Spectral Distributions of Clear Sky Light and Their Chromaticities

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The spectral radiant flux distribution of clear sky light varies mainly from the following factors : aerosol density, solar altitude and angular distance from the sun, and reflected light from the ground surface. This paper investigates the relation between cause and effect of variation of clear sky light. The spectral radiant flux distributions of clear sky light are not measured but calculated theoretically.

The following conclusions were obtained :

(1) The chromaticities of daylight in high latitudes are distributed up to the higher region of correlated color temperature (CCT) than in low latitudes and a number of chromaticities of daylight in low latitudes are distributed at the low region of CCT compared with in high latitudes.

(2) The chromaticities of north sky light in low latitudes are distributed with a slight shift into green side at high CCT and into purple side at low CCT compared with that of north sky light in high latitudes.

(3) The difference of the distributions of chromaticities of daylight falling on a horizontal surface of the ground between in high latitudes and in low latitudes is much smaller than that of the distributions of chromaticities of north sky light between in high latitudes and in low latituydes.

1. Introduction

There is known a number of actual measurement studies on spectral distributions and distributions of chromaticities of clear sky light. According to them, it is already discovered that the variaion of spectral distributions and chromaticities of overcast sky light is small but that of spectral distributions and chromnaticities of clear sky light is very large. It is also known that the variation of spectral distributions and chromaticities of half-clear sky light (intermediately clear sky light) is locatable between the variation of clear sky light and that of overcast sky light, where the half-clear sky means a sky with scattered clouds or a sky covered entirely with a thin cloud which makes a solar position just confirmable. In order to discuss the variation of spectral distributions and chromaticities of sky light, it is especially important to solve the relation between cause and effect of the variation of spectral distributions and chromaticities of clear sky light. However, it is impossible only by actual measurement study to solve the relation between cause and effect of the variation of spectral distributions and chromaticities of clear sky light because the variation is complexly in the clear sky light.

Therefore, as already reported[1], the auther obtained the spectral radiant flux distributions of cloudless sky light by means of numerical analysis of the formulas derived from a scattering theory on the basis of the following phenomena and solved the relation between cause and effect of the variation of spectral distributions and chromaticities of cloudless sky light. The cloudless sky light consists of two components of scattered light. One is the scattered light of sunlight which is generated in the process that the sunlight is scattered in sequence by air and serosol as it penetrates the atmosphere. Another is the scattered light of the reflected light from the ground surface which is generated in the process that the sunlight and the scattering light of sunlight are reflected by the ground surface and scattered through the atmosphere repeatedly. And these scattered lights transmit through the atmosphere with a directive characteristic, respectively.

Among the factors for varying the spectral distributions of clear sky light, the following three main factors are most influential[1].

(1) Aerosol density
(2) Solar altitude and angular distance from the sun
(3) Reflected light from the ground surface

In this paper, the relation of the variation of spectral distributions and chromaticities of clear sky light to these factors is discussed. Also, the characteristics of the spectral distributions of daylight in high latitudes and in low latitudes are described.

2. Spectral Distributions of Reflectance of Ground Surface

The ground surface is classified broadly into land and sea. On the land, a variety of objects is scatterent and the feature of the land surface is different between urban and village or between mountain and seashore. In the same district, the state of land surface changes according to the season and even during a day.

Terefore, the feature of the spectral reflectance distributions of the land surface is complicated so that it is difficult to obtain a mean spectral reflectance distribution.

In this study, it was assumed that the ground surface was covered with soil[2] and wood[3] having representative spectral reflectance distributions as shown in Fig. 1. Then, an areal ratio of soil and wood covering the ground surfase was determined so that the spectral distributions of cloudless sky light obtained from numerical analysis would agree well with the spectral distributions of actual clear sky light. For that purpose, the spectral distributions of cloudless sky light on the ground surface obtained from numerical analysis were compared with the spectral distributions of CIE reconstituted daylight with the same chromaticities, wherein the areal ratio of the ground surfaces covered with such soil and wood having the spectral reflectance distribution as shown in Fig. 1, respectively. Resultantly, it was found that both spectral distributions agreed well with each other when it was assumed that the ground surface was covered with such soil and wood at the ratio of 80% and 20% respectively. Terefore, in this paper, the ground surface covered with the soil and wood having the spectral reflectance distributions as shown in Fig. 1 at the ratio of 80% and 20% respectively, was assumed as the base for study.

3. Atmosphere Transmittance

It is estimated that the atmospheric transmittance (P) of Rayleigh atmosphere is about less than 0.91[4], where Rayleigh atmosphere is the atmosphere that does not include water vapor or aerosol at all so that only molecular scattering can be taken into account. According to calculation by the auther, it is appropriate to assume it approximately as $P=0.88$. That is because there exists an ozone layer of about 0.3cm at standard state (15℃, 760mmHg) far up in the atmosphere, which transmittance is about 0.97[5], consequently the atmospheric transmittance of Rayleigh atmosphere is obtained as $P=0.97\times0.91=0.88$

Generally, an actual atmospheric transmittance can be estimated as about 0.85 when the sky is bright and clear, about 0.75 when it is an usual clear sky and about 0.55 when it is a clear sky with a higher content of water vapor or aerosol[4].

However, according to this study, a mean atmospheric transmittance of clear sky can be estimated as 0.70. That is because the value of transmittanc of an atmosphere containg the representative or average aerosol density measurable on the ground, the value being calculated by a scattering theory, when multiplied by the transmittance of the ozone layer, results in 0.70.

By the way, the auther et al measured the correlated color temperature (CCT) of north sky light in the direction of altitude 45° at the meridian hour in Nagaoka City for several years since 1966. Fig.2 shows a dispersion diagram of monthly mean CCT depending on solar altitude in clear sky (cloudiness 0−2) obtained from the measurement results. Its regression straight line can be compared with a similar characteristic curve of the atmospheric transmittance of 0.70 obtained by numerical analysis in Fig. 2. Although the latter, characteristic curve, is straight in the range of $30^\circ < h < 90^\circ$, its gradient is slightly lower than the former, regression straight line. That is because it is estimatable that the actual aerosol density becomes higher from spring to summer and becomes lower from autumn to winter[6]. Except that, both characteristics agree well with each other.

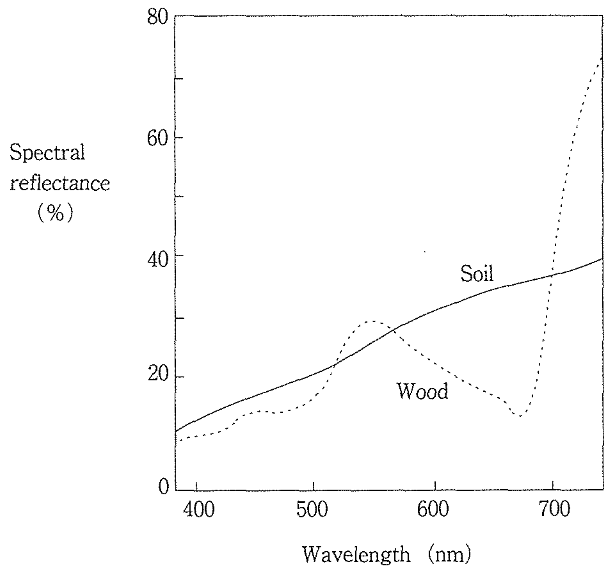

Fig. 1 Spectral reflectance distribution of soil and wood[2)3)]

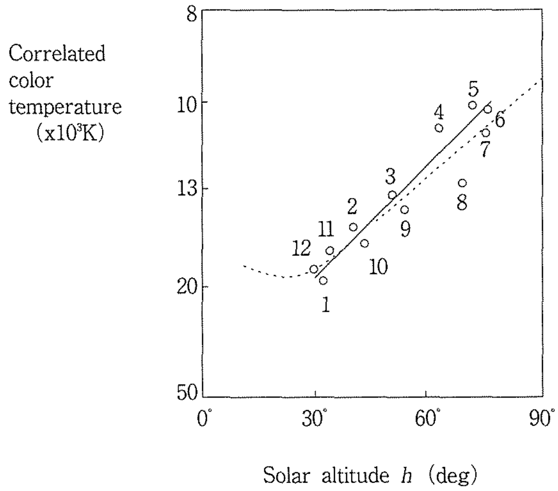

Fig. 2 Characteristic of monthly correlated color temperature of north sky light (altitude 45°) depending on solar altitude

Condition : clear sky (cloudness 0−2), at the meridian hour

Straight line : regression straight line

Broken line : characteristic curve of atmospheric transmittance of 0.70 obtained by numerical analysis

Number in Fig. : month

4. Characteristic of Spectral Distributions of Clear Sky Light

Fig.3 and Fig.4 show the spectral distributions of clear

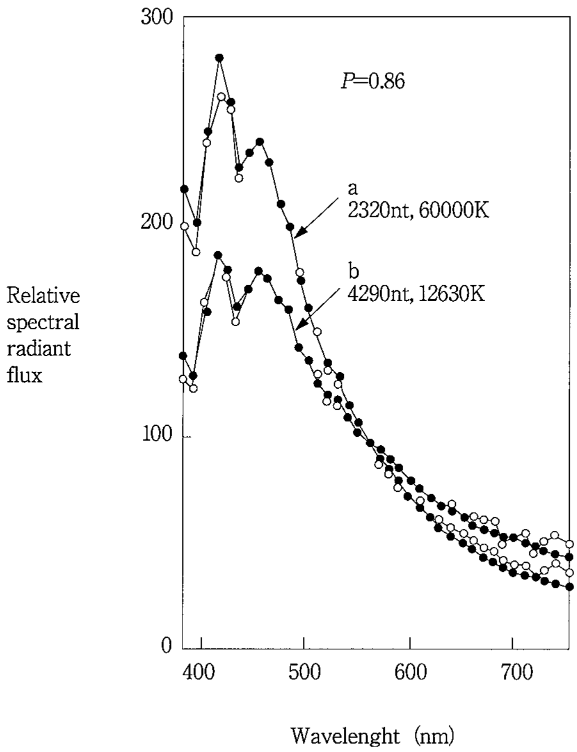

Fig. 3 Spectral distribution of clear sky light obtained by numerical analysis
Condition :
Atmospheric transmittance $P=0.86$
Solar altitude $h=50°$
Sky direction (altitude θ, azimuth from solar direction ψ)
For spectral distribution a ($\theta=30°$, $\psi=180°$)
For spectral distribution b ($\theta=60°$, $\psi=0°$)
● mark : Spectral distribution obtained by numerical analysis
○ mark : Spectral distribution CIE daylight of the same color

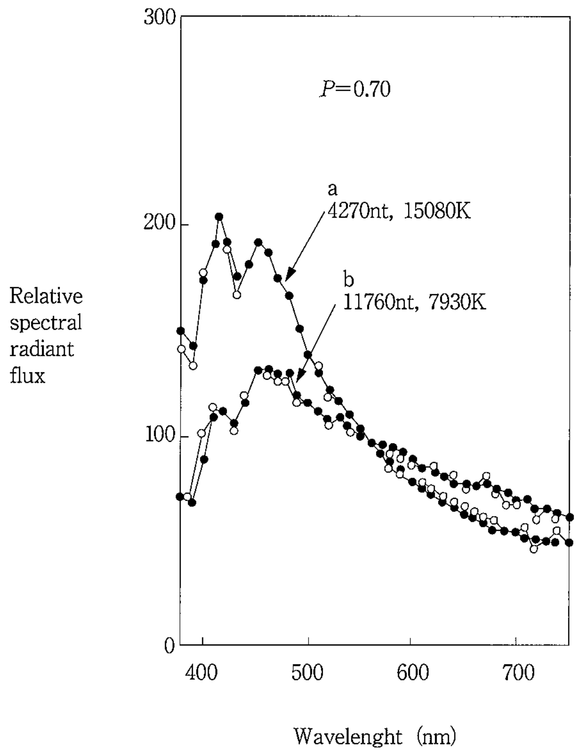

Fig. 4 Spectral distribution of clear sky light obtained by numerical analysis
Condition :
Atmospheric transmittance $P=0.70$
Solar altitude $h=50°$
Sky direction (altitude θ, azimuth from solar direction ψ)
For spectral distribution a ($\theta=30°$, $\psi=180°$)
For spectral distribution b ($\theta=60°$, $\psi=0°$)
● mark : Spectral distribution obtained by numerical analysis
○ mark : Spectral distribution CIE daylight of the same color

sky light obtained by numerical analysis by using the Thekaekara's measurement value[7] recommended by CIE for the value of spectral radiant flux of solar radiation outside of the atmosphere. Fig.3 is an example of $P=0.86$ and Fig.4 is an example of $P=0.70$. As far as the aerosol density is concerned, the aerosol density at $P=0.86$ is only about 0.06 times the aerosol density at $P=0.70$[1].

In order to compare the spectral distributions obtained by numerical analysis with actually measured spectral distributions, the spectral distributions of CIE reconstituted daylight of the same chromaticity are shown together in these figures.

Since the molecular extinction by O_2 and H_2O is not taken into account for the spectral distributions obtained by numerical analysis, it is more smooth at the long wavelenth range than the spectral distributions of CIE reconstituted daylight. However, both characteristics are agree well with each other essentially. Therefore, the characteristic of the variation of specatral distributions of actual clear sky lightwill be explained by the studies of the representative spectral distributions obtained by numerical analysis. The representative spectral distributions of cloudless sky light obtained by numerical analysis on the cloudless sky having a mean atmospheric transmittance $P=0.70$ are shown in Fig. 5, Fig. 6 and Fig. 7. Fig. 5 shows how the spectral distribution of sky light from the cloudless sky component in the zenith direction ($\theta=90°$) changes according to the solar altitude h. Fig. 6 shows how the spectral distribution of sky light from a cloudless sky component near horizon with an altitude $\theta=10°$ and an azimuth of 180° from the sun changes according to h. Fig.7 shows how the spectral distribution of sky light from each sky component along a great circle passing through sun and zenith changes according to angular distance γ from the sun, provided at $h=50°$.

4.1 Characteristic of Variation Depending on Aerosol Density

When the aerosol density is raised, the atmospheric transmittance will decrease. Then, the clear sky light will lose its blueness and get whiteness. This phenomenum is

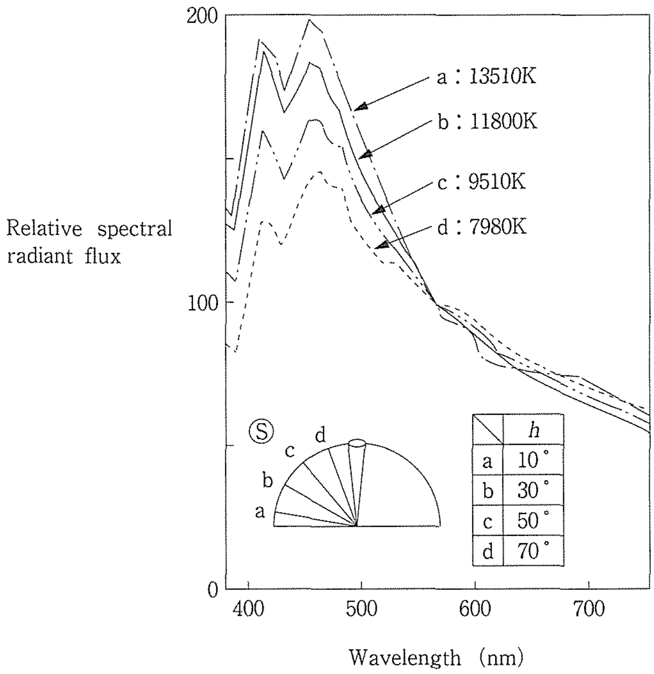

Fig. 5 spectral distribution of clear sky light obtained by numerical analysis
Atmospheric transmittance P=0.70
Ⓢ : Solar direction (altitude h)
Sky direction : Zenith
(altitude h=90°)

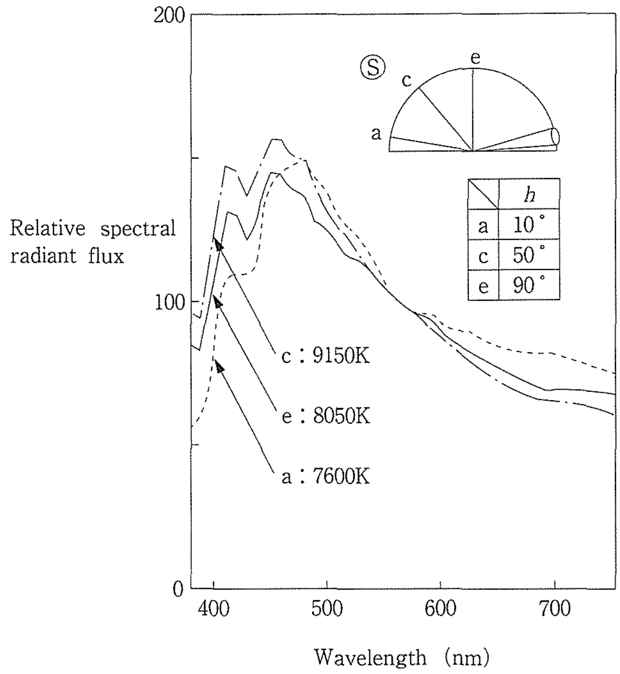

Fig. 6 spectral distribution of clear sky light obtained by numerical analysis
Atmospheric transmittance P=0.70
Ⓢ : Solar direction (altitude h)
Sky direction : Altitude θ=10°, azimuth from the sun (altitude h=90°)

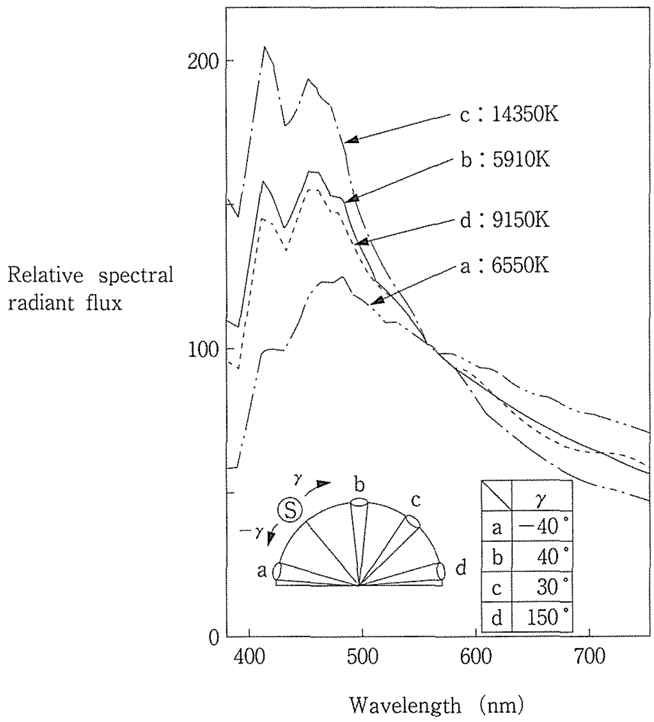

Fig. 7 spectral distribution of clear sky light obtained by numerical analysis
Atmospheric transmittance P=0.70
Ⓢ : Solar direction (altitude h=50°)
Sky direction : (angular distance from the sun γ)

well known by experience.

The intensity of scattered light by air is inversely proportional to 4th power of wavelength, therefore the shorter the wavelength, the higher the light intensity[8]. On the other hand, the intensity of scattered light by aerosol is inversely proportional to about 0.82 power of wavelength[1]. Consequently the higher the aerosol density, the higher the ratio of the radiant flux at long wavelength range to the radiant flux at short wavelength range, as far as the spectral radiant flux distribution of clear sky light is concerned. As a result, the CCT of clear sky light will be lowered. Such a characteristic is obvious from Fig. 3 and Fig. 4, if compared.

4.2 Characteristic of Variation Depending on Solar Altitude and Angular Distance from the Sun

The variation of clear sky light depending on the solar altitude h and angular distance γ from the sun depends on the directive characteristic of atmospheric scattering and the air mass (relative optical air mass)[8].

(1) The light transmitted through the atmoshpere is scattered. The directive characteristic of scattering is different between by air and by aerosol. The intensity of scattered light by air has the same rate in forward and backward scattering[8] but the intensity of scattered light by aerosol has an extremely higher rate in the forward scattering than in the backward scattering[1]. The wavelength characteristic of the intensity of scattered light is different between by air and by aerosol. The intensity of scattered

light by air is inversely proportional to 4th power of wavelength and the intensity of scattered light by aerosol is inversely proportional to about 0.82 power of wavelength.

Therefore, the higher the aerosol density, the stronger the intensity of forward scattered light, consequently in the spectral radiant flux distributions of scattered light the rate of the radiant flux distributions of scattered light at long wavelength range to the radiant flux at short wavelength range is higher in proportion to the increase of aerosol density. As a result, the primary scattered light of sunlight which is the main component of clear sky light has such directive characteristic that in the scattering region of $90° < \gamma < 120°$ the ratio of the radiant flux at long wavelength range to the radiant flux at short wavelength range is most low, in the forward scattering region of $\gamma < 90°$ the ratio rapidly increases according to the decrease of γ and in the backward scattering region of $\gamma > 120°$ the ratio slightly increases according to the increase of γ [1].

(2) The light transmitted through atmosphere is attenuated by scattering. Relating to the attenuation of transmitted light, the higher the aerosol density, the more the radiant flux at long wavelength range is attenuated and the longer the relative optical air mass, the more prominent the attenuation at short wavelength range than the attenuation at long wavelength range[1].

The variation of spectral distributions of clear sky light depending on the solar altitude will be described in accordance with Fig. 5 and Fig. 6.

As obvious from Fig. 5, the CCT of cloudless sky light from the sky component in the zenith direction is the highest when the sun is positioned in the horizontal direction and decreases monotonously according to the increase of h. That is because in the forward scattering region of $\gamma < 90°$ the primary scattered light of sunlight which is the main component of clear sky light increases the ratio of the radiant flux at long wavelength flux to the radiant flux at short wavelength range according to the decrease of γ.

On the other hand, as obvious from Fig. 6, the CCT of cloudless sky light from a sky component near the horizon in the direction opposite the sun is the highest at $30° < h < 50°$ and decreases in either case of higher or lower h. That is resulted from the following reason. The angular distance γ of sky compoment near the horizon in the direction opposite the sun is the lowest when the sun is positioned in zenith and increases according to the decrease of h. The primary scattered light of sunlight which is the main component of clear sky light decreases the ratio of the radiant flux at long wavelength range to the radiant flux at short wavelength range according to the increase of γ and is the lowest in the region of $\gamma = 90°$ to $120°$. Then, in the backward region of $\gamma > 120°$ the ratio slightly increases again. Furthermore, the sky light from a clear sky component in the direction of $\gamma = 90°$ to $120°$ has the lowest intensity of primary scattered light so that the rate of higher order scattered light, in which the ratio of the radiant flux at long wavelength range to the radisnt flux at short wavelength range is lower than that of primary scattered light, is the highest. Resultantly, the CCT of sky light from a clear sky component in the direction of $\gamma = 90°$ to $120°$ is the higrest.

Now, the variation of spectral distributions of clear sky light depending on the angular distance γ from the sun will be described according to Fig.7. The spectral distribution b, c, d has $\gamma = 40°, 80°, 120°$ and the CCT of 9510K, 14350K, 9150K, respectively, in this order and the CCT is exceedingly higher in c than in b or d. Furthermore, both absolute angular distance $|\gamma|$ of a and that of b are $40°$ but the CCT of a is 6550K which is lower than that of b.

The spectral distribution b will be measured in the forward scattering region nearer to the sun than c, so that the CCT of b is lower than that of c. On the other hand, since the spectral distribution d will be measured in the backward scattering region, the air mass is longer in d by 4.3 times than in c, so that the CCT of d is lower than that of c. The CCT of a is lower than that of b which has the same $|\gamma|$, because the air mas is longer in a by 4.3 times than in b. Also, the CCT of a is lower than that of d which has the same air mass as a and the longer mean transmission distance of scattered light because d is positioned in the backward region on one hand and a is positioned in the forward region on the other hand.

In Fig. 5, the spectral distribution a has a flat portion at the long wavelength range which is different from the other spectral distributions. In Fig. 6, the spectral distribution a is attenuated extremely at the short wavelength range below 480nm compared with the other spectral distributions and has different distribution at the long wavelength range from others. Such characteristics are resulted from the fact that the solar direction is near the horizon where the air mass is very long. Such characteristics appear remarkably in the spectral distributions of daylight measured when the solar altitude is actually $10°$ or less[9].

4.3 Characteristic of Variation of Reflected Light from Ground Surface

Concerning the reflected light from the ground surface, (1) the higher the solar altitude, the more it has an effect on the clear sky light, (2) the nearer to the horizon the clear sky component, the more it has an effect on the sky light from the clear sky component, and (3) the variation of aerosol density has little effect on the variation of clear sky light by the reflected light from the ground surface[1]. Fig. 8 (a) shows the spectral radiant flux distributions of scattered light of sunlight generated by atmospheric scattering without including the reflected light from the ground surface. Fig. 8 (b) shows the spectral radiant flux distributions of scattered light generated by repeating reflection of sunlight and its scattered light by the ground surface and scattering by atmosphere. The spectral radiant flux distributions of clear sky light are the sum of these two spectrl radaiant flux distributions. These relative spectral radiant flux distributions are those shown in Fig. 7. In the spectral radiant flux distributions shown in Fig. 8 (b), the feature of (2) as abovementioned is noticed obviously.

In addition, the reflected light from the ground surface has following effects on the clear sky light. (4) Generally, the longer the wavelength, the higher the spectral reflectance of the ground surface (see Fig. 1). Consequently, by an effect of reflected light from the ground surface, the CCT of clear sky light is lowered over entiere sky. (5) The reflected light from the ground surface has a more effect for lowering the CCT of sky light from the clear sky compornent in the horizontal direction than in the zenith direction.

The spectral radiant flux distributions vary according to the different main structures on the ground or the different state of the ground surface. For example, the spectral reflectance of wetted soil is approximately half of that of dried soil[2], so that the CCT of clear sky light becomes higher after rainfall.

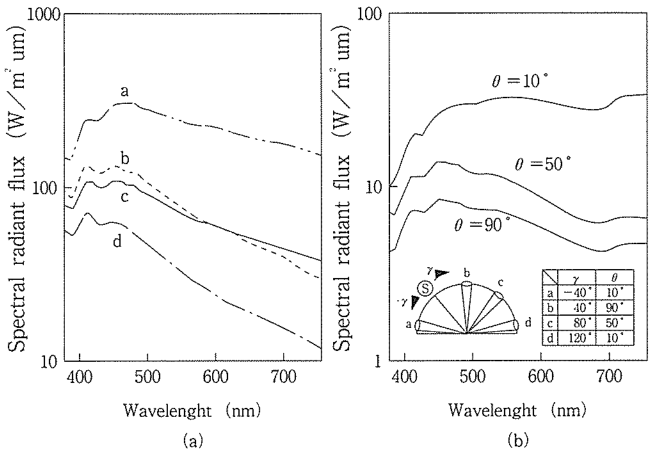

Fig.8 (a) Spectral radiant flux distribution of scattered light of sunlight ; and
(b) Spectral radiant flux distribution of scattered light of reflected light from the ground surface
Atomspheric transmittance P=0.70
S : Solar direction (altitude h=50°)
Sky direction : Altitude Angular distance from the sun
Sky direction a, b, c, d in Fig. 8 (a) correspond to a, b, c, d i Fig. 8 (b), respectively.

5. Varaiation of Chromaticities of Clear sky Light

In 1964, CIE determined the daylight chromaticity locus, the chromaticity locus of CIE daylight, and established a method for calculating the spectral distribution of daylight with an arbitraty chromaticity, the spectral distribution of CIE reconstituted daylight, and furthermore adopted that of D_{55}, D_{65}, D_{75}, with the CCT of 5500K, 6500K, 7500K, respectively. This is based on the measurement results obtained by judd et al in Britain, Canada and North America[10]. The chromaticities of daylight measured by Judd et al are distributed in the neighborhood of green side along the chromaticity locus of full radiator and the mean chromaticity locus (The chromaticity locus of CIE daylight) is approximately parallel to the chromaticity locus of full radiator. Thereafter, a number of measurement results of the spectral distributions and chromaticities of daylight was reported in domestic and overseas. Although these chromaticity distributions are similar to the distributions of Judd et al, the chromaticity locuses cross with the chromaticity locus of CIE daylight so that the chromaticity distributions are liable to be shifted into the green side of chromaticity locus of CIE daylight in the higher CCT region and into the purple side in the lower CCT region[11].

In this chapter, the variation of chromaticities of clear sky light will be described. Fig.9 (a), (b), (c) show the chromaticity distributions of sky light from cloudless sky components in the sky direction along a great circle passing through sun and zenith at the solar altitude of h=90°, 50°, 20°, respectively. The atmospheric transmittanc is P=0.70. Fig.10 shows the chromaticity distributions at P=0.86 and h=20°.
Fig.11 shows the chromaticity distribution at P=0.70 and h=90° when it is assumed that there is no reflected light at all from the ground surface.

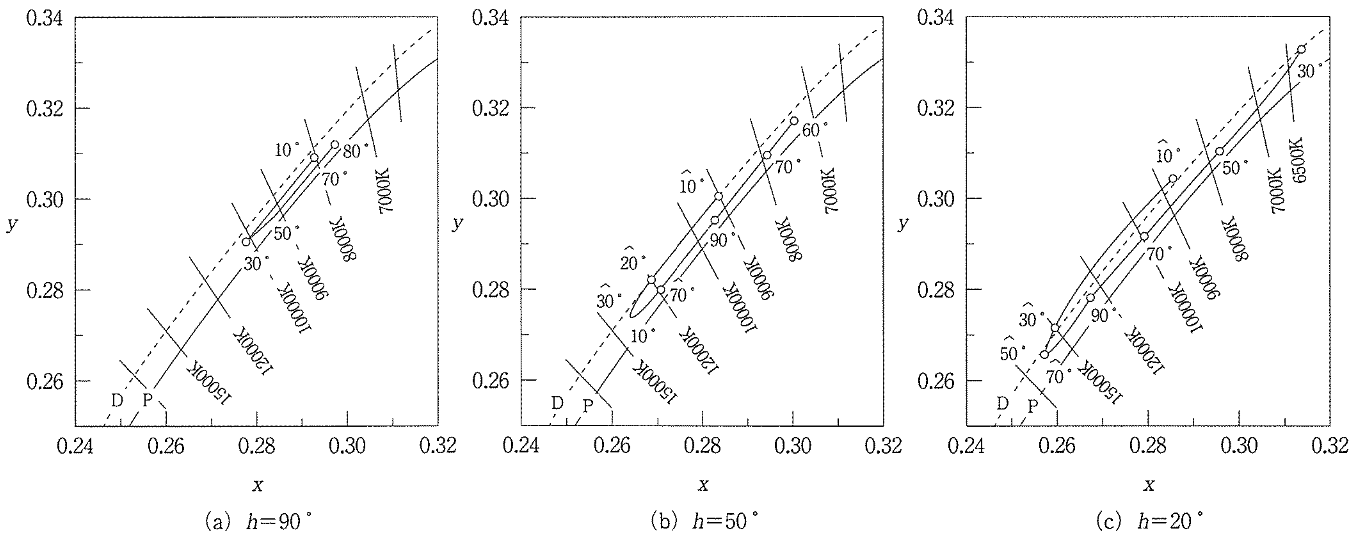

Fig. 9 Chromaticity distributions of clear sky light obtained by numerical analysis
Atmospheric transmittance P=0.70
Solar altitude : (a) h=90°, (b) h=50°, (c) h=20°
Sky altitude : Without∧ : azimuth from the sun ψ= 0°
With ∧ : azimuth from the sun ψ=180°
Solid line P : Chromaticity locus of full radiator
Broken line D : Chromaticity locus of CIE daylight

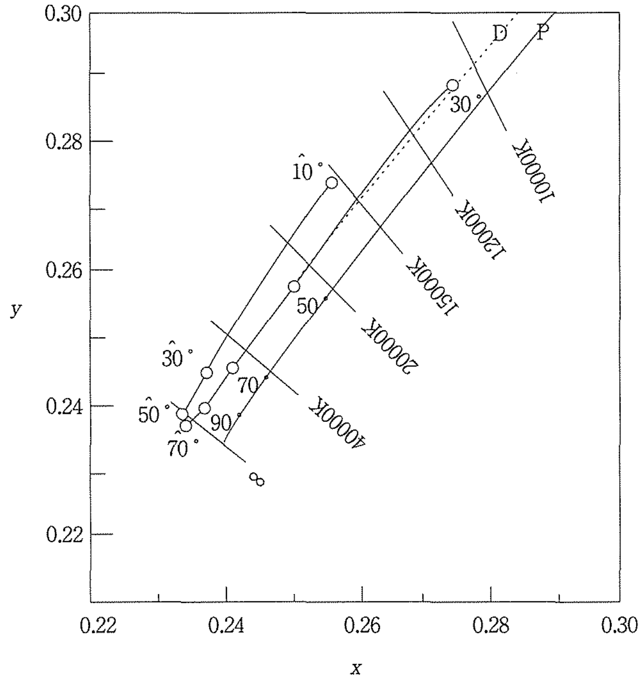

Fig. 10 Chromaticity distribution of clear sky light obtained by numerical analysis
Atmospheric transmittance P=0.86
Solar altitude : h=20
Sky altitude : Without ∧: azimuth from the sun ψ=0
With ∧: azimuth from the sun ψ=180°
Solid line P : Chromaticity locus of full radiator
Broken line D : Chromaticity locus of CIE daylight

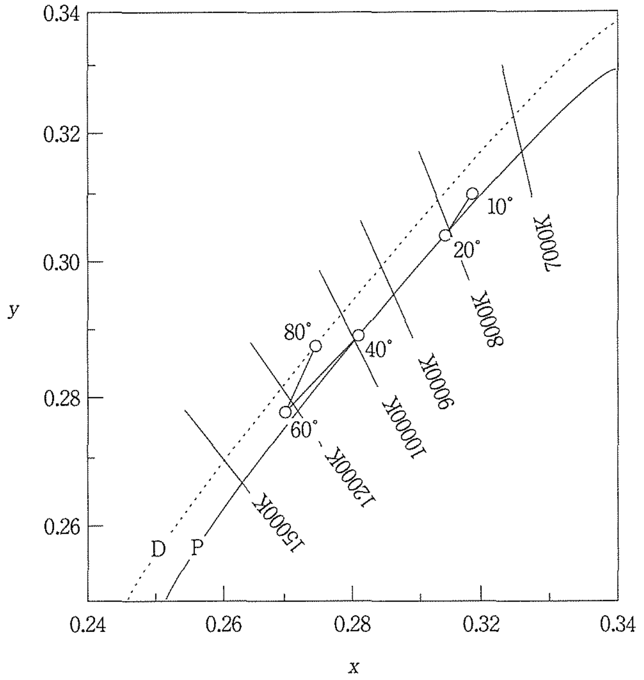

Fig. 11 Chromaticity distribution of clear sky light obtained by numerical analysis
Atmospheric transmittance P=0.70
Solar altitude : h=90°
Sky altitude : =10°—80°
Solid line P : Chromaticity locus of full radiator
Broken line D : Chromaticity locus of CIE daylight

5.1 Characteristic of Variation Depending on Aerosol

Now, the chromaticity distributions of Fig. 9 (c) and Fig.10 will be compared. When the aerosol density is low and the atmospheric transmittance is high, the range of chromaticity distribution of clear sky light into the direction along the chromaticity locus of full radiator becomes narrow, the chromaticity distribution being shifted into the generally higher temperature region and into the green side. Also, the angular distance γ of the cloudless sky component, in which the CCT reaches to maximum, from the sun becomes small.

The reason, why the chromaticity distributions of clear sky light are shifted into the green side when the aerosol density is lower and the atmospheric transmittance is higher, is explained as follows. Since the refractive index of air decreases slightly towards the longer wavelength, the wavelength (λ) characteristic curve of volumetric scattering coefficient of air forms a concave curve against a straight line of λ^{-4} on the semilogarithmic graph[1]. On the other hand, the wavelengrh (λ) characteristic curve of volumetric scattering coefficient of aerosol is a straight line of approximately $\lambda^{-0.82}$.[1] Therefore, when the aerosol density is lowered and the scattering by air is going to dominate, the attenuation of green component of the scattered light becomes relatively lower compared with the other wavelength components. As a result, in the clear sky light, the green component of the spectral radiant flux distribution becomes relatively higher, so that its chromaticity is shifted into the green side.

5.2 Characteristic of Variation Depending on Solar Altitude and Angular Distance from the Sun

Each chromaticity distribution of Fig. 9 will be described. When the sun is positioned in the zenith direction, the variation range of chromaticity distributions of clear sky light into the direction along the chromaticity locus of full radiator becomes most narrow and according to the lowering of solar altitude h the range of its chromaticity distribution become wide. That is to say that according to the lowering of h the CCT of sky light from a clear sky component near the solar direction becomes further lower and the CCT of sky light from a clear sky component opposite the sun will become much higher. If the angular distance of a sky component from the sun is expressed by γ, the γ at which the maximum CCT of clear sky light will be obtained is about 60° at minimum when the sun is positioned in the direction of zenith and is about 110° at maximum when the sun is positioned in the horizon direction. Such characteristics are explained as follows. (1) The scattered light has a higher ratio of the radiant flux at short wavelength range to the radiant flux at long wavelength range when the γ is smaller in the forward scattering region. (2) The attenuation of radiant flux of sky light from a clear sky component near the solar direction is larger at the short wavelength range than at the long wavelength range because the air mass becomes longer according to the lower solar altitude. (3) The higher the order of scattered light, the more uniform the scattering directive characteristic of scattered light due to a compensation of directive charcteristic. Also, the higher the order of scattered light, the lower the ratio of the radiant flux at long wavelength range to the radiant flux at short wavelength range. Therefore, the direction of clear sky component, in which the highest CCT will be obtained, is the direction,in which the intensity of primary scattered light having the strongest scattering directive characteristic will be minimum. In that direction, the ratio of the radiant flux of higher order scattered light to that of primary scattered light is the highest. (4) The nearer to the horizon the sky component, the rapidly longer the air mass in the horizontal direction, therefore the air mass in the horizontal direction being about 40 times the air mass in the zenith direction. Consequently, the nearer to the horizon the clear sky component, the rapidly lower the CCT of sky light from the clear sky component near the horizon direction. According to Fig.9 (c), the CCT of sky light from the clear sky component in the direction of about $\gamma = 110^\circ$ is the highest and its chromaticity is located on the chromaticity locus of CIE daylight. The chromaticity distribution of clear sky light is shifted into the purple side of the chromaticity locus of CIE daylight in the foward scattering region of $\gamma < 110^\circ$ and into green side in the backward scattering region of $\gamma > 110^\circ$. That is mainly because on th clear sky light the smaller the γ in the forward scattered region, the higher the rate of intensity of scattered light by aerosol and in the backward scattering region the rate of intensity of scattered light by air is dominating.

From the above-mentioned study, it can be concluded that concerning the chromaticity distribution of north sky light at the merridian hour there will be discovered the following differences between in high latitudes and in low latitude.

(1) The mean solar altitude at the meridian hour in high latitudes is lower than in low latitudes. Therefore, the mean value of angular distance γ of north sky light from the sun in high latitudes is longer than in low latitudes. Cnosequently the chromaticities of north sky light in high latitudes are distributed up to higher CCT region than in low latitudes.

(2) It is because the aerosol density is low that the chromaticities of north sky light in low latitudes are distributed up to higher CCT region in the same or higher degree as in high latitudes. Therefore, in the chromaticity distribution region having a higher CCT, it is most probable that the chromaticities of north sky light in high latitudes are distributed into the purple side than in low latitudes. On the other hand, since the mean solar altitude at the meridian hour is lower in high latitudes than in low latitudes, the rate that a north sky component obtains the angular distance from the sun $\gamma > 90^\circ$, i. e., the frequency of appearance of backward scattering region,is higher in high latitudes than in low latitudes. As a result in the chromaticity distribution region having a lower CCT, it is most probable that the chromaticities of north sky light in high latitudes are distributed into the green side than in low latitudes. That is to say that in high CCT region the chromaticities of north sky light in low latitudes are distributed with a shift into the green side and in low CCT region with a slight shift into the purple side compared with the distribution in high latitudes.

There is found such a characteristic in each chromaticity distributions of CIE dalylight[10], Japaneses daylight[12] and Pretorian daylight[13].

5.3 Characteristic of Variation Depending on Reflected Light from Ground Surface

By comparing Fig.9 (a) and Fig.11, there is understood a characteristic of variation of clear sky light depending on the reflected light from the ground surface as described in 4.3. As obvious from the directive characteristic of scattering[1], the intensity of primary scattered light of sunlight which is the main component in the clear sky light is the strongest in the sky light from a clear sky component near the solar direction, becomes weaker according to the increase of angular distance γ from the sun, is the weakest approximatelly at $\gamma = 110^\circ$ and then goes to be stronger slightly according to further increase of γ. Therefore, the reflected light from the ground surface has little effect on the sky light from a clear sky component near the solar direction but has a great effect on the sky light from a clear sky component having a large γ. Resultingly, the higher the reflectance of the ground surface, the narrower the chromaticity distribution range of clear sky light and the CCT of clear sky light will be lowered over the entire sky. The higher the solar altitude, the more outstanding such a characteristic. Therefore, the clear sky light in low latitudes, where the mean solar altitude is higher than in high latitudes,will receive more strongly the effect of reflected light from the ground surface, the reflected light having an effect for lowering the CCT, than in high latitudes.

6. Chromaticity Distribution of Total Sky Light

As described in the above, the chromaticities of clear sky light from a clear sky component depend on the direction of the clear sky component to a great extent. One of its main factors is resulted from the differense of angular distance γ from the sun. However, there will not be discovered any variation resulted from γ in the chromaticities of total sky light from the all sky components of clear sky. That is because the total clear sky light is obtained by integrating all of sky light from clear sky component falling on a horizontal surface of the ground over all γ, i.e., over all sky components.

The chromaticities of total cloudless sky light at the solar altitude $h=90^\circ$, 50°, 30°, 20° were obtained by numerical analysis for the case including the sunlight and for the case not including the sunlight, respectivily. Their chromaticity distributions are shown in Fig.12. The chromaticity distributions of total cloudless sky light including the sunlight vary only slightly according to a large change of aerosol density and the chromaticities are distributed in the neighborhood of green side of chromaticity locus of full radiator with the CCT of about 6000K. On the other hand, chromaticities of the total cloudless sky light not including the sunlight vary largely according to the aerosol density in such a behavior that at usual atmospheric transmittance

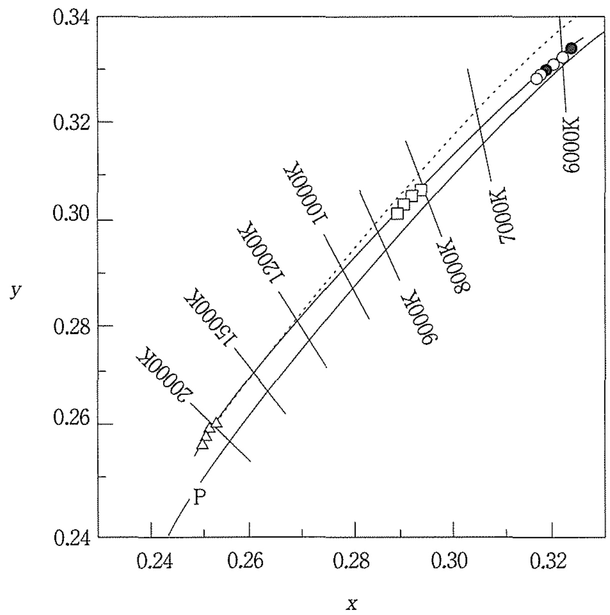

Fig. 12 Chromaticity distribution and chromaticity locus of clear sky light obtained by numerical analysis
● : P=0.70 Total sky light + sunlight ;
□ : P=0.70 Total sky light ;
○ : P=0.86 Total sky light + sunlight ;
△ : P=0.86 Total sky light ;
Solid line P : Chromaticity locus of full radiator
Broken line D : Chromaticity locus of CIE daylight

P=0.70 the chromaticities are distributed approximately at the middle between chromaticity locus of full radiator and chromaticity locus of CIE daylight with the CCT of about 8500K and at P=0.86 when the aerosol density is very low the chromaticities are distributed in the neighborhood of green side of chromaticity locus of CIE daylight with the CCT of 20000K. Furthermore, all of chromaticities (x, y) are distributed on the curve expressed by the equation (1) without any variation in the direction of green-purple (direction along isotemperature line) relating to γ.

$$y=2.026x-1.713x^2-0.142 \cdots\cdots (1)$$

There is a report describing the spectral distributions and the chromaticity distributions of total cloudless sky light measured in Australia[14]. In that chromaticity distribution, the characteristic of Fig.12 is represented remarkably. The width of chromaticity distribution in the direction of green-purple is very narrow compared with the width of chromaticity distributions of CIE daylight and both of its chromaticity locus and the chromaticity locus shown in Fig.12 are parallel while the former is shifted to green side a little.

The fact that the chromaticity locus measured in Australia is shifted a little to purple side compared with the analysis result is explained by the fact that the measured spectral distributions have a relatively higher rate of spectral radiant flux at long wavelength range above 600nm than the spectral distribution of CIE daylight with the same chromaticity. It is estimated that it is because the district where the measurement was performed was covered by the ground surface such as satelite soil having a high reflectance at the long wavelength range above 600nm[2].

In Tanashi-Cith (Tokyo), an total clear sky light including sunlight was measured. The result shows that its mean CCT is about 5900K, its chromaticities are distributed concentratedly in the neighborhood of green side of full radiator and its mean chromaticity locus agrees approximately with the chromaticity locus of Fig.12[15].

As described in 5.2, the difference of chromaticity distribution in the low CCT of north sky light between in high latitudes and in low latitudes relates to the angular distance γ of sky components from the sun. On the other hand, since the total clear sky light is the light condensed from all of sky components, its chromaticity distribution do not produce any difference relating to γ. Since the aerosol density and the mean spectral reflectance distribution of the ground surface are different place by place, the mean chromaticity locus of total clear sky light is also different place by place. However, in the chromaticity locus of total clear sky light, there is hardly seen any difference relating to the latitude, this case being different from the case of north sky light.

From the above description, it can be estimated that the chromaticity locus of total cloudless sky light obtained by numerical analysis agrees well with that of the actual total clear sky light and the actual total clear unobstacled sky light including sunlight.

7. Conclusion

The relation between cause and effect of the variation of spectral distributions and chromaticities of clear sky light, which could not be solved without difficulty only by actual measurement results, was disclosed, as a result the following conclusions were obtained.

(1) The chromaticities of daylight in high latitudes are distributed up to the higher region of CCT than in low latitudes and many chromaticities of daylight in low latitudes are distributed at the low region of CCT compared with in high latitudes.

(2) The chromaticitis of north sky light in low latitudes are distributed slightly to green side at high CCT and a little to purple side at low CCT compared with the chromaticities of north sky light in high latitudes.

(3) In the chromaticity distribution of total clear sky light, the variation width in the direction of green-purple is narrow and there is hardly seen a difference depending on the latitude.

The numerical calculation was carried out by using the EDPS Center of Niigata University.

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