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Use of Landsat data in monitoring patterns of aerosol pollutants and mesometeorological events

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16. Abstract

NASA's Landsat-1 satellite, with its high resolution and multispectral capabilities, has been found useful in the detection and analysis of smoke from large point sources (power plants, steel mills, etc.), and widespread atmospheric stagnations. Smoke plumes from the Chicago-Northern Indiana industrial complex have been tracked over Lake Michigan for more than 100 km. This has important implications with regard to air pollution control strategems. If indeed there is significant inter-regional pollution transport, our concepts of Air Quality Control Regions may have to be revised.

Experience has shown that smoke plumes are relatively easy to detect in Landsat imagery over water (in the 0.6-0.7 micrometer band) but much more difficult over land surfaces. Pattern recognition techniques (cluster analysis) were applied to the digital Landsat data and it was found that the smoke plumes indeed had a unique spectral signature. Studies are currently underway examining the use of measured plume geometries to obtain quantitative estimates of diffusion over water surfaces.

Landsat data have also shown great utility in the detection of inadvertent weather modification, in particular, the formation of convective clouds within steel mill plumes. Contrails are also easily identifiable.

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PREFACE

With the call for proposals and the initial publication of the ERTS (Landsat) design specifications, it became apparent to the Air Pollution Analysis Laboratory of the University of Wisconsin-Milwaukee that such a satellite could have unique monitoring capabilities for detection of atmospheric aerosol plumes and the mesoscale meteorological regimes in which they are transported. Indeed the multispectral and high resolution images over the Great Lakes have fulfilled the promise. These images were also suitable for inclusion in a large-scale cloud climatology project over Lake Ontario conducted under the auspices of the International Field Year on the Great Lakes (IFYGL). These data are still being analyzed but ERTS imagery was successfully employed in "calibrating" lower resolution meteorological satellite data and comparing them with surface based all-sky photographs. In total, all images over Lake Michigan (from launch through October 1974) and all Lake Ontario basin images during IFYGL (launch through June 1973) were examined. These data will be employed as valuable ancillary inputs to a number of Great Lakes mesometeorological studies for years to come. It is in the area of detection of air pollutants by satellites however that a coherent body of data has been formulated, and this forms the basis of this report.

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INTRODUCTION

Since the launch of the first meteorological satellite, TIROS I, in 1960, the meteorological community has been increasingly involved in the field loosely referred to as "Remote Sensing." The earliest vidicon images of the earth's cloud systems yielded signatures of the structures and patterns of atmospheric motions. As image resolution gradually increased to its present 0.3 mile maximum for operational meteorological satellites, more and more detail about the all-important mesoscale atmospheric processes could be discerned.

Even with the increased image resolution, meteorologists concerned with air quality control and monitoring of atmospheric pollutants took relatively little note of the potential of satellite monitoring. Various sensors and platforms have been employed for sensing pollution (see Colvocoresses [1]). These have included free floating balloons, tethered systems, kites and aircraft. It took the successful launching of NASA's first Earth Resources Technology Satellite (ERTS-1)[1] with its vastly increased resolution and multispectral sensors before the meteorological community developed its current interest in the use of spacecraft as reliable pollution monitors.

The above is not to say that spacecraft imagery has not been applied to air quality problems, however. Numerous 70 mm photographs of smoke plumes were returned from the manned Gemini and Apollo earth orbital missions (Figure 1). These clearly demonstrated that smoke plume detection from these altitudes was feasible given adequate sensor

[1]Now designated Landsat-1

resolution. The Nimbus IV satellite made a number of relevant observations. A massive turbidity "cloud" associated with Sahara dust storms was observed drifting westward over the tropical Atlantic for a five-day period in April, 1970. As ash plume over 300 km long was found emanating from the erupting Beerenberg Volcano on Jan Mayen Island (September,1970). Massive clouds of smoke associated with southern California brush fires and agricultural burning on Yucatan Peninsula have been noted by several satellites.

McClellan[2]was among the first researchers to attempt the use of digital data from the Applications Technology Satellite (ATS-III) to study urban scale atmospheric pollution. Analysis of radiance values over the Los Angeles basin, after comparison with other target areas, suggested that some correlation did exist between radiance values and atmospheric aerosol loading (as indicated by visibility reports). The comparatively low resolution (2.8 km) and difficulties in geometric navigation have frustrated attempts at using these data for anything but the most qualitative use.

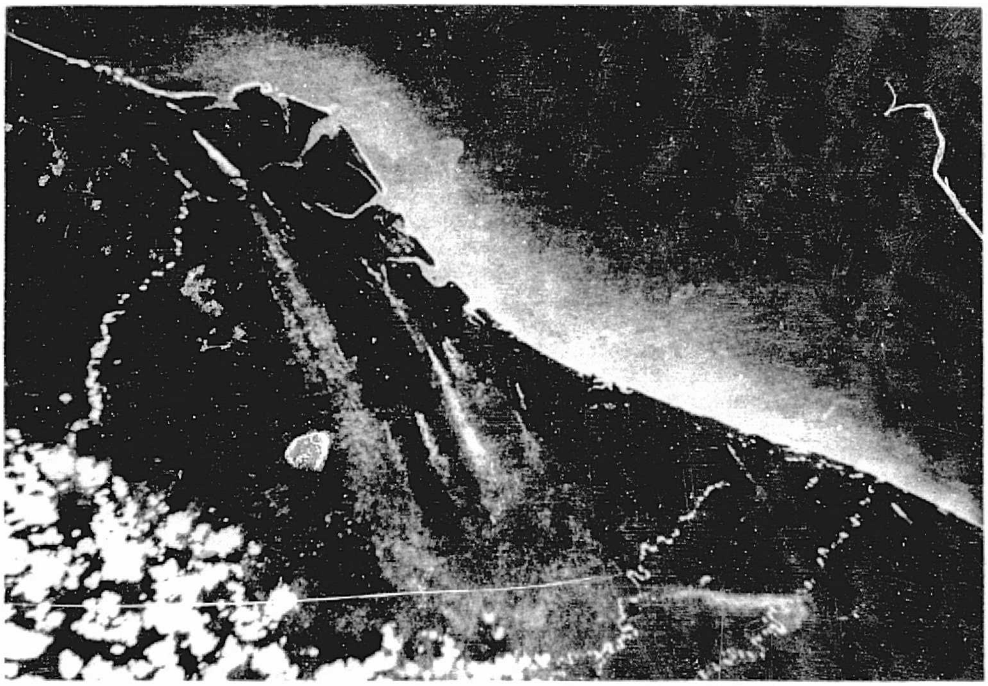

Figure 1. - 70mm photograph taken during Gemini manned orbital mission showing smoke plumes along a shoreline.

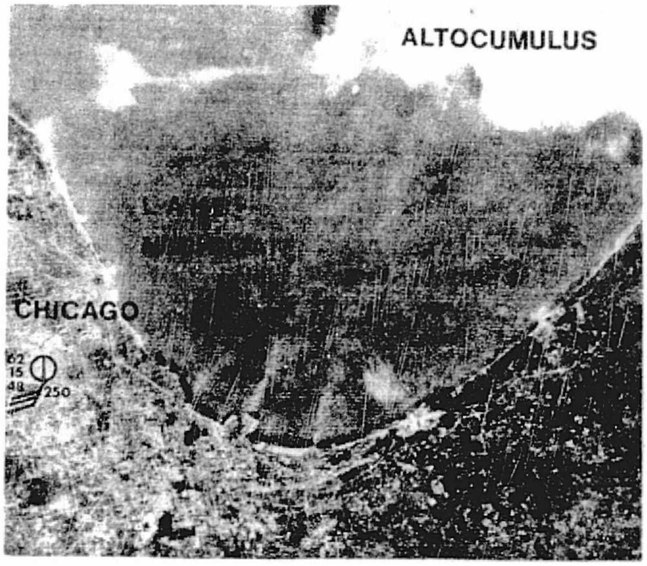

Figure 2. - Landsat-1 image, band 5 (0.6-0.7 micrometers), 1 October 1972, showing smoke plumes from steel mills drifting over Lake Michigan.

The two great advantages of Landsat are its extremely high resolution and a multispectral imaging capability. The original specifications for the multispectral scanner (MSS) called for 100-200 m resolution. Initial results have shown some high contrast targets as small as 50 m. Highways, airport runways, small ponds, jet contrails, harbor breakwaters, etc., are routinely visible. The four spectral bands are (1) MSS-4, 0.5-0.6 μm ("green" band); (2) MSS-5, 0.6-0.7 μm ("red" band); (3) MSS-6, 0.7-0.8 μm; and (4) MSS-7, 0.8-1.1 μm ("near infrared" band). Landsat products are available in several formats including digital tapes, 9½ by 9½ inch black and white and color prints and transparencies, and most routinely, 70mm negative and positive transparencies [5].

Because the four spectral bands are viewed simultaneously in space and time, it is possible to use color-additive viewing techniques to produce color-coded results. Combining MSS bands 4, 5, and 7 results in a false-color infrared image. The red color associated with foliated vegetation makes this color analysis a valuable diagnostic tool in agriculture, forestry, and land-use studies, but for the meteorologist the Landsat multispectral imaging techniques are most useful in penetrating thick haze, revealing cloud shadows, delineating snow cover from vegetation, and demarcating land/water boundaries.

The author has followed the lead of Pease and Bowden [6] in using Kodak 35mm Ektachrome Color Infrared [CIR] film for environmental monitoring. The greatest success has been found using a 160 ASA, and 80 B, Wratten 12, and polarizing filters. Numerous CIR pictures of ground targets and smoke plumes have been made from the University of Wisconsin-Milwaukee (UWM) instrumented aircraft coincident with Landsat overflights.

The various design characteristics of Landsat prompted the UWM Air Pollution Analysis Laboratory to submit a proposal to study Landsat-1 data. It was hoped that a satellite with these characteristics would be capable of detecting major plumes of suspended particulates, making possible synoptic studies of interregional pollution transport over the southern Lake Michigan basin.

DETECTION OF SMOKE PLUMES BY LANDSAT

The heart of the Chicago-Gary industrial complex stretches from the southeastern part of the city of Chicago eastwards along the shoreline of Lake and Porter Counties, Indiana, to east of Gary. Figure 4 is an aerial view of a part of this region taken from an NCAR Queen Air at 6000 feet AGL on the morning of 15 July 1968 when brisk southwesterly flow was advecting numerous smoke plumes over the lake.

A total of 16 major particulate sources have been located in the study area. The size of some of these sources is truly remarkable.

Source 3, a cement plant, discharges over 140,000 tons/year of particulates. In comparison, all of Milwaukee County, Wisconsin, a relatively industrialized area, had a 1970 suspended particulate emission of only approximately 45,000 tons/year.

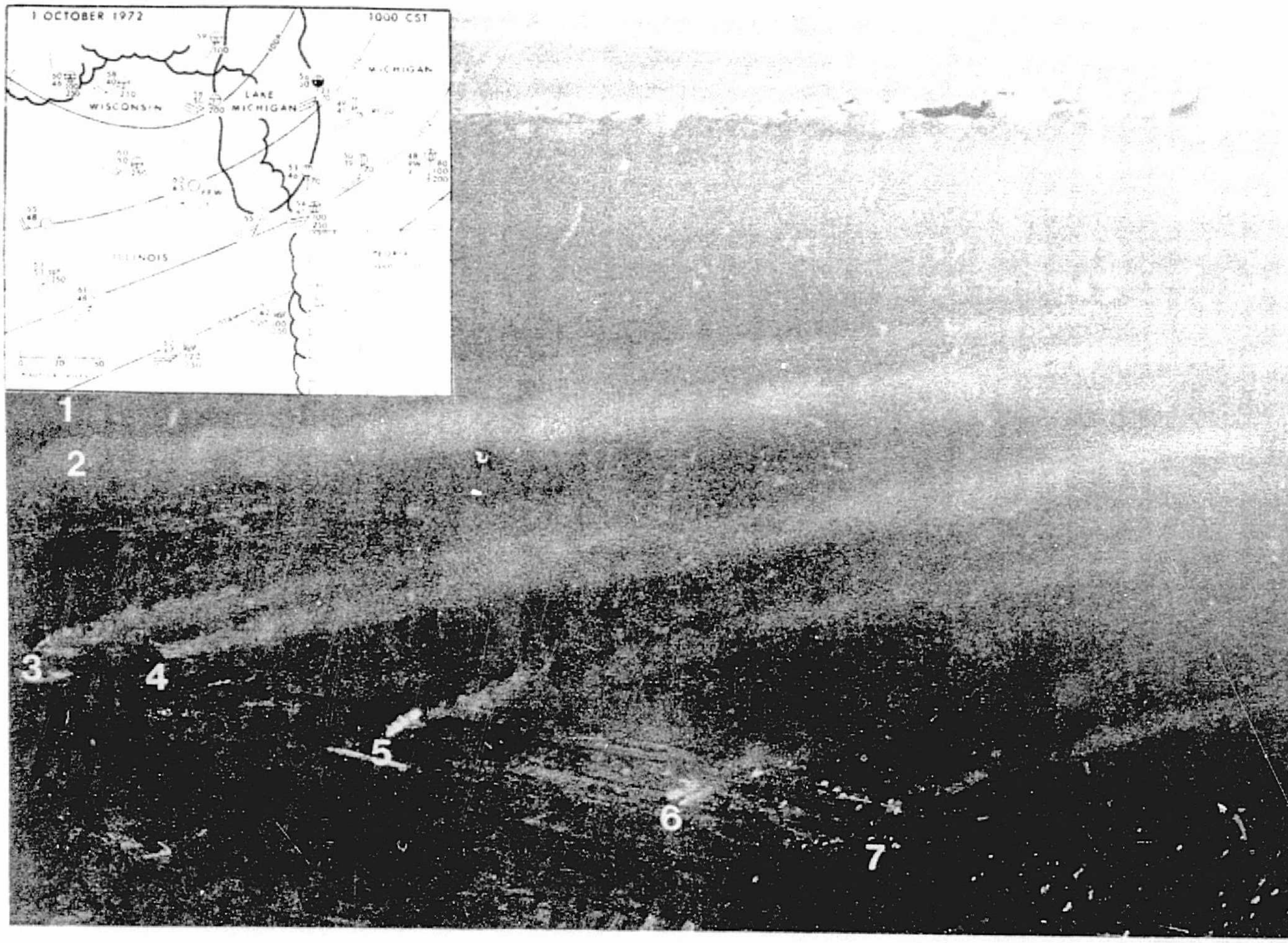

Figure 3. - (inset). Synoptic conditions, 1000 LST, 1 October 1972. One wind barb equals 5 kts. Peoria, Illinois, radiosonde taken 0600 LST shown.

Figure 4. - Photograph, looking north, of a portion of the Chicago-Gary industrial complex, 0700 LST, 15 June 1968, from NCAR Queen Air, at 6000 feet MSL.

During the morning of 1 October 1972, brisk southwest surface flow covered the southern Lake Michigan basin area (Figure 3). A bank of altocumulus clouds was present to the north and east of the Chicago region and was moving rapidly northeastwards. A strong nocturnal radiation inversion had been present at 0600 CST according to the Peoria, Illinois (PIA) sounding (Figure 3). Figure 2 is a portion of the Landsat images taken at approximately 1003 LST. A number of particulate plumes can be seen streaming northeastward, disappearing beneath the altocumulus cloud deck at a distance of about 60 km.

It should be noted that due to the various degradations involved both in making the photographic print and in publication, the plumes do not appear as clearly as they do in the original 70 mm negative. The prints were also photographically dodged to maximize details over both land and water.

The plumes visible in this image, for the most part, are not from single stacks, but from entire steel mill complexes. The total spread of the visible plume at 60 km downwind is about 4.5 km. Measurements of plume spread can be converted into useful information regarding overwater mesoscale diffusion of pollutants. The visible plume may be correlated to a parameter such as the point where concentration drop off to 10% of the centerline value, or 2.15 σ_y, in the parlance of Pasquill and Gifford. If that were the case, then this plume would appear to have a diffusion rate characteristic of Class E (rather stable atmosphere) in the empirical classification of atmospheric stabilities used in Gaussian plume diffusion calculations. Work is currently underway to subject transparencies of these and other plume images to microdensitometric analysis. This would yield profiles of optical density (presumably related to particulate loading) as a function of distance, from which estimates of diffusion rates could be made. These are valuable data sets inasmuch as little data for the overwater spread of plumes from large point sources (such as power plants) is available. Brookhaven National Laboratory has for the past several years attempted to make actual measurements over the waters around Long Island. The formidable operational difficulties have made data collection expensive and tedious. Use of Landsat data could be a valuable adjunct to these programs.

An important consideration is the choice of the appropriate Landsat spectral band to provide optimum discrimination of a particulate plume against the underlying surface, in this case water. The plume will be most visible on the photograph when the difference between the optical density of the plume image and the optical density of the lake-surface image is greatest. Plume visibility over a water surface will thus be enhanced by: (1) decrease in the spectral albedo of the lake surface, (2) increase in overall image contrast, and (3) increase in the amount of radiation scattered and/or reflected vertically upwards from the solar beam by the plume. In the case of a plume advecting over a surface of very high spectral albedo, a fourth factor would have to be considered; the extent to which a plume attenuates solar radiation reflected vertically upwards from the surface, a factor dependent on the geometry of scattering and absorption of radiation by the plume.

The first of these major considerations, the spectral albedo of the lake surface, shows a marked variation by wavelength. Direct reflection of solar radiation from the lake surface makes a relatively minor contribution to the variation of lake spectral albedo in the four Landsat bands. Reflection vertically upwards from the lake surface is small (approximately 2%) and for a solar elevation angle of 40° shows only slight wavelength dependence with very slightly higher values in the lower wavelengths of the visual spectrum.

Far more important in influencing the spectral albedo of the lake is the wavelength dependence of solar radiation absorption within the lake itself. The lower the spectral absorption coefficient within the lake for any wavelength, the greater is the penetration of incident solar radiation into the lake and the greater is the likelihood of backscattering upward by water molecules and hydrosols, i.e., Rayleigh and Mie scattering, respectively. For distilled water, maximum transmissivity occurs at 0.46 μm, and absorption increases rapidly with increasing wavelength, resulting in a darker lake image. As an example, the mean absorption coefficient for pure water in Landsat band 4 is approximately six times less than the coefficient for band 5, and the lake thus should appear brighter. Increased amounts of suspended and dissolved matter shift the wavelength of minimum absorption and maximum lake albedo to longer wavelengths. Sea water (and lake water?) typically has minimum absorption near 0.55 μm, which is the center of Landsat band 4.

An additional consequence of the greater transparency of water in the blue and green portion of the spectrum occurs in the case of shallow water, where reflection from the lake bottom may further increase values of surface lake albedo and limit the ability to detect pollution plumes near shore.

The net result is that the lake generally appears brightest in band 4 and nearly jet black in band 7. An exposition of the spectral dependence of backscattering from suspended particulates becomes even more complex. A complete discussion of the topic is presented by Lyons and Pease [7]. Various theoretical arguments suggest that the highest inherent brightness of smoke plumes would probably be in the "red" portion of the visible spectrum.

An inspection of the four spectral bands for the image shown in Figure 2 reveals that in band 4 the smoke plumes were virtually invisible due to the extreme "brightness" of the lake which eliminated almost all inherent contrast. While the plumes were seen over water in bands 6 and 7, the best plume contrast over moderately clear and deep lake water was found in band 5.

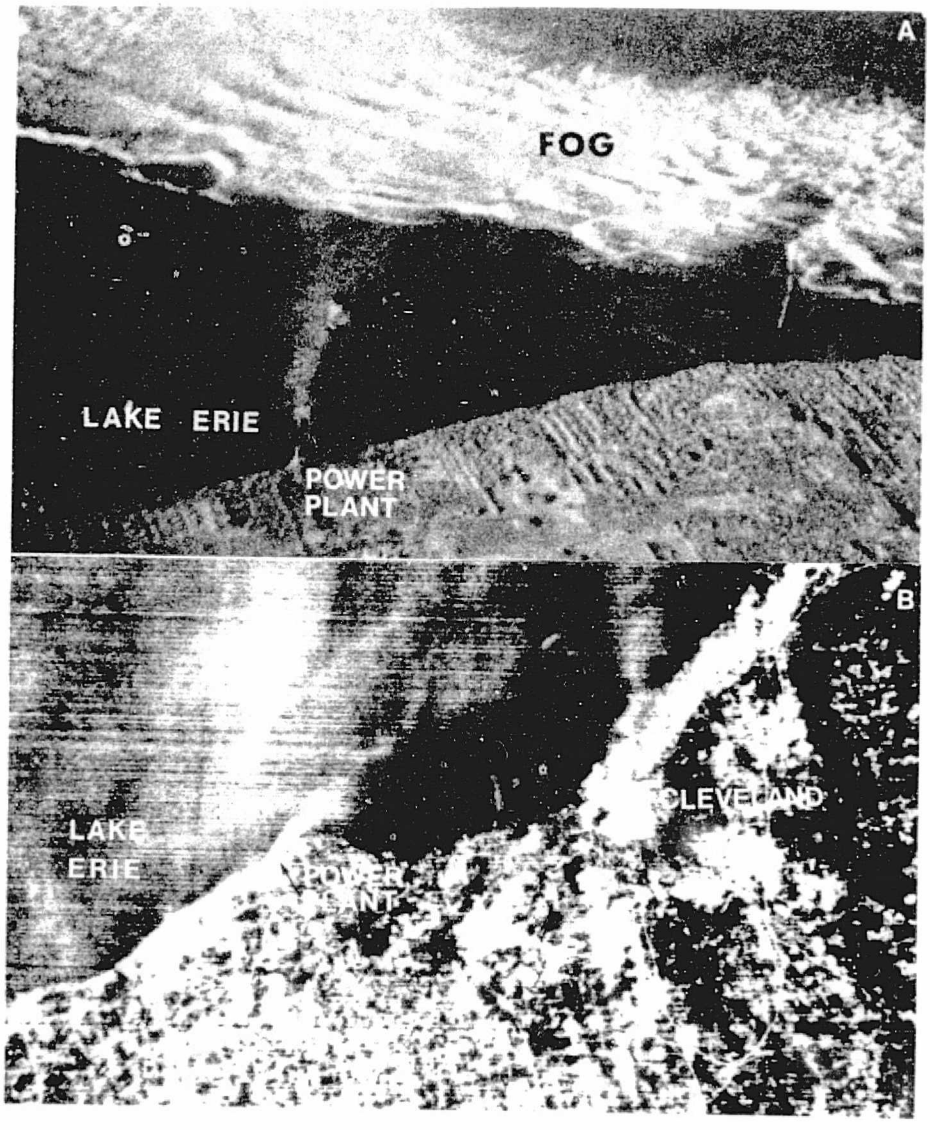

Figure 5(a) - Large fossil fuel power plant near Loraine, Ohio, on southern shore of Lake Erie with smoke plume drifting northeastward over fog shrouded lake.

(b) - Landsat-1 image band 5, showing plume from same plant advecting over the lake on 4 September 1973.

Figure 5a shows a large coal-burning power plant located on the southern shore of Lake Erie near Loraine, Ohio. Most of the particulate matter emanates from a single stack. In this view, the plume is drifting northeast over the lake (with patches of fog forming over the cold lake surface). This picture was taken from about 32,000 feet using 35mm CIR film. A Landsat-1 band 5 image of the same plant taken on 4 September 1973 shows the plume remarkably well. This Landsat image was specially processed by projecting the 70mm positive transparency onto a Kodalith negative from which the print was made. This greatly increases the contrast, and though there is a severe loss of ground target resolution, the smoke plume is greatly enhanced. A pall of smoke from sources in Cleveland is also visible, as is the considerable turbidity in the lake water. The power plant plume is visible in the original for over 15 km downwind.

The examples discussed so far have all been for plumes from major point sources traveling over water. It has been found that it is far more difficult to detect plumes over land. Copeland, et al. [8] have had some success, but these were for unusually dense smoke plumes. The generally higher albedo of the land surface generally reduces inherent contrast between the smoke and the underlying surface. The mottled and uneven nature of the terrain further complicates the matter. Smoke from brush and forest fires has been detected occasionally, sometimes made easier by the large areas of blackened earth left behind according to Wightman [9].

To illustrate the contrast between over water and over land plume detection, refer to Figure 6. In Figure 6a, we see the same Gary, Indiana, industrial complex, this time taken from 33,000 feet using 35mm CIR film at 0950 LST, 7 March 1974. Extremely stable northeasterly flow off cold

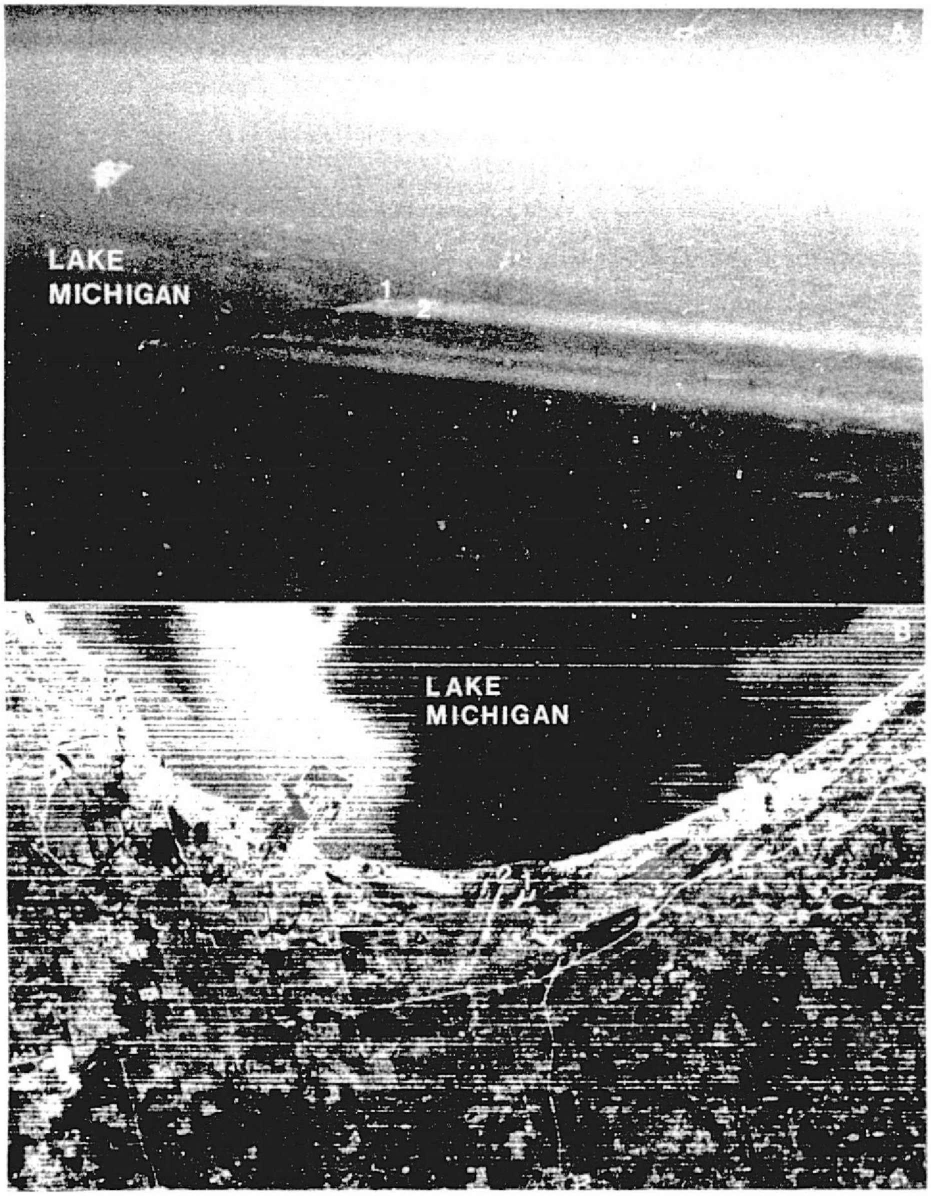

Figure 6(a) - View looking east, at 33,000 feet, of Gary, Indiana plumes, using CIR film, 0950 LST, 7 March 1974. Plume 1 is condensation from large cooling tower; plume 2 is smoke from steel mill.

(b) - Landsat-1 image, band 5, taken at 1003 LST, 7 March 1974, of same area.

Lake Michigan had trapped these elevated plumes and they were traveling on inland without undergoing significant mixing. Figure 6b is an enhanced Landsat-1 band 5 image taken at virtually the same time. Several plumes are visible. The short, very white plumes labeled 1 are clouds of condensate from large cooling towers which are evaporating only a short distance from their sources. The smoke plume labeled 2 is from the steel mill complex in downtown Gary. It can only be tracked for about 10 km over land before becoming invisible. Thus, while smoke and condensate plumes are visible over land, they must be unusually large and dense. In any case, their detectability is far less than an equivalent plume over a water surface.

MACHINE PROCESSING OF LANDSAT DATA

The mere visual inspection of Landsat images can be most helpful in gaining insight into the behavior of air pollutants, but even more advanced methods are being developed to treat such data. The Robotics and Artificial Intelligence Laboratory (RAIL) of the University of Wisconsin-Milwaukee has established both hardware and software capability for automatic image interpretation using Landsat digital tapes. Pattern recognition is a powerful statistical approach to classification of image features, especially those obtained by multispectral sensors. Identification of crop types using Landsat digital data processed entirely by computer often exceeds 80% accuracy.

As a test of the RAIL system, a small portion of the image shown in Figure 2 was processed using cluster analysis techniques developed by Eigen and Northouse [10]. A section of the image which showed an industrial landfill peninsula (with several steel mills) and two major smoke plumes was chosen. All four Landsat bands were available in digital tape format. Processing was accomplished on a MODCOMP II/25 computer with line printer output. After several runs experimenting with the best clusters, a final version was selected (Figure 7). Here all land features (roads, corn fields, etc.) were suppressed, accounting for the blank spaces. Water with its distinct spectral characteristics was easily isolated from other features, and was printed everywhere as ----. The smoke from the sources (steel mills and a cement plant to the east) also were found to have rather homogeneous spectral signatures. These are indicated in Figure 7 by a ⊛ and are clearly delineated. This technique has also been used to automatically distinguish clean from "polluted" water in and around Milwaukee harbor.

Computer image processing has other capabilities besides simply making an automatic classification of the nature of the scenes in each pixel of a Landsat image (60x80m). For instance, since radiance values are the raw material of the tape data, digital density slicing can be accomplished easily, and with color CRT output, graphic displays can be obtained. The next step is using the system as a digital microdensitometer combined with pattern recognition algorithms to automatically detect "smoke" and make estimates of total particulate loading in the atmosphere below the satellite. For this, "ground truth" is necessary, and a Cessna 182 aircraft has been instrumented for this purpose. It has both total aerosol mass monitors and 2 channel particle counters recorded in digital format on magnetic tape). It is hoped to obtain a complete profile of the Gary plumes simultaneously with a Landsat overflight so that image radiance values could be calibrated and yield some measure of total aerosol mass loading.

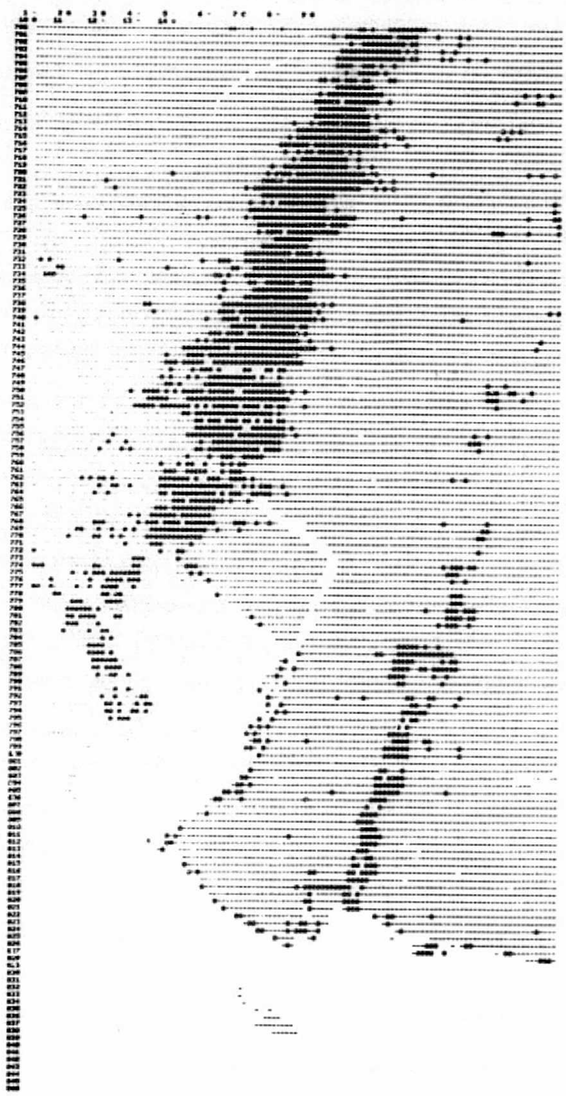

Figure 7. - Computer processed Landsat-1 digital data, small segment of frame shown in Figure 2. Water of lake is indicated by (-), all land signatures are suppressed (and therefore blank), and smoke is denoted by (⊗). Note man-made peninsula and breakwater protruding into lake.

INTERREGIONAL POLLUTION TRANSPORT

The Federal Clean Air Act of 1967 (amended 1970) divided the United States into Air Quality Control Regions (AQCR). The boundaries of these regions ideally were chosen to delineate independent, self-contained "air sheds" where air quality levels were determined by emissions from sources within that region. The actual boundaries selected were often compromises between meteorological and political realities. An AQCR's final compliance with national Air Quality Standards is ultimately dependent upon the successful formulation and implementation by regional authorities of the necessary emission control strategy for sources within that region. In reality, however, two adjacent AQCR's might occasionally find themselves breathing each other's effluents due to long-range interregional transport of pollutants. A case in point is the Southeast Wisconsin AQCR (the seven counties of southeastern Wisconsin, including metropolitan Milwaukee) and the Chicago Interstate AQCR (northeast Illinois and the two northwesternmost counties of Indiana). In the latter, there exist the numerous extremely large point sources mentioned above. The evidence has gradually been accumulating that these sources are indeed more than just local problems.

In August 1967, the author participated in the flight of an aircraft from the National Center for Atmospheric Research instrumented to monitor ice nuclei. The object of the study was the dispersion of anthropogenic ice nuclei emanating from the Chicago-Gary steel mill complex. Under conditions of brisk southwesterly flow over southern Lake Michigan, with a rather strong synoptic-scale subsidence inversion around 1300 m, a clearly defined plume of ice nuclei was easily tracked to the vicinity

Battle Creek, Michigan (some 180 km downwind). On several summer days with south-southeasterly flow over the lake, elevated layers of red iron-oxide smoke have been seen drifting past Milwaukee [7]. Again, the most likely origin of this smoke was the mills at the southern end of the lake -- almost 165 km away.

The effect of the much larger Chicago Interstate AQCR upon Milwaukee is probably significant, but most difficult to ascertain qualitatively. It has been estimated that approximately 10% of the suspended particulates measured in the Milwaukee area originate in and around Chicago. Frequently in Milwaukee, several hours after the surface winds shift to the south or southeast, there is a rapid increase in haze and smoke, presumably the influence of interregional transport from the Chicago area. Certainly in any megalopolis, such as found along the East and West coasts, adjacent AQCR's could indeed be exchanging pollutants on a regular basis.

In the emerging Great Lakes megalopolis, which shows signs of extending from Green Bay, Wisconsin, to Buffalo, New York, in the not-too-distant future, the peculiar meteorological effects of the Great Lakes often exacerbate this interregional transport. When continental air masses advect across the relatively warm lakes in winter, any plume moving over a Great Lake will be rapidly dispersed. Turbulence generated by the convection rising from the surface can be extreme, sometimes to the point of generating a myriad of miniature waterspouts or "steam devils." Thus, if plumes from northern Indiana are to pass over Lake Michigan into southwestern Michigan or Wisconsin, they probably arrive diluted to a great degree. From early spring through late summer quite the opposite situation prevails; air temperatures frequently exceed those of the lake by 10, 20, and sometimes 30°C. Extremely intense, though shallow (100 to 200 m), surface conduction inversions form over the lake (Lyons [11]). Air streams advecting over cold lakes not only are rapidly cooled in their lowest layers but, due to the absence of upward convective heat transport, do not warm and destabilize in the overlying layers as occurs over land during the day. The almost total lack of cumulus clouds over the Great Lakes on summer afternoons is one manifestation of this. A plume from a large elevated point source such as a steel mill or power plant may travel for long distances over water with relatively little dilution and arrive above a downwind shoreline in still very high concentrations. If such a plume arrives on a downwind shore during mid-day, and solar radiation is sufficiently intense, the plume is then rapidly mixed to the surface by the turbulence forming over the heated ground in a process called fumigation. This causes high pollution levels several kilometers inland, the origin of which could be quite baffling to local control officials (Lyons, Keen, and Northouse [12]).

Figure 8. - Landsat-I, band 5, image of Chicago, Gary and southern Lake Michigan, 1003 LST, 14 October 1973. Smoke plumes advect across relatively cold lake showing little diffusion, only to fumigate on downwind shoreline near Benton Harbor, Michigan.

Figure 2 clearly suggests that plumes can travel for great distances over water during the "warm season" with relatively little dilution (in this case some 60 km). Figure 8 is an even more convincing example, a Landsat band 5 image acquired at 1003 LST, 14 October 1973. On this day, skies were clear, the overlying air mass was warmer than the lake water, and brisk southwesterly flow advected the Gary plumes into southwestern lower Michigan, almost 100 km away. The almost total lack of penetrative convection over the cold, smooth lake surface allowed the plumes to arrive near Benton Harbor, Michigan in still high concentrations. It is almost a certainty that these plumes were fumigated to the surface beginning about five kilometers inland. This effect, which could have continued for most of the day, would undoubtedly have caused considerable consternation to any local control officials who might have been monitoring in that region.

Landsat has also been useful in studying the interregional transport of photochemical pollutants from the Chicago-Gary complex northwards into southeastern Wisconsin. These invisible gases cannot be detected by the Landsat sensors. The extremely high resolution images have shown, however, the details of cloud structures associated with lake breeze fronts. This information in turn assists in the formulation of models of the complex local wind fields in the area which apparently results in the advection of massive amounts of ozone and other materials along the western Lake Michigan shoreline (Lyons and Cole [13]).

The problem that is raised by these discoveries is a legal and political, as well as meteorological one. Simply stated, if one AQCR fails to meet the prescribed Federal Air Quality Standards, will it be penalized due to the "sins of emission" of an adjacent one? Should one AQCR be forced to have stricter clean-up regulations simply because another up-wind has numerous sources?

It should be reiterated that sensors of the type employed by the Landsat system cannot be used to detect gaseous pollutants. However, some indirect information can be gathered. By using color infrared's capability to detect changes in vegetation characteristics, severe forest damage in Ontario has been used by Murth [14] as a bioindicator of sulfur dioxide dispersion from major point sources (smelters).

SYNOPTIC SCALE POLLUTION EPISODES

Up until this point we have been discussing the use of Landsat data in the detection and measurement of pollution on the mesoscale (less than 100 km); however, it is possible for entire synoptic scale air masses to become polluted. This generally occurs when a high pressure system stagnates over a several state region for a period of several days to over a week. The combination of light winds and reduced mixing depths due to the overlying subsidence inversion allows suspended particulates (and other pollutants) from thousands of sources to commingle and steadily increases the pollution levels over a wide area. Such a large scale weather phenomena usually results in the issuance of an Air Stagnation Advisory by the National Weather Service. Conditions such as these resulted in the 1966 New York City Thanksgiving Day episode when over 400 excess deaths were recorded due to the build-up of SO_2 and particulates in the atmosphere over a wide region.

During early September 1973, a late season heat wave associated with stagnant anticyclonic conditions over the eastern U.S. prompted the issuance of numerous Air Stagnation Advisories. Landsat-1 provided a graphic illustration of the extent to which entire air masses may become polluted. Figure 9a shows a typical view of eastern Lake Ontario during a time when relatively unpolluted cP air covered the region. Figure 9b is the identical region, on a day with only a few clouds scattered through the area. On 1 September 1973, the air mass was so filled with particulate matter that image contrast was reduced to the point where the lakeshore was barely visible. Both views were in band 4 (0.5-0.6 μm) which accentuates the scattering effects of both molecules and larger aerosols. If problems associated with varying turbidity levels of water can be solved, comparison of contrast and total radiance values for selected water (and perhaps ground) targets from image to image shows promise in making satellite estimates of total suspended aerosol burden on a large scale (Griggs [15]).

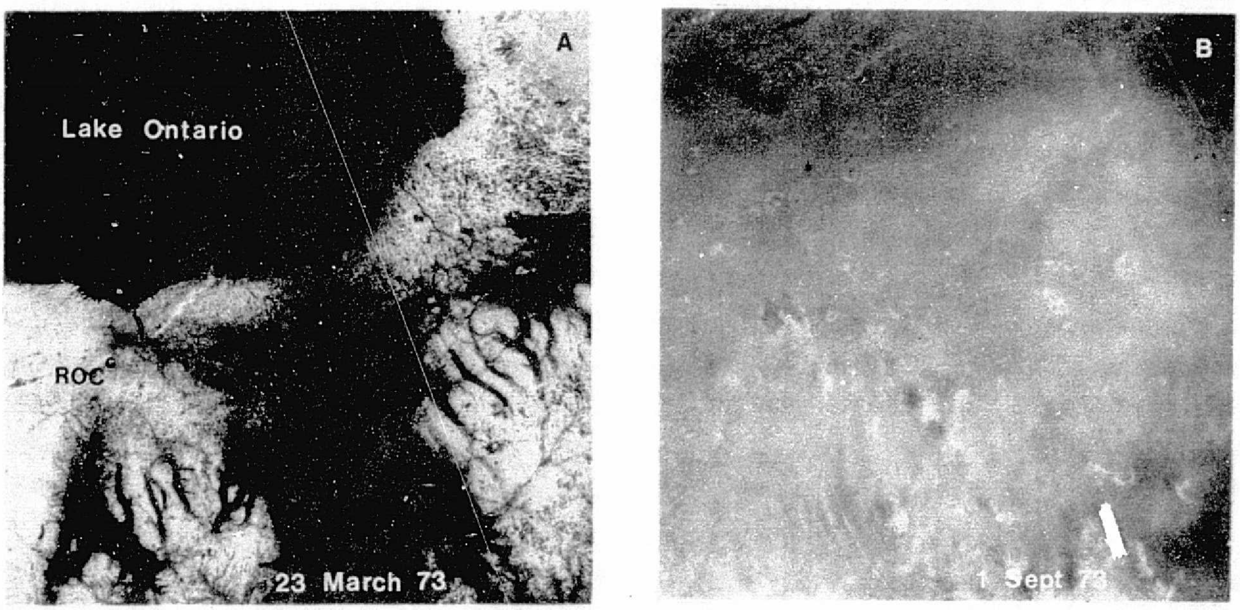

Figure 9(a) - Landsat-1 image, band 4, 0945 LST, 23 March 1973, of eastern Lake Ontario and the Finger Lakes, on a cloud-free day with low atmospheric turbidity. Snow cover is spotty through the region. Rochester, New York indicated by ROC.

(b) - Identical geographical area, band 4, 0945 LST, 1 September 1974, on a cloud-free day but with a highly polluted atmosphere associated with a synoptic scale air stagnation episode.

One of the sources for the aerosols seen by Landsat-1 on 1 September 1974 was most likely the complex of coal-fired power plants which have proliferated in Ohio and West Virginia near the strip mines which provide their fuel (Figure 10). The generally southwest winds on these days caused these plumes (along with others from Pittsburgh, etc.) to merge into one massive smoke dome which gradually covered New York State, Lake Ontario, and southern Ontario. This last fact illustrates that significant pollution exchange also occurs across international boundaries.

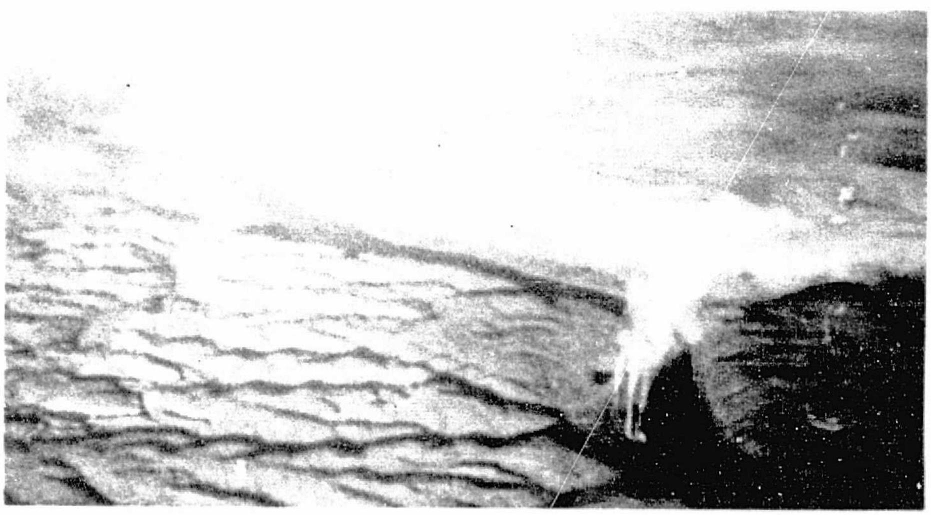

Figure 10.- Just one of many coal-burning power plants in southeastern Ohio and West Virginia which contribute to the general turbidity of the atmosphere during frequent air stagnations in the Appalachian region.

OBSERVATIONS OF INADVERTENT WEATHER MODIFICATION

Man's inadvertent modification on the earth's climate and weather has recently become a much studied topic in the meteorological community. As summarized by the 1970 Presidential Council on Environmental Quality, there exists a wide spectrum of potential mechanisms. Proper assessment of the many theories, however, must await the collection of a considerable body of appropriate climatological data and the development of reliable numerical models of global climate. More amenable to immediate study are local climatic variations and the specific weather alterations from which they arise. In the area of man-made influences on cloud and precipitation processes, however, speculation seems still to outstrip proven fact. The La Porte, Indiana precipitation anomaly is a case in point. The existence of the La Porte anomaly as a physical reality, rather than an example of spurious data, has not at all been universally accepted. Some doubt even the existence of the La Porte anomaly. In any case it is still an effect searching for a cause. The same can be said for apparent precipitation increases downwind of numerous large urban areas, extimated as high as 27% of the summer season rainfall. The list of possible causes includes: (1) anthropogenic sources of ice and condensation nuclei from industrial and perhaps automotive sources, (2) inputs of sensible heat from urban sources, (3) inputs of moisture from certain industrial activities, and (4) changes in boundary layer wind flows due to variations in surface thermal and roughness characteristics. Project METROMEX[2] is currently trying to assess the magnitude and isolate the cause(s) of urban-induced weather changes in the St. Louis, Missouri area.

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[2]See "Project METROMEX: A Review of Results," Bulletin of the American Meteorological Society, 55, February 1974, pp. 86-121.

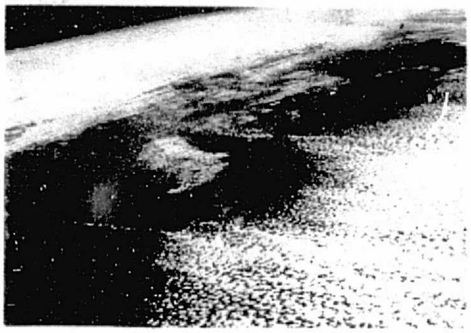

Figure 11. - Apollo manned orbital flight photograph of east coast, from Virginia to New York, during period of cold westerly flow over relatively warm ocean. The expected cumulus clouds form, but the two bands of clouds forming closer to land downwind of major industrial centers.

The La Porte and St. Louis studies have one feature in common. Proof of any effect will be obtained as a result of sophisticated statistical tests on vast amounts of climatic data correlated with numerous case studies involving extensive physical measurements. It is a relatively rare event when the atmosphere is actually "caught in the act" of responding to man's activities. Some exceptions can be noted, such as cirrus contrails spreading over a sky, cooling ponds and towers producing localized fogs, clouds, and light rain or snow, and valleys filled with fog from industrial sources of moisture and nuclei. Small areas of light snow resulting from power plant and factory effluents entering supercooled fogs are sometimes noted. However, any observations of direct cause-effect relationships between man's activities and atmospheric processes are usually fortuitous. Without data gathering systems designed to detect specific incidences of inadvertent weather modifications, this "catch-as-catch-can" situation will continue.

Some photography obtained by manned orbital missions occasionally saw evidence of inadvertent weather modification. Figure 11 shows the east coast of the U.S. during a period of cold westerly flow over the warmer ocean. Cumulus formed, as expected, over the water. What is unusual is the two cumulus lines which begin considerably closer to the shore and downwind of the Baltimore and eastern Virginia industrial complexes. Landsat, while actually developed for studies of land usage, water quality, agriculture and the like, thus has the capability of making observations of sufficiently high resolution to detect many instances of inadvertent weather modification.

Landsat-1 took a remarkable series of images over Lake Michigan at 1003 CST, 24 November 1972, which apparently show modification of 1.5 km wide cumulus cloud streets by the effluents of the industries at the southern end of the lake (Figure 12). On this day, the Lake Michigan region was under the influence of southwest flow about a cold high pressure cell centered in Kentucky (Figure 12). Minimum temperatures west and south of the lake during the prior night ranged from 20F to 29F. A few scattered ship water temperature reports indicated that the lake surface had cooled to about 39-45F. Thus, the presence of cumulus over the relatively warm lake is as expected.

A pilot report over the western Michigan shoreline at the time of the Landsat image noted cloud tops of 2700 feet AGL, with clear skies above. The vertical extent of the clouds was apparently limited by the strong synoptic-scale inversion (Figure 13).

A closer inspection of Figure 12 reveals numerous interesting phenomena, the most important of which is the apparent alteration of the cumulus clouds along the axis of the major pollution plumes. The general cloud cover was largely restricted to the southern portion of the lake, perhaps a reflection of somewhat warmer water temperatures there. Experience and theoretical indications suggest that the optimum contrast between smoke and underlying water should occur around 0.65 μm, that is, within band 5 (Lyons and Pease [7]). In this case, however, the turbidity of the water was so considerable that MSS-band 6 (0.7-0.8 μm) achieved slightly better plume/water contrast.

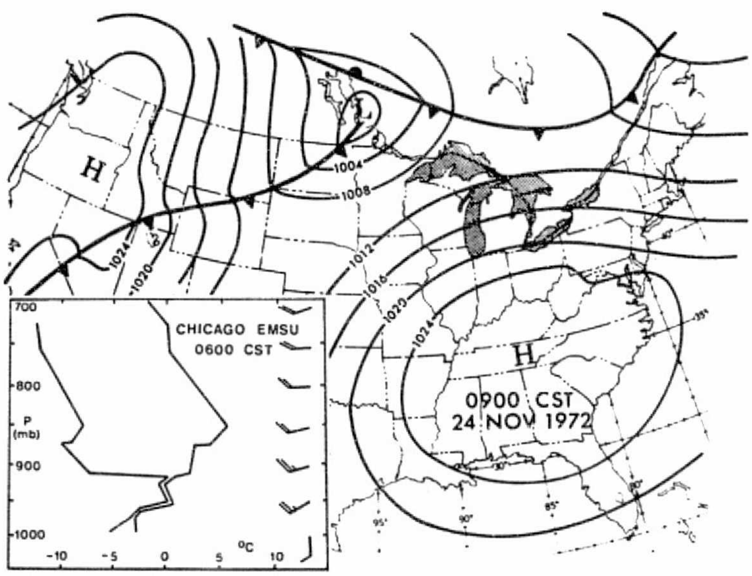

Figure 12. - Landsat-1 image, band 6 (0.7-0.8 micrometers), over southern Lake Michigan, 1003 LST, 24 November 1972. Image photographically enhanced. Only a very light snow cover actually was present. Midway Airport (MDW) shows clear skies, 31 degrees, and southwest winds. Four major particulate plumes emanate from shoreline sources. Cumulus clouds form over relatively warm lake, and those arising out of smoke plumes begin forming closer to shore and become larger and brighter.

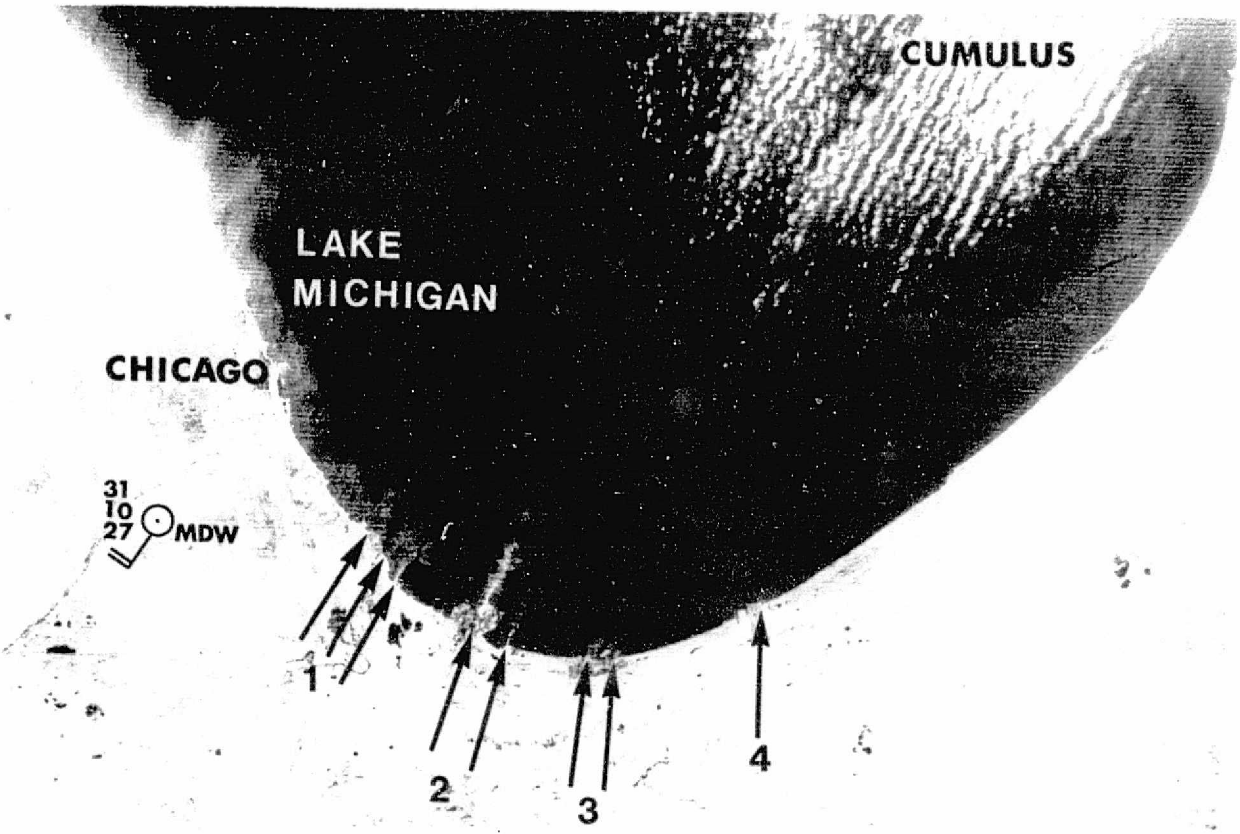

Figure 13. - Synoptic situation, 0900 LST, 24 November 1974. Inset shows Chicago radiosonde ascent at 0600 LST, with strong inversion present in lowest 4000 feet.

In Figure 12 it is quite clear (especially in the original 70mm transparencies) that four clusters of industries form large combined plumes that advect northeastwards over the lake while diffusing. The following behavior was noted along these plume axes: (1) the clouds began forming closer to the shore, the first fragments appearing within 15 km of the plume sources, and (2) the individual cloud elements forming the lines were larger and had higher reflectivities (and thus presumably were thicker). No particular enhancement of the cloud streets is noted within plume 4. This plume, however, is from an isolated steel mill complex which has very well-controlled particulate emissions and is smaller than those to the west. See Lyons [16] for additional details.

The Landsat observation showed that the cumulus cloud lines forming within the pollutant plumes began somewhat closer to the shore and were better developed than those presumably not affected by significant industrial effluent. Exactly what caused this behavior, however, is not discernable from a Landsat picture. Heat, moisture, ice nuclei, and cloud condensation nuclei are all candidates. Isolating the specific cause(s) awaits further study. The simple fact is that a mere image is not adequate to determine what has caused the effect. In situ measurements of nuclei concentrations and cloud microphysical parameters in conjunction with such satellite imagery would provide a powerful research tool.

What is exciting about the Landsat image is the fact that something indeed has been clearly related to industrial activity. A continued inspection of Landsat images in the vicinity of Chicago (and also Cleveland, Buffalo, etc.) could very well prove extremely enlightening.

If downwind cloud modification from industrial activity does indeed occur frequently, it would appear that any future attempts at management of Great Lakes water levels by operational cloud seeding might run into some very "interesting," or rather challenging, problems of verifying seeding effectiveness.

An extensive radar-echo climatology for the southern basin of Lake Michigan during three summer seasons revealed slightly greater frequencies of thunderstorm-related precipitation over the lake northeast of Gary than in other quadrants. What is rather startling about this finding is that the project set about to prove that lower echo frequencies should exist due to the well-documented suppressive effects of the lake on certain warm season convective rain systems. This tantalizing shred of evidence suggests that perhaps these same plumes act also as effective enhancers of warm season precipitation systems to the extent that the lake effects are more than cancelled out. The "La Porte Anomaly" could conceivably be part of a much larger area of urban precipitation enhancement northeast of Chicago-Gary which is unrecognized at this time due to lack of precipitation data over the lake itself.

Lyons and Olsson [17] reported occasionally seeing what appear to be lines of cumulus clouds growing out of the steel mill and power plant plumes around Chicago during periods of onshore flow in summertime. Figure 14 confirms these observations. The Landsat-1 band 6 image taken 1003 LST, 16 July 1973, shows cumulus around the southern basin of the lake. There was a light northeasterly flow present during the day along the southern and western shores. Cumulus appeared in a random manner after about 20 km of overland fetch - except downwind of several major steel mills and industries in Gary and Chicago where there were definite lines (arrows). What relationship these cloud lines might have, if any, to the urban enhancement of precipitation cannot yet be ascertained, but another effect upon convective clouds by industrial processes is clearly shown.

An additional effect of man's use of energy upon the environment has been reported by Lyons and Pease [18]. Man-made cirrus (ice crystal clouds) produced by the condensation trails (contrails) of high-flying jet aircraft are being considered as a potential modifying factor on both local and global climates. Under certain conditions of moisture, these artificial clouds may diffuse over much of the sky in thin films at heights above 20,000 feet. Denver has reported a significant increase in high cloudiness since 1958, when commercial jet traffic was inaugurated. Cirrus clouds, even though thin enough to see through, are highly reflective and can cause a significant amount of the sun's radiation to be returned to space. It is conceivable that man could be unwittingly altering the global energy budget in such a way as to induce disastrous changes in the earth's mean temperature. Assuming that the many computerized models of climate can someday be perfected, they will still be of little use if proper input parameters are not available. Much of the furor over the SST resulted from the lack of solid data as to how much increased cloud cover might result. Landsat has been shown capable of detecting jet contrails, and thus may serve as a prototype of a monitoring system able to make these arrangements.

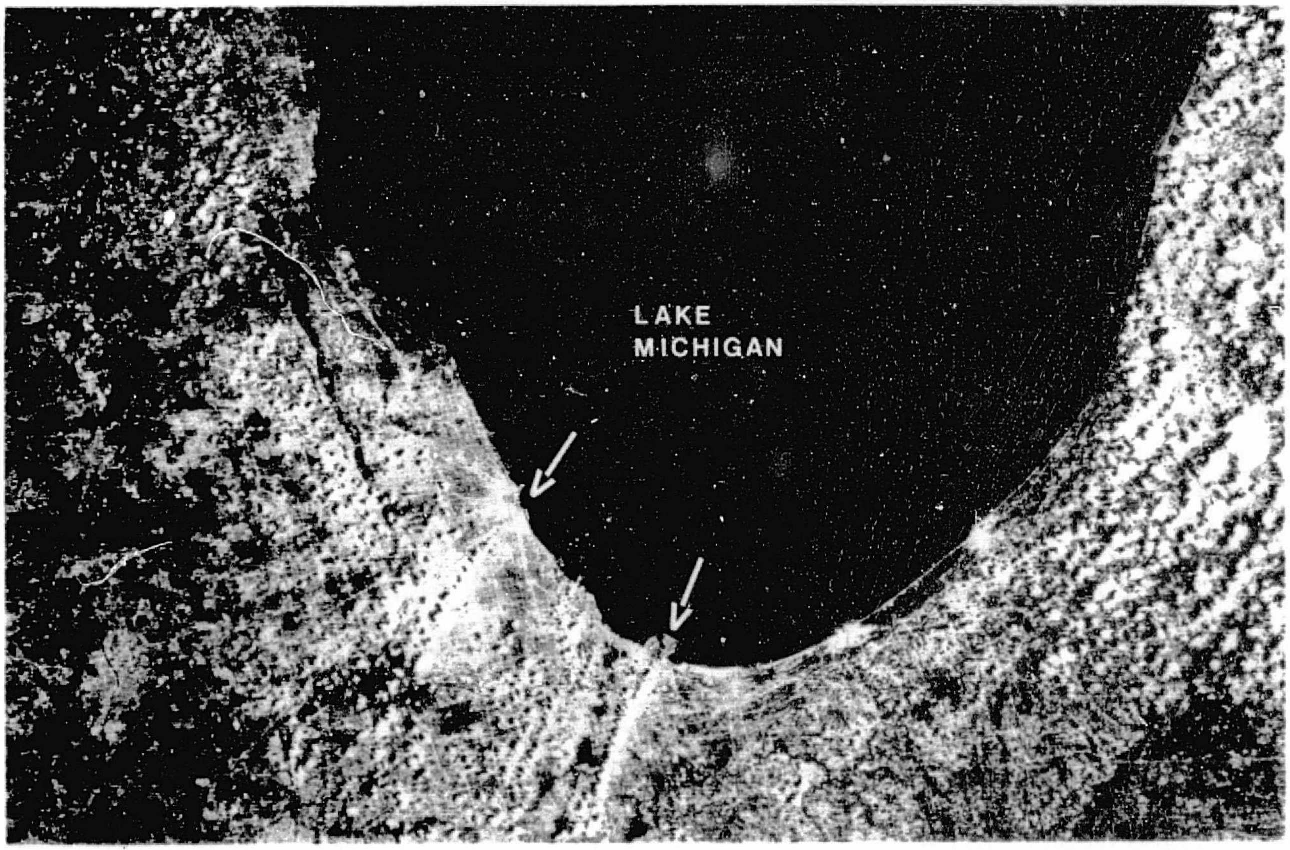

Figure 14. – Landsat-1 image, band 6, Chicago and southern Lake Michigan, 1003 LST, 16 July 1963. There was a general northeasterly flow throughout area, although a weak lake breeze was just pushing onshore along eastern shore. This caused the abrupt edge of cumulus there. Cumulus gradually reformed along the southern and western shore, with noticeable lines of clouds forming out of the plumes of major steel mills and industrial complexes (arrows).

Figure 17 shows another scene of the Milwaukee area on 20 October 1972. On this day considerable natural cirrus was present. An inspection of the band 4 image shows numerous contrails which, due to the high ambient humidity, were able to diffuse to great widths. Some were at least 11 km wide. In band 7 distinct contrail shadows could be seen on the ground.

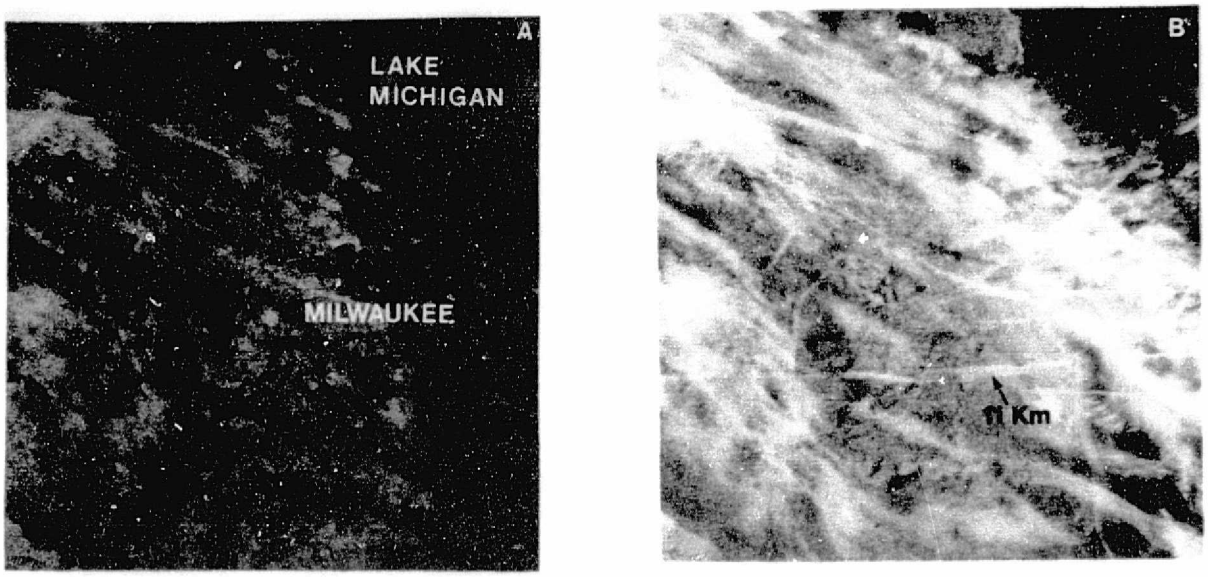

Figure 17(a) - Landsat-1 image, band 7, 1003 LST, 20 October 1972, over southeastern Wisconsin, revealing surprising degree of transparency of cirriform (ice) clouds in the near infrared. Also visible are distinct shadows from jet contrails.

(b) - Same, but for band 4, showing natural cloud cover commingled with jet contrails. In the moist environment at about 25,000 feet, some contrails have diffused to widths of at least 11 km.

NEEDS FOR THE FUTURE

A comprehensive evaluation of remote sensing for resource and environmental surveys (especially with respect to the Landsat System) has been prepared by the National Academy of Science [19]. It concurs that such systems as Landsat have shown considerable promise in assisting in the solution of many of the environmental problems being faced today. The multispectral scanner approach has been proven effective in its first full scale test from orbital altitude. The Academy recommended that work proceeded on several fronts including: (1) improving the sensor resolution by a factor of two to four, which should greatly help in the detection of smaller particulate plumes, (2) moving the Landsat system from an experimental to an operational basis, thus allowing for the receipt of data on a more frequent basis than the current 18 day cycle, and (3) the development of a thermal channel to expand the multispectral approach.

This last point is very important for many reasons. A sensor working in the 10-12 μm region with a resolution approaching that now achieved in the visible range would immensely add to the overall detection and identification powers of subsequent systems. It is unlikely that it would be of significant assistance in the detection of pollutants per se, but could be of enormous help in understanding the environment in which plumes disperse. In particular, if high resolution maps of lake water surface temperature could be obtained, it would be possible to better estimate atmospheric thermal stability over water. The extreme differences in atmospheric states existing between land observing stations, even just a few miles from a lake shore, and those over the water proper are just now being fully appreciated. For instance, Figure 18 shows a section of a Landsat-1 image of Lake Michigan, near Door County Peninsula, Wisconsin, on 18

April 1973. Southeasterly winds were advecting humid 65F land air over 35-45F lake water. An intense conduction inversion formed in the lowest 100m [11]. Conditions became saturated within this layer and a thin fog deck formed. Unusual wave patterns can be seen in the fog, indicative of the complex motions that can occur in stable air. More importantly, one sees that the fog bank extended inland only a few miles along the Wisconsin shoreline.

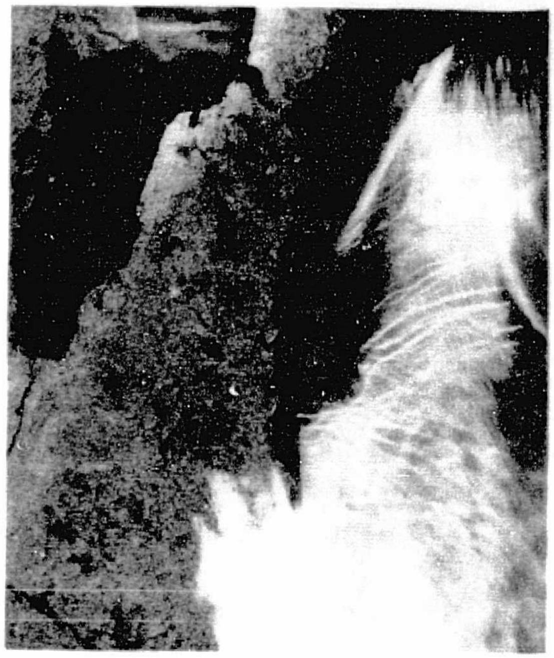

Figure 18. - Landsat-1 image, band 5, 18 April 1973, over Lake Michigan near Door County Peninsula, Wisconsin. Shallow fog within lake conduction inversion manifests complex wave patterns. Fog also extends inland several miles further down the coast.

Figure 19 is a summary of observations made on the Milwaukee shoreline on a similar type day. In the space of about 10 km, relative humidities vary from 55% to over 90%. Such intense local patterns, which occur frequently throughout the "warm season," are of considerable importance when one must design such energy related facilities as fossil and nuclear power plants, cooling towers, cooling ponds, etc. In almost all shoreline regions of the Great Lakes, official National Weather Service stations are too far inland to adequately measure shoreline meteorological conditions. The addition of a thermal channel to a Landsat successor system would be a big step towards obtaining the necessary climatological data base for this region. We could then make a more intelligent assessment of the environmental impact of numerous transportation and power production projects.

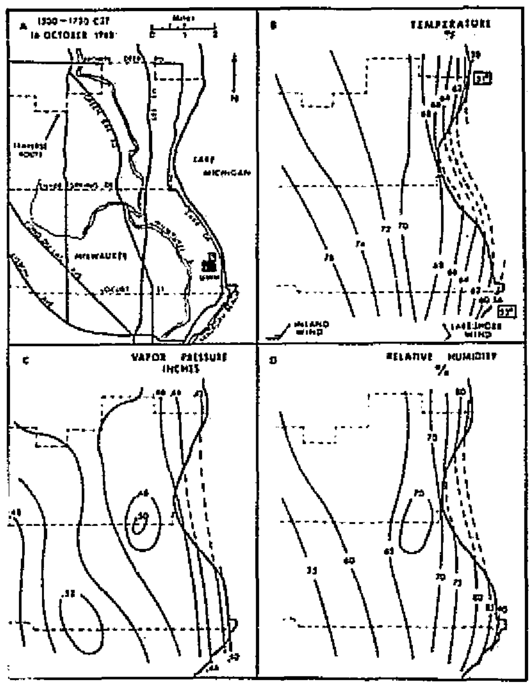

Figure 19 - Summary of observations of temperature and humidity made in Milwaukee on 16 October 1968 on a day with southeasterly onshore flow over a relatively colder lake. Notice strong gradient in relative humidity from 55% in western part of city to 90% at lakeshore. Data courtesy of Mr. John Chandik.

SUMMARY AND CONCLUSION

It has been shown that the monitoring of major suspended particulate plumes is feasible from satellite altitudes at least under ideal conditions. Increases in resolution and frequency of the data will be necessary in order for such to reach even a remotely operational status. At this time Landsat should not be considered for applications such as routine monitoring of such local events as cooling tower stratus and fog. But for studies of such phenomena as large (or even urban) scale smoke and turbidity patterns, jet contrails, air mass turbidity, and some aspects of inadvertant weather modification, numerous "targets of opportunity" do present themselves. It is not yet feasible to detect gaseous pollutants on the scale discussed in this paper, but there are rapid developments in sensor technology which may make such detection possible in the not-too-distant future.

It will be many years, perhaps decades, before satellite systems can be expected to become the prime air quality monitoring tool. The requirement for large numbers of *in situ* sensors will remain. But as sensor quality and data processing techniques increase in sophistication, satellite observations of at least certain air quality parameters will become both routine and vital additions to our information pool.

ACKNOWLEDGEMENTS

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ATTACHMENTS

1. W. A. Lyons and S. R. Pease. Detection of Particulate Air Pollution Plumes from Major Point Sources Using ERTS-1 Imaging. Bulletin of the American Meteorological Society. 1973. 1163-1170.

2. W. A. Lyons. Inadvertent Weather Modification by Chicago-Northern Indiana Pollution Sources Observed by ERTS-1. Monthly Weather Review. 1974. 503-508.

ATTACHMENT A

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DETECTION OF PARTICULATE AIR POLLUTION PLUMES FROM MAJOR POINT SOURCES USING LANDSAT-1 IMAGERY

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detection of particulate air pollution plumes from major point sources using ERTS-1 imagery[1]

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Abstract

The Earth Resources Technology Satellite (ERTS-1) launched by NASA in July 1972 has been providing thousands of high resolution multi-spectral images of great interest to geographers, cartographers, hydrologists, agriculturists, etc. The meteorological content of these observations, however, has only been slightly realized. In particular, it has been found possible to detect the long-range (over 50-km) transport of suspected particulate plumes from the Chicago-Gary steel mill complex over Lake Michigan. The observed plumes are readily related to known steel mills, a cement plant, refineries, and fossil-fuel power plants. This has important ramifications when discussing the inter-regional transport of atmospheric pollutants, in this case from the Chicago Interstate to the Southeast Wisconsin Air Quality Control Region. Analysis reveals that the Multispectral Scanner Band 5 (0.6–0.7 μm) provides the best overall contrast between the smoke and the underlying water surface.

1. Introduction

The Federal Clean Air Act of 1967 (amended 1970) divided the United States into Air Quality Control Regions (AQCR). The boundaries of these regions were ideally to be chosen to delineate independent self-contained "air sheds" where air quality levels would be determined by dispersion from sources within that region. The actual boundaries selected often were compromises between meteorological and political realities. An AQCR's final compliance with national Air Quality Standards is ultimately dependent upon the successful formulation and implementation by regional authorities of the necessary emission control strategy for sources within that region. In reality, however, two adjacent AQCR's might occasionally find themselves breathing each other's effluents due to long-range inter-regional transport of pollutants. A case in point is the Southeast Wisconsin AQCR (the seven counties of southeastern Wisconsin, including metropolitan Milwaukee) and the Chicago Interstate AQCR (northeast Illinois and the two northwesternmost counties of Indiana). In the latter, there exist numerous extremely large point sources, especially of suspended particulates from steel mills, fossil-fuel power plants, refineries, and cement operations. The evidence has gradually been accumulating that these sources are indeed more than just local problems.

In August 1967, the principal author participated in a flight of an NCAR Queen Air, instrumented to monitor ice nuclei (Langer, Biter, and Dascher, 1968). The object of the study was the dispersion of anthropogenic ice nuclei emanating from the Chicago-Gary steel mill complex. Under conditions of brisk southwesterly flow over southern Lake Michigan, with a rather strong synoptic-scale capping subsidence inversion around 1300 m, a clearly defined plume of ice nuclei was easily tracked to the vicinity of Battle Creek, Mich. (some 170 km downwind). More recently, on a spring day with south-southeast flow up the lake, elevated layers of red iron-oxide smoke were seen drifting past Milwaukee (Fig. 1). Again the most likely origin of this smoke was the mills at the southern end of the lake—160 km away.

The effect of the much larger Chicago Interstate AQCR is probably significant, but most difficult to ascertain qualitatively. It has been estimated that approximately 10% of the suspended particulates measured in

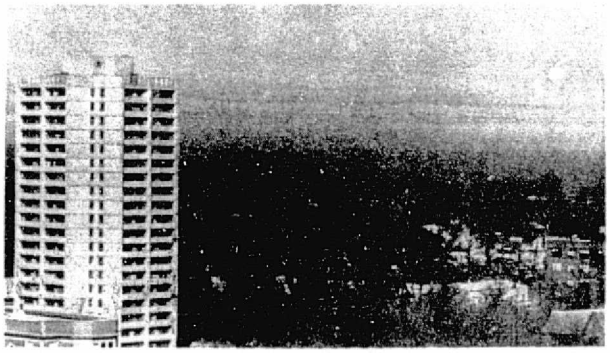

FIG. 1. Photograph, looking east, from University of Milwaukee–Wisconsin campus, showing layers of iron oxide red smoke over Lake Michigan, during brisk south-southeast winds and very stable conditions in March 1973. The source of the smoke is presumably the Chicago-Gary area.

[1] This paper is Report No. 10, Air Pollution Analysis Laboratory, University of Wisconsin–Milwaukee.

FIG. 2. Smoke plume from large fossil fuel power plant located south of Milwaukee's Mitchell Airport (MKE). This plume, photographed looking north from an NCAR Queen Air on 22 August 1968, was advecting over a relatively cold lake. The air was so stable that the plume could be seen extending for over 100 km to the east.

the Milwaukee area originate in and around Chicago.[2] Frequently in Milwaukee, several hours after the surface winds shift to the south or southeast, there is a rapid increase in haze and smoke, presumably the influence of inter-regional transport from the Chicago area. Certainly in any megalopolis, such as found along the East and West Coasts, adjacent AQCR's would indeed be expected to be exchanging pollutants.

In the emerging Great Lakes megalopolis, which shows signs of extending from Green Bay, Wis., to Buffalo, N.Y., in the not-too-distant future, the peculiar meteorological effects of the Great Lakes often exacerbate this inter-regional transport. When continental air masses advect across the relatively warm lakes in winter, any plume moving over a Great Lake will be rapidly dispersed. Turbulence generated by the free convection rising from the surface can be extreme, sometimes to the point of generating a myriad of miniature waterspouts or "steam devils" (Lyons and Pease, 1972). Thus, if plumes from northern Indiana are to pass over Lake Michigan to southwestern Michigan or Wisconsin, they probably arrive diluted to an extreme degree. From early spring through late summer, quite the opposite situation prevails: air temperatures frequently exceed those of the lake by 10, 20, or sometimes 30C. Extremely intense, though shallow (100–200 m) surface conduction inversions form over the lake (Lyons, 1970). Air streams advecting over cold lakes not only are rapidly cooled in their lowest layers, but due to the absence of upward convective heat transport do not warm and destabilize in the overlying layers, as they do over land during the day. The almost total lack of cumulus clouds over the Great Lakes on summer afternoons is one manifestation of this stabilizing process (Lyons, 1966). A plume from a large elevated point source such as a steel mill or power plant may travel for long distances over water with relatively little dilution and arrive on a downwind shoreline in still very high concentrations. Fig. 2, a plume from a large fossil fuel power plant south of Milwaukee, dramatically illustrates the point.[3] This plume could be seen extending over 100 km to the east with minimal dispersion evident. If such a plume arrives on a downwind shore during mid-day and insolation is sufficient, it is fumigated to the surface after a few kilometers of inland travel (Lyons and Cole, 1973) and may cause high pollution levels, the origin of which could be quite baffling to local control officials.

That there is inter-regional pollution transport in the vicinity of the Great Lakes is clear, but measurement of actual amounts is a problem. Until recently, reliable instruments for measuring total suspended particulate matter using an aircraft in real time was not available. Even with technology providing the measuring device, obtaining a quasi-synoptic profile of plumes extending for at least 100 km downwind from an area as large as Chicago-Gary is both difficult and expensive, particularly if such measurements are needed on a semi-regular basis. The ideal solution would be a satellite monitoring system. Until recently no satellite was capable of such observations, but with the launching of NASA's Earth Resources Technology Satellite (ERTS-1) on 23 July 1972, the prospect has improved markedly.

2. The Earth Resources Technology Satellite

ERTS was designed specifically for environmental monitoring. It was placed in a nearly circular, 99.11 degree orbit, nominally about 915 km, with a period of 103.267 minutes. The sun-synchronous orbit has a descending node time of 0942 LST. Images are 185 by 185 km on a side. It takes 251 revolutions (18 days) to make one complete global coverage. Thus every portion of the earth (between 81° north and south latitude) is viewed at least once every 18 days. At the latitude of Chicago, there is approximately 35% horizontal image sidelap, so some locations can be seen on successive days. A one-year mission life was contemplated and, as of March 1973, more than 34,000 images had been collected. All images are characterized by a zero or near-zero zenith angle, with illumination depending on the solar elevation angle, a function of date and latitude of observation.

The two great advantages of ERTS are its extremely high resolution and a multi-spectral imaging capability. The original specifications for the multi-spectral scanner (MSS) called for 100–200 m resolution. Initial results have shown some high contrast targets as small as 50 m. Highways, airport runways, small ponds, jet contrails, harbor breakwaters, etc., are routinely visible. The four spectral bands are 1) MSS-4, 0.5–0.6 μm ("green" band);

[2] "A Statewide Implementation Plan to Achieve Air Quality Standards for Particulates, Sulfur Oxides, Nitrogen Oxides, Hydrocarbons, Oxidants, and Carbon Monoxide in the State of Wisconsin." Regulations proposed by the State of Wisconsin, Department of Natural Resources, January 1972.

[3] Subsequent to the taking of this photograph in 1971, the particulate emissions from this power plant were largely eliminated.

2) MSS-5 0.6–0.7 μm ("red" band); 3) MSS-6, 0.7–0.8 μm; and 4) MSS-7, 0.8–1.1 μm ("near infrared" band). ERTS products are available in several formats including digital tapes, 9-1/2 by 9-1/2 inch black and white and color prints and transparencies, and most routinely, 70-mm negative and positive transparencies (Mac Callum, 1973).[4]

Because the four spectral bands are viewed simultaneously in space and time, it is possible to use color-additive viewing techniques to produce color-coded results. Combining MSS bands 4, 5, and 7 results in a false-color infrared image. The red color associated with foliated vegetation makes this color analysis a valuable diagnostic tool in agriculture, forestry, and land-use studies, but for the meteorologist the ERTS multispectral imaging techniques are most useful in penetrating thick haze, revealing cloud shadows, delineating snow cover from vegetation, and demarcating land/water boundaries.

The various design characteristics prompted the UWM Air Pollution Analysis Laboratory to submit a proposal to study ERTS-1 data. Before launch, it was hoped that a satellite with these characteristics would be capable of detecting major plumes of suspended particulates, making possible synoptic studies of inter-regional pollution transport over the southern Lake Michigan basin.

3. The study area

The heart of the Chicago-Gary industrial complex stretches from the southeastern part of the City of Chicago eastwards along the shoreline of Lake and Porter Counties, Indiana, to the east of Gary. Fig. 3 is an aerial view of a part of this region, taken from an NCAR Queen Air at an altitude of about 200 m early on the morning of 15 July 1968, when brisk southwesterly flow was advecting numerous smoke plumes over the lake.

A total of 16 major particulate sources have been located in the study area (Figs. 3 and 6). The estimated annual output of particulates (provided by local air pollution control officials) and the source type are listed in Table 1. The size of some of these sources is truly remarkable. Source 3, for example, a cement plant, discharges over 140,000 tons/year of particulates. In comparison, all of Milwaukee County, Wis., a relatively industrialized area, had a 1970 suspended particulate emission of only approximately 45,000 tons/year.

4. The observation

During the morning of 1 October 1972, brisk southwest surface flow covered the southern Lake Michigan basin area (Fig. 4). A bank of altocumulus clouds, associated with a trough, was present to the north and east of the Chicago region and was moving rapidly northeastwards. A strong nocturnal radiation inversion had been

[4] Details on ordering ERTS products can be directed to: The EROS Data Center, U.S. Department of the Interior, Geological Survey, 10th and Dakota Aves., Sioux Falls, S.D. (605) 339-2270.

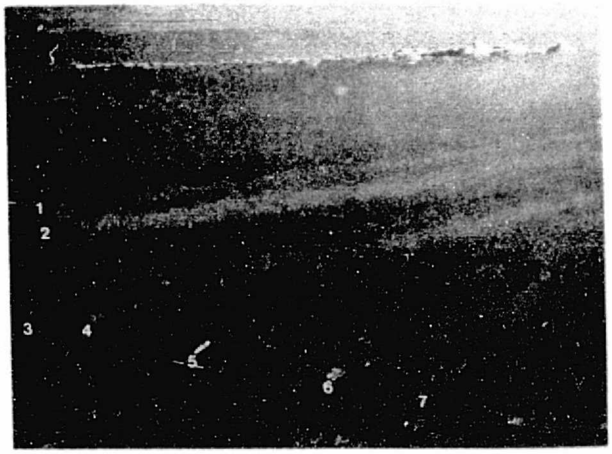

FIG. 3. Photograph (looking north) of a portion of the Chicago-Gary industrial complex, taken from an NCAR Queen Air, on the morning of 15 July 1968. The numbers refer to the sources listed in Table 1.

present at 0600 CST according to the Peoria, Ill. (PIA) sounding (inset, Fig. 4). The synoptic situation was thus similar to that when the aircraft photographs shown in Fig. 3 was taken. Figures 5 and 6 are portions of the ERTS images taken at approximately 1003 CST.[5] They have been enlarged to show a region approximately 90 n mi wide. Figure 5, in band MSS-4, appears to be a relatively low-contrast image. Any plumes emanating from the steel complex are barely discernible, the radiance of the lake surface being so large as to be comparable to that of the smoke plumes in that portion of the spectrum. The 1000 CST airway observations are superimposed. However, in Fig. 6, band MSS-5, a number of particulate plumes can be seen streaming northeastward, disappearing beneath the altocumulus cloud deck

[5] NASA ERTS Image Identification Number 1070 16041.

TABLE 1. Estimated annual tonnage of suspended particulate emissions from major point sources in the Chicago Interstate Air Quality Control Regions.

No.	Type source	Emissions (tons/year)
1	Steel mill fabrication	20,394
2	Steel mill	82,474
3	Cement plant	142,675
4	Fossil fuel power plant	1,952
5	Steel complex	88,597 (sources 5–8)
6	Steel complex (open burning)*	
7	Steel complex	
8	Steel complex	
9	Steel mill	24,000
10	Fossil fuel power plant	4,752
11	Steel mill/fabrication	4,000
12	Steel mill	5,900
13	Oil refinery	1,596
14	Oil refinery	1,978
15	Oil refinery	1,014
16	Steel mill	3,562

* Probably short-lived ground site.

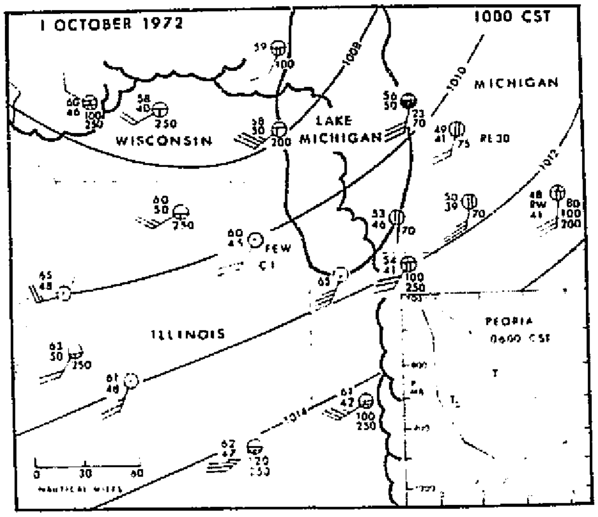

FIG. 4. Synoptic conditions, 1000 CST, 1 October 1972. An overcast area of altocumulus is present to the north and east of the study area. Isobars every 2 mb, one wind bar equals 5 kt. Inset shows 0600 CST Peoria, Ill., radiosonde.

at a distance of about 60 km. The solar elevation angle is approximately 40°.

It should be noted that due to the various degradations involved both in making the photographic print and in publication, the plumes do not appear as clear as in the original 70-mm negatives. The prints were also photographically dodged to maximize details over both land and water.

The plumes in these images, for the most part, are combinations from several point sources. The most pronounced plume, from source 8, is not exclusively from a single stack, but from an entire mill complex, with one stack dominating. The total spread of the visible plume at 60 km downwind is about 4.5 km. The plume apparently emanating from source 2 actually is the combined result of emissions from two large steel complexes (with probably 30 stacks in total) plus smaller plumes from refineries upwind from the shoreline (sources 14 and 15). The cement plant, source 4, can be seen emitting its own discrete plume; however, it is only detectable for about 10 km out over the lake. It would seem likely that, in the period just prior to ERTS's passage, it was emitting at a rate far less than its yearly average would suggest.

Measurements of plume spread can be converted into useful information regarding over-water mesoscale diffusion of pollutants. First, however, it must be determined what the visible edge of the plume represents in reality. Sometimes, the visible plume may be correlated to a parameter such as the point where concentrations drop off to 10% of the centerline value, or 2.15 σ_y, in the parlance of Pasquill (1961) and Gifford (1961). If that were the case, then this plume would appear to have a diffusion rate characteristic of Class E (rather stable atmosphere) in the empirical classification of atmospheric stabilities used in Gaussian plume diffusion calculations. Until aircraft measurements of suspended particulates are made in conjunction with ERTS images to relate radiance to some physical parameter, the actual estimates of plume spread characteristics must remain tentative.

5. Analysis

An important consideration is the choice of the appropriate ERTS spectral band to provide optimum discrimination of a particulate plume against the underlying surface, in this case water. The plume will be most visible on the photograph when the difference between the optical density of the plume image and the optical density of the lake-surface image is greatest. Plume visibility over a water surface will thus be enhanced by: 1) decrease in the spectral albedo of the lake surface, 2) increase in overall image contrast, and 3) increase in the amount of radiation scattered and/or reflected vertically upwards from the solar beam by the plume. In the case of a plume advecting over a surface of very high spectral albedo, a fourth factor would have to be considered: the extent to which a plume attenuates solar radiation reflected vertically upwards from the surface, a factor dependent on the geometry of scattering and absorption of radiation by the plume.

The first of these major considerations, the spectral albedo of the lake surface, shows a marked variation by wavelength. Direct reflection of solar radiation from the lake surface makes a relatively minor contribution to the variation of lake albedo in the four ERTS bands. Reflection vertically upwards from the lake surface is small, of the order of 2%, and for a solar elevation angle of 40° shows only slight wavelength dependence, with very slightly higher values in the lower wavelengths of the visual spectrum (Kondratyev, 1969).

Far more important in influencing the spectral albedo of the lake is the wavelength dependence of solar radiation absorption within the lake itself. The lower the spectral absorption coefficient within the lake for any wavelength, the greater is the penetration of incident solar radiation into the lake and the greater is the likelihood of backscattering upward by water molecules and hydrosols, i.e., Rayleigh and Mie scattering respectively. For distilled water, maximum transmissivity occurs at 0.46 μm, and absorption increases rapidly with increasing wavelength, resulting in a darker lake image. As an example, the mean absorption coefficient for pure water in ERTS band MSS-4 is approximately six times less than the coefficient for MSS-5, and the lake thus should appear brighter. Increased amounts of suspended and dissolved matter shift the wavelength of minimum absorption and maximum lake albedo to longer wavelengths. According to Kondratyev (1969), sea water (and lake water?) typically has minimum absorption near 0.55 μm, which is the center of ERTS band MSS-4.

An additional consequence of the greater transparency of water in the blue and green portion of the spectrum occurs in the case of shallow water, where reflection from the lake bottom may further increase values of surface lake albedo and limit the ability to detect pollution plumes near shore.

Another important factor influencing lake spectral albedo is the variation by wavelength of scattering geometry beneath the lake surface. As Rayleigh scattering has more pronounced backscatter than Mie scattering, increased Rayleigh scattering will produce higher values of lake spectral albedo In the blue portion of the spectrum, about 40% of all scattering within the lake is Rayleigh scattering by water molecules. In contrast, at the center of band MSS-5 (0.65 μm), only about one in every 35 scattering events is typically molecular Rayleigh scattering (Plass and Kattawar, 1969); the rest are strongly forward-scattering Mie scattering events produced by hydrosols. This, coupled with the higher absorption coefficients at longer wavelengths, produces a much darker lake image in band 5 than in band 4. In fact, in the near infrared (MSS-7), water surfaces appear black, the result of very high absorption coefficients of the lake water and the very low amounts of Rayleigh backscattering at long wavelengths.

All other factors constant, a higher value of lake spectral albedo will produce a higher value of upward hemispheric radiant flux. The surface albedo is a measurement of the ratio of radiation reflected or scattered upwards in all directions, i.e., upward hemispheric radiant flux immediately above the surface, to incident downward hemispheric flux. The very narrow scan angle of the ERTS scanner, however, intercepts only that portion of the total flux that is directed vertically upwards. Spectral variations in directional radiation intensity (radiance) in the upward vertical direction may exceed spectral variations in the total hemispheric radiant flux which is produced by difference in lake spectral albedo, including reflect n in all directions. In a theoretical study by Plass and Kattawar (1969) of the angular distribution of the radiance over an ocean surface, it was found that for a solar beam incident angle near 40% (as in the present study) and a wavelength of 0.65 μm (MSS-5), a pronounced minimum of upward radiance in the vertical direction occurs which is an order of magnitude smaller than maximum values found near the horizon. For shorter wavelengths, however, upward radiance is distributed much more uniformly over all zenith angles, and the radiance value in the vertical direction is several times greater than at 0.65 μm. If a similar qualitative relationship holds over a turbid lake, then the greater angular variations of radiance at longer wavelengths would further accentuate differences in spectral albedo to produce darker lake images with increasing wavelength.

The second major consideration limiting our ability to detect particulate plumes against an underlying surface is reduction of overall image contrast. Atmospheric Rayleigh scattering and Mie scattering from haze or pollution layers generally act to increase overall radiance. Because image density of a positive transparency ideally is inversely proportional to the logarithm of exposure and hence, in the case of ERTS imagery, to the logarithm of the radiance, a given increase in radiance due to atmospheric scattering will produce a greater decrease in image density for a low radiance target than for a high radiance target. As a result, the photographic image of a low-albedo target such as a lake shows a greater increase in brightness due to atmospheric scattering than does a highly reflective target such as a cloud or pollution plume, and overall image contrast is reduced. Because scattering varies with wavelength, maximum inherent image contrast (defined for convenience as the difference in photographic density between a target having an albedo equal to unity and a target with zero albedo), will also show variation between spectral bands.

Greatest variation of maximum inherent image contrast between ERTS spectral bands occurs as a result of sky luminance produced by Rayleigh scattering. Although Rayleigh scattering is most pronounced at the short-wavelength end of the visual spectrum, the average Rayleigh scattering coefficient in ERTS band MSS-4 (0.5 to 0.6 μm) is still relatively high, amounting to 45% of the coefficient for 0.4 to 0.5 μm (Kondratyev, 1969), but decreases rapidly for longer wavelengths. The spectral variation of Mie scattering by atmospheric aerosols is much less than for Rayleigh scattering and is marked by gradual decline with increasing wavelength. Computer simulation models of Rayleigh and Mie scattering in a normally hazy atmosphere (Plass and Kattawar, 1968) indicate that maximum inherent image contrast (as defined above) may be over twice as great at 0.7 μm as at 0.4 μm, and maximum inherent image contrast is even greater in the near infrared. Increasing aerosol content increases the contribution of Mie scattering, produces a more uniform distribution of radiance over all zenith angles (i.e., more isotropic), and increases values of upward radiance in the vertical direction. The resulting reduction of image contrast with increase in aerosol content occurs for all wavelengths, but is most pronounced for shorter wavelengths of the solar spectrum (Plass and Kattawar, 1970).

The combined effects of high lake spectral albedo and low inherent image contrast can be seen by examining Fig. 5. Although urban features of the Chicago-Gary area, regions of high turbidity in Lake Michigan, and the deck of altocumulus to the northeast are readily visible, plumes advecting over the lake from Gary and Chicago are virtually undetectable at distances exceeding 5 to 10 km downstream from the lakeshore because of the bright lake and reduced image contrast. Attempts to enhance contrast photographically through dodging and use of high contrast paper rendered plumes visible only very near shore where particulate concentrations were highest.

From the above discussion, it might be expected that the optimum spectral band for plume tracking over a lake, in the absence of ice cover, would fall in the near-

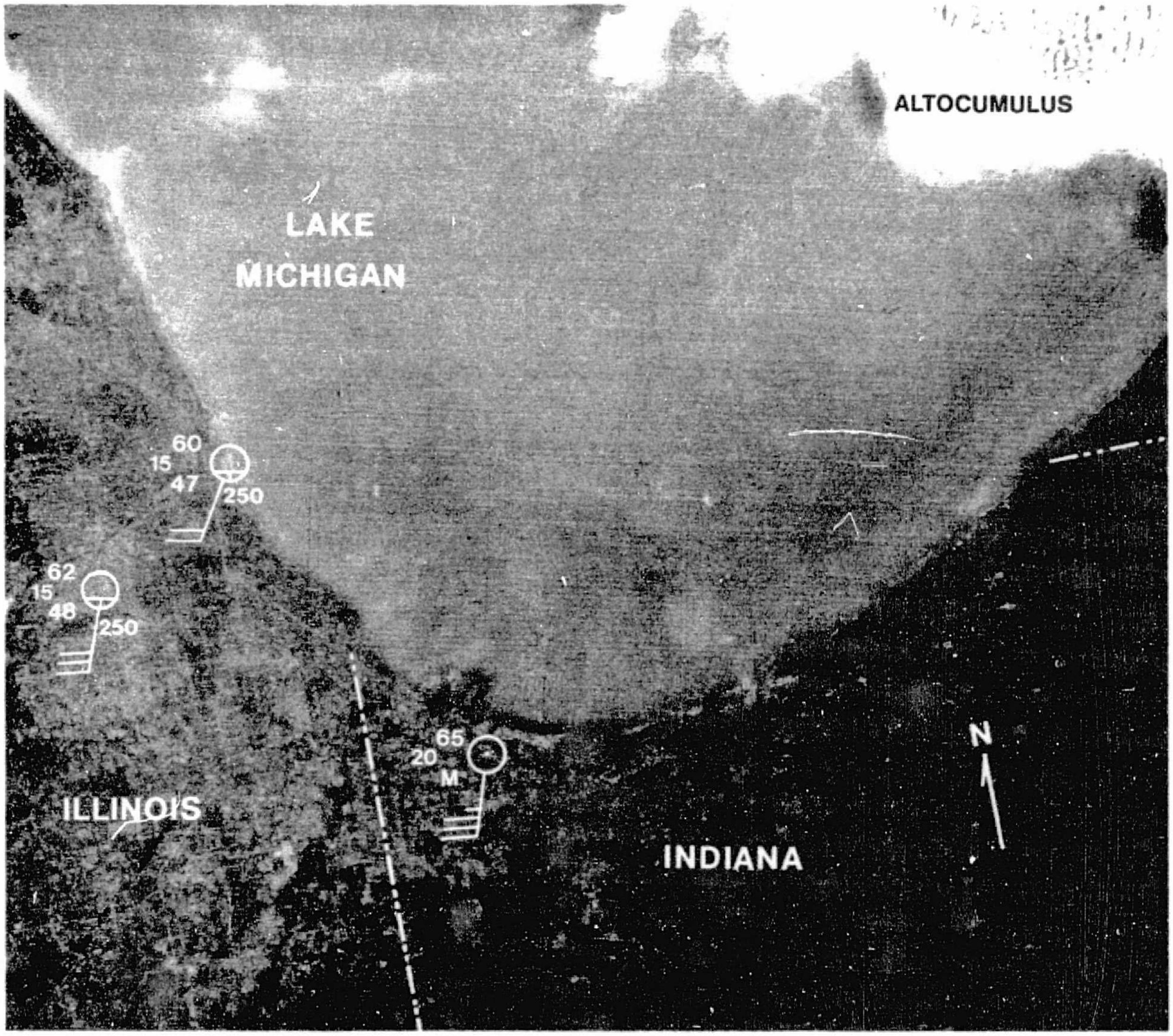

FIG. 5. ERTS-1 image, MSS-4 (0.5–0.6 μm) taken at 1003 CST, 1 October 1972. Aviation weather observations superimposed.

infrared range. For band MSS-7 (0.8 to 1.1 μm), sky luminance is negligible, and a high absorption coefficient for the lake water produces very low spectral albedo values and a very dark lake image on a positive photograph. For liquid-water clouds, whose albedo is practically independent of wavelength up to 1.3 μm (Kondratyev, 1969), band MSS-7 does indeed provide maximum contrast in image density between cloud and lake. Such does not seem to be the case for particulate plumes, however, because of a third major consideration: the spectral variations in albedo of a dense particulate plume. Data on the geometry of multiple scattering and diffuse reflection from pollution plumes are limited. However, tables of primary Mie scattering (deBary *et al.*, 1965) indicate a dependence of angular scattering intensities on wavelength, as mentioned above. For the present case, considering scattering vertically upwards from a solar beam with an elevation angle of 40°, primary scattering coefficients in the near-infrared (1.0 μm) are only 45 to 75% of the values at the center of the green band (0.65 μm). Furthermore, computer simulation models of short-wave radiative transfer in a highly turbid aerosol layer (Plass and Kattawar, 1972) show higher values of upward radiance (measured at the top of the atmosphere) at 0.7 μm than at 0.9 μm (within band MSS-7) for all zenith angles. If the same qualitative relationship holds in the case of multiple scattering in a highly turbid particulate plume, then maximum inherent brightness should occur in the lowest visual wavelengths rather than in the near infrared.

Thus, from various theoretical considerations it would appear that the poorest plume discrimination above a water surface would be in the shortest wavelengths, as confirmed by MSS-4 (Fig. 5). On the other hand, while it was initially expected that the near-infrared (band 7) would optimize plume contrast over water, as is the case with liquid-water clouds, the higher inherent brightness of plumes in the visible spectrum results in the "red" band being the best for smoke detection. The plumes were visible in bands MSS-6 and 7; band 5, however, provided the best compromise between the high lake spectral albedo and low contrast of the shorter wavelengths and the diminished plume albedo in the longer wavelengths.

6. Conclusions and future research

From this case study, it now appears highly likely that when the proper meteorological conditions (south-southeasterly winds) coincide with an ERTS passage, we will be able to detect major air pollution plumes entering the Southeast Wisconsin "airshed" from sources over 100 km removed. If it can be shown that this interregional pollution transport contributes significantly to the observed particulate levels in the Milwaukee area, a most interesting question will arise. If Southeast Wisconsin fails to reach its air quality standards for suspended particulates, should it be penalized for the "sins of emission" of other regions?

While ERTS images such as the ones discussed are of great interest in themselves, their value is somewhat limited by the unavailability of actual "ground truth" supporting data. UWM's Air Pollution Analysis Laboratory has now instrumented a Cessna 336 aircraft with an array of air pollution and meteorological sensors. Included are fast response devices for monitoring total suspended particulate mass loadings and particle concentrations in several size ranges. Onboard processing and tape data logging will make it possible to fly repeated profiles of selected plumes coincident with ERTS. Thus it may be possible to determine radiance/mass

FIG. 6. ERTS-1 image, MSS-5 (0.6–0.7 μm). Smoke plumes clearly visible. Numbers refer to sources listed in Table 1. Altocumulus clouds are visible to northeast. Patches of cirrus and near shore water sediments can also be noted.

loading relationships, and also to ascertain how well the actual plume conforms to the Gaussian profile so often imposed in numerical studies. Densitometric analysis of ERTS negatives would also accompany such studies.

Unless they are unusually dense, smoke plumes are harder to detect over land than over water. Land surfaces are generally much brighter than water and exhibit marked spatial and seasonal variations in radiance. Using false-color infrared, at least during summer, seems to be reasonably successful at times, but visual detection of many plumes may not be routinely possible. The next analysis step then should be smoke detection by computerized pattern recognition techniques employing the primary ERTS digital tape data rather than photographically reconstructed products.

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ATTACHMENT B

INADVERTENT WEATHER MODIFICATION BY CHICAGO-NORTHERN INDIANA POLLUTION SOURCES OBSERVED BY ERTS-1

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Inadvertent Weather Modification by Chicago-Northern Indiana Pollution Sources Observed by ERTS-1[1]

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ABSTRACT

NASA's Earth Resources Technology Satellite (ERTS) now provides extremely high resolution (50–200 m) multi-spectral images of any given portion of the earth (between 81° north and south latitude) every 18 days. These are the best unmanned satellite data to date for the detailed study of mesoscale cloud patterns. An ERTS view of the southern basin of Lake Michigan at 1000 CST, 24 November 1972 reveals what certainly appears to be an example of inadvertent weather modification. Cold southwesterly air flow is producing the usual cumulus cloud activity over the relatively warm lake. What is unusual, however, is that the easily visible smoke plumes from a number of major industrial complexes in the Chicago-Gary, Ind., area appear to be markedly affecting the cumulus patterns. Cloud streets developing over Lake Michigan are observed to undergo enhancement when aligned with the industrial plumes. Specifically, the cumulus elements of the cloud streets become larger and brighter (and presumably thicker) than those forming in "unpolluted" air.

1. Introduction

Man's inadvertent modification of the earth's climate and weather has recently become a much studied topic in the meteorological community. As summarized by the Presidential Council on Environmental Quality (1970), there exists a wide spectrum of potential mechanisms. Proper assessment of the many theories, however, must await the collection of a considerable body of appropriate climatolgical data and the development of reliable numerical models of global climate. More amenable to immediate study are local climatic variations and the specific weather alterations from which they arise. In the area of man-made influences on cloud and precipitation processes, however, speculation seems still to outstrip proven fact. The La Porte, Ind., precipitation anomaly is a case in point (Changnon, 1968). The existence of the La Porte anomaly as a physical reality, rather than an example of spurious data, has not at all been universally accepted. While Hidore (1971) tended to agree that a localized precipitation near La Porte did indeed exist, others disputed the fact (Holzman and Thom, 1970). Studies of tree rings (Ashby and Fritts 1972), and vegetation types (Harmon and Elton, 1970), did not yield conclusive evidence one way or the other.

Thus, some doubt even the existence of the La Porte anomaly. In any case, if it is real, it is still an effect searching for a cause. The same can be said for apparent precipitation increases downwind of numerous large urban areas, estimated as high as 27% of the summer season rainfall by Huff and Changnon (1972). The list of possible causes includes: 1) anthropogenic sources of ice and condensation nuclei from industrial and perhaps automotive sources, 2) inputs of sensible heat from urban sources, 3) inputs of moisture from certain industrial activities, and 4) changes in boundary layer wind flows due to variations in surface thermal and roughness characteristics. Project METROMEX[2] is currently trying to assess the magnitude and isolate the cause(s) of urban-induced weather changes in the St. Louis, Mo., area.

The La Porte and St. Louis studies have one feature in common. Proof of any effect will be obtained as a result of sophisticated statistical tests on vast amounts of climatological data correlated with numerous case studies involving extensive physical measurements. It is a relatively rare event when the atmosphere is actually "caught in the act" of responding to man's activities. Some exceptions can be noted, such as cirrus contrails spreading over a sky, altering surface radiation values (Jacobs, 1971), cooling ponds and towers producing localized fogs, clouds, and light rain or snow (Hewson, 1970), and valleys filled with fog from industrial sources of moisture and nuclei. A small area of light snow resulting from power plant and factory effluents entering a supercooled fog was described by Agee

[1] Report Number 94, Center for Great Lakes Studies, University of Wisconsin-Milwaukee.

[2] See "Project METROMEX: A Review of Results," *Bull. Amer. Meteor. Soc.*, 55, February 1974, pp. 86–121.

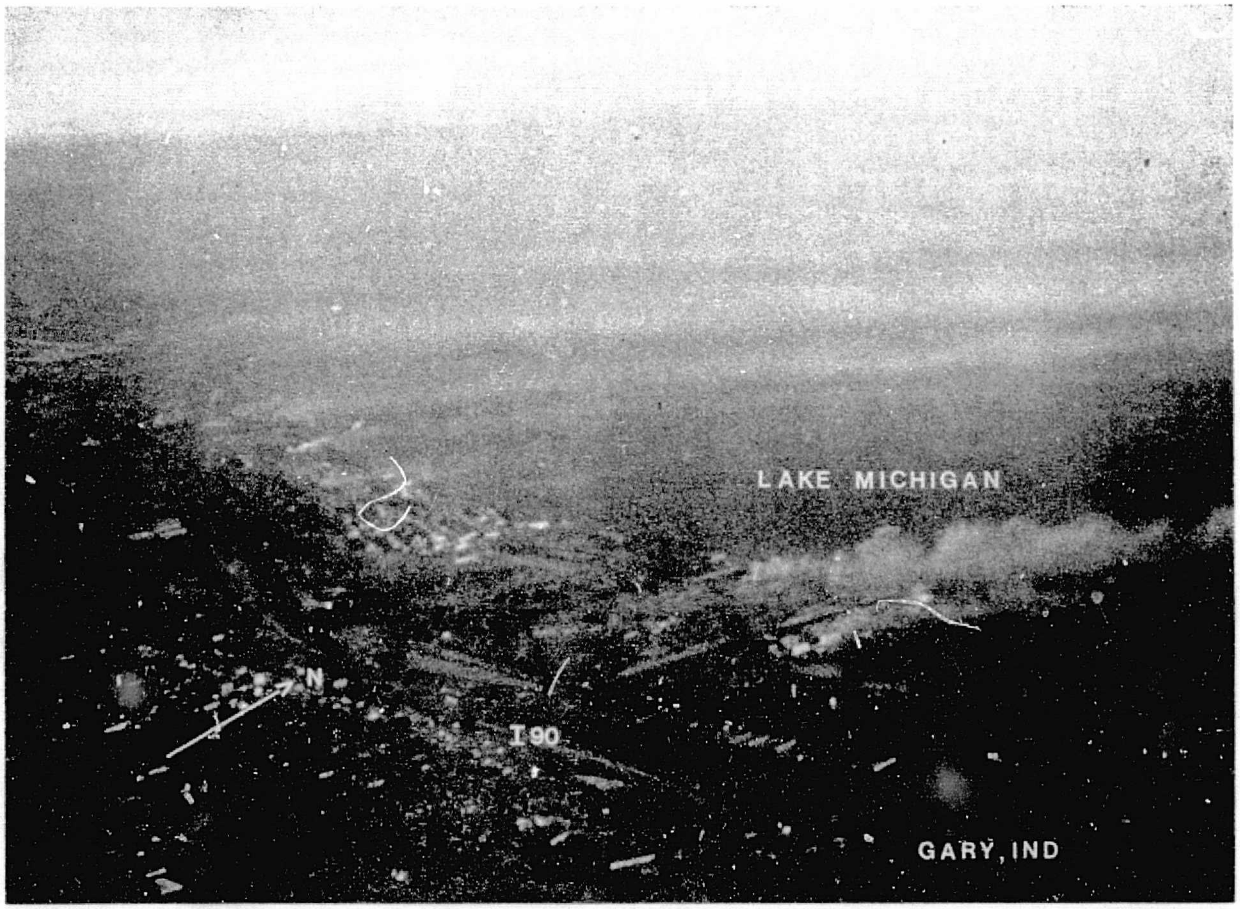

FIG. 1. View looking northwest, 4000 ft AGL, over Gary, Ind. from an NCAR Queen Air, 0630CST 15 July 1968. Plumes in foreground correspond to cluster 3 in Fig. 2, and those in the distance are cluster 2.

(1971). Lyons and Olsson (1973) noted large cumulus clouds occasionally building over the steel mills of Chicago and Gary. However, any observations of direct cause-effect relationships between man's activities and atmospheric processes are usually fortuitous. Without specific data gathering systems designed to detect specific incidences of inadvertent weather modifications, this "catch-as-catch-can" situation will continue.

The Earth Resources Technology Satellite (ERTS), while actually developed for studies of land usage, water quality, agriculture and the like, has the capability of making observations of sufficiently high resolution to observe many instances of inadvertent weather modification. Based on ERTS-1 images, this paper will discuss what appears to be a clear-cut case of cloud modification by the effluents from numerous industrial sites in the Chicago-Gary complex.

2. The Earth Resources Technology Satellite

NASA's Earth Resources Technology Satellite (ERTS-1) was launched in July 1972. A multispectral scanner (MSS) acquires images of 185×185 km in four spectral regions: 0.5–0.6 μm ("green" band), 0.6–0.7 μm ("red" band), 0.7–0.8 μm, and 0.8–1.1 μm (near infrared). The design resolution is between 100 and 200 m. A complete description of the satellite's characteristics and its ability to detect smoke plumes from major point sources is given by Lyons and Pease (1973).[3]

3. The Chicago-Gary industrial corridor

Along and near the southern shore of Lake Michigan is found one of the largest industrial agglomerations in the world. The zone of heaviest industrialization stretches along the shoreline from the southern part of the city of Chicago through Whiting, Hammond, and to about 20 km east of Gary, Ind. Figure 1 is an aircraft view showing smoke plumes drifting northeast-

[3] ERTS-1 data are available in numerous formats, including 70 mm negative and positive transparencies, 9.5-inch square black and white prints, and color transparencies and prints, and as digital tapes (MacCallum, 1973). Specific information regarding purchase of ERTS-1 products can be obtained through the EROS Data Center, U. S. Department of the Interior, 10th and Dakota Aves., Sioux Falls, S. Dak. 57198.

FIG. 2. ERTS-1 MSS Band 6 (0.6–0.7 μm) image over southern basin of Lake Michigan, 1003 CST 24 November 1972 (ERTS image ID No. 1124-16050). Hourly aviation weather plotted (one wind barb equals 2.5 m sec^{-1}). Four major clusters of industry (arrows) form large combined plumes of suspended particulates. The width of the image shown is 165 km.

wards from a complex of oil refineries, cement plants, and steel mills. It corresponds to the plume clusters numbered 2 and 3 in Fig. 2.

Thirteen of the larger sources in the region have a combined yearly output of approximately 582,000 tons of suspended particulates. The various pollution sources are also producing large amounts of heat and moisture, although very little quantitative information is available as to how much. It is known, in addition, that certain of these industries, probably steel mills, are prolific

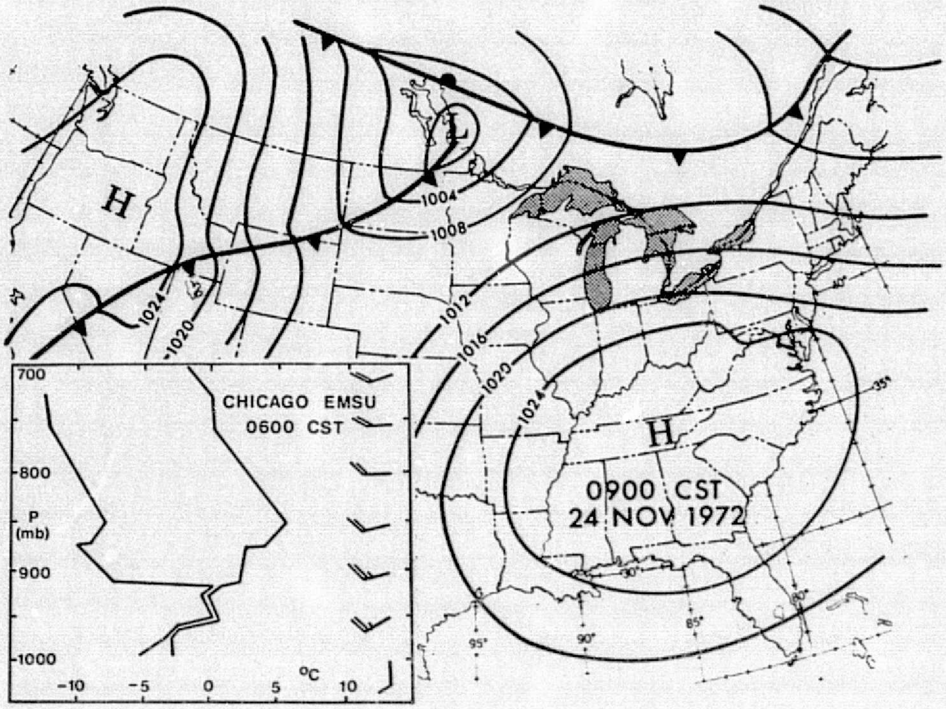

FIG. 3. Surface synoptic map, 0900 CST 24 November 1974. Inset shows 0600 CST temperature, humidity, and wind soundings from the Chicago (MDW) EMSU radiosonde ascent (one wind barb equals 5 m sec⁻¹).

producers of ice nuclei. The author participated on a flight of an NCAR Queen Air (14 August 1967) which was instrumented to measure ice nuclei (Langer *et al.*, 1968). Readings many orders of magnitude higher than the prevailing background were found directly downwind of this region, and a distinct plume of high ice nuclei counts was tracked with the winds to Battle Creek, Mich., some 190 km downwind.

Naturally, in light of the La Porte study, questions have been raised as to whether or not this industrial complex has the potential to systematically alter cloud and precipitation processes. Large swelling cumulus clouds are occasionally seen which appear to be developing from the plumes of steel mills. On other occasions, decks of supercooled stratocumulus clouds drifting inland off the lake on winter days have been noted to develop large clear areas downwind of the mills—presumably the effect of "overseeding" with ice nuclei. Thus the ERTS image discussed below reveals an effect not totally unexpected.

4. The observation

ERTS-1 took a remarkable series of images over Lake Michigan at 1003 CST, 24 November 1972, which apparently show modification of 1.5-km wide cumulus cloud streets by the effluents of the industries at the southern end of the lake (Fig. 2). On this day, the Lake Michigan region was under the influence of southwest flow about a cP high pressure cell centered in Kentucky (Fig. 3). Minimum temperatures west and south of the lake during the prior night ranged from 20F to 29F (−7C to −2C). A few scattered ship water temperature reports indicated that the lake surface had cooled to about 4C to 7C. Thus, the presence of cumulus over the relatively warm lake is as expected.

Conditions at the time of the ERTS-1 observations are shown in Fig. 2. The cloud bases observed on the downwind shore varied from 1000 to 1600 ft AGL during the morning hours. A pilot report over the western Michigan shoreline at the time of the ERTS image noted cloud tops of 2700 ft AGL, with clear skies above. The vertical extent of the clouds was apparently limited by the strong synoptic-scale inversion (Fig. 3). Though considerable cumulus cloud activity was generated by the lake, there were no reports of snow flurries by the Chicago radar or at any station in Michigan.

A closer inspection of Fig. 2 reveals numerous interesting phenomena, the most important of which is the apparent alteration of the cumulus clouds along the axis of the major pollution plumes. The general cloud cover was largely restricted to the southern portion of the lake, perhaps a reflection of somewhat warmer water temperatures there. Experience and theoretical indications suggest that the optimum contrast between smoke and underlying water should occur around 0.65 μm, that is, within MSS-band 5

(Lyons and Pease, 1973). In this case, however, the turbidity of the water was so considerable that MSS-band 6 (0.7–0.8 μm) achieved slightly better plume/water contrast.

In Fig. 2, it is quite clear (especially in the original 70-mm transparencies) that four clusters of industries form large combined plumes that advect northeastwards over the lake while diffusing. Along these plume axes, the following behavior was noted: 1) the clouds began forming closer to the shore, the first fragments appearing within 15 km of the plume sources; 2) the individual cloud elements forming the lines were larger and had higher reflectivities (and thus presumably were thicker). No particular enhancement of the cloud streets is noted within plume 4. This plume, however, is from an isolated steel mill complex, which has very well-controlled particulate emissions and is smaller than those to the west.

The EMSU radiosonde sounding at Chicago (MDW) at 0600 CST is shown in Fig. 3. A shallow (200 m) isothermal layer at the surface is capped by a moist, stable layer which extends to 910 mb. Surface winds during the morning ranged from 190° to 220° at 4–7 m sec^{-1}, and veered sharply with height to 240° at 12 m sec^{-1} at 300 m. Both the orientation of the plumes and the author's numerous prior observations of the plumes suggest that plume rise for most was adequate to cause them to stratify in the stable layer between 200 and 500 m.

There is relatively little horizontal diffusion evident in these plumes, even after downwind fetches of over 30 km. Only as the top of the convective mixing layer rising from the warm lake surface reached the plumes should significant diffusion begin to occur. At this distance, however, the cumulus clouds would have also begun to form and any horizontal spreading of the plumes would be difficult to observe.

There are several other features in this image that might be noted. Over central Lake Michigan, there exists a rather good example of an open polygonal array of Rayleigh cellular convection (Agee *et al.*, 1973). These cells (1–3 km across) likely exist within a convecting layer of weak vertical shear in the horizontal wind. The clouds generally thicken towards the eastern shoreline, and the convection mode changes, possibly the result of increasing wind shear. Particularly in the Muskegon (MKG) area one notes that there is a rapid transformation from a cellular pattern to longitudinal-cloud banks within a few kilometers of landfall. Along this stretch of shoreline there are almost continuous bluffs and sand dunes 50 to 100 m in height. This apparent influence of orography upon cloud morphology has been noted on other ERTS images.

5. Discussion and conclusions

The ERTS observation showed that the cumulus cloud lines forming within the pollutant plumes began somewhat closer to the shore and were better developed than those presumably not affected by significant industrial effluent. Had synoptic conditions this day been more favorable for snow squall production, it does not seem unreasonable to speculate that precipitation within the affected cloud lines could have possibly been enhanced. Exactly what caused this behavior, however, is not discernable from an ERTS picture. Heat, moisture, ice nuclei, and cloud condensation nuclei are all candidates. Isolating the specific cause(s) awaits further study. The simple fact is, a mere image is not adequate to determine what has caused the effect. *In situ* measurements of nuclei concentrations and cloud microphysical parameters in conjunction with such satellite imagery would provide a powerful research tool.

What is exciting about the ERTS image is the fact that something indeed has been clearly related to industrial activity. A continued inspection of ERTS images in the vicinity of Chicago (and also Cleveland, Buffalo, etc.) could very well prove extremely enlightening.

If downwind cloud modification from industrial activity does indeed occur frequently, it would appear that any future attempts at management of Great Lakes water levels by operational cloud seeding might run into some very "interesting," or rather challenging, problems of verifying seeding effectiveness. Weickmann (1972) has already noted precipitation apparently caused by steel mill effluents in the Buffalo area, coincident with attempts at advertent cloud seeding of Lake snow squalls.

An extensive radar-echo climatology for the southern basin of Lake Michigan during three summer seasons (Lyons and Chandik, 1973) revealed slightly greater frequencies of thunderstorm-related precipitation over the lake northeast of Gary than in other quadrants. What is rather startling about this finding is that the project set about to prove that lower echo frequencies should exist due to the well-documented suppressive effects of the lake on certain warm season convective rain systems. This tantalizing shred of evidence suggests perhaps that these same plumes act also as effective enhancers of warm season precipitation systems to the extent that the lake effects are more than cancelled out. The "La Porte Anomaly" could conceivably be part of a much larger area of urban precipitation enhancement northeast of Chicago-Gary, unrecognized at this time due to lack of precipitation data over the lake itself.

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