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AIR POLLUTION DETECTION BY SATELLITES: THE TRANSPORT AND DEPOSITION OF AIR POLLUTANTS OVER OCEANS

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Abstract—Research is continuing towards the possible detection of air pollution by remote sensing techniques, and satellite imagery has been examined to find evidence of cross-Atlantic transport of air pollution. Pollution masses from industrial areas are often carried out over the Atlantic Ocean by tropospheric winds. However, the pollution mass is generally steered by convergent flows and fronts of extra-tropical cyclones, and wet deposition and scavenging of air pollutants within clouds occur primarily over the cold ocean, especially during the occlusion stage of a cyclone. As a result, the oceanic area from Cape Hatteras to 1500 km ENE of Newfoundland (the SW sector of the Icelandic low area) is often a 'dumping ground' (sink region) for air pollution from N America.

However, a dust cloud generated by a volcanic eruption and a smoke plume from large-forest fires in western N America have been observed near the W coast of Europe. Saharan dust carried to N America by trade winds have been identified on satellite imagery. The massive smoke generation by large forest fires in Siberia is also identified in the present study. The results of research on forest fire smoke are currently being used by scientists studying the atmospheric effects of a large-scale nuclear war. It is suggested that the area between the S of Japan and the SW section of the Aleutian low is another principal sink of air pollutants and dust originating from NE Asia.

Key word index: Air pollution detection by satellites, air pollution sink over the ocean, trans-Atlantic air pollution.

Résumé—On poursuit la recherche sur les possibilités de la télédétection dans le domaine de la pollution atmosphérique. On a examiné des images de satellites pour montrer que les polluants atmosphériques traversent l'Atlantique. Les vents troposphériques transportent souvent au-dessus de l'Atlantique les masses de pollutants des zones industrielles. Toutefois, ces masses de pollutants suivent en général les écoulements convergents et les fronts des cyclones extratropicaux. Ainsi, le dépôt humide et l'entraînement des polluants atmosphériques dans les nuages a-t-il principalement lieu au-dessus des eaux froides de l'océan, particulièrement lors de la phase d'occlusion des cyclones. La région océanique, depuis le cap Hatteras jusqu'à 1500 km à l'ENE de Terre-Neuve (secteur sud-ouest de la dépression islandaise), sert souvent de 'dépotoir' (puits) aux pollutants atmosphériques de l'Amérique du Nord.

Toutefois, on a observé près de la côte ouest de l'Europe un nuage de poussière produit par une éruption volcanique et un panache de fumée provenant de grands incendies de forêts, dans l'ouest de l'Amérique du Nord. On a identifié sur des images de satellites des nuages de poussières du Sahara poussés par les alizés et s'approchant de l'Amérique du Nord. La présente étude examine aussi la production massive de fumée par de grands incendies de forêts en Sibérie. Les spécialistes des effets atmosphériques d'une guerre nucléaire à grande échelle utilisent actuellement les résultats de la recherche sur la fumée des incendies de forêts. On suggère aussi que la région située entre le sud du Japon et le secteur sud-ouest de la dépression des Aléoutiennes est un autre grand puits de polluants atmosphériques et de poussières provenant du NE de l'Asie.

1. INTRODUCTION

Before the 1960s scientists concentrated their investigations on small-scale transport of air pollutants and local air quality. Since the mid-1970s, however, many studies have also been concerned with the medium- and large-scale transport of air pollution in order to help understand the reasons for the wide-spread occurrence of acidic precipitation and forest damage attributed to air pollution. Acid rain is closely related to long-range transport of air pollutants (LRTAP). The current knowledge of the transport of air pollution should be improved in order to understand the increasing problems in air quality management, and there is a need for studies to demonstrate the LRTAP using visual means.

As Husar *et al.* (1981) have pointed out, haziness is a measure of light scattering and absorption by aerosols, and is also closely related to the concentration of air pollutants. Meteorological satellites are capable of measuring these radiational characteristics, thus satellite imagery has been used to detect dense haze, dust and smoke (McLellan, 1971; Munn and Bolin, 1971; Ernst, 1975; Lyons and Husar, 1976; Lyons *et al.*, 1978). According to Lyons and Husar (1976), a widespread haziness is a characteristic of aerosols and thus a reduction in surface visibilities. The polluted airmass usually appears somewhat brighter, i.e. milky or blurry, than the low albedo surfaces particularly in visible (Channel 1) images.

Recently, the detection of continental-scale transport of smoke plumes from forest fires in W Canada has been demonstrated (Chung and Le, 1984). The present paper is intended to give examples of large-scale transport of forest-fire smoke plumes, dust clouds and industrial air pollutants. The feasibility of trans-Atlantic transport of air pollution is also discussed.

2. TRANSPORT AND SINK OF AIR POLLUTION OVER THE OCEAN

2.1. *Transport over the N Atlantic*

Lyons and Husar (1976) have successfully shown, from using satellite data, that a large haze area prevailed over the central and eastern U.S. and found that the haziness was well correlated with the sulphate concentrations of the ambient air. From satellite imagery, Ernst (1975) has discussed a hazy area drifting from the U.S. to the Atlantic seaboard.

We have also observed that, especially in the summer, a large area of haze from the eastern U.S. moves out over the Atlantic Ocean approximately every 1–2 weeks. As can be seen in Fig. 1, a hazy area near the E coast of the U.S. is often detectable on satellite imagery. High concentrations of air pollutants, such as O_3: 200 $\mu g\, m^{-3}$, sulphate: 30 $\mu g\, m^{-3}$ and total suspended particulates (TSP): 100 $\mu g\, m^{-3}$ are readily measurable within the build-up area of haze. Galloway *et al.* (1984) have estimated the flux of air pollutants and found that of the S and N emitted to the atmosphere of eastern N America, about 34 and 24–71 %, respectively, travel E to the Atlantic Ocean. Quantitatively, satellite data are being used to establish the columnar mass density of sulphates as discussed by Fraser *et al.* (1984).

Simplified axes of maximum frequency of occurrence of cyclones over the NW Pacific and Atlantic (Palmén and Newton, 1969: p. 95) are shown in Fig. 2. Figure 3 also illustrates the cyclone families and frontal systems over mid- to high-latitudes in the NW Atlantic. Cyclones travel along the polar frontal zone which frequently forms in the lee of the continent, and the series of cloud bands associated with fronts generally move E or NE semi-periodically.

As air pollutants start to built up, the aerial extent of haze increases with time in the rear (i.e. SE of a cold front) of a slow moving anticyclone, and the haze is intensified over the region between the mid-western States and the SW of Lake Erie, where numerous industrial areas and urban centres exist. When the shroud of haze crosses the Appalachian Mountains, it tends to weaken somewhat over the barrier due to the

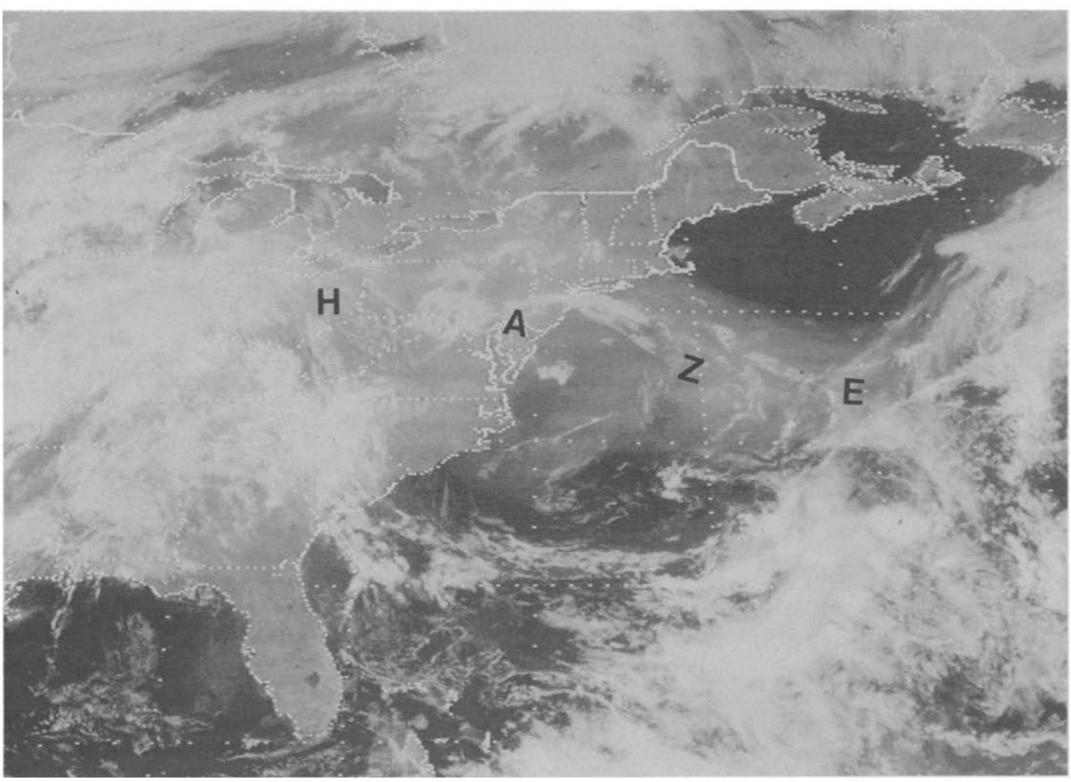

Fig. 1. GOES-E visible image taken at 1431 GMT on June 1979, illustrating the grey-milky appearance of the haze over eastern N America and over the Atlantic Ocean.

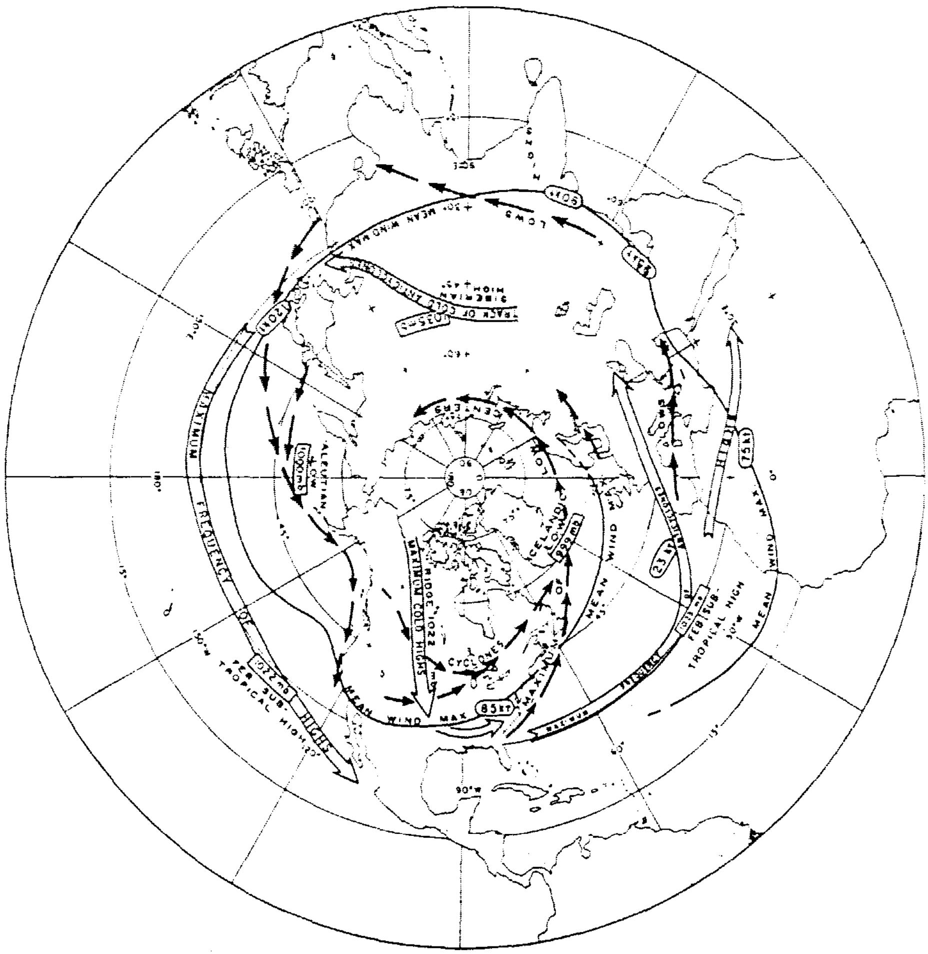

Fig. 2. Simplified axes of maximum frequency of occurrence of cyclones (short arrows) and the axis of mean maximum wind (heavy line) for the winter season. After Palmén and Newton (1969). Reproduced with permission.

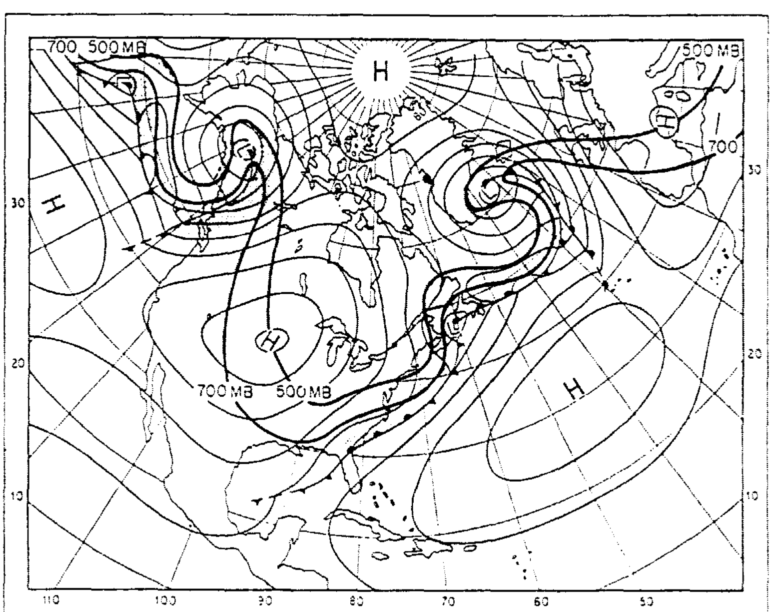

Fig. 3. Schematic sea-level map showing cyclone families and frontal surface topography. After Palmén and Newton (1969). Reproduced with permission.

deposition of pollutants and the formation of divergent airflows. Over the eastern seaboard, however, it re-intensifies with a new supply of pollutants in that area. As the air descends from the orographic barrier towards the ocean, the airflow becomes convergent. This convergent flow often merges with and is superimposed on a front where a semi-permanent baroclinic zone forms in the lee of a continent due to the change of orography. As the convergence of northeasterlies and southwesterlies occurs, a 'trapezoidal-shaped' area of haze generally results over water (Fig. 1). The haziness persists within the planetary boundary layer (PBL) below the level of 1.5–2.5 km, and the mixing depth over the cool ocean becomes shallower than that over warm land.

Using about 20 selected cases, an attempt has been made to study the possibility of trans-Atlantic pollution of industrial origins. It was found that a hazy area originating in E N America is often steered by a large cloud area associated with the polar front and a cyclone. The polar front is commonly connected to the Icelandic low area (see Fig. 3), and the haze layer can be well mixed, particularly with low clouds in the occlusion stage of a cyclone. The processes of a cyclonic evolution occur more or less continuously until the occlusion stage. Subsequently, the precipitation scavenging (i.e. rain and washout) of air pollutants should occur within the life cycle of an extra-tropical cyclone, and thus the haziness becomes weaker as a result of these processes.

The air temperature over the Icelandic low area is much lower than the ambient temperature that is associated with a situation of air pollution build-up over land. The mixing heights are generally low over cold water and this results in effective plume fumigation at a relatively short distance (cf. summer vs winter atmosphere). The decrease in mixing depth over cold waters from land can be another factor for the relatively fast deposition occurring in the marine boundary layer. The abundant availability of water vapour also enhances the condensation process for hygroscopic nuclei and aerosols along the frontal zone of a cyclone.

In the N Ontario environment (Chung, 1978), we observed a 60–70% reduction in concentrations of O_3, SO_4^{2-} and TSP at Moosonee after 48 h when the polluted air from industrial sources in the U.S. had drifted 1400 km. The eddy deposition rate of sulphates, for example, is typically 0.4 cm s^{-1} with a half life of 48 h. In turn the decay of pollutants appears to occur in the cool, humid air within 3–4 days as a result of the processes described above during Atlantic transport. The haziness gradually loses its intensity in a cyclone as it moves E and the hazy area usually dissipates well before reaching 30° W. Thus the oceanic area from the S of Cape Hatteras to 1500 km ENE of Newfoundland appears to be a 'dumping ground' of industrial air pollution from N America.

2.2. *Transport over E Asia*

Figure 4 is an example of satellite pictures showing a dust storm over Korea and Japan (20 April 1980) that originated in N China. Meteorological observers in Korea and Japan reported a visibility reduction on 13 May 1981 due to the dust storm generated on 8 May 1981 in China, and this can be also seen in the synoptic chart shown in Fig. 5. The distance from N China to meteorological stations that observed dust in N Japan is 1600 km. The dust storms are carried long distances by cold air outbreaks, commonly W–NW winds, after the passage of a 'dry' cold front. The airborne sand and soil dust are called "yellow sand" in the Far East, and a

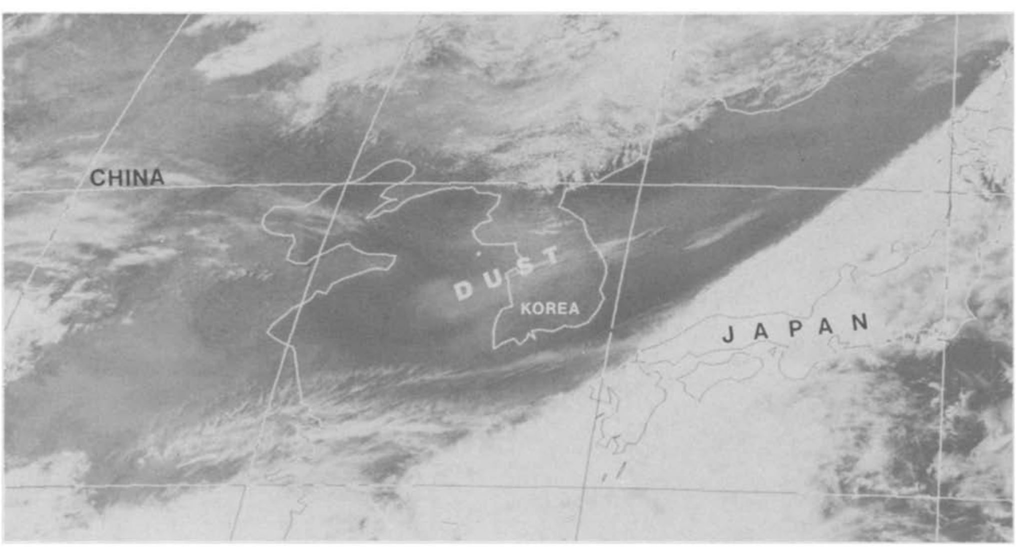

Fig. 4. An example of the satellite pictures showing a dust cloud over and near Korea at 0600 GMT, 20 April 1980 (GMS Orbit 0532; VIS). The dust storm had originated in N China and was moving towards Japan.

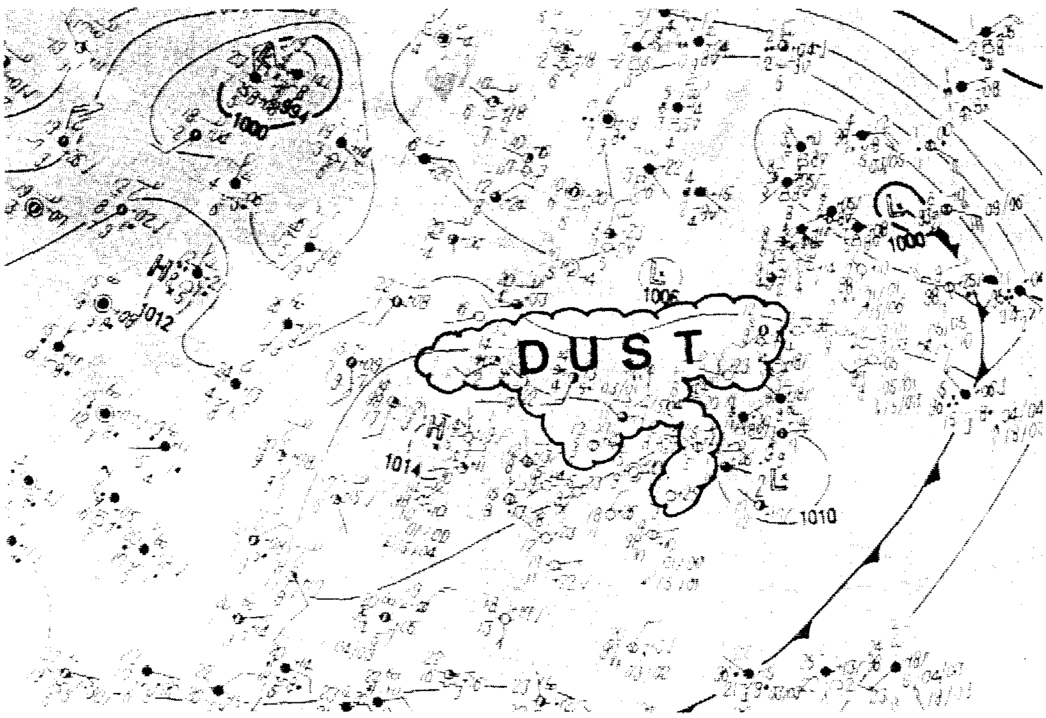

Fig. 5. A surface map of the Japan Meteorological Agency showing observations of dust and yellow sand (enveloped) in Korea and Japan (1200 GMT, 13 May 1981).

reduction of visibility to 1–2 km can be observed in March–May with the invasion of Korea and Japan by dust clouds from China.

There is another semi-permanent frontal zone in the oceanic area from the S to NE Japan and this polar frontal zone is often connected to the Aleutian low area. From the examination of dust clouds originating in N China, it was observed that dust storms are usually steered by the polar front over the NW Pacific and they undergo a marked decrease in intensity as they are carried by synoptic-scale disturbances over water. Nevertheless, recent studies (e.g. Uematsu *et al.*, 1986) indicate that aerosols from dust originating in China were measured at a few sites in the central N Pacific. In some cases, Uematsu *et al.* have observed dust transport over 10,000 km, and their estimation suggests that about 20 M t of mineral dust are removed by winds from E Asia each year. Using satellite digital data, an effort has been made to compute the optical characteristics and the columnar aerosol density of dust plumes over the NW Pacific by Takayama and Takashima (1986) in Japan.

3. INTER-CONTINENTAL TRANSPORT

It is of interest to note that the first solo Atlantic balloon flight was successfully completed by Mr J. Kittinger during 15–18 September 1984 and was reported by Williams (1984). The flight was designed to cross the Atlantic as quickly as possible without merging into a cyclone, and the time to cross the Atlantic from Maine, U.S. to Capbreton, S France took 68 h. Although the highest altitude achieved was 4.9 km MSL, the He balloon was maintained at altitudes of 3.3–3.9 km (650 mb) over water. As forecast, Kittinger successfully demonstrated that maintaining high altitudes with favourable winds, and avoiding cyclonic disturbances, are required for trans-Atlantic crossing. Our experience indicates, however, that air parcel trajectories in the frictional layer (PBL) generally deviate to the N and that a balloon or aerosols at the lower altitude would have travelled further N, even with the same meteorological conditions.

3.1. *Volcanic dust and smoke*

There are several well-documented cases showing the atmospheric transport of volcanic dust clouds over distances of up to several thousand km (e.g. Chung *et al.*, 1981). As shown in Fig. 6, two dust clouds were formed by the Mount St. Helens volcanic eruption on 18 May 1980. The tropospheric dust cloud moved via Montana towards N Ontario and dissipated in an extra-tropical cyclone over Hudson Bay and N Quebéc. With this cloud, dust falls of 1–2 mm were observed in the S of British Columbia and in Alberta and Saskatchewan near the U.S. border. Suspended particulates observed on 21 May were in the range of 365–945 $\mu g\,m^{-3}$ at Winnipeg, Regina, Saskatoon, Moose Jaw, Calgary and Lethbridge. With the volcanic dust and smoke prevailing, observed values of sulphate aerosols only increased from 4.84 to 6.33 $\mu g\,m^{-3}$ at three sites in Regina and Saskatoon on

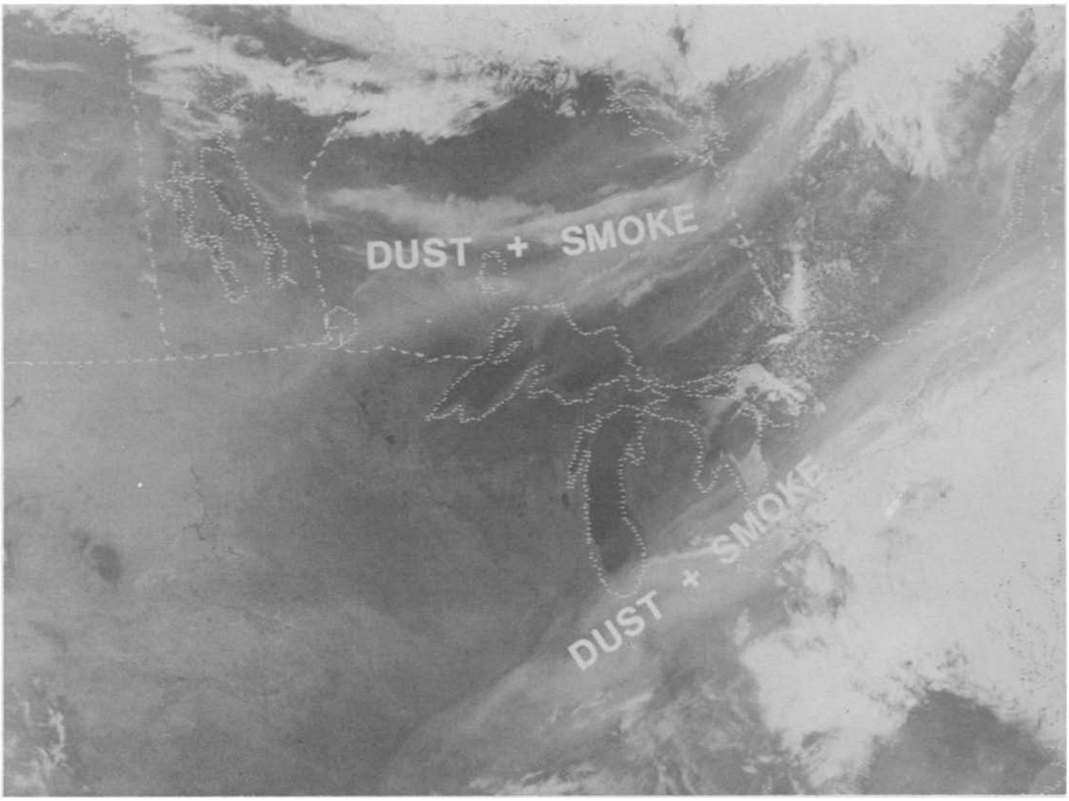

Fig. 6. NOAA-6 Satellite (VIS) image, 1406 GMT, 21 May 1980, showing two dust clouds from the Mount St. Helens volcanic eruption. The tropospheric dust cloud was over N Ontario and Québec and the dust cloud at the jet-stream level was drifting over Missouri, Illinois, Michigan, Ohio, S Ontario, etc.

the same day. The second dust cloud, which was in the lower stratosphere, travelled with jet-stream winds further to the E and reached Europe in a week. However, a major portion of the high-level dust cloud rapidly lost its intensity due to a cyclonic disturbance over the Atlantic, and consequently, the volcanic dust was not clearly identifiable when it reached the Iberian peninsula.

As shown in Fig. 7, the volcanic eruption in Mexico on 4 April 1982 has also been detected by the AES satellite imagery. Robock and Matson (1983) have successfully shown that a dust cloud from the eruption of the El Chichon volcano travelled around the world in 20 days. The highest concentrations of the volcanic smoke and dust was at about 26 km, and the circum-global transport was possible because there are no significant disturbances at that level in the tropics. Even one year later, the Mexican volcanic dust aerosols were still observed in the stratosphere (Shah and Evans, 1985). The tropical air mass is characteristically stable and homogeneous in the stratosphere.

3.2. *Forest fire smoke*

Smoke plumes generated by large forest fires are often observed to drift at the level 2–4 km due to intensive heating and initial ascending currents. Thus, the motion of a smoke plume can be independent of the dispersion conditions prevailing in the PBL. For example, Bull (1951) reported his observation of a smoke plume in Europe which had originated in Alberta, Canada. Using satellite imagery, the continental-scale transport of forest-fire smoke plumes over distances greater than 5–6000 km was discussed by Chung and Le (1984). It can be seen in Fig. 8a that the leading edge of the smoke plume, from NW Canada, was drifting above the PBL and had reached 10° W. The smoke plume eventually merged with a large cloud over Europe. Figure 8b also shows a plume observed near 20° W and moving towards W Europe. The distance from the tip of Newfoundland to SW Ireland is about 3200 km, hence the plume had travelled over 9000 km from the source region in W Canada.

Figure 9 depicts another case of massive smoke generation resulting from large forest fires in Siberia. The giant smoke plumes were merging into various clouds and persisted over the subarctic area of the U.S.S.R., and a portion of the hazy area slowed gradually as it moved to the Canadian Arctic. It is believed that the influence of forest fire emission is one of the causative agents for Arctic haze. It should be noted, however, that a forest-fire smoke plume can usually be detected on visible channel (1) of the AVHRR and GOES products.

Fig. 7. Computer enhanced (Channel 1, 2 and 4) image of the NOAA-6 Satellite, 5 April 1982, showing a volcanic dust and smoke cloud (purple or grey) over the ocean extending from S Mexico to the SE of Cuba.

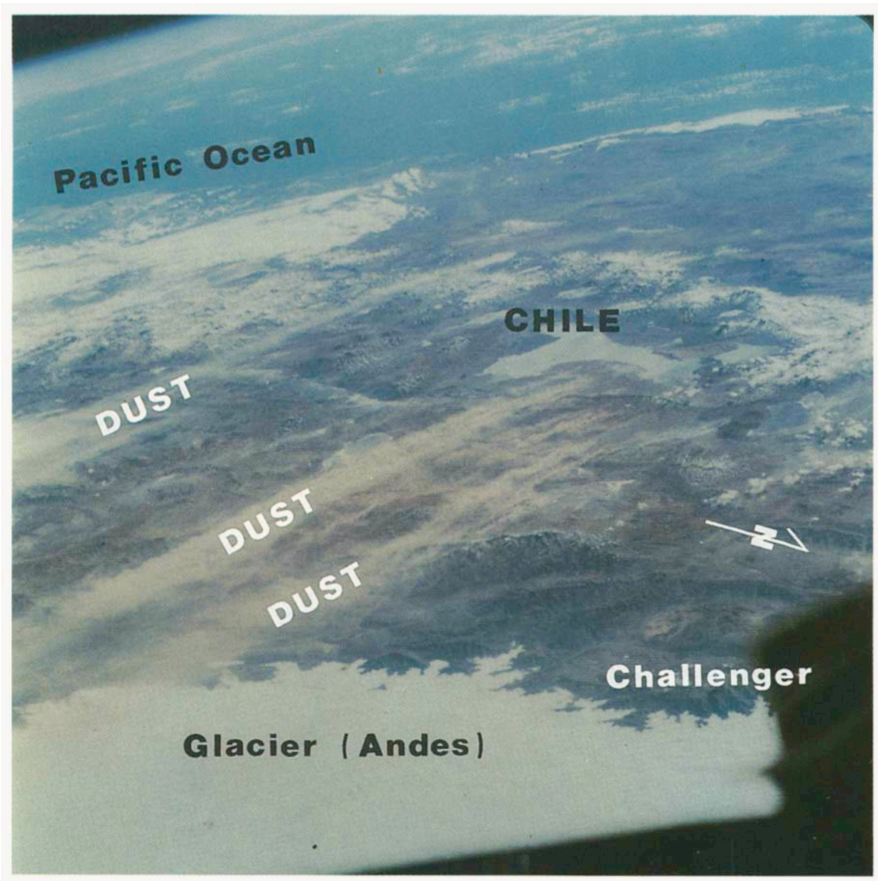

Fig. 11. U.S. Space Shuttle view of a dust strom over the Andes. The photograph was taken from the Challenger on 7 April 1984 looking towards the Pacific, and streaks of dust are crossing a glacier. (Courtesy of Dr M. R. Helfert.)

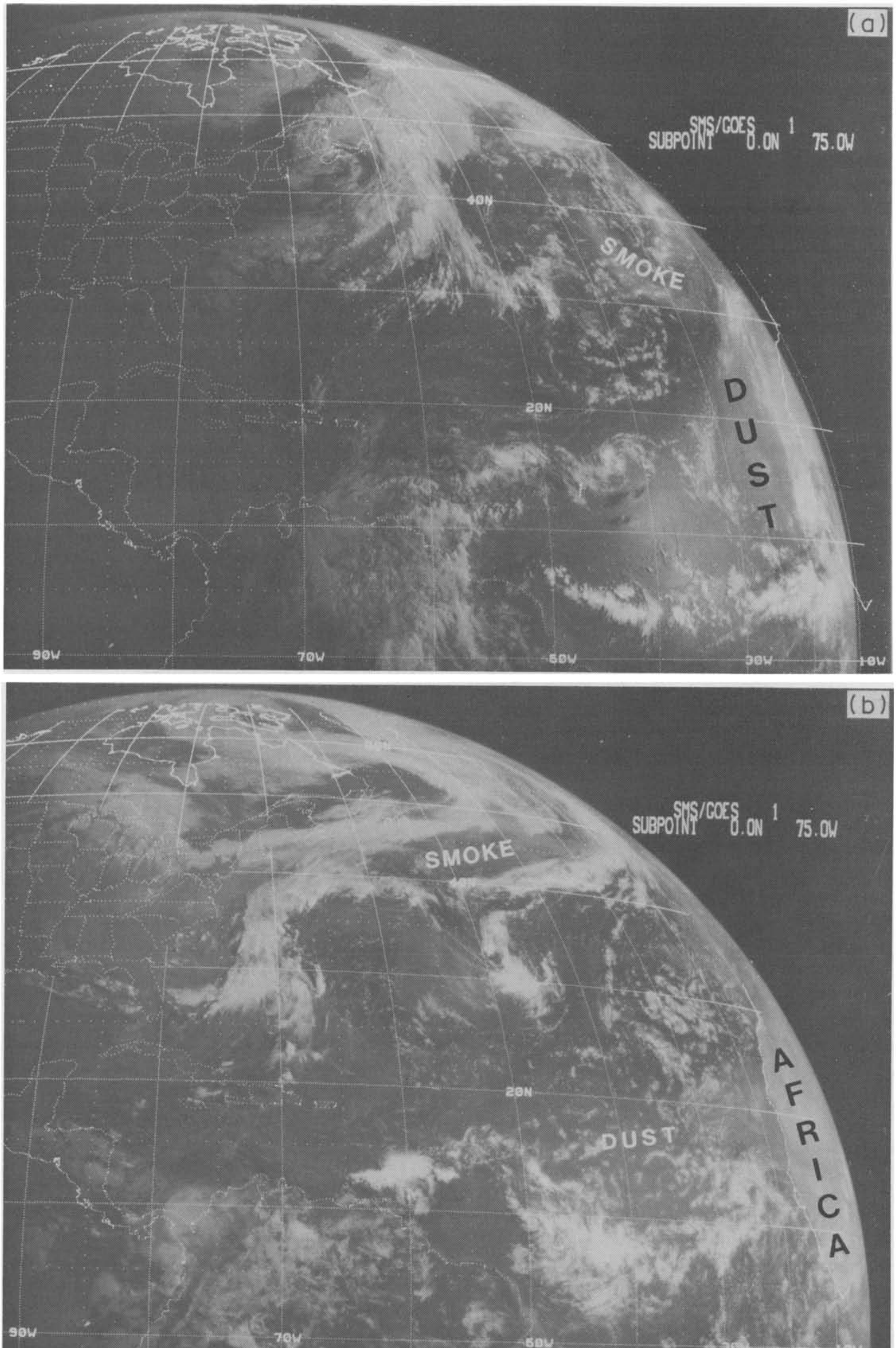

Fig. 8. (a) Visible GOES-E Satellite image, 1100 GMT, 18 August 1981, showing a smoke plume extending from the central N Atlantic to 10° W. (b) Visible GOES-E Satellite image, 1201 GMT, 3 August 1982, showing extensive smoke plumes around 46° N and 30° W. These smoke plumes were generated in Yukon and NE British Columbia during the period of 26–29 July and reached Europe during 5–6 August 1982.

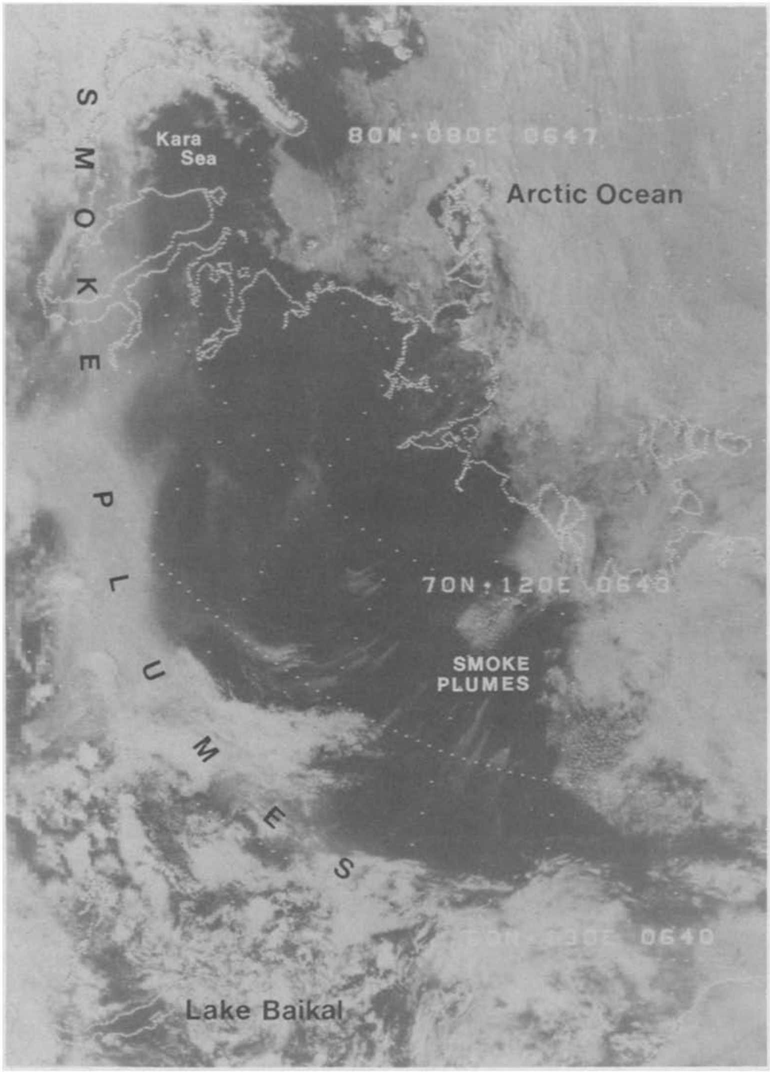

Fig. 9. NOAA-7 Satellite visible (GAC data) imagery, 0647 GMT, 24 July 1984, showing massive smoke plumes originating from numerous forest fires in Siberia, U.S.S.R. A giant plume from forest fires to the NE of Lake Baikal is drifting over 3000 km into the Kara Sea of the Arctic Ocean.

3.3. *Industrial pollutants*

As noted earlier, the transport of air pollutants to Europe is much reduced by the dry deposition over cool water and especially by the precipitation scavenging associated with the polar front over the NW Atlantic. With this in mind, we have examined the levels of sulphate observed at sites along the W coast of Europe. According to data obtained for the summer of 1981–82, variations in concentrations of sulphate aerosols were found to be very low; usually less than 1–2 $\mu g\, m^{-3}$ but, on occasion, can exceed 2–3 $\mu g\, m^{-3}$ even with persistent W flows originating from the eastern U.S. With cold NW flows, however, background concentrations of SO_4^{2-} can be estimated at 0.1–0.4 $\mu g\, m^{-3}$. Recordings of other pollutants, such as NO_3^-, Mg and NH_4^+ in rain, consisted of small values but they were quite variable with cyclones originating from or near N America. The observed pH values were generally 4.7–5.5 (i.e. slightly acidic) with these cyclones, which implies anthropogenic inputs of pollutants into extra-tropical cyclones from N American sources. The pollution data for the stations of Valentia, Ireland; Irafoss, Iceland; Faerøene-Akraberg, Denmark; Goonhill, England; and Vert-le-Petit in France were examined. The examination of these data was carried out with the aid of meteorological charts and satellite data obtained from Germany.

3.4. *Dust storms*

Figure 10 shows the dust storm originating over N Mexico as displayed on the satellite imagery. The dust plume was detectable in the visible image (Fig. 10a) and 3 days later in the infrared region (Fig. 10b). The streaks of dust were moving towards the Great Lakes steered by a large cloud mass associated with a cyclone. Interestingly, U.S. Space Shuttle astronauts were also able to observe dust storms and smoke plumes over many lands. One example is included (Fig. 11) in which long dust plumes were occurring over the highlands of the Andes and the leading edge of the dust cloud streaks was crossing a glacier. Vermillion (1977) has published satellite data demonstrating the development of a dust cloud in Colorado, U.S. and its successive movement to the W Atlantic. By using this case, Reiter *et al.* (1984) have inferred that aerosols measured at a mountain top in Germany during 4–5 March 1977 were the result of the transport of a dust storm cloud which originated in Colorado on 23 February 1977.

Saharan dust observed at Barbados, 5000 km away from Africa, was the subject of a study by Carson and Prospero (1972). They measured dense haze at the surface over a wide area of the Caribbean in the 10–25° N latitude belt and suggested that the average travel time of dust clouds was about 5 days. The highest concentrations of dust were found at the 3.2 km level above a strong inversion. In the tropics, the height of a mixed layer can be much higher (2–4 km) than that in high latitudes. Therefore, dust plumes in very warm air can travel long distances with a long life span. At any rate, following the arrival of the Saharan dust, dense haze with dust 78 $\mu g\,m^{-3}$ was observed at a Miami site. In another study, Savoie and Prospero (1977) recorded Saharan dust at Miami in the range of 0.2–90 $\mu g\,m^{-3}$ with the mean value of 10.5 $\mu g\,m^{-3}$.

Satellite imagery is shown in Fig. 12 to demonstrate the massive dust cloud of high intensity from the Saharan Desert. The aerial extent of the dust cloud is also visible to a lesser degree in Channels 2, 3 and 4 of the AVHRR of NOAA satellites, so that a dust storm consists of relatively large aerosols, i.e. 0.5–11.5 μm. The large-scale transport occurred as a result of the absence of a synoptic disturbance in the tropics, in contrast to the cases for pollution sinks with frontal activity prevailing in mid-latitudes. During this period the inter-tropical convergence zone (ITCZ) was further S. The extensive dust cloud moved to the West Indies (over 6000 km) from the Sahara in 6 days carried by trade winds. Further examination of satellite data and meteorological charts indicated that some weaker dust plumes moved to the E seaboard of the U.S.

According to the summary of Morales (1979), the soil erosion and dust transport from the Sahara Desert

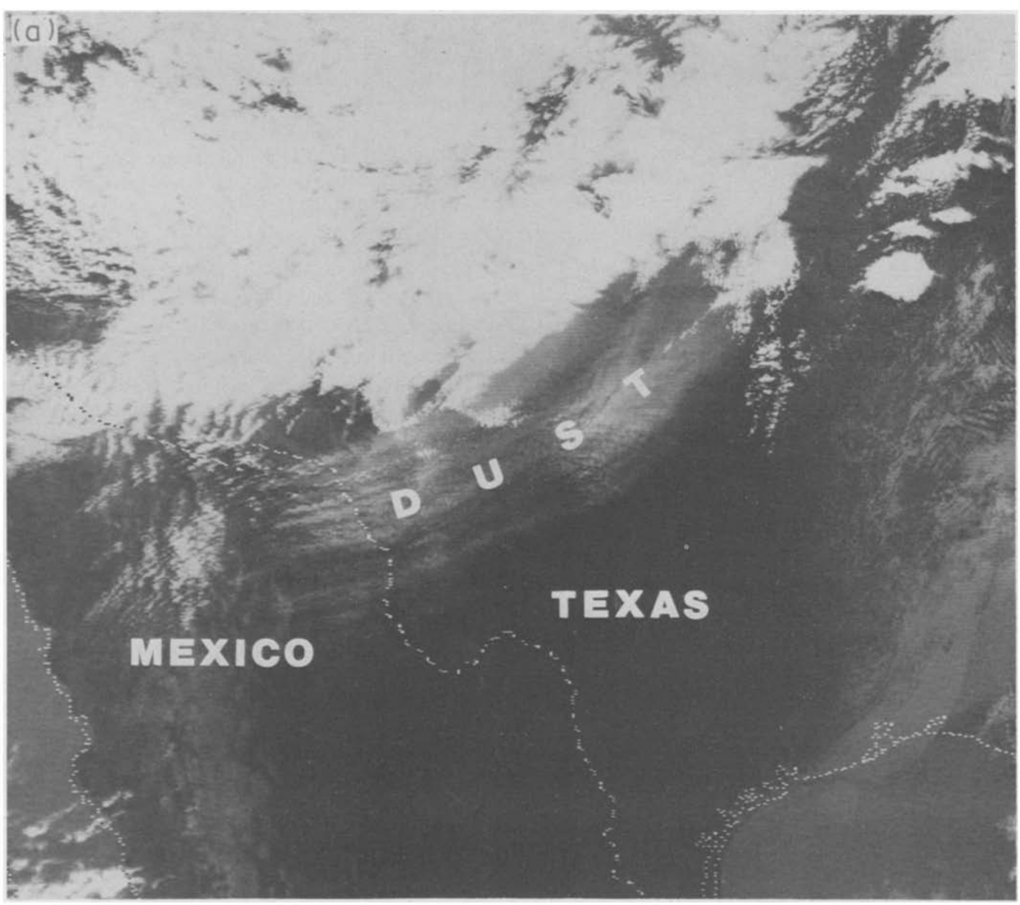

Fig. 10(a)

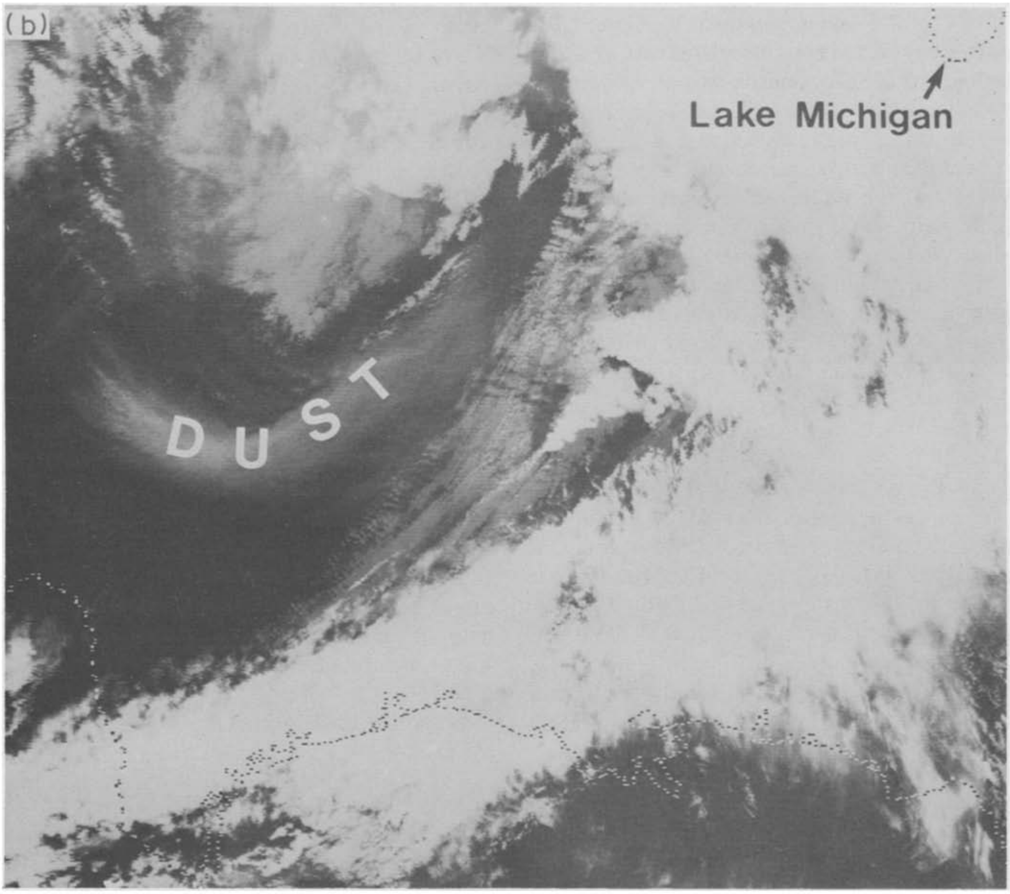

Fig. 10(b)

Fig. 10. NOAA-7 Satellite imagery showing a dust storm: (a) Channel-2 imagery taken at 2146 GMT, 26 April 1984; 900 km long streaks of dust plumes that originated in N Mexico (south of El Paso) are visible. (b) Channel-4 imagery taken at 2110 GMT, 29 April 1984. The leading edge of dust plumes was reaching Kansas and Missouri over a distance 1400 km from Mexico. The dust plumes are clearly entering the cloud system associated with a front.

were estimated to contribute 60–200 $M\,t\,a^{-1}$ to the troposphere.

In Canada, the number of yearly forest fires *exceeds* 9000. Annual emissions from Canadian forest fires for the year 1980–1981 were estimated at over 200 $M\,t\,a^{-1}$ (Chung, 1984). Also, pH values in rain water measured in the forest fire regions in W Canada were lower than the values recorded in other areas, as shown in Fig. 13. During the forest fire season, they may be responsible for the observed increase in acidity and for Arctic haze.

The presence of a large quantity of aerosols in the atmosphere is generally believed to produce a cooling effect at the low-level atmosphere. Accordingly, many scientists (e.g. Crutzen *et al.*, 1984; Hare, 1985) are currently utilizing research information on forest fire smoke to study the atmospheric effect of a large-scale nuclear war.

4. SUMMARY AND CONCLUDING REMARKS

Satellite data have been used in order to demonstrate the detection of forest-fire smoke plumes, industrial air pollution, and dust-laden clouds from deserts and volcanoes. Photographic data in the present study include visual examples of LRTAP over distances of 1000–9000 km.

By examining the aerial extent and motion of pollution-laden air masses, it has been observed that a pollution mass undergoes significant modification over waters due to frontal and cyclonic activities. The deposition of polluted air over the cold water appears to occur with convergent airflows and large clouds in synoptic disturbances. The dry deposition within the humid marine boundary layer and precipitation scavenging over water are therefore responsible for the reduction (say 85–95%) of air pollution.

According to the satellite imagery examined, the Atlantic appears to be a sink of air pollution originating in eastern N America. The SW sector of a semi-permanent low, commonly situated at the S of Greenland–Iceland, is the favoured area for the sink. For air pollution originating in the Far East, on the other hand, the favoured sink over water appears to be in the area from S of Japan to S of the Aleutian Islands, where a semi-permanent frontal zone usually forms.

In contrast to the frequent interception of air pollution by cyclonic disturbances at high latitudes,

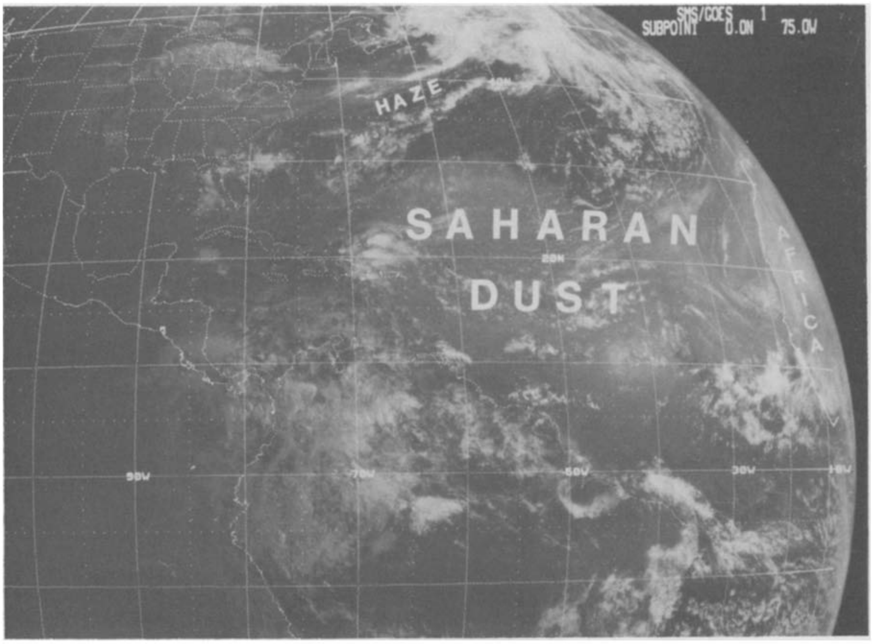

Fig. 12. Visible GOES-E Satellite imagery, 1202 GMT, 27 July 1982, showing an extensive Saharan dust cloud, 5–6000 km long and 2000 km wide, over the Atlantic Ocean. The leading edge of the dust cloud invaded West Indies and the coastal region of N America.

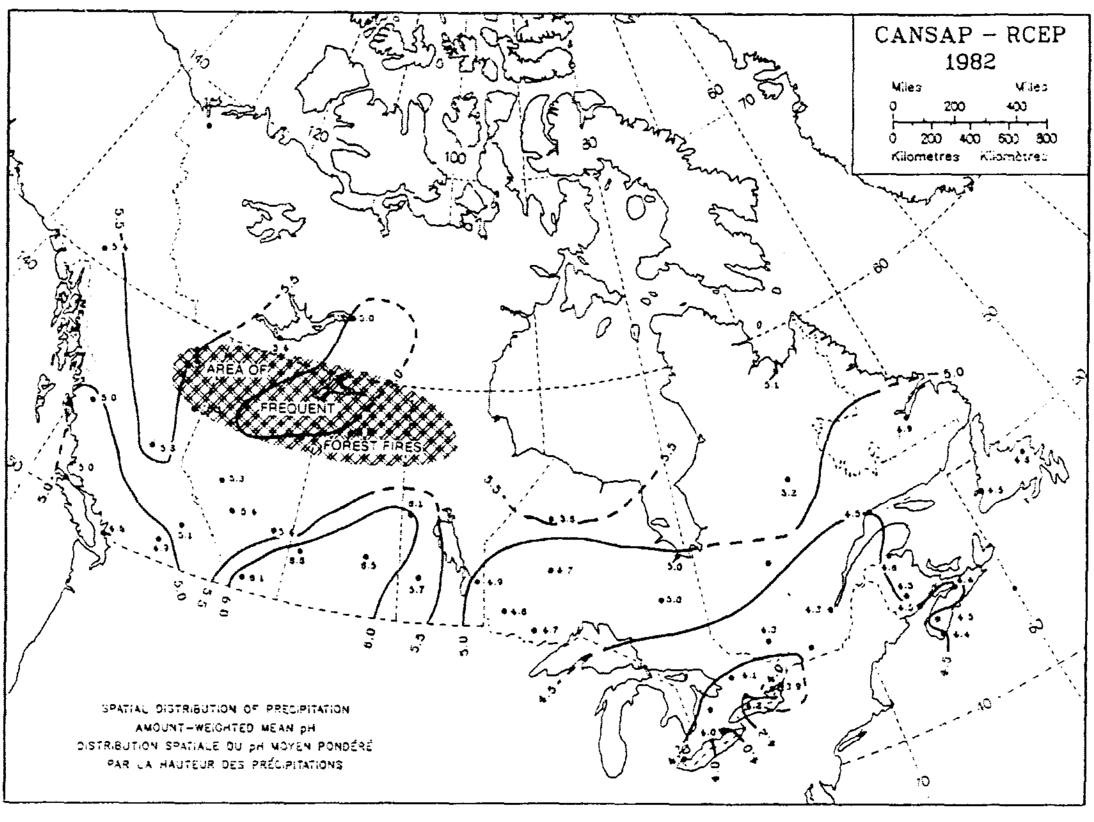

Fig. 13. Spatial distribution of the mean pH in precipitation in Canada for the year 1982. High acidity is generally found in S Ontario and Québec and slight acidity is observed in forest fire regions in W Canada. (Courtesy of Dr A. Sirois.)

extensive dust-laden air masses from the Sahara Desert are seen to cross the Atlantic Ocean. The trans-Atlantic dust clouds are observed in the absence of the ITCZ when the mixed layer appears to be generally thick due to the intense heating in the tropical environment. Satellite imagery has shown that trans-oceanic transport of pollution can occur even at higher latitudes when emissions from forest fires or volcanoes are lifted above the convergent zone.

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