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THE ROLE OF METEOROLOGY IN THE DETROIT-WINDSOR AIR POLLUTION STUDY

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Meteorological Service of Canada

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INTRODUCTION

Last December, newspapers carried the story of the most disastrous London fog on record. London and fog are associated in our minds. The thing that made this fog front page news and later a subject for parliamentary debate was that hundreds of people died as a result of the poisons suspended in the fog. What makes the situation even more interesting to us as meteorologists is that the only abnormal feature about the surrounding circumstances was the weather. Although it is evident that a lethal concentration of impurities was present in the air, there has been no suggestion that greater than normal amounts were being emitted at the time by the factories, homes, and trains. The stagnation of the air was so complete and so prolonged that the air became dirtier and dirtier until finally toxic levels were reached. The deadly fog continued to hang over London, killing off asthmatics and cardiacs, those least able to stand an additional strain, until weather again intervened. The air began to circulate freely again; the poisons were diluted; the fog thinned.

Something similar happened in the Meuse Valley in Belgium in 1932, and again at Donora in Pennsylvania in 1948. Air pollution has reached the irritation level in Los Angeles where lachrimation is experienced during smogs. It has reached the nuisance level in almost every large city. Until the smogs of the past winter at London, air pollution disasters had been confined to valleys where the valley walls helped to confine the pollution. Now, that rule of thumb has been broken. Will there be more air pollution disasters? There could be. So little is known about the physiological mechanism whereby a smog kills people, that each city has no precise idea how closely they are running to toxic pollution levels. In this large area of ignorance, the best we can do is adopt any available measures to keep pollution levels as low as possible, either by collection of wastes at the source, or by scheduling emissions in phase with the weather's capacity to eliminate them.

AIR POLLUTION IN CANADA

The history of air pollution in Canada includes such places as Trail, Sudbury, and St. Catharines. In 1938 the Canadian Meteorological Service commenced its first researches into the problem when it assigned Dr. Hewson to conduct a meteorological study for the Technical Consultants to the Trail Smelter Arbitral Tribunal. The National Research Council of Canada had been investigating the environmental and other aspects of the Trail pollution problem for a number of years in the 1930's with a team of experts under Dr. Morris Katz. Out of these investigations (1939) on the effects of sulphur dioxide on vegetation, and Dr. Hewson's work (1944), came the Arbitral Tribunal's program for meteorological control of air pollution at Trail, B.C. Other air pollution investigations followed at Sudbury, at St. Catharines, and now at Windsor, to name a few. Today in Canada the public and industry are becoming more and more concerned about the problem of air pollution. There is an investigation under way at Sarnia. There is another survey projected for the Oakville area. Hamilton is trying to decide if it wants to have a survey made. No doubt there are others. And in the absence of surveys, municipal control and abatement officials are planning and enforcing smoke codes in order to avoid a more serious situation.

One of the leading workers in the field of air pollution in Canada is Dr. Morris Katz (1939, 1949, 1952). During the past twenty years Dr. Katz has been identified with the Trail investigation, the Sudbury investigation, an earlier Windsor survey, and many others. His continuing interest in the problems of diffusion of gases, and the effects of gases on plants and humans made him the logical person to lead the Canadian section of the border air pollution investigation at Detroit and Windsor.

ORIGIN OF THE DETROIT-WINDSOR AIR POLLUTION STUDY

The Detroit-Windsor air pollution study came about in the following way. From April to the end of November the Detroit River is one of the busiest waterways in the world. 100 vessel-passages a day is a fair average. The vessels are frequently guilty of emitting large quantities of black smoke. Land-based stacks in Detroit and Windsor are compelled to abide by local codes which restrict the amounts of black smoke that can legally be emitted. But when smoke abatement officials of the two cities attempted to enforce their smoke codes on the vessels, they were advised that they had no jurisdiction over vessels plying the international boundary waters. Only the International Joint Commission, a treaty body formed by the United States and Canada, had jurisdiction over the vessels.

The cities of Detroit and Windsor appealed to their two federal governments for action to alleviate the obvious nuisance of the smoke from vessels. The two governments referred the matter to the International Joint Commission. The International Joint Commission is a treaty body consisting of three Canadians and three Americans, each of whom is appointed for life. The Commission does not employ technicians. When faced with a problem requiring the use of technicians, the two sections enlist technical help from their respective civil services and appoint a Technical Advisory Board. The Technical Advisory Board is also composed of three Canadians and three Americans. Dr. Morris Katz, as chairman of the Canadian Section of the Technical Advisory Board on Air Pollution, is responsible for the planning and carrying out of all phases of the Canadian contribution to the study.

To guide the Commission's Technical Advisory Board in its investigations, the two governments provided the Commission with detailed terms of reference. The following is extracted from the terms of reference:

> "The Commission is requested to enquire into and to report to the two Governments upon the following:
>
> "1. Is the air over, and in the vicinity of, the cities of Detroit and Windsor, on either side of the international boundary, being polluted by smoke, soot, fly ash or other impurities, in quantities detrimental to the public health, safety or general welfare of the

citizens, or to property interests on either side of the international boundary line?

"2. If the foregoing question, or any part thereof, is answered in the affirmative, to what extent are vessels plying the waters of the Detroit River, or any of them, contributing to this pollution; what other major factors are responsible and to what extent?

"3. If the Commission should find that vessels plying the waters of the Detroit River, or any of them, are responsible for air pollution to an extent detrimental to the public health, safety or general welfare of the citizens, or to the property interests on either side of the international boundary line,

"(a) What preventive or remedial measures would, in its judgment, be most practical from the economic, sanitary and other points of view?

"(b) What would be the probable cost of such measures?

"(c) By whom should such cost be borne?"

GENERAL STATEMENT OF THE POSITION OF METEOROLOGY IN AIR POLLUTION

The removal and dilution of man-made airborne wastes is a problem in diffusion. Under average meteorological conditions we can release substantial amounts of gaseous and particulate contaminants into the air, and be sure that they will not only be removed from the source region, but also quickly diluted, so that they will not present a serious nuisance or hazard to the neighbours. The ventilation of a polluted area by the inflow of clean air is easy to visualize. This is simply advection without diffusion. What takes place downwind from the source is diffusion, specifically Eddy Diffusion, because molecular diffusion does not begin to account for the dilutions that are observed.

There would be no problem if the extent of dilution by eddy diffusion were constant. But like every other meteorological element or process, eddy diffusion undergoes variations through a wide range, both periodically and at random. Corresponding variations in the pollution loading of the air take place. To the air pollution control official, or to the industrial hygienist, meteorology seems to offer the best hope of prediction of pollution loadings, so the meteorologist is called in early in any comprehensive air pollution study.

THEORETICAL ASPECTS OF THE DIFFUSION PROCESS

Theoretical discussions of turbulence and diffusion are to be found in most textbooks on meteorology. Sutton (1951) in a survey of the theory of turbulence and diffusion, outlines the many attempts to describe turbulent motion in mathematical terms, pointing out that the theories all break down at some point. The oldest theory used to explain turbulent motion is the Mixing-Length Hypothesis borrowed directly from the kinetic theory of gases, and substituting such concepts as the mixing-length for the mean free path, and eddy viscosity for kinematic viscosity. The theory has no real physical counterpart, but it has been used to develop wind profile equations and diffusion equations which approximate moderately well to observation. In recent years there have been attempts to extend the theory to non-adiabatic conditions. Diffusion equations based on the Mixing-Length Hypothesis work well for distances up to 1,000 m, over level terrain of uniform roughness.

Another approach to turbulence and diffusion has been offered in the Statistical Theory of Turbulence, in which an effort is made to describe turbulent motion in terms of relationships between the statistical properties of the fluctuations and the mean motion. The theory has been extended by Sutton (1947) to yield a diffusion equation for an elevated point source. The equation takes into account variations in lapse rate. The expression gives satisfactory results over surfaces of homogeneous roughness. The treatment is mathematical and makes no effort to explain the physical mechanism of diffusion.

Recently Cramer (1953), working with Dr. Hewson's group at the Round Hill Field Station, has advanced a new theory to explain the physical mechanism of diffusion. It borrows from the entrainment theory, picturing air flow as a series of adjacent pencils which alternately speed up and slow down. When a particular pencil is speeding up there is entrainment or inflow from neighbouring pencils, thus diluting the original mass of air. When the pencil is slowing down there is outflow, thus transferring mass, and any property such as a pollutant, to the neighbouring pencils. Diffusion can be pictured as proceeding in stages in this way. It is planned to test this new theory against observation at Round Hill Field Station. Attempts will also be made to expand the theory to less elementary models.

One other item of turbulent theory which bears on the problem of air pollution is Richardson's criterion, advanced in order to take into account the gravitational field which is important if lapse rates are other than adiabatic. Richardson's criterion states that the kinetic energy of the eddying motion will increase or decrease if the rate at which energy is extracted by the Reynold's stresses exceeds or falls below that at which work has to be done against gravity by the turbulence. This statement of the criterion for turbulent flow is expressed mathematically in the expression

$$R_i = \frac{g(\partial \overline{T}/\partial z) + \Gamma}{T(\partial \bar{u}/\partial z)^2}$$

in which R_i is the Richardson number, T is the absolute temperature of the environment, $\partial \bar{u}/\partial z$ is the wind shear, and $\partial \overline{T}/\partial z + \Gamma$ is the difference between the actual lapse rate and the dry adiabatic lapse rate. Richardson postulated turbulent motion if $R_i < 1$ and laminar motion if $R_i > 1$. It follows that turbulent motion exists if the lapse rate exceeds the dry adiabatic value regardless of the wind profile. It also follows that a lapse rate less than the dry adiabatic is one of the requirements for laminar motion, but not the only one. In practice it has been found that near laminar motion results in the lower layers when there is an inversion. Smith (1951) and Barad (1951) show that typical wind direction traces for inversion periods approximate a straight line, indicating an absence of eddies. Hence the emphasis that has been placed on inversions in studies of air pollution. For when the eddy component of air flow disappears, eddy diffusion ceases.

All theoretical treatments of diffusion to date describe such ideal conditions as single point or straight line sources, constant rates of emission, homogeneous and flat terrain, and so on. These are conditions not met at the engineering level of air pollution in a large city. There is still a big gap between the theory of diffusion, and the diffusion problem that is encountered in an area such as the Detroit-Windsor one.

Attempts to apply the Richardson criterion rigorously to problems of urban pollution are rather pointless at the present time. Such a distinguished authority as Sutton (1953) states that "attempts to verify Richardson's criterion for the lower atmosphere have not been entirely successful, and there is some doubt whether a unique value, applicable to all types of surface, can be said to exist". What we can do is apply the underlying idea that certain temperature and wind stratifications can impose a laminar flow and arrest diffusion. We can apply the observed fact that a temperature inversion alone is usually enough to give laminar flow conditions.

OUTLINE OF THE DETROIT-WINDSOR METEOROLOGICAL INVESTIGATION

In the Detroit-Windsor study we are going to concentrate on wind speed and direction, wind gustiness, and lapse rates through the lower few hundred feet. This phase of the program constitutes the attack on the diffusion problem. Secondary interest centres on the effect of rain on air pollution, and the use of meteorological instruments which are sensitive to relative pollution loadings because of the light scattering effect of pollution. Special equipment has been ordered by the Technical Advisory Board in order to carry out the investigations. Some of the instruments are already in service.

During the past year, existing meteorological instruments in the area have been useful in revealing qualitatively some of the facts about air pollution in the Detroit-Windsor area. It is evident that pollution levels are highest when winds are lightest and when the air is most stable. It is also evident that stability is greatest when above normal temperatures are observed at 850 mb. There have been enough smoggy days to confirm that serious pollution problems are associated with warm, stagnant high pressure cells.

Reference to Figure 1 shows that there are no special terrain effects. There is no significant valley along the Detroit River which might serve as a trap for airborne wastes. Furthermore the normal surface temperatures of Lake St. Clair and Lake Erie are within a few degrees of normal air temperatures for the area. It is the feeling, therefore, that the lakes are not one of the main influences upon the pollution in the area. The problem is distinctly different from the Los Angeles one where high hills confine the city's effluents on three sides, and inversions based anywhere below the tops of the hills act as a lid on the area. In the Detroit-Windsor area an inversion must be based at the surface to materially influence the pollution level.

DETAILS OF THE DETROIT-WINDSOR STUDY

Returning to the subject of special investigations and instrumentation for this study, I would like to include a word about the philosophy underlying our plans. Because of strict manpower and budget limitations it has been decided to concentrate on a few measurements that will have area-wide significance, rather than to accumulate a multitude of micrometeorological measurements which might only have neighbourhood significance.

To study the problem of diffusion, a Bendix-Friez Aerovane, eight resistance thermometers and a multipoint recorder, have been purchased. To study the effect of rain on air pollution, a Nash and Thompson rainfall detector and rate of rainfall recorder have been purchased. To give a measure of the amount of pollution in the air, two daylight illuminometers have been ordered.

The Bendix-Friez Aerovane is a dual purpose instrument. It gives a record of wind speed and direction on strip charts which need to be changed only once a month using a chart speed of $1\frac{1}{2}$ in/hr. It can also be used to measure the amount and type of turbulence present. Smith (1951) points out that the directional traces of the aerovane are characteristic of the type of turbulence present. He states that:

"In practice four relatively discrete classes have been found:

"1. Overall angular width of direction trace exceeds 90 degrees during a one-hour period. (Thermally induced turbulence predominates; wind speeds are light.)

"2. Angular hourly width of trace 15 to 90 degrees; fluctuations are sufficiently irregular that a straight line cannot be drawn through the solid central core in a one-hour period. (Turbulence reflects a combination of thermal and mechanical origin.)

"3. Angular width of trace 15 to 90 degrees; fluctuations are of high frequency and are remarkably uniform. A straight line can easily be drawn through the solid central core representing a one-hour period. (Mechanical turbulence is strongly predominant.)

"4. Angular width of trace 0 to 15 degrees; trace often approximates a straight line. (Turbulence is reduced to a minimum.)"

These relatively simple groupings are most likely to be realized when the aerovane is mounted 200 - 300 feet above the ground. We hope to be able to arrange such an exposure of our aerovane eventually, but for the time being we have it mounted about 20 feet above ground at one of the pollution sampling stations. Even with such an exposure we are obtaining directional traces that show abrupt changes in character, which apparently reflect the degree and nature of the turbulence.

Earlier I mentioned that eight resistance thermometers and a multi-point recorder had been purchased. Most turbulence studies have a tower installation in order to study lapse rates. In the Detroit area, we have been trying for many months to locate a suitable radio or television tower upon which to mount resistance thermometers. Considerable progress has been made, and unless some unforeseen difficulties arise, we hope eventually to complete a tower installation. The projected installation would be on a new television tower which is scheduled for completion in September. Resistance thermometers could be installed to a height of 870 feet. The tower will be in an open site about 12 miles from the river. If we can achieve such an installation, it would likely become the focus of the meteorological study. It would be desirable to install the aerovane on the same tower in order to study the effect of lapse rate on the characteristic of the directional trace. We realize that many technical problems are going to arise in such an installation, but every effort will be made to meet and overcome them.

The effect of rainfall on air pollution is a separate problem. Some industrial scrubbers used to eliminate pollution at the source involve the use of sprays. It is easy to slip from that picture to one in which rainfall is pictured as a great spray, cleansing the atmosphere. You can see that the picture envisages a kind of stationary atmosphere, or at least an unchanging airmass, with the rain clouds passing over and dropping the cleansing rain. Something like that probably happens in the case of air mass showers. But in the Detroit area, most rainfall is frontal in nature. The end of rainfall usually means that a new air mass has invaded the area, and most frequently this new air mass is polar in origin. As a result it is almost always the case that pollution levels are lower the day after the rain than on the day of the rain, but the air mass change rather than the rain is the cause.

Nevertheless there is interest in the subject and we are going to study it. Previous researches in England and the United States, of a more elaborate nature than the Detroit-Windsor undertaking, have failed to agree on the effect, if any, of rainfall on pollution. In Windsor we are concentrating on studying the effect of rate of rainfall on pollution. We are using a rainfall gauge which measures total rainfall in either one-minute or three-minute intervals. It is located at one of the sampling sites where measurements of airborne impurities are taken. The rainfall gauge has only been in operation a few weeks, and there is still insufficient data to begin analysis. We think we are going to find that particulate concentrations in the surface layer are increased during periods of heavy rain. Perhaps we will find that the amount of the increase is related directly to the rate of rainfall. As for the effect of rainfall on sulphur dioxide, we approach that with an open mind.

Finally I would like to say a word about the measurement of pollution using instruments which make use of the light-scattering effect of airborne pollution. On the Canadian side of the border we will be using two daylight illuminometers, an instrument designed to measure and record total incoming daylight, both direct and reflected, in the visible portion of the spectrum. We are going to install one at McGregor as representative of the available daylight in the surrounding countryside, and another in downtown Windsor. We will express the readings of the Windsor unit as a percentage of that recorded in the surrounding countryside. Similar studies (Hand 1949) have been carried on at Boston where urban radiation was about 82 percent of that received in the surrounding countryside, and at a number of places in Great Britain (1944) where annual means range from just over 50 percent at Glasgow to nearly 90 percent at Leeds. This phase of the study awaits the arrival of the equipment.

CONCLUSION

In the Detroit-Windsor Air Pollution Investigation, the meteorological study is only one phase of a broad, integrated study. Other phases of the investigation include environmental studies of pollution, vessel observations, the health study, vegetation studies, and others. The goals of the investigation have been stated in the original reference. It is my hope that the meteorological studies will materially contribute to the realization of those goals.

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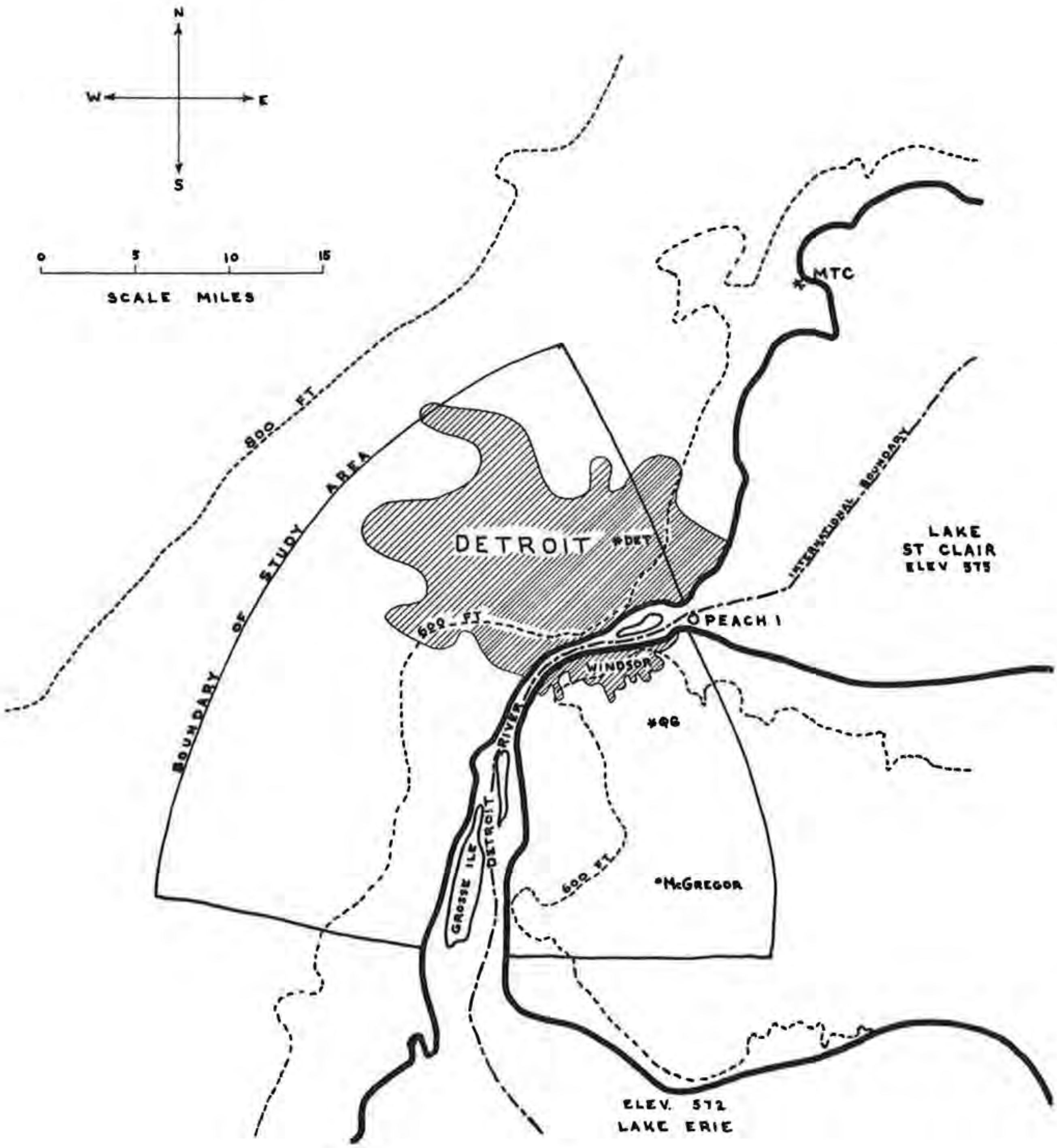
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INTERNATIONAL BOUNDARY
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ELEV 575
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WINDSOR
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RIVER
DETROIT
GROSSE ILE
600 FT
McGREGOR
ELEV. 572
LAKE ERIE

FIGURE 1