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DEDICATION

This issue of *Atmosphere* is respectfully dedicated to Dr. Andrew Thomson, in celebration of his 80th birthday. On May 18, 1973, the Canadian Meteorological Society conferred Honorary Membership on Dr. Thomson in recognition of his outstanding dedication to the advancement of Meteorology. Many of his friends, colleagues and associates have united together to contribute articles for this issue especially to honour him for his endeavours to foster and promote the science of Meteorology.

Andrew Thomson: A Profile

M.K. Thomas
Atmospheric Environment Service, Toronto
[Manuscript received 29 November 1973]

Dr. Andrew Thomson retired from government service in 1959, more than 14 years ago, and consequently, is not known personally by a large percentage of people working in Canadian meteorology today. To those of us who joined the Meteorological Branch during wartime, however, Dr. Thomson will always remain a very important person in our meteorological world. As Assistant Controller he was the man who had the final word on whether or not you were hired and where you were posted, and he was the man with whom you visited if you ever had the opportunity to go to Toronto on leave. Few of us ever saw, let alone had the opportunity of talking with, the Controller at that time, Dr. John Patterson, and while there were usually a few experienced meteorologists at Headquarters to look after the training courses and to administer the postings and other details, we knew that behind it all was "Andy" Thomson who had the last word regarding the wartime Meteorological Assistants hired for service with the British Commonwealth Air Training Plan.

In my particular case, I first visited with Dr. Thomson one January day in 1942, at the end of meteorological Short Course No. 4, to see if I could avoid a posting to Gander. Not that I had anything against Newfoundland, but when I was told that it would be four to five years before married accommodation was to be made available at that station, I knew some drastic action had to be taken. I planned to be married in a few months and fortunately was able to locate a classmate from Western Canada who in no way wanted to go back to the Prairies. With Dr. Thomson's blessings we traded postings and I started my meteorological career in Manitoba rather than in Newfoundland. Subsequently, I remember visiting Headquarters at 315 Bloor Street West on occasions during annual leave and discussing with Dr. Thomson some of the important points of the day – why we weren't in uniform, what was wrong with the pressure observations in northern Quebec, why couldn't the main forecast offices get their forecasts on the teletype faster, and what were the chances of a posting back to Ontario? I expect many aging meteorologists in the service today have similar early memories of Dr. Thomson!

If Andrew Thomson ever became exasperated with his young meteorologists and their vocal (and in retrospect very selfish) clamorings for postings nearer home, and their constant demands to be put into RCAF uniform, he didn't show it. Well he might have, however, since he had had a most unusual and widely travelled career – working and studying in several countries after graduation – and had accumulated a wealth of experience before returning to Toronto late in 1931 to join the Meteorological Service.

Of Scottish descent, Andrew Thomson was born at Dobbinton, near Owen Sound, Ontario, on May 18, 1893. He graduated in Honour Physics from the University of Toronto in 1915, and returned for a Master's degree in 1916, after which he was awarded a Townsend Fellowship at Harvard University. In May 1917 he was employed by the Carnegie Institution of Washington, D.C. and later that year became a mathematical aide to Thomas Edison. Following a brief period in the U.S. Army, he rejoined the Carnegie Institution and in 1919 was sent to northern Brazil to observe the atmospheric effects during an eclipse of the sun.

In October 1919, Dr. Thomson accepted an opportunity to carry out atmospheric electricity research on a voyage of the brigantine Carnegie around the world. During the voyage, which lasted more than two years, Dr. Thomson was fascinated with the South Pacific. Consequently, when the opportunity arose in 1922, he accepted the directorship of the geophysical observatory at Apia in Western Samoa. The territory was then under the trusteeship of New Zealand and, in 1929, Dr. Thomson moved to that country where he was employed as an aerologist. The following year, however, he decided he needed some refresher training and so went to Europe to study in Germany and Norway. In the latter country he became a good friend of Dr. Jacob Bjerknes and the other Norwegian meteorologists who had evolved, a few years earlier, the basic air-mass and frontal theory.

Following study in Europe, Dr. Thomson returned to the Carnegie Institution in Washington, but he had retained his Canadian citizenship, and soon decided to return to this country. In January 1932, he took up an appointment as head of the Physics Division at the Headquarters of the Meteorological Service of Canada. In the Service, the long regime of Sir Frederic Stupart had come to a close in 1929 and Dr. John Patterson had been appointed Director. Primarily because of the demands of aviation, increased governmental attention was being given to meteorology at this time, and it was realized that to provide the service required, the new meteorological theories and methods had to be used. However, soon after Dr. Thomson arrived back in Toronto, and before much expansion could take place, the depression snuffed out any real development of meteorological services.

Despite a slashed budget, Dr. Thomson became the prime organizer and promoter for two programs that began in 1933–34. The first was the organization of Canadian participation in the second International Polar Year. The first such year in 1883–84 had seen the establishment of observing posts in Canada by the United Kingdom and the United States, but the Meteorological Service had not participated. This time, however, and largely through Dr. Thomson's efforts, there were four special Canadian observing stations – Coppermine, Chesterfield, Cape Hope's Advance and Meanook, ALTA., all staffed by keen young scientists selected and recruited by him. This was Canada's first participation in an international geophysical research program – it was successful and it spurred research in Canadian universities and government at the very time it was needed. Dr. Thomson's other special project during his first years in the Service was the planning and organization of an M.A. course in Meteorology at the University of Toronto, to be given in cooperation with the Meteorological Service. He planned well; both the course and the co-operation are still in evidence after 40 years and hundreds of graduates.

Despite the depression, aviation continued to develop rapidly in Canada during the mid-1930's and it became necessary for the government to plan for substantial meteorological services to support it. Accordingly, in November 1936, the Meteorological Service became the Meteorological Division of the Air Services Branch of the new Department of Transport. Dr. Thomson became the Assistant Controller of the new Division, although he was not officially appointed to the position until early in 1940. To again refresh himself in the rapidly developing field of meteorological theory, Dr. Thomson spent six weeks during 1937 visiting the meteorological services in Britain, Norway and Germany. Later the same year he participated directly in the first forecasting work at Botwood in Newfoundland for trans-Atlantic flying, and in 1938 he was instrumental in staffing and setting up forecast centres across the country for the first flights of the new Trans-Canada Airlines. Shortly after the outbreak of war in September 1939 the British Commonwealth Air Training Plan was conceived and Dr. Thomson became the main organizer and administrator of the extensive meteorological program that was subsequently required. Dr. John Patterson was, of course, the Controller throughout the 1930's and during the war; veteran AES staffers will recall that all the correspondence coming out of Toronto headquarters bore his signature. Dr. Thomson has admitted, however, that early in the war Dr. Patterson had him learn to sign a passable "J. Patterson" so that there would be continuity in all written orders coming out of headquarters regardless of where Dr. Patterson's duties took him!

Wartime administration of meteorology in Canada must have been a terrific burden on John Patterson and Andrew Thomson. Dr. Patterson, then in his early 70's, and Dr. Thomson were called upon to expand the Meteorological Service nearly tenfold within a very few years. At first, the RCAF felt that 27 meteorological officers would be needed at about two dozen training stations. Every few months the estimated need increased until by 1943–44 there were nearly 350 wartime meteorologists on duty at approximately 70 training and operational bases. In addition, the civil aviation networks of observing stations and forecast centres were expanded in size and activity. College and high school graduates had to be found and trained as meteorologists and technicians; instrument procurement became very difficult; coordination with the American and British military meteorological services was not always easy, nor were dealings with federal manpower and financial officials. A few meteorologists were taken from operational duties to assist in the administrative and training work, but the continuing and prime responsibility for the program rested with Dr. Thomson. In 1944, however, flying training began to be phased out and after mid-1945 the wartime meteorological system was quickly dismantled. As Dr. Patterson was nearing the end of his career, Andrew Thomson now took on the problem of how best to organize Canadian meteorological services for peacetime.

During Technical Commission meetings of the International Meteorological Organization at Toronto, August 1947. *Left to right*: Miss C.D. Coleman (Secretary), John Patterson, J. Keranen (FINLAND), Andrew Thomson. *Photo: Canada Pictures, Toronto*

Named an Officer of the British Empire in 1946 for his wartime contributions, Dr. Thomson became Controller of the Meteorological Division later that year. His first accomplishment was the organization of headquarters into an administrative structure which was to last for more than 25 years. He selected for his first divisional chiefs P.D. McTaggart-Cowan, A.J. Connor, R.C. Jacobsen, D.C. Archibald, J.R.H. Noble, and E.W. Hewson, and these men began to plan for and build the Service we have today. As a result of retirements and resignations during the first few years, C.C. Boughner, H.H. Bindon and D.P. McIntyre were added to this echelon and have similarly left their marks on Canadian meteorology.

During the immediate postwar years Dr. Thomson became the Service's first Ottawa commuter as he made almost weekly visits to Air Services, D.O.T., and other departmental headquarters. The Ottawa trips took longer in those days too – Dr. Thomson would catch the 11:20 p.m. sleeper from Toronto and, if he was fortunate, return the next day on the afternoon train leaving Ottawa at 3:00 p.m. If his meetings lasted all day he would return on the sleeper to Toronto, or perhaps spend another night and day in Ottawa.

It was also during this period that Dr. Thomson began to boost Canada to a rather prominent place in international meteorology. During August 1947 he was the host at Toronto meetings of the nine Technical Commissions of the then long-established International Meteorological Organization. In the years that followed he was one of the founders of the present World Meteorological Organization and served for many years on its Executive Committee. This required long trans-Atlantic flights for the annual meetings of the Committee in Geneva where he was a well known and frequent guest at the Eden Hotel. In fact, during these years, before the introduction of jet aircraft, Dr. Thomson became a virtual globe trotter, visiting his fellow directors of meteorology in Africa, Asia and Australasia, as well as in the countries of Western Europe. At home he was host at the combined Royal Meteorological Society-American Meteorological Society meetings at Toronto in 1953, and assisted in sponsoring the Toronto meetings of the International Union of Geodesy and Geophysics in 1955. Over the years Dr. Thomson has maintained contact with many of the world leaders in meteorology – if retained and published, his exchanges of correspondence with them would make a very interesting and valuable volume.

Within the public service Dr. Thomson was not only a very resourceful administrator in dealing with departmental and other government people in Ottawa, but he was also one who got things done in his own Service. Many of us have vivid memories of his unannounced tours through the offices at headquarters during which he would stop at a desk and ask innocently "And what are you doing today Mr. ...?". It didn't take many visits of this kind to spur young meteorologists into not only being sure of what they were doing, but also to have a special little study underway which could be reported to Dr. Thomson. Very active in the Royal Society of Canada and always looking for papers for it, "AT" frequently encouraged a meteorologist to complete his study and present the results to the Society at its next annual meeting.

In 1952 Dr. Thomson was awarded the Gold Medal of the Professional Institute of the Public Service of Canada – an honour which only a few public servants ever acquire. In 1958 McGill University honoured him with an honorary degree of Doctor of Science, and in 1965 a few years after his retirement, he was awarded the Patterson Medal for his outstanding contribution to Canadian meteorology for more than 25 years. The citation which accompanied that award emphasized Dr. Thomson's leadership in forging a link between the universities and the government service, and stressed his service to international meteorology through his lengthy membership on the Executive Committee of the World Meteorological Organization.

When he retired in 1959, Dr. Thomson had presided over a period of rapid and remarkable growth of the postwar Meteorological Branch. The rate of growth which the Service had acquired during wartime did not diminish during the postwar period. In 1946, when Dr. Thomson took over control, the budget of the Service was less than three million dollars, but by 1959, his last year in the Service, it had reached $13,500,000. Accounts of the achievement of the Meteorological Branch during those postwar years are to be found in the annual reports and other histories of the Service, and they include marked advances in forecasting services, research, instrument development, climatology and training methods as meteorology flourished in Canada as never before. The man who presided over all of this was Andrew Thomson.

Presentation of the Gold Medal of the Professional Institute of the Public Service of Canada, May 22, 1952. *Left to right*: Dr. O.M. Solandt, J.S. McGiffin (Secretary-Treasurer, PI), Andrew Thomson, President H. McLeod, Hon. Paul Martin, Hon. Lester B. Pearson. *Photo: Capital Press Service*

Today Dr. Thomson has been in retirement for many years, but in a sense he has never retired from meteorology at all. On his occasional visits to AES headquarters he still asks "And what are you doing today Mr. ...?", or makes penetrating enquiries about current departmental and Service policy. A founder of the Canadian Branch of the Royal Meteorological Society, Dr. Thomson has never ceased being a supporter of it and its successor, the Canadian Meteorological Society. He has undoubtedly attended more Society meetings in Toronto than anyone else, and for many years has subsidized the Society's "Andrew Thomson Undergraduate Student Prize". The several young Canadian meteorologists who have received this prize have been significantly encouraged in meteorology by Dr. Thomson.

In his retirement, Dr. Thomson divides his time between his long time Toronto residence and a farm in the Caledon Hills near Orangeville, thirty-four miles northwest of the city. Andrew Thomson has been a unique figure in Canadian meteorology for more than forty years, and is, in many ways, responsible for the stature the Atmospheric Environment Service has attained today, both in government circles and in the public domain. Few men have been so devoted to the subject of meteorology, and it would be difficult to find anyone in our time who has contributed so much to the Canadian meteorological scene.

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Photo page 126: National Film Board

Remarks on Climatic Intransitivity and the 1972 Pacific Anomaly[1]

H. Flohn
Meteorologisches Institut der Universität Bonn
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1 Regional climatic instabilities

Recently E. Lorenz (1968, 1970) postulated, in quite general terms, a sort of instability or (to use his own word) semi-intransitivity of our climate, without giving much attention to the evidence, which had been presented, on a regional scale only, by E. Kraus (1955, 1956). One could add the more or less simultaneous large-scale variations of water balance as revealed in the fluctuations of African Lakes, from L. Nyasa (about 15°S) to L. Chad (about 13°N), with a significant correlation (+0.72) between the variations of L. Chad and the summer rainfall in the Ethiopian Highlands, as reflected in the Nile discharge at Aswan. Looking at the enormous fluctuations of seasonal rainfall in East Africa – e.g., in the 5-month rainy season of 1961/2, the area-averaged rainfall amounted to 319 percent (of normal) in a 606,000-km^2 area of Kenya; in October and November, even up to 423 percent; similarly in Uganda and Tanzania – no really convincing meteorological interpretation has been presented up to now.

Another example of regional instabilities are the vagaries of rainfall and water temperature in the regions of equatorial upwelling in the Pacific (J. Bjerknes, 1966, 1969; Doberitz *et al.*, 1967; Doberitz, 1968a, 1968b; Allison *et al.,* 1971; Flohn, 1972) and Atlantic (Eickermann and Flohn, 1962; Doberitz, 1969), extending to the regions of coastal upwelling along the western coasts of America and Africa. These anomalies are connected with strong deviations of the heat and water budgets of the ocean-atmosphere system. While the evaporation of the equatorial ocean can deviate by 20–25 percent of normal (Henning, c.f. Flohn, 1972), the area-averaged precipitation amount (Quinn and Burt, 1972) may vary by a factor as large as 5–10. Since equatorial rainfall is the most effective source of energy of the tropical Hadley cell, its far-reaching effect on the atmospheric circulation can be convincingly demonstrated (J. Bjerknes, 1966; Rowntree, 1972).

The physical interpretation of the nearly simultaneous occurrences of marked anomalies of rainfall and sea temperature (positively correlated) in a belt along the equator is based on the concept of the wind-driven Ekman drift of the upper oceanic layer (J. Bjerknes, 1966, extended by Flohn, 1972). Fig. 1 gives three possible stages: in (a) with equatorial upwelling of cold water, caused by a more or less symmetric wind-field with two belts of convective activity on both sides of the equator (as in normal years during February-

[1]In honour of the 80th birthday of Dr. Andrew Thomson, formerly Director of Apia Meteorological Observatory.

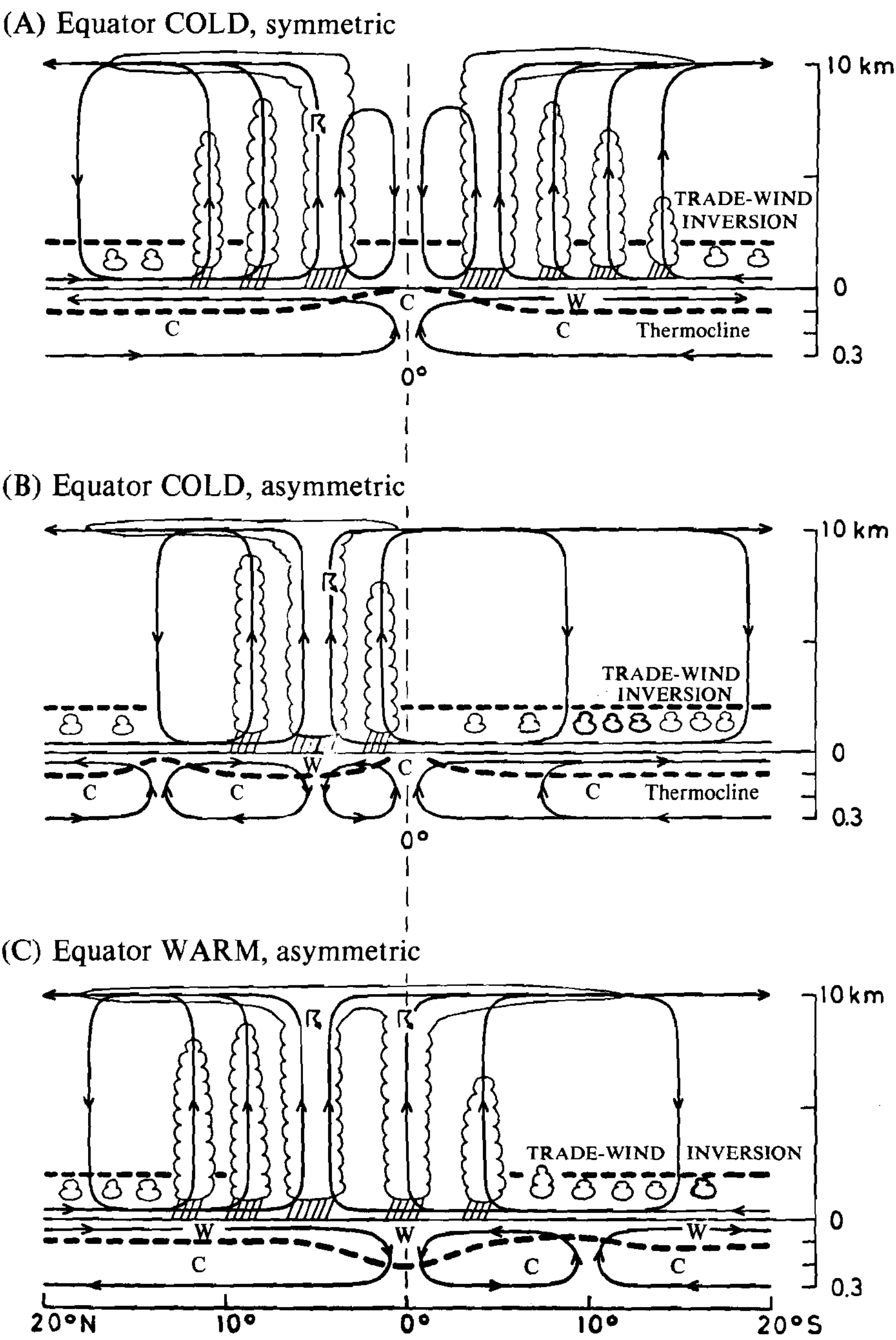

Fig. 1 Meridional atmospheric and oceanic circulation patterns and cloud distribution in the eastern Pacific (see text).

March); in (b) with equatorial upwelling and only one convergence zone caused by an asymmetric wind-field (most frequent), and in (c) with equatorial downwelling and a southward extension of the intertropical rainfall belt to the equatorial region, causing high sea temperatures and strong convective rainfall (representing anomaly-years). The "El Niño"-Phenomenon at the western coast of Ecuador-Peru occurs simultaneously with these anomalies, but with much greater regional complexity. Unfortunately, lack of meteorological data in the eastern part of the South Pacific (between about 75°W and 130°W) does not allow the large-scale anomalies of the subtropical anticyclone responsible for the deviations of the surface winds to be investigated. Since rainfall anomalies occur either simultaneously with or shortly before the water temperature anomalies (Doberitz, 1969), atmospheric controls are apparently predominant; this certainly does not exclude the possibility of a large-scale air-sea interaction, e.g., in the sense of a "Walker" circulation along a zonal axis (Bjerknes, 1969) or a more diagonal trough axis (Flohn, 1971).

Transitions between the two opposite stages – "cold" and "warm" equator – occur rather rapidly: apparently no intermediate stage can be maintained for a long time (more than a few months), nor the coexistence of both stages in the same system of surface ocean currents, at least not in the vast Pacific area between the Galapagos and the date-line. Therefore the two opposite stages of the atmosphere-ocean system with its climatic anomalies apparently are excluding each other: this may be recognized as a typical example of a regional intransitivity as postulated by Lorenz.

Defining climate as the normal state of the complex geophysical system atmosphere + ocean + ice – with its many degrees of freedom, its in-built positive and negative feed-backs and non-linear interactions and its diffuse patterns of energy conversions – the occurrence of transitive and intransitive climatic fluctuations is by no means surprising. Looking at the evolution of climate in a geological time-scale, it must be recognized, that the enormous climatic fluctuations of the last few million years – the vacillations between interglacial and glacial periods – do not gradually occur over some 10^4 years, but in quite dramatic, even catastrophic events lasting perhaps less than a century. This type of global instability deserves much attention, even if these events repeat themselves only in a (non-periodic) time-scale of a few 10^4 years. We must refrain here from a (necessarily inadequate) sideways-look at this problem, which will be reviewed in another article.

2 Statistical properties of equatorial upwelling

An impressive collection of facts and correlations about the climatic fluctuations of the equatorial Pacific has been given by Allison and collaborators (1971). Periods with positive anomalies are short and comparatively rare: 1891, 1905, 1911, 1919, 1925, 1930, 1941, 1953, 1957, 1965 are their central years. Now, 1972 will be added to the most remarkable years (cf. next paragraph). At Canton Island, the correlation between simultaneous monthly averages of sea temperature and rainfall (1950–1965, deviations from normal) is

TABLE 1. Coherency K^2 (in 0.01, only values significant above 2σ) of rainfall (R) and water temperature (T_w) (only Pto. Chicama) anomalies (after Doberitz, 1968a). C_s = covariance contributed by significant periods in percent.

	Station pairs	Simultaneous observations	K^2 (period in months) 120	60	40	30	24	C_s
R	Nauru-Apia	1890–1965	41	44	38	.	.	39
	Nauru-Fanning	1903–1961	41	58	74	80	62	67
	Fanning-Canton	1935–1961	99	98	81	.	.	51
	Fanning-Ocean I.	1903–1961	67	70	72	74	58	66
	Fanning-Malden	1900–1925	65	72	75	69	.	54
	Canton-Nauru	1937–1962	64	64	.	.	.	39
	Canton-Ocean I.	1937–1963	90	82	78	66	.	63
	Canton-Penrhyn	1937–1963	88	86	69	.	.	49
T_w	Pto. Chicama-Fanning	1925–1965	51	62	59	.	.	46
	Pto. Chicama-Canton	1937–1965	72	67	57	.	.	46
	Pto. Chicama-Ocean I.	1925–1965	72	80	75	.	.	54
	Pto. Chicama-Nauru	1925–1965	60	69	72	47	.	61

+0.56. In spite of its statistical significance ($>3\sigma$), this value indicates only a partial correlation, i.e., the occurrence of an additional effect with a larger scale than local stabilization of the air alone. One of the most remarkable properties is the high persistence of water-temperature anomalies remaining 9–11 months above the 3σ-level of significance: this is the role of the extended memory of the ocean.

Based on spectrum and cross-spectrum analysis, Doberitz (1968a, 1968b) found an elongated belt of 115°Long. × 12°Lat. along the southern side of the equator, with a large coherency K^2 (Table 1), which does not extend beyond 10°S; its northern boundary has only partly been investigated. So the long records of Apia/Samoa, Suva/Fiji, Port Vila (New Hebrides) and other stations situated near the diagonal upper trough of the Southern Pacific reveal hardly any coincidence with the equatorial belt. It has been demonstrated, that the well-known biannual cycle – as exhibited, above the equator, by the slow downward displacement of westerly and easterly stratospheric winds independent of longitude – is not predominant in the precipitation records; even the annual cycle nearly disappears. In fact, the phenomenon is quite irregular, with intervals of 2–7 years (and more) between individual peaks, each lasting not more than 1–2 years.

A similar phenomenon has been observed on a smaller scale in the Atlantic, extending from the Gulf of Guinea to the area of northeastern Brazil, but restricted, in normal years, to the northern summer (June-October). This anomaly correlates the nearly simultaneous droughts and wet periods on both flanks of the south-equatorial Atlantic, but is negatively correlated with the El-Niño-Phenomenon in the Pacific region (Doberitz, 1969; Caviedes, 1973).

3 Some evidence on the 1972 El Niño-Phenomenon

Unfortunately, a description of the 1972 events cannot be adequately documented now. Our main sources are: *Monthly Climatic Data for the World*

(WMO-NOAA) and the publications of the Meteorological and Hydrological Service of Ecuador; data from Peru have been available only from "Witterung in Übersee" of the German Seewetteramt, Hamburg.

Only one complete record is available from the equatorial Pacific: that of Tarawa, within a distance of more than 100°Long. from South America. Here a period of excessive rain starts in March 1972; Apia and Atuona (Marquesas Isl.) are not affected, in agreement with Doberitz' results. While a short but very intense rain period occurred during March 1971 in Ecuador and the Galapagos, without any recognizable temperature increase, a strong and extended El Niño-Period began in February 1972, with abundant rainfall at all Galapagos stations especially in April (El Progreso, 805 mm). Preliminary and incomplete annual averages are given in Table 2; a long-term average is only available for Salinas (100 mm).

TABLE 2. Annual precipitation 1970–1972 (mm).

	1970	1971	1972
West Coast South America			
Salinas, Ecuador 2°11′ S	18	299	282
Trujillo, Peru 8°06′ S	33	32	119
Galapagos Islands (90°W, 0–1°S)			
Ch. Darwin, Sta. Cruz	63	294	677
El Progreso, S. Cristobal	645[a]	1371	3281
Gilbert Islands			
Tarawa (1°21′ N, 172°55′ E)	1644	731	4835

a: without March

TABLE 3. Air temperature differences, 1972–1971.

	Feb.–Apr.	May–Aug.	Sep.–Nov.
Salinas, Ecuador	+1.5	+3.4	+2.3
Talara, Peru (4°34′ S)	+1.8	+3.6	+2.8[a]
Trujillo, Peru	+3.2	+3.3	+2.8[a]
Lima-Callao (12°00′ S)	+2.2	+4.2	+1.7[a]
Ch. Darwin	+0.7	+2.9	+2.4
El Progreso (250 m)	+0.5	+2.2	+0.3
Pto. Villamil (Isabela)	+0.6	+3.2[b]	+2.3

a: October–December b: June–August

Instead of water temperatures we may use a few air temperature records from representative coastal and island stations (cf. Table 3). They show that from 1971 to 1972 a remarkable increase up to 3 °C and more (Salinas, July +3.9 °), occurred at the beginning nearly simultaneously at all stations, in marked contrast to interior Ecuador and Peru. The nearly complete breakdown of the very high Peruvian fishery production during this year may be taken as a hint as to the intensity of the phenomenon, lasting well beyond the usual El Niño-Period until the end of 1972, at the Galapagos until February 1973.

4 The task ahead

This far-reaching and effective anomaly occurred simultaneously with a catastrophic drought period in West Africa (Senegal, Mauritania, Mali, Upper Volta, Niger, Chad, partly also Ethiopia) lasting throughout the whole summer rainy season (June to September) and with an extended failure of the monsoon rains in large areas of India and Pakistan. Other coincident events are the drought in the USSR and a remarkably persistent cold period in the Canadian Arctic; in Egedesminde (W. Greenland, 68°42′N) an uninterrupted period of negative anomalies lasted from March 1971 till December 1972.

Are such coincidences fortuitous? The study of atmospheric teleconnections, as initiated by Sir Gilbert Walker in 1918, has been badly neglected. Weather Services are mostly interested in forecasts and, to a lesser degree, in climate as expressed in 30-year (or more) averages. Medium and long-range forecasting ends at a time limit of a few months; investigations of climatic fluctuations usually start with decadal (or better, decennial) averages. In the hierarchy of meteorological time-scales, the gap between one and ten years – considered by climatologists as noise – appears to be forgotten. However, the simultaneous occurrence of strong anomalies reducing seriously the food production in several key regions of the globe can by no means be disregarded; it is highly interesting from the scientific point of view. The slowly aggravating food crisis – as a consequence of the continuous exponential increase of population – obliges our discipline to study this time-scale not only from a local or regional view-point, but in its hemispheric and global interdependencies.

The author had the privilege, on two daytime flights (Hamburg-Anchorage and Honolulu-Pago Pago-Suva) in late July and early August 1972, to observe these climatic anomalies in action: the formation of new ice (with snow flurries) in spite of the 24-h polar day at Kennedy Canal and the waters around Ellesmere Land; and the extension, with varying intensity, of the inter-tropical cumulonimbus zone from 12°N to about 0.5°S, with no indication of a cool water belt.

Acknowledgements

Thanks are extended to Dr. W.O. Roberts (UCAR), Prof. F.K. Hare (Ottawa) and several scientists of a UNEP symposium on "Outer Limits to Growth" (Aspen, Colo., August 1973) for stimulating discussions.

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Oscillations in a Basin of Cold Air

Bernhard Haurwitz
Geophysical Institute, University of Alaska[1]
[Manuscript received 20 September 1973]

ABSTRACT

Temperature fluctuations with periods of about half an hour have been recorded at hill stations near Fairbanks, Alaska during periods of strong surface inversions. These fluctuations can be explained as seiches in the lake of cold air enclosed on three sides by the hills surrounding Fairbanks.

During periods of stagnant anticyclonic weather situations over polar continental regions strong inversions develop in the surface layer, as discussed by Wexler (1941). In the location of Fairbanks, Alaska which is surrounded by hills on three sides, and by a much lower range of hills on the fourth side, a basin of very cold air is thus formed over which warmer air is situated. Under these conditions, strong temperature variations have been observed at thermograph stations on the bordering hills. These temperature variations have periods of about half an hour. The suggestion is made here that these fluctuations can be interpreted as internal seiches in the lake of cold air formed by the topographic features.

To investigate the feasibility of this hypothesis we neglect the compressibility of the air and assume that the stability of the stratification is entirely expressed by the density difference between the cold air in the basin and the warmer air aloft. It can be shown that the compressibility and the density stratification in each layer do not noticeably modify the results as far as oscillations with the observed periods are concerned. We consider a basin of rectangular vertical cross section (Fig. 1) of length b and depth h, extending along the x-axis. Variations normal to the x-direction will be neglected because they would not affect substantially our later quantitative estimates. The density ρ in the basin will be assumed constant. The fluid above the basin may have the constant density ρ', and its depth may be regarded as infinite.

The equations of motion and continuity for the lower layer are:

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x}, \quad \frac{\partial w}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} \tag{1}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

[1]Also associated with the Department of Atmospheric Science, Colorado State University, and with the National Center for Atmospheric Research (sponsored by the National Science Foundation).

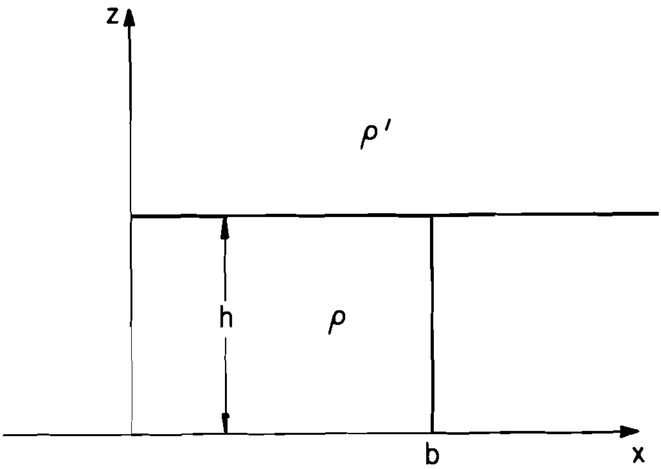

Fig. 1 Showing the geometry of the model.

where u and w are the horizontal and vertical velocity components, p the pressure. Similar equations, distinguished by primed quantities, hold for the upper layer. The velocity components may be expressed by a stream function ψ,

$$u = -\frac{\partial\psi}{\partial z}, w = \frac{\partial\psi}{\partial x}.$$

The vertical velocity, w, and therefore also ψ, must vanish at the ground, $z = 0$. Hence, a suitable solution of (2) is

$$\psi = K \sinh \alpha z \sin \alpha x \cos \beta t$$

where β is the frequency, τ the period, $\tau = 2\pi/\beta$, K an integration constant. If the basin is closed at both ends, $x = 0$ and $x = b$, u must vanish at these locations, hence

$$\alpha = \frac{n\pi}{b}; \quad n = 1, 2, 3, ... \tag{3}$$

If the basin is open at $x = b$, u must have a maximum here since fluid from outside the basin can flow in and out freely at this end, and hence

$$\alpha = (n - \tfrac{1}{2})\pi/b; \quad n = 1, 2, 3, ... \tag{4}$$

In both cases the fundamental modes are given by $n = 1$, the overtones by the larger values of n. Since the solution must be bounded in the upper layer which extends to infinity, an appropriate solution for this layer is

$$\psi' = K' e^{-\alpha z} \sin \alpha x \cos \beta t.$$

When ψ and ψ' are known the perturbation pressures are found from (1), viz.,

$$p = \rho\beta K \cosh \alpha z \cos \alpha x \sin \beta t$$
$$p' = \rho'\beta K' e^{-\alpha z} \cos \alpha x \sin \beta t.$$

Because of the constant density the undisturbed pressure distribution is given by

$$P = -g\rho z + \text{const}$$

$$P' = -g\rho' z + \text{const.}$$

In the absence of oscillations let the interface be at $z = h$. Then for the oscillating interface

$$P - P' + (p - p')_{z=h} = 0$$

that is, at the interface the total pressure must be continuous; since the pressure perturbations are small we may substitute here for the actual position of the disturbed interface z its mean position h. Thus

$$z - M \cos \alpha x \sin \beta t = \text{const} \tag{5}$$

is the equation for the oscillating interface with the amplitude

$$M = \frac{\rho K \cosh \alpha h + \rho' K' e^{-\alpha h}}{g(\rho - \rho')} \beta.$$

Since the time variation of the height of the interface must equal the vertical velocities $\partial\psi/\partial x$ and $\partial\psi'/\partial x$ at the interface it follows that

$$\beta M = \alpha K \sinh \alpha h$$

$$\beta M = \alpha K' e^{-\alpha h}.$$

Here, for the vertical velocities their values at the undisturbed position of the interface have been substituted because this simplification introduces only an error of higher order. If these two expressions for K and K' are substituted in the foregoing formula for M an expression for the frequency β is obtained

$$\beta^2 = \alpha \frac{g(\rho - \rho') \tanh \alpha h}{\rho + \rho' \tanh \alpha h} \cong \frac{g(\rho - \rho')}{\rho} \alpha^2 h. \tag{6}$$

The approximate form of this expression holds if the depth h is considerably smaller than the horizontal length b, which is true in the example to be considered. A similar formula for a stratified lake was given by W. Schmidt (1908). The approximate equation (6) is, of course, the formula for the velocity of long waves at a density discontinuity if α is the horizontal wave number.

With the approximate value for β the expressions for the stream function and the pressure perturbation in the cold air become

$$\psi = [g(\rho - \rho')h/\rho]^{\frac{1}{2}}(z/h)M \sin \alpha x \cos \beta t \tag{7}$$

$$p = g(\rho - \rho')M \cos \alpha x \sin \beta t. \tag{8}$$

Since $M \cos \alpha x \sin \beta t$ is the vertical displacement of the interface the pressure perturbation is entirely due to the replacement of a column of density ρ by an equally high column of density ρ', as is to be expected since the oscillations in a long shallow basin must be of the nature of long waves for which the quasi-static approximation holds.

In order to determine the order of magnitude of the periods τ in an open basin the value of α from (4), may be substituted in (6). Further, the density may be replaced by the temperature by means of the equation of state

$$P = R\rho T$$

where P and R, the undisturbed pressure and the gas constant, are the same on both sides of the interface. Then

$$\tau = \left[\frac{T'}{gh(T' - T)}\right]^{\frac{1}{2}} \frac{4b}{2n - 1} \quad . \tag{9}$$

If $b = 5000$ m, $h = 200$ m, $T = 240$°K, $T' - T = 15$°C, $n = 1$ for the fundamental mode

$$\tau = 1865 \text{ s.}$$

The numerical values used here are of the right order of magnitude for the cold air basin formed by the air around Fairbanks, and the computed period τ is of a similar duration as the periods recorded on thermographs, strongly indicating that the observed temperature fluctuations are in fact due to standing internal oscillations.

In connection with these temperature oscillations it has often been noticed that fairly strong winds exist at and above the level of the surrounding hills while the air in the basin is calm. Simple calculations show that with such upper winds the oscillations should no longer be stationary, and that for sufficiently strong winds the oscillations may also become unstable. The observational program did not include suitable wind measurements, and it is therefore not possible to make a quantitative check of these theoretical conclusions. But observations without instruments from the surrounding hills, at times when a shallow layer of ice fog is present in the valley, indicate that waves move along the top of the fog layer, giving at least a tentative confirmation.

It has already been said that the length of the period computed for an incompressible fluid model is not modified appreciably if compressibility and density decrease in each layer are taken into account. But, as would be expected, this is no longer true for the waves of the acoustic-gravity type with their much higher frequencies. Such short-period oscillations of the cold air have been recorded at Fairbanks by means of acoustic sounders, but their discussion is outside the scope of this note.

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The Helicoid Anemometer

A Long Neglected but Valuable Anemometer

Gerald C. Gill[1]
University of Michigan, Ann Arbor
[Manuscript received 20 November 1973]

ABSTRACT

Although the helicoid anemometer has been known since 1887 (W.H. Dines) it was not until the 1940's that a rugged, accurate and reliable instrument was built (The Aerovane, by Bendix Friez). Some of the outstanding features of the helicoid anemometer are as follows: it is a primary sensor – it is not essential to calibrate in a wind tunnel; its rate of turning is linearly proportional to wind speed over a wide speed range; some versions have a very low starting speed; and some helicoids, fixed in position, measure only that component of the wind that is parallel to the axis of the helicoid.

1 Introduction

What is a helicoid? If one takes a capital T and raises it at a steady rate along its vertical axis and at the same time rotates the two arms at a steady rate, the shape cut out by these arms is a helicoid. Possibly the most frequently seen helicoid is that of the hand-turned steel auger used to drill wood. In Fig. 1a is shown a helicoid of soda straws, 10 in. diameter, with a 180° pitch in 6 inches (equal to 360° in 1.0 ft). In Fig. 1b is shown a current production four-blade helicoid propeller anemometer-wind vane. In this instrument the helicoid propeller has a diameter of 9 in. and a pitch of 360° in 1.0 ft. However the axial length of this propeller is only 1¼ in. so each blade section has a pitch of only 30°. The wind vane keeps the propeller oriented into the wind.

2 Historical background

W. H. Dines developed the first helicoid anemometer and apparently first described it in 1887. It is shown in Fig. 2. In the *Collected Scientific Papers of William Henry Dines* (Royal Meteorological Society, 1931), F. J. Whipple records thusly:

Dines's first invention, and perhaps the most ingenious, was the helicoid anemometer. This instrument never came into general use but it had the advantage that it was designed on kinematical principles and required no calibration. This instrument was described briefly in 1887, but for mechanical details the patent specification must be referred to. Apparently no anemometer of this type has survived. An illustration of the helicoid anemometer in its latest form is repro-

[1]Vice President of R. M. Young Co., Traverse City, Mich.

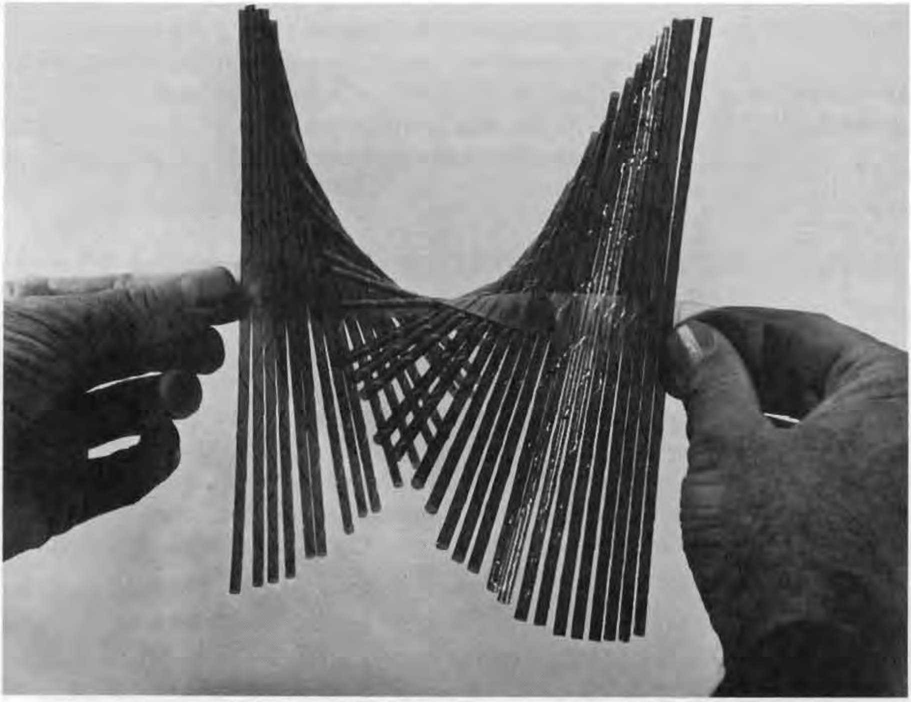

Fig. 1a Helicoid of soda straws (used for lecturing).

duced below (our Fig. 2). *The three moving parts mounted above the vane were: (1) a sheet of metal bent into the form of a helicoid; (2) a four-bladed fan; and (3) a windmill with a pair of sails.*

The idea was that in a wind of constant velocity the helicoid should be able to rotate, cutting through the air without disturbing its flow. The windmill was used to drive the helicoid whilst the fan was used to indicate whether the helicoid was turning at the right rate. The fan acted as a governor by altering the inclination of the windmill sails. The wind velocity was found by counting the turns of the helicoid. The instrument behaved according to expectation and gave accurate readings, but was not robust enough for general use.

As shown by Figs. 1b and 2, the helicoid must be aimed into the prevailing wind direction. However, Dines's anemometer was too complicated for general use and as Whipple points out: "Apparently no anemometer of this type has survived." But Dines had the idea of the helicoid; and if he had had present-day low-friction bearings his system undoubtedly would have been greatly simplified. Today there is no need for the "four-bladed fan and a windmill with a pair of sails."

It appears that the helicoid was not again used in anemometry until the Bendix Friez Company of Baltimore, under contract with the U.S. Navy, developed the Aerovane in the early 1940's after which it came into general use. The Aerovane is still manufactured with very minor changes, and is still

Fig. 1b 4-blade helicoid anemometer wind vane, 1965 to present.

Fig. 2 W.H. Dines helicoid anemometer, 1887.

one of the most outstanding wind vane anemometers used today. One of these is shown in Fig. 3.

In 1960 Gill and MacCready independently disclosed their intention of using light helicoid propellers in front of their bi-directional winds vanes so as to provide simultaneous readings of the three components of wind flow at a point in space – total speed, azimuth angle and elevation angle. During the following year both perfected their anemometer bivanes and these have been used fairly widely throughout the continent in basic turbulence studies. The 1960 version of Gill's instrument is shown in Fig. 4. After much searching both men had concluded that the helicoid anemometer had considerable benefits to offer in the form of a linear wind speed transducer: rapid response, independent of changes in air density, humidity or dust; low-starting speed; and ease of incorporation into their particular instruments. Experience has shown that the helicoid anemometer is an even better sensor than either of us had realized. (MacReady and Jex, 1964).

3 Some outstanding features

a *A Primary Sensor*

A primary sensor is one which is capable of measuring some parameter in standard units of mass, length, and time without requiring comparison with some other sensor measuring the same parameter. For instance, a mercury barometer is a primary sensor as it will measure the pressure of the atmosphere in units of mass, length, and time without ever being referred to any other pressure sensor. On the other hand, the aneroid barometer can only be calibrated by comparison with a mercury barometer in the final analysis. Similarly cup anemometers, hot-wire anemometers, pressure tube anemometers, etc., must all be calibrated by comparison with some other sensor in the wind tunnel. This is usually a pitot-tube water-manometer combination corrected for the ambient pressure and temperature in the wind tunnel. For the case of the helicoid anemometer (cf. Fig. 4) in a steady wind flow the propeller should cut through the air with a minimum of disturbance of the air and its rate of turning should depend only on the wind speed and on the pitch of propeller – it is not necessary to calibrate the sensor in the wind tunnel by comparison with any other sensor.

CONFIRMATION THAT HELICOID ANEMOMETER IS A PRIMARY SENSOR

1) The propeller of Figs. 1b and 4 has been subjected to many wind-tunnel and whirling arm tests, and has also been drawn through ducts of quiet air and of quiet water. For a very low speed calibration of the sensor eight different propellers were drawn separately through a duct two feet by two feet by forty feet in length at various speeds from 0.3 to 2.3 ft s^{-1}. Two of these same propellers were calibrated in the meteorology tunnel of the University of Michigan. The results of this calibration are shown in Fig. 5 where the true character of the helicoid propeller is illustrated, viz., that the helicoid anemometer cuts

Fig. 3 Bendix Friez Aerovane, 1940's to present.

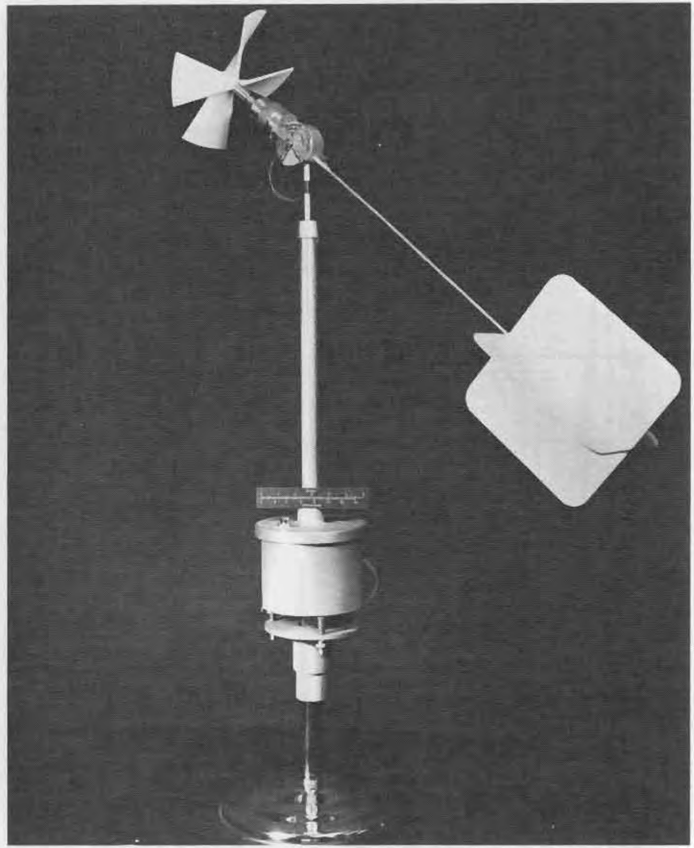

Fig. 4 Gill Anemometer Bivane, 1961 to present.

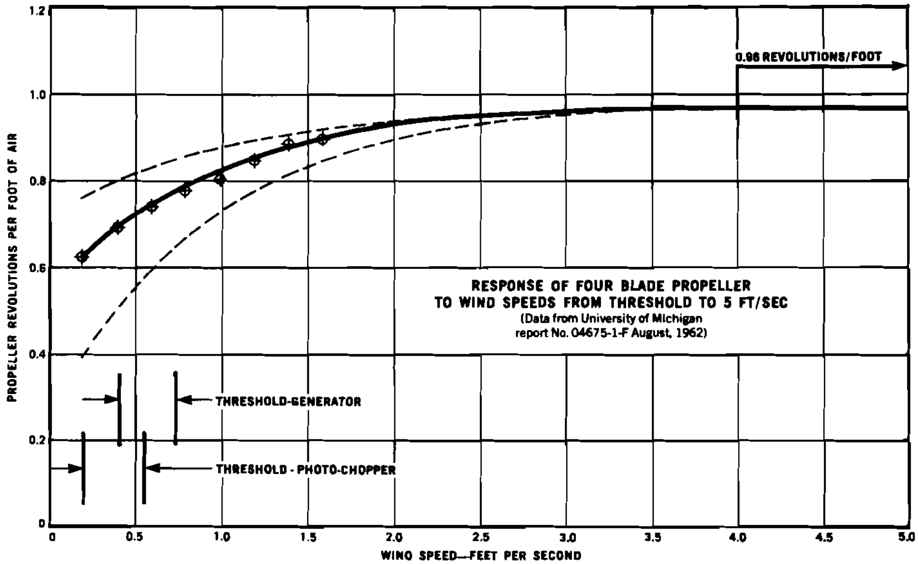

Fig. 5 Response curve of 4-blade helicoid anemometer from threshold to 5 ft s^{-1}.

through the air at a rate of 0.96 rev/ft of air passing, at all air speeds above a particular value – in this case 4 ft s^{-1}. At speeds below this the transducer load and bearing friction slow the propeller below its equilibrium speed.

The particular propeller mold used for these propellers was designed to have a pitch of 360° in 1.00 ft. However, the plastics manufacturer distorted the mold in trying to give a very wide range of propeller densities and distorted it so that the actual pitch is 0.96 rev/ft. Thousands of these propellers have been produced and numerous samples tested in various wind tunnels all show that the propeller turns at 0.96 rev/ft of air passing at speeds above about 4 ft s^{-1}.

2) A number of these propellers were tested at NASA's Langley Field facility (Hampton, Virginia) for possible use in measuring winds on Mars (Rhyne and Greene, 1969). First tests were made in the Dynamics Research Laboratory 55-ft vacuum chamber on a whirling arm about 50-ft in diameter. Later tests were conducted in the Transonic Dynamics Tunnel which has a test section 16 by 16 ft in cross-section with a 30-ft-long uniform flow region at subsonic speeds. Tests in both facilities were in air at pressures from 760 down to 8 mm Hg. Fig. 6 is a plotting of some of their results obtained in the large wind tunnel. It shows that these propellers change their calibration $\ll$ 1% in going from atmospheric pressure down to only 12% atmospheric (760 to 95 mm Hg); and by only 1% when going from atmospheric to 4% of atmospheric (30 mm Hg).

3) At the other end of the scale the Virginia Institute of Marine Science calibrated a number of these same propellers in water in a tow-tank operation. They found the propellers to make 0.96 ± 0.01 rev/ft of water passing.

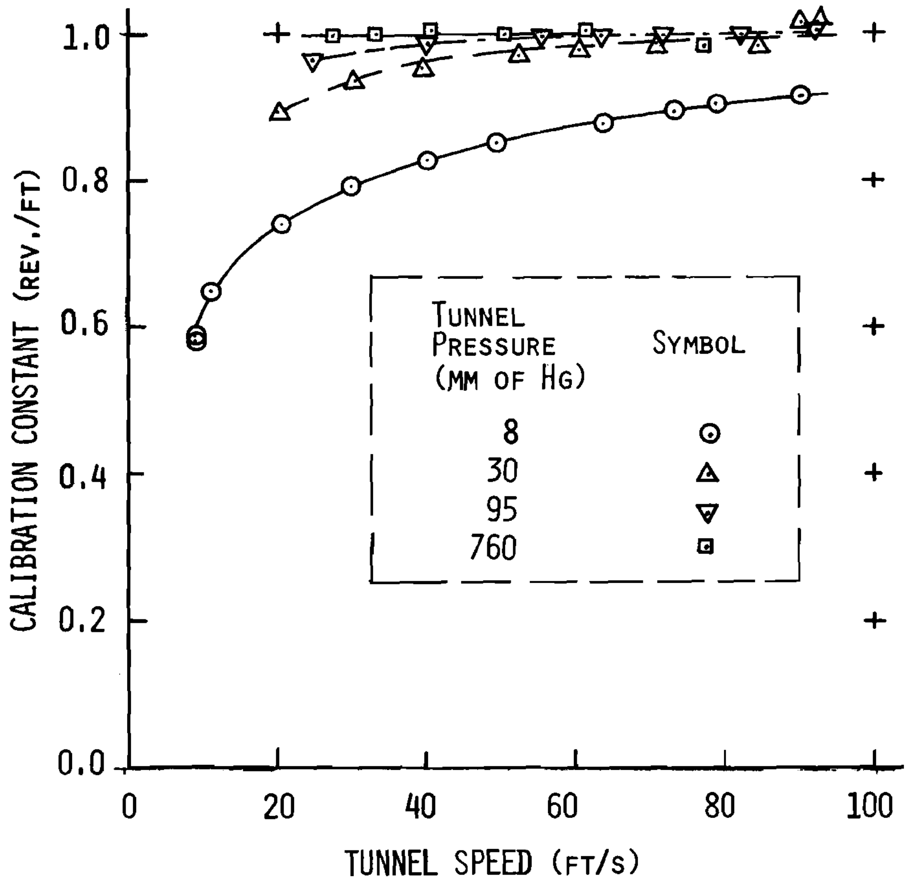

Fig. 6 Response curves of 4-blade helicoid anemometer at reduced air pressures (from Rhyne and Greene, 1969).

Thus over a fluid density range greater than 10^4 (from water at 1.00 g cm^{-3} to rarefied air at 0.00005 g cm^{-3}) the basic calibration of 0.96 ± 0.01 rev/ft held. In this writer's opinion it is doubtful if any other anemometer has ever been tested over such a wide range of density values and found to have such a linear and unchanging basic calibration. The true helicoid anemometer is an exceptional instrument, its basic calibration curve being dependent only upon the pitch of the propeller and not requiring comparison with any other sensor.

b *Low Starting Speed and Linear Calibrations*

With the helicoid anemometer faced into the wind the whole "shadow area" of the propeller develops a positive torque that contributes to a low starting speed if the load (friction of bearings and load of transducer) is kept very low. With miniature precision bearings and photo-electric pick-up the 9-in. diameter, well-balanced, four-blade anemometer of Fig. 1b, routinely has a starting

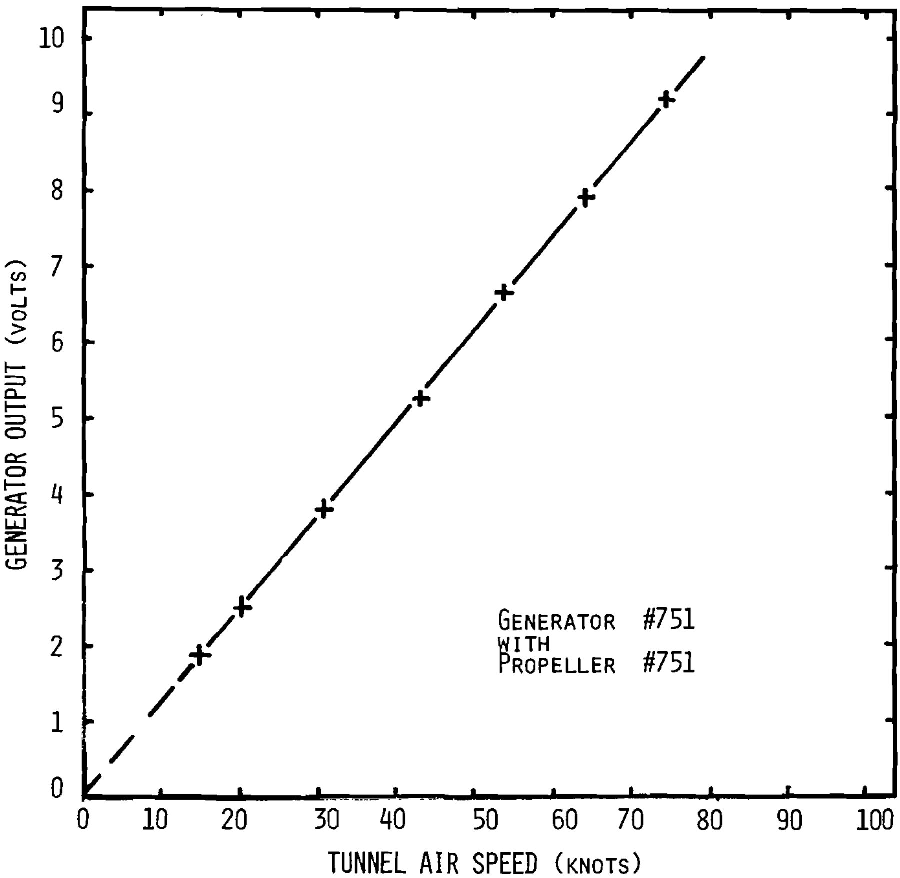

Fig. 7 Speed calibration of Bendix Friez Aerovane (from McKee's data, 1953).

speed of 0.1–0.2 mi h^{-1}. With a tiny precision tachometer generator the starting speed is < 0.5 mi h^{-1}. The best three-cup anemometers with photo-electric pick-up usually have a starting speed of 0.5–1.0 mi h^{-1}; and the best tachometer generator equipped units usually have a starting speed > 1.5 mi h^{-1}.

Much work was done in the 1920's and 1930's by such men as Patterson (1926), Fergusson (1934), Spilhaus (1934) and Brevoort and Joyner (1935) on the design of the cup wheel of the cup anemometer so that its calibration curve would be linear. By a combination of factors, viz., three cups instead of four, cups of conical shape rather than hemispherical, beaded edge cups rather than sharp edged cups, and a particular ratio between cup diameter and cup wheel diameter, we now have cup wheels whose calibration curve is linear. No such juggling of parameters is necessary for calibration linearity in the case of anemometers using true helicoid shaped blades – see Fig. 5 for the Gill 4-blade helicoid shown in Fig. 1b, and Fig. 7 for the 3-blade Aerovane shown in Fig. 3 (the work of J. W. McKee, 1953).

TABLE 1. 3-cup anemometer calibration table.*

Driven speed (r.p.m.)	Corresponding air speed (mph)	(knots)
0	2.3	2.0
300	32.4±0.1	28.1±0.1
600	62.4±0.1	54.2±0.1
900	92.5±0.1	80.3±0.1
1800	182.7±0.2	158.6±0.2

*From: Instruction Book for Type F420-C and Type CAA-227 Wind Measuring Equipment. Electric Speed Indicator Co., Cleveland, Ohio.

Since the torque developed by the helical propeller increases rapidly with air speed, above a certain speed (4 mi h^{-1} in the case of above 4-blade anemometer) the load becomes negligible relative to torque and the rate of turning of the propeller is linearly proportional to the wind speed as shown by the calibration curves in Figs. 5 and 7. Thus the extension of the straight-line portion of the calibration curve passes through 0.0. By contrast the friction of the 3-cup anemometer is significant at all speeds so that we have a "friction correction" at all speeds. For the large, well made and durable 3-cup anemometer of the Electric Speed Indicator Co. the calibration as supplied by the manufacturer, is shown in Table 1. (The author does not have similar data for any of the small, fast response 3-cup anemometers.) This table clearly indicates that the average "friction correction" of this cup anemometer is 2.3 mi h^{-1}. When using this instrument, we routinely offset the zero of the indicating meter, or the recorder, by this amount (2.3 scale divisions) so that when the anemometer cup wheel is turning, the recording will be approximately correct. But no such offset is required for indicating meters or recorders attached to helicoid anemometers, for the reasons given above.

c *Cosine Response of Some Helicoid Propellers*

The anemometer bivane of Fig. 4 gave excellent measurements of the three components of wind flow during dry weather, but the tail drooped in rain, or, when the wind was light and dew formed! Being unable to think of a simple corrective modification to the instruments, the writer decided to supply users with a propeller-speed correction curve for different angles of droop. To determine this curve, a special fixture was assembled that permitted the horizontal propeller axis to be rotated to any azimuth angle inside the wind tunnel without the propeller moving off the centre axis of the tunnel. One or more 4-blade propellers were tested at four fixed speeds between 6 and 30 ft s^{-1}. The shape of the curves for all speeds was the same. The average response curve is shown in Fig. 8. To our surprise, the response curve was very close to a cosine curve, i.e., the propeller turned at a rate almost directly proportional to the wind component parallel to its axis. This led to the vertical wind component sensor described by Holmes *et al.* (1964), and subsequently to the Gill UVW Anemometer of Fig. 9 (Gill *et al.*, 1967). This instrument has had wide acceptance

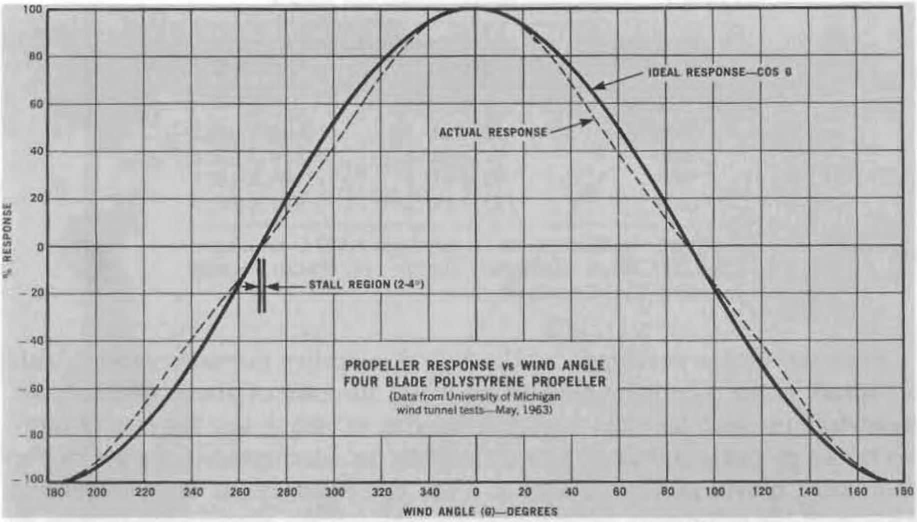

Fig. 8 Response curve of 4-blade helicoid propeller to winds travelling at various angles to the axis of the propeller.

Fig. 9 Gill UVW-anemometer, 1965 to present.

even though the response curve is significantly off the cosine curve. Some four hundred instruments are now in use in over thirty countries throughout the world. (Attempts have been made to improve the "cosine response" by changes in blade contour and blade number but so far, no marked improvement has been achieved. In fact, some three-blade helicoid propellers (including the aerovane) are much worse than that shown in Fig. 8. In two recent papers, Horst (1973) and McBean (1972) have shown how they used the UVW anemometers and compensated for their deviations from true cosine response.)

4 Summary

In review, helicoid anemometers may provide a sensor (or sensors) that has (or have) the following desirable features:

1) a primary sensor – no need to calibrate in a wind tunnel.
2) a sensor whose rate of turning is linearly proportional to the wind speed over a wide speed range.
3) a sensor with very low starting speed capability.
4) a sensor that may be used to measure one component of wind flow only, or, if three orthogonal sensors are used, to measure the three components of wind flow simultaneously at a point in space.

In this writer's opinion, the helicoid anemometer has not been properly appreciated for too many decades.

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Secular Increases in Summer Haziness in the Atlantic Provinces

R.E. Munn
Atmospheric Environment Service, Toronto
[Manuscript received 15 September 1973]

ABSTRACT

Since 1953, there has been a significant increase in the number of hours (May to October) of reported haze, smoke and/or dust at synoptic observing stations in the Atlantic Provinces and Eastern Quebec. Because the increase is associated mainly with south to southwest winds, and because there has in fact been a decrease in particulate emissions in eastern North America during this period, the suggestion is made that the increase in haziness is due to increasing photochemical activity, resulting from greater emissions of gases such as SO_2 and NO_x from sources along the United States eastern seaboard.

1 Introduction

Meteorological observations are made at hourly intervals at a large number of stations around the world. These reports include estimates of visibility and occurrences of haze, smoke and dust. In this connection, it should be noted that observing procedures for reporting visibility and the presence of haze have not altered in many years. Thus, the historical files of hourly observations can be interrogated to investigate long-term trends in visibility and haziness. When attempting to explain any trends that may be found, however, a number of factors must be considered.

There are many sources for suspended particulate matter in the lower atmosphere:

(a) man-made emissions in cities, as well as in the countryside (from slash burning, etc.);
(b) natural emissions such as forest fires;
(c) entrainment of surface dust during dry windy weather;
(d) the particulate products of photochemical reactions in the atmosphere.

The first and last components are of particular interest when studying secular trends; natural emissions do not change on the average, although they exhibit substantial year-to-year variations.

Man-made emissions of particulates are decreasing due to the implementation of pollution control programs and due to socio-economic factors. Downward trends in haziness are to be expected, therefore, unless one or more of the following changes has taken place:

(1) increased production of photochemical products, thus implicating distant sources;

(2) local changes in land use (for example, an airport observing location that once was rural might now be within a built-up area);
(3) secular fluctuations in climate (for example, a secular increase in the frequencies of southerly winds would result in an increase in haziness, because southerly flows generally contain more suspended particles than do northerly ones).

2 Winter haziness

There is no doubt that *winter* haziness is decreasing in populated regions. The black skies of the last century over Birmingham, England and Pittsburgh, Pa. have disappeared. Even in the last 20 years there have been some spectacular trends, as illustrated in Figs. 1 and 2. For the winter half of the year (defined here as the months January–April and November–December) the haziness decreased substantially between 1953 and 1971, at both Windsor and Vancouver Airports, even though the metropolitan areas have expanded towards the observing sites in both cases. These secular winter trends are typical of those in all Canadian cities.

3 Summer haziness

In summer, evidence is accumulating in several parts of the world that haziness is actually increasing. Lovelock (1972) suggests that this is happening in the rural parts of the United Kingdom while Miller *et al.* (1972) have documented the increases at the airports of Akron, Ohio, Lexington, Ky. and Memphis, Tenn. For the period 1962–1971 and excluding hours with rain and/or relative humidities of 70% or more, Miller *et al.* have obtained the trends shown in Table 1. At all three airports, there have been three- to five-fold increases in the frequencies of reduced visibilities. The authors have examined climatic changes in wind-roses during the period of record, and have concluded that visibility trends could not be explained by this mechanism. In their conclusion, they express the hope that their statistical results "will stimulate photochemical research and standardized tropospheric monitoring and analysis."

Referring again to Figs. 1 and 2, the number of hours with haze in summer did not increase at Windsor and Vancouver Airports during the period of record, although the downward trend at Windsor levelled off in 1962. Possible explanations for a behaviour different from that found in Ohio (see Table 1) are as follows:

(a) Major sources for particulates in the Vancouver area in summer are tepee-burning in the Fraser River valley, and slash burning in the surrounding forests. These sources have slowly diminished over the last 10 years, producing the downward trend in summer haziness.
(b) The Detroit-Windsor metropolitan area is heavily industrialized. The continuing effort to control particulate emissions in the last 20 years may be responsible for the decreasing frequency of haze in summer as well as in winter.

At both sites, therefore, secular increases in the photochemical production

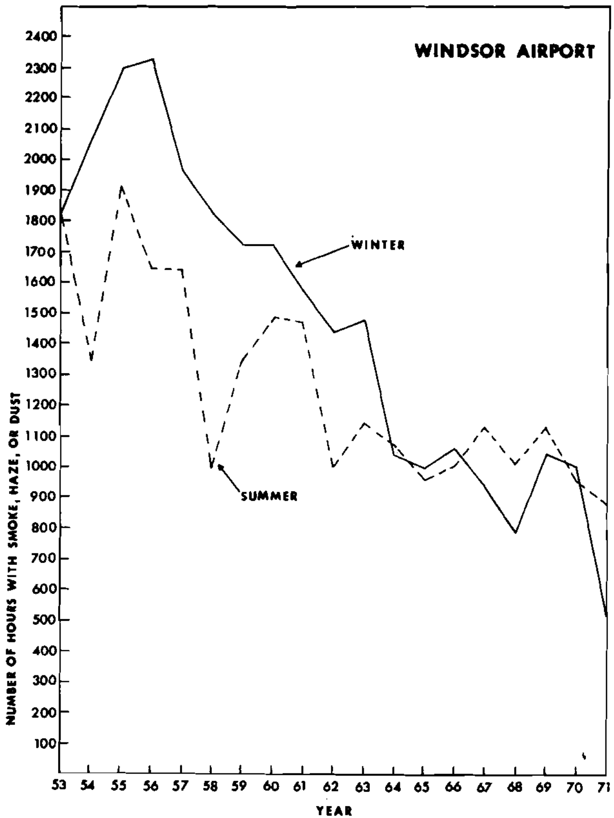

Fig. 1

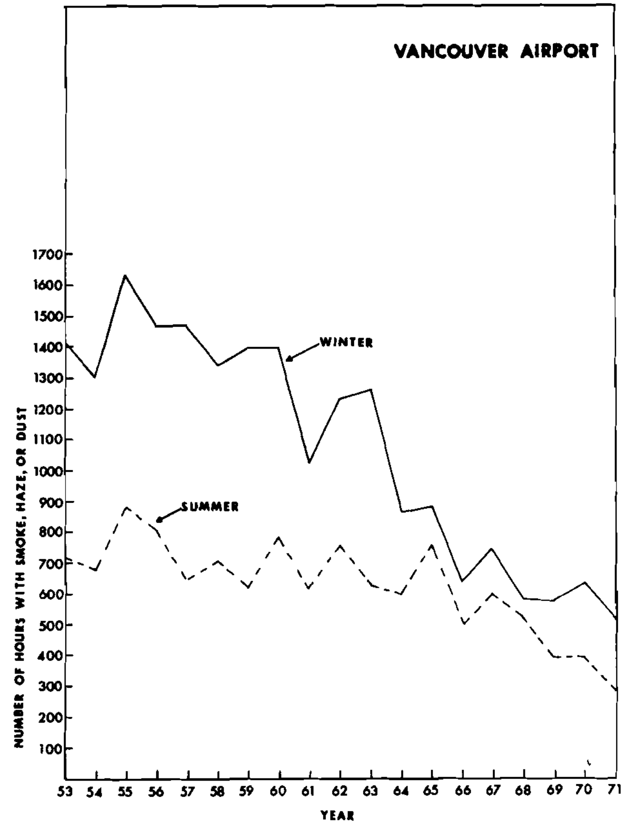

Fig. 2

Fig. 1 Secular trends in the number of hours of smoke, haze or dust at Windsor Airport in the period 1953 to 1971. Summer totals are for the months May to October; winter totals are for the months Jan. – April and Nov. – Dec.

Fig. 2 Same as Fig. 1, except for Vancouver Airport.

TABLE 1. Frequencies of visibilities of 0–10 km (0–6 mi) during the months June–September, inclusive, excluding hours with rain and with relative humidity of 70% or more (Miller *et al.*, 1972).

Station	Hour (EST)	Years 62–63	64–65	66–67	68–69	70–71
Akron, Ohio	1300	9.1	12.5	22.7	24.3	36.9
	1600	6.4	5.5	22.7	24.5	31.0
Lexington, Ky.	1300	6.7	11.7	23.8	20.7	25.6
	1600	6.5	12.8	26.2	18.4	29.5
Memphis, Tenn.	1200	6.0	8.7	15.1	7.4	13.4
	1500	1.6	6.3	10.1	7.2	10.5

of particulates might be hidden by secular decreases in direct emissions of particulates.

These questions were of sufficient interest to warrant study of haziness trends at all stations (about 80) in the Canadian hourly weather observing network. To summarize the results for the summer months (May–Oct.):

(a) In the arctic and sub-arctic, haze and smoke occurrences were rare except during a few individual summers when forest fires were burning.

(b) Elsewhere, the most notable trends occurred in the Atlantic Provinces and Eastern Quebec. Here, the summer haze frequencies generally doubled between 1953 and 1971. Fig. 3 displays the trends for Fredericton, Gander and Mont Joli airports. That the upward summer trends are not the result of changes in the atmospheric general circulation is indicated in Table 2, which shows for each wind direction at Fredericton Airport, the percentages of hourly observations with haze, smoke and/or dust. Four-year periods have been selected to provide some smoothing of the data. For north and northwest winds, there has been little change in haze frequencies between 1953–56 and 1968–71. For south and southwest winds, on the other hand, there has been a six-fold increase.[1] Amongst other things, these results confirm that there has been no change in observational procedures over the years; otherwise, the trends would be similar for all wind directions.

The Fredericton results suggest that there has been a strengthening of the urban and industrial gaseous plumes in the United States Eastern Seaboard, transporting photochemical products to the Atlantic Provinces and Eastern Quebec. An alternative explanation, an increase in particulate emissions, can be ruled out because of the downward trends in haziness during the winter months in Eastern Canada and because of the evidence (Spirates and Levin,

[1]The increases are smeared across some of the other directions because: (a) the surface wind is not always representative of the main flow (due to local effects and a general veering with height); and (b) the surface wind is only moderately correlated with regional streamlines and particle trajectories.

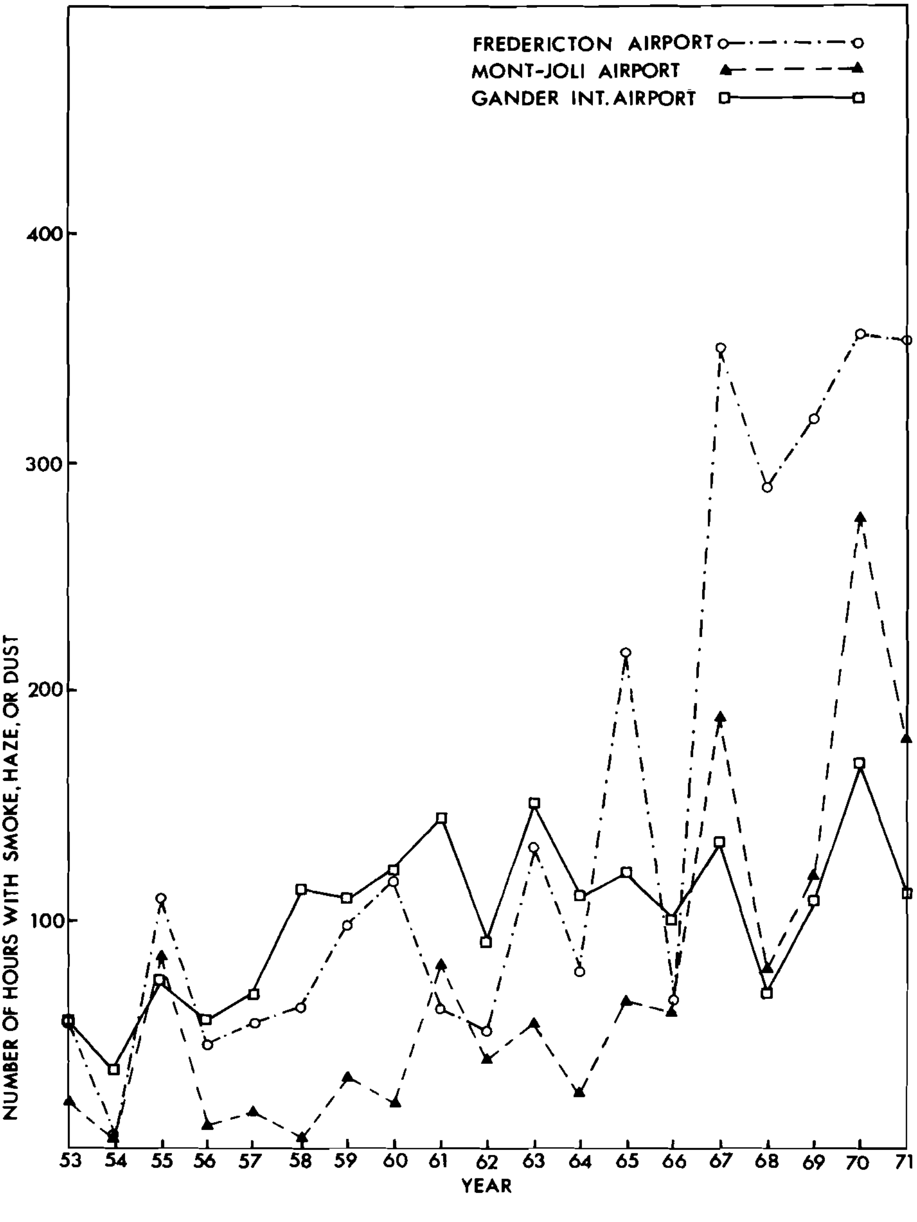

Fig. 3 Secular trends in the number of hours of smoke, haze, or dust at Fredericton, Gander and Mont Joli airports for the months May to October for the period 1953 to 1971.

TABLE 2. For the summer months (May to October) and for each wind direction, the percentages of hourly observations at Fredericton Airport with haze, smoke or dust, separately for the years 1953–56 and 1968–71.

	Wind Direction									
Years	N	NE	E	SE	S	SW	W	NW	Calm	All Cases
1953–56	1.1	0.4	0.5	0.6	2.2	1.7	0.4	1.0	1.3	1.2
1968–71	1.3	1.2	2.2	6.4	13.9	13.0	4.3	1.6	4.7	7.4

1970) that particulate loadings are decreasing within cities across the United States. It is more likely that increased emissions of gases such as SO_2 and NO_x from industrial power-plant and transportation sources in the Eastern USA are participating in photochemical reactions.

4 Conclusion

Winter frequencies of haziness have been decreasing in recent years in the populated parts of Canada due to air pollution abatement programs and socio-economic factors. In summer, haze frequencies are no longer decreasing, and have, in fact, doubled in the Atlantic provinces and Eastern Quebec since 1953. An analysis of wind frequencies at Fredericton airport supports the hypothesis that this increase is due to a strengthening of the urban and industrial gaseous plumes from the Eastern United States, transporting the particulate products of photochemical reactions to the Atlantic Provinces.

Acknowledgement

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Lidar Evidence of Thermal Plumes in an Urban Environment

V.E. Sells and D.R. Hay
Department of Physics
University of Western Ontario, London
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ABSTRACT

A laser radar (lidar) operating at the ruby line 0.6943 μm has been observing horizontal profiles of particulate concentration in the air some 30 m above the surface within the city of London over a period of one year. Anomalous features in these profiles are interpreted as natural thermal plumes carrying particles upwards from surfaces such as paved roadways, paved parking lots, treed parks, residential construction sites, open ploughed fields, and the river. Insolation of the ground is required for their formation, and neutral thermal stability aloft favours their incidence.

1 The thermal plume

The plume as a structure of thermal convection in the lower troposphere has been recognized in several experimental studies recently. Kaimal and Businger (1970) have made a case study of a single plume above an open flat field with the aid of an instrumented 32-m tower. It appears as an orderly structure of turbulence, extending upwards from the unstable region at the ground during strong insolation. There is vertical continuity in the temperature and velocity profiles within the plume; the latter is inclined downwind, with an abrupt rise in temperature at the upwind boundary and marked flow upwards within the plume adjacent to this boundary. The plume is most clearly defined in the morning when winds are light, the air is clear and the instability in the boundary layer is developing. A plume may exist for at least several minutes, and horizontal translation of the plume may occur at a rate that differs from the local wind. Haugen *et al.* (1971) and Businger and Frisch (1972), through aircraft and tower observations over uniform terrain, have found that the persistence of a migrating plume will cause upwards transport of cool air when it passes from a warmer to a cooler surface.

Other characteristics of the thermal plume have been summarized by Coulman (1969, 1970) and Telford (1970, 1972). Over uniform and level terrain, the plume diameters range from a few tens of metres to several hundred metres. Their upwards extension grows with the surface heat influx to several hundred metres. The volume between the plumes is characterized by gentle subsidence. It is of interest to note that many of these plume features have been observed in a water-tank simulation of the lower troposphere, in the writers' laboratory (Fanaki, 1971, 1973; Hay, 1971). Atmospheric reflections as observed by microwave radar (Konrad, 1970), acoustic radar (McAllister *et al.*, 1969) and laser radar (Naito *et al.*, 1968) also have supported this thermal plume model.

The writers recently have assembled a laser radar (lidar) to examine the concentrations of particulate in the air, as indicators of thermal convection. This lidar is at an elevated position overlooking the city of London. Since the evidence for thermal plumes noted above has been obtained generally over open and homogeneous terrain, it is of interest to look for the effects of surface inhomogeneity within the city on plume generation. In practice, thermal plumes may be a means of pollutant transfer from sources at or near the ground.

2 The lidar

In principle, the lidar directs an intense flash of light at wavelength 0.6943 μm horizontally in a collimated beam through the air. Simultaneously, the backscattering is observed from particulate that is irradiated by this beam. Since the outward travelling flash irradiates an instantaneous volume that is only a few metres along each side, the lidar record or "signature" yields a detailed profile of the particulate concentration in the air at that instant along the path of the beam. Changes in the profile as derived from repetitive observations may be studied for information on the convective process. Here, the characteristics of the underlying surface also must be considered for the purpose of differentiating between particulate transfer by thermal convection and by mechanical means such as automobile motion or flow separation above tall buildings. Further details on the lidar and the method of "signature" analysis are found in Hay and Sells (1973).

The Pasquill stability index is derived from local weather information for the interval about each lidar observation. For this purpose, the procedure described by Turner (1961) is followed, taking into account the solar elevation (Chamberlain, 1961), cloud cover, and wind speed measured at a height 5 m above the laboratory roof (25 m above ground). These air stability indices range from 1 through 4 to 7, corresponding to very unstable through neutral to very stable tendency, respectively. While the significance of this stability index (and the related Richardson number) in an urban environment remains a topic for further study and interpretation (see, for example: Hage, 1972), it nevertheless provides a useful indicator at the heights of the lidar observations as noted in the next section.

3 Observed convective structures

Approximately 1100 profiles of particulate concentration have been recorded by the lidar during its first year of operation. Visible plumes originating from industrial and domestic stacks are detected readily at ranges up to 6 km. Their diameters generally are of the order of several metres. No special effort has been made to study this type of plume at the present time, and no further reference will be made to them in this paper.

Other details in the concentration profiles suggest the existence of isolated thermal plumes similar to those described in Section 1. Their diameters range from 30 to 90 m, their heights extend at least 30–40 m above ground, and they possess a central maximum of particulate concentration. In some of the sequences of observations taken at 1-min intervals along a fixed direction, an isolated anomaly appeared at approximately the same position in three successive profiles. There was some indication of migration of this feature with the mean wind. Since these features usually are not visible to the unaided eye, the sources of particulate are not readily confirmed. However, their positions in the city are known within a few metres; they appear to be associated with paved parking lots, major traffic arteries, the river, open ploughed fields, residential construction sites, and treed parks.

TABLE 1 Summary on anomalous plume-like features as observed by lidar.

Pasquill stability index	Number of lidar observations	Number of anomalous plume-like features
1	28	0
2	321	15
3	306	10
4	434	56
5	0	0
6	25	0
7	3	0

Table 1 lists the incidence of these anomalous plume-like features for a wide range of Pasquill stability indices, during the period October 1972 to October 1973. Although more extensive observations are desirable for confirmation, two trends appear to be developing. The first is that neutral thermal stability strongly favours their incidence. Secondly, surface insolation is required for their formation; while the numbers in the table may not illustrate this adequately, continuous lidar observations around sunset have shown an abrupt disappearance of the plume-like features after sunset. It is of interest to note that convective penetration into a region of neutral stability is a known characteristic of thermal plumes.

Acknowledgements
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The Heat and Water Budgets of a Beaver Pond

E. Vowinckel and Svenn Orvig
Department of Meteorology, McGill University, Montreal
[Manuscript received 17 November 1973]

ABSTRACT

Small water bodies create their own characteristic local meteorological environments. The heat and water budgets will generally vary with surface area and water depth. If a small pond gradually becomes covered by vegetation, its meteorological conditions will change. On occasion, a vegetated area may change into a pond, complete with vegetation established in the water and extending above the surface. Such are beaver ponds and other flooded areas.

The paper discusses the main features of the development of beaver ponds and their heat and water budgets at different stages. The energy budget programme used was previously developed by the authors, but it has been modified to account for the different phases of the pond development. The effects of the various physical changes are evaluated by comparing the individual heat and water budget terms for different stages between an open lake surface and a forest cover.

The local heat budget will only be affected on a small scale by the establishment of a beaver pond, but the influence on the water budget has far-reaching consequences.

1 Introduction

In reporting to the 1970 Reading Symposium on World Water Balance, Storr (1970) presented a survey of water-balance studies in Alberta. He stated that beaver dams at present create the largest obstacle to attaining a water balance in a particular area: the Spring Creek Basin. Besides reducing the peaks on the hydrograph the beavers also release water at intervals and create problems in establishing the base flow rate. In addition, the varying sizes of the ponds behind the dams create difficulties in estimating evapotranspiration.

A beaver pond is usually a temporary phenomenon, lasting for a number of years until the local food supply is exhausted. Some ponds may be old, however, ages of 400 to 1000 years have been reported (Warren, 1927). Construction is always in progress, so a certain portion of the Canadian forest land is constantly covered by ponds in various stages of development. It should therefore be of interest to examine this special "beaver factor" in the heat and water budgets of a forest. It might give some understanding of the changes in energy fluxes caused by variations of local environmental conditions, under otherwise identical synoptic situations.

The original site of a beaver pond is a creek or river valley with original vegetation varying from meadow to mature forest. The first stage of the succession is generated when the dam is built: flooded forest or meadow with the vegetation alive for perhaps 3 years. The second stage is characterized by dying vegetation and the establishment of an open water surface. Stage three is the gradual filling of the pond, i.e., it becomes shallow and progressively more overgrown until it disappears. Generally, the first two stages exist simultaneously as the beaver increases the dam height and thereby floods additional areas.

2 Method and data

The influences of the changes in surface conditions can be investigated in two ways. One can either observe the energy budget terms in all stages of pond development, or one can use regular meteorological observations for the calculation of the various budget terms and introduce different surface conditions, typical of the various stages of the pond. In the first method, the measurements are difficult to perform, and the results will be local as each site is unique. On the other hand, the second method is problematical because the real processes can only be simulated approximately in the energy exchange calculations and all the required data are never collected. Also, calculations must be performed as if the processes are subsequent while, in reality, all exchange processes operate simultaneously.

It is apparent that the errors in the results will increase with the length of the time step and with the number of processes which in reality are simultaneous. In the present investigation calculations were performed according to the energy budget programmes designed and described by Vowinckel and Orvig (1972). The data used were synoptic surface and upper-air observations from Maniwaki, P.Q. (46°22′N, 75°59′W, 170 m asl) for the year 1967. One daytime and one night-time observation were used for each 24-h period for the whole year. The following are the terms calculated:

SGA: Short-wave (solar) radiation absorbed at the surface
RLU: Long-wave radiation from the surface
DSTG: Ground heat storage change
QE: Latent heat flux
QS: Sensible heat flux

3 Results

a *Short-Wave Radiation*

Table 1 gives short-wave radiation absorbed at the surface for different conditions and stages. The variations in SGA are caused by changes in albedo. If deciduous forest is regarded as standard, then the first stage of pond development (flooding) is accompanied by an overall slight increase in SGA, caused by higher absorption in early summer. In late autumn the values are actually lower in the flooded area. In spring and early summer much of the solar radiation penetrates to the surface, and water albedo will give a rise in SGA. Later,

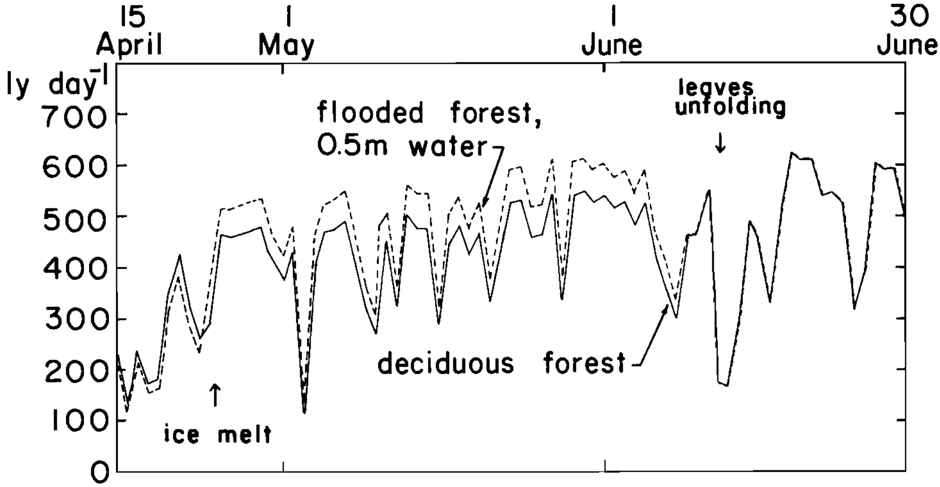

Fig. 1 Solar radiation absorbed at the surface.

when the leaves have unfolded, the differences in ground albedo will be less important.

During the snow period, SGA is generally smaller in the flooded area because the ground will not have as much organic material to reduce the albedo. Before flooding, such organic material will have an effect, especially in late autumn and early winter when the snow cover is still thin.

Fig. 1 illustrates the daily values of SGA for spring and early summer for condition of deciduous forest and of flooded forest. Winter conditions, before ice melt, show values a little higher for forest (without leaves) than for flooded area. The spring period, after ice melt but before leaves, is clearly noticeable with its darker water area. This condition is terminated abruptly in the calculations for early June when leaves unfold. From then on there is little difference in albedo between forest and flooded forest. In nature and locally, of course, the period of leaf unfolding will be a gradual process and its timing depends on the tree species, e.g., poplar, elm and oak come into leaf at different times.

It would be possible to incorporate degree days and a gradual leaf unfolding in the programme, but both air and ground (root-zone) temperatures are then necessary, and the ground temperature change is strongly affected by flooding. This is seen from Fig. 2. At the time of ice melt, around 20 April, the flooded area is coldest, but shortly afterwards the shallow water warms quickly. Without more detailed knowledge of the role of ground and air temperatures in the process of leaf unfolding, it would seem unwarranted to attempt a more intricate programme.

The albedo difference between forest and flooded forest varies from day to day in spring (Fig. 1). This difference is caused by the variations of surface moisture in the forest. In the present case these differences remain small since the soil is generally wet in spring in eastern Canada. In other climates this factor will be significant.

Table 1 shows that the increase of water depth of a flooded forest has little

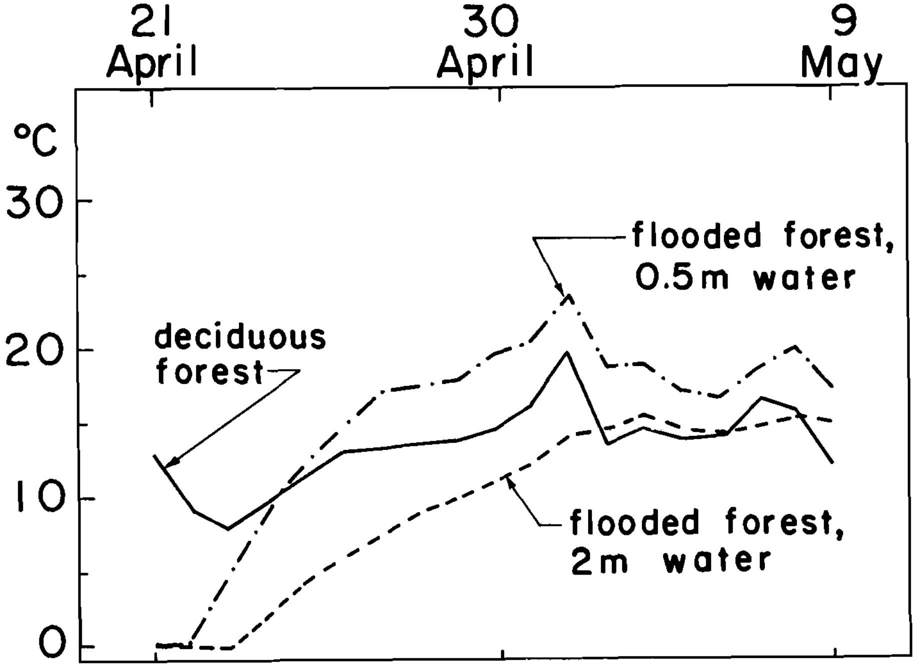

Fig. 2 Temperature at 1-cm depth.

effect on the absorbed solar radiation. A slight gain is noticeable in late autumn (November), the result of a delay in ice formation on deeper water. No greater water depth than 2 m has been introduced, as the vegetation could not survive.

Table 1 also shows that the annual average daily value of SGA is only 8 cal cm^{-2} higher in the flooded forest. The total annual energy increase, however, amounts to almost 3,000 cal cm^{-2}, or 3.2% of the solar energy absorbed by the forest. The gain is concentrated in the short spring period and is not negligible.

As the pond ages and the vegetation disappears, the SGA term increases due to still lower albedo in summer and also because of shortened duration of ice cover on deeper ponds. Comparing the deepest pond (16 m) with non-flooded coniferous forest (Table 1), it is seen that the annual total absorbed solar radiation is practically identical. The main difference is found during the snow period when coniferous forest has much lower albedo than an ice covered pond.

In addition to the numerical values of SGA for different conditions, the local importance of these ponds may be shown by a comparison as follows. London (1957) has given the gradient of absorbed solar radiation as 6.2 ly day^{-1} per 1° latitude, for the annual average, and 5.1 ly day^{-1} per 1° latitude for spring, in the latitude belt 45–55°N. The creation of a pond therefore equals a 1.5° latitude shift southwards in the annual mean and a full 7° latitude shift in spring.

Considering the time sequence, the absorbed radiation in the flooded area is

TABLE 1. Short-wave radiation absorbed at the surface.

	cal cm^{-2} day^{-1}													kcal cm^{-2} year^{-1}	
	J	F	M	A	M	J	J	A	S	O	N	D	Annual average	Annual total	Difference from deciduous forest
Deciduous forest	29	49	85	287	432	465	478	426	357	214	129	48	250	91.2	—
Coniferous forest	52	87	144	335	484	499	504	449	376	233	145	70	282	102.9	+11.7
Deciduous forest															
0.5 m water	30	41	104	302	485	482	480	428	358	228	111	42	258	94.1	+2.9
2 m water	30	41	104	300	485	482	480	428	358	228	139	42	260	94.9	+3.7
No vegetation															
0.5 m water	30	40	109	306	497	512	517	461	386	239	107	41	270	98.6	+7.4
2 m water	30	40	109	306	497	512	517	461	386	239	124	41	272	99.3	+8.1
16 m water	30	40	109	316	497	512	517	461	386	239	157	101	280	102.2	+11.0

TABLE 2. Ground heat storage change.

	cal cm^{-2} day^{-1}													kcal cm^{-2} year^{-1}	
	J	F	M	A	M	J	J	A	S	O	N	D	Annual average	Annual total gain	Difference from deciduous forest
Deciduous forest	12	16	13	−25	−26	−36	−29	−18	−3	8	25	29	−3	−4.2	—
Coniferous forest	4	5	2	−15	−24	−33	−27	−18	−3	10	24	9	−6	−3.7	0.5
Deciduous forest															
0.5 m water	16	24	−23	−126	−9	−13	−7	2	4	11	22	39	−5	−5.4	−1.2
2 m water	16	24	−23	−166	−76	−17	−15	15	35	33	50	43	−7	−9.0	−4.8
No vegetation															
0.5 m water	25	27	−10	−137	−8	−19	−11	5	3	11	32	48	−3	−5.6	−1.4
2 m water	25	27	−10	−190	−79	−58	−13	25	47	40	69	49	−6	−10.6	−6.4
16 m water	19	22	−15	−203	−294	−375	−213	−17	90	209	325	211	−20	−34.0	−29.8

Positive sign: heat transport towards the surface, i.e., ground loses heat.
Negative sign: heat transport away from the surface, i.e., ground gains heat.

about 10 days ahead of that in the forest on 1 May, and mid-summer values are reached in the flooded area around 15 May.

b *Ground Heat Storage*

The physical properties of the ground are also changed drastically by flooding. In addition to the amount of available water, the thermal properties are altered. The heat capacity will increase, as will the possibility of heat transport by turbulence. During the cooling phase, the turbulence will be assumed equal in pond and lake, but during the warming period the mechanical turbulence caused by wind will be different in pond and lake. The reason is the presence of vegetation in shallow water. No plant growth is allowed in water depths exceeding 3 m due to insufficient light at that depth. Plant growth is made dependent on light in the calculations, the intensity being proportional to the fraction of light that penetrates to the pond surface. It has further been assumed that aquatic plant growth has temperature requirements similar to plants on land and that the growth proceeds gradually, reaching its maximum only after a certain number of growing days. Finally, if vegetation exists above the water surface, the wind speed is decreased in proportion to the fractional density of vegetation.

Table 2 gives the monthly mean values of ground heat storage change (DSTG). It is seen that the calculations did not reach a balance in the annual average after one year, because heat export by runoff of melted snow has not been deducted from DSTG, and a corresponding heat gain by freezing did not take place. In the 1967 average this amounted to 5.8 ly day^{-1}. Allowing for this export, most of the annual average values in Table 2 are near balance. An exact balance could not be expected as the initial values of temperatures below the surface were estimated and, in any case, a period of one year is too short.

Considering the total energy entering storage in the course of the year, it is seen that the value increases sharply with greater water depth. The main reason is the cool water surface of early summer which retards the heat expenditure terms and allows more energy to be stored. The higher storage values for open water compared to flooded forest result from the shielding of the water surface by vegetation and a drop in absorbed solar radiation. Then the energy exchange will be mainly via long-wave radiation and the day-time heat excess is transformed in the forest canopy. The heating of the water from increased downward long-wave radiation is less effective than direct absorption of solar radiation. Over the year as a whole, however, DSTG is only an energy sink as far as melting of snow is concerned. This has the same value for all surface conditions and otherwise the gain amounts represent the heat available for redistribution in time in order to approach equalization of the summer and winter energy budgets.

Fig. 3 shows the daily values of DSTG for two typical conditions. The daily amounts become larger with increasing water depth. It is seen, however, that the main characteristic is an increase in variability of the storage change term with deeper water, and the sign of the term begins to change more frequently.

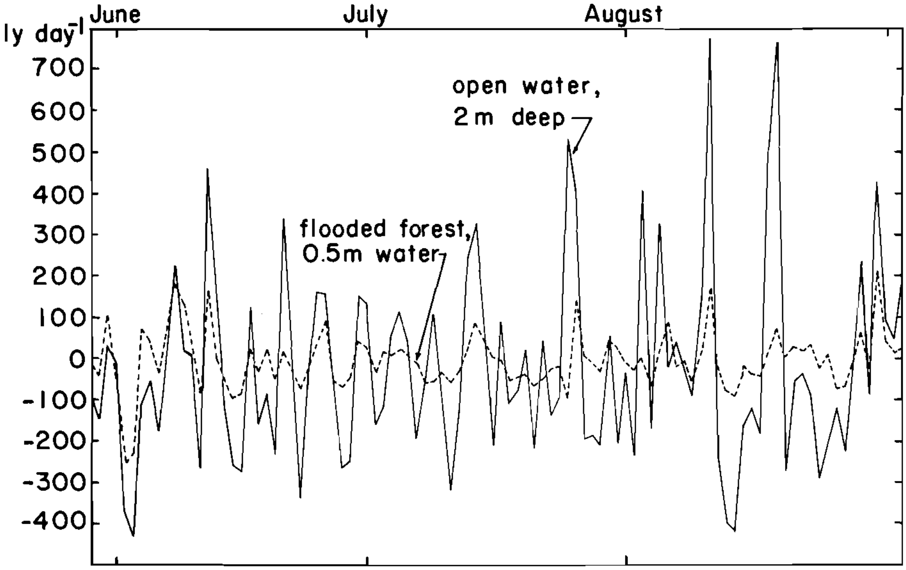

Fig. 3 Change in ground heat storage.

The number of days with positive DSTG (ground heat loss) in July, for instance, is three for flooded forest but fourteen for 2 m deep open water. For solid surfaces the low conductivity of the soil demands that practically all heat received at the surface must be retransmitted upwards. The surface temperature will therefore fluctuate widely. The difference between July mean day-time and mean night-time surface temperatures is 7.8 °C for deciduous forest, 1.1 °C for flooded forest with 0.5 m water, and 0.3 °C for flooded forest with 2 m water. At water surfaces the temperature is inoperative as a regulating mechanism due to the turbulent heat exchange in the water. The energy stored in the water is therefore used to balance the surface budget, and the heat storage is constantly adjusting to synoptic conditions which govern the supply and demand at the surface. It is evident that the variability of DSTG will tend towards a maximum at some intermediate water depth. Its value will depend on the synoptic period. The calculations indicate that the critical water depth for the region of Maniwaki is about 4 m.

Although the storage is merely a process of shifting available energy from one season to another, it can change the expenditure terms considerably when the stored energy again becomes available. It can be used in either of the turbulent terms or as long-wave radiation. Similarly, during the period of accumulation it may reduce any of these.

c *Evaporation*

The turbulent terms (QS and QE) stand in intimate relation to DSTG. Evaporation (QE) shall be discussed here. Fig. 4 shows daily values of latent heat flux for the three summer months for two surface conditions. Again it is seen

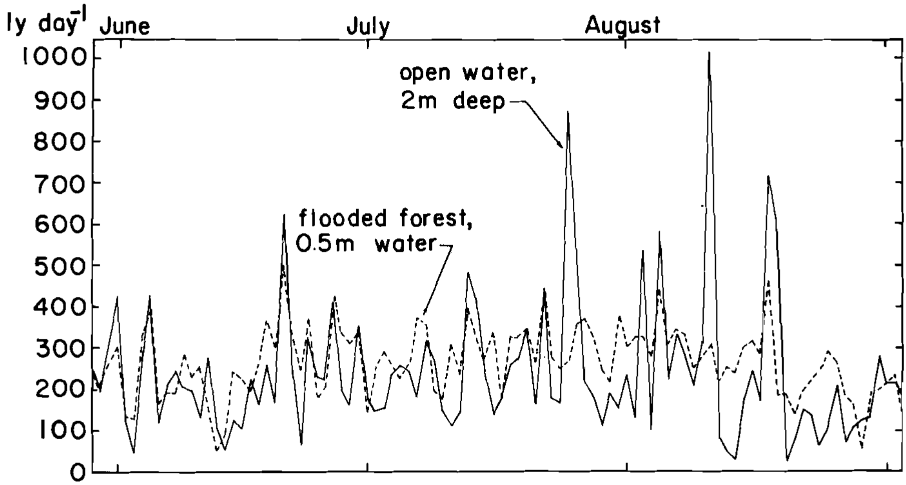

Fig. 4 Latent heat flux.

that extremes are more pronounced with deeper water. However, the mean values of evaporation are not, at Maniwaki, determined by the extremes and the monthly values in summer are lower for the deeper, non-vegetated water than for flooded forest (Table 3). The table shows that the annual evaporation totals are lower for undisturbed forest than for the other conditions, with the exception of the deepest pond (16 m), which has coldest water. Also, evaporation decreases as vegetation is removed from a pond. Three parameters are critical for evaporation, in addition to atmospheric conditions, namely the water holding capacity of the soil, the area of evaporating surface, and the physiological factor which limits evaporation. In the case of the first of these, as water is drawn from the ground reservoir, it becomes gradually more difficult to remove further amounts by evaporation. In the present computations this relation has been included so that, with constant precipitation, the evaporation will vary directly with the water holding capacity. Of course, the influence of soil water holding capacity will disappear if the daily precipitation always exceeds evaporation. This is the case in only a few places in the world such as some islands in middle latitudes in the southern hemisphere and an area of southern Chile. The water holding capacity is also irrelevant in conditions of flooding. A beaver pond can have no water deficit and will, therefore, have higher evaporation.

As regards the effective surface area, evaporation has here been calculated for a flat surface. In reality, the problem is formidable when the surface is vegetated. In a forest, particularly, the real surface area will vary from one location to another and change with time. The turbulent exchange is also intimately related to the wind speed and surface temperature, both of which vary drastically in the vertical and the horizontal in vegetation. In agricultural research one has introduced the "leaf area index" which gives a measure of the effectiveness of a given vegetation type in the exchange process, compared to unit surface. A site with a large index will experience a considerable drop in evaporation when the original vegetation cover disappears due to flooding.

Finally, there is the physiological factor of limiting transpiration by the conducting capacity of the plant tissue. This is temperature-dependent in a complicated manner. An upper limit has been used in the present calculations, simply dependent on temperature. Considering all of these influences, it is evident that a young beaver pond, i.e., a recently flooded forest, should have the highest average evaporation. This is seen in Fig. 4 for most of the days which did not experience extremes.

In calculations such as those discussed here, using synoptic data, it is important to consider the wind speed at the pond surface. Generally, the real wind speed over the pond will be less than the observed wind at a regular observing site. The smaller the pond, the lighter the wind. Table 3 also shows results of evaporation calculations for a small pond, assuming a wind speed ½ of that observed in an open area. The sharp reduction in evaporation is evident, becoming less than the undisturbed forest values. On most days the difference in evaporation calculated with strong and light wind is not great; the major reduction occurs on the few days with peak evaporation. The high values result from particularly strong wind on these days.

Table 3 shows that the difference between pond and forest evaporation is mainly a summer-time phenomenon. This is in contrast to the lake (16 m) results, which show an evaporation curve quite different for the whole year except in mid-winter. The water runoff was calculated for the various conditions by including precipitation, evaporation and soil storage for each month. Table 4 gives the runoff values. The calculations showed the highest accumulated soil water deficits to be reached in August. Then, the shallow flooding (0.5 m) caused an accumulated deficit of about 20 cm water. The annual runoff figures in Table 4 show the significant influence of the beaver ponds on the water budget.

4 Conclusions

Fig. 5 shows the monthly means of the major surface energy budget terms for different pond conditions. It is remarkable how relatively small the changes are in absorbed short-wave radiation (SGA), especially when compared to the turbulent terms (QS and QE). The effect of reducing the wind speed is seen only in QE and not in QS. The air-water temperature difference is small on days with strong wind, and reducing the wind speed will increase water surface temperature, thereby steepening the air temperature gradient. This will enhance the thermal turbulence to compensate for reduced mechanical turbulence, leaving QS practically unchanged. Fig. 5 also shows that the main difference between evaporation (QE) from pond and forest is a summer-time phenomenon. The consequence for the local heat budget of establishing a beaver pond is only important on a small scale, although the change in absorbed solar radiation at the pond itself is equal to a southward shift of 1.5° latitude in the annual mean and around 7° latitude in spring. Typical spring and summer values of SGA

TABLE 3. Monthly and annual evaporation (1/10 mm).

	J	F	M	A	M	J	J	A	S	O	N	D	Annual total
Deciduous forest	−3	17	47	285	685	1182	1218	967	906	313	90	25	5732
Coniferous forest	3	20	68	318	716	1239	1240	967	660	313	96	3	5643
Deciduous forest													
0.5 m water	−3	11	34	180	840	1323	1527	1368	834	319	81	16	6530
2 m water	−3	11	34	108	657	1314	1507	1417	924	366	138	16	6489
No vegetation													
0.5 m water	0	20	40	231	1048	1296	1380	1252	723	313	90	19	6412
2 m water	0	20	40	105	846	1158	1361	1296	804	353	90	19	6092
16 m water	0	20	40	123	338	252	806	1190	663	707	570	260	4969
2 m water small pond	0	20	40	93	645	987	1184	1101	738	313	141	19	5281
Precipitation	877	683	233	711	539	1194	341	924	1305	1432	825	456	9520

TABLE 4. Runoff (1/10 mm).

	J	F	M	A	M	J	J	A	S	O	N	D	Annual total
Deciduous forest	880	666	186	426	0	0	0	0	0	464	735	431	3788
Coniferous forest	874	663	165	393	0	0	0	0	0	600	729	453	3877
Deciduous forest													
0.5 m water	880	672	199	531	0	0	0	0	0	0	268	440	2990
2 m water	880	672	199	603	0	0	0	0	0	0	237	440	3031
No vegetation													
0.5 m water	877	663	193	480	0	0	0	0	0	0	458	437	3108
2 m water	877	663	193	606	0	0	0	0	0	0	652	437	3428
16 m water	877	663	193	588	201	942	0	0	0	636	255	196	4551
2 m water small pond	877	663	193	618	0	101	0	0	0	666	684	437	4239

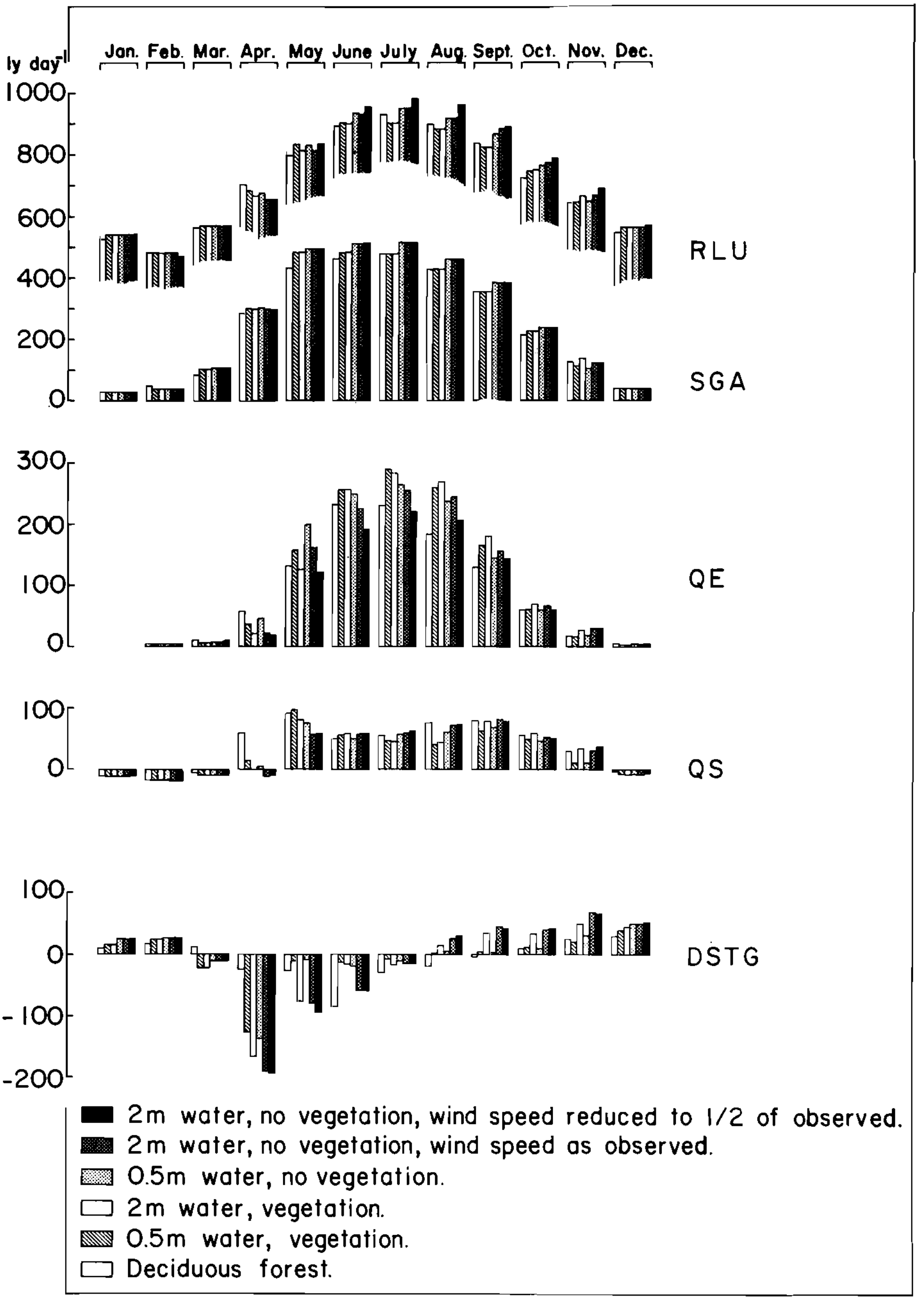

Fig. 5 Monthly means of major energy budget terms .

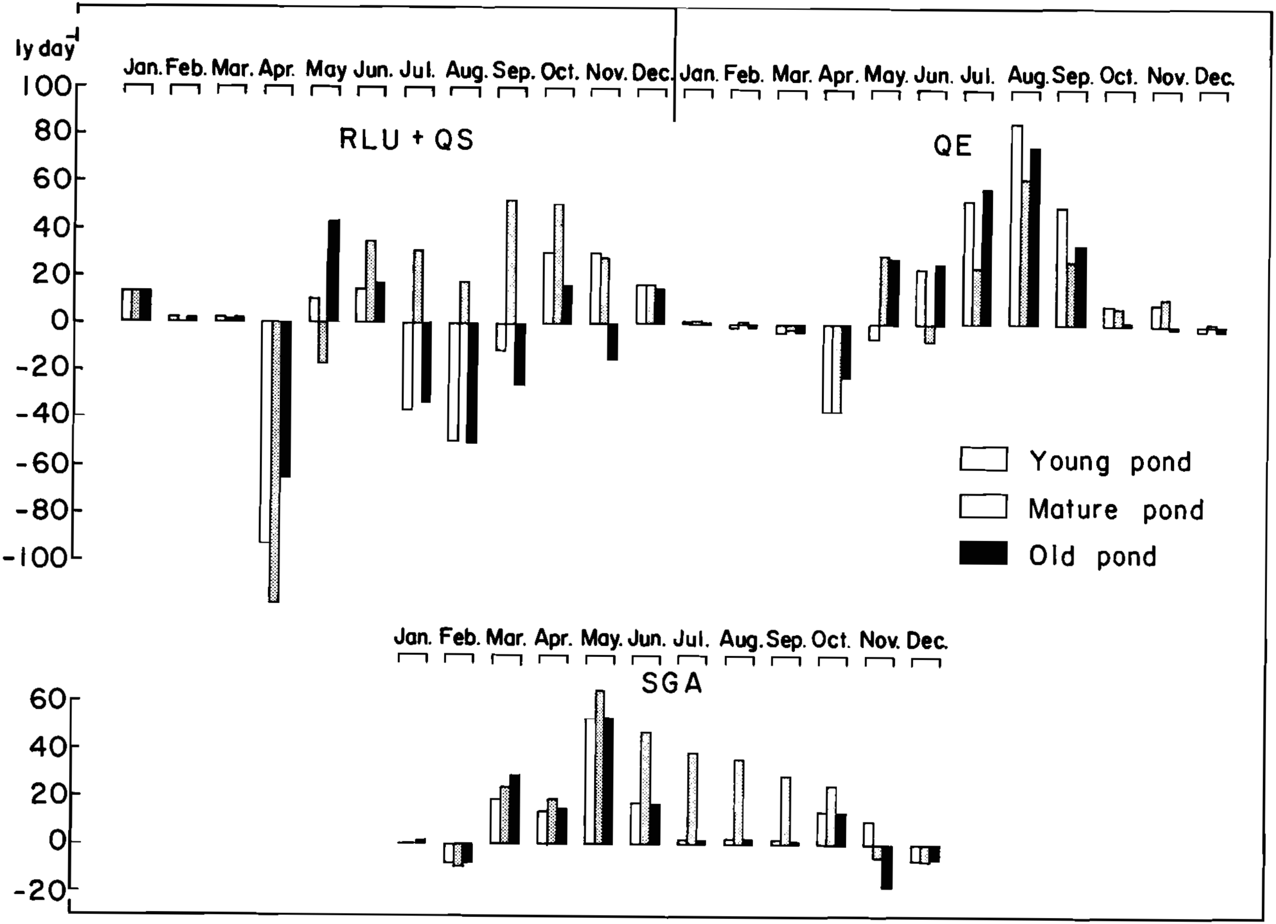

Fig. 6 Differences in heat gain and loss over forest and pond (pond value minus forest value).

occur much earlier over the flooded area itself than in the undisturbed forest. However, the influence of beaver ponds on the water budget has more far-reaching consequences, as can be seen from the annual runoff figures in Table 4. This problem is an important one in land management.

The influence of a beaver pond on the environment is different for individual energy terms. It will change with the age of the pond and the time of year. This can be seen in Fig. 6, which gives monthly differences between pond and forest for three stages of pond development. Three aspects of the energy budget are shown: absorbed solar radiation, evaporation, and the sum of upward long-wave radiation and sensible heat flux. It is apparent that there is high variability with season and age of the pond.

It seems that it is possible to use the present method and actual weather data from any suitable region to assess the influence of a beaver dam on the environment. The computations of the budget terms must, however, be done on a daily basis. Monthly mean values cannot be used because the budget terms generally act in short bursts which will be masked by long-term mean values of the variables.

The assumption was made in this investigation that the atmospheric conditions do not change as a result of a changed surface energy budget. This can only be said to be valid if the changed surface area is quite small. The critical size of such a surface "disturbance" will depend on the magnitude of the heat exchange processes, i.e., on the particular weather situation, and on the accuracy desired in the results. Of importance is also the degree to which the synoptic observations are representative of undisturbed conditions. The effect of surface modifications on air-mass characteristics is important in studies of climatic change, and the present investigation can be said to be a first step in such research.

Returning to the statement of Storr (1970), about the beaver dams creating obstacles to hydrological research, one might add the point of view that such dams are, nevertheless, beneficial in the water budget. They retard storm flows and, generally, provide a more even stream flow. In addition, the gradual silting of the ponds generates good soil. This is particularly beneficial in areas of eastern Canada where the retreating ice left sparse soil and where weathering is slow.

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The Effect of Particle Size Distributions on the Dynamics of Falling Precipitation Zones

Roland List and Terry L. Clark[1]
Department of Physics, University of Toronto
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ABSTRACT
A simplistic study of the dynamics of a falling particle ensemble is described. It shows the effect created by the introduction of particle size distributions on precipitation onset and duration and compares it to the case where air motions or pressure fields triggered by the particles are neglected. The assumption of homogeneously sized raindrops seems adequate if precipitation rates and total rainfall are considered. As soon as timing is involved a more refined treatment is required.

1 Introduction

The cloud physics group of the University of Toronto has been concerned since 1967 with the dynamic interaction of precipitation and the surrounding air. Thereby considerable effort was directed at the effect that ensembles of raindrops or hailstones have on the air motion, and at the pressure perturbations caused by particulate matter (Lozowski and List, 1969; List and Lozowski, 1970; Lozowski, 1970; Clark, 1971; Clark and List, 1971). While these studies considered only mechanical interactions, the work was later expanded to include thermodynamic relationships (Girard, 1973). This widening of scope led to more complex buoyancy forces. Most of the studies listed above were treating the ensemble-air interactions by assuming the presence of homogeneously sized particles only. It is the purpose of this paper to describe the interaction of air with particles defined by a size spectrum (according to Clark, 1971). Qualitative effects will be investigated in order to gain a first insight into the physics of the problem and to assess the possibilities of parameterization.

This latter attempt is useful for the discussion of two-dimensional models where weighted mean terminal particle velocities were used for the advection of rain water (Kessler, 1969; Takeda, 1965; Liu and Orville, 1968; Orville and Sloan, 1970; etc.). The two-dimensional models by Takeda (1971) and Clark (1973) are exceptions since these authors consider particle size spectra. However, since they are modelling precipitation in an advanced fashion, starting from cloud formation, the "spectrum" effect cannot be isolated.

As in Clark and List (1971) attention is given to the motion of the overall particle zone, the sub-zones of particles of a given size class, and the centres

[1]Present address: Atmospheric Environment Service, Toronto.

of mass of the different sub-zones. Comparisons of different approaches will be based on the study of the onset and duration times of precipitation.

2 The model

The initial configuration of the particle zone in slab symmetry (all parameters independent of y) is shown in Fig. 1. The troposphere is represented by a height interval $0 < z < 10$ km and extends in width from $x = -10$ km to $x = +10$ km. At time zero the precipitation particles are evenly distributed within a region of height 7–9 km and a width of 4 km, centred about the axis of symmetry, $x = 0$, and the air is at rest. Immediately afterwards the particles will fall at their individual terminal speeds, V_{Ti}, with respect to the air and will set the air into motion.

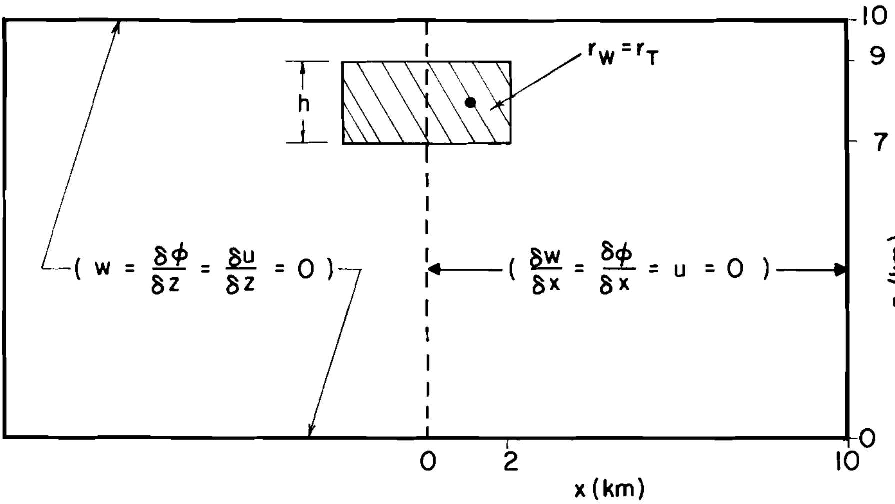

Fig. 1 Boundary and initial conditions imposed on Eqs. (1) to (4) with a slab symmetry for a two-dimensional model; hatched area indicating particle zone at time zero. Heavy dot in zone indicates zone's centre of mass in the positive x-z quadrant.

In order to facilitate the solution the following simplifications were introduced:

(i) only mechanical interactions on the basis of drag are considered; thermodynamic effects like the creation of buoyancy due to raindrop evaporation are not considered; this applies also to the stability of the atmosphere;

(ii) the particles are non-interacting, i.e., no coalescence or breakup is considered;

(iii) the air density is constant and equal to 1 kg m^{-3}, because it can be argued that the zone drag is independent of density. (Clark (1971) showed that density variations do not have a substantial effect, a fact which was later confirmed by comparison with a height dependent density by Girard (1973).)

On this basis the *governing equations* can be written as follows:

$$\frac{dw}{dt} = -\frac{\partial\phi}{\partial z} - gr + \nu_e \nabla^2 w, \tag{1}$$

$$\frac{du}{dt} = -\frac{\partial\phi}{\partial z} + \nu_e \nabla^2 w, \tag{2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0, \tag{3}$$

$$\frac{dr_i}{dt} = \frac{\partial}{\partial z}(V_{Ti} r_i), \tag{4}$$

where w and u are the vertical and horizontal air velocity components, respectively, $\phi = P/\rho + gz$, with P the total air pressure, ρ the air density, and g the gravitational acceleration; r is the liquid water mixing ratio and r_i represents the same parameter for the raindrop size class i; ν_e is the eddy viscosity and V_{Ti} the terminal speed of a particle of size class i.

Equations (1) and (2) represent the momentum equations, (3) is the continuity equation for air for ρ = const., and (4) describes the water mass conservation for each size class.

The eddy viscosity of the air was set at $\nu_e = 1000$ m^2 s^{-1} (for a 500-m grid) in order to achieve computational stability and to simulate the real viscosity. The comparison for homogeneously sized particles with data obtained in more elaborate stable computational schemes with variable eddy viscosity (Girard (1973)) demonstrated that this value for ν_e is about right. While eddy viscosity was applied to air, no comparable term was applied for particle diffusion due to (sub-grid scale) eddy diffusion. This is a problem which is not understood at present and requires careful investigation.

The initial *particle size distributions* used in the calculations are depicted in Fig. 2 with the initial liquid water mixing ratio r_i as function of the particle diameter D_i for eleven size classes. Case I corresponds to a loose fit of the Marshall-Palmer distribution to the eleven sizes by setting the total mixing ratio

$$r_T = \sum_{i=1}^{11} r_i = \sum_{i=1}^{11} 2D_i^3 \, e^{-\lambda D_i} = 0.01, \tag{5}$$

which results in $\lambda = 12.23$ cm^{-1}. Case II is Case I inverted, i.e., the new values of r_i are replaced by the Case I values of r_{12-i}. Case III is an even distribution given by $r_i = 0.01/11$ for all i.

The terminal velocities V_{Ti} are also shown in Fig. 2. The weighted mean terminal velocity $\overline{V}_T$ is expressed by

$$\overline{V}_T = \sum_{i=1}^{11} r_i V_{Ti} \Big/ \sum_{i=1}^{11} r_i \ . \tag{6}$$

For the cases considered the $\overline{V}_T$ values calculated on this basis are in agreement (difference < 6%) with the values obtained by Liu and Orville's (1968) formula.

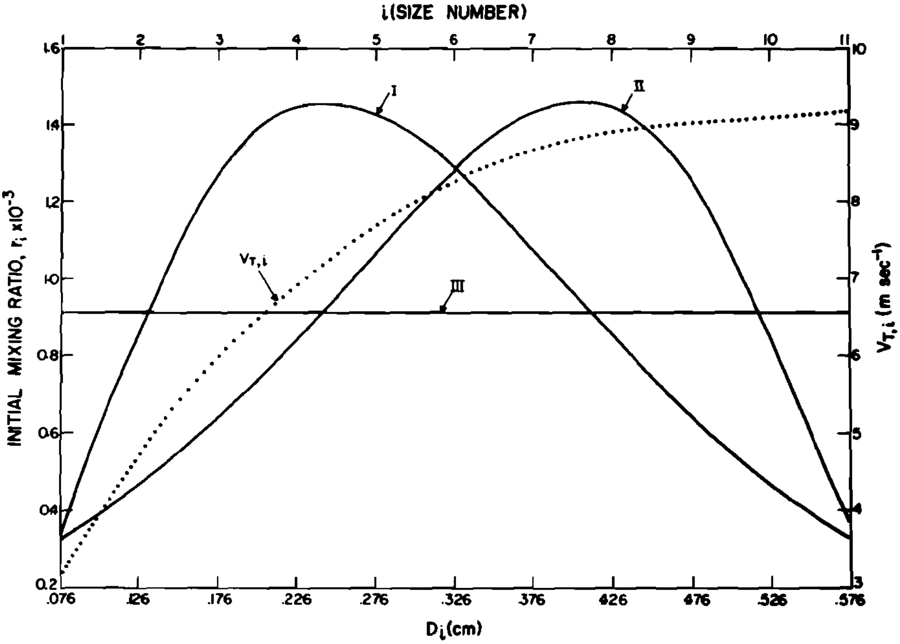

Fig. 2 Initial particle size-distributions; solid lines represent initial mixing ratios for cases I, II and III versus diameter D_i and size number i. The dotted line represents the terminal velocity versus D_i and i for all cases. Total mixing ratio $r_T = 0.01$.

The *numerical approach* used is a mixed Eulerian-Lagrangian method. The air motion is treated using an Eulerian scheme with the two-dimensional half space divided into 22 by 22 grids, each 500 m × 500 m. The particles are followed in a Lagrangian way through the displacement of 9 tracer particles per size class and original grid. For this purpose the particles are assumed to move with the air in the horizontal and also at their terminal speed in the vertical, according to Eq. (4), by exerting their weight on the air. These assumptions are justified by the difference in time scales of the changing air motion and the possible particle accelerations. It may be added that the velocity of a tracer particle at the centre points of the grids is based upon the four nearest air speeds taken in the middle of the four segements of the grid boundaries. The values of ϕ and r_i are calculated for each grid centre.

After setting up the initial fields the particles are moved according to the air speed and the terminal velocities. Then the number of tracer particles in each grid is used to determine the new liquid water mixing ratio r. The Eulerian fields for u, w and ϕ are then used with the new r-field to determine the new ϕ values. This in turn allows the solution of the equations of motion (1 and 2) giving the new velocity components u and w. Thus the new information is available for the next time step which deals with the further particle displacement, etc., etc.

Some of the boundary conditions are shown in Fig. 1. It may be added that all the walls are frictionless boundaries. For further information see also Clark and List (1971).

3 Results

The typical *behaviour* of a *falling particle zone* is represented in three different ways for a distribution according to Case I and for a total liquid water mixing ratio of $r_T = 0.01$. Fig. 3 depicts the centres of mass of each size class in the right-half space at different times. At time zero all particle groups are centred at the 8-km height level, 1 km away from the symmetry axis. After 250 s the different particle zones are spread out because the smaller particles fall slower. This separation increases with time, but it is obvious that all centres of mass are falling essentially within a very narrow region. The shapes of the regions containing 50% of the particles of a given size are shown in Fig. 4. The spreading in distance and in height is clearly recognizable; so is the upward bending of the outer zone regions, which is due to smaller vertical air velocities. The solid contours for the times 250 and 500 s indicate where the particles would be if they were falling at an average terminal speed $\overline{V}_T$ relative to the air. No

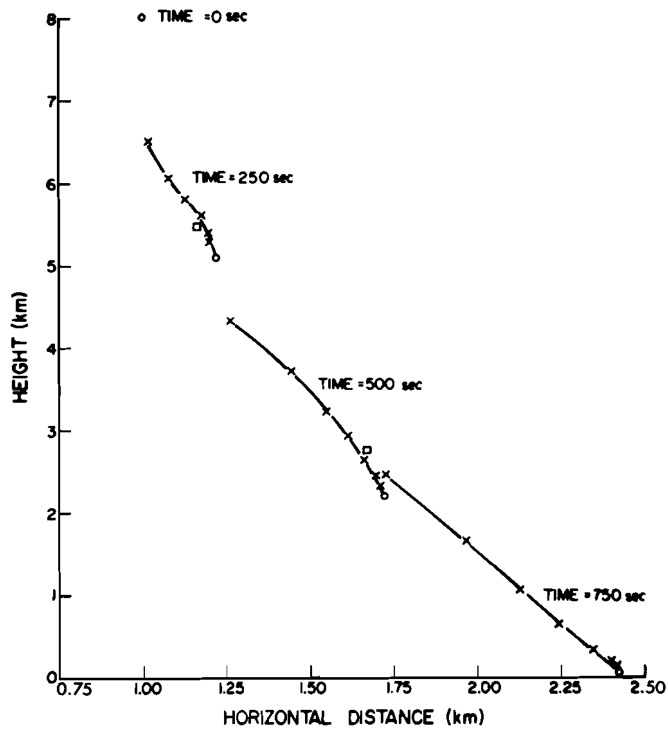

Fig. 3 Mean positions in positive x-z quadrant of different sized particles at different times. Open circle signifies more than one size present, crosses signify only one size present and open squares represent positions of all sizes as calculated using weighted mean terminal velocity. Initial mixing ratio distribution according to Marshall-Palmer raindrop spectrum, $r_T = 0.01$ (case I).

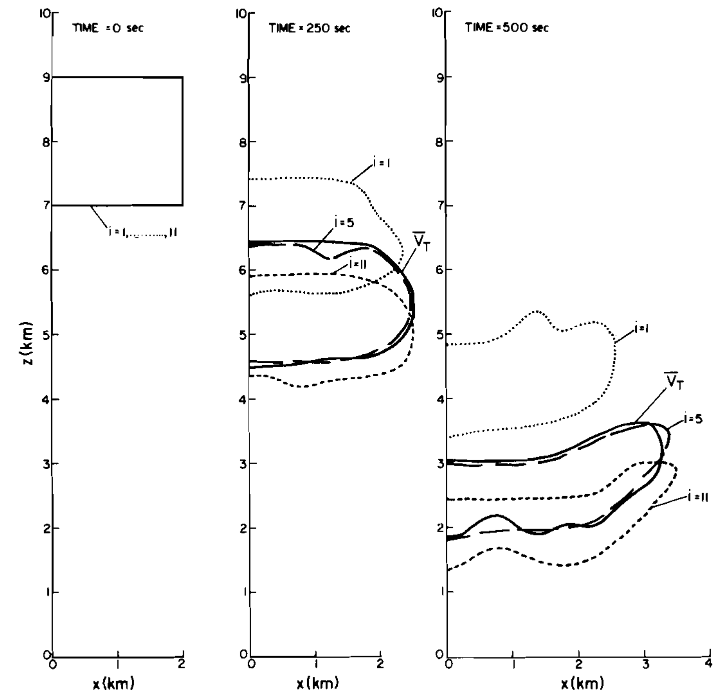

Fig. 4 Contours representing positions of zones with particle size numbers 1, 5 and 11 at three times. Solid line represents position of all sizes of particles as calculated using a weighted mean terminal velocity. Contours contain approximately 50% of all initial drops of each size class; conditions for case I distribution and $r_T = 0.01$.

vertical separation would occur, rather a compression in zone height, which in turn would result in a horizontal spreading similar to the zone of the particles of size class $i = 5$.

If no distinction is made between size classes and only the outer contours of the particle zone and isolines of equal liquid water content are required, then the necessary information can be found in the dashed background curves of Fig. 5. This display also shows the vertical and horizontal flow fields as well as pressure field contours. At time 500 s the highest downdraft occurs behind the falling particle zone. This is caused by the fact that the raindrops have fallen out of the zones they just accelerated, and it implies that the smaller particles take advantage of the downward air speeds created by the larger drops, and are, thus, enabled to keep up with them much better than expected without this wake entrainment effect. While the average terminal fall speed for the particles is 7.46 m s^{-1}, the downdraft created by them is larger than 8 m s^{-1} at time 500 s. The horizontal velocities within the zone are all directed outward with a maximum of about 4 m s^{-1}. Return flow occurs above the

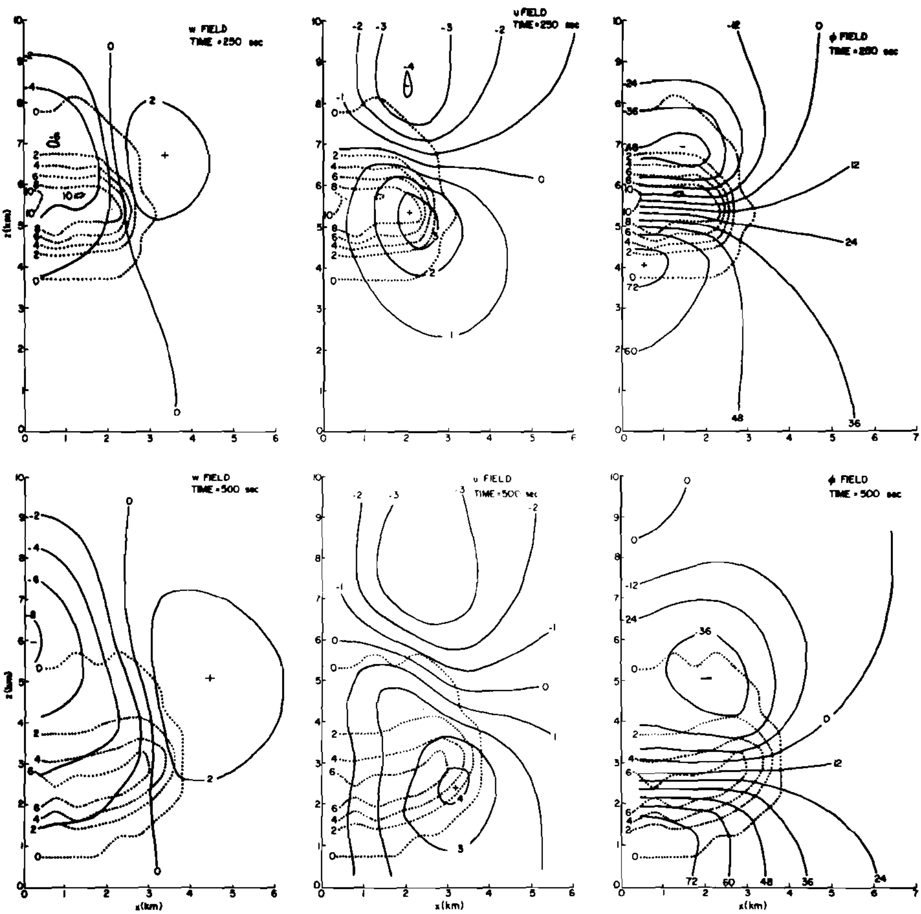

Fig. 5 Two-dimensional plots of w (m s^{-1}), u (m s^{-1}), ϕ (m^2 s^{-2}) and r_T (g kg^{-1}), in a sequence of time for a case I distribution with an initial r_T = 0.01. Dashed lines represent constant mixing ratios in g kg^{-1}; the contour interval for ϕ corresponds to 0.12 mb for an air density of 1 kg m^{-3}.

particle zone, thus completing the vortex-like motion. The ϕ or pressure field keeps the acceleration of the particle zone within limits by counteracting a large fraction of its weight.

Precipitation on the ground is another aspect of falling particle or rain zones. If it can be modelled adequately it may represent the key parameter for comparisons with natural rain. Therefore, the differences caused by the consideration of raindrop spectra instead of homogeneous drop sizes (or representation by $\overline{V}_T$) should be studied. Two aspects are important: the *onset time* and the *duration of precipitation*. These two times shall be compared to the times obtained assuming no acceleration of the air by the particle zones. Fig. 6 gives the ratio of onset times for two total liquid water mixing ratios, 0.005 and 0.01,

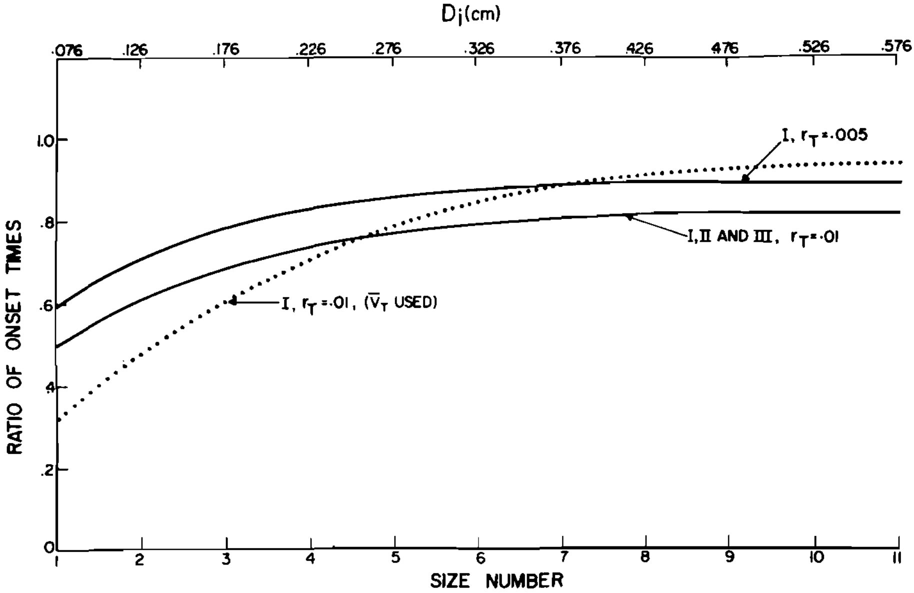

Fig. 6 Arrival times of the precipitation at the ground, represented by onset times of the different size sub-zones versus size number. The time is plotted as a ratio: onset time over onset time for the case where no air motion is assumed to be triggered by precipitation.

and the three drop spectra as represented in Fig. 2. While the sub-zones with the large drops arrive about 10–15% faster at the ground, the smallest drop category needs only 50–60% of the time required without particle effects on the air motion. This effect of being favoured in the downward moving wake of the larger drops would be over-emphasized by a factor of about two for the smaller drops if average terminal velocities $\overline{V}_T$ were to be used.

The *duration of precipitation* (Fig. 7) is even more affected by the vortex motion of the air mainly due to the sidewise spreading of the particle zone to more than twice the original width. Using average terminal speeds does not affect the duration as much as the onset time. The *precipitation rates*, however, were found to be about equal (within 10%) for all cases; only the duration changed.

4 Summary and comments

A simplified treatment of a falling zone of particles with different size distributions shows that there are considerable differences with respect to the case of homogeneously sized particles or, which is equivalent, particles falling at an average weighted speed. These differences do not depend much on the type of the size distribution.

The development of downdrafts in the wake of falling particle zones was discussed previously by Clark and List (1971). Extended to particle size dis-

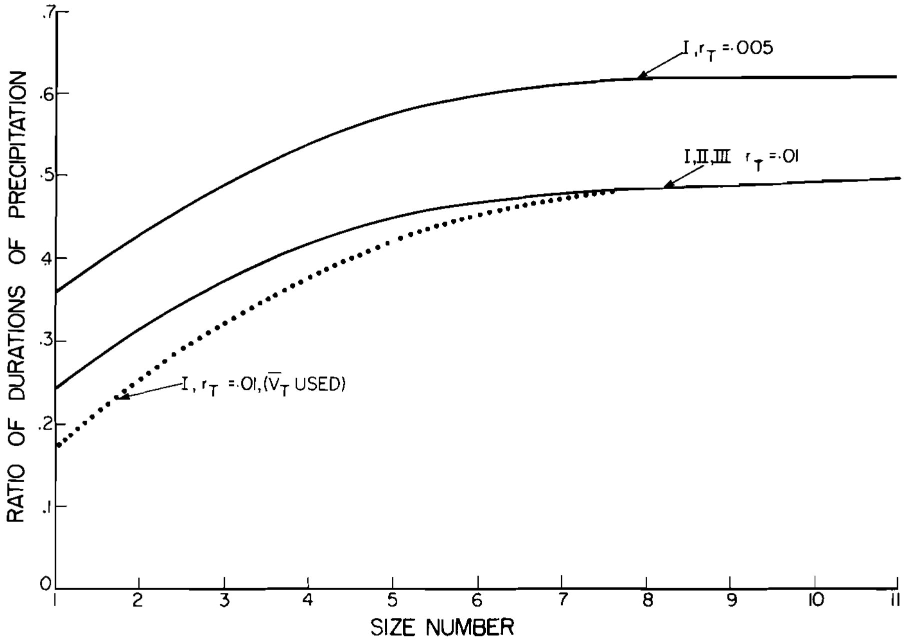

Fig. 7 Duration time of precipitation versus size number. Time is plotted as a ratio: duration time over duration time for the case of non-moving air.

tributions, this conclusion explains the finding that smaller particles can follow larger ones faster because they get the benefit of an increased local downdraft in the wake of the leader particles. The existence of a vortex motion can easily be seen as well as a pressure field which checks the downward acceleration of the particle zones.

Considering onset and duration times of precipitation one has to conclude that precipitation indeed reaches the ground faster due to the coupling with the air motion, and the duration is considerably shorter with the coupling because the precipitation spreads over a much wider area. The degree of spreading by factors of 2 to 3.5 is such that the precipitation rates remain essentially unchanged.

In terms of parameterization the conclusions are as follows. In an adequate model, the motion of marker particles has to be followed individually and no simplification is justifiable in which the size dependent free fall speed can be replaced by a mean particle fall speed $\overline{V}_T$ if precipitation onset or duration are to be investigated. However, precipitation rates and depth can be accurately predicted by using $\overline{V}_T$.

While it is recognized that the treatment of falling precipitation zones is still in a primitive stage, it seems that the insight gained into the physics of their behaviour is quite general. The above conclusions should essentially hold also in the explanation of the mechanics of falling precipitation zones when thermodynamics and particle interaction are included in the model.

Acknowledgements

The authors are grateful for the opportunity to have this paper printed in *Atmosphere* in honour of Dr. A. Thomson, a man and leader dedicated to the development of the science of meteorology in Canada.

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Hail, Science and Politics

W.F. Hitschfeld
McGill University

[Manuscript received 3 December 1973]

1 Introduction

These comments are triggered by recent changes in the orientation of ALHAS – *Alberta Hail Studies*, a project initiated with the enthusiastic support of Andrew Thomson – and by my participation at the first International Scientific Conference on Weather Modification at Tashkent in October. My purpose is to describe the different attitudes that different groups seem to be taking to cloud seeding for hail suppression. It is possible that similar dilemmas exist in regard to rain-making by seeding.

ALHAS was created in 1956 by the Research Council of Alberta, the National Research Council and the Canadian Meteorological Service, with the Stormy Weather Group of McGill University providing scientific advice and initiative. The major purpose was to discover how hail formed so that one might design, or examine, methods for its suppression, and (if possible) to initiate such suppression. The hail damage in Alberta averages $30 million p.a., so that even partial relief, or relief at considerable cost, would be worthwhile. At very modest funding levels (it took till 1967 before the project had access to an acceptable radar facility!), ALHAS was one of the prime developers of quantitative information on hail: on the structure of the storm, on location and shape of storm drafts, on the development of precipitation and the fall-out of hail and rain, etc.[1]

2 Seeding science

It all began about 1946 in Irving Langmuir's laboratory at General Electric in Schenectady. This great man and Bernie Vonnegut and Vincent Schaefer had succeeded in creating ice crystals in a cloud of super-cooled water droplets in a deep-freeze, simply by dropping bits of dry ice among them. After a search, they found that crystals of silver iodide (AgI) could produce similar effects more conveniently. They understood that these ice crystals would grow at the expense of super-cooled water till all the cloud was glaciated, or settled out, and sometimes indeed could confirm this expectation by spectacular visual effects in real clouds. This it was felt, was "rain making" by cloud seeding, and a first important step to man's control of the weather. Eventually, and with embarrassingly similar techniques, activities aimed at hail suppression followed.

Even now, after years and thousands of experiments and studies many

[1]Results appear in reports of the sponsors and in a series at McGill, which includes a 15-year review (Scientific Report MW-61, 1971). The most recent major publication is *Alberta Hailstorms* by A.J. Chisholm and Marianne English, *Meteorol. Monog.*, **36**, 1973.

important details of how AgI stimulates the freezing remain unknown. The absence of a satisfactory theory may seem a small flaw to practical people, but the fact is that it prevents theoretical considerations from being an important component in the evaluation of whatever seeding accomplishes.

We are in a similar position with regard to effects on the larger scale. Assuming the seeding increases the concentration of ice particles in the cloud by a given factor, what does this do to the cloud and its precipitation? Qualitative guesses have not been lacking of course. Regarding hail suppression, the claim is made that growth of large hail is inhibited through the introduction of many potential hailstones, all competing for the same finite supply of supercooled water. While such ideas make a strong appeal to our imagination, they do not fully stand up under quantitative scrutiny. Recently numerical studies have been made to model the growth of natural hail, attempts which will eventually provide guidance as to how modification by nucleation might function. Not surprisingly, these studies require simplifying assumptions of uncertain validity. For one thing they involve overly simplified notions of the draft pattern in the storm, and of the effect of the changed precipitation on the draft pattern. For another, they notably disagree with each other, and fumble, regarding the point at which the tiny ice crystals resulting from AgI nuclei become part of the hail-embryo population of the storm. Again from a practical point of view, these difficulties may *appear* academic. But they imply that the growth theory is not yet a predictor of the effects of seeding, not even of whether seeding has desirable or undesirable results.

3 Seeding operations

Almost at once after the discovery of the nucleating effects of CO_2 and AgI, and stimulated by the tentative experiments of Langmuir, hopes rose that by nucleation rain could be enhanced, and eventually that rain or fog could be dispersed, hail suppressed, or the fury of convection abated. With these hopes in the hearts of farmers, foresters, hydrologists and others came the *cloud seeders* who contracted to inject AgI (or other materials, but chiefly AgI) into clouds to change them in the desired way. Even with handsome profits, the services offered were cheap on the scale of the potential benefits. The seeders thus offered a service at a price many farmers and others in need thought they could not afford not to pay. Not surprisingly, seeders have been doing a brisk business in many parts of the world. Hail suppression is attempted routinely in Canada, the United States, at least eight European countries, eleven areas of the U.S.S.R., Argentina and two African states, and undoubtedly elsewhere.

4 Verification

Thorough efforts to monitor and verify results were made in only a small fraction of seeding operations. In the late Fifties and early Sixties, notable examples were the work of Iribarne and Grandoso in Mendoza (Argentina), and in the Hagel Grossversuch in Switzerland. Both led to essentially negative conclusions.

A new and powerful push to undertake seeding-for-suppression was provided by reports from the Soviet Union, starting in the mid-Sixties. The Russians were persuaded that they could mitigate hail, and that they were doing so routinely. Visitors to their operations (including two of us from Canada) were convinced that *they* were convinced. Their theory made little impact on us, and no visitor had sufficient knowledge of, or sometimes respect for, the data on which the claims were based, to be convinced by them. Hence we *had* to discover by our own seeding experiments following more or less according to the practice in the Caucasus, what the potential was. ALHAS eschewed a statistical seeding experiment, but added a program of well conceived and executed trials to their observations, and adapted the latter to "physical" comparison of seeded and unseeded regions. They researched the seeding procedure, applying tests for silver to collected samples of rain and hail to establish the fate of the seeding material. The tracing of the seeding material was more successful than the search for an effect on the hail out-fall, or on the radar-observed storm morphology. Certainly there was no powerful effect, but then the concentrated seeding was so limited in time and space that a considerable local effect might just possibly have been obscured by the random point-to-point variability of hail at the surface that occurs naturally (and incidentally bedevils the setting of hail insurance rates). An effect was found in the radar records, of a sort that could be deemed favourable to the seeding, but the analysis of the records was sophisticated rather than powerful. Certainly, by 1972 when this phase of the program terminated no pertinent conclusions could be drawn.

On a much more ambitious scale, though focused on a test area of only 600 mi^2, the *National Hail Research Experiment* (NHRE) of north-east Colorado (1972–1976) includes similar physical investigations, but its essential tool is statistical randomization. This means that the storms over the test area are seeded by a specified procedure, or they are not seeded, according to a previously determined randomized sequence. The quantities of hail collected on the ground by a network of well designed collectors under seeded and unseeded storms are then compared. The reliability of such methods can be good, provided enough cases are studied. The number of cases required depends critically on how much change the seeding really produces. The law is nonlinear. Thus it was estimated[2] that for a 60% reduction of hail damage 3 years of tests would be needed to establish (at an acceptable significance level) that the seeding is effective; 9 years for 40%, but 47 years if the seeding is only 20% effective! (For areas of lower hail frequency, much longer times would be needed, e.g., for Illinois a similar study calculates 7, 18 and 100 years in the three cases mentioned.) Hence in general, and except for seeding of very high effectiveness, horrendously long periods appear to be required: no wonder that not many such experiments can be carried out! Moreover, the statistical

[2]P.T. Schickedanz and S.A. Changnon, in a report of the Illinois State Water Survey to NHRE, 1970.

analysis usually prohibits changes in the seeding methods during the experiment, so that many years of experiment allow the evaluation of only one approach. To study improvements in the method, one would need to do other experiments of comparable duration! Similar problems arise when the method is to be transferred to another geographic area.

In practical terms, we must therefore conclude that reliable methods of verification are not readily available. There is no adequate *theory* that covers the long chain of events from the AgI burner to the change in the hail fall-out; neither has it been possible to *observe* all the events as they unfold; and the statisticians prescribe conditions and durations which are long and expensive, probably unacceptably so in many places. This is a bleak picture. Can it be improved? It is just possible that less stringent statistics, *combined* with the closest possible physical monitoring, with improved theory of nucleation and with improving notions of precipitation and storm dynamics could – if pursued all at the same time – turn out to be more convincing and more promising than attempts at acceptable levels of significance in each one of these three approaches. As any one approach makes a given result look likely, more modest levels of significance or reliability would be needed for the others – if they supported each other. At present no adequate and generally accepted theory for such trade-offs exist; maybe it can be constructed. Unfortunately in weather modification there has long been an ill-tempered debate between believers and agnostics, between wishful thinkers and often unhelpful critics. Nothing is needed more badly than clear evaluation by techniques beyond dispute.

5 Different conclusions

At present, no other position behooves the *scientist* than that of agnostic. Claims of success have been widely made by seeders and by farmers, and many of us have wished ardently to believe and to find supporting evidence. But until it is found and meets objective standards of credibility we must remain doubting Thomases. In this matter more than in others: the likelihood of public enthusiasm requires a cool judgment, and there is no one else to give it. It follows that scientists should not endorse or conduct any seeding operation lacking a credible chance of verification. And they should push for quantitative concepts for the proposed process.

By contrast, many *farmers* and other practical men will argue that seeding is "cheap". If only somewhat successful, seeding will pay for itself; the fact that we do not know whether it pays or not, only means that we should look at it as a form of insurance – like taking vitamin C when one fears a cold coming. Thus the farmer is apt to demand that public authorities seed, or he may hire the seeder himself.

The *politician* will give, or will not give, public support for such operations, depending on the political strength of the farmer, as opposed to other pressures. The *civil servant* behind the politician has a harder time: he hears the farmer and follows his argument. But he should have the broader picture in mind – the economy, the social and political context, and harder still, he must remember what the scientist tells him: every operation (without adequate physical concept and verification) increases the noise of the system, and further obscures the elusive truth. Whatever the political or other advantages of seeding, there will be no clarification of issues and no improvement of the method for the future.

In thus trying to appreciate the attitudes which might be adopted by different groups, I have quietly made one very widespread and rarely questioned assumption, namely that seeding will do no harm. This assumption is not justified however. If it is true – as I have argued – that we cannot tell whether seeding is 10% or even 40% effective, we also cannot tell whether it is 10% or 40% counter-productive! Certainly, there are qualitative suppositions as to why seeding might often increase hail. I don't necessarily believe them, but they are as convincing as are the hopes to the contrary. It has been argued that seeding may be justified purely for its psychological effects which are likely to outweigh any physical damage it may do. Such "benefits" could indeed be important in the short run. Yet I cannot accept the argument: a placebo may make a patient feel better and so enhance his powers of recuperation. But no sense of well-being of seeders and farmers will reduce the hail. And where will scientists, politicians and civil servants stand when it is discovered that there is no Santa Claus?

I am afraid it is as cruel as this: without a finely elaborated theory or detailed observations or meticulous and protracted statistics, we just cannot tell what seeding does. As long as this condition prevails, any rational justification of the apparently opposite positions of farmers and scientists really disappears: there should be agreement to stop routine seeding! If I convey a sense of dejection, the Tashkent meeting inspired it. It demonstrated clearly that after some 20 years we are still in a most unsatisfactory position. But there was much candour at the meeting and the recognition that things must change. Whether this will be in the direction of mixed techniques of verification or whether really bright new ideas will be forthcoming I do not know. The Soviet scientists who had pioneered importantly in seeding technology and who remain strongly committed to solving the problems they have posed realize as much as anyone that the days of rough and ready verification, based too much on the optimism of farmers, engineers and scientists, are gone.

6 Cloud seeding and weather modification

These concepts are not coterminous. Unfortunately public enthusiasm and funding policies over many years have made it appear so, with the result that hardly any ideas for ameliorating the weather other than AgI seeding have been produced. This is serious for it is possible that with current seeding techniques we are in a cul-de-sac. If weather modification is really a socially desirable goal other approaches should be tried. (The standard approach to deal with polio through the Fifties was to provide better wheel chairs; biochemistry provided a better way.)

7 ALHAS

Whether under this old name or not, large-scale seeding for hail suppression operations are planned by the Government of Alberta for much of central Alberta for 1974 to 1978. Funds and opportunities for research also exist, at least for the area north of Red Deer. In the light of my remarks, the elaboration of a promising mix of research, verification and seeding will not be easy. But it is an opportunity for scientists to design, or experiment with, methods of verification, and with new approaches to hail suppression. It will not be easy; if it were, it would have been done already.

BOOK REVIEW

COMPRENDRE, INTERPRÈTER, APPLIQUER—LA MÉTÉOROLOGIE. Par Paul Devuyst. Editions Eyrolles – Paris – 1972, 164 pp. Paul de Visscher, éditeur. (Bordas-Dunod, Montréal Inc. $20.50)

L'auteur de cet ouvrage est le chef du service météorologique de la force aérienne belge. Le livre de 168 pages (24 × 32 cm) qui est vraiment bien fait en pleine toile, contient quelques 100 photographies dont 40 en couleurs ainsi que 145 tableaux. Le texte scientifique exact est adapté au niveau du technicien météorologique avancé ou du pilote aérien désireux d'approfondir ses connaissances météorologiques. Utile aussi à tous scientifiques non-météorologistes qui ont besoin d'une connaissance en météorologie et aux amateurs scientifiques intéressés à la météorologie et à ses applications. Les météorologistes professionels trouveront cet ouvrage très intéressant mais probablement trop rudimentaire pour augmenter leurs connaissances scientifiques. C'est pourquoi je trouve que ce livre devrait occuper une place de choix dans nos bibliothèques et nos écoles de météorologie.

Le livre se divise en deux parties – théorique et appliquée. Dans la partie théorique, l'auteur ne fait appel qu'à peu de mathématiques. Les concepts du calcul infinitésimal sont absents dans le texte. Ceci a l'avantage d'éviter les contre-sens reliées quelquefois à l'usage de méthodes trop simplistes en ce domaine. Par contre une mise au point de ces concepts est réalisée grâce à de simples explications basées sur quelques idées fondamentales non-mathématiques. Des graphiques clairs et précis remplacement avantageusement l'appareil mathématique. Les treize chapitres de cette première partie traitent l'atmosphère, la pression, le rayonnement et la température, l'eau dans l'atmosphère, le vent, les nuages, le brouillard et les précipitations, les masses d'air, les fronts et les perturbations, l'orage, les météores, la turbulence et le courant jet.

La partie théorique m'a beaucoup plu parce que l'exposé est simple, précis et surtout exact. La définition de la troposphère (p. 16) est un peu déconcertante. Il écrit, "la troposphère est la portion de l'atmosphère en contact avec la surface terrestre". Je trouve inutile de citer la liste (p. 96) des noms féminins des ouragans dés 1969 jusqu'à présent. On peut parler de l'ouragan Camille (1969) sans devoir se referér à une liste complète. Le chapitre XIII "Le courant jet" est trop court à mon avis. L'auteur devrait signaler l'existence de plusieurs courants jets. De plus quelques cartes de 300 mb (par exemple) pourrait être utilisées pour illustrer l'étendue horizontale et le déplacement des courants jets.

La deuxième partie, "la météorologie appliquée" consiste de cinq chapitres de 35 pages intitulés: observations et transmissions, les cartes météorologiques, les prévisions, l'impor-

Continued on page 202

A Source of Hail Embryos

J. Stewart Marshall and Walter Hitschfeld
McGill University
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In consideration of the growth of hailstones, one difficulty encountered is to find or devise an environment rich enough in liquid water. A sufficient liquid water content may be "found" in the form of rain, but at temperatures for which rain can be expected to exist as a liquid, the resultant hailstone would be in large part liquid and only in small part solid.

To obtain an environment at once rich enough and cold enough, English (1972, 1973) took a rapidly rising column of cloud – assuming that no larger-than-cloud hydrometeors would form by normal precipitation processes – to quite a great height and quite a cold temperature (English mentions values of 8 to 10 km and −35 to −40C). In that situation the fraction of the liquid water content that was lost by freezing was negligible, and so a rich yet cold environment of liquid water was achieved. It was for this environment that she postulated the existence of drops of various diameters from 0.1 to 5.0 mm, all well beyond cloud droplet size, as hail embryos, in number density small enough to yield the small number density of hailstones. These grew (on paper) in satisfactory fashion, to yield hail in reasonable resemblance to observations, without much difficulty arising from the liquid fraction of the stone being too high.

English makes a double assumption about precipitation particles (drizzle or rain drops, or the same frozen, or graupel) as distinct from cloud droplets: (i) that they are absent in the large number densities that would result from normal precipitation processes; (ii) that they are present in the much smaller numbers appropriate to hail. Assumption (i) is supported by theoretical work of Leighton and Rogers (1974). They found the normal precipitation process to proceed slowly enough that, over the required ranges of height and temperature, and with a strong updraught, most of the mass of condensed water remains in the form of supercooled cloud droplets.

It is with regard to assumption (ii) that the present note is written. We have for some time held some misgiving, that excellent work being done on the investigation and consideration of the regions of intense updraughts in showers was not being paralleled a little more obviously by consideration of the remainder of the shower. In that situation, it was our reaction to the problem of the source of hail embryos, our eventual rather than immediate reaction, to look to the "remainder of the shower" to provide these embryos in the form of graupel or raindrops, their number densities suitably reduced by dilution in the migration process into the region of strong updraught.

It is some years now since this view was put forward within the Stormy

Weather Group. Since then, Leighton and Rogers have done the work mentioned above in relation to assumption (i), and are considering the development of small precipitation drops or particles (assuming low number density) to large ones. Regarding our proposal for assumption (ii), however, two sorts of things remain to be considered: (a) in terms, say, of radar records, the juxtaposition of regions of graupel and/or rain generation to strong-updraught "vaults"; and (b) in theoretical terms, possible migration processes for the graupel or rain, with an appropriately large dilution of number density.

In our proposal of a source of hail embryos, are we not just using new language to describe the re-entrant process for hail growth suggested by others? If we change that question to read "are we not proposing one more re-entrant process", it is possible to answer with a definite "yes", but we suggest that it differs considerably from the other "re-entrant" suggestions taken as a class. The first cycle, in our case, took the hydrometeor only as far as raindrop or more likely graupel, as a member of a group having high number density, not necessarily in the updraught of the second cycle, and more likely elsewhere. The first cycle differed in no way from the precipitation process, or an aspect of the precipitation process, found in any shower. To make large hail, the product of that ordinary first cycle finds its way, very much diluted, into an extraordinarily strong updraught offering for a suitable length of time the cold-temperature high-liquid-water-content cloud in which the graupel or frozen raindrop can grow rapidly as hail, without the stones acquiring a liquid-water content, at least not one that would lead to shedding, or destroy the mechanical integrity of the stone.

Large hail is observed to have a narrow distribution with diameter, and a very low number density, in comparison with rain. In the process proposed by English (1973), the number density is established by the number of embryos. (Narrowness of distribution would then be attributable to the near-sameness of trajectory and growth experience along it for all the stones.) This note reports a suggestion as to the source of the embryos: that they are raindrops and/or graupel particles that have grown in cumulus cloud outside but adjacent to the strong updraught in which embryos grow to hail, and then had migrated by turbulent diffusion into that updraught, their number density being greatly reduced in the process.

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Hydrometeorology in the Atmospheric Environment Service

T.L. Richards
Atmospheric Environment Service, Toronto
[Manuscript received 26 November 1973]

1 Introduction

Hydrometeorology is defined in the Encyclopaedic Dictionary of Physics as "the application of meteorology to hydrological problems". By this definition the Canadian Atmospheric Environment Service (AES) and its forerunner, the Meteorological Service of Canada, have been providing a variety of hydrometeorological services for a good many years. However, it was not until after the memorable visit of Hurricane Hazel to Southern Ontario in October 1954 that an identifiable and continuous hydrometeorological effort has been undertaken.

It is a matter of record that in Ontario the arrival of Hurricane Hazel was a well-forecast meteorological event, yet scores of lives were lost and millions of dollars damage resulted. This disaster was due, at least in part, to the fact that there was no one to translate a set of meteorological conditions into a set of hydrological conditions. This was not just a matter of translating the meteorological forecast into a flood warning at the time of the event. It was also the equally important matter of establishing, at an earlier date, the critical meteorological conditions deemed to be possible for the area – information so necessary for the establishment of engineering design criteria for dams, bridges and culverts and for safe town planning and proper zoning regulations.

In 1955, as a direct result of Hurricane Hazel, Dr. Andrew Thomson, then the Director of the Meteorological Service of Canada seconded meteorologist J.P. Bruce to the Conservation Authorities Branch of the Ontario Government where he quickly established the reputation as a highly respected hydrometeorologist and tireless worker. It soon become evident that what Jim Bruce was doing on a provincial scale should also be undertaken on a national scale. As a result, in 1958 he was brought back to the Meteorological Service of Canada Headquarters to organize and head a new Hydrometeorology Section. He was replaced in the provincial department by meteorologist D.M. McMullen who has since also built a solid reputation as a hydrometeorologist. In 1970, by agreement between the two governments Don McMullen transferred to the provincial department.

The new Hydrometeorology Section was placed in the Climatology Division then under the leadership of C.C. Broughner. This location was chosen primarily because the necessary data were held in the Division's archives and the equally necessary computer was located in the Climatology Data Processing Unit.

2 Hydrometeorological Services

The first activities of the new Section included hydrometeorological analyses of all the major Canadian storms on record and the identification of the probable maximum storm precipitation for selected areas of Canada – this latter for the development of engineering design criteria. Of equal importance was the establishing of short duration rainfall statistics required for the design of storm sewer and other drainage systems. Particular attention was also given to the development of the tipping bucket raingauge network and the evaporation pan network and to the analysis of the resulting data. Special studies of critical meteorological conditions were undertaken for a number of major river basins where new dams or hydrologic operations were planned, viz., the Columbia, Fraser, Peace, St. John, Churchill, and Bay d'Espoir (Newfoundland). This area of work eventually became the responsibility of the Hydrometeorological Services Unit which has had the successive good leadership of Ulrich Sporns, D.M. Sparrow and the present head D.M. Pollock.

While continuing the original activities of the Unit a new thrust has appeared in the area of radar climatology. Under Dave Pollock's guidance a system has been devised that will eventually have composite low-level radar photographs taken at 15-min intervals from ten sites across Canada. These photographs will be archived in the Unit where a Precipitation Data Integrator has been developed for digitizing and analyzing the radar information in terms of precipitation amounts.

3 Lakes Investigations

In 1961 the Hydrometeorology Section was expanded to include a Lakes Investigation Unit under T.L. Richards. This Unit was given the responsibility for investigating the effects, not only of lakes on the weather of the surrounding land areas, but also of meteorological elements on the lakes themselves. The Lakes Unit worked closely with the Great Lakes Institute of the University of Toronto, at that time the major force in Canadian Great Lakes research. Early undertakings included cooperative programs: at the nuclear reactor site at Douglas Point and at the Institute's Field Station at Baie Du Dore, both on Lake Huron; also on the research vessel CCGS Port Dauphine. More recently cooperative programs have been undertaken with the Canada Centre for Inland Waters and the Ontario Ministries of the Environment and Natural Resources. The ultimate in cooperative programs was the International Field Year for the Great Lakes (IFYGL), the data collection phase of which was completed in the spring of 1973.

The Lakes Unit's first efforts were directed toward the effect of precipitation and evaporation on the levels of the Great Lakes. This led to extensive studies of evaporation losses from the lakes which required an improved knowledge of surface water temperatures. This, in turn, led to a highly successful Airborne Radiation Thermometer (ART) program which regularly measures surface water temperatures of the lakes from an aircraft using the infrared thermometer technique. Other work has included exploitation of the data collected by the CCGS Port Dauphine and featured studies concerned with over-lake/over-land ratios of wind, humidity and incoming radiation. Other major studies dealt with the climatology of ice cover and synthesized over-lake winds and waves.

In 1966 when Jim Bruce became Director of the new Canada Centre for

Inland Waters at Burlington, Lloyd Richards replaced him as Superintendent of the Hydrometeorology Section and in 1967 J.A.W. McCulloch arrived to head the Lakes Unit. Under Jim McCulloch the Unit widened its activities in the areas of wave climatology and of wind-driven set-up and storm surges on the Great Lakes and the Atlantic and Pacific. D.W. Phillips spear-headed the climatological efforts of the Unit culminating in a volume, *The Climate of the Great Lakes Basin* (with McCulloch). J.G. Irbe is now in charge of the ART program and has published extensively dealing with surface-water temperature patterns on the Great Lakes. M.S. Webb is responsible for special lakes projects. His work has included the temperature regimes of the Great Lakes and many smaller lakes in Northern Ontario, the effects of the Niagara River ice boom on navigation and the potential effects of cloud seeding on the hydrology of Lake Erie (with D.W. Phillips).

4 Hydrometeorological Projects

In 1965 the Hydrometeorological Section was further expanded to include a Hydrometeorological Research Projects Unit. The impetus for its formation was the International Hydrological Decade which began that year. The first responsibility of the Unit, started by H.F. Cork, was to organize the supply of meteorological instruments for the projects which were undertaken as part of Canada's participation in the Decade. Advice regarding the proper meteorological variables to measure, what instruments to use, and suitable siting and network planning proved an important part of this service. At one time during the Decade more than sixty projects were receiving support from AES through this Unit. In fifteen of the projects meteorological considerations were of major importance. These were sponsored by the AES and the investigations and analyses were directed by the Unit. This phase of the work began with the arrival of H.L. Ferguson in 1966 as Head. A wide range of problems was examined, including: (1) a study of topographical factors in the areal distribution of precipitation in British Columbia; (2) the energy budget and formation of ice in the upper Niagara River; (3) the possibility of using the flux of tritiated water from a small water body (Perch Lake) as an independent measure of evaporation; (4) an assessment of the value of weather satellite data for hydrological purposes; and (5) the areal variability of precipitation in a flat grassland area. Investigations in these and other projects were assisted by A.D.J. O'Neill (1967–1973), by D.G. Schaefer (1970–1971), and also by H.F. Cork throughout the entire period.

One of the most important groups of projects concerned the supply of water flowing eastward from the Rocky Mountains. The principal site was Marmot Creek, where, after a calibration period, selective cutting of a mature spruce forest will be carried out to discover the best means to increase water yield with minimum ecological damage. D. Storr, working out of Calgary, has done most of the on-site research for these projects.

5 Hydrometeorological Research

With the reorganization of the AES in 1972 a new Hydrometeorological Research Division was established in the Atmospheric Research Directorate. The original component – now called the Hydrometeorology and Marine Applications Division – remained in the Central Services Directorate under T.L. Richards as Chief. A number of staff members from the Special Projects (IHD) Unit formed the nucleus of the new Division and H.L. Ferguson was appointed Acting Chief.

Hydrometeorological research can be defined as the study of all meteorological processes affecting the hydrological cycle. While the emphasis is on an understanding of physical processes, the new Division is highly conscious of its role in research and development for improved meteorological services to hydrology, and shares common objectives with the Hydrometeorology and Marine Applications Division. Staff members include G. den Hartog and B.E. Goodison and the Calgary Hydrometeorological Research Unit under Don Storr.

The development of computerized techniques in hydrometeorological basin research, initiated by the Hydrometeorological Research Projects Unit in the late Sixties, is continuing in the Hydrometeorological Research Division. The Division has completed grid-square water balance models of mean precipitation and evapotranspiration over the Okanagan Basin as the AES contribution to a multi-disciplinary Federal-Provincial project. A pioneering aspect of the models is that the meteorological variables are directly related, in a detailed rational fashion, to physiography and surface cover, and optimized for consistency with the hydrological elements of water balance equations. This basic technique is also being applied on a large-grid national scale and co-operative studies with the University of Toronto have provided data on the cover characteristics of the country for newly-published maps in *The National Atlas of Canada*.

The Division has also developed an automatic recording and telemetering station which has been successfully interfaced with the Earth Resources Technology Satellite. One station has been installed in Northern Ontario and a second is about to be installed in the Fraser River Basin in British Columbia, in co-operation with Environmental Management Service, DOE. These stations provide a new capability for obtaining meteorological and hydrological data from remote areas in "real time".

The Division has an established competence in the applications of remote sensing to hydrometeorology. One project of this type is a recently completed study of the use of an airborne gamma-ray spectrometer for snow surveying and, potentially, for soil-moisture surveying. Support was also provided to a co-operative program spear-headed by the Geological Survey of Canada and the Environmental Management Service.

6 Education

An important role of both Divisions is the support and guidance of post-graduate work in hydrometeorology. At the present time the staff is involved in the thesis work of one M.SC. and five PH.D. candidates. Staff members also provide a lecture course on hydrometeorology at the University of Toronto.

7 Regional activities

With the gradual expansion of the hydrometeorological components within Headquarters came a similar expansion of services at the regional level. An early step in this direction came with the secondment of G.A. McKay to PFRA Headquarters in Regina. From 1959 to 1966 Gordon McKay became well known as the hydrometeorological expert in the Prairies conducting an active program in all phases of the science. A change in the secondment policy led the Meteorological Service, in 1967, to establish a Prairie Hydrometeorological Office at Regina under the able leadership of S.J. Buckler. This office, although administered under the AES Central Region, has acknowledged responsibilities as well in the AES Western Region and was designed to service all the hydrologic and water resources interests in the Prairie Provinces. Technical channels to Headquarters remain through the Hydrometeorological and Marine Applications Division. More recently W.C. Thompson was temporarily assigned as a hydrometeorologist to the Prairie Provinces Water Board's Project Office in Calgary after a brief tour by W. Pogue. This position received close-in support from the Regina office with backup support and line direction from the Hydrometeorology and Marine Applications Division.

With the formation of the Scientific Support Units in the six AES Regions across Canada a number of meteorologists have, to varying degrees, been assigned hydrometeorological responsibilities. Although within the operational framework of the AES Field Service Directorate, technical channels are open directly to the Headquarters hydrometeorology components to assure a free exchange of information.

8 International activities

The AES hydrometeorological components also have an active role in international activities. Jim Bruce represented Canada at the first sessions of the World Meteorological Organization's Commission for Hydrometeorology, CHy I in 1961, and CHy II in 1964. During this time he served on the Working Group for Technical Regulations and Guide to Hydrometeorological Practices. Lloyd Richards followed at CHy III in 1968, CHy IV in 1972 and WMO Technical Conference of Meteorological and Hydrological Services in 1970. At the present time Howard Ferguson is the CHy Rapporteur on the Applications of the World Weather Watch to Hydrology and Dave Pollock is the Rapporteur on Areal Precipitation.

Jim Bruce was also one of the early organizers of the global UNESCO International Hydrologic Decade program attending preparatory meetings in 1963 and 1964. Lloyd Richards continued by participating in the Mid-Decade Conference in 1970 and the 1971 IHD Coordinating Council meeting which was responsible for the early planning of the new International Hydrological Program.

9 Summary

Canada's national meteorological service has always had hydrometeorological responsibilities. However, it took the disaster of Hurricane Hazel superimposed on the floods of the Fraser (1948) and the Red Rivers (1950) and the enthusiastic leadership of J.P. Bruce to first crystallize these activities into a viable organization. Today, thanks to the dedicated work of a relatively small group of scientists the Atmospheric Environment Service has a system of regional hydrometeorological specialists backed up by a Headquarters' centre of competence to supply a service which is recognized nationally and internationally as second to none.

Book Review continued from page 194

tance de la météorologie appliquée et l'avenir. Cette partie est de beaucoup trop courte pour l'exposition des divers problèmes importants sur ce sujet. Il y a beaucoup de détails sur le système de pointage et le dessin des cartes et peut-être trop sur les codes, formes et symboles qui sont déjà désuets. Il serait mieux qu'on obtienne les renseignements de ce genre dans les publications de l'OMM ou de celles des services météorologiques nationaux. Un livre comme celui-ci ne peut rester à jour longtemps au sujet des codes, etc.

Par contre le chapitre ce qui a trait à l'importance de la météorologie appliquée est une initiation vraiment utile. Il contient entre autre un exposé de divers problèmes météorologiques reliés à l'homme et son milieu, tels la pollution, la pathologie des grandes villes, l'énergie, l'agriculture, les loisirs, les transports, etc. Je regrette que l'auteur n'ait pas écrit trois ou quatre chapitres à ce sujet au lieu d'un seul.

Il y a six appendices intitulés, l'atmosphère standard, prévision de dissipation du brouillard, classification des cristaux de glace, observations météorologiques et leurs codes, pointage des cartes et problèmes particuliers à l'aviation. Ce dernier donne un très bon aperçu des problèmes de la météorologie aéronautique et l'auteur est bien compétent pour nous renseigner sur ce sujet. Je n'estime pas que les autres appendices soient vraiment très utiles (utiles sans doute pour les spécialistes) au but général de ce livre.

Chose qui m'a agacée un peu sont les fautes d'orthographe (ou bien une mauvaise correction des épreuves) au sujet des noms de météorologistes renommés. On trouve, par exemple, dans le texte et dans la bibliographie, l'orthographe fautive comme NARGULES, HASSELBERG, LOOMS, GLASHIER, HAURWITZ G., PETTERSEN, VAN MIEGHEN et une drôle de gaffe MAC GRAW-HILL BOOK CY., etc. Chose infime, en verité, mais agaçante quand même dans un si beau livre comme celui-ci. Je laisse aux lecteurs le loisir de corriger l'orthographe. Si ce n'est pas évident à première vue aux météorologistes, j'admettrai alors être trop exigeant.

Cependant, à toute fin pratique, il faut juger la valeur de ce livre d'après son contenu météorologique et je crois que pour cette raison ce livre aura du succès.

C.M. Penner
Atmospheric Environment Service
Toronto

Kelvin-Helmholtz Billows – A Visual Example

K.D. Hage[1]
Atmospheric Environment Service, Toronto
[Manuscript received 30 November 1973]

Several documented cases of breaking waves in the atmosphere have been reported in recent years. An excellent summary of this work and some new examples can be found in Browning *et al.* (1973). However, relatively few visual sightings have been published, perhaps not because they are rare, but for lack of quantitative data or suitable conditions for photography.

Sequential photographs of breaking wave clouds are shown in Figs. 1a, b, and c. The photos were taken at 1905 (1a), 1912 (1b), and 1917 (1c) MST on March 17, 1973 at Devon, ALTA. Fig. 1c was taken with a telephoto lens (magnification 2.6 relative to Figs. 1a and 1b). Radiosonde data were collected between 1615 and 1645 MST in the lower atmosphere over Stony Plain, ALTA. about 25 km west-northwest of the viewpoint. The photos were taken towards 290°. Winds at cloud base were estimated to be from 240° at 12 m s^{-1}. The translatory motion of the waves and the apparent breakaway of a cloud fragment at the crest of the third wave from the right are quite evident from the photos. Airflow as reflected by cloud appearance seemed to be most turbulent in and below the wave crests.

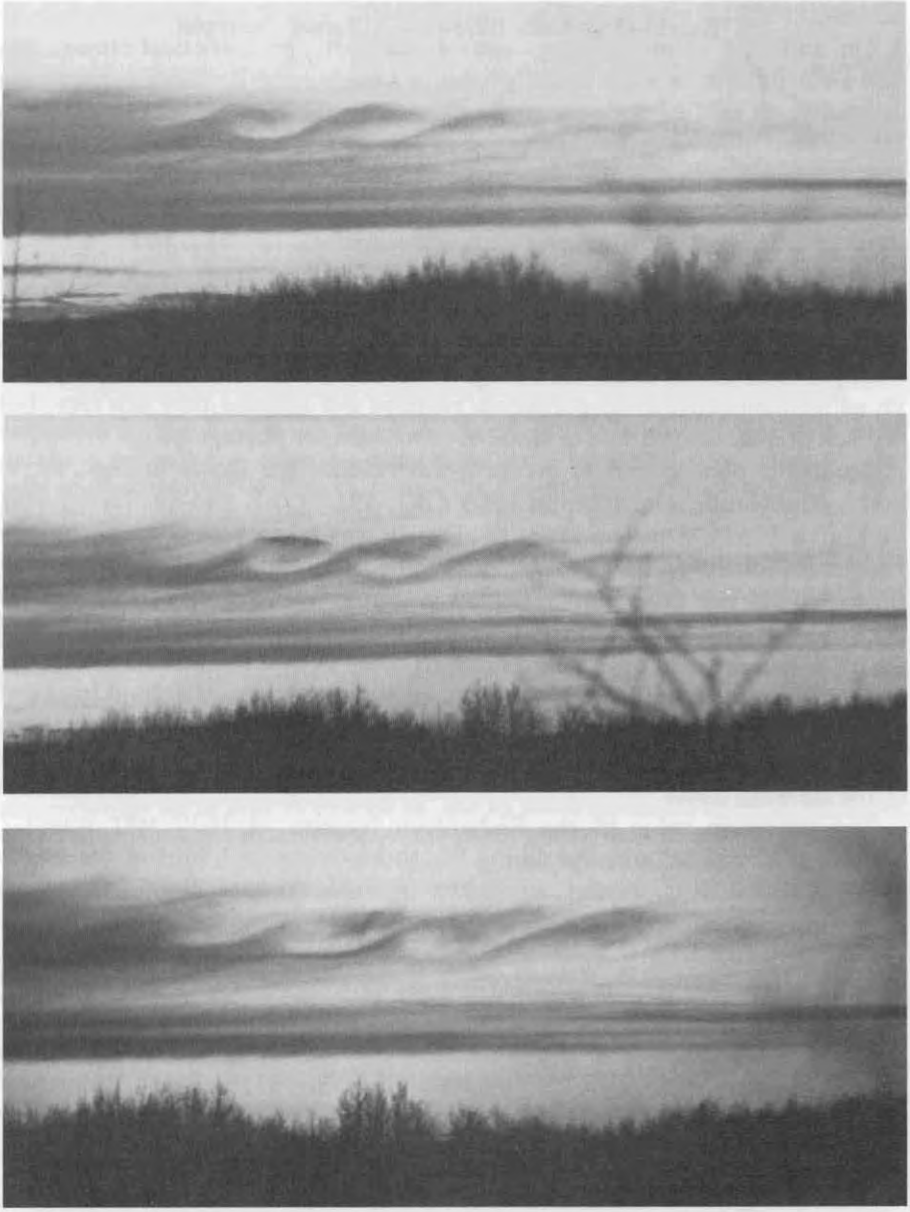
The minimum value of the Richardson Number at 1630 MST was 1.2 (400-m layer) at 3.7 km. Assuming this to be the mean height of the waves at 1900 MST, the characteristics shown in Table 1 were derived from the photos and radiosonde data.

TABLE 1 Inferred and observed wave characteristics.

Mean crest-to-trough amplitude	760 m
Mean wavelength	2.8 km
Mean wave speed	12 m s^{-1}
Speed of crest cloud fragment relative to wave speed	1.8 m s^{-1}
Wind shear required for critical Ri = 0.25	2.0 m s^{-1} $(100\ m)^{-1}$
Maximum radiosonde wind shear (400-m layer)	0.9 m s^{-1} $(100\ m)^{-1}$

The characteristics in Table 1 are comparable to those reported by Browning *et al.* (1973) and others except that the implied shear is low. However, because of the small scale and short lifetime of breaking billows the use of radiosonde data not taken at the exact time and site of the phenomenon is at best a questionable procedure.

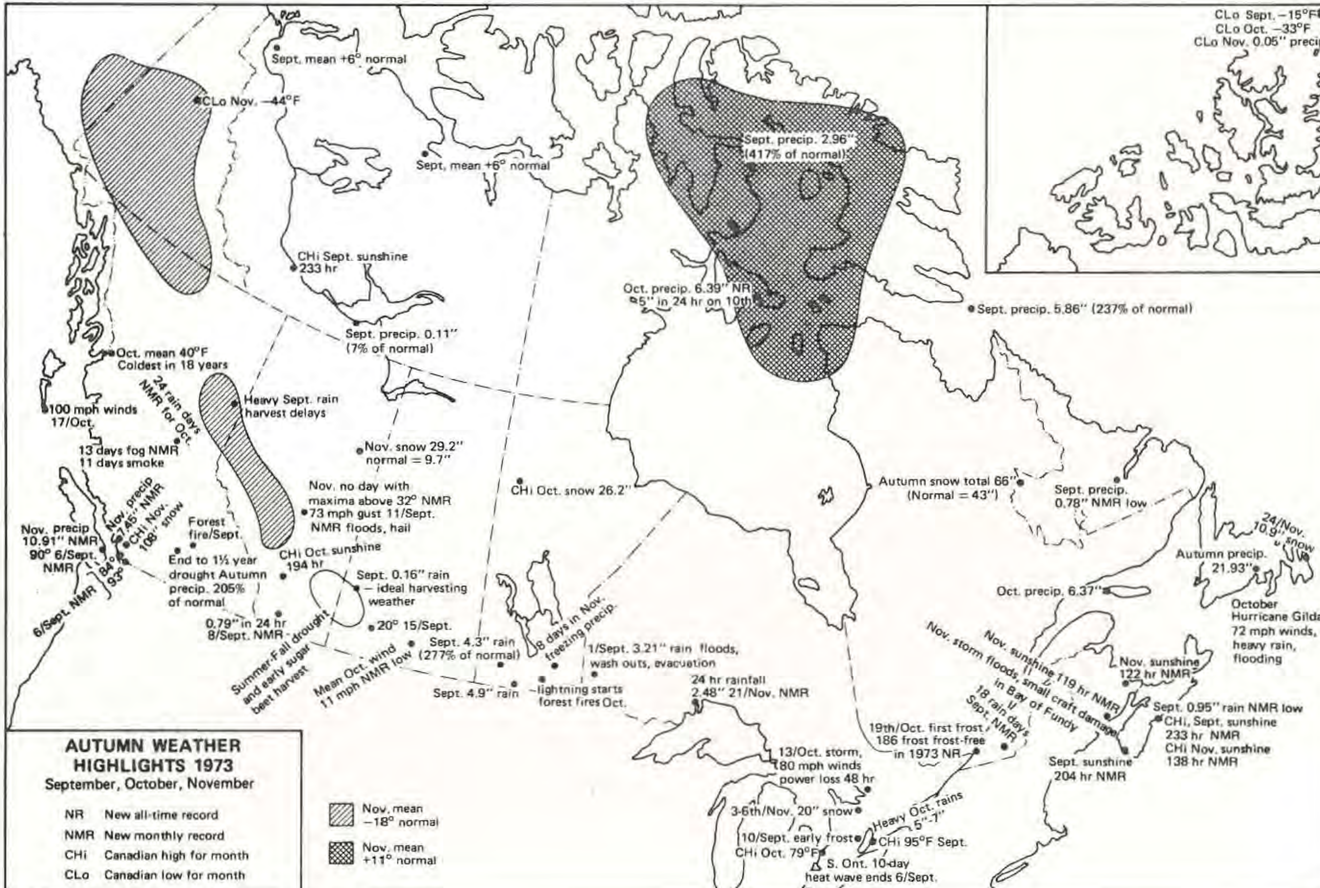
[1]On leave from the University of Alberta.



Figs. 1a, b, c from top.

Reference

BROWNING, K.A., G.W. BRYANT, J.R. STARR and D.N. AXFORD, 1973: Air motion within Kelvin-Helmholtz billows determined from simultaneous Doppler radar and aircraft measurements. *Quart. J. Roy. Meteorol. Soc.*,**99**, 608–618.


AUTUMN WEATHER HIGHLIGHTS 1973
September, October, November
NR New all-time record
NMR New monthly record
CHi Canadian high for month
CLo Canadian low for month
Nov. mean −18° normal
Nov. mean +11° normal
CLo Sept. −15°F
CLo Oct. −33°F
CLo Nov. 0.05" precip.
Sept. mean +6° normal
CLo Nov. −44°F
Sept. mean +6° normal
Sept. precip. 2.96" (417% of normal)
CHi Sept. sunshine 233 hr
Oct. precip. 6.39" NR 5" in 24 hr on 10th
Sept. precip. 5.86" (237% of normal)
Sept. precip. 0.11" (7% of normal)
Oct. mean 40°F Coldest in 18 years
24 rain days NMR for Oct.
Heavy Sept. rain harvest delays
100 mph winds 17/Oct.
13 days fog NMR 11 days smoke
Nov. snow 29.2" normal = 9.7"
CHi Oct. snow 26.2"
Autumn snow total 66" (Normal = 43")
Sept. precip. 0.78" NMR low
Nov. no day with maxima above 32° NMR
73 mph gust 11/Sept.
NMR floods, hail
Nov. precip 7.45" NMR
CHi Nov. 108" snow
Nov. precip 10.91" NMR
90° 6/Sept. NMR
84°
93°
6/Sept. NMR
Forest fire/Sept.
End to 1½ year drought Autumn precip. 205% of normal
CHi Oct. sunshine 194 hr
Sept. 0.16" rain – ideal harvesting weather
24/Nov. 10.9" snow
Autumn precip. 21.93"
Oct. precip. 6.37"
October Hurricane Gilda 72 mph winds, heavy rain, flooding
0.79" in 24 hr 8/Sept. NMR
20° 15/Sept.
Summer-Fall drought and early sugar beet harvest
Mean Oct. wind 11 mph NMR low
Sept. 4.3" rain (277% of normal)
8 days in Nov. freezing precip.
1/Sept. 3.21" rain floods, wash outs, evacuation
Sept. 4.9" rain
lightning starts forest fires Oct.
24 hr rainfall 2.48" 21/Nov. NMR
Nov. storm floods, small craft damage in Bay of Fundy
Nov. sunshine 119 hr NMR
18 rain days Sept. NMR
Nov. sunshine 122 hr NMR
Sept. 0.95" rain NMR low
CHi, Sept. sunshine 233 hr NMR
CHi Nov. sunshine 138 hr NMR
19th/Oct. first frost 186 frost frost-free in 1973 NR
Sept. sunshine 204 hr NMR
13/Oct. storm, 80 mph winds power loss 48 hr
3-6th/Nov. 20" snow
Heavy Oct. rains 5"-7"
10/Sept. early frost
CHi 95°F Sept.
CHi Oct. 79°F
S. Ont. 10-day heat wave ends 6/Sept.

Atmosphere

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Section B: CMS subject index
Section C: General subject index

Figures in italics refer to 7th Annual Congress issue of *Atmosphere*.

Section A: Index of Contributions by Author

Section B: CMS Subject Index

Section C: General Subject Index

NEW EDITORIAL ADDRESS

Editorial correspondence and manuscripts for *Atmosphere* should be sent to the following address:

Dr. I.D. Rutherford
Editor, *Atmosphere*
Dynamic Prediction Research Division
5th Floor, West Isle Office Tower
2121 Trans-Canada Highway
Dorval, P.Q. H9P 1J3

CALL FOR PAPERS – EIGHTH ANNUAL CONGRESS

The Eighth Annual Congress and Annual General Meeting of the Canadian Meteorological Society will be held at York University, Toronto, Ontario, May 29–31, 1974. The theme of the Congress will be *Meteorology and the Community* and it is intended to emphasize the interface between meteorologists and the general public. Papers on weathercasting, urban meteorology and other aspects of the theme topic are particularly invited. Sessions will be held on cloud physics, dynamic meteorology, weather forecasting, micrometeorology, atmospheric electricity, remote sensing and other aspects of meteorology depending on contributions.

Members and others wishing to present papers at this meeting should send titles and definitive abstracts (preferably less than 300 words) to the Program Chairman, Dr. G.A. McBean, Atmospheric Environment Service, 4905 Dufferin Street, Downsview, Ontario, M3H 5T4, no later than **March 1, 1974.**

Information on registration, accommodation, etc. can be obtained by consulting *Atmosphere* and the CMS Newsletter or by writing R.A. Miller, the Local Arrangements Chairman, at the above address.

NOTICE TO CMS MEMBERS

Membership dues for 1974, as determined at the Seventh Annual Congress of the CMS, stand as follows:

General Member	$15.00
Student Member	$ 5.00
Sustaining Member	$50.00 (min.)

Contents

The Canadian Meteorological Society / La Société Météorologique du Canada

The Canadian Meteorological Society came into being on January 1, 1967, replacing the Canadian Branch of the Royal Meteorological Society, which had been established in 1940. The Society exists for the advancement of Meteorology, and membership is open to persons and organizations having an interest in Meteorology. At nine local centres of the Society, meetings are held on subjects of meteorological interest. *Atmosphere* as the official publication of the CMS is distributed free to all members. Each spring an annual congress is convened to serve as the National Meteorological Congress.

Correspondence regarding Society affairs should be directed to the Corresponding Secretary, Canadian Meteorological Society, P.O. Box 160, Ste-Anne-de-Bellevue, P.Q. H9X 3L5

There are three types of membership – Member, Student Member and Sustaining Member. For 1973 the dues are $15.00, $5.00 and $50.00 (min.), respectively. The annual Institutional subscription rate for *Atmosphere* is $10.00.

Correspondence relating to CMS membership or to institutional subscriptions should be directed to the University of Toronto Press, Journals Department, Front Campus, Toronto, Ontario, Canada M5S 1A6. Cheques should be made payable to the University of Toronto Press.

La Société météorologique du Canada a été fondée le 1er janvier 1967, en remplacement de la Division canadienne de la Société royale de météorologie, établie en 1940. Cette société existe pour le progrès de la météorologie et toute personne ou organisation qui s'intéresse à la météorologie peut en faire partie. Aux neuf centres locaux de la Société, on peut y faire des conférences sur divers sujets d'intérêt météorologique. *Atmosphère*, la revue officielle de la SMC, est distribuée gratuitement à tous les membres. À chaque printemps, la Société organise un congrès qui sert de Congrès national de météorologie.

Toute correspondance concernant les activités de la Société devrait être adressée au Secrétaire-correspondant, Société météorologique du Canada, C.P. 160, Ste-Anne-de-Bellevue, P.Q. H9X 3L5

Il y a trois types de membres: Membre, Membre-étudiant, et Membre de soutien. La cotisation est, pour 1973, de $15.00, $5.00 et $50.00 (min.) respectivement. Les Institutions peuvent souscrire à *Atmosphère* au coût de $10.00 par année.

La correspondance concernant les souscriptions au SMC ou les souscriptions des institutions doit être envoyée aux Presses de l'Université de Toronto, Département des périodiques, Campus Front, Toronto, Ontario, Canada, M5S 1A6. Les chèques doivent être payables aux Presses de l'Université de Toronto.

Council / Conseil d'Administration: 1973–74