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ON THE OCCURRENCE OF YELLOW SAND AND ATMOSPHERIC LOADINGS

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Abstract—The phenomena of yellow sand (dust cloud) which occurred in Korea during the springs of 1993 and 1994 were studied in detail. In 1993, there were six cases which lasted a total of 15 days, while only three cases of yellow sand were observed in 1994—mainly by aircraft. It was found that the chief layer of a dust cloud usually travelled in the level between 1000 and 3000 m and moved to the east and southeast by a steering airflow at 850–500 hPa. The lower visibility with yellow sand was often observed during daytime than nighttime. Also, the area covered by a vast dust cloud once exceeded 0.6 Mkm^2. The estimated atmospheric loadings for this cloud were 1.5 Mton. Copyright © 1996 Elsevier Science Ltd

Key word index: Yellow sand, a dust storm in East Asia, natural emission, atmospheric loadings of a dust cloud, aircraft measurements in Korea.

1. INTRODUCTION

The yellow sand (YS) phenomenon is a dust storm which occurs in East Asia. In spring dust storms occur in deserts and dry loess plateau, e.g. Gobi and Taklamakan in Mongolia and NW China. These vast areas are located in the lee of the massive East Asian Mountains—Tienshan, Altai and Sayan Mountains where a convergent air flow and a lee cyclone occur on a synoptic scale. The downslope forms a very dry surface and annual rainfall in the majority of the desert and/or semi-desert area is less than 300 mm. In particular, a convergent flow in a lee cyclonic system enhances an upward motion, and YS produced by mechanical and dynamical turbulence can be transported to the mid-troposphere.

The fine particles of YS may play a role in the condensation nuclei in the atmosphere. The YS is deposited over the ground surface and sedimentation in the sea also occurs (Chung, 1986, 1992; Gao *et al.*, 1992a, b). The YS associated with a light shower which occurs in a cold front usually deposits "sandy and soily rain" on open surfaces. If YS is mixed with anthropogenic air pollutants, the effect on our health and vegetation also increases. The YS causes an eye irritation and a person wearing contact lenses is advised to take out their lenses during the phenomenon. Beyond the health effects, there are numerous environmental degradation, including visibility reduction which causes a "flight vertigo" in pilots to the detriment of aviation.

The purpose of the present study is to investigate the phenomena of YS which occurred in both 1993 and 1994. Observational data including satellite imagery, pilot weather reports (PIREP), meteorological charts, trajectory analyses, and measurements of total suspended particulates (TSP) are used here to estimate the total amount of atmospheric loadings of dust clouds which occurred in 1993. Discussion of our results of aircraft measurements and meteorological analysis is presented.

2. YELLOW SAND EVENTS IN 1993

Figure 1 shows the events of YS observed by the Korea Meteorological Administration during 1979–1994. In particular, there were six events of YS for 15 days in Korea in 1993: There appears to be a slight increase in the occurrence in recent years, and in 1993 the largest number of YS events in Korea was recorded (see Table 1).

In a meteorological office the recording of YS and visibility are usually done by an observer by eye-sight. During a nighttime and rainfall, observation is difficult to carry out, and there may be slight discrepancies in the subjective determination of visibility. In aeronautical meteorology, however, visibility measurement is normally done objectively by equipment. Aircrafts used here for PIREP are also equipped with electronic measuring devices for wind and

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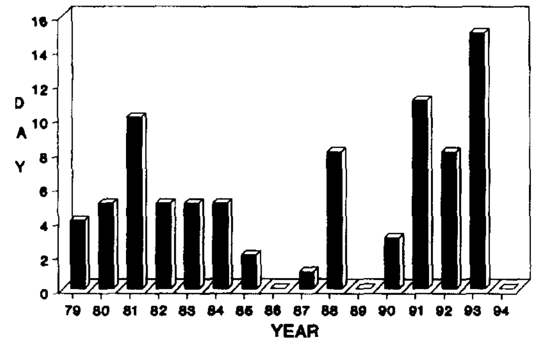

Fig. 1. Number of days with yellow sand observed in Korea (1979–1994).

Table 1. Duration of yellow sand phenomenon observed at Chongju in 1993

Date	Day and Time (h)	Duration (h)
4.1–2	4.1. 11–4.2. 03	16
4.3–4	4.3. 12–4.4. 13	25
4.7–8	4.7. 06–4.8. 12	30
4.23–24	4.23. 11–4.24. 16	29
4.27	4.27. 10–24	14
5.8–10	5.8. 11–5.10. 24	61

visibility recordings. In the present study, observational data obtained at stations of the Meteorological Office, Environment Office and Air Force Base (AFB) in central Korea are used together with PIREP.

Table 2 shows the six cases of YS phenomenon which occurred in 1993. The duration of events usually exceeded 20 h. It usually prevailed for 2–3 d due to the wide spread of a dust cloud over East Asia. There is a trend that the occurrence of YS increases in recent years, possibly due mainly to the regional desertification of both Mongolia and NW China (Walker, 1982).

3. METEOROLOGICAL FACTORS AND DISCUSSION

Figure 2 shows meteorological variables which were observed at the weather station of Chong-ju AFB from 17 April to 1 May 1993. During this 14-d period there were five cases of cyclones and of weak troughs passing through Korea from Mongolia and China. The frequent passage of cyclones and troughs had produced many cloudy days with precipitation including thunderstorms.

On 22 April an intense cyclone associated with a cold front developed in S Mongolia, passed through the Korean peninsula and produced rain showers with a thunderstorm that evening. When the cold front was near Chong-ju, around midnight, strong winds gusting at 50–60 knots occurred. (In aeronautical meteorology, it is still customary to use these measuring units: knots (kts), feet (ft), miles (mi); e.g. Table 2. If possible we will use the standard units.) The following day was sunny with a migratory anti-

Table 2. PIREP on dust cloud and visibility during 23–24 April 1993

Time	Site	Altitude (ft)	Visibility (mile)
	Kim-hae	2000–14,000	3–4
	Kwang-ju	2000–11,000	3–4
23 April		11,000–16,000	6
0200 GMT	Su-won	SFC–12,000	3–4
	Chong-ju	2000–8000	3–4
		2000–13,000	3
	Won-ju	1000–15,000	2–3
	Tae-gu	SFC–3000	4–5
		3000–10,000	2–3
23 April		10,000–12,000	5
0600 GMT	Chong-ju	SFC–3000	4–5
		3000–10,000	2–3
		10,000–15,000	5
	Seoul	SFC–2000	3
		2000–10,000	4–5
	Sang-dong	SFC–8000	6
24 April		8000–17,000	4–5
0100 GMT	Tae-gu	4000–14,000	4–5

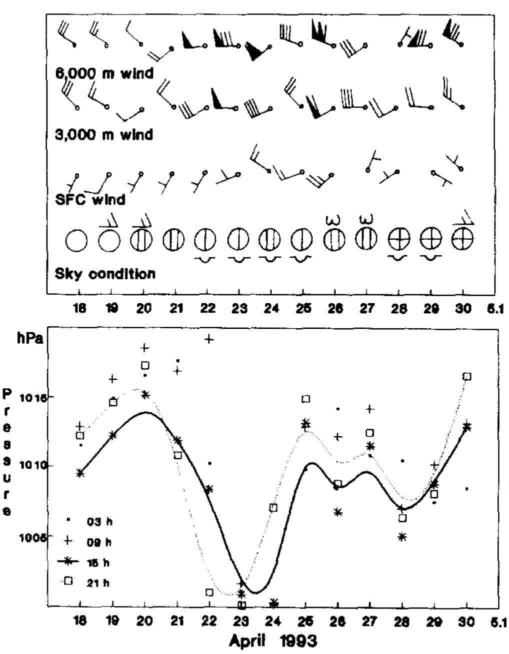

Fig. 2. Pressure, upper wind (kts) and sky condition observed at Chongju on 18 April–1 May 1993.

cylcone that came from China, but a dense YS phenomenon prevailed across the entire Korean peninsula. In the evening of the same day, a cyclone situated in the Bohai Bay approached and a dusty (YS) rain with a thunderstorm occurred both in Choug-ju and central Korea. On 24 April the anticyclone situated in central China extended its strength to the east and YS occurred in Chong-ju with 25–30 kts winds. In the late afternoon, however, the dust phenomenon dissipated completely. On 25 April strong

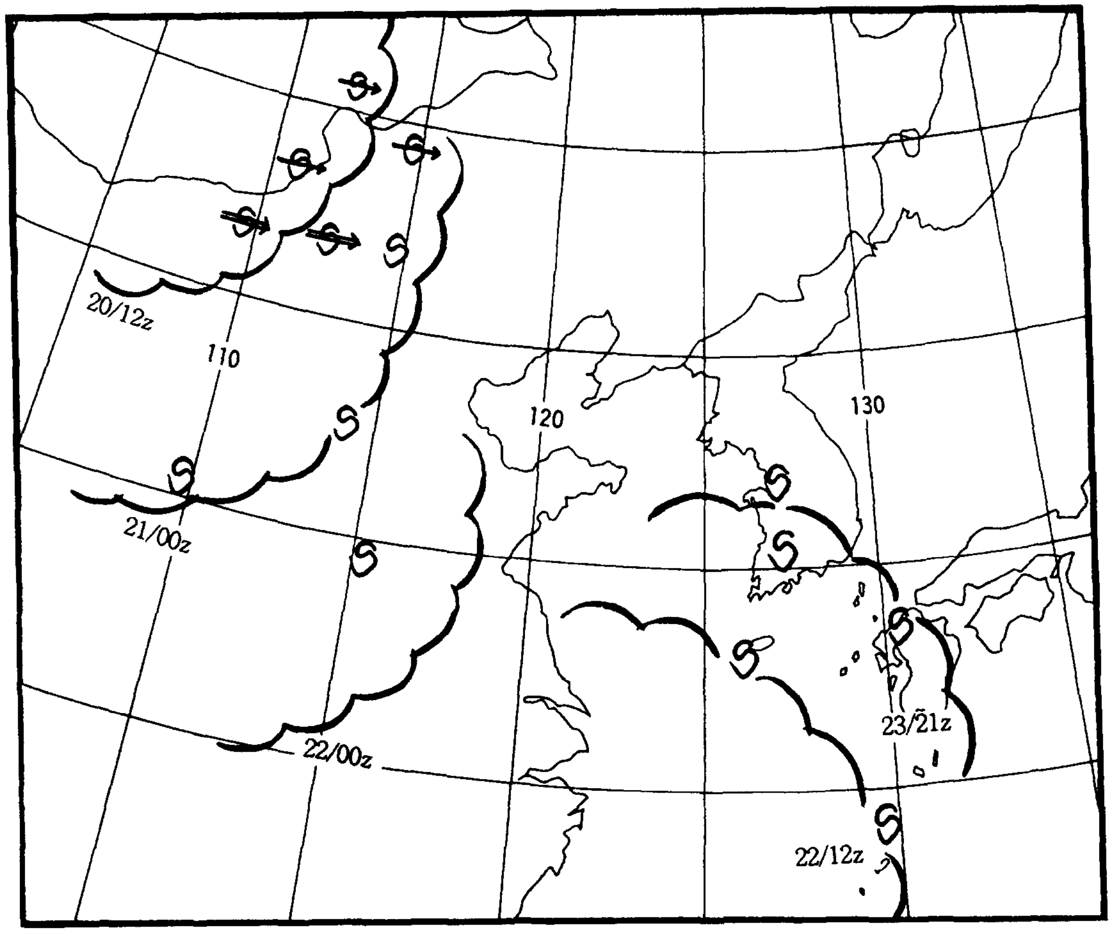

Fig. 3. A chart showing the movement of the forwarding edge of a dust cloud during 20–23 April 1993.

winds of 20–30 kts blew continuously. By late afternoon, there was a light rain shower brought on by the influence of a trough situated over southern Manchuria. The next day a pressure trough passed through without causing rain showers but strong winds gusting 30–45 kts occurred. The YS was again observed on 27 April.

From 18 April 1993 the air pressure rose gradually. It started to fall after 22 April. It reached a minimum value on 23–24 April. During the 25–26 the air pressure rose again due to an anticyclone in the south, but it went down and minimum pressure was recorded on 27–28 April. The phenomenon of YS occurred when minimum pressure was recorded, while the intensification of dense YS began with the rise of air pressure (Fig. 2). During the period of YS both on 22 and 26 April, upper-level winds at 3000–6000 m were westerlies of 50–100 kts which were 2–3 times stronger than the winds associated with non-yellow-sand cases (Fig. 2).

On 20 April, according to a surface meteorological chart an intense cyclone with the central pressure of 994 hPa developed over northern Mongolia. At that time a dust storm occurred in the south of the "dry" cyclone especially over the Gobi Desert and the northwestern area of Yellow River (Fig. 3). The surface cyclone (996 hPa) moved southeastward and positioned itself around Bohai Bay, as the result, intermittent rain showers occurred in the north of Korea. By that time the YS had shifted southeastward to the Herbai Province in China with the southern edge of YS appearing at Cheju Island in the south of Korea. On the 23 a cold front passed through the Korean peninsula and, after the frontal passage, clear skies appeared in Korea. However, the occurrence of intense YS over central and southern Korea was recorded.

Figure 3 shows the consecutive tracks of the southeastern edges of a YS cloud from Mongolia to Korea and to southwestern Japan. The edge at 1200 GMT, 20 April represents the dust storm in the Gobi Desert and in the dry region near the northwest branches of the Yellow River (42°N, 120°E). With the steering motion of upper-level winds, the dust cloud moved to Cheju Island by the late afternoon of 22 April. During the next day the belt of a dust cloud hung over from the Yellow River, including Shanghai and Shantung in China, to south Korea.

In the initial stage of a dust cloud formation which occurred on 20–21 April, the wind at 3000 m was 20 kts of 290°. During the period of 23–24 April, however, the upper-level winds were 30 kts of 250°, and the cloud moved to the east. The YS prevailed for 29 h in Korea. Meanwhile, the dust cloud took 48–60 h to travel 2000 km to reach Korea from the source region in the dry land.

4. TRAJECTORY ANALYSIS

Backward trajectory analysis was carried out by computing geostrophic winds over 127 km grids on isobaric surfaces of 850, 700 and 500 hPa. Trajectories in Fig. 4 show the isobaric trajectories each arriving at Osan AFB in central Korea. The isobaric trajectories represent the common type of airflows that we

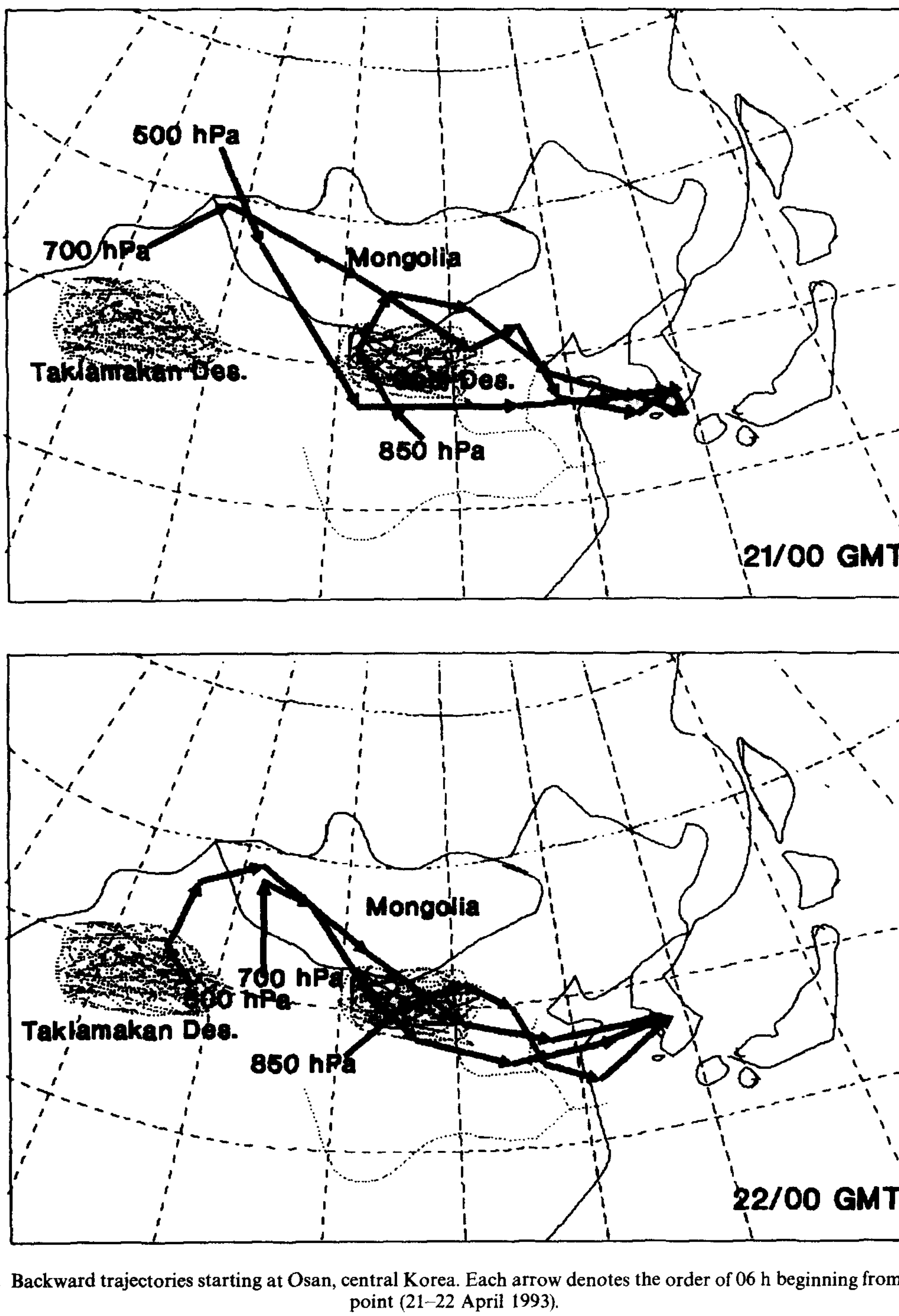

Fig. 4a. Backward trajectories starting at Osan, central Korea. Each arrow denotes the order of 06 h beginning from the end point (21–22 April 1993).

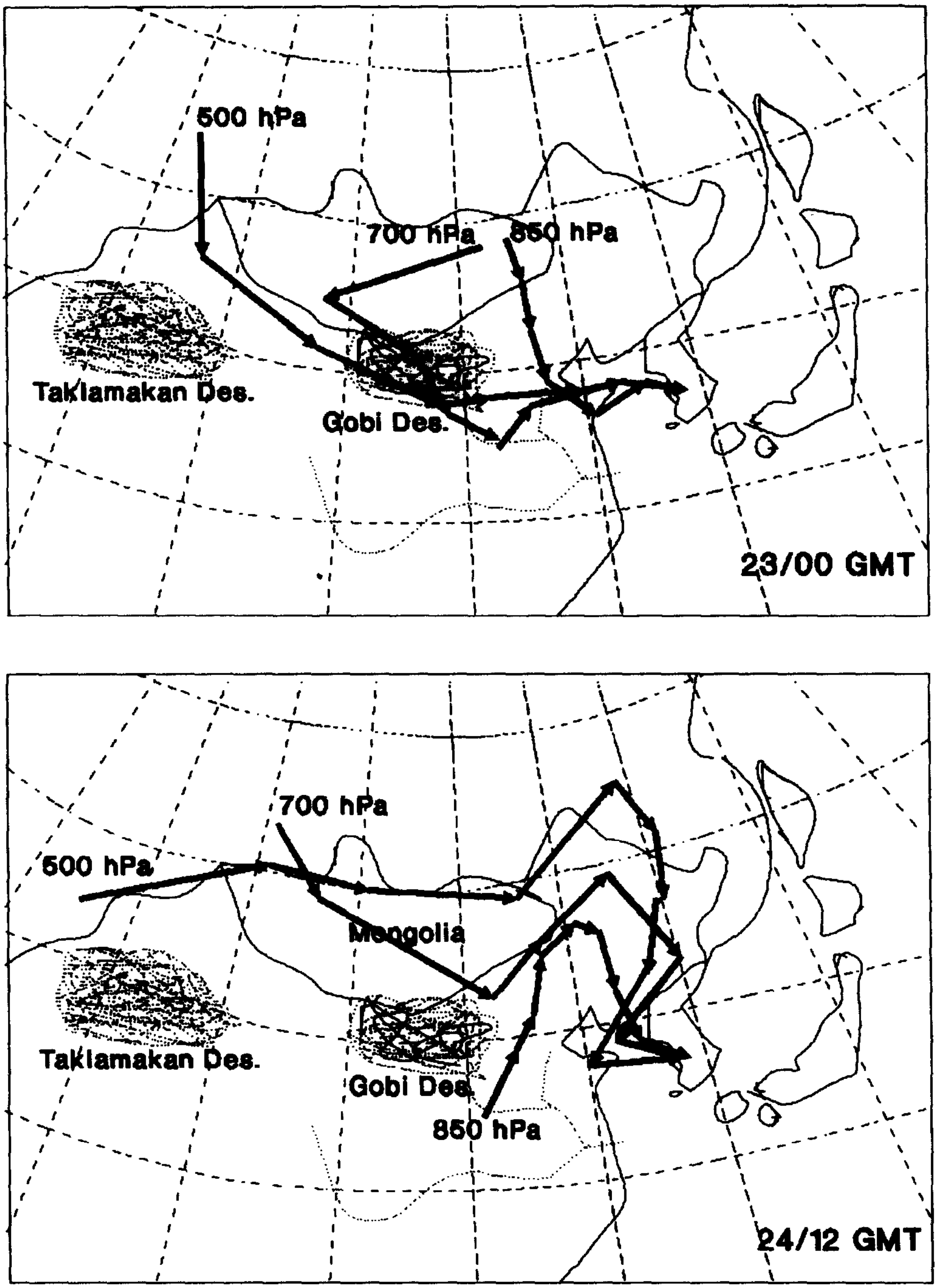

Fig. 4b. Same as Fig. 4a, but for 23–24 April 1993.

observed with YS. As can be seen in Fig. 4, an individual trajectory has west–east moving characteristics due to general westerlies present in East Asia. On 22 April the air parcel on all three upper levels moved via the Gobi Desert from the arid lands of Mongolia and of NW China. In particular, both trajectories at the levels of 700 and 500 hPa moved into Korea from northern China and Mongolia and brought a YS cloud to the sink area in Korea. The trajectory analyses agree well with meteorological charts of YS observations.

5. SATELLITE OBSERVATIONS

An analysis of satellite imagery is a useful technique to detect dust storms. An intense dust storm is readily detectable especially over ocean. However, the

(a)

(b)

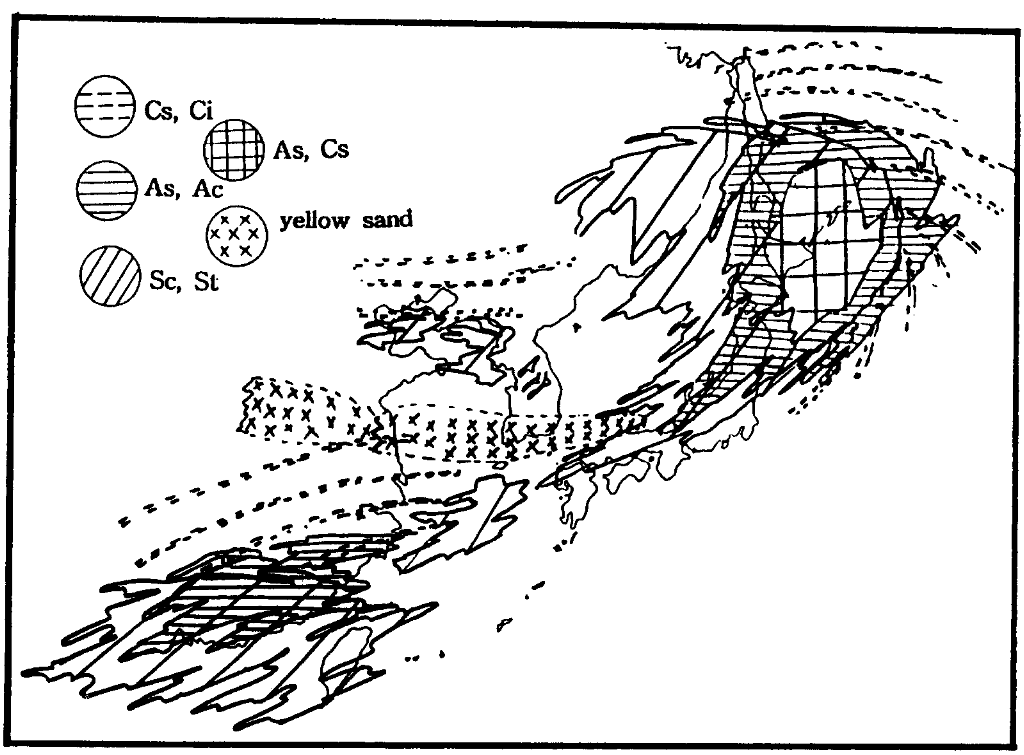

Fig. 5. (a) VIS image of GMS-4 (0300 GMT, 23 April 1993). (b) Detailed analysis of satellite image (xxx a band of yellow sand).

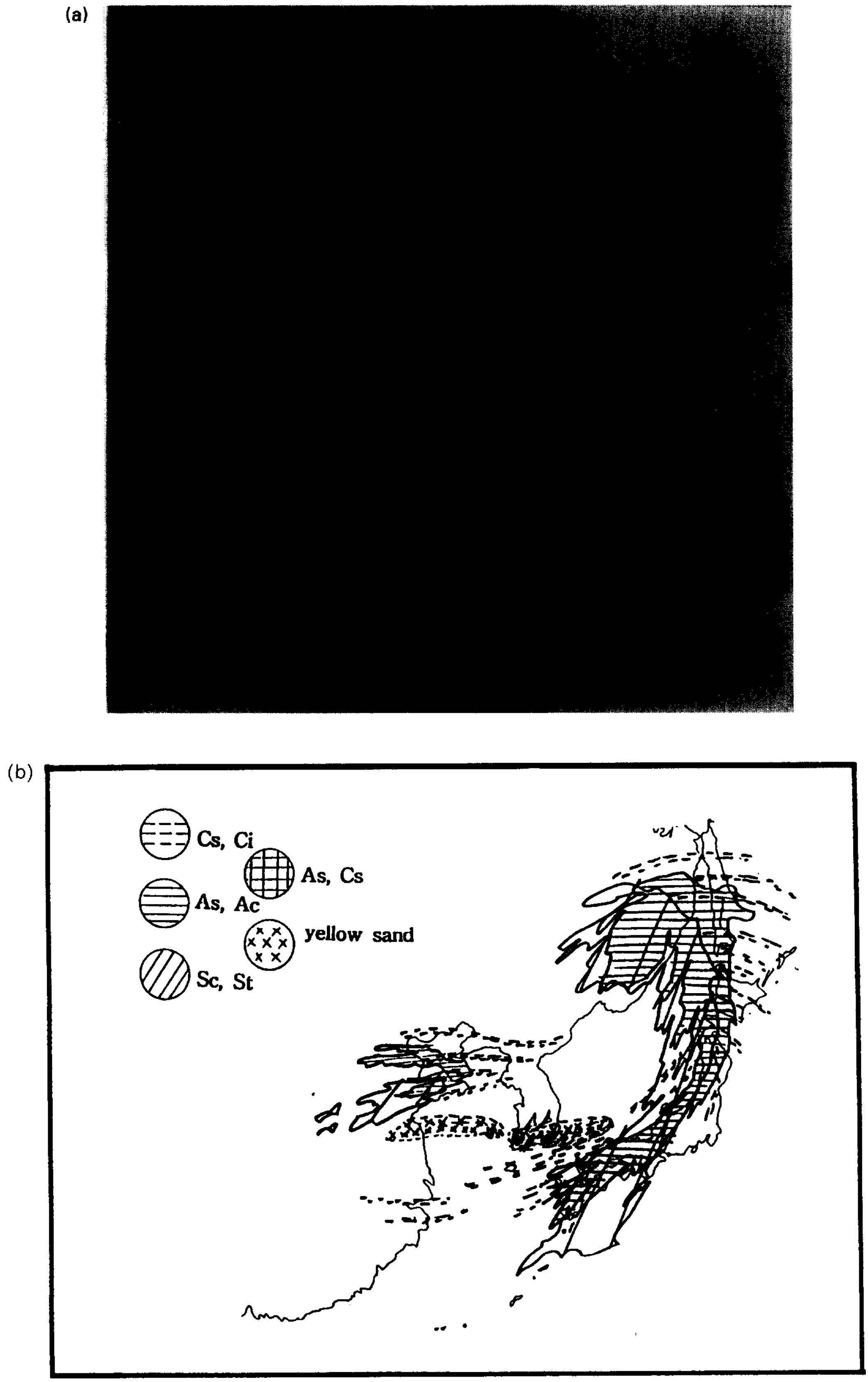

Fig. 6. (a) VIS image of NOAA (2300 GMT, 26 April 1993). (b) Detailed analysis of satellite image (xxx a band of yellow sand).

moisture (clouds) and temperature profiles present some difficulties in studying YS both qualitatively and quantitatively. As with earlier cases (Chung, 1986, 1992), we have also included satellite imagery to identify the YS clouds with other meteorological observations.

Figure 5a shows a satellite image which was taken at 0300 GMT (1200 LST), 23 April 1993. The dust cloud was clearly over central China–Yellow Sea–southern Korea (plus Cheju Is.)–SW Honshu of Japan. It looked like a thin cloud layer or stratus clouds. However, it was quite distinguishable from the rain clouds of frontal systems over Mongolia and northern Japan and from the convective clouds over southern China. A detailed analysis is shown in Fig. 5b and the dust cloud is marked with xxx. The length of YS cloud over southern Korea and the Yellow Sea is over 3000 km long with a width of 300 km. The horizontal area estimated with a subgrid system is about 0.6 Mkm^2. Additionally, another image (not shown here) taken at 0200 GMT (1100 LST) of the following day clearly shows the elongated band of a YS cloud with the cloud shifted to northwards about a 2° latitude toward central Korea.

According to a GMS-satellite image of 0100 GMT, 26 April 1993, the cloud of YS is visible over the Yellow Sea. Four hours thereafter the same cloud was still over the sea (not shown here). At this time upper winds at 3000 m were strong northwesterlies of 40–50 kts, but by the afternoon, the winds shifted and became south-southwesterlies. Figure 6a also shows a NOAA satellite image of 2300 GMT (0800 LST, 27), on 26 April. The YS cloud was flowing over southern Korea and towards Japan. A detailed analysis of the satellite image is shown in Fig. 6b. At this time the length of YS cloud was over 1000 km with the width of about 200 km. In this case the estimated horizontal extent of the dust cloud was about 0.2 Mkm^2. In Korea YS at the ground level was observed from 1000 LST for 10 h. In summary, it is evident that the satellite image discussed here clearly agrees with the meteorological observations, and it can be used for estimating the area coverage of YS (Section 8).

6. PILOT REPORTS

In aviation a pilot often gives reports on significant en route weather. The pilot's weather report normally includes visibility, wind, turbulence, thunderstorm, etc. In preparation for this project, pilots attended an orientation on YS phenomena, then ten pilots at Chong-ju AFB were instructed to record the visibility and wind during their mission. The weather elements were recorded with the aircraft-self-installed instruments, and the observations made were relatively accurate. More importantly, pilot reports were given during and right after their flights to a YS Monitor on the ground. Also, after each complete mission an interview on YS was conducted with the present weather forecaster (Yoon).

From this aviational study we have gathered the following information and summarize thus:

(1) YS and haze can be distinguished by colour—the YS is a reddish-dark brown, while haze has a milky-dark-faint colour.

(2) YS appears like a large cloud mass in the air.

(3) Haze is homogeneously distributed but has a distinctive boundary with a superficial horizon; however, YS appears inhomogeneously and has an indistinctive boundary without a horizon. As a consequence, flight vertigo may result.

(4) When YS phenomenon occurs the lower visibility usually is recorded in daytime due to the development of sea breeze.

(5) On a clear day the band of a YS cloud is visible in satellite imagery, while it is not usually distinguishable in a cloudy condition.

Table 2 includes the reports of pilots' (instrument) visibility observations during 23–24 April 1993. The YS missions were ended at about 0200 GMT (1100 LST) and 0600 GMT (1500 LST) on 23 April. On the following day the PIREP were given at about 0100 GMT (1000 LST). Over Chong-ju station the visibility at 1100 LST was 5–6 km at an altitude of 600–3400 m, and at 1500 LST it was 6–8 km at an altitude 900–3000 m. However, visibility was 8 km at the altitudes between 3000 and 4500 m. But above that altitude unlimited visibility was reported. Interestingly, the Pibal launched for the observation of upper-level winds at 1500 LST, disappeared at 2400 m. This suggests that vertical visibility was only 2.4 km at this time of PIREP!

PIREP and other meteorological observations support the occurrence of a major YS phenomenon in the southern part of Korea on 23 April. The vertical distribution of YS was mainly at the 0.6–3 km level with visibility of 4–5 km. Less dense dust with a visibility of 6.5–8 km was in the biosphere and between 3 and 4.6 km level. On 24 April, visibility over the west coast improved from below the 3 km level to 6–7 km, and pilots reported that the dust cloud had moved up to the 5.5 km altitude over the east coast and the southern part of Korea. Since the main layer of YS had transferred to a higher level visibility increased. A schematic diagram showing the case of 23–24 April is included in Fig. 7.

The YS also occurred on 27 April 1993. On this clear day a migratory anticyclone was in the region, but some of the flight missions were cancelled because of the thick cloud of YS (dust is bad for jet engines). At 1000 LST visibility of 10 km was reported over Chong-ju at 450–1500 m, but at 1200 LST there was a visibility of 3–5 km at the 900–5100 m level. From 1500 LST a layer of middle clouds moved in and the pilot's measurements were no longer possible over the Chong-ju area. The YS then moved southeastward; and in southern Korea the visibility at the level between 1500 and 4500 m was 3–5 km (with the exception of 8 km at 4500–6000 m). When compared with

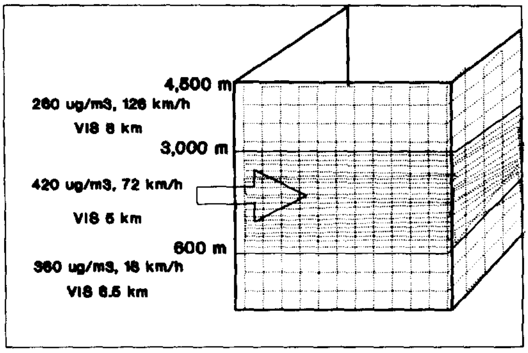

Fig. 7. A schematic diagram showing upper wind, concentration of TSP and visibility reported by PIREP during 23–24 April 1993.

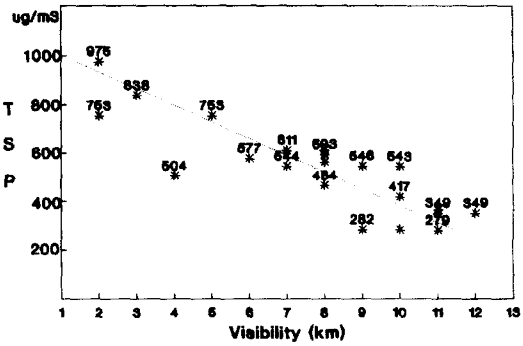

Fig. 8. The relationship between visibility and concentrations of TSP during the yellow sand phenomena occurred in 1988–1993.

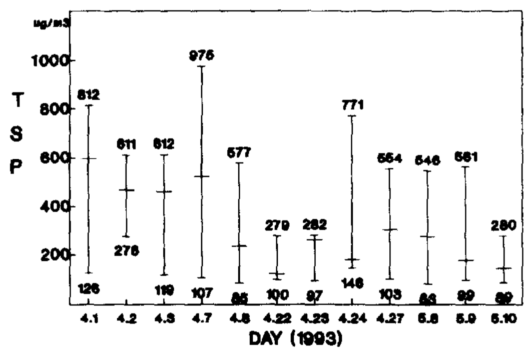

Fig. 9. Atmospheric loadings of TSP in the period of yellow sand (April–May 1993), and a bar represents a daily mean value.

the case of 23–24 April, the YS cloud of 27 April was at 300–600 m higher level. However, the YS was thicker with a lesser extent of the dust cloud.

7. VISIBILITY AND TSP

In order to study the importance of visibility (PIREP and surface) observations, concentrations of TSP were also examined with data obtained from the Ministry of the Environment. The visibility observation of 1500 LST made at Chong-ju AFB were studied with the TSP concentrations measured when the phenomenon of YS occurred during 1988–1993. At our site concentrations of TSP were measured with the Andersen Beta Gauge.

Figure 8 shows the relationship between visibility and concentrations of TSP. By using this relationship, for example, when horizontal visibility is 5 km the expected TSP is 750 $\mu g\,m^{-3}$, while for 8 km it is 555 $\mu g\,m^{-3}$.

Figure 9 includes the concentrations of TSP measured during the period of YS in April and May 1993. In Fig. 9, daily minimum, maximum and mean values are shown. The mean TSP value for the entire events of YS in Korea is 537.8 $\mu g\,m^{-3}$.

8. ATMOSPHERIC LOADINGS

Based on the above observations and discussions, Table 3 was constructed for various factors and elements in the case of 23–24 April 1993. According to the PIREP, visibility up to the 0.6 km level was 6.5 km. Also, the estimated concentrations of TSP from the relationship of visibility were 550 $\mu g\,m^{-3}$. The duration of the YS phenomena was 29 h (Table 1). The measured TSP concentrations were 364–771 $\mu g\,m^{-3}$, and with reduction of 194 $\mu g\,m^{-3}$ the estimated loadings of YS were 170–577 $\mu g\,m^{-3}$. Meanwhile, the entire area covered by the YS was over 0.6 Mkm^2. With a similar calculation method, we have estimated the total atmospheric loadings for the 23–24 April case, and they were at least over 1.5 Mton as shown in Table 4.

For the other case of YS occurred on 27 April 1993, an estimation of atmospheric loadings has been made and summarized in Tables 5 and 6. The total atmospheric loadings were estimated at about 0.3 Mton on 27 April.

Table 3. Estimation of total atmospheric loadings with the data of yellow sand during 23–24 April 1993

Altitude (km)	Visibility (PIREP, km)	TSP-VIS ($\mu g\,m^{-3}$)	Mean wind speed ($km\,h^{-1}$)	Duration (h)	Width (km)	TSP conc. ($\mu g\,m^{-3}$)	GMS-4 (VIS)
0–0.6	6.5	645 (451)	18				
						282–771	0.4×10^6 km^2
0.6–3	5.0	750 (556)	72	29	300	(88–577)	
3–4.5	8.0	555 (361)	126				

Table 4. Estimation of total atmospheric loadings for the case of 23–24 April 1993 with satellite image, PIREP, and concentrations of TSP

GMS-4 VIS	1 layer		0.2–1 × 10^6 ton
PIREP	SFC–0.6 km	0.04 × 10^6 ton	1.5 × 10^6 ton
	0.6–3 km	0.84 × 10^6 ton	
	3–4.5 km	0.6 × 10^6 ton	

Table 5. Estimation of total atmospheric loadings with the data of yellow sand 27 April 1993

Altitude (km)	Visibility (PIREP, km)	TSP-VIS ($\mu g\,m^{-3}$)	Mean wind speed ($km\,h^{-1}$)	Duration (h)	Width (km)	TSP conc. ($\mu g\,m^{-3}$)	NOAA (VIS)
SFC–1.5	7	610 (416)	32				
1.5–4.5	4	790 (596)	56	10	200	103–554 (0–360)	0.2 × 10^6 km^2
4.5–6	8	555 (361)	48				

Table 6. Estimation of total atmospheric loadings for the case of 27 April 1993 with satellite image, PIREP, and concentrations of TSP

NOAA VIS	1 layer		0.5 × 10^6 ton
PIREP	SFC–1.7 km	0.05 × 10^6 ton	0.3 × 10^6 ton
	1.7–5 km	0.19 × 10^6 ton	
	5–6.7 km	0.06 × 10^6 ton	

Table 7. Total atmospheric loadings of yellow sand dust estimated by recent investigations

Author	Total mass (× 10^6 ton)	Remark
Iwasaka *et al.* (1983)	1.63/1 case	April 1979, Japan
Arao and Ishizaka (1986)	4.1–5.3/year	Japan
Present study	1.5/1 case	23–24 April 1993, Korea
	0.3/1 case	27 April 1993, Korea

Table 7 is shown for a comparison of atmospheric loadings of YS estimated by recent studies. Iwasaka *et al.* (1983) were able to estimate that the total mass of YS was 1.63 Mton for one case in April 1979. Arao and Ishisaka (1986) estimated that the atmospheric loadings of dust clouds for one year were 4.1–5.3 M ton. By using satellite observations, PIREP, and measurements of TSP, the present study has estimated that the atmospheric loadings of 23–24 April were 1.5 and 0.3 Mton in the case of 27 April 1993. According to meteorological analyses we further estimated that about 10–20% of these loadings were depositing in the Korean peninsula. In earlier studies, long-range transport of Asian dust to the North Pacific including Hawaiian Island has also been shown (e.g. Duce *et al.*, 1980).

9. YELLOW SAND EVENTS IN 1994

The phenomenon of YS occurred during April–May 1994. Several cases of YS occurred over the source regions but only three cases were transported to the Yellow Sea and to Korea. On 8 April, a band of YS cloud hung over central Korea and the Yellow Sea, we sent several aircrafts to observe this important phenomenon. The pilots reported (table not shown) that the visibility from the ground to the 2400–3000 m level was 11 km. However, from the 2400 (3000 over Su-won) to the 4500 m level visibility was reduced to 5–6 km which meant that the main dust layer was centered around the 3300–3600 m level. In this case no ground observation of visibility reduction due to the dust cloud was made by any station in Korea.

On 13 April another cloud of YS flowed in the middle atmosphere. PIREP stated that over Chong-ju visibility was reduced to 10 km because of the dust cloud which occurred from the ground to the layer between 1800 and 4500 m. In the Kwang-ju area of southwestern Korea, YS with a 11 km visibility occurred from the ground to the 450 m level, but from that level to the 3000 m level flight visibility was measured at 8–10 km. This also suggests that the main level of YS was somewhere between 1800–3000 m. At the Chongwon, where we are situated, the measured maximum concentration of TSP on the day was

247 $\mu g\,m^{-3}$ which was twice the usual amount without YS. Except the present research team this case of YS phenomenon was not observed at any other regular meteorological station.

On 20 May a layer of YS was measured by pilots over Joongwon AFB in central Korea. The significant level of dust was between the levels of 3000–5000 m with the horizontal visibility 6–8 km. From this reason and because of easterly winds, we conclude that the YS was well dispersed and was not recorded at the ground meteorological stations.

From these three 1994 cases, it is evident that there were many more events of YS in the middle altitudes and that many of them were not observed by ground meteorological stations. Interestingly, in the spring of 1994, intense cyclones did not occur in the lee of the East Asian Mountains. As a result intense dust storms were not associated with the synoptic system as it moved southeastward from the source region. Albeit, it is clear that even with weak dust storms, like the ones which occurred in 1994, we should expect the impact of its atmospheric loadings on Korean peninsula and on the rest of East Asia.

10. SUMMARY AND CONCLUSION

From the above-described observations and analyses we have obtained the following summaries and conclusions.

(1) In 1993 the phenomenon of YS occurred frequently (a total of 15 d) and there appeared to be an increase in the impact of atmospheric dust.

(2) As with the earlier cases, a YS cloud usually moved in with a cold frontal system, and a severe reduction in visibility for 2–3 d occurred after the frontal passage with a new migratory anticyclone.

(3) According to aircraft measurements, the main layer of a YS cloud was usually between the level of 1000–3000 m, but the visibility reduction was also observed at the level of 5000 m (530 hPa).

(4) Some of YS clouds had passed through a sink area without any observation made at the ground meteorological station. However, a detailed study has revealed that a dust plume of YS still contributes to the concentration of TSP at the ground level.

(5) Visibility and concentrations of TSP may be expressed with a linear relationship.

(6) The phenomenon of YS was observed when the concentrations of TSP were at least three times higher than the usual daily TSP values without YS.

(7) The area covered by a YS cloud was estimated at over 0.6 Mkm^2 for the case of 23–24 April 1993, and the estimated atmospheric loadings were 1.5 Mton.

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