

Application of Geostationary Satellite Observations for Monitoring Dust Storms of Asia

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ABSTRACT

In this study, data provided by the geostationary satellite GMS-5 S-VISSR was used to monitor dust storms. Although other satellites, such as TOMS, provide information regarding dust cover and air quality over specific locations, their limited orbital observation time makes it hard to issue real-time warnings for dust storms. Since geostationary satellites are capable of providing hourly observations, they offer a higher temporal resolution. Both infrared channels of GMS-5 were used in this study to mitigate misdetections of neighboring dust cloud cluster regions. The accuracy of the results obtained, using this method, demonstrated that this mode of observation has practical applications, for monitoring dust storm events, which warrant further investigation. An automatic operation system was also successfully constructed for dust storm monitoring, from GMS data. Quantitative analysis indicated a high possibility for accurate intensity levels of dust storms from GMS-5 data and a positive potential for dust storm warning and forecasting, from this data. Nonetheless, more cases should be investigated to test actual applications for this method.

(Key words: GMS, Dust storm, Air quality)

1. INTRODUCTION

The frequency of dust storms, over Mongolia and the arid areas of northwestern China, which makes up part of the Central Asian dust storm area, seems to have grown over the past few years (Qiu and Yang 2000; Xinhua New Agency 2001a). The dust particles of the arid

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area spread via atmospheric circulations to include regions of Mainland China, the Korean peninsula, Japan, Taiwan, and even North American (Arndt et al. 1998; Ichikawa and Fujita 1995). The concentration of suspended particles has increased dramatically and had a negative impact on regional air quality (Liu and Shiu 2001; Siheng et al. 1999). Since poor air quality has serious implications for the global environment and poses significant health and ecological risks (Pope et al. 1995), timely detection and monitoring of dust storms is important.

Growing concern about environmental protection and the development of innovative techniques have resulted in a keen interest in developments and applications for remote sensing. Satellite remote sensing can play a vital role in monitoring environmental changes, including deterioration of air quality from dust storms, the power and frequency of which has increased over the past few decades (Kaufman et al. 1990). With observational capabilities for wide area and high temporal resolution, the GMS satellite seems to be the best choice, at present, for dust storm monitoring around the Asian area. Based on the different characteristics of clouds, terrain, and dust storms exhibited in GMS-5 S-VISSR data (Stretched-Visible and Infrared Spin Scan Radiometer, see also Table 1), dust storms can be detected and monitored (Liu et al. 2002). Various errors still occur however, especially around regions with low cloud cover because of a similar albedo for dust particles and neighborhoods of clouds.

Table 1. The bandwidth and spatial resolution of the GMS-5 S-VISSR channels (Japan Meteorological Agency 1993).

Channels	Bandwidth (μm)	Nadir spatial resolution (km)
VIS	0.55~0.90	1.25
WV	6.5~7.0	5.0
IR1	10.5~11.5	5.0
IR2	11.5~12.5	5.0

To correct the error in detection around the neighborhood of clouds, two infrared channel data sets - IR1 and IR2 were employed to provide water vapor information, which would distinguish dust particles and cloud neighborhoods. The results demonstrated improved delineation for dust particles. An operational system was also constructed from GMS-5 data for daily dust storm monitoring around the Asian area. This system automatically provided near real time information of dust storm occurrences for affected areas.

2. METHODOLOGY

2.1 Overview

The albedo (apparent reflectance) observed by the visible channel was readily obtained when a large concentration of suspended particles presented in the atmosphere. Data from the visible channel was then applied to detect the occurrence of dust storms from the environmental changes they produced. The characteristics of different geographical environments, such as clear sea surfaces, clear lands, dust areas, and cloudy areas, were distinguished by employing data from the GMS-5 satellite in the VIS and IR channels, coupled with observations from the Earth Probe, Total Ozone Mapping Spectrometer (TOMS) (Liu et al. 2002). Digital count scatter plots for the GMS-5 S-VISSR VIS and IR channels clearly identified distinct environmental aspects, except when the data was various and vague. This data indicated the presence of dust and cloud particles, as in Fig. 1 (Liu et al. 2002). Background data sets (dust storm free) were established before a dust storm occurred, so regions, from whence the dust storm originated, and affected areas could be detected by variances of the observed data.

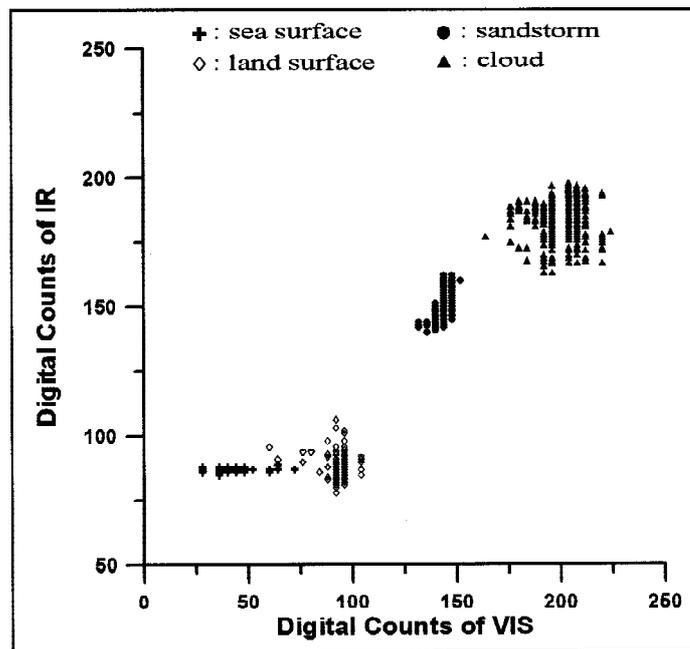


Fig. 1. The scatter plots of digital counts acquired by the GMS-5 S-VISSR VIS and IR channels, 02:40Z April 7, 2001 (Liu et al. 2002).

2.2 Improvements and Verification

Two sets of GMS-5 S-VISSR images were acquired from 1 to 4 and 10 January 2002. These images covered much of Asia and were used to detect and examine a dust storm. The data set acquired from January 1 to 4, with no dust storm formation whatsoever, was used to construct the normal background data set (dust-free image of Fig. 2). The data set of January 10 was applied to detect and monitor the formation of a dust storm and delineate the regions it influenced with the aid of the background set. The results for areas affected by dust particles are shown in Fig. 3a. To illuminate the results of the dust storm detected by the GMS-5 data, the “Sand Index” was used for the dust indication (Liu et al. 2002), and defined by variation of digital counts in the visible channel with that of the dust-free image. In Fig. 3a, green depicts areas unaffected by dust, for which the albedo varied under 0.027. Yellow, dark yellow, magenta, red and purple represent variance of albedo in the VIS channel greater than 0.027 and indicate areas affected by dust for different dust levels (Table 2), while white represents areas with cloud coverage. January 10 was virtually dust-free, except for yellow regions over the Yellow Sea, which indicate that the particle concentration was above normal. Figure 3a demonstrates that neighborhood cloud clusters appeared in regions, delineated by purple, for areas over the western Pacific Ocean (Fig. 3a). The main contributors to misdetection include similar reflection characteristics of dust particles and cloud neighborhoods, as well as a lower dynamic range of S-VISSR in the visible channel (0 - 63). Correction of these errors would enhance the degree of accuracy for dust detection.

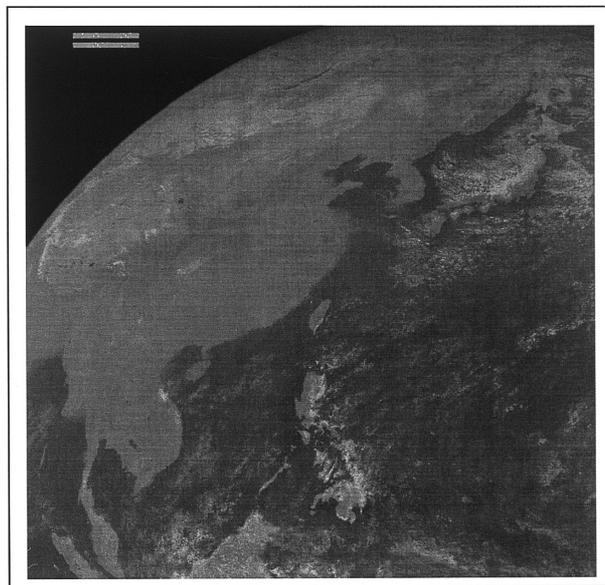


Fig. 2. The background data set (dust storm free image) of GMS-5 S-VISSR VIS channel composed from January 1 to 4, 2002.

Table 2. The definition of Sand Index with the variation of digital counts in the visible channel of GMS-5 data.

Sand Index	Digital counts variation	Albedo variation	Expressive color
0	< 4	< 0.027	Green
1	5 – 12	0.027 – 0.038	Yellow
2	13 – 20	0.038 – 0.065	Dark yellow
3	21 – 28	0.065 – 0.095	Magenta
4	29 – 36	0.095 – 0.126	Red
5	> 36	> 0.126	Purple

Many efforts have been made to estimate the total amount of water vapor over land and ocean surfaces using NOAA/AVHRR thermal infrared and DMSP/SSM/I microwave remote sensing data (Eck and Holben 1994 and Sobrino et al. 1999). The estimate for this method was based on the linear relationship exhibited between the total atmospheric water vapor and the brightness temperature difference of split-window (channels of 11 and 12 μm) because the difference of brightness temperatures on split-window channels provides information about the amount of total water vapor. Since the main difference between dust objects and clouds is water vapor content, the split-window channels (IR1 and IR2) of GMS-5 data were used to distinguish between dust objects and neighborhoods of clouds. After examination, both criterion for brightness temperatures difference and characteristics of cloud pixels on VIS and IR channels were used for cloud recognition. The improved results are shown in Fig. 3b. The original misdetection depicted in purple (Fig. 3a) has nearly been corrected for areas over the western Pacific Ocean, while the actual dust affected region over the Yellow Sea was still highlighted. These results clearly demonstrate that use of both infrared channels of GMS-5 provided a greater degree of accuracy for the separation of dust objects and cloud neighborhoods.

To verify the accuracy of dust detection by GMS-5, a comparison was made between this data and that of the aerosol optical depth (AOD) retrieved from the Moderate-resolution Imaging Spectroradiometer (MODIS) of the Terra satellite (Tanre et al. 1999; Kaufman et al. 2002). MODIS is a key instrument on board the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the Earth passes from north to south across the equator in the morning, while that of the Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS observe the Earth's entire surface every 1 to 2 days, acquiring data in 36

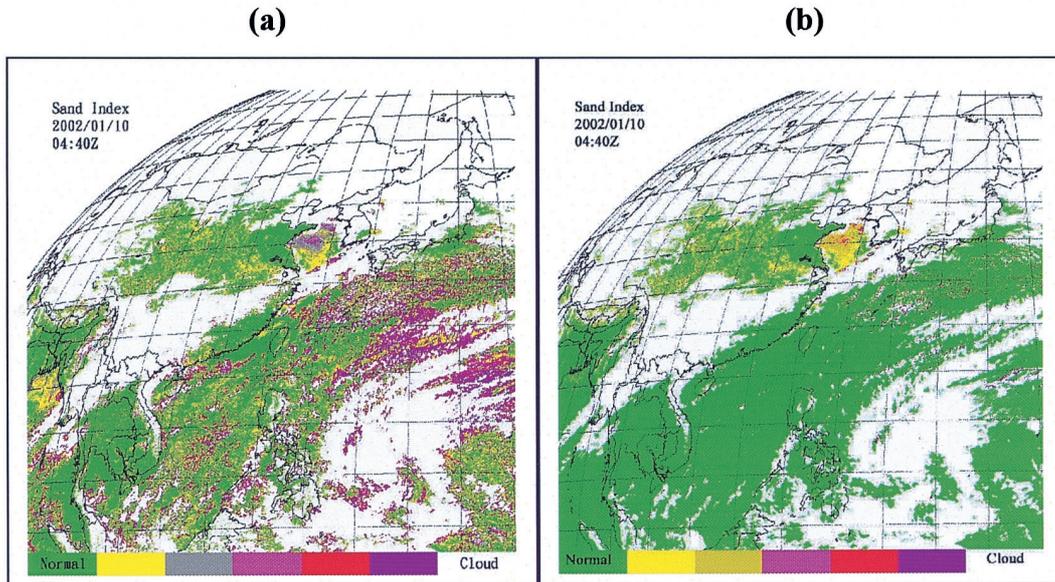


Fig. 3. (a) The result of dust detected from the GMS-5 S-VISSR VIS and IR channels at 04:40Z on January 1, 2002. (b) Same as (a), but VIS, IR1 and IR2 channels are used.

spectral bands (from $0.4 \mu\text{m}$ to $14.4 \mu\text{m}$). These data should improve our understanding of the global dynamics and processes, occurring over land, sea, and the lower atmosphere. MODIS is beginning to play a vital role in the development of validated, global, interactive Earth system models.

Figure 4 depicts results of dust detection, for a dust storm, which affected a region over eastern Mainland China from March 4 to 9, from GMS-5 data and the distribution of AOD retrieved from MODIS on March 7 in 2002. Figure 4a depicts GMS-5 data, which represents the dust storm that affected the region around the East Sea. Figure 4b depicts the AOD observed from MODIS data at about the same time and black represents areas of cloud coverage or a bright surface, such as a desert or beach. The retrieved AOD from MODIS might be affected by particles of sulfate, industrial pollution and biomass burning, as well as dust. However MODIS' AOD product can provide dust information. In Fig. 4b, the distribution of AOD demonstrates amounts of AOD that were above normal around the eastern China areas, indicating they were affected by dust. The patterns of dust detected by GMS-5 and AOD retrieved by MODIS data for the test region generally correlated well, except for southwestern Taiwan, where the higher AOD value might be caused by industrial pollution or biomass burning.

GMS-5 and MODIS data acquired on March 17 in 2002 provided further verification of the method, with similar distributions demonstrated once again (see also Fig. 5). It should be noted that twice in Figs. 5a and b there are different values of AOD for colors represented. The

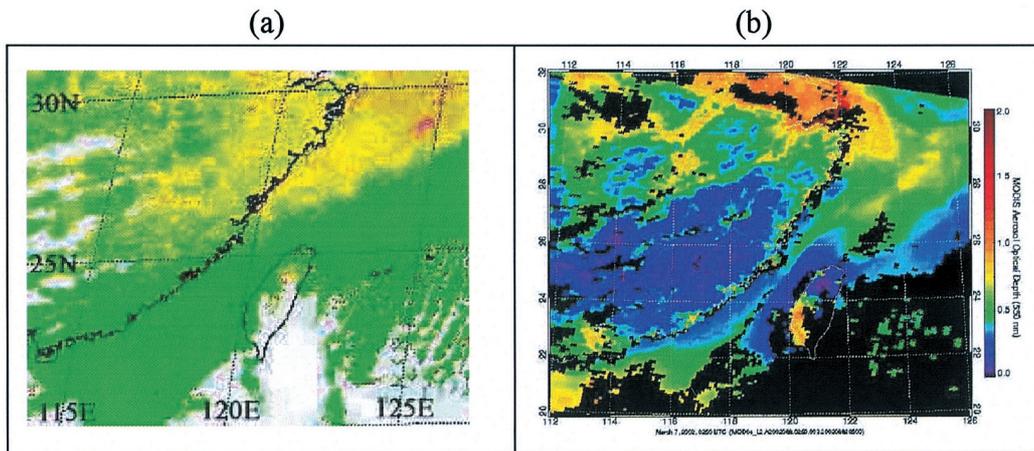


Fig. 4. (a) The dust detection from GMS-5 data at 02:40Z on March 7, 2002. (b) The aerosol optical depth retrieved from Terra/MODIS at 02:50Z on March 7, 2002 (From GSFC/NASA, USA).

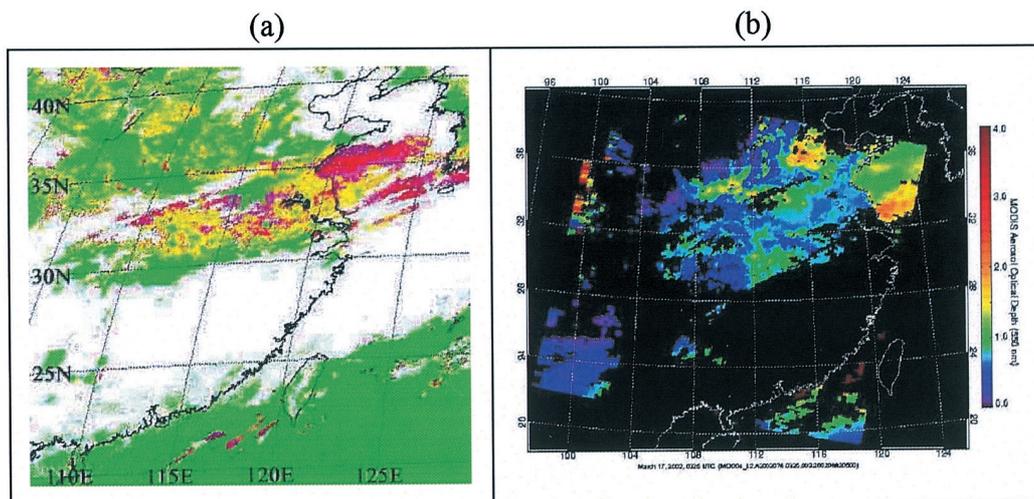


Fig. 5. (a) Same as Fig. 4a, but at 04:40Z on March 17, 2002. (b) Same as Fig. 4b, but at 02:50Z on March 17, 2002 (From GSFC/NASA, USA).

results of this examination demonstrated good potential for GMS-5 data to improve dust detection and monitoring, compared with data derived from MODIS observation.

3. A CASE STUDY OF DUST STORM DETECTION

Several strong dust storms occurred over the Mongolian region and seriously affected northeast China and the Korean peninsula during March 2002, in particular March 22 to 24. Figure 6 depicts results of GMS-5 data used to detect the evolution of the dust storm in the affected regions. The dust-free areas are represented by green, while white represents areas covered by cloud. Yellow, orange, red and purple represent areas affected by the dust in different situations. Although there were a lot of cloudy areas, the regions affected by the dust storm were easily detected for clear sky conditions for this period. On March 22, the dust storm could not be completely monitored at 02:40Z because of cloud coverage, as demonstrated in Fig. 6a, but detection was significantly enhanced at 06:40Z for eastern China and the Yellow Sea, as demonstrated in Fig. 6c. On March 24, the dust storm constantly affected these areas, and continued in influence to spread out to the Korean peninsula region. This influence is said to be the strongest dust storm recorded around the Korean peninsula for the last few years (see Fig. 6i). Fortunately, an existing cold front and rainfalls around Taiwan significantly decreased the intensity of the dust storm. In this case study then, the efficacy of the GMS-5 S-VISSR data for timely dust storm monitoring was demonstrated briefly.

The dust information in the areas where the cold front was passing was not observed because of the constraints of remote sensing channels. GMS-5 channels do not provide information under cloud layers and the low dynamic range of S-VISSR in the visible channel (0 - 63) provides low sensibility for reflective differences between pure cloud and dust-cloud pixels. For these reasons, information on dust over cloud-covered areas was difficult to determine using the approached developed for this study, and since the visible channel was used, this approach was applied for daytime only.

4. OPERATIONAL SYSTEM AND QUANTITATIVE ANALYSIS

4.1 Construction of Operational System

Since dust storms possess quick mobility and cause significant damage, providing timely information about a dust storm requires urgent attention, especially for regions around the Central Asian dust storm area. The speed and impact of dust storms necessitated the construction of an automatic monitoring system for detecting dust storm formations, their evolution and the areas affected. Based on analysis of the automatic approach in this study, the operational mode of dust storm detection and monitoring was established from the GMS-5 satellite receiving system data. Results of this analysis and data from 1 January 2002 to 21 May 2003 can be found on the website, <http://MSL.csrsl.ncu.edu.tw>, which is operated by the Meteorological Satellite Laboratory of Center for Space and Remote Sensing Research. The automatic monitoring system constructed for this study should also greatly assist in further analysis,

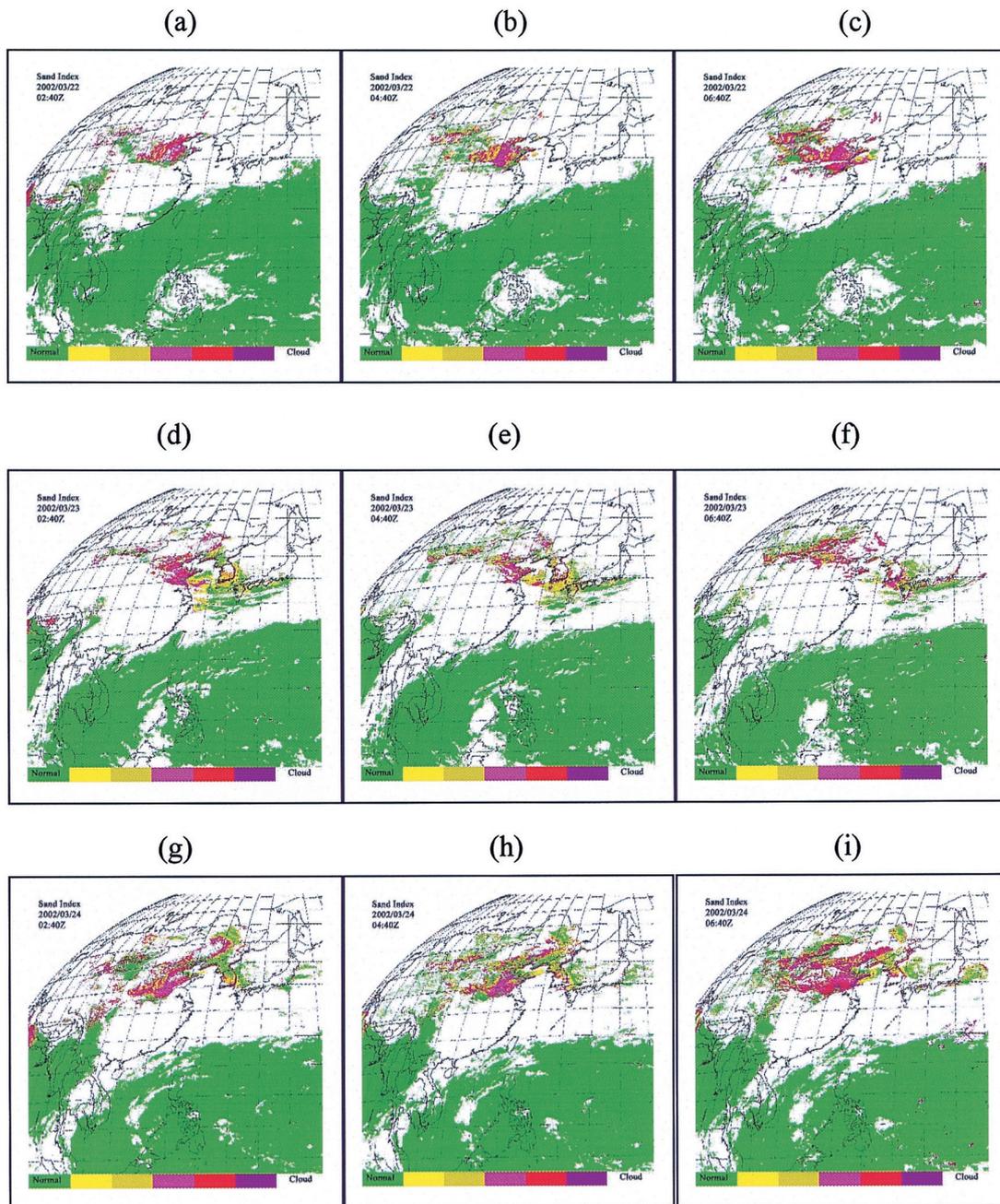


Fig. 6. The results of dust storm detection from GMS-5 data during March 22 to 24, 2002, respectively.

forecasting dust storms, warnings and so forth.

4.2 Quantitative Analysis

To enhance procedures of dust detection and effect practical applications, for dust storm warnings, forecasting and air quality monitoring, quantitative analysis of dust storms is necessary. The strongest reported case of a dust storm in 2001, occurred near the area of Mongolia on April 7 and was used for the quantitative analysis in this study (Xinhua New Agency 2001b). The Aerosol Index (AI) produced by data from the Earth Probe TOMS (Torres et al. 1998) is operational for global dust detection and used frequently on the free website (<http://TOMS.gsfc.nasa.gov>). The products of TOMS' AI were examined for quantitative analysis of a dust storm in this study. Figure 7 depicts the distribution of AI retrieved from TOMS data (Torres et al. 1998) on April 7, for areas affected by the dust storm around northeastern China and Korea. Figure 8 depicts a similar distribution of dust detection derived from GMS-5 data on the same date. Since the spatial resolution of TOMS' AI is 1×1 degree, the dust detection product of GMS-5 was re-sampled from 5×5 km to 1×1 degree (about 110 km on

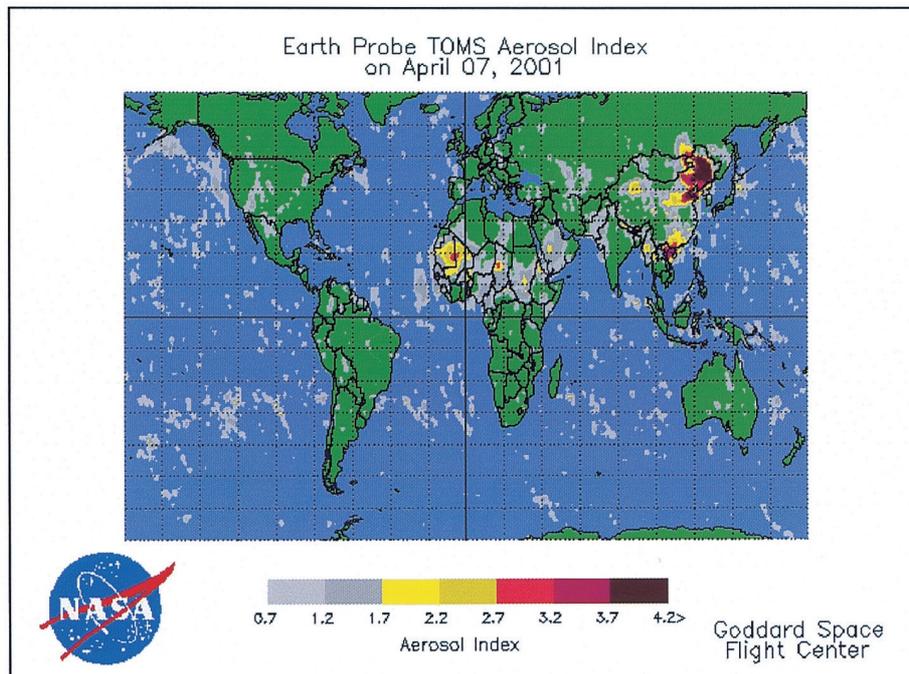


Fig. 7. The distribution of Aerosol Index from the Earth Probe TOMS data on April 7, 2001, from <http://TOMS.gsfc.nasa.gov>.

the mid-latitude) for quantitative analysis of the dust storm. The same spatial resolution data of TOMS and GMS-5 over the areas around northeastern China and the Yellow Sea (affected by the dust storm) were then used for comparison and analysis of the dust storm. Figure 9 demonstrates a good linear relationship between AI and the digital count variation in the visible channel of GMS-5. The intensity levels obtained from GMS-5 data indicate a very good potential for this data to provide dust storm forecasts and warnings. Of course, more data should be collected and analyzed so that the quantity estimation of dust storms can be improved for practical applications.

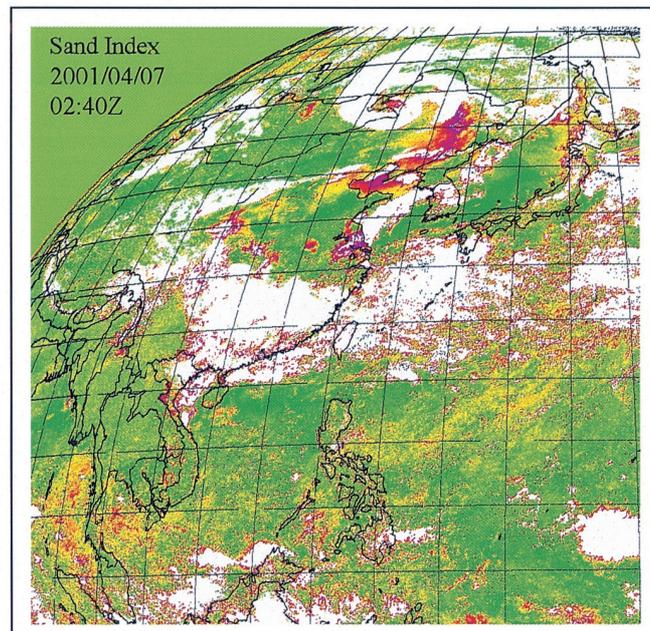


Fig. 8. The result of dust storm detection from GMS-5 data at 02:40Z on April 7, 2001.

5. SUMMARY

In this study, the errors in dust recognition around cloud clusters were successfully corrected by using both infrared channels of the S-VISSR. As a result of this correction, it was determined a dust storm can be detected and monitored more accurately with GMS-5 data. The results demonstrated this approach is both practical and effective, and that it is worthwhile using this approach to conduct investigations of dust storms in the future. To assist policy makers in making accurate decisions concerning the protection of our environment, the auto-

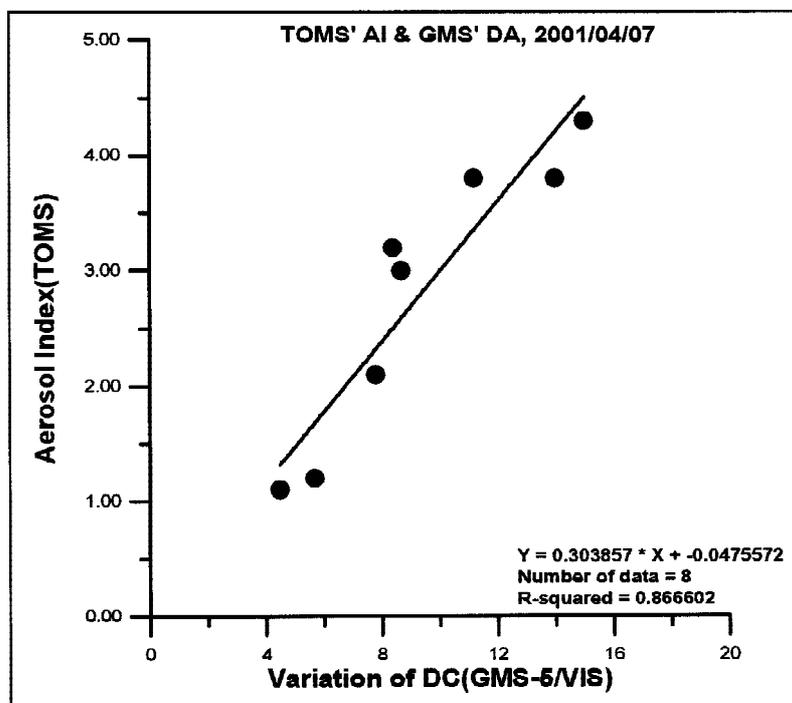


Fig. 9. The relationship between TOMS' AI and variation of digital count in GSM-5 visible channel on April 7, 2001.

matic monitoring system was constructed on a combined GSM-5 satellite receiving system to expedite the provision of information about dust storm occurrence, evolution and affected areas. Still, more data of dust storm cases, together with other satellite data (such as TOMS, AVHRR or MODIS), should be collected and analyzed, to enhance the detection of intensity levels for dust storms and facilitate dust storm warning and forecasting.

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