VERY HIGH RESOLUTION METEOROLOGICAL SATELLITE
STUDY OF OIL SANDS WEATHER
"A FEASIBILITY STUDY"

by

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METEOROLOGY AND AIR QUALITY COMMITTEE

ALBERTA OIL SANDS ENVIRONMENTAL RESEARCH PROGRAM

PROJECT ME 1.7

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ABSTRACT

Imagery from both meteorological and environmental satellite sensor systems was analyzed to determine its applicability in monitoring weather conditions at the Alberta oil sands. Two sensor systems were the objects of investigation, the multispectral scanner (MSS) aboard the environmental LANDSAT satellites and the Very High Resolution Radiometer (VHRR) aboard the NOAA meteorological satellites.

Weather conditions such as clear and cold, convective cloudiness, and widespread precipitation were studied with the available satellite imagery. The images and known weather conditions were then compared to determine the capability of the satellite-based sensors to identify specific meteorological phenomena. Particulate and thermal conditions of rivers and lakes were also considered.

LANDSAT could resolve meteorological features, such as single cloud elements, but since a given spot is observed only once every nine days, it is quite unsuitable for studying the motion of weather patterns. Slow-changing phenomena such as lake ice, snow cover and particulate content of water bodies are more effectively defined. NOAA satellites provide the twice-daily coverage needed for monitoring fog, smoke, plumes, and small-scale cloud patterns. Unfortunately, the resolution of the NOAA-VHRR was generally inadequate for identification of small meteorological features associated with industrial development.

Satellites of the near future will have better instruments for covering the meteorology of the oil sands but no combination of their output is expected to provide ideal time and space resolution.

Future studies of this type should find satellite images easily available because of rapidly improving Canadian sources and because of the explanation of image acquisition given in this study.

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1. INTRODUCTION

The first artificial earth satellite was launched into a successful orbit in 1957. Since that time, advances in the field of remote sensing, using the satellite as an instrument platform, have been made at a very rapid rate. The technology involved with designing and placing into orbit instruments of increasingly greater complexity and more diverse purpose has, in many areas, far exceeded the user community's ability to make adequate use of the resulting high rate of data flow. It is not surprising, therefore, that the sensors on board currently orbiting satellites have not been adequately evaluated for use in detecting and monitoring meteorologically related phenomena for environmental purposes over a small area such as the Alberta oil sands.

The potential advantages of monitoring any phenomenon on or above the earth's surface from an orbital vantage point are many. The view of earth from space can be regional, or even global in scope, however, with the rapidly improving resolution of satellite-based instrumentation, resolution of surface features smaller than 80 meters across is now readily available. This resolution opens the way for using satellite-based sensors to monitor relatively small surface and atmospheric features across virtually any portion of the earth. Limitations are placed on this type of remote surveillance by the nature of the target objects and the amount and type of cloud cover present. For monitoring surface features the clarity of the atmosphere and image contrast are probably the most important limitations.[1] For monitoring clouds, the frequency of images, the obscuring of clouds by clouds, and lack of illumination were the important limitations encountered in this study.

Some of the chief advantages of using orbital platforms for mounting remote sensing instruments are the comparatively low cost of

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[1] Lyons and Pease. Bull. Amer. Meteor. Soc. V54, p. 1165-1169.

making observations of significant detail over large and often remote areas, repeated coverage, nearly uniform viewing angle over very large areas, and increasingly, the sophistication and diversity of the types of observations which are possible with the new satellite instrument packages.

For the purpose of this study, two types of satellite-based remote sensing systems currently offer possibilities for practical application to the monitoring of environmental conditions in the Alberta oil sands area (Figure 1). These are the LANDSAT environmental satellites and the NOAA series of meteorological satellites. These satellites provide a choice of both visible and near-infrared sensors in the case of LANDSAT with visible and thermal-infrared sensors available on the NOAA series. Future missions along with their planned instrumentation will be discussed later in this report.

A comprehensive investigation of data availability which has proven to be a critical area in the information flow between the sensing instrument and the potential user application is also included in this study.

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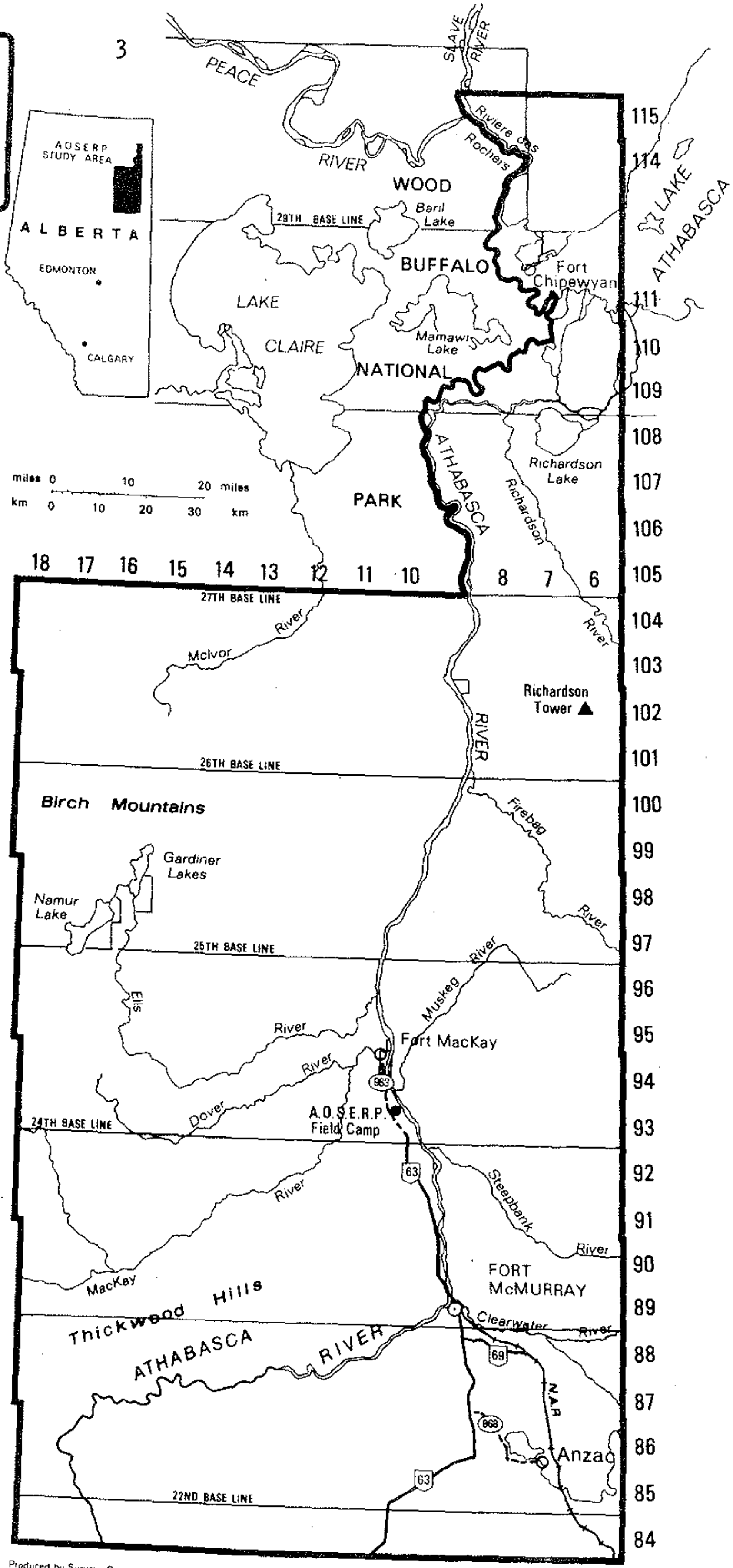

Produced by Surveys Branch, Alberta Transportation

WEST OF THE FOURTH MERIDIAN

FIGURE 1. Location of the AOSERP study area.

2. INSTRUMENTATION AND METHODOLOGY

2.1. SATELLITE OBSERVING SYSTEMS

The instruments used during this study are all mounted on satellite observing platforms. Their main sensors are scanning radiometers which are designed to be sensitive to a narrow range of wavelengths in the visible, near-infrared or thermal-infrared bands. The sensors aboard the LANDSAT system were designed primarily for environmental monitoring of surface features and those on the NOAA system were designed for meteorological purposes.

2.1.1. LANDSAT 1 and LANDSAT 2

The instrument packages aboard LANDSAT 1 and 2 are essentially the same. These satellites, launched into a polar sun-syncronous orbit, are capable of providing complete sensor coverage of the earth every 18 days. The orbits are adjusted so that there is a maximum of nine days between successive imaging of any given area. Image overlap between successive passes (days) makes it possible to sense the same area on two succeeding days in the northern and southern regions, however, the orbits are barely tangent at the equator eliminating any useable overlap in the tropics. At the latitude of the Alberta oil sands (57°N) the overlap is sufficient to allow a total of four days coverage out of every 18 days (two days by each satellite). In the Canadian system these images are designated by track (orbit) number and image center (IC).[2] For the Alberta oil sands the primary track number is 45 with either IC20 or IC21. Because of the overlap, track number 46 and the same IC's will provide coverage on the succeeding days, leaving eight days before coverage is again possible by the other satellite. The LANDSAT 1 stabilizing system is now beginning to fail and until LANDSAT C is launched in September 1977 the coverage every nine days will be more and more sporadic until LANDSAT 1 fails completely. The failure was expected; in fact LANDSAT 1 has already exceeded its nominal expected life of one year by about three years. The orbit of LANDSAT C is expected to duplicate the orbit of LANDSAT 1, resulting in a return to reliable nine-day coverage.

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[2] Ken Campbell, Alberta Center for Remote Sensing. Personal communication.

2.1.1.1. LANDSAT sensor specifications.[3] Satellite altitude is about 920 km (572.24 mi.) with a period of 103 min. The orbit is adjusted so that the earth rotates below the satellite at such a rate that the sensor coverage on successive days just touches at the equator with progressively increasing overlap toward higher latitudes.

The instrument package contains a return beam vidicon (RBV) which is essentially a television camera, and a multispectral scanner (MSS). The RBV operates in three wavelength bands: .475-.575 μm, .580-.680 μm, and .690-.830 μm with a surface resolution at the point directly below the satellite (nadir or subpoint) of 45 meters (147.60 ft.). The RBV on LANDSAT 1 failed shortly after launch, but the one on board LANDSAT 2 still continues to function. Data from the RBV was not used in this study because of its form (computer compatible tape) and very high cost ($200 per image).

The MSS collects information in four discrete wavelength regions designated 4 through 7. Bands 4 and 5 are visible and bands 6 and 7 are near-infrared. The surface resolution of each band is 78 meters (255.84 ft.). Band 4 (green) covers 0.5 to 0.6 μm wavelengths and is designed for the detection of sediment movement in rivers, lakes and seas. Band 5 (red) is sensitive to radiation in the range from 0.6 to 0.7 μm and is used for observing cultural features. Band 6 (near-infrared) including wavelengths between 0.7 and 0.8 μm is particularly good for the detection and study of vegetation and for mapping land-water boundaries. The second near infrared band (band 7) covers the spectrum between 0.8 and 1.1 μm. This band is used for purposes similar to band 6, however with the longer wavelengths, haze penetration is much better. These indicated uses are only an indication of their individual potential. The imagery from various bands are frequently used in combination to increase the amount of information which can be extracted.

Another feature of the LANDSAT satellites is the local image time which is very nearly the same each image day. The azmuth angle of the sun is, therefore, also the same while the sun elevation angle

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[3] United States Geological Survey. The EROS Data Center, p. 7-9.

varies with the season. The image time over the Alberta oil sands is about 10:30 A.M. Central Standard Time. The controlling agency (NASA) usually will not operate the satellite sensors when the sun elevation is below about 10°.[4] This limits coverage of the Alberta oil sands area for December and January because the angle is near 10° for much of that period.

2.1.1.2. LANDSAT data availability. The availability of LANDSAT satellite data was a major problem in this study. However, what has been learned about obtaining data will greatly assist in the operational use of satellite imagery in the future.

LANDSAT imagery is available from two principal sources, Integrated Satellite Information Services Ltd. (ISIS) in Canada, and the Earth Resources Observation System (EROS) Data Center in the United States. The addresses can be found in the Appendix. The delay from image date to image availability varies from a month for United States sources and three to six weeks for Canadian sources.[5] Orders from Canadian sources may be further delayed due to an image processing backlog in Ottawa. This additional delay can be on the order of several months. Some images are available from ISIS almost immediately. They are called quicklook microfiche negatives and they are usually available within 24 hours in bands 5 and 6. Quicklook can be used to evaluate image quality and cloud cover but the images lack resolution. Normal ordering time for processed images is one to two weeks from ISIS and three to four weeks from EROS. There is a difference in data quality between the two processed products which might influence a decision about where to order satellite products. In Canada, the range of film densities used to represent the satellite data range from 0.92 to 1.56, while in the United States, EROS uses 0.98 to 2.25.[6] This gives a

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[4] NASA. LANDSAT C Mission Requirements and Data Needs. p. 1-14.

[5] Integrated Satellite Information Services Ltd. Personal communication.

[6] See Footnote 2.

significant improvement in the contrast of images obtained from the U.S. sources.

2.1.2 NOAA 3, NOAA 4 and NOAA 5

These three satellites all have essentially the same instrument packages. NOAA 3 has been used as the standby for NOAA 4. Soon after the launch of NOAA 5, which was late in July 1976, NOAA 4 will be designated standby, allowing the aging NOAA 3 to be switched off.

The orbital parameters of NOAA 5 are similar to its predecessors. Altitude is near 1460 km (908.12 mi.) with an orbital period of 115 min. The coverage from NOAA satellites is much more frequent than for LANDSAT. The greater orbital altitude combined with the addition of a thermal-infrared channel for both day and night viewing, provides twice daily imaging of equatorial areas with increasing image frequency toward higher latitudes. The Alberta oil sands area receives coverage several times during each 24 hour period. The times of NOAA satellite passes over a given area vary from day to day, unlike LANDSAT. This makes it necessary to calculate pass times on a daily basis.

2.1.2.1. <u>NOAA sensor specifications</u>[7]. The primary instruments on board the NOAA series satellites are the vertical temperature profile radiometer (VTPR), the scanning radiometer (SR) and the very high resolution radiometer (VHRR). The VTPR was not applicable to the nature of this study but, briefly, it observes the emission of infrared by carbon dioxide at several closely-spaced wavelengths, the purpose being to obtain a vertical temperature profile of the atmosphere above cloud level. The SR operates in both visible (0.5-0.7 μm) and thermal-infrared (10.5-12.5 μm) with an optimum ground resolution of 8 km (4.98 mi.) in the visible and 16 km (9.94 mi.) in the infrared at nadir. Unfortunately, this resolution is not sufficient for this study since these SR images are available from the University of Alberta and many other places in Canada.

Most of the operational hopes of this study were based on the VHRR. This instrument has the same spectral coverage as the SR but

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[7] American Meteorological Society. Bulletin, V55, p. 46-47.

with much better ground resolution. The resolution in both visible and thermal infrared channels is 0.9 km (0.56 mi.) at the nadir point.

2.1.2.2. NOAA data availability. This study was to be based on the availability of VHRR imagery from the AES Satellite Data Laboratory in Toronto. Problems were encountered, however, both at AES and in the United States, when specific imagery was ordered. To fully investigate the capabilities of the VHRR for detailed monitoring of small meteorologically related phenomena in the Alberta oil sands, special processing of the VHRR image was found to be necessary. For instance, many different gray-scale enhancements and image scales were needed. These will be discussed later in this report. The AES Satellite Data Laboratory under the very able direction of Mr. Charles Taggert was able to supply only a limited amount of the required imagery due to severe manpower and equipment restrictions. The Satellite Data Laboratory is in the development and experimentation stages at the present time and, as such, is not equipped to produce large quantities of special request products.[8] It has been operating since September 1975 so a large inventory of taped imagery is not available. VHRR imagery is not more readily available because of the very high cost of the necessary receiving equipment compared to the more common SR receivers.

As an alternative source of specialized VHRR imagery, the National Climatic Center (NCC) in the United States was contacted.[9] Some imagery was ordered from the NCC but it is unable to produce the required gray-scale enhancements so their products were of limited value. The ordering time required for VHRR imagery from the NCC is about six weeks. VHRR imagery is also available from ISIS. This firm is expecting to upgrade its facilities in 1977 to include digital processing and special thermal-infrared enhancement capabilities.[10]

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[8] Dave Steenbergen. Small-scale Processes Research Division, Meteorological Services Research Branch, AES. Personal communication.

[9] See Appendix for address.

[10] D. Fisher, Integrated Satellite Information Services Ltd. Personal communication.

The lack of specially processed VHRR images forced this study to proceed without adequate imagery. Inference and extrapolation from the available data became the primary occupation. Even though these difficulties were encountered, a good assessment of the present and future capability of satellite-based sensors to monitor meteorological conditions over the Alberta oil sands was obtained.

2.2. METHODOLOGY

The procedures for interpreting the available images were very basic. Satellite imagery and weather conditions were coordinated and then carefully analyzed to determine what the satellite-borne sensors could reliably detect and identify.

2.2.1. Identification of weather conditions

Several different types of weather conditions including clear and cold days, showery weather, and days with widespread precipitation were identified. The VHRR image inventory at the Satellite Data Laboratory in Toronto was limited to the period beginning in September 1975. Some dates prior to September 1975 on which specific weather conditions occurred, such as clear and very cold, were also selected because the earlier imagery was available from other sources. The use of alternate data sources was expanded when it was discovered that the imagery for the coldest days during the 1975-76 winter, i.e., January 1976, occurred on days for which VHRR imagery was not available from Toronto due to problems of satellite transmissions during that month.

The source of weather data from conventional sources was primarily the climatological records from AES Edmonton, although some temperature and fog data were obtained from observations taken at the oil sands development site.[11]

2.2.2. Satellite coverage

Satellite coverage of the Alberta oil sands area for the past three years was determined for both LANDSAT and NOAA satellites.[12,13]

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[11] A. Mann, AES Edmonton. Personal communication.

[12] Integrated Satellite Information Services Ltd. LANDSAT 1 and LANDSAT 2 Timetable. See Appendix for address.

[13] National Oceanic and Atmospheric Administration, Key to Meteorological Records Documentation, No. 5.4. Monthly.

Availability of imagery for other geographical areas was also determined because a study of all types of weather conditions over a relatively short period of time required the consideration of weather conditions in other parts of Canada. Once the weather conditions and imagery dates had been selected and coordinated, the relevant imagery was ordered. As previously stated, this step caused the most difficulty during the study.

2.2.3. Integration of weather data and satellite imagery

The weather data for the time of each satellite image was plotted on a transparent template which was designed for the individual image. The template was then placed on the image and direct comparison between weather conditions and image detail were made. This method proved particularly effective for images with extensive cloud cover. For winter images which were nearly free of clouds, ice fog or effluent plumes were the targets of investigation. For this purpose, an image of known accuracy and detail was compared with the image being studied because the only clue to the existence of a fog patch or plume might be the subtle obscuration of some otherwise visible surface feature.

2.3. EQUIPMENT

The equipment used to analyze the satellite photographs consisted of simple magnifying lenses, a scale, and a small electronic calculator. The magnifying lenses were used to confirm identification of features. Once identified, all important details could easily be recognized without optical aid. The scale and calculator were used to determine the actual size of features detected during the analysis. In addition to these instruments, the quicklook microfiche viewer at the Alberta Center for Remote Sensing[14] was extensively used to screen LANDSAT images for suitability before ordering actual processed imagery for study. Considerable use was also made of ground truth information and control images which consisted mainly of large-scale maps and several high-quality, cloud-free images from both LANDSAT and NOAA satellites.

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[14] See Appendix for address.

3. DISCUSSION OF OBSERVED FEATURES

At the outset, there were few preconceived ideas about what localized meteorological phenomena could be identified. All possible meteorologically related surface and near-surface features were looked for with varying degrees of success. Key targets were ice fog, effluent vapor plumes, and potentially important, but highly localized cloud systems. The success of these investigations is given in this section. The following section includes an overall evaluation of the operational value of using satellite-based sensors for monitoring meteorologically related conditions over the Alberta oil sands area.

3.1. FEATURES OBSERVABLE USING NOAA-VHRR IMAGERY

3.1.1. Cloud Shadows

Cloud shadows as small as 15 km (9.33 mi.) long and 3 km (1.87 mi.) wide could be identified (Photograph 1).

3.1.2. Advancing cloud shields

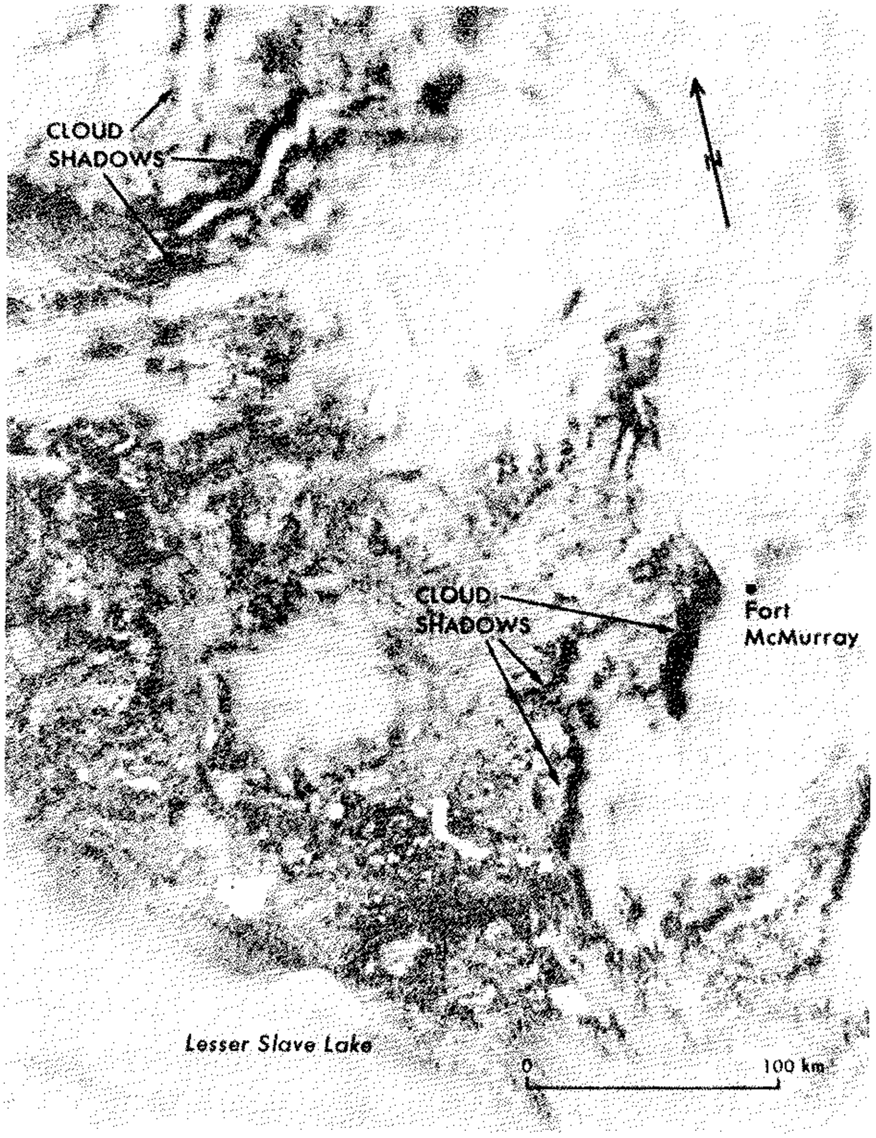
The change from generally clear to generally cloudy weather frequently precedes an advancing low pressure area or frontal system. This synoptic scale cloud movement is not difficult to follow with conventional observations, however, the exact cloud boundary can be determined using the VHRR (Photograph 2).

3.1.3. Frontal waves

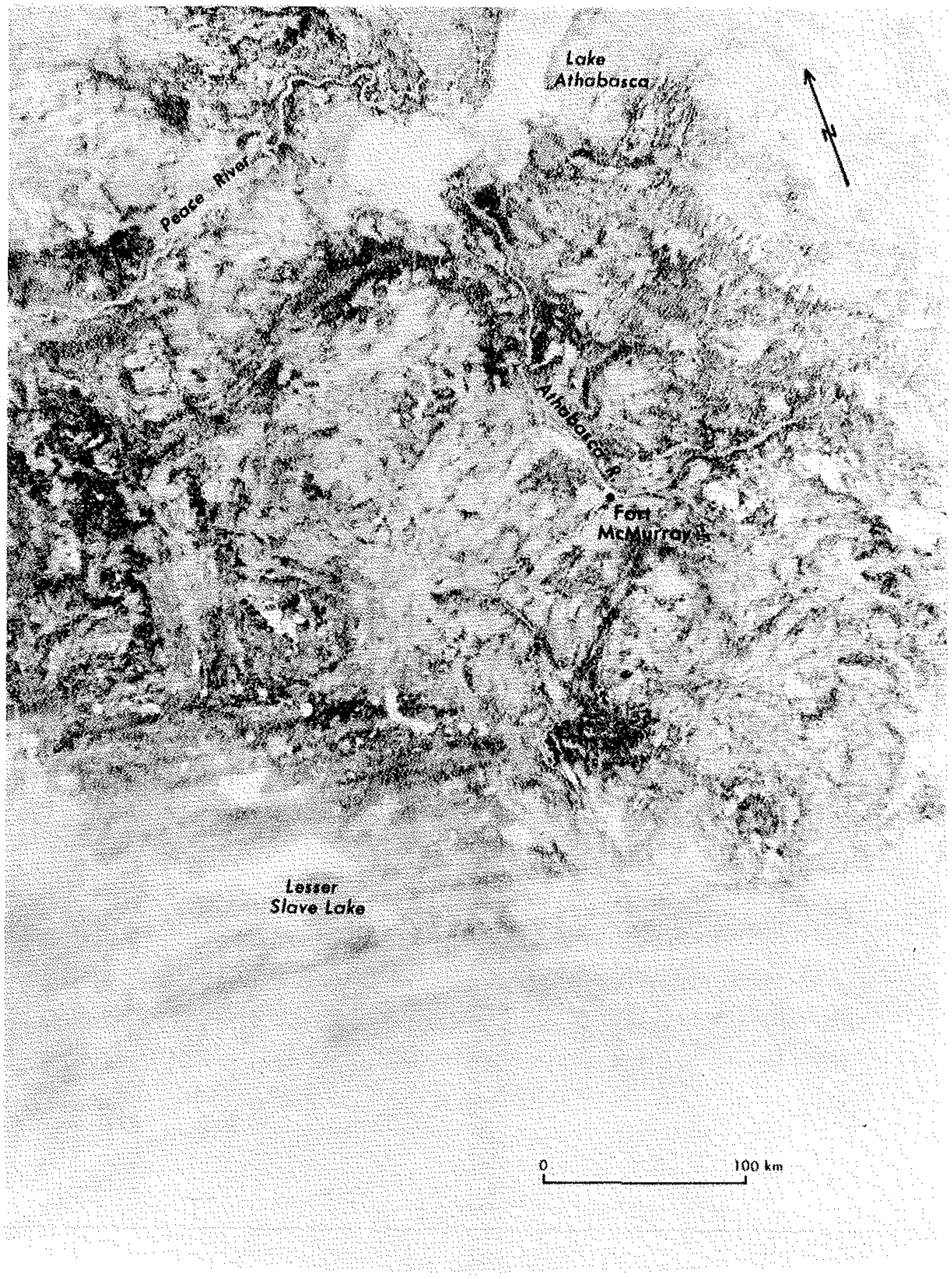
Frontal waves are usually too large to be readily identified on a single 1:3,000,000 VHRR image unless 1:8,500,000 VHRR images (Photograph 3), auxiliary synoptic data, or standard SR images are also available. The VHRR can, however, identify many of the circulation details of a frontal wave and aid in determining its exact location.

3.1.4. Small precipitation cells

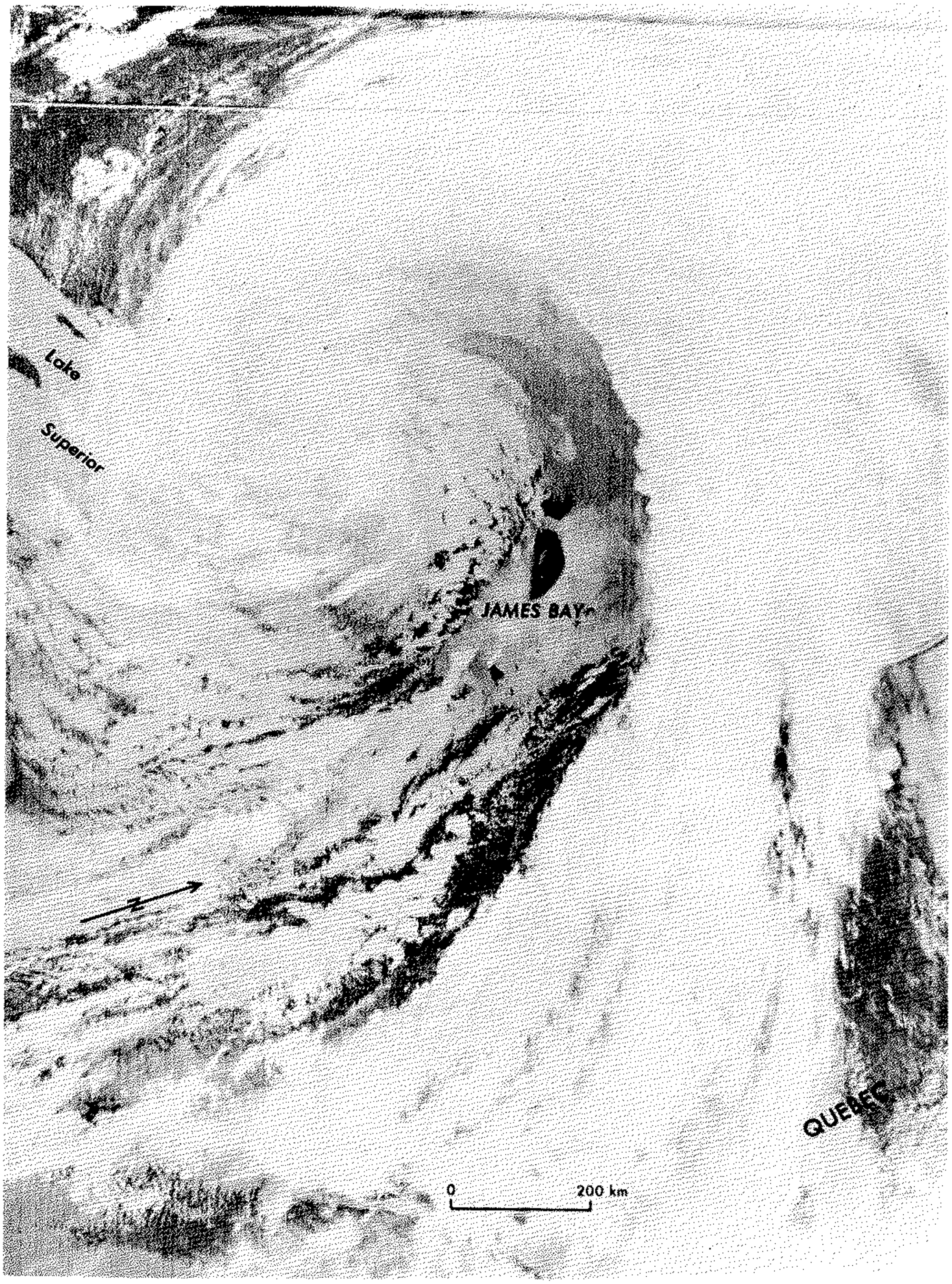
Within major cloud systems there are often localized areas of convection with precipitation. This is particularly true of the large winter cyclonic disturbances which cross the prairies. By referring to synoptic surface observations in conjunction with VHRR visible band imagery it is possible to identify many of the small precipitation cells which may occur over areas where no surface observing network exists, such as the AOSERP study area. An example is not



PHOTOGRAPH 1. VHRR visible-band image showing cloud shadows. Original image scale 1:3,000,000. (Photo courtesy AES Satellite Data Laboratory)



PHOTOGRAPH 2. VHRR visible image of the Alberta oil sands area showing a cloud shield advancing from the south. Original image scale 1:3,000,000. (Photo courtesy AES Satellite Data Laboratory)



PHOTOGRAPH 3. VHRR thermal-infrared image of a cyclonic disturbance and associated frontal cloud band. Original scale 1:8,500,000.

provided with this report because a reproduction of an original image will not bring out the necessary detail.

3.1.5. Cold-air drainage

Cold-air accumulation in valleys cannot be observed using the visible channel of the VHRR. The VHRR thermal infrared sensor is able to clearly identify cold-air in valleys along the eastern slope of the Rocky Mountains (Photograph 4). This detection of cold-air drainage depends heavily on the gray-scale enhancement curve used. If the surface temperature being investigated should be known to within a few degrees, the gray-scale in the relatively narrow range of identified temperatures can be expanded at the expense of other portions of the sensor's operational range to bring out details of the cold air extent and movement.

PHOTOGRAPH 4. VHRR thermal-infrared image showing the accumulation of cold air in valleys along eastern slopes of the Rocky Mountains. Gray-scale range -45°C (white) to -18°C (black). Original image scale 1:3,000,000. (Photo courtesy of AES Satellite Data Laboratory)

3.1.6. Water temperature

The temperature of both lakes and rivers is an important environmental feature which is readily detected by thermal-infrared sensors. Resolution of the VHRR is sufficient to identify thermal differences in considerable detail in larger lakes and to recognize large temperature variations in rivers from orbital levels (Photograph 5).[15]

The most prominent thermal feature identified during this study was the relatively warm water of Cold Lake during December 1975 (Photograph 6). The temperature difference between Cold Lake and the surrounding area is about 20°C (36°F). No exact temperature determination can be made because the sensor was not calibrated with known surface control temperatures. For absolute temperature sensing of surface features the apparent temperature, as sensed by the radiometer, must be related to actual surface temperature. Following this technique, thermal accuracy of about 0.7°C (1.26°F) is possible using VHRR data.[16] It should be noted that the high thermal radiation from Cold Lake is coming from below the ice surface and therefore a cover of ice does not completely prevent the monitoring of water temperatures. Other lakes, notably Beaverhill Lake, east of Edmonton, also showed relatively warm temperatures despite their being ice-covered. This fact may have further implications for fish and wildlife studies.

Thermal differences due to ice thickness variations and open water leads could also be identified on both Lake Athabasca and Great Slave Lake (Photograph 7). The width of the smallest lead to be detected was 1.2 km (0.75 mi.). The accuracy of temperature measurements through the ice is not known nor has the quantitative relationship between temperature variations and ice thickness been determined. Both of these questions are in need of further research.

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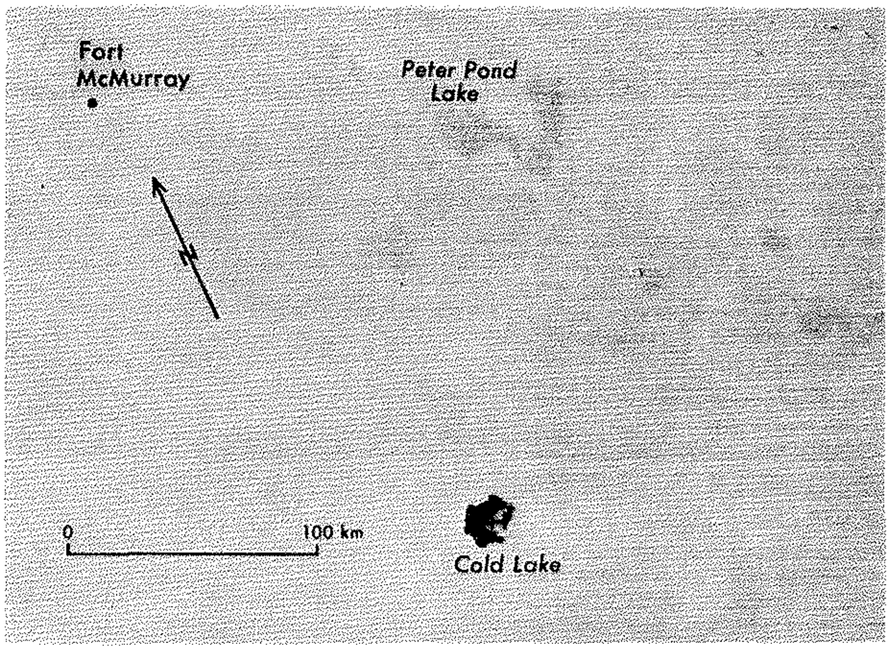
[15] Strong, Strumpf, Hart, and Pritchard. Ninth International Symposium on Remote Sensing of Environment - Proceedings. p. 923-932.

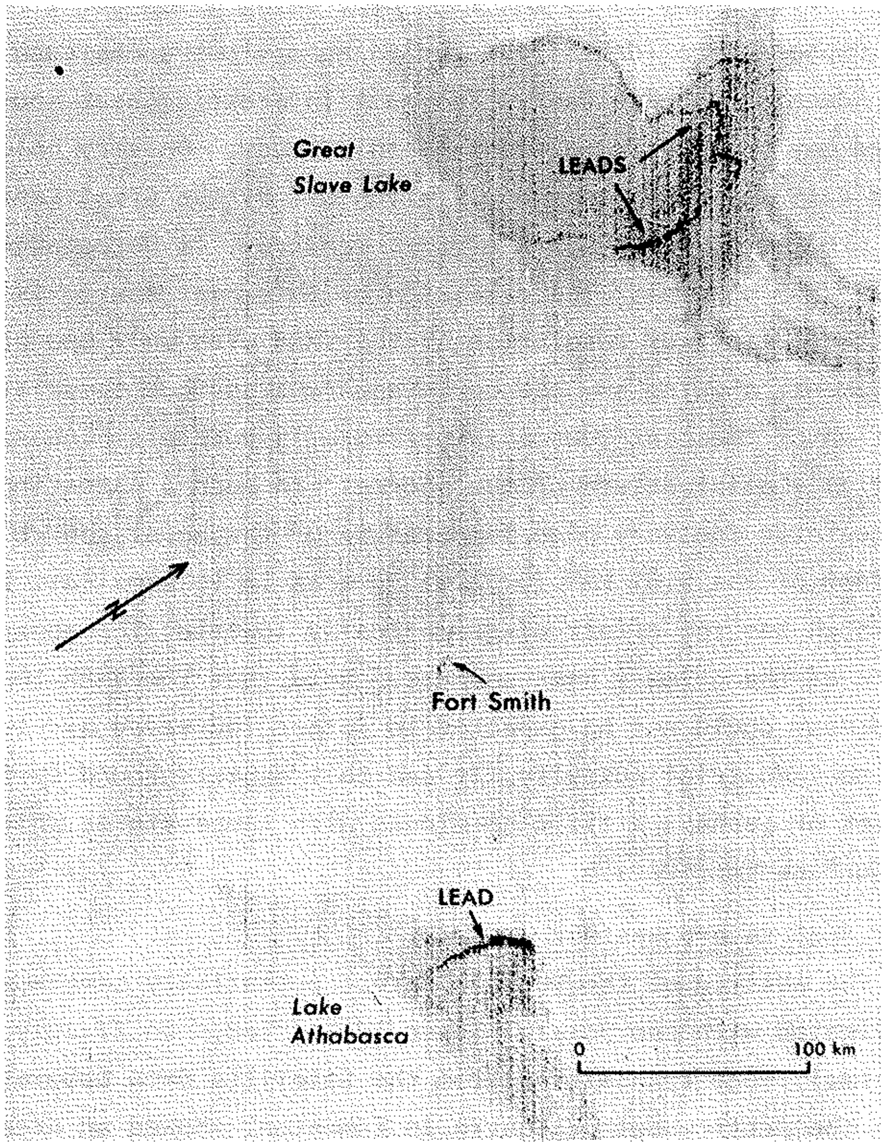
[16] Seifert, Carlson, and Kane. Operational Applications of Satellite Snowcover Observations. p. 149.

PHOTOGRAPH 5. VHRR thermal-infrared image showing temperature variations in the Gulf Stream. The gray-scale range is -10°C (white) to +20°C (black). Original scale 1:4,500,000. (Photo courtesy of AES Satellite Data Laboratory)



PHOTOGRAPH 6. VHRR thermal-infrared image showing the relatively warm temperature of Cold Lake, Alberta. Gray-scale range -45°C (white) to -10°C (black). Original image scale 1:3,000,000. (Photo courtesy of AES Satellite Data Laboratory)

Identification of thermal differences along major rivers is also possible using VHRR data and several examples were discovered during this study. Warming, apparently due to natural causes, was noted along the upper Peace River west of the town of Peace River (5°C (9°F)) and also in the vicinity of Vermilion Falls (15°C (27°F)), about 70 km (43.54 mi.) east of Fort Vermilion. Both of these apparent warm areas are probably due to higher speeds of river flow either keeping the water free of ice or only allowing a very thin coating of ice to form. Another area of apparent warming (15°C (27°F)) was located along the Slave River near the town of Fort Smith (Photograph 7). This warm-appearing area extended downstream for about 18 km (11.20 mi.) leading to the conclusion that heat was being added to the river by some effluent source at Fort Smith.



PHOTOGRAPH 7. VHRR thermal-infrared image showing open leads on Lake Athabasca and Great Slave Lake. The gray-scale range is -35°C (white) to -15°C (black). Note also the warm area near Fort Smith. Thermal screen temperatures are -30°C or lower. Original scale 1:3,000,000. (Photo courtesy of AES Satellite Data Laboratory)

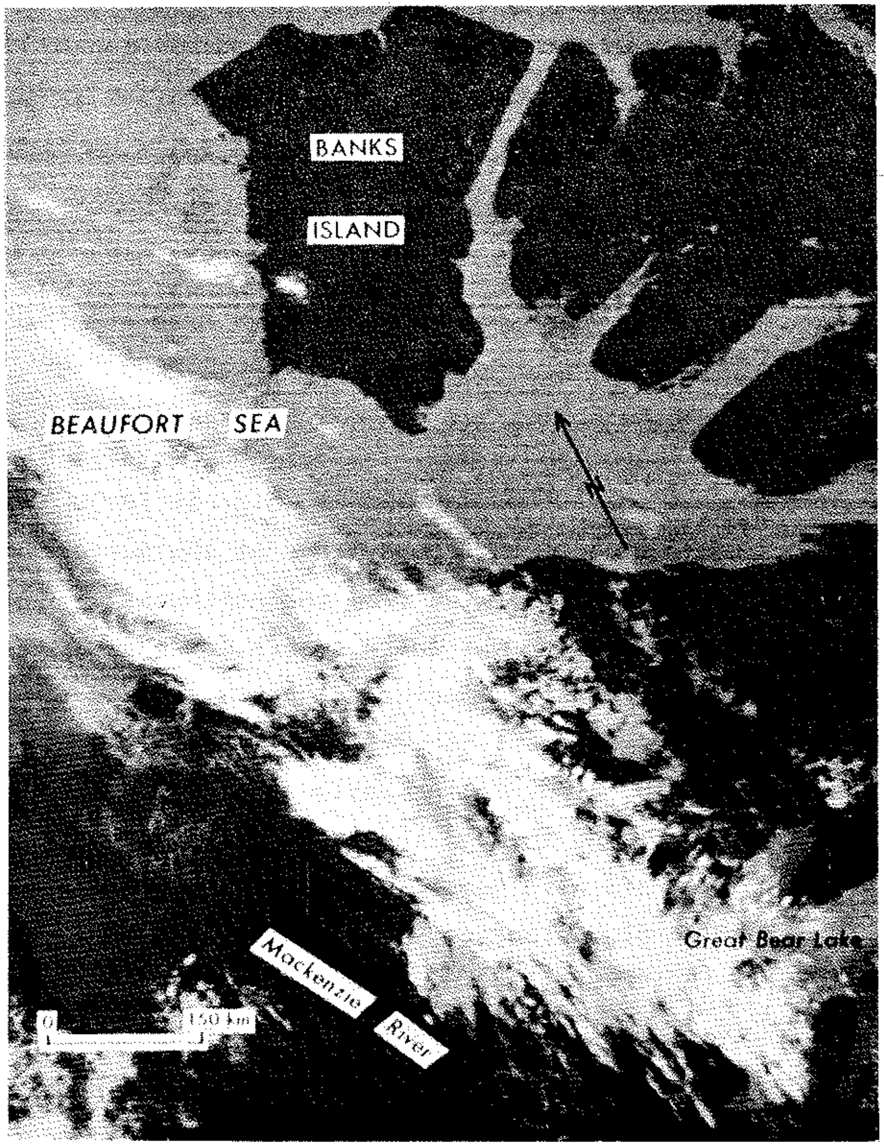
3.1.7. Industrial heating

Several examples of man-made heat being given off directly to the atmosphere were identified, including obvious areas such as the cities of Edmonton and Red Deer. The most interesting heat source to be detected may prove very relevant to this study. On very cold days (below -15°C (5°F)) heat, apparently given off by the Great Canadian Oil Sands processing plant north of Fort McMurray, is detectable using the thermal VHRR channel. The dimension of this heat source is below the theoretical limit of resolution of the VHRR with only one or two picture elements showing any change in apparent surface temperature. No estimation of the heat source temperature is possible because of the essentially point nature of the source. In such a situation, the sensor integrates the very high temperature of the point source with the remainder of the 0.81 km^2 (0.32 $mi.^2$) area in its smallest resolution element, which has the effect of dramatically lowering the apparent temperature of the primary heat sources. Note that the VHRR thermal-infrared sensor could not be expected to detect increased air temperatures due to industrial activity; it can only detect ground surface temperatures or perhaps artificial clouds with temperatures which differ from the surface temperature.

3.1.8. Local severe weather

The ability of the VHRR to detect potentially severe weather was investigated with one possible case identified. On 27 July 1976, a VHRR thermal image transmitted from the Satellite Data Laboratory in Toronto to the Arctic Weather Centre in Edmonton, showed an area of apparent convective-type clouds with very cold tops extending from over the Beaufort Sea southward to Great Bear Lake (Photograph 8). The cold tops, identified by small, very white (cold) elements, indicate strong vertical development to a great height. Such clouds would produce showery weather. The individual cloud masses ranged in apparent size from 180 km (111.96 mi.) down to 3.5 km (2.18 mi.) in diameter. However, the scale of the image (~1:7,000,000) was much smaller than that employed for most of the VHRR images used in this study (1:3,000,000) making the smallest features more difficult to identify. Individual features as small as

1 km (0.62 mi.) in diameter should be identifiable if there is sufficient temperature contrast and proper gray-scale enhancement.



PHOTOGRAPH 8. VHRR thermal-infrared image of strong convective activity over the Beaufort Sea. Gray-scale range -25°C (white) to +25°C (black). Original scale 1:7,400,000. (Photo courtesy of AES Arctic Weather Centre.)

3.2. FEATURES OBSERVABLE ONLY WITH LANDSAT IMAGERY

The main differences between VHRR imagery and LANDSAT imagery are frequency of observation, lack of thermal infrared on LANDSAT, and the much greater resolution of the LANDSAT sensors. Obviously, any feature detected by the visible channel of the VHRR will also be detectable in even greater detail by LANDSAT. Thermal features detected by the VHRR will be invisible to the MSS on LANDSAT. This discussion will pertain only to those features too small to be detected using the visible VHRR channel, but clearly observable on LANDSAT imagery.

3.2.1. Effluent plumes

On clear, cold days, effluent plumes are easily identified if their length exceeds about 0.3 km (0.19 mi.). Identification of even shorter plume lengths is possible with experience and accurate ground truth data. Photograph 9 and Figure 2 show several plumes emanating from between east Edmonton and Redwater at 10:30 MST on 10 January 1975. On this day the temperature at the surface was -25°C (-13°F) to -30°C (-22°F) with a wind from the northwest at 6 m/sec (13.42 mi/hr). The atmosphere was quite stable, with an isothermal lapse rate through the lowest 440 meters (1443.20 ft.) as determined by the AES radiosonde station at Stony Plain, Alberta[17] at 0500 MST on 10 January 1975. The Stony Plain station is 22 km (13.68 mi.) west of Edmonton. The wind through the same layer increased gradually to 13 m/sec (29.07 mi/hr) with no significant change in direction.

Examination of Photograph 9 reveals plumes ranging from 0.3 km (0.19 mi.) to 19 km (11.82 mi.) in length with an average width of about 0.5 km (0.31 mi.). The longest plume (19 km (11.82 mi.)) is believed to be from the cooling tower of Sherritt Gordon Mines Ltd. The water vapor loss from the Sherritt Gordon cooling tower on 10 January 1975 was an average of 65,047 kg/hr (143,276 lb/hr).[18]

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[17] Atmospheric Environment Service. Monthly Bulletin, January 1975, p. 16.

[18] B. Weizenbach. Personal communication.

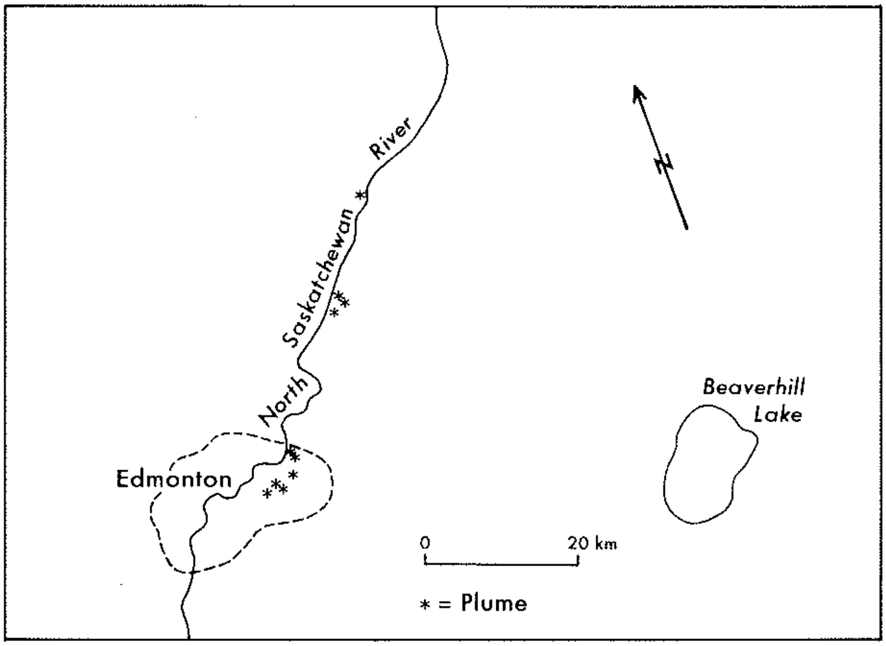
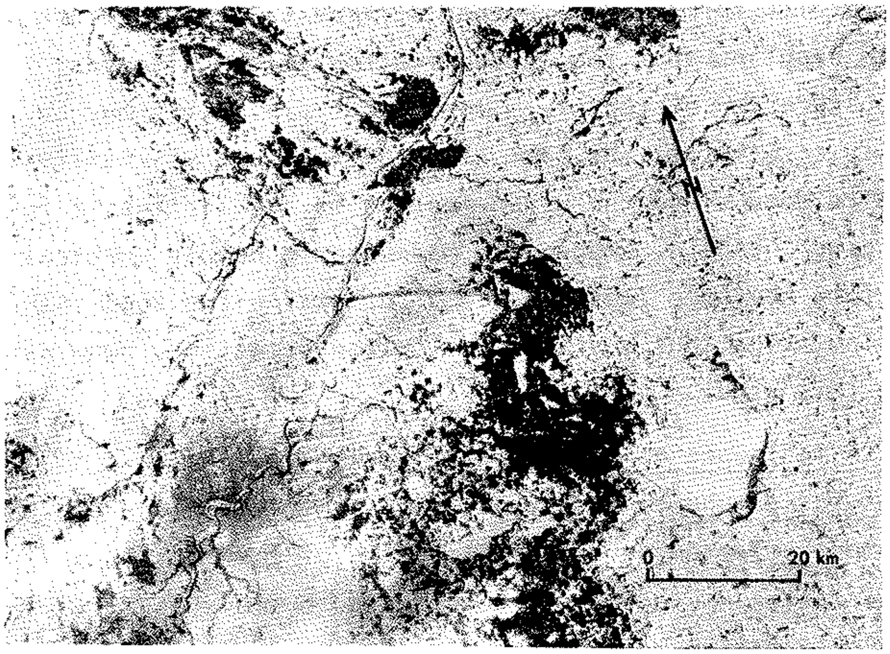


FIGURE 2. Schematic showing location of plumes visible on Photograph 9.



PHOTOGRAPH 9. LANDSAT 1, band 6 image showing several cloudy plumes in the Edmonton, Alberta area. Original scale 1:1,000,000.

Data from other companies regarding vapor loss on the same date was not obtained.

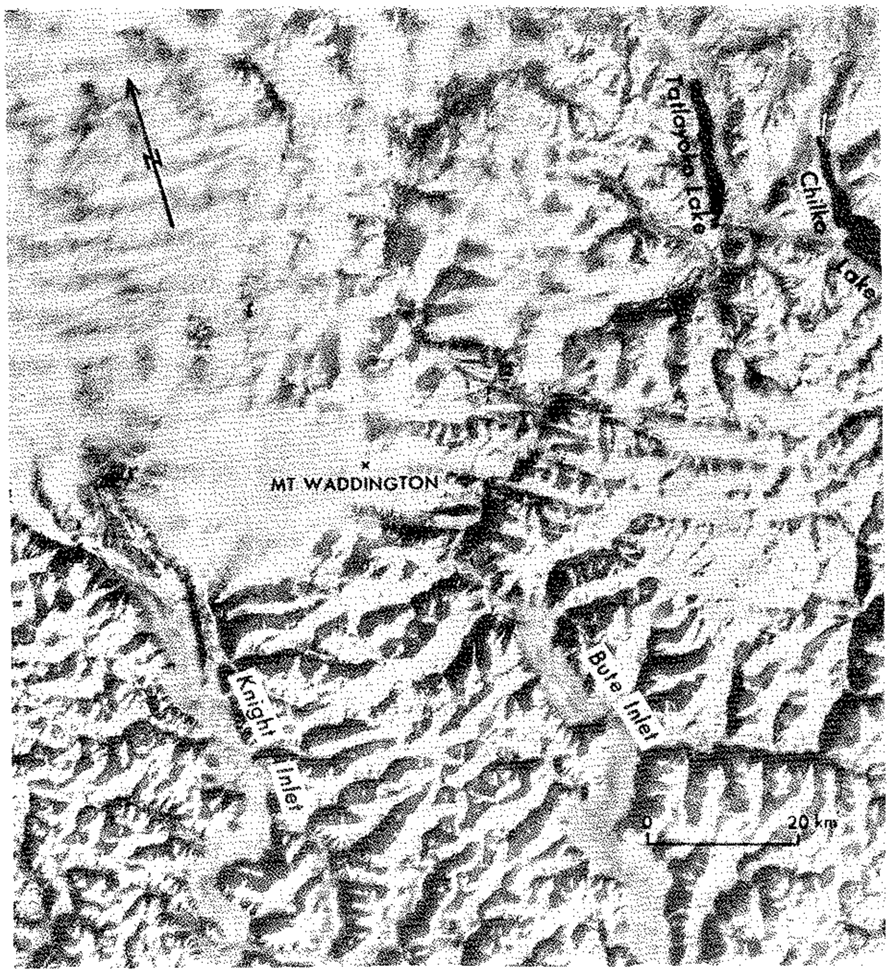
Examination of imagery from the MSS bands 4, 5, 6, and 7 showed an advantage to sensing cloudy plumes using the longer wavelengths (near-infrared). A thermal-infrared image with similar resolution such as that proposed for the next LANDSAT mission may be even more valuable in plume detection. The plumes in Photograph 9 suggest that a complete set of band 7 LANDSAT images for Edmonton and the oil sands would be useful to researchers studying plume dispersal in the oil sands. Edmonton is suggested because it gets all winter LANDSAT images while the oil sands are frequently too dark and also because the cooling towers currently in operation in Edmonton are similar in emissions to those proposed for the oil sands extraction plants.

3.2.2. Fog

No observations of any fog type other than some water droplet fog in the large valleys and fjords of southwestern British Columbia (Photograph 10) were detected from imagery during this study. Ice fog detection using LANDSAT is difficult because of the lack of available light in northern latitudes during the time of year when the temperatures are low enough for its formation. Another difficulty is the nature of ice fog. Unlike regular vapor fog, urban ice fog seldom, if ever, forms a total obscuration of the sky. Horizontal visibility may be reduced to nearly zero but at the same time the vertical visibility is likely to be quite good since the urban ice fog is usually just a few tens of meters deep. LANDSAT images are made from a nearly vertical angle and therefore have the least chance of detecting ice fog. Although further investigations may lead to ice fog detection, none was observed during this study.

3.2.3. Terrain influence on cloud formation

Except for ground-based clouds (fog), cumulus clouds are the ones which are most affected by terrain in terms of its heating and cooling characteristics. Heating can be affected by many factors, including terrain orientation, slope, and surface characteristics. For example, the formation of cumulus can be observed to occur first over



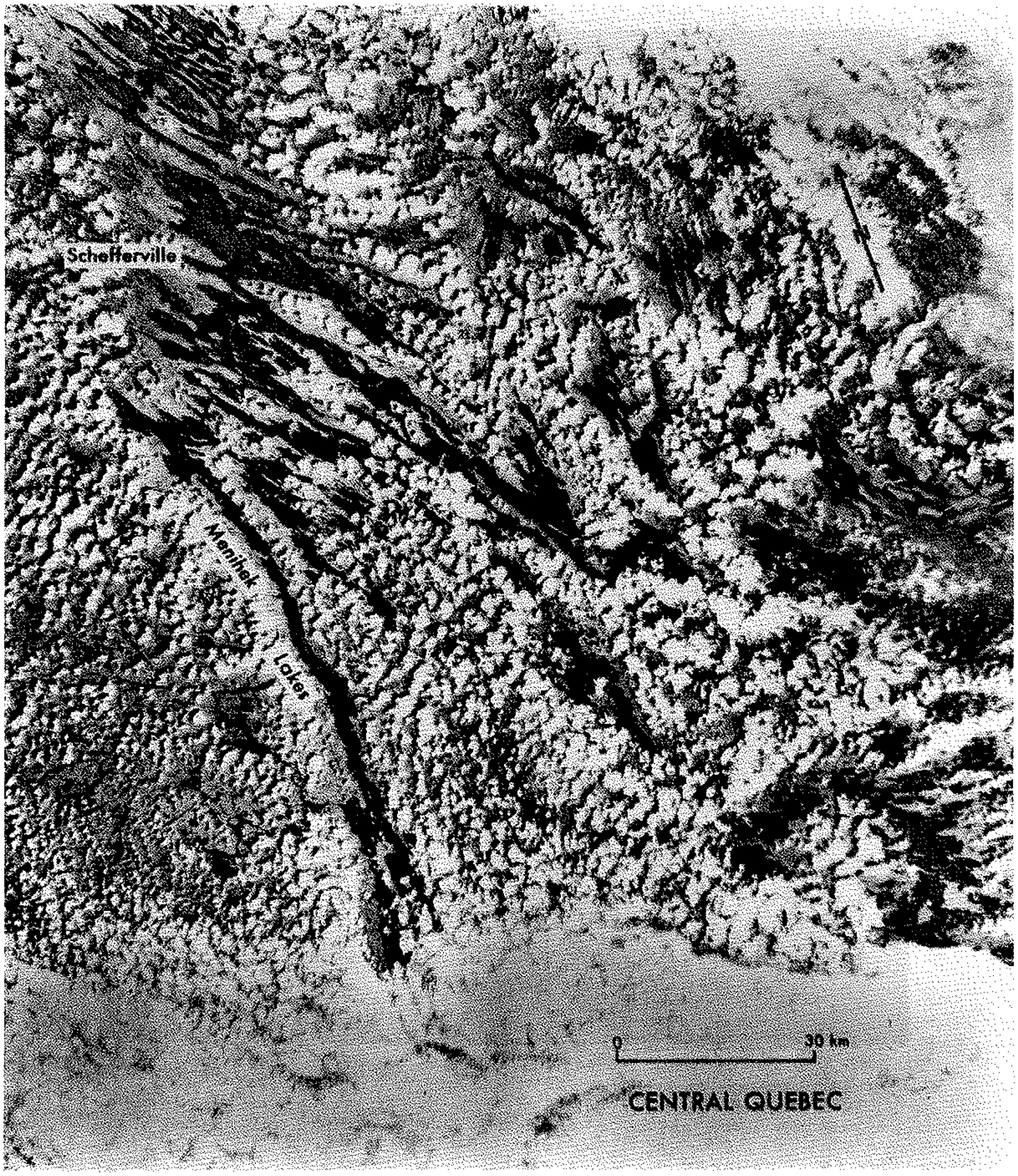
PHOTOGRAPH 10. LANDSAT 1, band 6 image of coastal fog in Bute and Knight Inlets of British Columbia. Original scale 1:1,000,000.

southeast-facing slopes due to the greater absorption of solar energy on this slope early in the day. The resolution of LANDSAT sensors is more than adequate to detect this type of terrain effect, provided a topographic map is used in conjunction with the satellite imagery in areas of gentle relief. No example images are available due to problems with the imagery-ordering process. Examples may be viewed at the Alberta Remote Sensing Center where quicklook microfiche of LANDSAT imagery are on file. One particular date to consult is 7 June 1976 where cumulus can be seen developing in response to terrain variations just north of Fort McMurray.

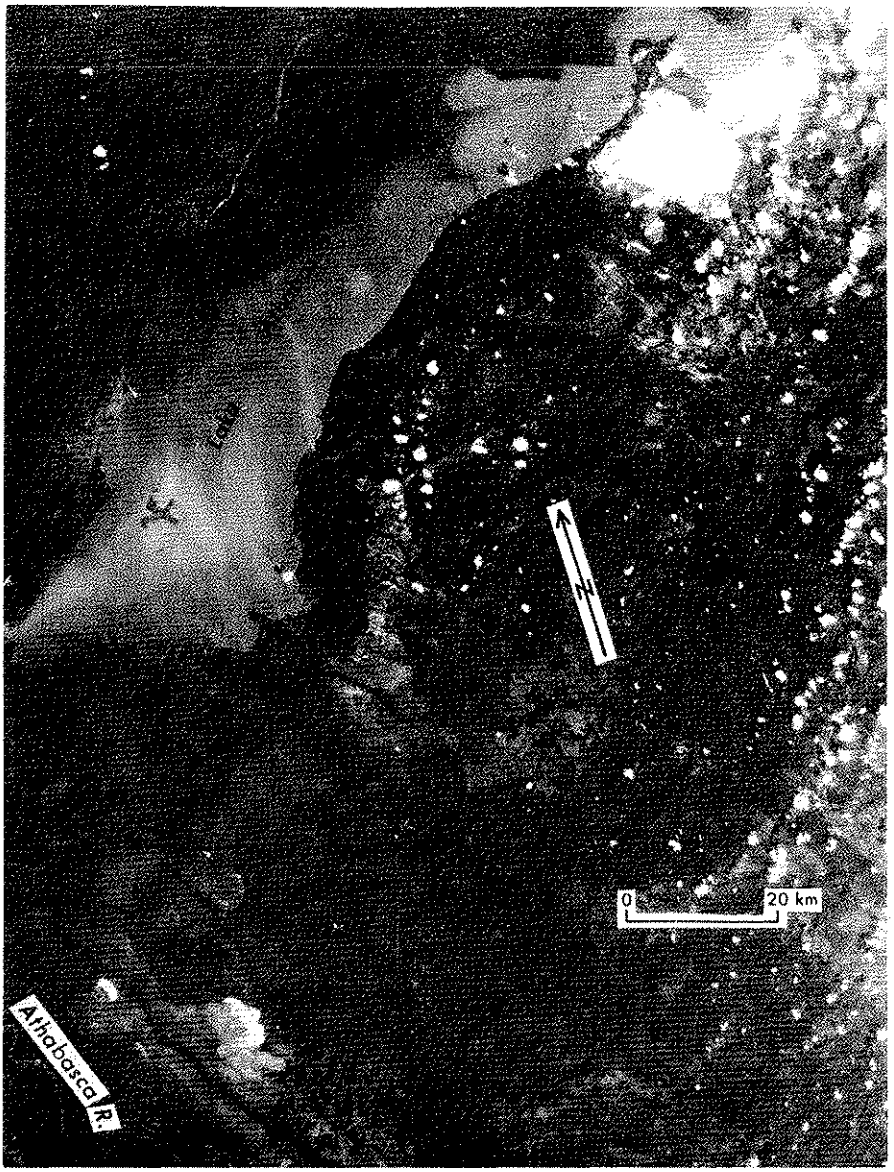
Another example of terrain effect on cumulus formation occurs where water is present on the landscape (Photograph 11). In this image, the cumulus can be seen in close association across most of the image, however, they are completely absent over the colder lake and marsh areas. This is not the case with the cloud shields produced by large-scale overrunning which are visible in the lower and upper right portions of the image. The resolution of individual cumulus elements is excellent with clouds as small as 0.25 km (0.16 mi.) in diameter easily identified.

3.2.4. Particulate pollution

The value of LANDSAT for detecting particulate pollution in bodies of water has been extensively studied. Two examples are presented here. The first image, made on 19 July 1973 (band 5), shows turbid water in Lake Athabasca resulting from stream discharge (Photograph 12). Very small details of the lake circulation (0.2 km (0.12 mi.)) are identifiable on the original image. The second image, made on 7 July 1973 (band 5), shows turbid water in the Arctic Ocean resulting primarily from the muddy discharge of the Mackenzie River (Photograph 13). Again, details as small as 0.2 km (0.12 mi.) across are visible on the original image. The choice of MSS band to use for detecting water-borne particulates depends on the water depth to be observed because the shorter wavelengths penetrate much deeper than do the longer ones. Bands 4 and 5 are generally used for this type of monitoring.



PHOTOGRAPH 11. LANDSAT 1, band 7 image showing cumulus formation conforming to land-water pattern. The image location is central Quebec. Original scale 1:1,000,000.



PHOTOGRAPH 12. LANDSAT 1, band 5 image of silt movement into Lake Athabasca. Original scale 1:1,000,000.

PHOTOGRAPH 13. LANDSAT 1, band 5 (visible red) image showing the movement of silt-laden water into the Beaufort Sea from the Mackenzie River. Original scale 1:1,000,000.

4. EVALUATION OF OPERATIONAL CAPABILITY OF HIGH-RESOLUTION SATELLITE SENSOR SYSTEMS TO MONITOR WEATHER CONDITIONS IN THE AOSERP STUDY AREA

Each of the objectives of the study have been evaluated in terms of their suitability for satellite monitoring. This was done after assessing the results of image analysis which was summarized in the previous section and taking into consideration the availability of appropriate satellite imagery.

4.1. EFFLUENT PLUMES

Cloudy plumes, at least on days with temperatures below -20°C (-4°F) are clearly visible on LANDSAT imagery if their length exceeds 0.25 km (0.16 mi.). VHRR imagery should be capable of plume detection using the visible wavelengths if the plume length is greater than about 4 km (2.49 mi.), assuming a high quality image and good background contrast are available. VHRR infrared imagery may be capable of even higher resolution if the proper gray-scale enhancement can be produced. In both cases (visible and thermal infrared), an image scale near 1:3,000,000 is assumed on which 1 cm (0.39 in.) equals 30 km (18.66 mi.).

4.2. PARTICULATE POLLUTION IN WATER

The Athabasca River is large enough to exhibit a recognizable width on LANDSAT imagery and therefore detection of discolorations in the river water are possible with bands 4 and 5 if the contrast in colors is great enough. No such detection would be possible using VHRR imagery because of the much poorer resolution.

Lake pollution detection using LANDSAT imagery has been repeatedly demonstrated by many researchers working on environmental problems. The VHRR imagery received during this study proved to be inconclusive in demonstrating a capability for detecting particulate pollution in lakes. This was due to both the lack of high quality imagery and imagery with the correct processing for surface feature identification. Unfortunately, most VHRR products are produced specifically for the purpose of cloud detection. With proper gray-scale enhancement and image scales, however, limited detection of particulate pollution in lakes larger than 4 km (2.49 mi.) in diameter will probably be possible using VHRR imagery. The corresponding resolution limit for LANDSAT imagery would be lakes larger than 0.4 km (0.25 mi.) in diameter.

4.3. THERMAL POLLUTION IN WATER

LANDSAT 1 and 2 have no thermal infrared detectors so detection of thermal features is not possible.

VHRR imagery in the thermal band (10.5-12.5 µm) has the capability to produce quite detailed thermal images of both land and water surfaces. During winter, discharges of warm water into the Athabasca River should be detectable as a warm spot or line when the temperature contrast is large enough. Absolute thermal accuracy of VHRR imagery is on the order of 0.7°C (1.26°F). For a target which is significantly smaller than an individual resolution element (0.81 km^2 (0.32 $mi.^2$)), integration of environmental temperatures greatly reduces the precision of measurement.

The possibility of detecting thermal pollution occurring in Lake Athabasca or other lakes larger than about 4 km (2.49 mi.) in diameter will be practical using VHRR imagery. In these cases the maximum accuracy of 0.7°C (1.26°F) could be approached and used to detect very small temperature changes, assuming they occur over areas larger than about 1 km^2 (0.39 $mi.^2$). Reaching this capability depends on availability of a high quality image, proper gray-scale enhancement, and large image scale. The largest scale which is practical using VHRR imagery is 1:3,000,000 on which 0.3 mm (0.01 in.) represents 1 km (0.62 mi.). However, this scale of imagery is not routinely available. The standard scale of VHRR imagery is 1:8,500,000, making small details very difficult to resolve. Two sources of commercially available specialized VHRR products were located. In Canada, Integrated Satellite Information Services Ltd. can supply custom VHRR products at regular consulting fee prices. In the United States, the National Environmental Satellite Service, Environmental Products Group can provide some customized VHRR products for limited periods. Addresses for imagery ordering purposes can be found in the Appendix.

Experimental production of special VHRR imagery with only limited operational application has been carried out by the AES

Satellite Data Laboratory in Toronto and the Satellite Receiving Station at Gilmore Creek, Alaska near Fairbanks. These facilities should not, however, be expected to respond to requests for routine VHRR imagery.

4.4. FOG DETECTION

Based on the plumes visible on LANDSAT imagery, the resolution of individual cloud elements of 0.3 km (0.19 mi.) size, and the fog visible in some British Columbia valleys, fog patches of 0.5 km (0.31 mi.) in diameter or larger, should be readily detected using LANDSAT imagery. Allowance must be made for the density of the fog however, particularly the vertical visibility through it. Since ice fog usually is shallow and has good vertical visibility, it would not be detected except in cases of very deep accumulations. The infrequent observations (every nine days), make ice fog monitoring even less of an operational possibility using LANDSAT.

The poor resulution of the VHRR, relative to the MSS on LANDSAT makes the detection of ice fog highly unlikely using either visible or infrared channels. Normal water droplet fog, with an area at least 4 km (2.49 mi.) in diameter, should be detectable using the visible channel if good quality ground truth information is available for comparative purposes.

4.5. DEVELOPMENT AND MOVEMENT OF CLOUD SYSTEMS

The primary value of either VHRR or LANDSAT imagery for operational monitoring of local weather conditions across the AOSERP study area will be in identifying areas of possible severe weather not reported from the normal observing stations. This capability was demonstrated during transmission of VHRR infrared imagery by AES in support of the Beaufort Sea oil exploration (Photograph 8). The VHRR on NOAA satellites is the preferable because of its thermal-infrared sensing capability which allows cloud-top temperatures to be measured resulting in a better estimation of vertical development.

Other uses for both LANDSAT and NOAA imagery for general weather observations are the ability of both satellite sensor systems to detect possible areas of localized precipitation and the ability to accurately determine the extent and exact location of even very small cloud elements. For VHRR imagery, the smallest cloud element normally detectable is about 1.2 km (0.75 mi.) in diameter assuming sharp cloud outlines and a good contrast background. The corresponding figure for LANDSAT is 0.25 km (0.16 mi.).

In addition to the observation of highly localized cloud systems, the VHRR can be used to observe and track the movement of major cloud systems with a high degree of precision. Using this type of information, very accurate short-range forecasts of weather conditions across the AOSERP study area are possible.

4.6. ICE

Determining the existence of ice on rivers and lakes using either LANDSAT or VHRR imagery is quite straightforward. The main difference between the two systems is the resolution capability. When using LANDSAT, band 7 (0.8-1.1 μm) should be used for this purpose. The near-infrared wavelengths are strongly absorbed by liquid water which appears very dark on an image while even a thin covering of ice changes the water surface to a highly reflective one which then appears white. The liquid or frozen state of small bodies of water or details in larger bodies of water of about 0.25 km (0.16 mi.) in diameter can be detected by LANDSAT. A major problem with LANDSAT is the coverage only once every nine days with even this frequency often reduced when clouds cover the area of interest during satellite passes.

The technique for using the VHRR is slightly different since there is only one visible band with no special provision for viewing the near infrared. To determine the liquid or frozen state of a water surface using VHRR imagery, both the visible and thermal infrared channels can be used. Normally the visible channel is most valuable with liquid water appearing dark and an ice cover appearing white. Depending on the ice thickness and the temperature of the surrounding ground surface, the thermal-infrared channel will normally indicate a slightly warmer (darker image) area in the case of a liquid water surface. The thermal infrared image should be compared with the visible image to make a positive determination. The resolution limit for VHRR imagery is a water area of about 2 km (1.24 mi.) in diameter with high quality imagery.

4.7. SNOW COVER

The imagery available for this study was not sufficient to determine the capability of either satellite sensing system to measure the extent of snow cover. A very fine study involving the use of VHRR imagery in Alaska for hydrologic purposes[19] is available and should be consulted for further information in this subject area. The results of this study clearly show the great value of VHRR imagery for determining snow cover information on an operational basis providing proper imagery processing and temperature controls are also available.

4.8. FLOODING

The capability of the VHRR to detect flooding could not be demonstrated during this study; however, this potentially valuable use of VHRR imagery was investigated by Wiesnet, McGinnis, and Pritchard (1974) during flooding on the Mississippi River in 1973. They found that the VHRR on NOAA 2 could provide valuable information about the extent and spread of flooding along a major river. Although most of the rivers and streams in the AOSERP study area are too small for flooding to be detected by the VHRR, the Athabasca River and the low areas surrounding the larger lakes could easily be monitored for increasing water area.[20] For this purpose, a high quality control image would be a necessity for comparative purposes.

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[19] See Footnote 16.

[20] See also Seifert, Carlson, and Kane. Operational Applications of Satellite Snowcover Observations, p. 154 for photograph.

5. OPERATIONAL PROGRAMS FOR NOAA-VHRR IMAGERY AND PLANS FOR FUTURE SATELLITE MISSIONS

5.1. OPERATIONAL PROGRAMS

The original meteorological satellites were designed primarily for observing clouds. Little could be seen on the earth's surface because of poor resolution and poor image contrast. Today, relatively high resolution, good image contrast, and a variety of image enhancement techniques increase the number of applications of data from the new meteorological satellites. Some of the current operational uses[21] of NOAA-VHRR imagery which are not totally meteorological include the preparation of:

(1) Weekly composite charts depicting water masses and thermal fronts in the Gulf Stream along the east coast of the United States. These charts are distributed to users by both the National Facsimile System and by mail. The charts are also used to prepare the Gulf Stream Wall Bulletin which is broadcast by radio.

(2) Ice advisaries and forecasts to assist shipping along the north coast of Alaska by the National Weather Service in Fairbanks, Alaska.

(3) Great Lakes ice charts which are transmitted twice each week on the National Facsimile Circuit. This program was credited with extending the 1974-1975 shipping season by more than 30 days.

(4) Quantitative estimates of snow cover over 18 river basins in the United States and four basins in Canada.[22]

Research is increasing the application of NOAA-VHRR imagery as well as imagery from other meteorological satellite instrument systems such as the geostationary SMS-1 and SMS-2 satellites which are positioned over the equator. Unfortunately, these satellites are positioned too far south to be of much use north of about 50°N latitude.

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[21] NOAA, Satellite Activities of NOAA, 1975, p. 7-8.

[22] AES Hydrometeorology and Environmental Impact Research Division, Annual Report - 1975, p. 2-4.

5.2. FUTURE SATELLITE MISSIONS

Three new satellites, scheduled for launch during the next two years, have potential for use in monitoring the AOSERP study area. These are the Heat Capacity Mapping Mission (HCMM), LANDSAT C, the third in the LANDSAT series, and the NASA prototype of TIROS-N. The most important specifications of each satellite and its package of sensors are described below.

5.2.1. Heat Capacity Mapping Mission[23]

The Heat Capacity Mapping Mission (HCMM) is scheduled for launch late in 1978. The capabilities of this observational satellite are of interest to many, including meteorologists, biologists and operational workers in many other fields. A few of the mission objectives include the following:

(1) Produce thermal maps at optimum times for thermal inertia measurements (~2:30 AM and 1:30 PM LST)
(2) Measure plant canopy temperatures
(3) Study soil moisture effects - temperature cycle
(4) Map thermal effluents
(5) Investigate geothermal source locations
(6) Provide frequent snow cover observation for runoff prediction.

The radiometer planned for the mission is the Surface Composition Mapping Radiometer which was developed for the NIMBUS E satellite and has now been renamed the Heat Capacity Mapping Radiometer (HCMR). The HCMR will be placed in a sun-synchronous orbit with a 2:00 PM local time ascending node (equatorial crossing) at an altitude of 600 km (373.20 mi.). The radiometer will operate in two channels, 0.8-1.1 μm (near-infrared) and 10.5-12.5 μm (thermal-infrared). These correspond to LANDSAT, band 7 and the VHRR thermal bands, respectively. Resolution of the HCMR will be 500 m (1640 ft.) at nadir which is inferior to LANDSAT (78 m (255.84 ft.)), but superior to VHRR (900 m (2952 ft.)).

The satellite orbit will be adjusted to provide selected

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[23] Smith. Applications Explorer Missions - Mission Planners Handbook, Sec. 5, p. 1-16.

areas with coverage twice each day, about 1:30 PM and 2:30 AM local time over northern latitudes. Specifications as to where the selected areas will be has not been released, however, they are expected to include most of North America. Data from the HCMM will be available through the EROS Data Center in South Dakota (see Appendix).

5.2.2. LANDSAT C[24]

LANDSAT C is scheduled for launch during September 1977. The objectives of this mission are largely environmental in nature, however, several meteorologically related objectives are also considered. A partial list of objectives of particular interest to AOSERP includes the following:

(1) Mapping extent of snow cover
(2) Flood mapping
(3) Mapping of man-made surface alterations
(4) Determination of factors relating to stress on crops and forests
(5) Delineation of promising areas for mineral exploration
(6) Determination of water runoff patterns.

The satellite will carry both a multispectral scanner (MSS) and return beam vidicon (RBV), the same package as carried on both LANDSAT 1 and 2. Several important differences exist in the new instrumentation. First, an additional thermal-infrared band has been added to the MSS (band 8), operating in the wavelength range of 10.4-12.6 μm with a ground resolution of 238 meters (780.64 ft.). This spectral range matches the thermal band on the VHRR, however, the resolution is much better. This should make the thermal effluents from development operations much more easily detected than with the VHRR. The RBV has also been modified to provide better resolution. The discrete spectral bands used on the previous RBV's have been combined into a single panchromatic instrument (0.505-0.750 μm). The additional energy gained through this combination allowed the lens focal length to be doubled. The result is a ground resolution of

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[24] See Footnote 4.

40 meters (131.20 ft.). Even though RBV imagery is expensive, the 40 meter (131.20 ft.) resolution may make its purchase worthwhile in some cases for selected AOSERP investigations.

Beginning with LANDSAT C, NASA will greatly increase its image production and the delay from image time to image availability will be reduced from two or three weeks to two days or less. The new processing system will be at the Goddard Space Flight Center with the data being available only through the EROS Data Center in South Dakota.[25]

5.2.3. TIROS-N[26]

A prototype of the third generation of polar-orbiting meteorological satellites (the NOAA series is the second generation), designated the TIROS-N series, will be launched early in 1978. The prototype model will include an Advanced Very High Resolution Radiometer (AVHRR) in addition to the TIROS Operational Vertical Sounder, Space Environment Monitor, and Data Collection and Platform Location system. The primary difference between the AVHRR and the current VHRR will be the addition of multispectral capability.[27] This will consist of four bands, 0.55-0.9 μm (visible), 0.725-1.0 μm (near-infrared), 3.55-3.93 μm (thermal-infrared), and 10.5-11.5 μm (thermal-infrared). Resolution in each band will be 1.1 km (0.68 mi.), compared with 0.9 km (0.56 mi.) for the VHRR. Imagery from the new system is expected to be available from the National Environmental Satellite Service.[28]

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[25] See Appendix for address.

[26] See Footnote 21.

[27] NOAA, APT Information Note 76-2, p. A-1.

[28] See Appendix for address.

6. CONCLUSION

The value of LANDSAT imagery in environmental monitoring has been demonstrated by numerous studies during the past few years. In this study, several very interesting meteorological phenomena were shown to be detectable. The high resolution and four spectral-channel capability of the MSS on Landsat makes it a very valuable instrument. Unfortunately, for monitoring short-lived phenomena such as clouds and effluent plumes, the nine-day coverage interval is usually much too infrequent. The detection of surface or near surface features is often delayed by cloud cover or by winter darkness. For observation of snow and ice cover, LANDSAT will likely be adequate in the AOSERP study area. The MSS and, if cost permits, the RBV on LANDSAT are highly recommended for the detection and routine monitoring of both snow and ice cover.

The VHRR on the NOAA series of satellites provides imaging of the AOSERP study area on a several-times-per-day basis in both visible and thermal-infrared radiation bands but it lacks the very high resolution of LANDSAT. The 0.9 km (0.56 mi.) resolution severely limits VHRR capability to detect the small details of weather conditions such as fog, plumes, river water conditions, etc. The only features that can be usefully monitored on a regular basis by the VHRR are fog patches greater than 4 km (2.49 mi.) in diameter (but not ice fog), frozen or liquid state of lakes larger than 4 km (2.49 mi.) in diameter, and the larger ice features on very large lakes such as Lake Athabasca. The overall recommendation is that the VHRR is unsuitable for use in monitoring the small, meteorologically related features of interest in the AOSERP study area.

The present capability of satellite sensor systems does not yet provide both the resolution and frequency of observation in one instrument package which would allow operational monitoring of daily local weather in the Alberta oil sands. Neither does such a satellite system seem likely in the near future. The LANDSAT C satellite will again provide high resolution but lack frequency of coverage. The HCMM will have an adequate frequency of coverage but the resolution, although better than the VHRR, will still be insufficient for satisfactory detection and routine monitoring of effluent plumes, ice fog, and other small meteorologically related features.

The answer to the present dilemma lies in the concept of the special-purpose satellite, consisting of an instrument package and orbital platform specifically designed for, and financially acceptable to, large projects such as development of the Alberta oil sands. Relatively low-cost launch vehicles with multiple payload capability must be developed as the need for frequent regional-scale data collection with high-resolution increases.[29]

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[29] Syncrude Ltd. Remote Sensing and the Athabasca Tar Sands - An Overview, p. 1-3.

7. APPENDIX

ADDRESSES OF FIRMS AND AGENCIES

NOAA and LANDSAT Imagery:

Integrated Satellite Information Services Ltd.
P.O. Box 1630
Prince Albert, Saskatchewan
S6V 5T2

Phone: 306-764-3602

Specialized VHRR Imagery:

Mr. Russ Koffler, Chief
Environmental Products Group
World Weather Building, Room 806
5200 Auth Road
Camp Springs, Maryland 20023
U.S.A.

Phone: 301-763-8142

Standard VHRR Imagery:

United States Department of Commerce
National Oceanic and Atmospheric Administration
Environmental Data Service
National Climatic Center
Satellite Data Services Branch
Washington, D.C. 20233
U.S.A.

LANDSAT Imagery:

EROS Data Center
Sioux Falls, South Dakota 57198
U.S.A.

Phone: 605-594-6511

Experimental Satellite Techniques:

Satellite Data Laboratory
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario
M3H 5T4

General Remote Sensing Information:

Alberta Center for Remote Sensing
10405 - 100 Avenue
Edmonton, Alberta
T5J 0A6

Canada Centre for Remote Sensing
Department of Energy, Mines and Resources
2464 Sheffield Road
Ottawa, Canada
K1A 0E4

Phone: 613-993-3350

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DAT 44 IP

Wiesnet, D.R., McGinnis, D.F., and J.A. Pritchard. 1974. Mapping of the 1973 Mississippi River Floods by the NOAA-2 Satellite. Ninth International Symposium on Remote Sensing of Environment - Proceedings. 421-427.