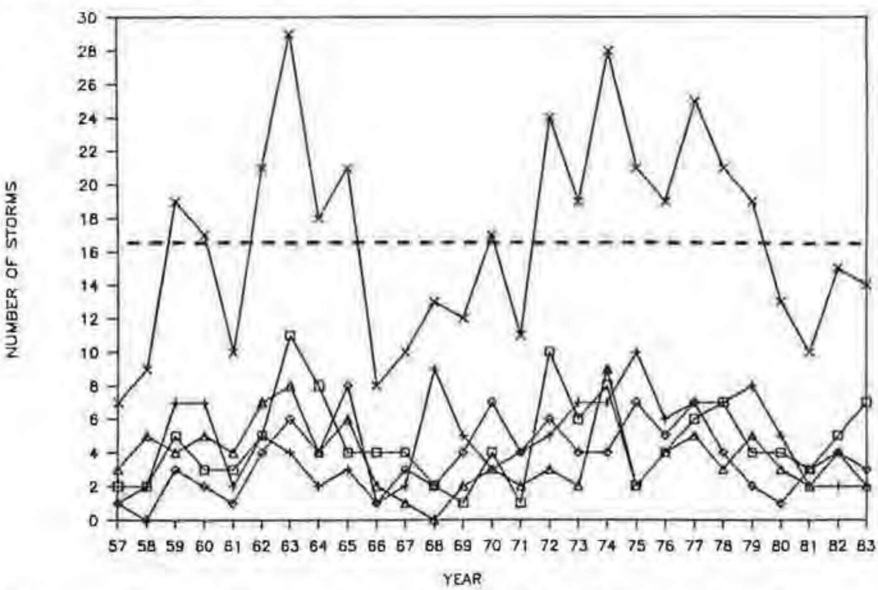



FIGURE 2. The annual frequency of severe storms for the four study areas combined (X——X), EC (□——□), WC (+——+), HF (◇——◇) and WA (△——△). Dashed line indicates mean of total number of storms (16.7).

approached with caution. However, when the four areas are compared, some climatological trends may be apparent. Given the total sample of 450 severe storms (although it should be noted that on some occasions the same storm may have affected two or, very rarely, three of the study areas), a uniform annual frequency for the 27-year period would give 16.7 storms per year. The period from 1966 to 1969 appears to have been relatively free of severe storms, while the period 1972–1978 had an above average number of severe storms.

Studies by Reitan (1979) and Zishka and Smith (1980) consider the frequencies of cyclone distribution over North America and surrounding waters. Reitan's study for the period 1949–1976 uses the four midseason months while that of Zishka and Smith considers only January and July distributions for the period 1950–1977. Unlike our results for severe cyclones, both studies identified a significant decrease in the total number of cyclones per year over each study period. Zishka and Smith also detected a decrease in the mean minimum pressure of the cyclone, implying an increase in cyclone severity with time. Similar to the annual distributions for the present study (Figure 2), Zishka and Smith (their Figure 6) also found, on average, a reduced number of cyclones in January with, more significantly, increased minimum central pressures for the period 1966–1969 while for 1972–1977, although less marked, the inverse was true. In a study considering storms which produced severe wave conditions over the coastal areas of eastern Canada in the period 1946–1982, Brown et al. (1986) also found the years 1972 and 1974 to be the most severe (in terms of frequency of storms) during their study period.

b) *Monthly Distribution of Severe Storms*

Figure 3 presents the monthly distribution of severe storms for the four study areas. Note that the ordinate scale has been adjusted to allow visual comparison between the differing sample sizes (125 storms for EC and WC, 100 storms for HF and WA). As might be expected climatologically, late winter produces more severe storms on the east coast while fall and early winter is the most severe period on the west coast. HF experiences an abrupt beginning to the severe storm season in September, a peak in January and February, and then a marked decrease in March. This sudden decline may be attributed to the intensification of anticyclones over Hudson Bay during early spring due to cooling from below which would tend to deflect storms away from the region (Johnson, 1948). The WA shows a steady increase in the number of severe storms beginning in September, a peak in January, and then, like Hudson Bay-Foxe Basin, a marked decrease in March to a level which remains low over the summer.

Table 2 gives the maximum wind speeds for the two most severe storms in each calendar month in each study area during the 27-year period. This gives an indication of the differences in maximum storm severity between areas and the intra-annual variability of severity within each area. In terms of absolute wind speed, storms occurring off the east and west coasts can be more

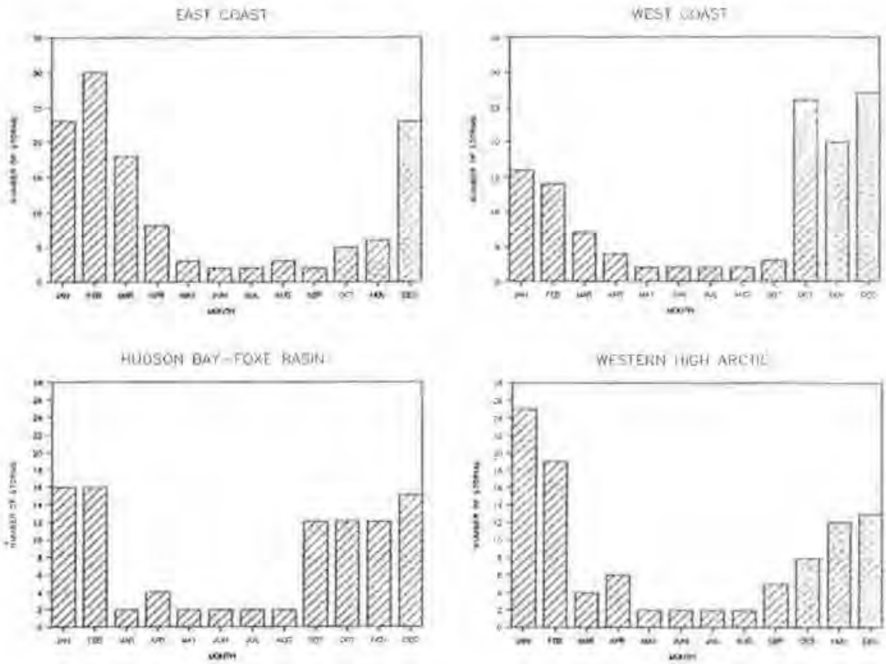



FIGURE 3. The monthly frequency of severe storms over the four study areas, 1957-1983. Note the change in ordinate scales between the upper and lower panels.

TABLE 2. Maximum wind speeds (knots) for the two most severe storms in each calendar month in each study area during the period 1957-1983. The numbers in parentheses indicate the number of storms with that same maximum wind speed.

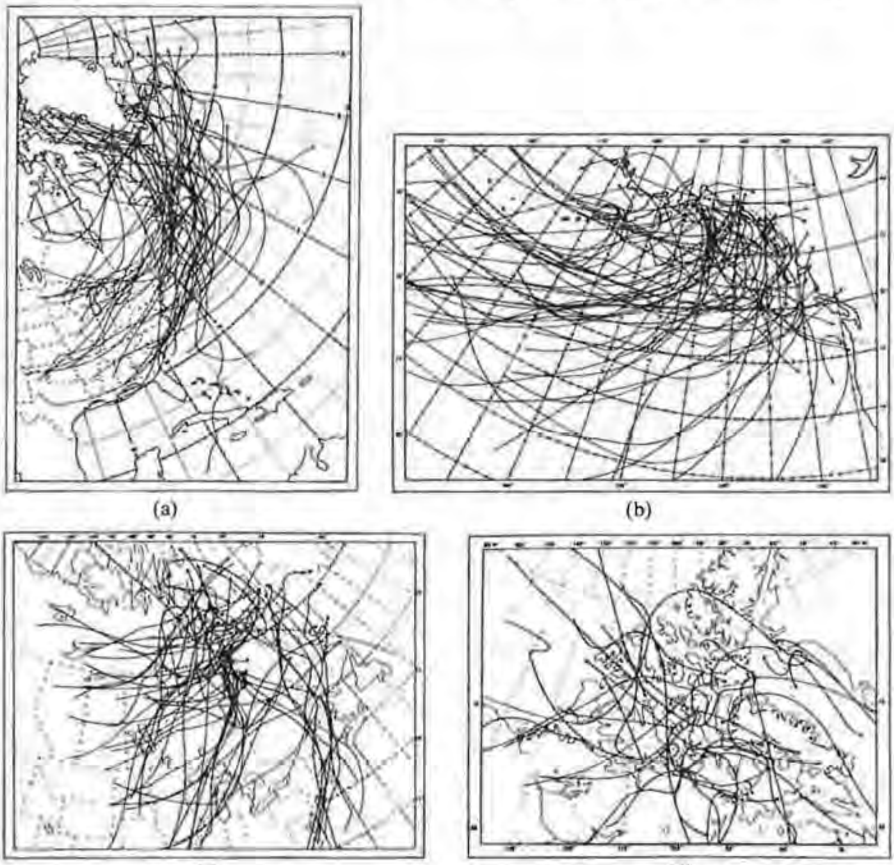
| | Region | | | |
|---|---|---|---|---|
| Month | East Coast | West Coast | Hudson Bay-Foxe Basin | Western High Arctic |
| Jan | 80 (3) | 85, 83 | 101, 83 | 74, 66 |
| Feb | 91 (2) | 93, 86 | 79, 73* | 61, 60 |
| Mar | 85, 80 (3) | 87, 86 | 69, 62 | 52 (2) |
| Apr | 80, 75 (2) | 85, 77 | 74, 68 | 63, 53 |
| May | 71, 70 | 63, 60 | 60, 55* | 54, 52 |
| Jun | 85, 65 | 62, 61 | 60, 55* | 50, 48 |
| Jul | 66, 61 | 62, 58 | 60, 50* | 48 (2) |
| Aug | 75, 66 | 70, 60 | 69, 50* | 50, 48 |
| Sep | 80, 74 | 80, 69 | 69, 63 | 65, 57 |
| Oct | 90, 86 | 96, 93 | 69, 63* | 55, 54 (3) |
| Nov | 94, 78 | 97, 95 | 69 (2) | 77, 60 |
| Dec | 100, 90 | 95, 87 | 74, 68 (2) | 74, 61 |

N.B. For Hudson Bay-Foxe Basin, all wind speeds except those flagged by * are hindcast wind values.

severe than those in the other two regions. However, the generally sparser observational network in the latter two regions reduces the likelihood of an extreme wind event being observed. Storms producing wind speeds greater than 60 knots have occurred off the EC and WC and over HF throughout the year, while for the WA, with the exception of July (48 knots), storms producing winds above 50 knots can be expected to occur at any time.

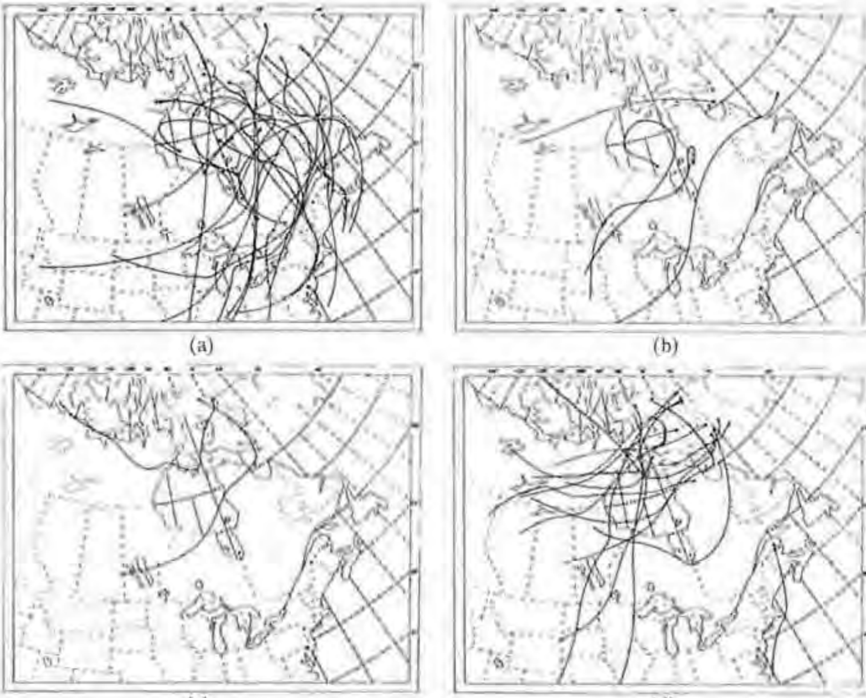
c) *Storm Track Summaries*

Figure 4 gives a sample of the decadal storm track summaries contained in each catalogue. It shows a composite storm track map for the decade 1967–1976 for each study area. While the EC and WC composite maps show a marked directional bias in storm approach to and passage over the study area and preferred areas of cyclolysis, the pattern is less consistent for the other two areas (especially the WA) with severe storms approaching both of these study



(a) (b) (c) (d)

FIGURE 4. Composite severe storm track summaries for the decade 1967-1976 for a) EC, b) WC, c) HF and d) WA.



(a) (b) (c) (d)

FIGURE 5. Composite severe storm track summaries for HF for a) January, b) April, c) July and d) October, 1957-1983.

areas from every direction except the north and northeast. Monthly composite storm track summaries were produced for the entire study period for the HF, WA, and WC catalogues. Figure 5 is an example, showing summaries for the months of January, April, July and October for HF. These monthly summary maps indicate the monthly and seasonal variations in the storm tracks. For the example given, severe storms approaching the HF study area from the southeast predominate in January, whilst for the other three months severe storms with an origin to the west of the study area are more likely to occur.

d) *Storm Types*

With a few exceptions, the 450 extreme wind events described in the four catalogues were associated with synoptic-scale extratropical cyclones. In many instances, however, the cyclone pressure gradient was tightened by the presence of an adjacent high pressure system. Indeed, in the WA area, there were severe "storms" in which the pressure gradient producing the storm-force winds maintained an anticyclonic curvature.

This is not to suggest that smaller-scale marine systems cannot produce strong winds. The spatially and temporally coarse observational networks used in the compilation of the catalogues will inevitably have resulted in many smaller-scale events going completely undetected. On occasion, a locally dense observational network allowed positive identification of mesoscale systems. Mesoscale lows were identified close to the west coast and, during the later years of the study period, over the Beaufort Sea when the observational network was greatly expanded due to increased drilling activity. Seven EC storms were identified as ex-hurricanes or tropical storms with much smaller dimensions than the usual extratropical cyclone. Outflow winds or katabatic wind caused by local topography are known to contribute to high wind speeds when synoptic conditions are favourable. Outflow winds are suspected to have contributed to the extreme wind speed reported in at least four of the WC storms and were likely to have been a factor in other storms, especially in the Arctic regions (e.g., see Ball, 1957; Dickey, 1961). It is also possible that some of the extreme wind observations rejected as erroneous due to lack of supporting evidence may have been caused by a real local phenomenon.

In the HF and WA catalogues, where storm selection categories and more detailed storm synoptic "types" were defined, analyses of the distribution of categories and types by month are included. Refer to Lewis (1986, 1987a) for more details.

## 5. CONCLUDING REMARKS

The four catalogue summaries of severe storms which have been outlined above should provide a significant contribution to the storm climatology of Canada's coastal zones and ocean waters. Although the types and sizes of the data sources used for storm selection varied somewhat between the four catalogues, efforts were made, including use of a standardized selection methodology, to ensure that the storms selected for description in each catalogue were representative of the worst storms (as defined by extreme wind speed) which occurred in each study area during the years 1957-1983. Large amounts of meteorological and oceanographic data have been synthesized and the 450 storm descriptions contained in the four catalogues are presented in a consistent format which will allow ease of comparison and selection of "worst case" storms. These catalogues will provide useful background information for future storm studies and for design and operational planning purposes in the various offshore and coastal industries active in Canada's ocean waters.

## ACKNOWLEDGEMENTS

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# The Use of Seasonal Wind Forecasts in Airline Schedule Development

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ABSTRACT

Airlines currently use climatological average seasonal winds to create the estimates of flight times needed for schedule development. Even in mean wind conditions, however, day-to-day windspeed fluctuations make some wind induced delays inevitable. The delay frequency is likely to change when wind conditions for a particular season depart from the mean. In order to assess the potential benefit of seasonal wind forecasts to the airlines, the potential impact of such changes was determined. A model, developed to isolate the effect of windspeed fluctuations from other factors influencing flight times, indicates that in mean conditions daily windspeed fluctuations create delays for more than 5% of flights only on routes with lengths greater than 1100 n.m. Commonly occurring seasonal anomalies may reduce this distance to about 800 n.m. The majority of U.S. domestic flights are shorter than this, so that the significance to the airlines, and thus the benefit of forecasts, is marginal. For the much longer transcontinental and transoceanic routes the frequencies of delay can rise rapidly in adverse wind conditions, and climatological forecasts of seasonal wind can have considerable benefit.

RÉSUMÉ

Les compagnies aériennes utilisent couramment les vents saisonniers de vitesse moyenne pour évaluer les temps de vol nécessaires au développement des horaires. Cependant, même dans des conditions de vent moyennes, les fluctuations de la vitesse du vent au jour le jour occasionnent des délais inévitables. Il est fort probable que la fréquence des retards change lorsque les conditions de vent pour la saison en question s'écartent de la moyenne. Pour mesurer le bénéfice éventuel des compagnies aériennes à prévoir les vents saisonniers, l'impact possible de ces changements a été déterminé. Un modèle, créé pour isoler l'influence des changements de vent des autres facteurs influant sur les temps de vol, indique que, dans des conditions moyennes, les variations journalières de la vitesse du vent causent des retards sur plus de 5% des vols, mais seulement sur des itinéraires de plus de 1100 milles marins. Des anomalies saisonnières courantes peuvent réduire cette distance à 800 milles marins environ. La plupart des vols nationaux américains sont cependant plus courts que cela, ce qui implique pour les compagnies aériennes que les bénéfices et le sens de ces prévisions sont limités. Pour les itinéraires beaucoup plus longs, transcontinentaux ou transocéaniques, la fréquence

des retards peut s'accroître rapidement dans des conditions de vent défavorables, et les prévisions de vent saisonnières s'avèrent alors avantageuses.

## 1. INTRODUCTION

Of the many potential effects of atmospheric events on airline operations, the most pervasive is the impact of windspeed on flight times. Flight times for any route will vary daily as a result of windspeed variations. However, airlines must publish and use schedules which have temporal stability. Hence schedules must be developed using mean windspeeds but must allow for daily variability. The result, obvious from even a brief perusal of these published schedules (e.g. the Official Airlines Guide), is that the time for flights between a given city pair depends on the direction of travel. Further, most airlines develop two basic sets of schedules, one for winter and one for summer, again reflecting the climatological conditions.

Competitive and economic pressures dictate that an airline produce for a particular route a schedule time sufficiently long to minimize the number of late arrivals but fast enough both to meet competition from other airlines and to minimize the time an aircraft is idle at a terminal. In schedule development many non-climatic factors, such as passenger demand, available gate space, and air traffic control considerations, must be considered, and allowances made for unforeseen events ranging from equipment failure to snowstorms at airports. Nevertheless, en-route wind conditions remain the single most important variable for developing flight schedules for a particular route and scheduling period.

Most airlines currently rely on climatological mean winds for each season for schedule production. However, the advent of climatological forecasting suggests that more efficient scheduling might well be achieved by using forecast wind conditions for a particular season rather than the climatological mean. In order to test this potential application of climatological information it is necessary to determine if seasonal windspeed anomalies are sufficient to have a significant effect on airline operations. In the present paper the wind impact is first isolated from other factors affecting flight times and then related to potential on-time performance in order to test the overall significance of the impact.

## 2. DATA

The approach adopted for isolating the impact of wind conditions depends greatly on data availability. The direct approach relating wind to flight times for individual flights cannot be used since flight time data are not publicly available. For similar reasons analysis of the impact through analyses of the scheduling technique used by the airlines is not possible. However, an indirect approach which isolates the impact in general terms without being confined to specific routes or airlines is possible using two readily available data sources: average route windspeeds and actual schedule times.

The actual schedule time, ST, is that published by the airlines in sources such as the Official Airlines Guide (1985). *ST* represents, approximately, the time between departure from the originating gate and arrival at the destination gate. It thus includes taxi-times as well as the airborne phase. However, for long-term averages over a number of routes this taxi-time can be regarded as constant. Hence it can be assumed that any schedule which is developed reflects the influence of mean route windspeed on the airborne phase. By analysis of the schedule time for a variety of routes and their associated windspeed, the windspeed impact can be estimated.

Aircraft performance is influenced by both the direction and speed of the wind (Figure 1). The appropriate wind vector, the equivalent wind, $W$, is given (Sawyer, 1950) by:

$$W = p - (q^2 + s^2/2)/2A \qquad (1)$$

where p and q are the components of the actual wind vector V parallel and normal to the aircraft track respectively, s is the standard vector deviation of the actual wind and A is aircraft airspeed. $W$ is calculated as a spatial average along the route. The short-term variability of the equivalent winds for a particular route has a normal distribution about the climatological mean value, so that the complete wind distribution is specified by the mean and standard deviation as published by Boeing (1975a, 1975b).

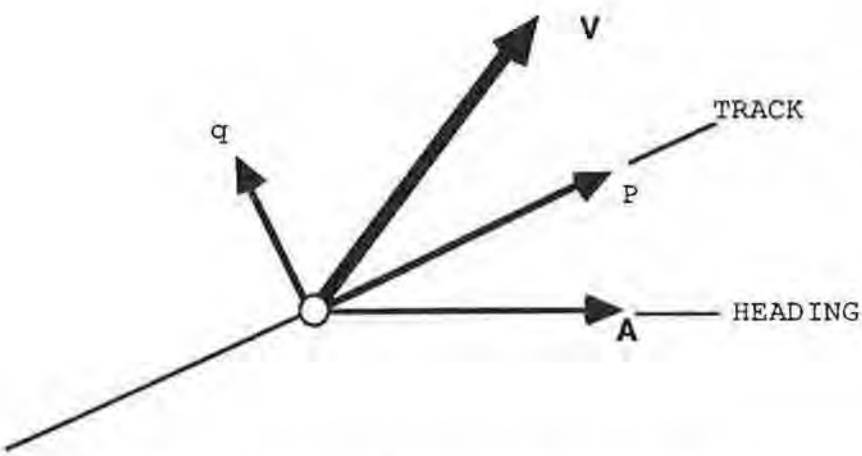


FIGURE 1. Wind vector relationships for determination of equivalent winds. (after Boeing, 1975a)

The impact of wind on individual routes was obtained by a regression analysis of variation of ST with W for a variety of routes, seasons and aircraft types. The relationship was initially established for flights of Boeing 727 Series aircraft, assuming a 30,000 ft flight altitude, to and from Atlanta and Dallas-Fort Worth airports in both summer and winter conditions. The relationship was then tested for other aircraft types and routes, but no statistically significant differences emerged from these tests. The general relationship obtained was:

$$ST = 22.934 + (0.142 \times D) - (0.017 \times D \times W), \quad (r^2 = 0.99) \tag{2}$$

where D, the interairport distance, is in nautical miles and ST is in minutes. W is in knots, with headwinds being negative (Boeing, 1975a). Although these are not standard international scientific units, they are the only ones currently "acceptable" for the U.S. domestic airline industry and hence must be used if the results are to have any practical application. Physically the first term of (2) is a constant combining airport taxi times and the safety factors incorporated into the schedule to compensate for unanticipated delays. The second term is the influence of flight distance without wind effects, while the last term is the wind effect itself, which in turn depends on the distance over which it acts. The strong dependence on D, and the relatively weak one on W, is clear. Although there are physically based underpinnings for the formulation, it is essentially a statistical relationship. Hence it can be used to analyse the influence of wind fluctuations on various routes. However, it cannot be used, for example, as a basis for the development of new schedules.

For conditions on an individual route, equation (2) can be differentiated and expressed in finite difference form to indicate the difference between the actual flight time, AT, and the scheduled time for a particular flight as a result of the windspeed effect:

$$(AT - ST) = 0.017\, D\, (W - W') \tag{3}$$

where the prime denotes the actual wind conditions for the flight. Since the equivalent wind has a normal distribution about the mean, this equation allows determination of the probabilities of delays of a given magnitude and frequency on any route. Because equation (2) forces an arrival to be exactly on time in the mean wind conditions, early and late arrivals are symmetrically distributed about this schedule time. Note that late arrivals, or "delays", are defined here entirely in the context of the wind impact. They do not necessarily constitute a delay of a particular flight as experienced by the passengers.

The distribution of delays is unique for each route since it depends on both the windspeed standard deviation and the route length. As the

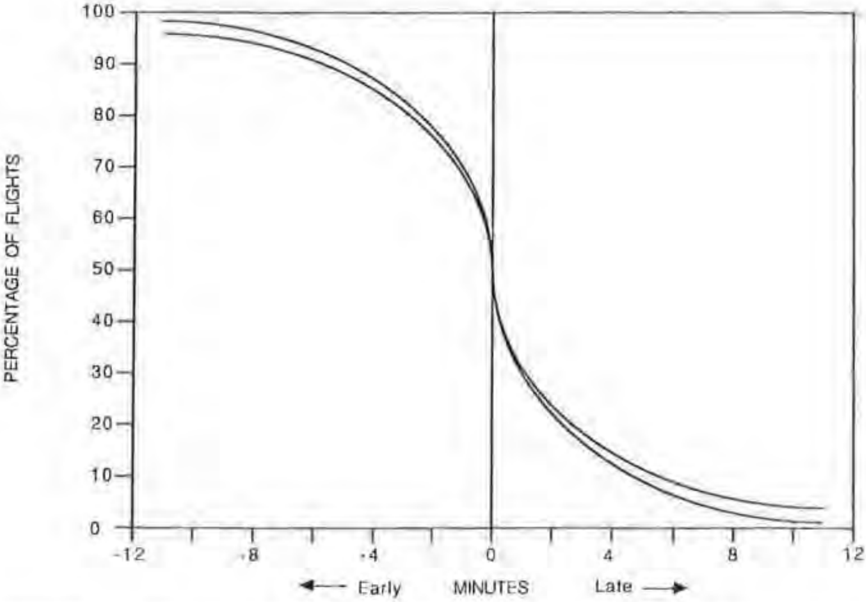


FIGURE 2. Frequency distribution of difference between scheduled and actual flight time with a mean equivalent headwind of 70kts and standard deviations of (A) 28kts and (B) 38kts. Times for route lengths of 500 n.m. and 1000 n.m. are shown.

standard deviation increases the distribution curve flattens and the frequency and length of delays increase, as expected from statistical considerations alone (Figure 2). Similarly, the curve becomes flatter as distance increases. Consequently, while all routes will have some delayed flights as a result of windspeed fluctuations, the frequency and severity, and hence the significance to the airlines, will vary from route to route.

## 4. OVERALL IMPACT

In order to assess the significance of the windspeed variations on various routes to overall airline operations, the impacts on flights to and from a single airport, Charlotte, North Carolina, were considered. This airport accounts for just over 1% of the total aircraft operations and passenger movements within the U.S.A., ranking 21st of the 121 domestic hubs (Federal Aviation Administration, 1986). It is reasonably typical of many United States domestic hub operations, with a wide range of flight distances and directions (Figure 3), but with a majority of short-haul flights (Table 1). Winter flights, when higher mean windspeeds and standard deviations are likely to produce the maximum impact, were used. The flights considered here were those available during mid-February, 1985. All flights are confined to the area of the mid-latitude westerlies, so that equivalent winds vary with flight direction in a roughly

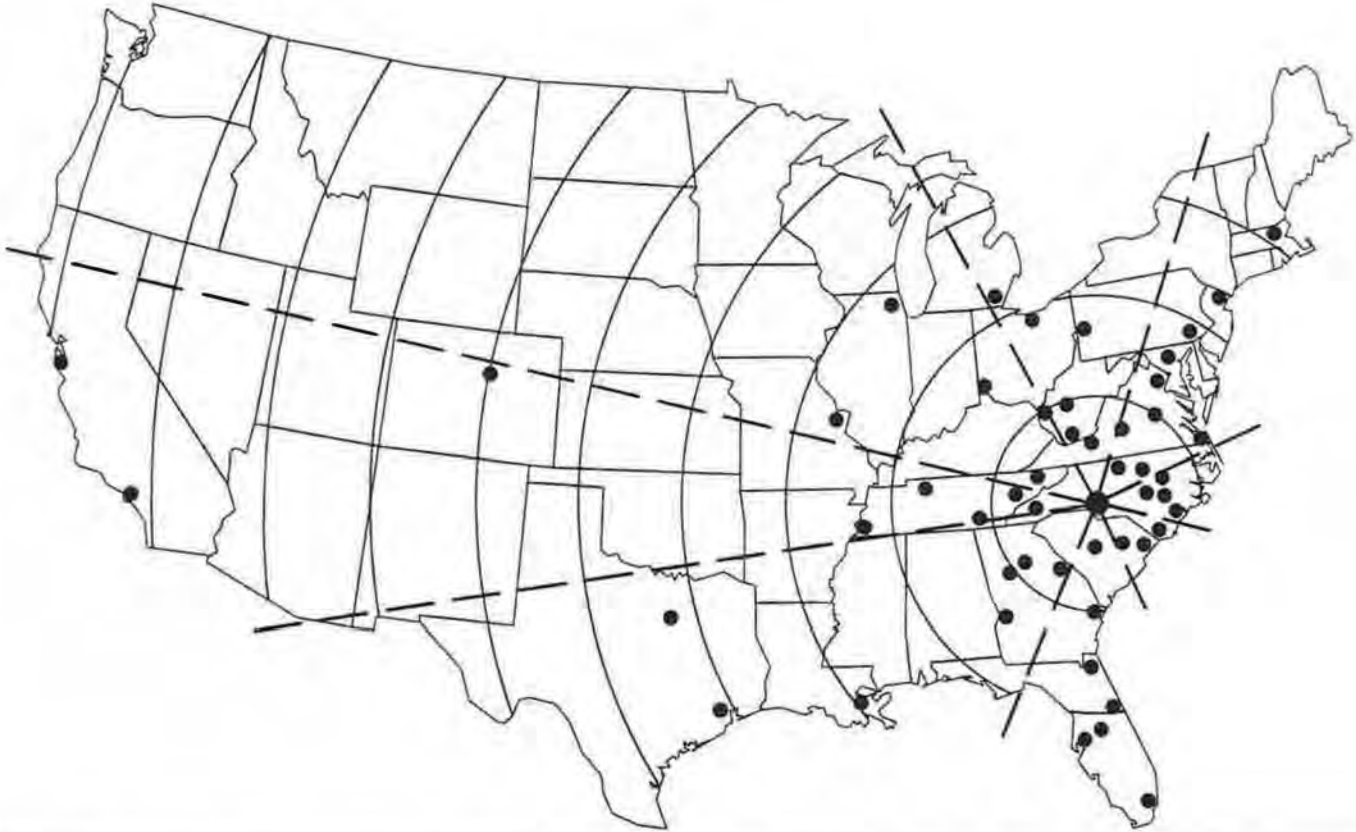

FIGURE 3. Cities served by non-stop service from Charlotte in February 1985, showing the zones of approximately equal equivalent winds. The partial circles indicate approximate airline distance from Charlotte in increments of 200 n.m.

TABLE 1. Number of flights per day, mid-February, 1985, to and from Charlotte, as a function of route length.

| | Route Length (n.m.) | | | | | |
|---|---|---|---|---|---|---|
| | 0-200 | 200-400 | 400-600 | 600-800 | 800-1000 | >1000 |
| # Flights | 342 | 146 | 108 | 15 | 14 | 8 |

systematic manner. To allow analysis of the overall impact, the routes were divided into eight zones each with approximately uniform equivalent wind conditions (Table 2).

The windspeed impact can be summarized by considering the flight lengths needed to produce 15-minute delays with frequencies of 1% and 5%. 15 minutes is used by the Federal Aviation Administration to define a delay, and commonly represents the delay which can be tolerated by an airline before connecting flights are affected. Delay frequencies of both 1% and 5% were used to investigate the variations in minimum flight length produced by a change in delay frequency. The former frequency indicates no delay in virtually all conditions, while the latter can be regarded as a value acceptable to the airlines given their other scheduling constraints.

The impacts of variations in seasonal wind conditions were investigated by considering the delay distance for: the mean conditions themselves (W, $\sigma_w$); an increase in the standard deviation of 10kts without change in the mean wind *(W,* $\sigma_w+10$); an increase in the mean equivalent wind of 10kts without change in standard deviation ( $W+10$, $\sigma_w$); and an increase in both the mean wind and the standard deviation of 10kts (W+10, $\sigma_w$+10) (Table 2). Such changes are typical of likely seasonal variations. The winter of 1984–5, for example, had winds at commercial flight altitudes for the southeastern United States more than 10kts below the mean (Robinson, 1986; Kousky, 1985). In contrast a speed more than 10kts above normal for much of the area served from Charlotte can be inferred for the winter of 1981–2 (Dickson, 1982).

In the mean wind conditions for which the schedules are developed the major factor affecting the flight distance before delays are felt is $\sigma_w$. Since $\sigma_w$ is similar for all directions except south, the distances before delays occur are similar, being over 800 n.m. before a delay frequency greater than 1% is reached, and over 1000 n.m. for a 5% frequency. For the southbound routes the distance is about 100 n.m. greater at both probability levels.

A 10% increase in the standard deviation alone decreases the route distance needed before the delay frequency reaches the 5% level by about 200 n.m., the corresponding value for the 1% level being 60 n.m. The decrease is most marked for the southbound flights, where the proportional increase in standard deviation is the greatest. A 10% increase in mean equivalent wind alone has a very similar effect. With 10% changes in both W and $\sigma_w$ incorporated, the distance decreases by about 300 n.m. at the 5% level, 200 n.m. at the 1% level (Table 2).

TABLE 2. Route distance (n.m.) at which wind induced delays occur with a frequency of 5% and 1% in winter wind conditions.

| Direction | Wind (kts) | | Route Distance | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | W | w | (W, $\sigma_W$) | | (W, $\sigma_W$+10) | | (W+10, $\sigma_W$) | | (W+10, $\sigma_W$+10) | |
| | | | 5% | 1% | 5% | 1% | 5% | 1% | 5% | 1% |
| W | -70 | 28 | 1175 | 855 | 945 | 760 | 950 | 730 | 810 | 660 |
| NW | -45 | 28 | 1175 | 855 | 945 | 760 | 950 | 730 | 805 | 660 |
| N | 6 | 30 | 1100 | 815 | 935 | 750 | 910 | 705 | 795 | 655 |
| NE | 55 | 30 | 1100 | 815 | 935 | 750 | 915 | 710 | 795 | 655 |
| E | 70 | 29 | 1125 | 825 | 940 | 755 | 930 | 715 | 800 | 660 |
| SE | 3 | 30 | 1100 | 815 | 935 | 750 | 910 | 705 | 795 | 655 |
| S | -25 | 25 | 1285 | 925 | 995 | 770 | 1035 | 785 | 840 | 670 |
| SW | -75 | 30 | 1100 | 815 | 935 | 750 | 910 | 705 | 795 | 655 |

TABLE 3. Percentage of flights to and from Charlotte subject to wind induced delays in various wind conditions

| Delay Frequency | (W, $\sigma$ w) | (W, $\sigma$ w+10) | (W+10, $\sigma$ w) | (W+10, $\sigma$ w+10) |
|---|---|---|---|---|
| 5% | 0.95 | 1.26 | 1.26 | 3.47 |
| 1% | 2.52 | 3.47 | 3.47 | 3.47 |

TABLE 4. Frequency of wind induced delay as a function of route distance for long routes

| Route | Distance (n.m.) | Mean Wind (kts) | | Delay Frequency (percent) | | | |
|---|---|---|---|---|---|---|---|
| | | W | $\sigma_W$ | (W, $\sigma_W$) | (W, $\sigma_W$+10) | (w+10, $\sigma_W$) | (W+10, $\sigma_W$+10) |
| TransPacific From W. Coast | 4500 | -35 | 7 | 6 | 26 | 42 | 47 |
| TransPacific From E. Coast | 5600 | -34 | 7 | 9 | 30 | 52 | 54 |
| TransAtlantic From W. Coast | 4800 | -25 | 7 | 6 | 27 | 47 | 48 |
| TransAtlantic From E. Coast | 3200 | -37 | 9 | 4 | 20 | 25 | 37 |
| TransContinental | 2100 | -42 | 10 | 1 | 10 | 6 | 22 |

Translating these results into the percentage of flights to and from Charlotte which are likely to be affected by seasonal wind variations, the overall impact is small (Table 3). Only the long routes to the west coast are affected in the mean conditions, while the Texas and Colorado routes are added in the more severe situation. These represent a small portion of the total operation. Since Charlotte has a typical route structure, the results indicate that for most domestic carriers the seasonal windspeed fluctuations are likely to have a rather marginal effect on operations.

The impact on the longer routes, however, suggests that the wind effect for transoceanic and transcontinental operations may be more significant. For such routes delays were assessed using generalized mean wind conditions developed from the data of Boeing (1975b) (Table 4). Since here the emphasis is on the frequency of delays for fixed, if somewhat generalized, route distances, the results are expressed as the frequency with which flights using the present schedule would be delayed in the changed wind conditions. For these long routes the frequency of delay rises rapidly as the conditions change. This certainly indicates that action by the airlines is required, and suggests that climatological wind forecasts are potentially very valuable for schedule development on these longer routes.

The information for the longer routes is presented in generalized form and should be treated with caution. The model used to relate winds to schedule time was developed for relatively short routes in an area of the westerlies where the permissible air lanes are closely prescribed. On longer routes flight paths can be chosen to utilize the most advantageous wind conditions. Several routes are transpolar, with some time outside the main line of the westerlies, and almost all are likely to be at a higher altitude than the modeled values. Nevertheless, they give a first suggestion of the likely impact of windspeed and the potential value of climatological forecasts.

## 5. CONCLUSIONS

Airline schedules are closely adjusted to climatological mean winds. Major seasonal wind variations are incorporated by the development of separate schedules for winter and summer. Within each season, however, occasional wind induced delays are inevitable because of day-to-day windspeed fluctuations. In the climatological mean wind conditions of winter, when these fluctuations are most marked, arrivals more than 15 minutes after the scheduled time are likely to occur more than 5% of the time only on routes more than 1100 n.m. long. For most United States domestic airline operations this involves only about 1 percent of the total flights (Federal Aviation Administration, 1986). If the same schedule is retained for a season when the wind conditions depart from the mean, delays will increase in frequency but are still likely to affect less than 5% of the total flights. This relatively small impact suggests that the gains which can be achieved by an airline through the use of seasonal wind forecasts are unlikely to outweigh the extra effort needed to develop the schedules.

The situation changes markedly, however, when transcontinental and transoceanic operations are considered. The longer routes increase the probability of delays in all wind conditions. Departures from the climatological mean conditions can lead to delays for a third or more of the flights. Although on these routes the flexibility in the choice of flight path may decrease the actual number of wind induced delays, a significant number are still likely to be affected. Hence for transcontinental and transoceanic operations seasonal forecasts have the potential to assist airlines in producing efficient schedules.

## 6. ACKNOWLEDGEMENTS

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# Lysimetric Calibration of a Canadian Soil Moisture Budget Model Under Bare Soil in Southern Africa

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ABSTRACT

An empirical soil moisture budget model was tested against bare soil lysimeter measurements taken at Bloemfontein, South Africa. Comparisons between computed and measured values of soil moisture contents, and actual evaporation taken daily and accumulated over the test period, are presented. Results show that the model could be reliably calibrated for the semi-arid South African climate. The potential for further application of the model in that climate is good, but more extensive field testing should be done before operational use of the model is attempted. The model was applied to climate records to examine long-term patterns of bare soil evaporation for the region. As an additional demonstration of the model, three recent drought years were placed in the resulting cumulative frequency distribution. The low rank of two of those years suggests that reduced rates of bare soil evaporation reflect drought episodes. Bare soil evaporation could be a factor in determining soil moisture reserves for field crops seeded in winter and spring.

RÉSUMÉ

Cette étude traite des résultats d'un modèle empirique du budget des eaux du sol, et les comparent à ceux d'un lysimètre situé à Bloemfontein, en Afrique du Sud. On y a comparé le taux d'humidité du sol au taux d'évaporation, tel que mesuré durant la période d'essai. Les résultats ont démontré que le modèle peut être efficacement calibré afin de tenir compte du climat semi-aride sud-africain. Bien que le modèle possède un potentiel d'applicabilité élevé, il est bon de poursuivre les analyses avant que soit entrepris son utilisation opérationnelle. Donc, ce même modèle a été utilisé afin d'examiner la trame d'évaporation à long terme des sols découverts de la même région.

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Trois années de sécheresse ont été ajoutés à la distribution initiale des fréquences cumulatives. Les résultats ont démontré que le rang inférieur obtenu pour deux des trois années a bien traduit la diminution du taux d'évaporation pendant les années de sécheresse. L'évaporation des sols découverts peut être un facteur important quant à la détermination des réserves en eau des cultures semées en hiver et au printemps.

## INTRODUCTION

Soil moisture estimates are required for many decisions related to agriculture. The derivation of these estimates frequently must take into account widely differing climates and extreme weather variations. Weather-driven computer simulation models are often used to provide these estimates. There is a growing recognition that models developed for crop growing conditions in North America could be of use in arid regions of the third world. Before these models can be used operationally, they require calibration and testing for climatic conditions in those regions. Experimental conditions are often less than ideal for this purpose in many third world countries.

Lysimetric techniques are used here to calibrate for the semi-arid South African climate a weather-driven soil water budget model developed in Canada. The weighing lysimeter is a powerful instrument for studying soil-plant-atmosphere relationships, since it gives direct, accurate measurements of water losses from soil evaporation and plant transpiration over long continuous periods. In this study, a lysimeter was used to measure bare soil evaporation rates during one growing season in South Africa. Comparison of simulated bare soil evaporation rates with these data is a useful test prior to application of the model in surrounding countries or regions. This study represents a rare opportunity to use a lysimeter for direct measurements of bare soil evaporation, rather than for crop transpiration analysis.

Following calibration, the model was used to simulate seasonal evaporation from a bare soil surface using a long period of climatological data at a nearby weather station. Cumulative frequency distributions were generated from the historical series to analyse the variability in moisture reserves in fallow soil during the dry season. The third test performed here was to identify the rank of three recent drought years in the cumulative frequency distribution of bare soil evaporation generated from the historical simulations. This test indicates to what extent bare soil evaporation rates are correlated with drought.

## BACKGROUND

The model tested is based on the Versatile Soil Moisture Budget (Baier and Robertson, 1966). This model has had many successful applications in North America (Baier et al., 1979) and has undergone many refinements (see Baier et al., 1972; Baier et al., 1979 and Dyer and Mack, 1984). Its general form, along

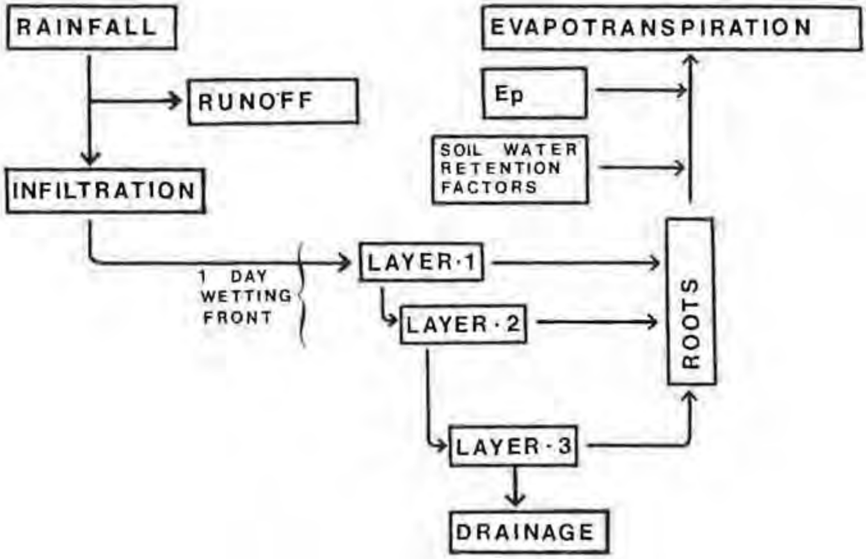


FIGURE 1. Flowchart of the soil moisture budget model used (based on Figure 1 from Dyer and Boisvert, 1985).

with a range of potential applications, has been discussed in detail elsewhere (Dyer and Boisvert, 1985). The form of the model used here is shown in Figure 1 for a soil divided into three layers. This flow chart illustrates the use of simple functions for root patterns and soil water retention characteristics. Although the model is applied to bare soil in this paper, the root function is still shown. In the absence of a root system, root coefficients in the second and third layers are reduced to account for upward moisture diffusion. The model is driven by daily values of potential evapotranspiration (*Ep*) and rainfall (R) and calculates daily actual evapotranspiration (*Ea*) as:

$$Ea = \sum_{J=1}^{n} k_{ij} Z_j S_j / C_j Ep \qquad (1)$$

where $Z = f(S/C)$ and $k_{ij}$ is a set of root water extraction coefficients for specific crop growth stages (*i*) and soil layers (*j*). The factor $Z_j$ is derived from a drying curve relating $Ea/Ep$ to specific values of $S_j/C_j$, *where* $S_j$ and $C_j$ are the soil moisture content on the previous day and the soil moisture storage capacity for layer *j*, respectively. *S* and *C* represent a range of soil water between the permanent wilting point (*WP*) and field capacity (*FC*). At *WP*, *S* is zero. *C* is equal to *FC–WP*.

Many earlier soil moisture budgets assume instantaneous infiltration of surface water (Holmes and Robertson, 1959; Baier and

Robertson, 1966 and Selirio and Brown, 1971). The model used here includes an infiltration sub-model (Dyer and Mack, 1984; Dyer, 1984) which simulates the delayed penetration of excess drainage water to deeper layers due to slow downward movement of the infiltration wetting front. This modification represents a significant improvement in monitoring the short-term changes of water content in soils with high clay content. This sub-model recognizes interim soil water storage in the range between field capacity and saturation due to slow drainage, in addition to the plant-available water storage above the permanent wilting point.

A further modification to account for rapid surface evaporation from a saturated soil, under the high *Ep* rates experienced throughout most of Africa, was introduced to the model and tested. Even under this climatic regime, surface evaporation is not likely to be a large term compared to transpiration, unless free water is present near the surface. This condition should not occur unless *S* exceeds *C* in the shallow soil layers. In previous applications surface evaporation rates were included with the root extraction coefficient (*k*) for the top soil layer (Baier et al., 1979). This modification must be used in conjunction with the sub-model for excess water infiltration proposed by Dyer (1984), in order to use this term in a daily water balance model. Wet soil surface evaporation (*Es*) is calculated as follows:

$$Es = \left[ \frac{\sum_{J=1}^{m} (S_j - C_j)}{\sum_{J=1}^{m} (Sat_j - C_j)} \right]^{1/3} (Ep - Ea) \qquad (2)$$

where $S_j$ exceeds $C_j$ and

*Sat* = water content at saturation, and
*m* = number of soil layers in the depth of one-day infiltration.

Computation of *Es* (eqn. 2) follows computation of *Ea* (*eqn.* 1) so that both *Ea* and *Ep* are already available for the day in question. Since wet surface evaporation (*Es*) is inversely related to the infiltration rate, *Es* was computed from the fraction of excess water retained in the one-day drainage depth (Dyer, 1984). However, *Es* can be very high with relatively small rainfall amounts, or with only a small fraction of the one-day drainage depth of soil being saturated. Although this layer is very deep relative to surface evaporation, its use in conjunction with *C* makes *Es* estimates sensitive to the same soil infiltration properties assumed in the infiltration sub-model. The cube root in equation 2 makes *Es* only moderately sensitive to the actual amount of excess water in the one-day drainage depth, until this water is nearly depleted. Then, *Es* decreases rapidly as the remaining excess water drains away.

## PROCEDURE

A weighing lysimeter was installed at the University of the Orange Free State experimental station in Bloemfontein (29° 06′S, 26° 14′E) during August, 1983. An electronic data logger (Campbell CR-21) was used to record mean hourly weight changes from January 12, 1984. A tipping-bucket rain gauge, silicon pyranometer, and temperature, relative humidity and wind speed sensors were operating during the experiment, 50 m south of the lysimeter. *Ep* was estimated by the Penman equation (Penman, 1948). Available thermal energy at the surface required in the Penman equation was approximated as that for a full wheat crop canopy by De Jager et al. (1982). The *Ep* calculation procedure was initialized when the data logging system was established and was therefore in place when this experiment was started. It was considered appropriate to use the wheat canopy based *Ep* because the bare soil model would eventually be integrated with a full ground cover model in any crops analysis application.

The dimensions of the soil sample in the lysimeter were 3.2 x 3.2 x 2 m of sandy clay soil, with volumetric water contents of 35%, 25% and 5% for saturation, field capacity and permanent wilting point respectively. Water loss by deep drainage was determined at intervals of several days by collecting water from the bottom of the lysimeter in containers which were then weighed. Volumetric soil water content measurements were taken in the lysimeter on 17 occasions throughout the experiment for the same soil thicknesses used in the budget. Disturbance of the lysimeter soil profile was minimized by limiting gravimetric moisture content readings to one per layer on each occasion.

Three soil layers were used in the model (see Table 1). They are relatively thick and few in number because this model deals with the destination of water at the end of each day, rather than the physical processes of water movement. Surface water was allowed to infiltrate the top two layers

TABLE 1. Soil characteristics assumed in the model.

| | | | % Water Content by Volume | | |
|---|---|---|---|---|---|
| Soil Layer (j) | Layer Thickness (cm) | $k_j$ | Saturation | Field Capacity | Wilting Point |
| 1 | 0-19 | .6 | 35 | 25 | 5 |
| 2 | 19-50 | .17 | 35 | 25 | 5 |
| 3 | 50-100 | .03 | 35 | 25 | 5 |

(500 mm) in one day but could not penetrate the third layer until the next day. This infiltration submodel had been introduced in previous applications (Dyer, 1984). The root water extraction coefficients ($k$) were held constant with time throughout the experiment, but decreased rapidly with depth to simulate a bare soil (see Table 1). Similar $k$ coefficients had been used by Baier (1972) on previous occasions to simulate both fallow-field and pre-emergent conditions in western Canada. This secondary use of $k$ maintains the simplicity of the model. In effect, $k_2$ and $k_3$ were assumed to account for water diffusing upward to replace soil water lost by surface evaporation since there were no roots. The use of 0.8 as the sum of $k_j$ was recommended for bare soil by previous authors (Baier et al., 1979). It represents the evaporation rate from a moist bare soil (at field capacity), as a fraction of the evaporation rate from a free water surface, under the same ambient conditions. Control parameters for the model are given in Table 1.

The soil water retention curves required to calculate $Z$ were approximated using a formula proposed by Dyer and Baier (1979). The shape of these curves was such that actual evaporative loss from each layer, expressed as a function of the potential rate of loss under moist conditions, decreased exponentially to zero as soil moisture decreased to the permanent wilting point. In reality, the soil would continue to dry below the permanent wilting point ($WP$), since $WP$ refers to the level of moisture where root extraction stops. Rates of soil drying by diffusion would be so slow at this point that, even under high $Ep$, the effect on the soil water balance can be ignored. Because the model would eventually be used with a crop for at least part of the year in Africa, the use of a crop-related $WP$ was felt to be a more realistic test of the model. Soil moisture was expressed as a fraction of the plant-available water holding capacity. When this fraction exceeded 0.95 the actual rate was set equal to the potential rate.

The model was tested against seven months of lysimetric measurements of actual soil water loss. Because a sub-model for surface soil drying was used for the first time here and because only one season of lysimeter data was available, these test results should be considered as a calibration rather than a verification of the model.

Following this lysimetric calibration (shown in Figures 2 to 4), 49 years of daily rainfall data from Glen, a nearby climate station, were used to run the soil moisture budget model from January 3 to June 30. For each year, $Ea$ was accumulated over periods starting January 3, and ending March 31, April 30, May 31 and June 30. For each period, accumulated $Ea$ was ranked in ascending order. Figure 5 shows the frequency distribution for accumulated $Ea$ for the period ending June 30.

## RESULTS AND DISCUSSION

Simulations of daily soil moisture during the period of lysimetric

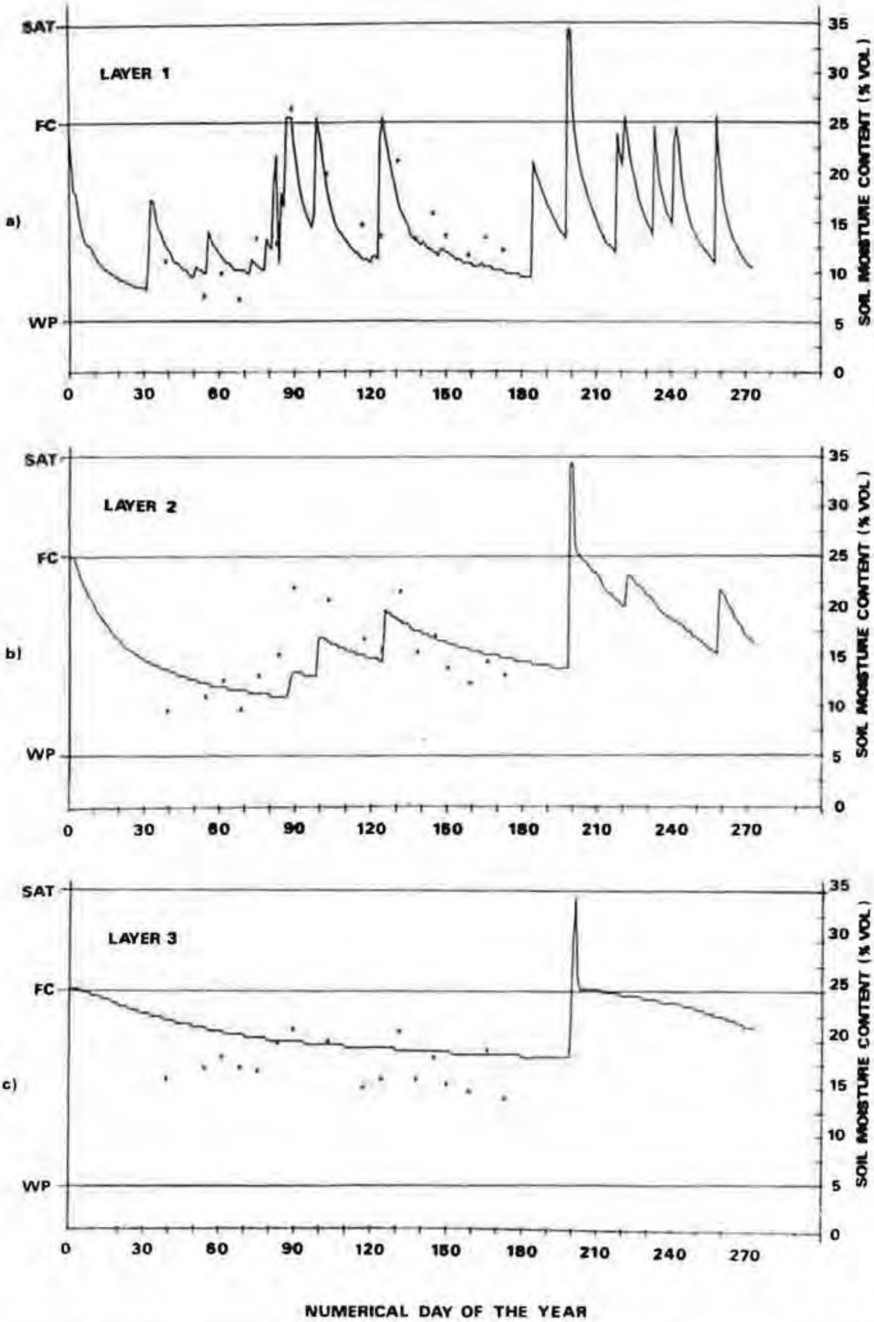


FIGURE 2. Daily soil moisture content simulation and measurements (o) in soil layers 1, 2 and 3 between January 1 and September 30, 1984 at Bloemfontein.

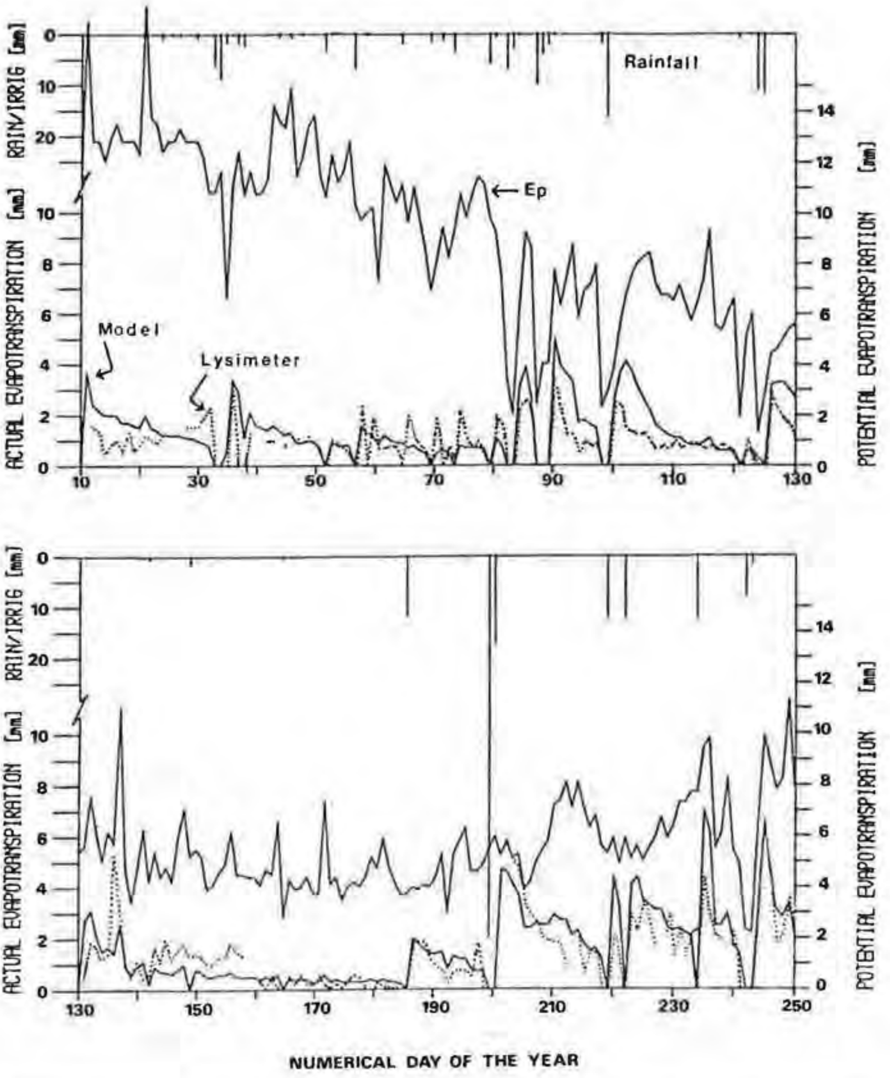


FIGURE 3. Comparison of *Ea* measured by the lysimeter, *Ea* estimated by the model, *Ep* and rainfall between January 10 and August 28, 1984 at Bloemfontein.

measurements (January through September of 1984) are shown in Figure 2. Simulated soil water contents in these plots are given by $S_j + WP_j$. Measurements of soil water contents in all three soil layers of the lysimeter, on 17 days throughout the experimental period, are also shown in Figure 2. Following a heavy rainfall event on December 31, the daily simulations were started from January 1 with the initial soil water content assumed to be at field

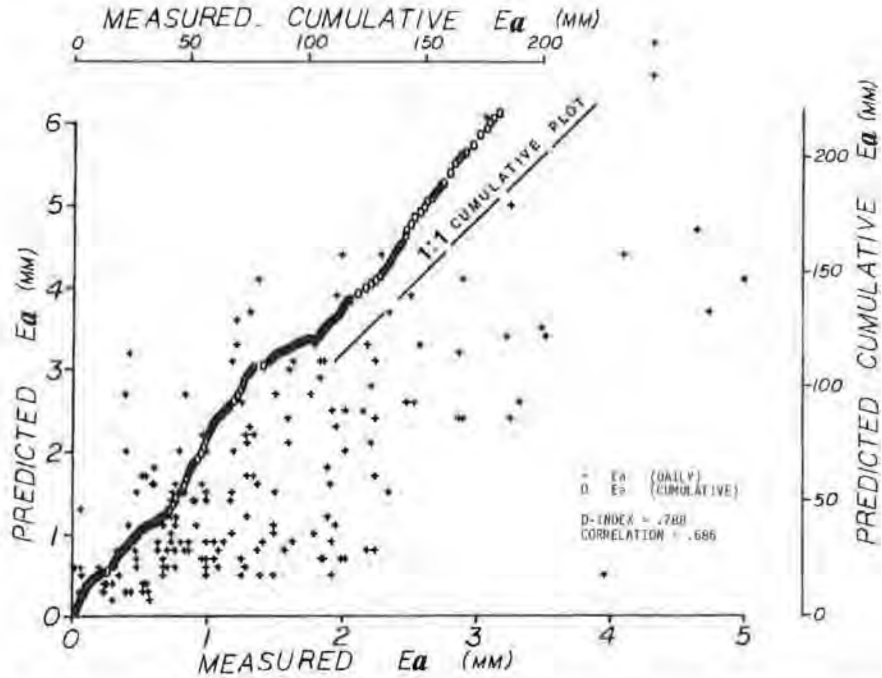


FIGURE 4. Comparison of simulated and lysimeter measured *Ea* on a daily basis (+) and accumulated (0) over periods starting January 1 and incremented daily throughout the experiment at Bloemfontein, 1984.

capacity. These assumed initial water contents may partly account for the over-predictions of soil moisture during the first 90 days. Dates are defined here by both the numerical day of the year and by month, day notations.

After Day 90 (March 30) the model under-predicts soil moisture in the top two layers (Figures 2a and 2b), with the largest discrepancy in layer 1. After Day 100 (April 9), the model showed good agreement in layers 2 and 3. Under bare soil conditions the soil moisture content in layer 3 would be expected to show little variation, as was simulated by the model (Figure 2c). The observed deviations between simulations and measurements are probably due to the use of single-sample measurements. However, layer 3 measurements of volumetric soil water content generally approximated 17%. This corresponded to the lowest value given by the model, prior to recharge on Day 199. The closeness in observed moisture contents of layers 1 and 2 throughout the experiment suggests that a significant amount of water diffused upwards from layer 2 to layer 1. Thus, the adoption of relatively high values for *k* in the two deeper layers in the model appears to be sound.

Comparisons between the simulated and observed daily *Ea*, rainfall and *Ep* are shown in Figure 3. During the summer months (Day 1 to Day 90 or

January 4 to March 29) when atmospheric demand (*Ep*) is high, modelled *Ea* shows good agreement with the lysimeter values. But, as evidenced by the plot of cumulative *Ea* from both the model and the lysimeter in Figure 4, there is a general tendency for the model to over-predict *Ea*. This error seems to be most apparent two to four days after a substantial wetting event and is usually smallest on the actual day of the wetting event, which suggests that the adjustment for surface evaporation immediately following a heavy rain was a necessary modification to that model. In most cases the simulated *Ea* approached the measured *Ea* six to ten days after each of the wetting events.

Accumulated *Ea* comparisons in Figure 4 do not fall exactly along the one-to-one line, since day-to-day comparisons are scattered. Statistical analysis confirms this observation. The coefficient of correlation is low at $r =$ 0.66. Although this result is significant at the 1% level, large random day-to-day errors occurred. Because these errors are random, integration of *Ea* over longer periods would result in much better agreement, as shown by the cumulative comparisons in Figure 4. Therefore, relative seasonal comparison of *Ea*, such as the application described below, would be an appropriate use of this model.

The most notable deviation occurs after substantial drainage (20 mm) occurred on Day 135 (May 14). From this drainage event until Day 158 (June 6), when further drainage occurred, measured *Ea* was noticeably higher than the predicted value. A drainage event is a maintenance operation of the lysimeter, whereby free gravitational water is pumped from the bottom of the lysimeter. The dramatic one-day difference between *Ea* and *Ep* on May 15 was probably the result of an offset correction error associated with removal of drainage water. This offset error could have persisted until the next drainage event on June 6, immediately following which date the measured and simulated *Ea* became almost identical. The slight changes in the relationship between the model predictions and the lysimetric measurements over the seven-month period may indicate that the soil in the lysimeter was still settling. Since the lysimeter was started only in August, 1983, soil settling is a likely factor. A noticeable change due to settling is most likely after a major drainage event, such as occurred on Day 135.

In the short term, from day to day, both measured and simulated *Ea* respond to *Ep*. However, over the seven-month period, there is a decreasing trend in *Ep* which is not apparent in *Ea*. This suggests that the drying rate of bare soil is relatively insensitive to seasonal changes in atmospheric demand. During early winter (Day 150 to Day 185 or May 30 to June 3) daily *Ea* is also insensitive to daily *Ep* until the rain on Day 185. This lack of response is the result of a combination of low soil moisture reserves (see Figure 2) and low *Ep* (see Figure 3). However, once the shallow soil has dried out, the hydraulic conductivity of the soil becomes much more important than the atmospheric demand for water, even when *Ep* is relatively high. *Ea* is relatively insensitive to *Ep* under these conditions.

An index for assessing simulation accuracy, defined as the D-index (Wilmott 1982), was applied to the data shown in Figure 4. In this type of work a value of 0.7 is considered to be acceptable accuracy. Hence the value of 0.79 attained here reflects acceptable reliability. The correlation and D-index tests indicate that the budget model should not be relied upon to estimate changes in soil moisture reserves over a few days, but that it is adequate for analysis of seasonal water balance. The use of *Ep* estimates based on a wheat canopy, rather than bare soil, could account for some of the errors noted in Figure 3 as well as for the simulated cumulative *Ea* values exceeding the measure cumulative *Ea* values in Figure 4. Calculations of *Ep* based on a wheat canopy would produce higher values than those based on bare soil because of the higher albedo of the latter.

## APPLICATIONS OF THE MODEL

The model application was designed to illustrate how simulated *Ea* accumulated over several months can be used to analyse climatic trends. Agricultural practices in the Glen region rely upon soil moisture storage during summer to carry wheat through the dry winter period. Soil moisture reserves at the start of the winter growing season depend heavily on rainfall during the previous few months. The above tests show that evaporative loss from bare soil over a long period is very insensitive to *Ep* (see Figure 3). Therefore, although *Ep* decreased from summer to winter, a fixed set of *Ep* were used for all years.

Table 2 gives the 1984 *Ea* accumulations for each period in relation to the mean values and in relation to their ranks in the overall distributions (from highest to lowest). To illustrate, the June 30 accumulation for 1984 has a rank of 36 out of 49, meaning that 27 percent of years had had lower

TABLE 2. Comparison of 1984 estimates of *Ea* (mm water) with historical estimates at Glen.

| Accumulation Period Ends | 1984 Estimate | Mean Estimate | % of Normal | Rank (49) | % of Years Lower |
|---|---|---|---|---|---|
| March 31 | 115 | 162 | 71 | 33 | 33 |
| April 30 | 155 | 210 | 74 | 36 | 27 |
| May 31 | 191 | 241 | 79 | 35 | 29 |
| June 30 | 200 | 256 | 78 | 36 | 27 |

TABLE 3. Ranking of 1982, 1983 & 1984 in the 49 year frequency distribution at Glen.

| | Accumulation Dates | | | |
|---|---|---|---|---|
| Year | March 31 | April 30 | May 31 | June 30 |
| 1982 | 22 | 18 | 17 | 17 |
| 1983 | 45 | 47 | 48 | 47 |
| 1984 | 33 | 36 | 35 | 36 |

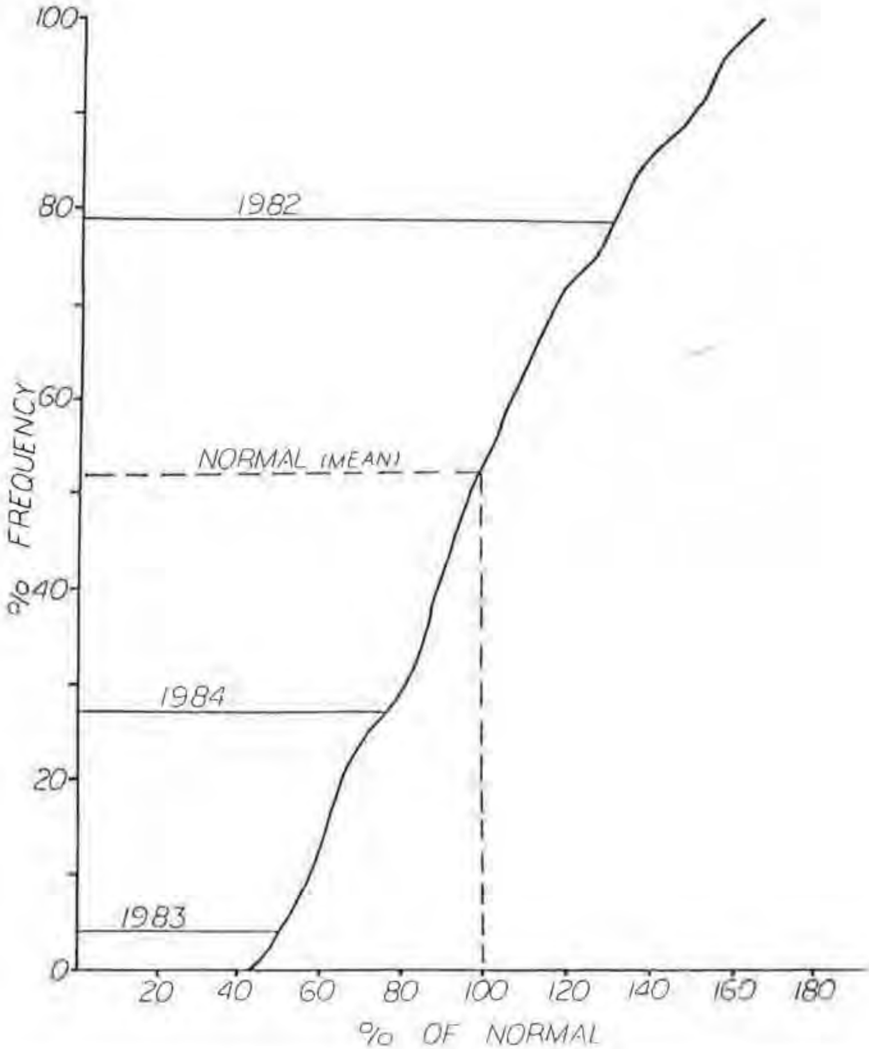


FIGURE 5. Accumulative frequency distribution of simulated bare soil evaporation expressed as % of normal between January 1 and June 30 from 1936 to 1984 at Glen, S.A.

accumulations. The percent probability of having lower values in the future was estimated on the basis of these ranks. As illustrated in Figure 5, approximately 27% of future years could be expected to have lower total evaporation by June 30 than 1984. The evaporation between January 3 and June 30 could be as low as 114 mm in the driest year or as high as 422 mm in the wettest year. Although 1984 was a dry year, the total evaporation was 80% of the 49 year average evaporation.

The three years 1982 to 1984 are considered to have been drought years at Glen. The ranks of these years are shown in Table 3 for all four accumulation dates. Their positions in the January 3 to June 30 distribution are shown in Figure 5. Both Figure 5 and Table 3 show that 1983 had an extremely dry late summer and fall season. Only 2 of the 49 years had had less evaporation by June 30 than did 1983, whereas 13 years had had lower values than 1984. While 1983 had only 50% of the normal evaporation, there was 40% above-normal evaporation for the test period in 1982.

Figure 5 indicates a lack of skewness in the distribution with the mean and median (50% frequency) values being very close. The year-to-year variability in Figure 5 and Table 3 suggests that bare soil evaporation is a factor in determining soil moisture reserves for field crops planted in winter or spring. Bare soil evaporation, prior to emergence of winter crops, would be much smaller and have less year-to-year variability than would summer rainfall. Also, bare soil evaporation and rainfall are directly correlated (with rainfall being the driving force), so that the impact on water supply to crops would be nullified. This suggests, however, that the recharge benefits of a rainy spring season to crop water supply may well be significantly reduced by increased bare soil evaporation prior to emergence.

## CONCLUSIONS

The correlation coefficient of the day-to-day fit of the model estimates to lysimeter measurements of *Ea* was low ($r = 0.66$), but significant at the 1% level. A prime limitation was the simplicity of the modelling procedure, including the one-day simulation time-step. This type of model was chosen over more complex, physically based models because simplicity is essential in a model suitable for application to extended weather data sets. Simplicity is particularly important if such a model is to have a similar application almost anywhere else in Africa.

The soil moisture content comparisons (Figure 2) show that the model reflects the overall water retention characteristics of the lysimeter soil, while the accumulated evaporation comparisons (Figure 4) demonstrate the model's ability to simulate seasonal water losses. Over-estimating of cumulative *Ea* can be explained by the use of estimates of *Ep* in the model based on a wheat canopy.

Although *Ep* is not a major source of year-to-year variability in the region, it is much higher than *Ep* experienced throughout most of Canada. The need to add *Es* to the Canadian model was not surprising under these almost tropical conditions. The function for *Es* proposed here (eqn 2) is a reasonable approximation, given other limitations of the model.

Further testing of the model against measurements for both bare soil and crop-covered soil should be done before it can be considered as fully validated for the region. With a crop present, the *k* coefficients in equation 1 would be evaluated for their intended role, which was to simulate root extraction of water, rather than upward diffusion in response to surface evaporation (Baier and Robertson, 1966). The lack of response of *Ea* to the long-term seasonal decay in *Ep* in Figure 3 suggests that the water retention characteristics of the soil were the dominant factor over evaporative demand in controlling seasonal bare soil evaporation.

The historical analysis shown in Figure 5 and Tables 2 and 3 also demonstrates the potential value of models for quantifying weather information on a regional and climatic basis once they have been verified using detailed measurements from a lysimeter. The use of this model to study climatic variability and in frequency distribution analysis in South Africa has been demonstratd elsewhere (Dyer and De Jager, 1986). However, before the model is used in any quantitative predictive applications in southern Africa, further field testing is required. Ideally, the period of lysimeter measurement used for validation should be independent of that used for calibration. Under the arrangement by which this work was carried out, an additional season of measurements was not possible. The performance of this model should be compared with those of other similar computer models, to determine whether it represents a significant improvement over other options. Such a comparison, however, should include both operational and scientific criteria. But the preliminary results described in this paper show promise for eventual use of the model described here in the southern African region.

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# ASSESSING IMPACTS OF CLIMATIC WARMING ON FRESHWATER FISHES IN NORTH AMERICA

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Our group began studying potential impacts of climatic warming on temperate freshwater fishes in 1983. Currently, it consists of fish ecologists and physiologists from the University of Toronto, Wilfrid Laurier University, the University of Wisconsin, Madison and the Ontario Ministry of Natural Resources. We are interested in potential effects of future climatic warming (Canadian Climate Centre 1986) on the distribution, growth and production of fish, especially fishes of the Great Lakes. See Meisner *et al.* (1987) for an initial assessment of the impacts of climatic warming on fish communities and their habitats in the Great Lakes basin.

Colleagues from the University of Toronto, the University of Wisconsin, Madison and the Ontario Ministry of Natural Resources are presently collaborating to summarize and interpret the likely effects of increased water temperature on growth, distribution and fisheries yields of preferred species in the Great Lakes. Analytical and empirical models of growth, recruitment and fisheries yield for different species (e.g. Christie and Regier 1988, Shuter *et al.* 1980) are being employed for these purposes.

Studies at the University of Toronto are currently focused on the zoogeography of fish and distributional shifts that may occur from climatic warming. Analyses have been conducted of similarities between the ecological characteristics of recent fish colonists of the Great Lakes basin and fishes that could expand their ranges northward in response to increased water temperatures (Mandrak 1988).

Early responders of climatic warming are being identified, e.g., brook trout and the larval stages of sea lamprey. The influence of stream and intra-gravel temperatures on sea lamprey larvae abundance is under investigation. Hydrometeorological models of the thermal regime in the brook trout zones in some southern Ontario streams are being constructed. These models will be used to simulate the effects of scenario-projected increases in air temperature on the thermal regimes in the study streams, and the extent to which brook trout habitat could be lost.

Research of the factors controlling the temperature of groundwater suggests that groundwater temperatures will rise with air temperatures as climatic warming occurs (Meisner *et al.* 1987). Groundwater discharge to streams is important to fishes because it provides baseflow and moderates the effect of seasonal air temperature fluctuations characteristic of temperate climates. The effects of elevated groundwater temperatures form part of the stream temperature simulation studies described above.

A workshop on the impact of climatic warming on North American inland fisheries was held at Wilfrid Laurier University in February 1987. During this workshop climatologists from the Canadian Climate Centre and fish ecologists from Canadian and American laboratories shared and consolidated research. Abstracts of papers presented at the workshop are available at the address listed above.

A major symposium on climate change and fisheries will be held at the American Fishery Society's annual meeting in Toronto on September 14-15, 1988.

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## EXPERT COMMITTEE ON AGROMETEOROLOGY ANNUAL MEETING

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This meeting of the Expert Committee on Agrometeorology (ECA) was held in Saskatchewan (Oct. 29 and 30, 1987) for the first time in the Committee's history. The main topics on the agenda included the regional reports, agrometeorological education, automated data acquisition, the Canadian Agricultural Research Council report, the Memorandum of Understanding between Agriculture and Environment Canada. Issues such as these, which are of both national and regional concern, were discussed and considerable information was exchanged. The next meeting of the ECA is to be held at Vancouver, British Columbia.