Jour. Korean Earth Science Society, v. 26, no. 2, p. 149−159, March 2005

Characteristics of MODIS Satellite Data during Fog Occurrence near the Inchon International Airport

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Abstract: Simultaneous observations of MODIS (Moderate-resolution Imaging Spectroradiometer) onboard the Aqua and Terra satellites and weather station at ground near the Inchon International Airport (37.2-37.7 N, 125.7-127.2 E) during the period from December 2002 to September 2004 have been utilized in order to analyze the characteristics of satellite-observed infrared (IR) and visible data under fog and clear-sky conditions, respectively. The differences ($T_{3.7-11}$) in brightness temperature between 3.75 μm and 11.0 μm were used as threshold values for remote-sensing fog (or low clouds) from satellite during day and night. The $T_{3.7-11}$ value during daytime was greater by about 21 K when it was foggy than that when it was clear, but during nighttime fog it was less by 1.5 K than during nighttime clear-sky. The value was changed due to different values of emission of fog particles at the wavelength. Since the near-IR channel at 3.7 μm was affected by solar and IR radiations in the daytime, both IR and visible channels (or reflectance) have been used to detect fog. The reflectance during fog was higher by 0.05-0.6 than that during clear-sky, and varied seasonally. In this study, the threshold values included uncertainties when clouds existed above a layer of fog.

Keywords: fog, Inchon Airport, MODIS, IR, visible, reflectance, remote-sensing

Introduction

A low visibility by fog causes traffic accidents over the land, sea, and air. The fog, defined as the case of horizontal visibility less than 1 km, also has influenced on crop growth and human life. Accurate forecasts about the fog occurrence and dissipation may bring economical effect because they can prevent a lot of accidents and disasters in advance.

Fog observations at ground weather stations have limitation because of sparse stations and the difficulty of nighttime observations (Ahn et al., 2003). Fog forecasts, based on numerical model, have not been actively utilized due to the time-consuming and microphysical processes (Maruyama et al., 2004; Byun et al., 1997). On the other hand, the remote sensing of fog from satellite observations provides its information over vast areas in a short period. However, the sensing contains several fundamental problems. In other words, it is inaccurate in measuring horizontal visibility, detecting fog while upper-level clouds exist, and the fog which is formed by regional topography (Bendix, 2002; Bendix et al., 2004).

Under the condition of existing clouds, the brightness temperature measured by satellite radiometer is remarkably decreased because infrared (IR) radiance is absorbed and emitted by water particles. However, the brightness temperature, emitted by fog (i.e. a cloud near surface), is similar to surface temperature. Emission of opaque water is 1.0 in the infrared channel at 11 μm, and 0.8-0.9 at 3.7 μm. Therefore, the brightness temperature at 11 μm under fog is close to surface temperature, but the brightness temperature at 3.7 μm becomes lower than the surface temperature (Anthis and Cracknell, 1999; Eyre et al., 1984). This physical difference has been used for detecting fog in previous studies (MSG, 2003; Ellrod, 1995). A particle of fog has character-

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istics of thermal absorption and emission for infrared radiance, and also high reflectance for solar radiation (Anthis and Cracknell, 1999).

For fog detection, Eyre et al. (1984) used the difference (i.e., $T_{3.7-11}$ in brightness temperature between channel 3 (3.7 μm) and channel 4 (11 μm)) from the data of Advanced Very High Resolution Radiometer (AVHRR). Ellord (1995) utilized the data of GOES-9 geostationary satellite to sense the fog. Anthis and Cracknell (1999) made use of the channels 3 and 4 of the AVHRR during nighttime, visible images of the METEOSAT and the AVHRR channel 1 (0.63 μm) and channel 2 (0.91 μm) during daytime over the Greek area. Bendix et al. (2003) derived the difference in brightness temperature between 3.9 μm and 10.8 μm using the data of the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Spinning Enhanced Visible and Infrared Imager (SEVIRI). Additionally, they showed that there was a little difference in the threshold value depending on satellite sensors. The difference in the value among sensors was confirmed in the study of Cermak et al. (2004). Bendix et al. (2004) revealed that the results from either polar-orbit or geostationary satellite for detecting fog were similar to each other.

In the meanwhile, several studies for cloud detection included the classification of fog as well as the cloud type. According to standard criteria of the International Satellite Cloud Climatology Project (ISCCP), the type was categorized using the cloud top pressure and the optical thickness of cloud (Simpson et al., 2001; Rossow et al., 1991). According to Hahn et al. (2001), the optical thickness of fog was greater than that of clear-sky globally. Kokhanovsky (2004) investigated reflectance of solar radiation as a function of solar zenith angle, size of water particle, and optical thickness. Also, he showed that the reflectance was sensitive to the zenith angle.

Using the difference in brightness temperature between the AVHRR channels 3 and 4, Park et al. (1997) derived the threshold values of $T_{3.7-11}$ for surface, cirrus, low clouds and fog over the Korean Peninsula. The threshold values over the land and the sea were determined by the study of Meteorological Research Institute (MRI; 2001) using the channels 21 (3.7 μm) and 30 (11 μm) of the MODIS. The reflectance of fog particle varies considerably with solar zenith angle (Bendix et al., 2003, 2004; Kokhanovsky, 2004).

The purpose of this study is to analyze the characteristics of the MODIS IR and solar channels for foggy and clear days during the period of 2002-2003 near the Inchon International Airport. Here we derived the difference (i.e., $T_{3.7-11}$ or threshold) in brightness temperature between 3.7 μm and 11 μm during foggy days and nights, and also other threshold value of solar reflectance in the daytime.

Data and Method

The Earth Observing System (EOS) has provided the algorithms in order to investigate cloud detection, and the physical and optical features of cloud, observed from the MODIS radiometer onboard TERRA and AQUA satellites in 1999 and 2002, respectively (Platnick et al., 2003). The MODIS that has 36 channels offers satellite data by passing over the equator four times a day (TERRA-10:30, 22:30 ECT AQUA-1:30, 13:30 ECT). This study used the MODIS data of solar channels 1-5 band and infrared channels 20, 23, 27-36 near the Inchon International Airport (37.2-37.7 N, 125.7-127.2 E) for the period from December 2002 to September 2004.

According to the study of Hahn et al. (2001), the fog could be remotely sensed in the process of cloud detection. Clouds are classified into high, middle, and low clouds, based on cloud top pressure (Fig. 1). Fog and stratus among low clouds could be differentiated using the difference in brightness temperature between 3.7 μm and 11 μm (MSG, 2003; Eyre et al., 1984). This study mainly has determined the threshold of $T_{3.7-11}$ near the Inchon International Airport during the period from December 2002 to December 2003. In the existence of clouds, infrared sensor of satellite is sensitive to

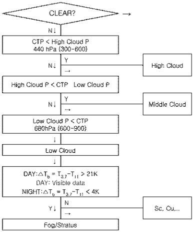

Fig. 1. Flow chart for the classification of cloud types and fog. Here the symbols of 'P' and 'CTP' stand for pressure and cloud top pressure, respectively.

cloud top temperature. Since atmospheric temperature decreases in the troposphere as altitude increases, the brightness temperature observed by satellite decreases while clouds develop vertically. However, since fog forms near the surface, it does not indicate a significant difference between the cases of fog and clear-sky.

The brightness temperature of the MODIS channels during foggy days is different from that during clear days because of the infrared absorption and emission by water particle. Thus, fog in this study could be detected by comparing characteristics of each channel during fog with those during clear-sky condition. Fog is defined that horizontal visibility is below 1 km, while clear-sky is defined that the amount of clouds is zero. Based on the foggy and clear days classified by ground observation from the weather forecast center in Yongjong-do, foggy and clear-sky days were chosen separately with simultaneous satellite observations of the MODIS over the area of this study.

The period of a day was divided into four time zones (0-6 h, 6-12 h, 12-18 h, and 18-24 h) considering ground observation and satellite-passing time over the area, and frequency of fog and clear-sky occurrences was examined (Table 1). During this study period, fog near the Inchon International Airport occurred average 10.7 times per month, and more frequently in nighttime (68) than in daytime

Table 1. Number of monthly foggy days at the Inchon International Airport (37.47 N, 126.43 E) during the period from Dec. 15, 2002 to Dec. 14, 2003 with the simultaneous observations of MODIS onboard AQUA and TERRA satellites. The numbers in parentheses indicate total number of foggy days, observed from ground station

	Number of Fog Days						
	TERRA		AQUA		Day	Night	Total
	10:30	22:30	1:30	13:30			
Jan	2 (5)	1 (2)	1 (3)	1 (4)	3 (9)	2 (5)	5 (14)
Feb	1 (7)	2 (3)	4 (5)	1 (1)	2 (8)	6 (8)	8 (16)
Mar	0 (3)	0 (1)	1 (3)	1 (1)	1 (4)	1 (4)	2 (8)
Apr	0 (2)	1 (3)	2 (3)	0 (1)	0 (3)	3 (6)	3 (9)
May	0 (3)	2 (2)	2 (2)	0 (1)	0 (4)	4 (4)	4 (8)
Jun	0 (6)	1 (3)	0 (7)	0 (1)	0 (7)	1 (10)	1 (17)
Jul	0 (4)	0 (1)	2 (6)	0 (0)	0 (4)	2 (7)	2 (11)
Aug	1 (6)	2 (4)	2 (6)	0 (0)	1 (6)	4 (10)	5 (16)
Sep	2 (7)	0 (1)	3 (4)	0 (0)	2 (7)	3 (5)	5 (12)
Oct	0 (2)	1 (1)	2 (3)	0 (0)	0 (2)	3 (4)	3 (6)
Nov	1 (3)	0 (0)	0 (4)	1 (1)	2 (4)	0 (4)	2 (8)
Dec	0 (2)	0 (0)	0 (1)	0 (0)	0 (2)	0 (1)	0 (3)
Sum	7 (50)	10 (21)	19 (47)	4 (10)	11 (60)	29 (68)	40 (128)
Mean	0.6 (4.2)	0.8 (1.8)	1.6 (3.9)	0.3 (0.8)	0.9 (5)	2.4 (5.7)	3.3 (10.7)

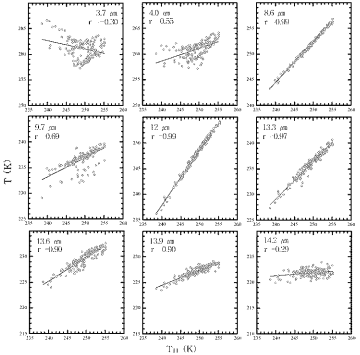

Fig. 2. Scatter diagrams in daytime MODIS brightness temperature (T) of nine other channels versus 11 μm temperature (T_{11}) near the Inchon International Airport (20×20 km) at 12:05 LST on January 10, 2003 during foggy day. The channels are 3.7, 4.0, 8.6, 9.7, 12.0, 13.3, 13.6, 13.9, and 14.2 μm. Least square line and the value of correlation are given in each panel.

(60). Fog formed most in summer and least in winter, for instances, in June (17), in August (16), and in December (3). Fog also occurred most around 10 : 30 a.m. (50 times) and occurred least around 13 : 30 (10 times), as shown in Table 1. This study examined the threshold value of $T_{3.7-11}$ based on the above foggy and clear days, together with the MODIS data of solar and infrared radiation.

Characteristics of MODIS Data during Fog Occurrence

To investigate the change of satellite-observed data for foggy and clear days, respectively, the MODIS data was used in the following infrared channels: 3.7, 4.0 8.6, 9.7, 11.0, 12.0, 13.3, 13.6, 13.9, and 14.2 μm. Each channel has its inherent features for weighting function, absorption gas, and usage. Brightness temperatures at 3.7 μm and 11.0 μm have been used to induce surface temperature. Maximum weighting functions at 8.6 μm and 9.7 μm are situated at the altitudes of 1000 hPa and 250 hPa, respectively, and theses channels are available in the measurement of ozone. The peaks of weighting functions at 12.0, 13.3, 13.6, 13.9, and 14.2 μm correspond to the altitudes of 1000, 900, 750, 500, and

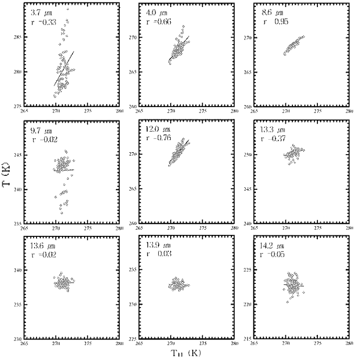

Fig. 3. Same as in Fig. 2 except for at 12:15 LST on January 8, 2003 during clear-sky condition.

350 hPa, respectively (Menzel and Gumley, 1998).

The cases of foggy and clear days under same time zones during each day and night were compared and analyzed (Figs. 2-4). The cases of 12 : 05 LST January 10, 2003 (Fig. 2) and 12 : 15 LST January 8, 2003 (Fig. 3) were chosen for daytime fog and clear-sky conditions, respectively. Also nighttime cases for fog and clear-sky were 22 : 00 LST January 13, 2003 (Fig. 4a) and 22 : 45 LST January 14, 2003 (Fig. 4b), respectively.

The value of brightness temperature at 11 μm (T_{11}) that reflected surface temperature was 240-255 K when the fog occurred in the daytime on January 10, 2003 (Fig. 2). The T_{11} highly correlated with brightness temperatures at 12 μm and 13.3 μm, and less correlated with those at other channels (i.e., 13.6, 13.9, and 14.2 μm) which had weighting functions in higher altitudes. The values of brightness temperature at 3.7 μm ($T_{3.7}$) which ranged from 275 K to 290 K were higher by about 30 K than those of the T_{11}. Both temperatures showed a low correlation with each other. The wavelength at 3.7 μm is located in the boundary between infrared (IR) and solar radiations. Thus, it is affected in the daytime by both radiations. Therefore, the $T_{3.7}$ value was enhanced due to the diffusion and emission effect of solar radiation by fog particles, and the correlation between $T_{3.7}$ and T_{11} became low.

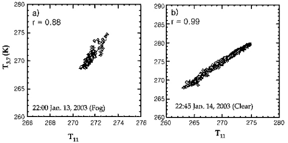

Fig. 4. Scatter diagrams in nighttime brightness temperatures of 3.7 µm ($T_{3.7}$) versus 11 µm (T_{11}) at the a) 22:00 LST on January 13, 2003 and b) 22:45 LST on January 14, 2003.

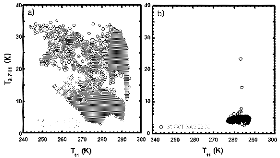

Fig. 5. Scatter diagram of $T_{3.7-11}$ (i.e., the difference in brightness temperature between 3.7 µm and 11 µm) versus T_{11}, during the fog duration near the Inchon International Airport (37.3-37.5 N, 126.3-126.5 E) at the a) 11:30 LST on August 3 and 22:25 LST on August 21, 2003, and b) 22:30 LST on October 31, 2003.

The daytime case of clear-sky on January 8, 2003 was different from that of fog on January 10, 2003 (Fig. 3). For instance, the T_{11} values (270 K) of daytime clear-sky in winter were almost constant. Similarly to the foggy case, there was a low correlation between surface (T_{11}) and the channels which reflected upper atmospheric temperatures. The correlation between 3.7 µm and 11 µm for daytime clear-sky was higher than that for daytime fog.

Fig. 4a showed the correlation between $T_{3.7}$ and T_{11} when fog occurred at night on January 13, 2003. Compared with the case of daytime fog, the correlation (0.88) was relatively high. Since there was only IR radiation without solar radiation at night, a high correlation between them was expected.

The correlation (0.99) between 3.7 µm and 11.0 µm for nighttime clear-sky on January 14, 2003 was remarkably higher than that (0.88) for nighttime foggy case (Fig. 4b). In order to detect fog at night, difference in the correlation between clear-sky and fog has been applied.

Now that fog occurs near the surface, the IR channel that has low correlation with surface temperature is not useful for detecting fog. Thus, previous studies utilized the threshold value of $T_{3.7-11}$ that was sensitive to water particles (MRI, 2001; Anthis and Cracknell, 1999; Ellrod, 1995; Erye et al., 1984).

Table 2. Values of brightness temperature (T) in the MODIS channels of 3.75 μm, 11 μm, 12 μm, 13.3 μm and the T difference ($T_{3.7\text{-}11}$) between 3.75 μm and 11 μm during the period from Dec. 15, 2002 to Dec. 14, 2003 at the Inchon International Airport (126.43 E, 37.47 N). The number in parentheses means standard deviation

Day/Night (LST)	Weather	Case	T (K)				$T_{3.7\text{-}11}$
			3.7 μm	11 μm	12 μm	13.3 μm	
Day (10:30)	Fog	2	300.4 (1.0)	264.1 (6.0)	263.2 (6.2)	250.2 (9.6)	36.33 (6.98)
	Clear	2	295.7 (5.5)	280.4 (8.9)	280.3 (8.2)	258.5 (4.7)	15.28 (3.38)
Day (13:30)	Fog	2	296.4 (16.9)	261.0 (0.2)	260.7 (0.9)	249.5 (0.7)	35.38 (16.64)
	Clear	2	296.5 (8.3)	283.0 (7.5)	283.3 (7.6)	259.5 (1.6)	13.45 (0.85)
Day	Fog	4	298.4 (10.0)	262.6 (3.9)	262.0 (3.9)	249.9 (5.6)	35.86 (10.43)
	Clear	4	296.0 (5.8)	281.7 (6.9)	281.8 (6.7)	259.0 (2.9)	14.37 (2.27)
Night (1:30)	Fog	8	276.0 (6.2)	272.0 (7.0)	271.7 (7.2)	256.2 (5.5)	3.98 (3.04)
	Clear	8	278.1 (5.7)	273.9 (6.1)	274.0 (6.1)	256.4 (4.8)	4.20 (1.24)
Night (22:30)	Fog	4	274.2 (7.7)	272.3 (6.4)	271.8 (7.3)	255.0 (7.2)	1.92 (3.98)
	Clear	4	277.3 (5.1)	271.7 (6.5)	271.9 (6.6)	257.7 (7.3)	5.60 (1.65)
Night	Fog	12	275.4 (6.4)	272.1 (6.5)	271.8 (6.9)	255.8 (5.8)	3.29 (3.35)
	Clear	12	277.9 (5.3)	273.2 (6.0)	273.3 (6.0)	256.8 (5.5)	4.67 (1.48)

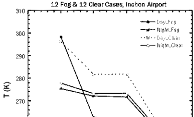

Fig. 6. Average values of brightness temperature (T) of the MODIS channels of 3.75 μm, 11.0 μm, 12.0 μm and 13.3 μm under the condition of either fog or clear-sky near the Inchon International Airport. Twelve observations are considered for the each weather condition.

Fog Detection

Infrared Channels

The brightness temperatures at 3.7 μm and 11.0 μm for clear day are close to surface temperature, but they become lower when fog and cloud exist. The emissivity at 11 μm for opaque water is 1.0, and at 3.7 μm is 0.8-0.9. As a result, the decrease of the temperature at 3.7 μm is greater than that at 11 μm. Physical difference between those two channels has been applied to detect fog (MRI, 2001; Anthis and Cracknell, 1999; Ellrod, 1995; Erye et al., 1984).

Fig. 5 showed scatter diagram of the T_{11} and $T_{3.7\text{-}11}$ values at 11 : 30 LST on August 3, 2003, and at 22 : 30 LST on October 31, 2003 under the fog condition. The $T_{3.7\text{-}11}$ values during day and night were clearly divided into two populations by a boundary of 15 K (Fig. 5a). The near-IR channel at 3.7 μm during daytime was affected by solar radiation as well as infrared radiation. Thus, the scattering and reflecting effect of solar radiation due to fog particles increased the temperature at 3.7 μm during daytime, compared to during nighttime. Additionally, this physical mechanism significantly contributed to the threshold values during day and night (Cermak et al., 2004; Bendix et al., 2003). The threshold value of $T_{3.7\text{-}11}$ for detecting fog during day and night depended on its optical thickness and if clouds exist above a layer of fog.

As shown in Fig. 5b, the values of T_{11} and $T_{3.7\text{-}11}$ were clustered in a narrow range of temperature only when fog and stratus were horizontally distributed. However, when clouds existed above a fog layer, the values were more widely distributed (Fig. 5a). Using the data of ground observation at the

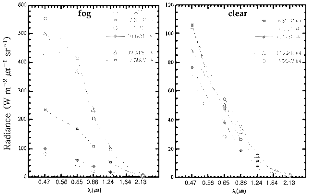

Fig. 7. Daytime MODIS radiance (Wm^{-2} μm^{-1} sr^{-1}) in seven visible channels near the Inchon International Airport for a) seven foggy days and b) seven clear-sky days.

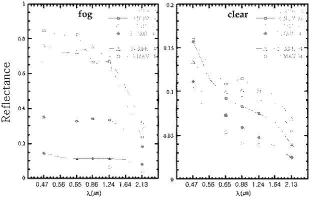

Fig. 8. Same as in Fig. 7 except for the MODIS reflectance.

Inchon International Airport and MODIS IR channels, the average values of $T_{3.7}$, T_{11}, T_{12}, $T_{13.3}$ and $T_{3.7\text{-}11}$ during fog and clear-sky were derived in this study (Table 2). The $T_{3.7\text{-}11}$ value during daytime fog was higher than that during daytime clear-sky, and during nighttime fog, vice versa (Fig. 6).

Channels of Solar Radiation

Since the threshold value of $T_{3.7\text{-}11}$ during daytime includes noise of solar radiation, it may not be used for detecting fog accurately. In addition to the value, solar reflectance has been utilized to detect fog during daytime in previous studies of Bendix (2004) and Cermak (2004) to solve the above problem.

In this point of view, this study analyzed seven cases when fog occurred near the Inchon International Airport during the period from January 2003 to August 2004, together with simultaneous satellite

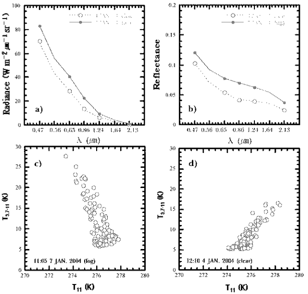

Fig. 9. The MODIS data of a) radiance, b) reflectance, c) $T_{3.7-11}$ versus T_{11} during foggy day (11:05 LST Jan. 7, 2004), and d) $T_{3.7-11}$ versus T_{11} during clear-sky (12:10 LST Jan. 4, 2004) near the Inchon International Airport.

observations of the MODIS. The value of solar radiance during fog was higher by about 20-370 Wm^{-2} μm^{-1} sr^{-1} at 0.65 μm than that during clear-sky (Fig. 7). The radiance values during fog and clear-sky exhibit maxima in May and minima in January due to seasonal variation of solar altitude. The difference in radiance at 0.65 μm between fog and clear-sky was maximum (300 Wm^{-2} μm^{-1} sr^{-1}) in May, and minimum (20 Wm^{-2} μm^{-1} sr^{-1}) in January.

Similarly to the case of radiance, the values of reflectance during fog were higher by 0.05-0.6 than that during clear-sky (Fig. 8). The values of reflectance during fog and clear-sky tend to decrease with increase of wavelength, except for the channel at 0.86 μm. This was because the reflectance was sensitive to the optical thickness of fog and solar zenith angle.

The radiance and reflectance during fog at 11:05 LST on January 7, 2004 were compared with those during clear-sky at 12:10 LST on January 4, 2004 (Figs. 9a-b). Figs. 9c-d show scatter diagrams of brightness temperatures for T_{11} and $T_{3.7-11}$. The radiance and reflectance during fog were higher by 15 Wm^{-2} μm^{-1} sr^{-1} and 0.03, respectively, than those during clear-sky (Figs. 9a-b). The T_{11} values during fog and clear-sky were about 276 K (Figs. 9c-d). The $T_{3.7-11}$ values during fog were mostly 8 K. The radiance (or reflectance) during foggy day at 11 : 05 LST on January 7, 2004, and clear-sky at 12 : 10 LST on January 4, 2004, have been compared with each other (Fig. 10). Since solar altitude in May is higher than in January, the values of solar radiance and reflectance are higher in May than in January. The value of reflectance during fog is higher by 0.04-0.05 than during clear-sky, because of scatter-

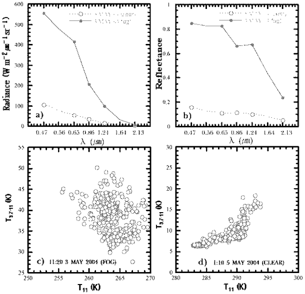

Fig. 10. Same as in Fig. 9 except for 11:20 LST May 3, 2004 and 11:10 LST May 5, 2004.

ing and reflecting of fog particles (Figs. 10a-b). The value of T_{11} (255-270 K) at 11 : 20 LST on May 3, 2004 during fog is lower by 25 K than that of T_{11} (280-295 K) at 11 : 10 LST on May 5, 2004 during clear-sky. Additionally, the $T_{3.7-11}$ value for fog is higher than that for clear-sky. In this case, vertically developed clouds have been inferred to partially exist above the fog layer near the Inchon International Airport.

Conclusion

In this study, we have investigated possible remote sensing of fog near the Inchon International Airport for the period from December 2002 to August 2004, using the MODIS IR and solar data onboard the AQUA (1 : 30, 13 : 30 ECT) and TERRA (10 : 30, 22 : 30) satellites. According to the analysis of nine IR channels (3.7-14.2 μm), the brightness temperatures at 3.7 μm and 11 μm were useful for detecting fog. The threshold value of $T_{3.7-11}$ during daytime was greater by about 21 K when it was foggy than when it was clear. However, the value during nighttime fog was less by 1.5 K than during nighttime clear-sky. This may result from the fact that emission of fog particle is 1.0 at 11 μm, and 0.8-0.9 at 3.7 μm. Based on these features of the satellite data, the threshold values of $T_{3.7-11}$ during day and night were derived. However, the values included errors when clouds existed above a layer of fog.

The near-IR channel at 3.7 μm was affected by solar and IR radiation in the daytime. Not only IR but also solar channels have been used to detect fog during daytime. Since fog particles resulted in high reflectance of solar radiation, the reflectance during fog was higher by 0.05-0.6 than that during clear-sky. As optical thickness of fog became greater, reflectance got higher. The value of reflectance was sensitive to the change of solar zenith angle.

In summary, the threshold values of $T_{3.7-11}$ have been derived in this study for detecting fog during day and night near the Inchon International Airport. However, the daytime value needs to be compensated by solar radiation and reflectance, together with radiative transfer simulation.

Acknowledgments

This research is supported by the project "Development of Meteorological Data Processing System for COMS" of the Korea Meteorological Administration.

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Manuscript received, January 15, 2005
Revised manuscript received, February 25, 2005
Manuscript accepted, February 25, 2005