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DETECTION OF FOREST-FIRE SMOKE PLUMES BY SATELLITE IMAGERY*

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Abstract—In support of the Canadian research programmes for Long-Range Transport of Air Pollutants (LRTAP), the present study was undertaken to examine the feasibility of using satellite imagery to detect large-scale pollution episodes. Atmospheric Environment Service (AES) satellite imagery records were scrutinized in conjunction with meteorological and air quality data. The LRTAP from large forest fires more than 5000 km away was identified. Further evidence was obtained from analysis of digital data from NOAA satellites by employing a 'false colour' technique. Computer enhanced images suggested that a smoke plume was well-defined and separated from clouds when smoke crossed over a lake and ocean.

It is suggested that many large forest fires with resulting intense smoke were due to atmospheric lightning. In particular, the area influenced by the widespread smoke, from large fires in northwestern Canada on 27–28 August 1981, exceeded the area covered by dust and smoke clouds in the low-level atmosphere from the Mount St Helens volcanic eruption on 18 May 1980.

Key word index: Forest-fire smoke plumes, smoke plume detection by satellite imagery, evidence of LRTAP, continental-scale transport of air pollutants.

1. INTRODUCTION

Research on the detection of forest fires in remote areas and smoke plumes is a challenging subject in view of both environmental damage and protection. Alberta forest fire smoke observed in eastern North America has been studied by Elsley (1952). Meanwhile, satellite detection on the forest fires in the northern environment of Alaska has also been reported (Ernst and Matson, 1977). Lyons and Dooley (1978) have given an excellent review of the 1970s research on satellite detection of air pollution episodes in the dimension of a few hundred kilometres.

During 1980–1982 we observed several cases of large-scale transport of smoke plumes up to several thousand kilometres originating from forest fires in western Canada. It is recognized that acid precipitation can be formed by the LRTAP and it causes some damage to natural and human environments. By examining AES satellite imagery and enhanced digital satellite data, evidence of LRTAP into eastern North America could be obtained. It is our purpose to discuss observations of forest fire smoke in the large scale and to describe the AES capability for detection of wildfires in remote areas of northern Canada. It should be also noted that evidence of large-scale pollution episodes is also required to verify air quality data analysis and for studies of numerical modelling.

* Dedicated to fire fighters in various Canadian forest services who are devoted to reducing environmental damage.

2. DIGITAL ANALYSIS OF SATELLITE IMAGERY

The present U.S. meteorological satellites are TIROS-N (NOAA) and GOES (geostationary). NOAA satellites are in sun-synchronous orbits at an altitude of about 850 km (Barnes and Smallwood, 1982), and use the Advanced Very High Resolution Radiometer (AVHRR). AVHRR provides five spectral channels for visible and infrared cloud images with a maximum spatial resolution of 1 km, and data from these instruments are available at AES.

To search for evidence of LRTAP, AES satellite imagery records for the years 1980–1982 were examined in conjunction with air quality and meteorological data. Initially, black and white photographic copies, for three channels (see Table 1) were scrutinized to detect smoke plumes. For this purpose, isolated smoke plumes originating from forest fires are ideal for detailed study. Several cases of LRTAP originating from large fires in cloud-free regions in western Canada were identified. A typical example is shown in Fig. 1. It should be noted, however, that such black and white photographs result in various interpretations, because white imagery of clouds and smoke is similar and supporting data are deficient.

AES is archiving digital satellite data of NOAA-6

Table 1. Channel characteristics and the assignment of colour in digital data analysis

Channel	Wavelength (μm)	Spectrum range	Colour
1	0.58– 0.68	Visible	red
2	0.72– 1.10	Near i.r.	green
4	10.50–11.50	Infrared	blue

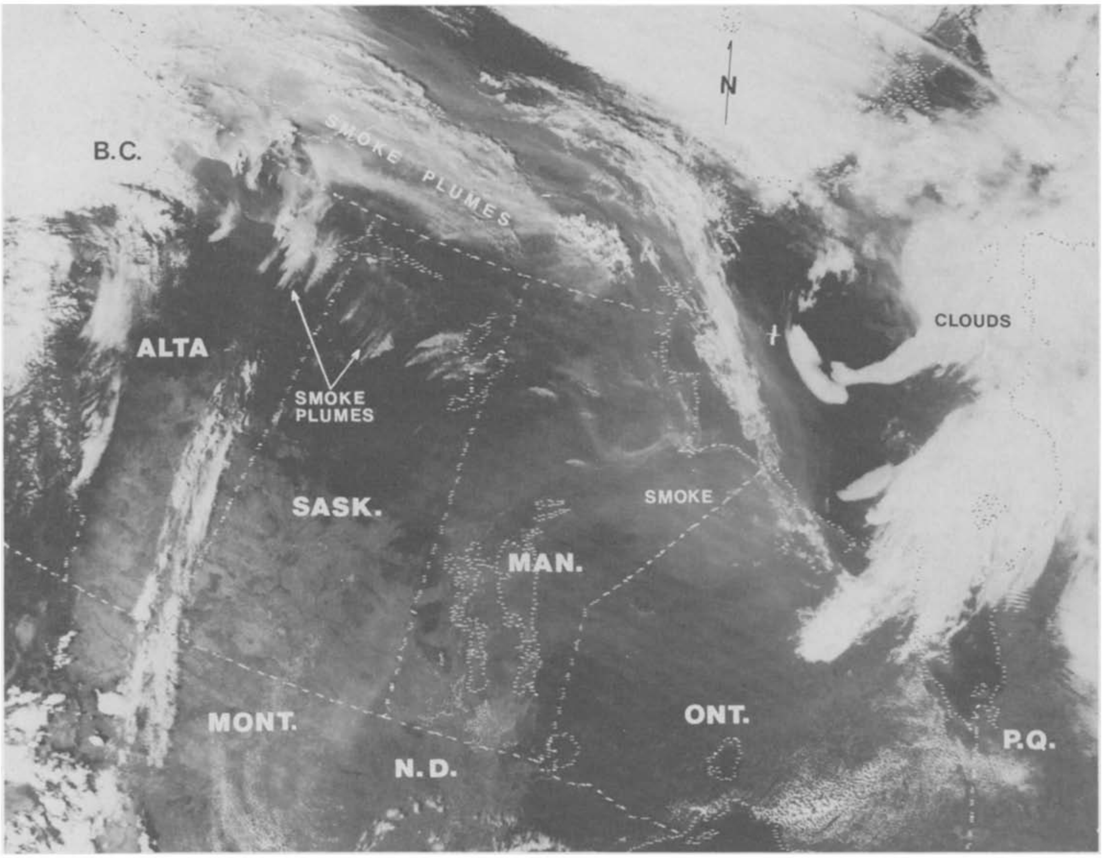

Fig. 1. NOAA-7 satellite visible image (orbit 923), 2016 GMT, 27 August 1981, shows massive smoke plumes from forest fires in the Northwest Territories, Alberta, Saskatchewan, and Manitoba extending over 3500 km into northern Ontario and James Bay. Many of the individual plumes are about 100–200 km long.

and -7 on tape. To provide further evidence of LRTAP, archived digital data were analysed by employing a 'false colour' technique, with the three basic colours as shown in Table 1. This technique was recently developed using the high resolution image-display system of the AES Meteorological Services Research Branch. The analysis scheme combines three different channels to produce a composite image in colour. The image produced on a cathode ray tube (CRT) is generated by one or more electron guns which each emits a beam at a specified intensity. Colours can then be obtained by assigning intensity values to the CRT electron guns red, green and blue. In the digital analysis Channel 1 (visible range) was assigned to the 'red' gun, and so on. A combination of red and green produced yellow; red, green and blue produced white (see Table 2). An enhanced satellite image using this colour scheme is shown in Fig. 2 (cf. Fig. 1).

Figure 3 illustrates digital data contained on tape and tape information is expressed in terms of histograms for the case of 27 August 1981. These histograms represent data for the entire image on the tape. For some of the analysis, however, insignificant intensity values were eliminated subjectively in order to enhance the unique feature of smoke plumes. In the analysis of digital data, tape information from three channels of a NOAA satellite was merged with the basic colours and the resulting imagery was then displayed on CRT. There were 256 intensity levels, and data on each tape contain an area of ~ 1024 km^2 (1024 × 1024 pixels). It is evident from this example that smoke plumes in analysed false colour have different characteristics from general cloud patterns, and that detection and isolation of smoke plumes is quite feasible by means of the current analysis of satellite imagery.

Table 2. Combination of basic three colours with three channels in digital analysis (0 for no intensity, and x for full intensity)

Channel 1 (red gun)	Channel 2 (green gun)	Channel 4 (blue gun)	Colour
0	0	0	black
x	0	0	red
0	x	0	green
0	0	x	blue
x	x	0	yellow
x	0	x	magenta
0	x	x	cyan
x	x	x	white

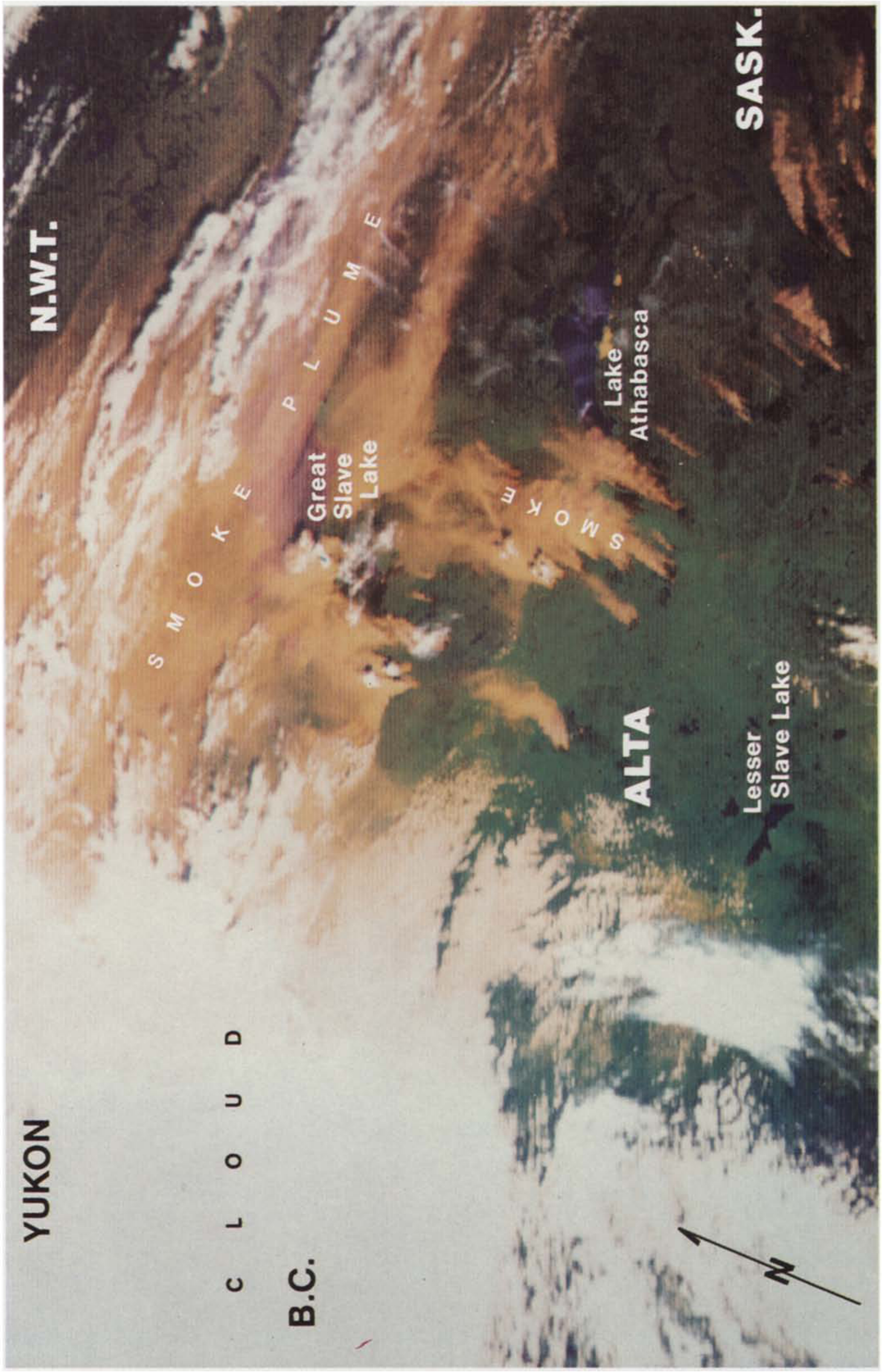

Fig. 2. Computer enhanced output for the satellite image (2015 GMT) of Fig. 1, showing yellow–orange smoke pollution from forest fires, purple smoke over lakes, and vast plumes extending from Alberta and the Northwest Territories over 1000 km into northern Manitoba. (Lake Athabasca is about 300 km long.)

Fig. 4(b). Computer enhanced output of the NOAA-7 satellite data (2004 GMT) of Fig. 4(a). Smoke generated by new fires in northeastern Alberta is clearly visible as well as portions of the buoyant plumes flowing out from the top of middle clouds. Widespread yellow–orange smoke is under mid-level clouds which are associated with a cold front.

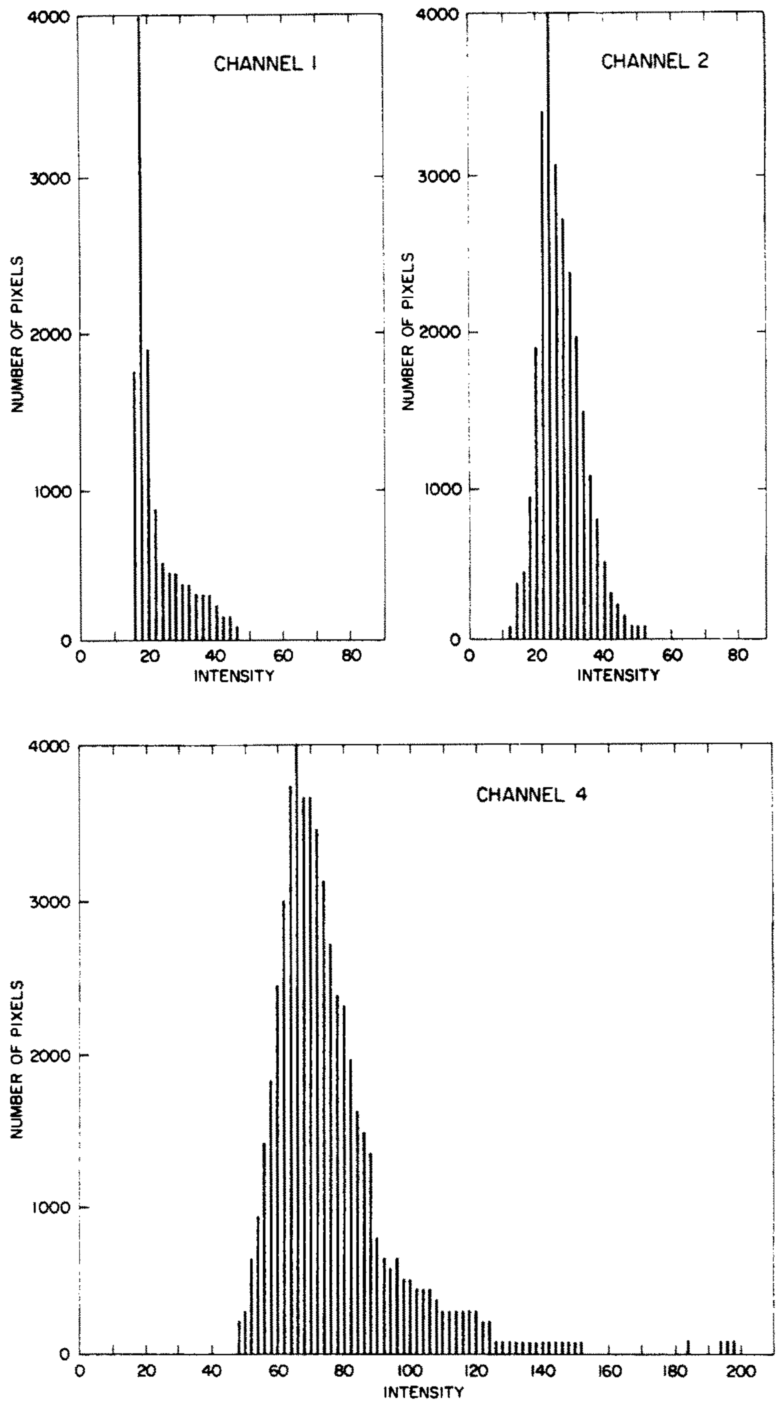

Fig. 3. Histograms of computer-processed digital data for Channels 1 (red), 2 (green) and 4 (blue) showing number of pixels for each intensity needed to produce the imagery in Fig. 2.

It is important to note that when a smoke plume was crossing over water a magenta or yellow–purplish colour emerged in the false colour analysis. Unfrozen lakes and oceans have a low albedo. Without the presence of air pollution, a lake surface generally appeared bluish. Satellite imagery over lakes clearly showed that plumes generated by forest fires can be detected. Using the current digital analysis scheme, industrial plumes crossing Lake Erie towards southern Ontario (with magenta) were also detectable and described elsewhere.

Aerosols in the smoke plumes are very effective in reducing visibility, and have particle sizes ranging from 0.01 to 60 μm in radius (Radke *et al.*, 1978). The majority of pollutants are 0.1–1.0 μm, and the medium size is about 0.6 μm which is a very effective size to scatter light to outer space. Consequently, pollutants with such sizes are quite visible. Since the visible sensor of the NOAA satellites operates in the 0.58–0.68 μm region, large-scale transport of smoke plumes is detectable as a milky white haze on visible black and white photographic imagery. However, these smoke plumes are less visible on Channel 2 than Channel 1, while the pollution is generally not detectable on other channels.

Aerosols in a smoke plume and water droplets in a cloud system have different optical properties. The optical characteristics vary depending on aerosol size distribution, aerosol density, depth and altitude of the layers and on different schemes of atmospheric scattering, reflection and absorption of solar radiation. These differences, therefore, seem to result in diversified colours in digital data analysis. In other words, the different colours between clouds and smoke plumes might indicate the variance in upward scattering of atmospheric radiation and optical characteristics of water vapour and pollutants in motion systems. Theoretical considerations of the density and optical thickness of aerosols are discussed in other studies (for example Griggs, 1975; Koepke and Quenzel, 1981, Kaufman and Joseph, 1982).

3. FOREST FIRES

The satellite imagery for 27 August 1981 in Fig. 2 shows typical large-scale forest fires in western Canada. About 50 individual fires can be identified, however, more than 100 wildfires were burning during the day. The smoke plumes drifting away from the Great Slave Lake area exceeded 1000 km in length. These plumes also extended to NE Ontario and James Bay about 3500 km from the source region. Meteorological data obtained from the AES network indicated visibilities were reduced by smoke; other photographic evidence suggested that the plumes passed through Quebec and Newfoundland to the Atlantic Ocean.

The smoke area in the satellite imagery was found to coincide well with the area where meteorological observers reported reduced visibilities. Because of massive smoke some stations reported visibilities

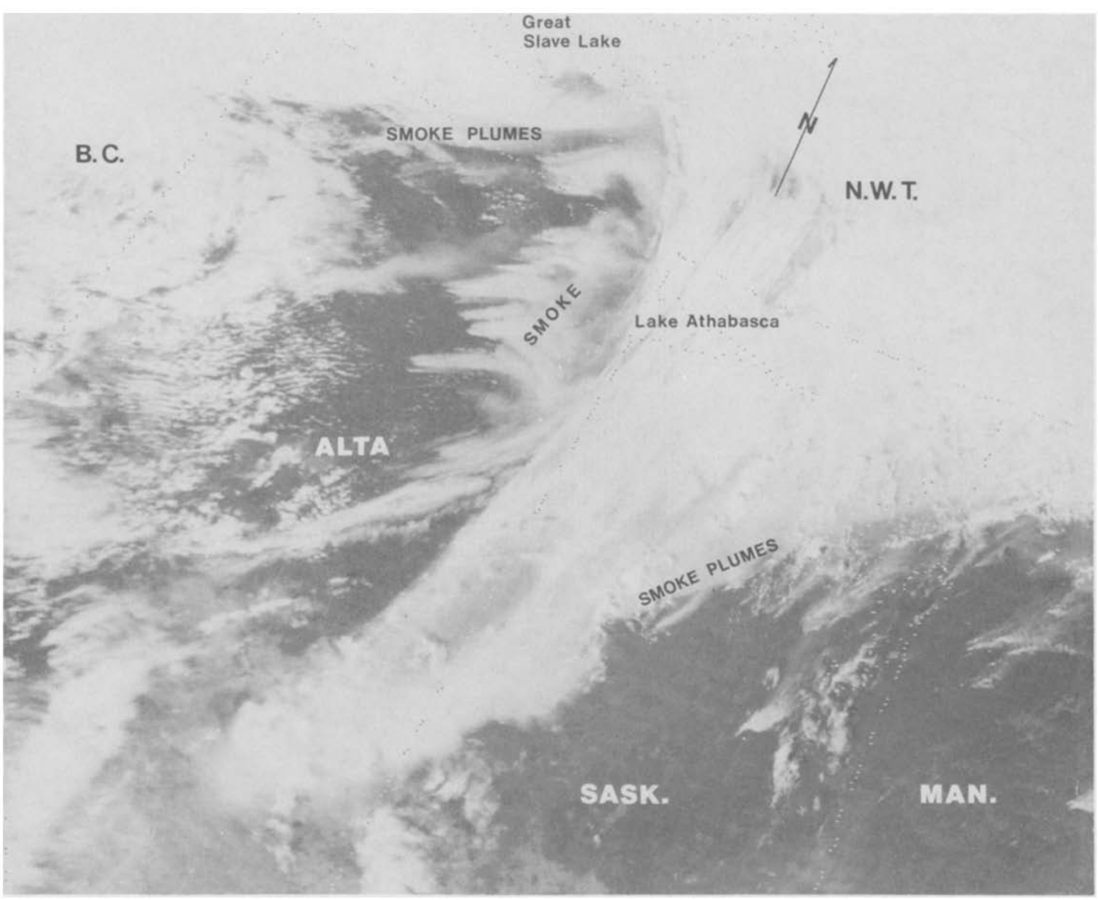

Fig. 4(a). NOAA-7 satellite visible image (orbit 937), 2004 GMT, 28 August 1981. Many smoke plumes are visible.

reduced to less than 0.2–1.0 km. Meteorological stations that recorded poor visibility and a smoke plume aloft included Norman Wells (65°N) and Contwoyto Lake in the Northwest Territories, Churchill in Manitoba, Fort Severn and Winisk in Ontario, Poste-de-la-Baleine, La Grande, Nitchequon and Schefferville in Quebec, and Goose Bay, Hopedale and Cartwright in Newfoundland (Fig. 5). The area covered by these smoke plumes during 27 and 28 August 1981 was estimated to be over 1.2×10^6 km^2, an area about twice the area of France (or five times the area of the U.K.). Interestingly, the area affected by smoke plumes from the large forest fires exceeded the area under the influence of dust and smoke clouds within the lower atmosphere over western Canada and northwestern United States on 21–22 May 1980 from the Mount St Helens volcanic emission (Chung *et al.*, 1981).

On 27–28 August 1981 most of the fires occurred in the Northwest Territories, northern Alberta and northern Saskatchewan where a prolonged period of very warm and dry weather prevailed during late spring and summer. These fires were confined to areas south of 63°N. Incidently, atmospheric lightning was reported at many AES stations. According to the Alberta Forest Service, most of the new fires were caused by the lightning. On August 27, more than 0.7 M ha of forests were burned. From the analysis of Fig. 2, the actual area burned can be estimated, i.e. the blackened areas where the smoke plumes originated. The detection of wildfires by means of remote sensing has become useful for uninhabited remote areas of northern lands in the Canadian sub-arctic. In any case, with the warm S winds and extremely dry weather prevailing, forest fires became more violent. In Alberta alone 0.3 M ha of forest burned in a 12-h period, of the 0.5 M ha that burned on 25–28 August and 27 August was recorded as "black Thursday" in the Alberta history of forest fire. While a 'dry' frontal system was passing through on 27–28 August, the new fires were ignited by lightning strikes over a broad area, as can also be noted in Figs 4(a) and (b).

In general, there are 7–8 days of lightning per summer month in northern Alberta; in the lee of the Canadian Rocky Mountains, and the descending air from the mountains is relatively dry due to the downslope motion, i.e. foehn or chinook. In particular, during many days in August 1981, daily air temperatures and heights of the 500 mb level were relatively higher than normal where extreme fire weather prevailed.

As can be seen from Fig. 4 and the trajectory analysis in Fig. 5 smoke plumes initially drifted northwards to the lee slope of the Rockies, and then shifted eastward towards Hudson Bay and Quebec. The trajectories estimated at the 850 and 700 mb levels also verify the paths of smoke plumes to the east.

During 9 and 10 September 1981 new forest fires were burning and about 0.1 M ha of forest was de-

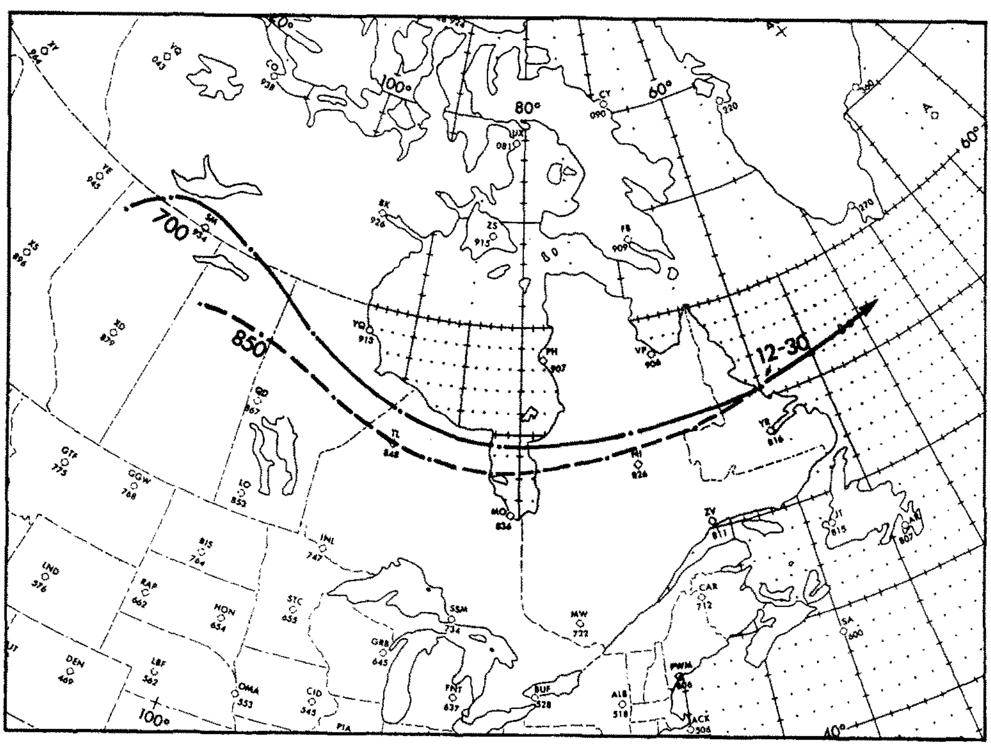

Fig. 5. Estimated 12-h backward trajectories, for the 850 and 700 mb levels, terminating at Hopedale, Newfoundland, 1200 GMT, 30 August 1981. The shaded area represents smoke or haze due to forest fires in western Canada.

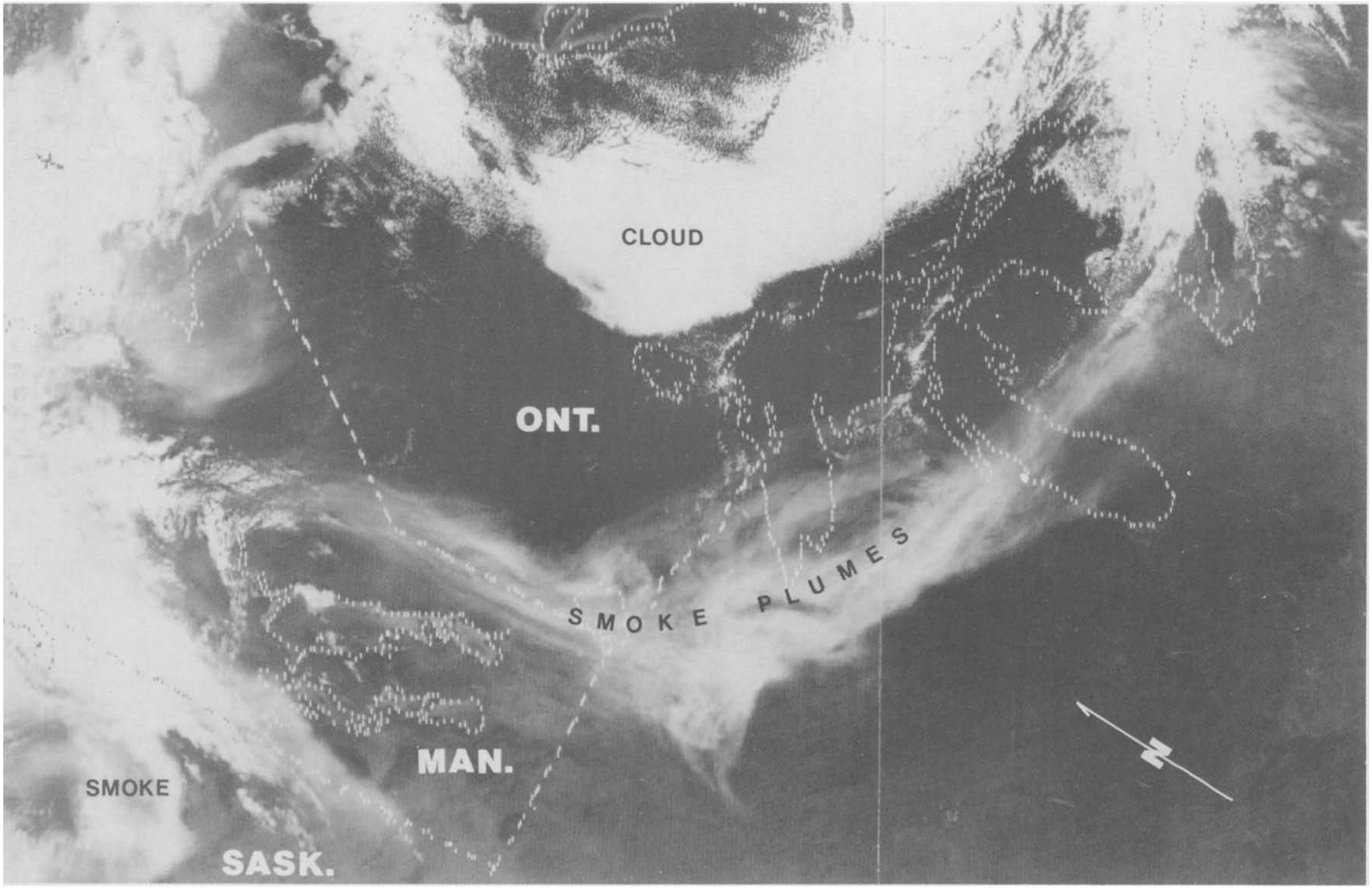

Fig. 6. NOAA-7 satellite visible image (orbit 1120), 1916 GMT, 10 September 1981. A long plume from forest fires in northern Alberta, Saskatchewan and Manitoba is drifting over 3000 km into Michigan, Ontario and New York.

stroyed in the Northwest Territories, Alberta and Saskatchewan. The resultant vast plumes were moving SE, as shown in Fig. 6. The smoke plumes extended from the source region to northwestern Ontario, Minnesota, Wisconsin, Michigan and southern Ontario. The plumes in the imagery are over 2000 km long. In addition, a forest area little more than 1 M ha was also burned during 15–19 September by wildfires and resulted in large amounts of smoke pollution.

4. SUMMARY

In this report we have discussed some of the environmental problems arising from Canadian forest fires and described the AES capability of detecting massive smoke plumes originating from forest areas. Using black and white satellite photographs, it was possible to identify several cases of smoke plume transport from forest fires in western Canada into eastern North America providing evidence of LRTAP. The transport of long plumes exceeding ~ 3000 km was detectable on a single photograph. In particular, two plumes drifted over 5000 km with the prevailing winds to the Atlantic from source regions in western Canada via either Quebec and Newfoundland or New York and Newfoundland.

AES has the capability of detecting forest fires by digital analysis of satellite data. Computer-enhanced satellite imagery using a false colour technique contributed further evidence to detect LRTAP from forest fires. The existence of air pollutants over lakes was indicated by a magenta or yellow–purplish colour. This technique can be applied for the detection of industrial pollution.

It was found that the area affected by smoke plumes originating from forest fires on 27 and 28 August 1981 exceeded 1.2×10^6 km^2. Many large forest fires that produce intense smoke occurred because of lightning strikes, particularly after a prolonged period of very dry and warm weather.

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