The Spectral Transmittance due to Water Vapor, Ozone and Aerosol of Cloudless Atmosphere over the Central Part of Thailand

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Abstract

The spectral solar irradiance (0.3-4 μm) is directly affected by the extinction processes i.e. scattering, absorption and reflection in the atmosphere. The absorption by trace gasses is mainly due to increase in water vapor, O_3 and aerosol, which significantly affect the spectrum of solar radiation on the earth. The objective of this paper is to estimate the spectral transmittance of cloudless atmosphere over the central part of Thailand where the O_3 and aerosol was observed. The estimation was carried out using the upper air, O_3 aerosol and visibility data, which were measured by the Thai Meteorological Department. Monthly spectral transmittance at the zenith is due to precipitable water, and O_3 and aerosol and were estimated using the correlationships proposed by Bird et al. (1986) and Angstrom. Results show that the spectral transmittance is due to precipitable water and varies in the range of 0.6 μm and 1.7 μm and near 4.0 μm whereas the spectral transmittance due to O_3 highly varies in the UV region in the range of 0.3 μm-0.345 μm and also varies in the range of 0.45 μm-0.768 μm. The spectrum of aerosol transmittance quasi-linearly increases until it reaches 1.0 μm.

Keywords: spectral transmittance, water vapor, ozone, aerosol, cloudless atmosphere

1. Introduction

Spectral solar irradiance (0.3-4 μm) is one of the most important parameters in a variety of applications spread in different disciplines such as atmospheric science, photosynthesis process as well as energy technology, e.g. photovoltaic systems, high performance glazing for daylighting and selective coatings etc. Spectral solar irradiance is directly affected by with the extinction processes in the atmosphere i.e. scattering by dust and particulate matter, absorption by atmospheric constituents and reflection by clouds [1].

The atmosphere consists mainly of nitrogen and oxygen, which account for about 99%. However, neither nitrogen nor oxygen is of prime importance for the spectral solar irradiance absorption in the atmosphere. The main contribution to this absorption process is being made by such quantitatively insignificant atmospheric components as water vapor, CO_2, O_3, NO_x, with some other aerosol components and other uniformly mixed gases [2].

The spectral absorption of the atmosphere extends over a wide range from the X-ray region to ultrashort radio waves, which makes the physical nature of absorption highly varied and greatly complicates the structure of the spectrum. However, the main factor is the content of the radiation absorbent. Moreover, the pressure and temperature in the absorbing medium are also important [1].

The absorption of solar radiation by water vapor in the region of 0.54 μm to 9 μm is caused by vibrational-rotational transitions and in the far-IR (from 9 μm to 1,500 μm) by purely rotational transitions. In the UV

($\lambda > 0.2 \mu m$) the absorption is determined by electronic transitions. Three types of normal vibrations of the water vapor molecule are observed to have the following main frequencies; f_1 =3670 cm^{-1}, f_2 =1675 cm^{-1} and f_3 =3790 cm^{-1} as shown in Figure 1.

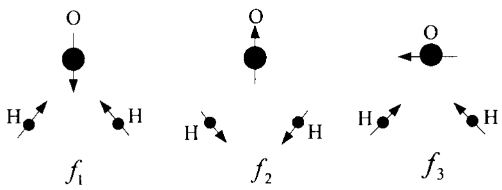


Fig. 1. Fundamental vibrations of the water vapor molecule [1].

Water vapor possesses a number of intensive absorption bands in the IR. The most intensive are the bands in the following spectral intervals: 1.6 μm to 11 μm, and 14.5 μm to 19 μm. The absorption of UV solar radiation by water vapor appears to be of importance to the energy of the upper atmosphere. For the troposphere, however, the presence of an intensive water vapor absorption spectrum in the IR is practically unimportant, since this radiation is fully absorbed in the upper atmosphere.

The CO_2 molecule is a linear molecule as shown in Figure 2 with the nucleus to nucleus carbon-oxygen distance of 0.000115 μm. The intensive bands of CO_2 absorption in the IR are due to vibrational transitions. Three types of normal vibrations of the CO_2 molecule are observed corresponding to the main frequencies: f_1 =1.361 cm^{-1}, f_2 =673 cm^{-1} and f_3 =2.378 cm^{-1}.

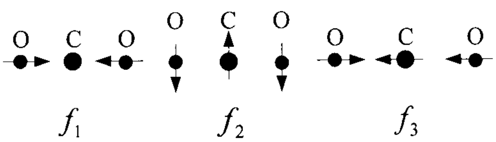


Fig. 2. Fundamental vibrations of the CO_2 molecule [1].

CO_2 is represented by several absorption bands in the IR spectral region having a wavelength interval > 1.3 μm. Also known is the presence of radiation absorption by CO_2 in the IR region ranging from 10 μm to 20 μm. The intensity of solar radiation in both these regions is quite low, and the absorption of solar radiation by CO_2 is rather weak.

Aerosols are powders or droplets suspended in the atmosphere with a typical particle diameter of about 1 μm and nowadays they are important in many fields of science and engineering. Recently it has been proposed that they might help prevent catastrophic global warming [3].

The atmosphere is filled with huge numbers of particles, from the surface right up to the stratosphere and higher. Being so small, the particles usually are invisible. They can occasionally grow large enough to scatter solar radiation, which is noticeable, which is then perceived as 'haze'. Or they can act as a nucleus for the condensation of water to make a relatively large cloud droplet. Aerosol particles interact with long-wave radiation, which is part of solar radiation.

O_3 has three atoms. It is very rare, only three out of 10 million molecules in the air are O_3. Ninety percent of O_3 is in the upper part of the atmosphere. The O_3 layer is a thin layer in the atmosphere, which is 10-50 km above the earth. The O_3 layer also absorbs most of the harmful UV-B radiation from the sun [4]. O_3 is an important radiation absorbent, which absorbs this component in the atmosphere. It was hypothesized at the end of the past century that the observed discontinuity of the spectral solar irradiance in the region of wavelength shorter than 0.3 μm was due to the absorption of the UV solar radiation by O_3. Later observations confirmed this supposition and demonstrated that O_3 does have several absorption bands in the spectral solar irradiance region with the most intensive band occurring in the UV interval.

The transmittance of the atmosphere to short wave solar radiation depends on the optical properties of gases, aerosol and clouds that vary with wavelength as well as external conditions such as solar angle. Besides zenith angle or solar elevation, which is necessary to estimate the transmittance, the following parameters are required, e.g. precipitable water in the vertical column measured in cm, vertical ozone column amount in $atm-cm$, Angstrom's turbidity coefficient (dimensionless) and Angstrom's wavelength exponent (dimensionless) [5].

All mentioned parameters have been used to calculate the spectral solar irradiance by King and Buckius 1979 [6], Birds 1981 [7], Iqbal 1983 [8], Santamouris 1987 [9], Santamouris 1991 [10] and Gueymard 1993 [11]. Water content and turbidity of the atmosphere in Thailand have been investigated by Exell 1978 [12] and recently the turbidity spread over Thailand has been investigated by Janjai 2003 [13]. Over the past two decades, anthropogenic emissions of chemical compounds into the atmosphere have caused many atmospheric changes. Consequently, the aim of this paper is to estimate the spectral transmittance of cloudless atmosphere over the central part of Thailand where the ozone and aerosol were merely observed on the basis of the contribution of precipitable water, ozone and aerosol only by using the routine measured data from the Thai Meteorological Department.

2. Estimation of Precipitable Water, Ozone and Aerosol Transmittance

The estimation was carried out using the upper air data in 1997 and ozone data during 1980-2001. Both were observed at the Bangkok Metropolis Station. The aerosol data was observed at Ko Sichang station in 1985. The visibility data during 1971-2000 was observed at the Bangkok Metropolis Station. The monthly spectral transmittances of cloudless atmosphere were estimated at the zenith.

2.1 Water Vapor Transmittance

The spectral transmittance due to water vapor absorption is approximated as [14]:

$$\tau_{w\lambda} = \exp[-0.2385 a_{w\lambda} w m_r (1 + 20.07 a_{w\lambda} w m_r)^{0.45}]$$

where $a_{w\lambda}$ is the spectral water vapor absorption coefficient [15].

The atmospheric precipitable water (w in cm) in a column of air with vapor pressure e (mbar), absolute temperature T (K) and height h (m) can be computed using the above air data provided by the Thai Meteorological Department (Rawinsonde) as given in the equation below [16]:

$$w = 0.021668 \frac{eh}{T}$$

The variations of the monthly mean precipitable water optical depth is computed from the data measured in Bangkok, which is illustrated in Figure 3 below.

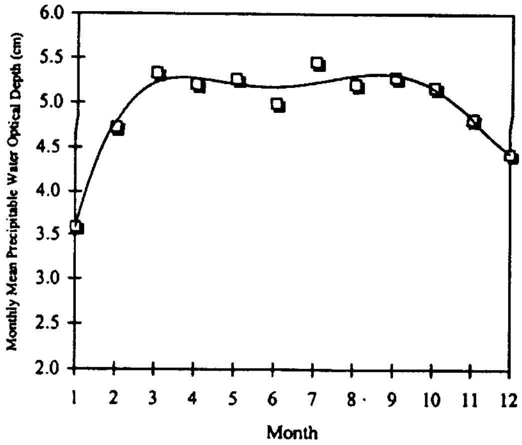


Fig. 3. Variation of monthly mean precipitable water optical depth (Bangkok 1997).

The relative optical air mass m_r of the average atmosphere can be determined from the solar zenith angle, which is a function of latitude, season, and time of day, and derived as given below [17]:

$$m_r = [\cos Z + 0.50572(96.07995 - Z)^{-0.6364}]^{-1}$$

where Z is the zenith angle in degrees.

2.2 Ozone Transmittance

The transmittance due to ozone absorption can be computed as [18]:

$$\tau_{o\lambda} = \exp(-a_{o\lambda} O_3 M_o)$$

where $a_{o\lambda}$ is the spectral absorption of ozone and O_3 is the ozone column density in $atm-cm$, M_o is the ozone mass as given by Iqbal [8]. The ozone mass is expressed as:

$$M_O = (1 + h_0 / 6370)/(\cos^2 Z + 2h_0 / 6370)^{0.5}$$

where h_0 is the height of maximum O_3 concentration, which normally varies with latitude and time of the year. In the estimation, the maximum concentration is 22 km, approximately.

The ozone optical depth is between 10 to 20 N latitude, varying from 0.23 – 0.28 cm [19]. In Thailand, the ozone optical depth can be obtained from Dobson's unit of the Thai Meteorlogical Department. The ozone optical depth during the last two decades in Bangkok is shown in Figure 4 below.

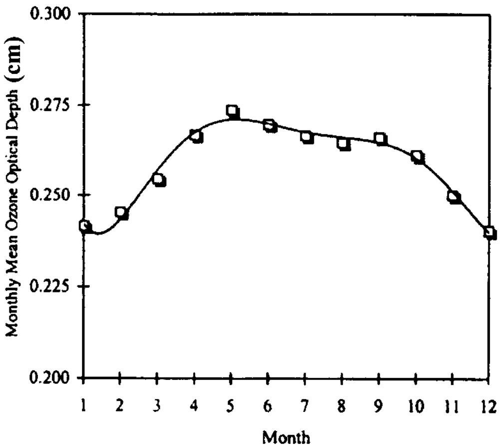


Fig. 4. Variation of monthly mean ozone optical depth (Bangkok 1980-2001).

2.3 Aerosol Transmittance

The spectral aerosol transmittance was described by Angstrom [20], which is related to Angstrom's turbidity coefficient given as:

$$\tau_{a\lambda} = \exp(-\beta\lambda^{-\alpha})$$

where β is the Angstrom's turbidity coefficient and α is the wavelength exponent closely related to the aerosol size distribution and the amount of aerosol in the atmosphere. The wavelength exponent was about 3.8 during January-April, about 2.7 during May-October and about 1.3 during November-December [15].

Janjai et al. [13] have proposed a correlation between β and visibility. The correlationship between β and its visibility is expressed as

$$\beta = 0.589 - 0.068(VIS) + 0.0019(VIS)^2$$

The visibility at Bangkok metropolis station during the last three decades was analyzed by the Thai Meteorological Department, which found that the monthly mean visibility varied between 8 to 12 km as shown in Figure 5.

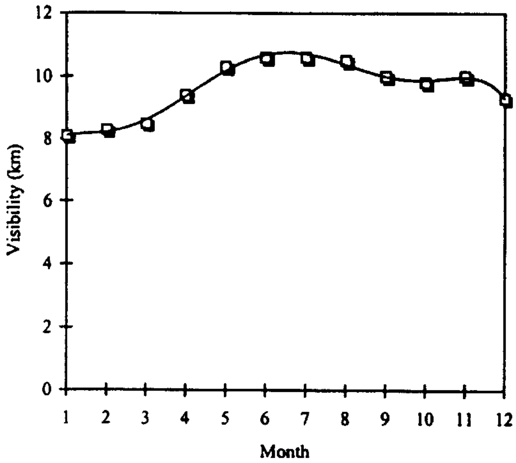


Fig. 5. Monthly mean visibility at Bangkok metropolis station during 1971-2000.

In Thailand, aerosol was measured at Ko Sichang station and was analyzed by the Thai Meteorological Department using a Volz sunphotometer. The analyzed aerosol optical depth at Ko Sichang in 1985 is shown in Figure 6.

3. Results and Discussion

Atmospheric spectral transmittances over the central part of Thailand were estimated on the basis of a clear sky using the routine measured data from the Thai Meteorological Department in order to investigate the effect of absorption by the atmospheric constituents, especially from the contribution of water vapor, ozone and aerosol.

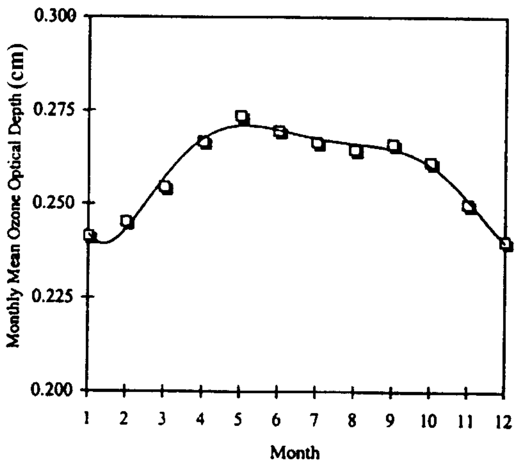


Fig. 6. Variation of monthly mean aerosol optical depth at Ko Sichang in 1985.

The spectral transmittances were estimated at zenith conditions. Monthly spectral transmittances of precipitable water, ozone and aerosol are shown in Figure 7 - Figure 12. The atmospheric transmittance is due to the contribution of the average precipitable water, ozone and aerosol and is shown in Figure13. From the spectrum of the transmittance, it can be seen that the spectral transmittance due to precipitable water strongly varies between 0.6 μm to 1.7 μm and nearly reaches 4.0 μm , which results from the strong absorption in this region of water vapor, whereas the spectral transmittance is due to O_3 highly varying in the UV region ranging from 0.3 μm to 0.345 μm and fluctuates in the range of 0.45 μm to 0.768 μm . The spectral transmittance of ozone indicates that the spectral solar irradiance is transmitted by ozone except in the region of 0.3 μm to 0.7 μm , which is the most important regime for further investigation. Apart from this region, the spectral transmittance becomes less significant for further investigation, because the transmittance is stable.

The spectral aerosol transmittance quasi-linearly increases until it reaches 1.0 μm. For the region of over 1.0 μm the spectral transmittance is approximated to be constant (0.99). The spectral transmittance of aerosol especially in the region of 0.3 μm to 0.5 μm varies from month to month during November to December due to the low content of aerosol during these months. For further investigation, the spectral transmittance of aerosol should be limited between 0.3 μm to 1.0 μm. Apart from this region the spectral transmittance due to aerosol is nearly unity. The variation of spectral transmittance of cloudless atmosphere occurs mostly due to the precipitable water as shown in Figure 13.

4. Conclusion

From the estimation, it is found that the spectral transmittance due to precipitable water varies between 0.6 μm to 1.7 μm and near 4.0 μm, whereas the spectral transmittance due to O_3 highly varies in the UV region in the range of 0.3-0.345 μm , and varies in the range of 0.45-0.768. The spectrum of aerosol transmittance quasi-linearly increases until it reaches 1.0 μm.

The estimation reasonably displays the spectral transmittance of cloudless atmosphere due to the contribution of water vapor, ozone and aerosol, however, the spectral transmittance due to the other atmospheric components such as CO_2, NO_x and uniformed mixed gases should be taken into account in order to increase the resolution of the spectral transmittance under cloudless atmosphere. Nevertheless, the estimation also requires that the accuracy be verified by routine high quality spectral solar radiation measurement.

5. Acknowledgement

The author gratefully acknowledges the Thai Meteorological Department for providing ozone, aerosol, and visibility data.

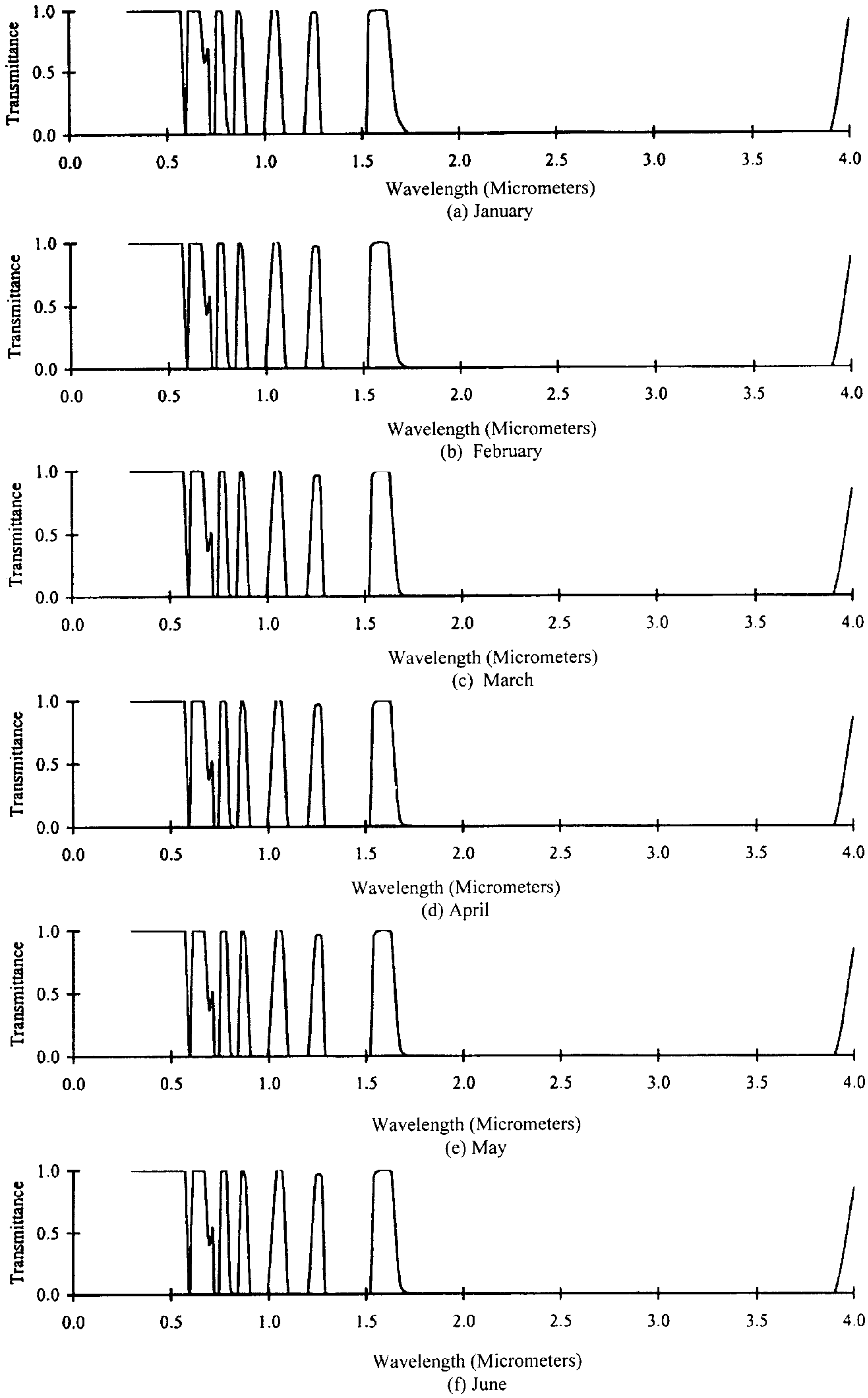


Fig. 7. The spectrum of precipitable water transmittance from January-June.

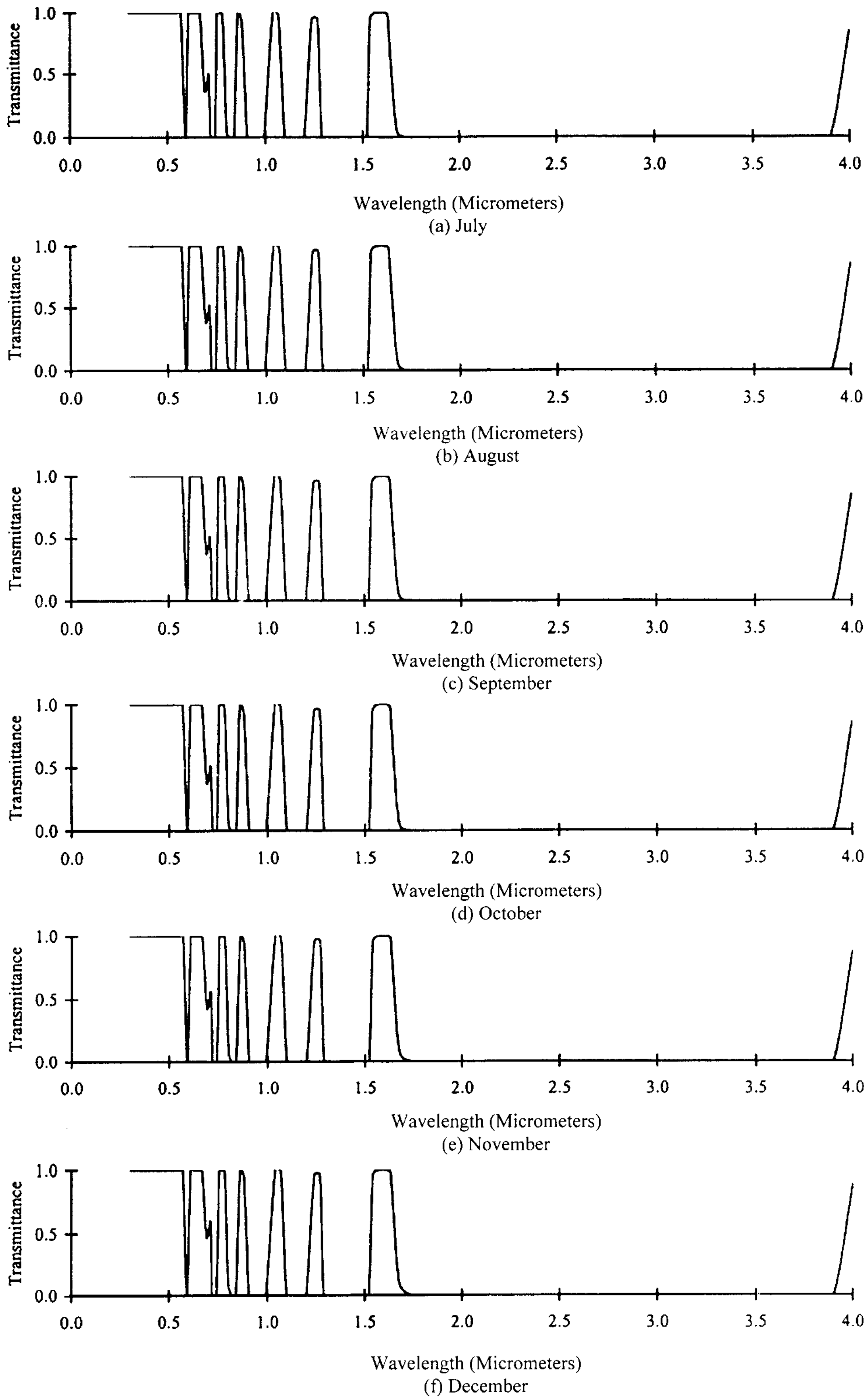


Fig. 8. The spectrum of precipitable water transmittance from July-December.

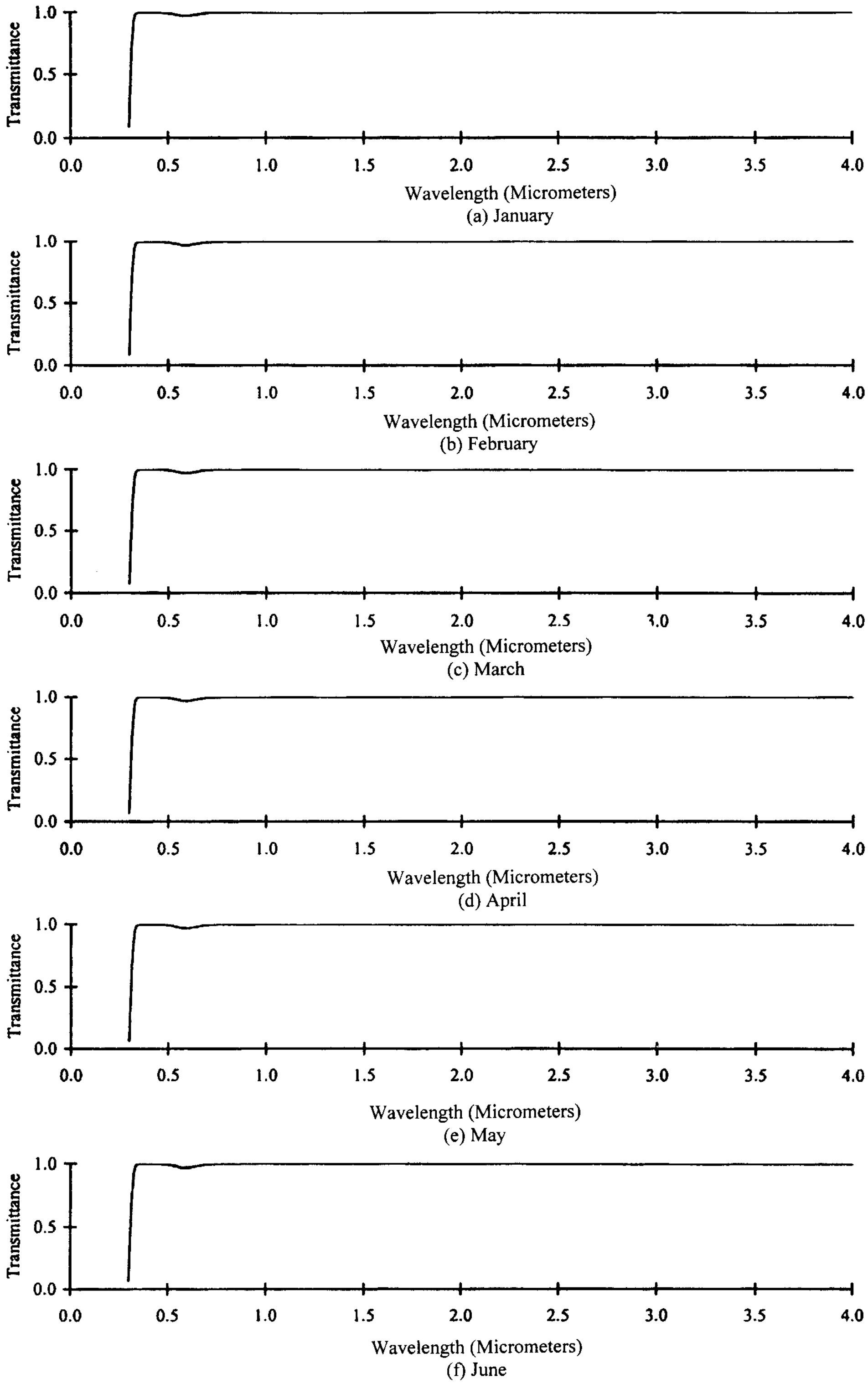


Fig. 9. The spectrum of ozone transmittance from January-June.

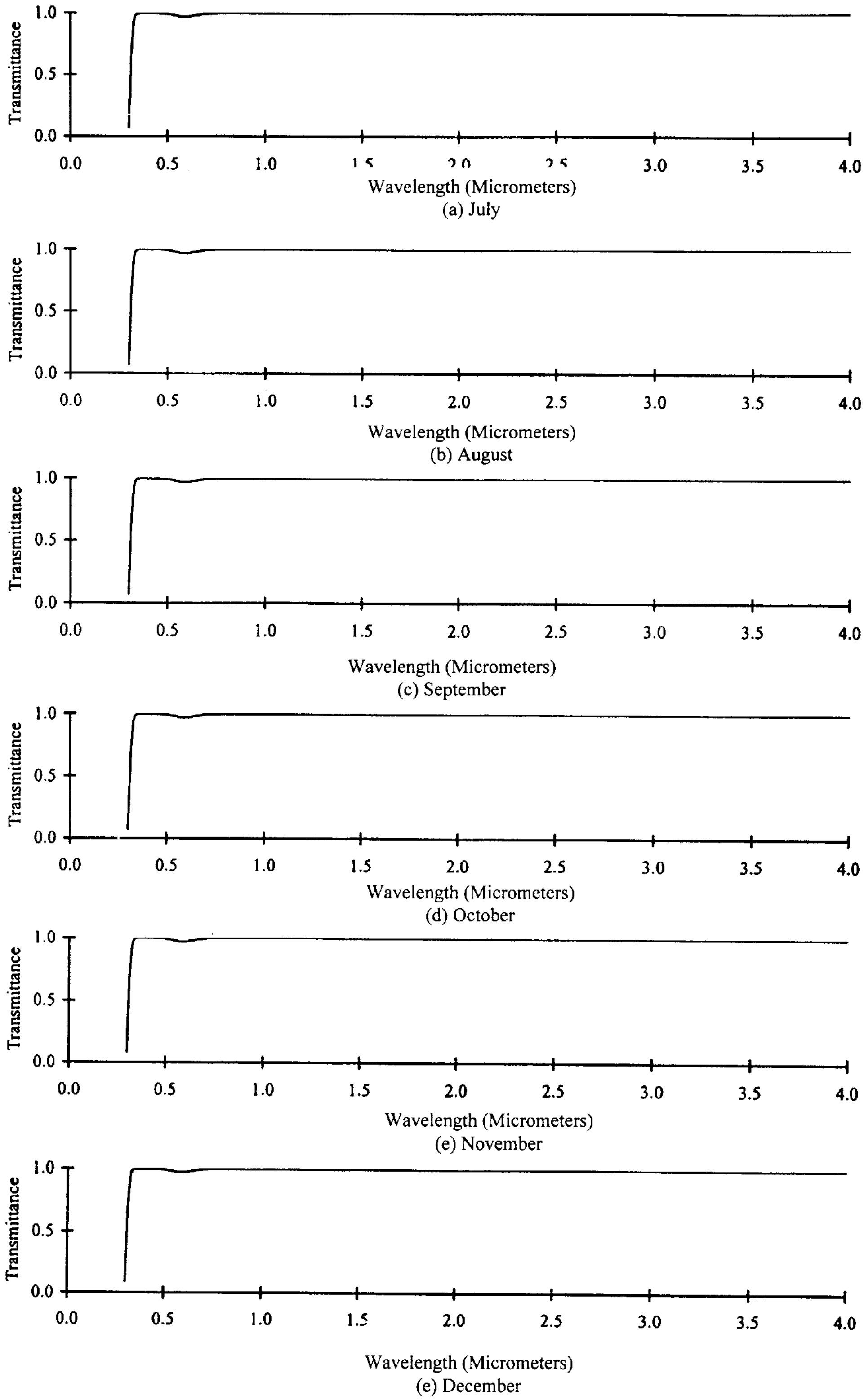
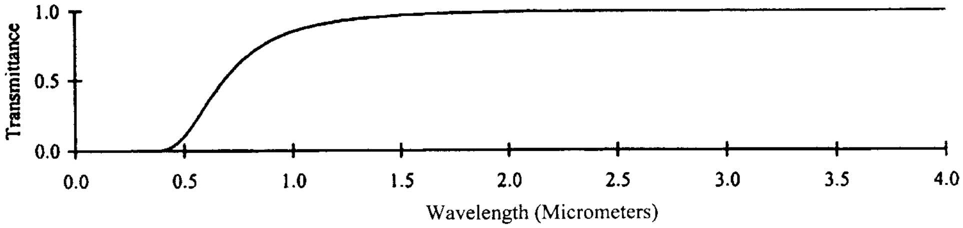
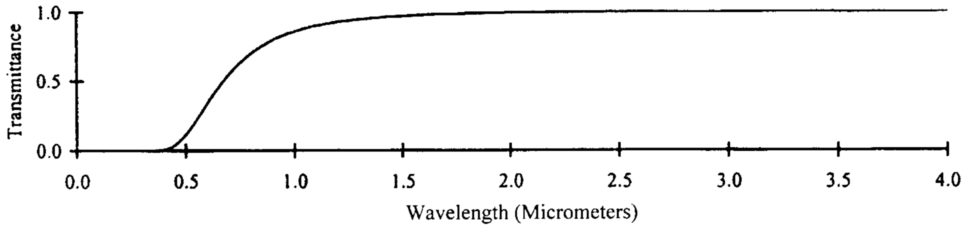


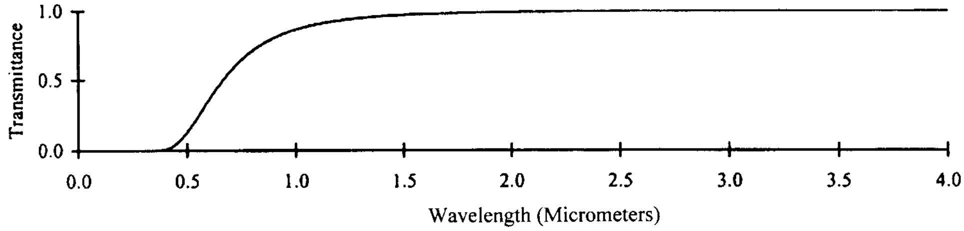
Fig. 10. The spectrum of ozone transmittance from July-December.



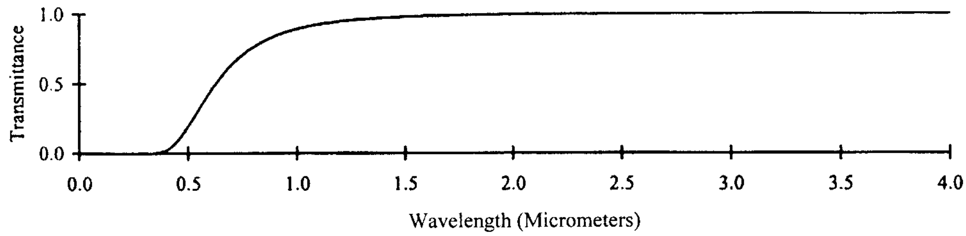
(a) January



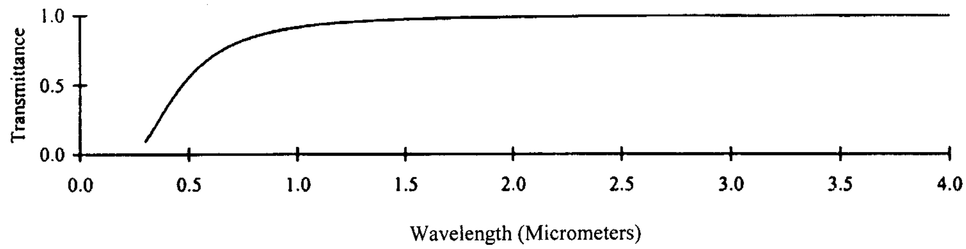
(b) February



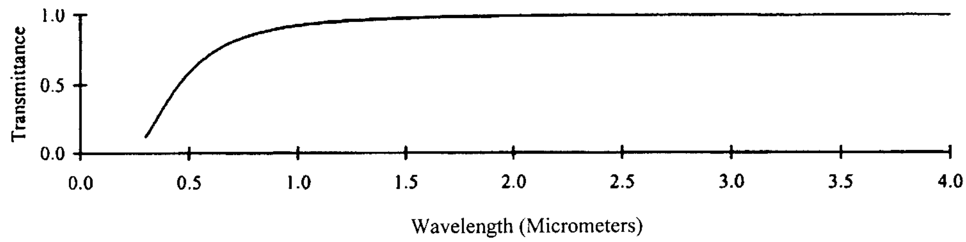
(c) March



(d) April



(e) May



(f) June

Fig. 11. The spectrum of aerosol transmittance from January-June.

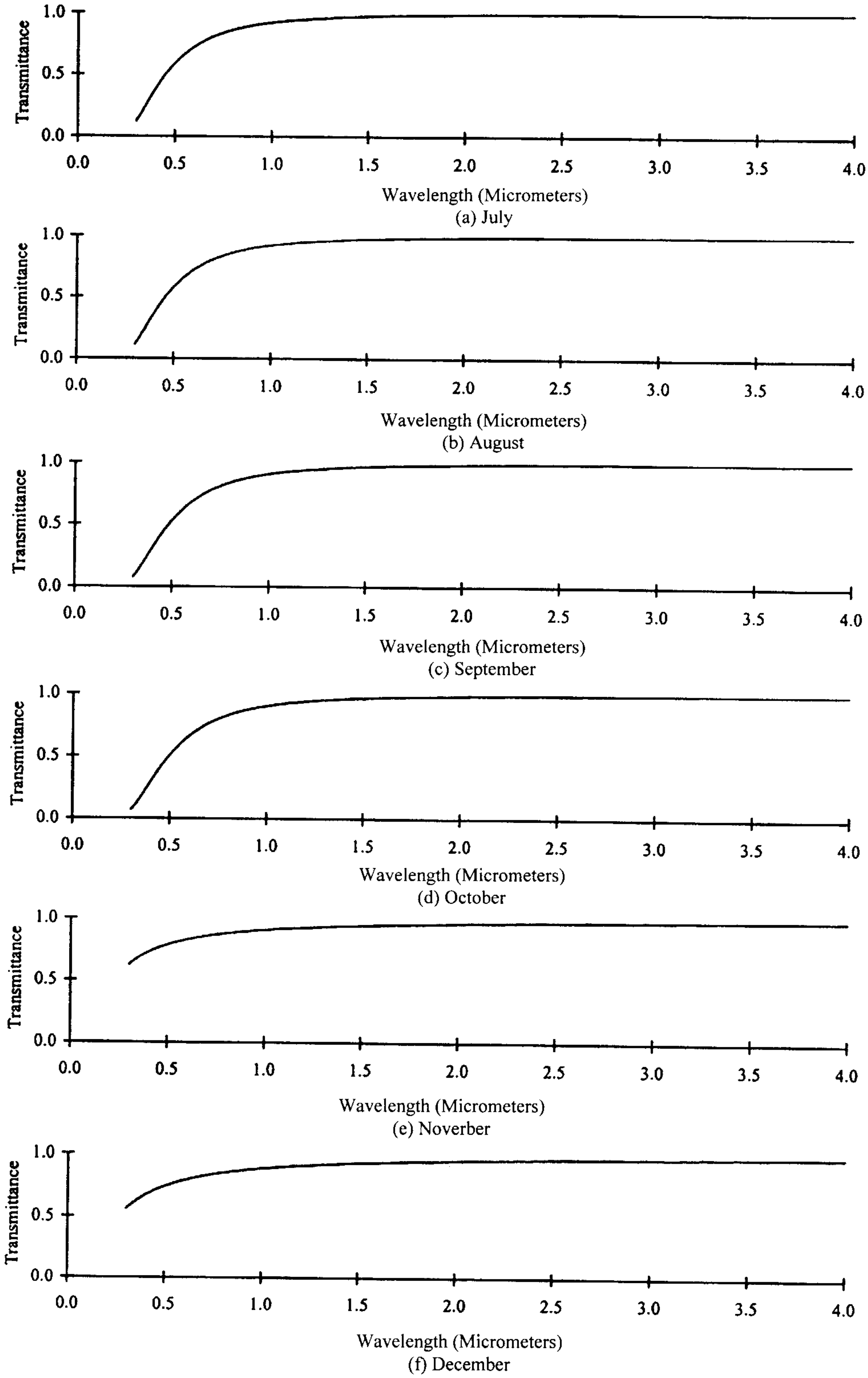


Fig. 12. The spectrum of aerosol transmittance from July-December.

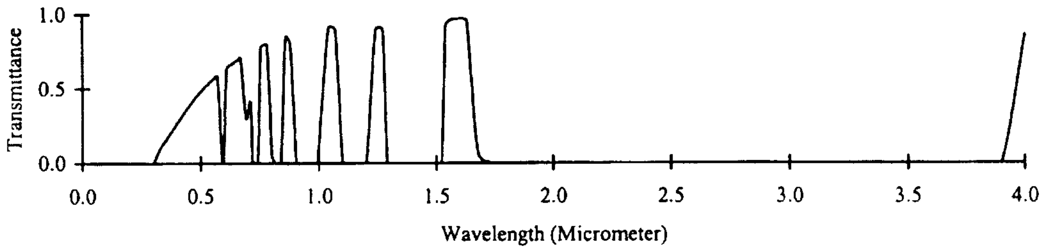


Fig. 13. The spectral atmospheric transmittance over the central part of Thailand.

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