Estimation of Sea Surface Temperature from Remote Sensing in the $3.7\mu\text{m}$ Window Region

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Abstract

The diffusely reflected radiation in the daytime and diffusely transmitted radiation at night from an inhomogeneous, plane parallel planetary atmosphere bounded by the ocean surface was calculated at the $3.7\mu\text{m}$ infrared window region. In the daytime the effect of the solar radiation from top was taken into account. This spectral region corresponds to the channel 3 of the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA-6 satellite. Thus the deviation from the sea surface temperature (SST) was evaluated in the mid-latitude region in summer, where it is defined by the difference between the given surface temperature and the calculated brightness temperature obtained at the top of the atmosphere. The present study has dealt with the problem of no cloud contamination in data. In the atmosphere, water vapor, molecular nitrogen, nitrous oxide, carbon dioxide and methane as absorbent constituents and aerosols as the scattering constituent were taken into account. The ocean surface as a lower boundary was simulated by many facets whose slopes are according to the isotropic Gaussian distribution (Cox and Munk, 1955). The slope of the facet depends upon the ocean surface wind. The refractive index of the ocean surface as well as the aerosols in the atmosphere is assumed to be that of water by Hale and Querry (1973).

Computational results show that it is suitable for deriving the optical thickness in the direction of about 15° away from the specular direction. Hence the ocean surface temperature can be evaluated with the aid of the optical thickness thus derived, whereas the influence of the atmosphere to SST can not directly be estimated by the use of single channel of $11\mu\text{m}$ window region. On applying this result to the NOAA-AVHRR data (30°N , 147°E) on Aug. 2, 1979 together with the wind speed reported by ship, the very clear atmosphere simulates SST within the accuracy of $1\text{--}2^\circ\text{K}$ at the center of the sunglint and within the accuracy of 0.5°K in the rest of the region. This atmospheric condition agreed with the ship data of visibility. To discuss the accuracy further, comparison of the radiometric measurements of SST by ships with temperature measured by satellite is essential.

1. Introduction

In the wavelength region ranging from 10.5 to $12.5\mu\text{m}$, the atmosphere is relatively transparent, thereby being suitable for determining the surface temperature. However sea surface temperature measured by satellites is usually lower than the real ocean surface temperature. This is mainly due to the absorption by water vapor in the atmosphere, which is estimated to be from 4 to 8°K in the tropical region (Prabhakara *et al.*, 1974). This correction is carried out by the use of climatological data on water vapor and vertical temperature profiles in the atmosphere.

It might be reduced to about 2°K for a cloud free condition in the vertical direction from space. Unfortunately the accuracy of temperature thus derived is still far from that of the user's requirement (0.5°K). Therefore it is urgent to improve the remote sensing satellite techniques for measurements.

In the region ranging from $3.5\mu\text{m}$ to $4.0\mu\text{m}$, the effect of water vapor absorption is believed to be less than in the window region ($10.5\text{--}12.5\mu\text{m}$). In fact Weinreb and Hill (1980) found that the radiation is less affected in the $3.7\mu\text{m}$ region by the constituents than in the $11\mu\text{m}$ region. In our computations, using the method

by Weinreb and Hill (1980), the optical thickness in the $11\text{ }\mu\text{m}$ window region is 0.372 due to the absorbent constituents in the mid-latitude in summer, whereas it is 0.230 in the $3.7\text{ }\mu\text{m}$ region. Therefore this region is, in this regard, better for deriving the ocean surface temperature. However to improve the temperature measurements to the accuracy of 0.5°K , even if the cloud free condition is permitted, the additional factors should be taken into account. Besides water vapor, molecular nitrogen and uniformly mixed gases such as nitrous oxide, carbon dioxide and methane as absorbent constituents and aerosols as the scattering constituent might affect the accuracy (Farmer and Houghton (1966), Shapiro and Gush (1966), McClatchy *et al.* (1972) and White *et al.* (1978)). In addition, the effect of the ocean surface emissivity should also be investigated for the further improvement. In the daytime, temperature deviation (ΔT) is quite large, particularly in the sunglint due to the solar radiation reflected directly by the surface. Temperature deviation is defined by the difference between the brightness temperature obtained at the top of the atmosphere and the given surface temperature. Therefore so far it is limited to use the night time data only for the temperature investigation at the $3.7\text{ }\mu\text{m}$ region. However the NOAA-6 satellite provides us the useful data regarding to the ocean surface temperature both in the daytime and at night by the channel 3 of the AVHRR. Therefore as a data utilization, it is worth while to investigate whether the correction of SST is possible or not to the required accuracy. In this paper, temperature deviation due to the atmospheric constituents and due to the surface condition is investigated in the daytime and at night. Furthermore, the optical thickness is derived in the sunglint and is applied to the investigation of SST. Toward the end the combined use of daytime data and night time data is also undertaken for the improvement of SST.

2. Model atmosphere-ocean surface

In the atmosphere, water vapor, molecular nitrogen and the uniformly mixed gases such as nitrous oxide, carbon dioxide and methane were taken into account as the absorbent constituents, in addition to aerosols as the scattering constituent. The mixing ratio of these constituents were given by McClatchy *et al.* (1972). The vertical temperature, pressure and water vapor concentration profiles are those of the U.S.

standard atmosphere in 1962 in mid-latitude region in summer. The ocean surface temperature and the solar temperature were assumed to be 294°K and 5800°K ($1.94\text{ ly}\cdot\text{min}^{-1}$), respectively. As for aerosols, visibility of the atmosphere is 23 km (clear) and 5 km (hazy), respectively defined by McClatchy *et al.* (1972). The size distribution of the aerosols was also given by the authors ($0.1\text{ }\mu\text{m} \leq n(r) \leq 10.0\text{ }\mu\text{m}$), where the aerosol size distribution function for both models is the same at all altitudes. The lower boundary (ocean surface) was simulated by many facets whose slopes are according to the isotropic Gaussian distribution (Cox and Munk, 1955). Upon computations, we divide this spectral region into 6 sub-intervals with $0.1\text{ }\mu\text{m}$ width, where the response function of the AVHRR channel 3 (Lauritson *et al.*, 1979) is integrated over the width. On estimating radiation observed by the AVHRR radiometer, these averaged response function were used.

The total amount of energy received from the sun on a unit surface perpendicular to the sun's rays is assumed to be 1.94 cal/min . Therefore the flux per unit wavelength at $3.7\text{ }\mu\text{m}$ is calculated to be $0.001192\text{ watts}\cdot\text{cm}^{-2}\text{ }\mu\text{m}^{-1}$ for the temperature of the radiating surface of the sun (5800°K), whereas it is $0.001140\text{ watts}\cdot\text{cm}^{-2}\text{ }\mu\text{m}^{-1}$ for 5900°K . This difference causes the evaluation of temperature particularly at the center of the sunglint. At $3.7\text{ }\mu\text{m}$ with wind speed of 1 m/sec under a clear condition, ΔT is 49.31°K for 5800°K at the sun nadir angle of 8.5° , while it is 48.14°K for 4900°K . The difference is 1.17°K . But outside the sunglint, this difference does not show any appreciable value (less than 0.05°K). Therefore unless the solar constant change, the temperature of the sun does not affect the radiation investigation.

On calculating the transmittance of the absorbent constituents (20 cm^{-1} width), the method by Weinreb and Hill (1980) was adopted. The computational procedure of the radiative transfer in the atmosphere-ocean surface was followed by Takashima *et al.* (1977).

3. Computational results and discussions

(a) Optical thickness and emissivity

Fig. 1 shows the optical thicknesses of the atmospheric constituents in the $3.7\text{ }\mu\text{m}$ window region with 20 cm^{-1} spectral intervals, which was calculated by using the method described in Weinreb and Hill (1980) for absorbing constituents, and by using the Mie's theory for

Fig. 1 Total optical thickness of the atmospheric major constituents in the $3.7\text{ }\mu\text{m}$ region (mid-latitude in summer). (1) Total of (2)-(6), (2) H_2O (line), (3) H_2O (self), (4) H_2O (foreign), (5) N_2 , (6) uniformly mixed gases and the shaded area is due to aerosols. The upper and lower boundaries represent hazy and clear conditions, respectively.

aerosols. The optical thickness calculations include the effects of water vapor lines and continua, the collision-induced N_2 band near $4\text{ }\mu\text{m}$, the uniformly mixed gases such as CO_2 , CH_4 and N_2O and aerosols. The optical thicknesses are strongly dependent on wavelength. Between $3.5\text{ }\mu\text{m}$ and $3.8\text{ }\mu\text{m}$, water vapor line absorption dominates. Throughout the $3.7\text{ }\mu\text{m}$ window there is also a small contribution from water vapor continuum. The center of molecule nitrogen absorption is located at $4.2\text{ }\mu\text{m}$, which affects in the longer wavelength region. Among the uniformly mixed gases, nitrous oxide contributes at the band near $3.89\text{ }\mu\text{m}$ (2570 cm^{-1}) and methane does at the band near $3.55\text{ }\mu\text{m}$ and $3.85\text{ }\mu\text{m}$. Near $4.17\text{ }\mu\text{m}$ (2400 cm^{-1}) carbon dioxide dominates, but it rapidly loses its strength toward shorter wavelength. The vertical profiles of temperature and the atmospheric constituents are given by the model of mid-latitude in summer and model of aerosol's clear and hazy conditions, given by McClatchey *et al.* (1972). On deducing the optical thicknesses, the total atmospheric layer is divided into nine layers, in which each

layer is consist of 14 homogeneous sublayers for absorbing constituents with about 8 mb thickness.

On calculating the transmittance of water vapor line absorption, the method treats the atmosphere as a succession of homogeneous layers, in each of which the pressure, temperature, and mixing ratio are constant. Over the path between the top and the bottom of the atmosphere, the transmittance is computed from the function of the layer's total pressure and temperature, and a scaled value of the water vapor amount, for which the form are expressed by a polynomial representation similar to that suggested by Smith (1969), of these values, using the technique of Weinreb and Neuendorffer (1973). For the transmittance of the two continua of water vapor absorption (self and foreign), the transmittance functions were taken from Burch *et al.* (1971). For continuum absorption of water vapor, the knowledge is poor so that the degree of absorption may be under-estimated by three times (White *et al.*, 1978). The functions for deriving the transmittance of molecule nitrogen in homogeneous sublayers were given by Weinreb and Hill (1980), which come from the results of Burch *et al.* (1971), and Susskind and Searl (1977) by the use of the data by Shapiro and Gush (1966) and Farmer and Houghton (1966). For uniformly mixed gases such as CO_2 , N_2O and CH_4 , the method of the calculations was taken from McClatchey *et al.* (1972) and Selby *et al.* (1978).

For precise derivations of optical thicknesses, it is necessary to calculate the radiation at a large number of closely spaced intervals in the region. However it requires prohibitantly long computer time if the radiation was calculated with scattering processes with 20 cm^{-1} spectral intervals over the $3.7\text{ }\mu\text{m}$ channel. Thereby for the radiation computations in this report, first of all, the optical thicknesses of nine layers were calculated at the central wavelengths ranging from $3.5\text{ }\mu\text{m}$ to $4.0\text{ }\mu\text{m}$ with $0.1\text{ }\mu\text{m}$ width, except at $3.5\text{ }\mu\text{m}$ where it is averaged over from 3.46 to $3.55\text{ }\mu\text{m}$, by integrating the 20 cm^{-1} interval data over the $3.7\text{ }\mu\text{m}$ region. These optical thicknesses are shown at Table 1. The 8-th column of the Table shows the averaged optical thicknesses weighted by filter response of the AVHRR. In the remainder of this paper, these averaged optical thicknesses with $0.1\text{ }\mu\text{m}$ spectral width are used in radiative transfer.

Table 2(a) shows the refractive index of water in the $3.7\text{ }\mu\text{m}$ window region, measured by Hale

Table 1 Optical thickness (τ) and transmittance (T_r) of the atmospheric constituents in the $3.7 \mu\text{m}$ window region (mid latitude in summer).

τ	$3.5 \mu\text{m}$	3.6	3.7	3.8	3.9	4.0	AVHRR (ch. 3)
water vapor (lines)	0.1345	0.1844	0.1788	0.1487	0.0327	0.0049	0.1349
(continuum)	0.0651	0.0511	0.0386	0.0302	0.0302	0.0376	0.0379
nitrogen molecule	0.0	0.0	0.0	0.0071	0.0341	0.1254	0.0117
minor constituents	0.0458	0.0113	0.0033	0.0106	0.1632	0.0303	0.0459
aerosol (clear)-(hazy)	0.0314– 0.1078	0.0289– 0.0993	0.0272– 0.0931	0.0257– 0.0880	0.0245– 0.0840	0.0235– 0.0806	0.0265– 0.0911
total (clear)-(hazy)	0.2768– 0.3532	0.2757– 0.3461	0.2479– 0.3138	0.2223– 0.2846	0.2847– 0.3442	0.2217– 0.2788	0.2569– 0.3214
T_r (clear)-(hazy)	0.7581– 0.7024	0.7590– 0.7074	0.7804– 0.7307	0.8007– 0.7523	0.7522– 0.7088	0.8011– 0.7567	0.7734– 0.7251

Table 2 (a) shows the refractive index of water in the $3.7 \mu\text{m}$ window region, measured by Hale and Querry (1973), and (b) shows surface emissivity variation in wind field, computed with the refractive index of water.

(a)

λ (μm)	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1
n	1.42	1.40	1.385	1.374	1.364	1.357	1.351	1.346
k	0.0195	0.0094	0.0052	0.0036	0.0034	0.0038	0.0046	0.0056

(b)

λ	$\theta=0$				40.6				76.1			
	$w=0$	5	10	15	0	5	10	15	0	5	10	15
3.5	0.972	0.972	0.972	0.973	0.967	0.966	0.965	0.963	0.745	0.773	0.794	0.808
3.7	0.975	0.975	0.975	0.976	0.970	0.969	0.968	0.967	0.752	0.779	0.800	0.814
3.9	0.977	0.977	0.977	0.977	0.972	0.971	0.970	0.969	0.758	0.783	0.804	0.818
4.1	0.978	0.978	0.978	0.979	0.974	0.972	0.971	0.970	0.762	0.786	0.807	0.821

and Querry (1973), and (b) surface emissivity variation in wind field, computed with the refractive index of water. It decreases with an increase of nadir angle of observations. It is 0.975 at the vertical direction at $3.7 \mu\text{m}$ in the case of specular surface, whereas it is 0.752 at the nadir angle of observation of 76.1° . It is noted that emissivity changes very little in the observation direction if the nadir angle of observation is less than 60° (not shown in this Table). For example, in the direction of 40.6° , emissivity changes only 0.1 percent with the change of wind speed from 0 m/sec to 5 m/sec. This difference could not cause the big change in temperature estimation of the ocean surface in the absence of the solar radiation (*i.e.* at night). In other words, the surface can be treated as a specular reflector. However in the daytime, the directly reflected radiation by the ocean surface depends

upon the probability of the ocean surface slopes which is defined by the orientations of the incident solar radiation and the reflected radiation. The probability of the reflected solar radiation to the observation direction is reduced dramatically in accordance with the Gaussian distribution of slopes, when it is away from the specular direction. Thus the directly reflected radiation is limited in the sun glint region.

(b) *Deviation from the ocean surface temperature in the absence of the solar flux at top*

Table 3(a) shows the computed temperature deviation (ΔT) from the ocean surface temperature (T) due to the effect of the major constituents in the atmosphere in the absence of the solar radiation from top. T is assumed to be 294°K which is representative value in mid-latitude in summer. Computations were carried out for 4

Table 3(a) Temperature deviation due to the atmospheric constituents and surface characteristics (emissivity) in the $3.7\text{ }\mu\text{m}$ window region, in the absence of the solar radiation from top (vertical direction). Temperature deviation is calculated for line absorption (L) and continuum absorption (C) of water vapor, absorption by N_2 and the other minor constituents in the absence of emission. Attenuation by scatterings is also shown for clear (c) and hazy (h) conditions. Contribution of surface emissivity is followed. The cases without any emission in the atmosphere is shown at the next (sum).

wav (μm)	3.5	3.6	3.7	3.8	3.9	4.0	AVHRR
water vapor (L)	2.801	3.935	3.922	3.356	0.766	0.199	2.675
(C)	1.363	1.102	0.857	0.688	0.706	0.901	0.812
N_2	0.	0.	0.	0.163	0.796	2.983	0.346
minor	0.961	0.245	0.073	0.241	3.775	0.727	1.251
aerosol (c)	0.659	0.625	0.603	0.585	0.573	0.564	0.593
(h)	2.248	2.132	2.056	1.997	1.956	1.926	2.021
wind 1 m/sec	0.591	0.570	0.558	0.547	0.543	0.541	0.555
5 m/sec	0.589	0.568	0.555	0.544	0.541	0.538	0.552
10 m/sec	0.582	0.561	0.548	0.538	0.535	0.533	0.546
sum c 1 m/sec	6.299	6.416	5.967	5.534	7.065	5.775	6.254
5 m/sec	6.279	6.414	5.964	5.531	7.063	5.772	6.252
15 m/sec	6.290	6.407	5.957	5.525	7.057	5.767	6.245
sum h 1 m/sec	7.834	7.870	7.373	6.904	8.393	7.093	7.634
5 m/sec	7.832	7.868	7.370	6.901	8.391	7.090	7.631
15 m/sec	7.825	7.861	7.363	6.895	8.385	7.085	7.625

different directions of observations. With the increase of nadir angle of observations, ΔT increases monotonically. It is 2.71°K , 2.84°K , 3.45°K and 4.97°K at the nadir angle of observations, 0° , 19.3° , 40.6° and 60° , respectively in the case of clear condition with wind speed of 1 m/sec in the AVHRR channel. Temperature deviation due to the absorbent constituents, aerosols and surface emissivity is also shown.

Among them the major individual factors to interfere the real ocean surface temperature are due to line absorption (2.7°K) and continuum absorption (0.8°K) of water vapor and minor constituents (1.3°K) at the vertical direction. In addition, the scatterings due to aerosols contaminate the value of surface temperature. Unfortunately the aerosol optical thickness changes in time and in space as other atmospheric constituents do. Two representative conditions, clear and hazy, are investigated. Their deviations are 0.6°K and 2.0°K , respectively. The another factor is due to the surface emissivity which is slightly different from a perfect black body radiator. It counts 0.55°K - 0.56°K depending upon the state of the surface, which is simulated by a function of wind speed at present. The

simple sum of these deviations due to attenuation by the atmospheric constituents and surface emissivity, reaches approximately $6\text{--}8^\circ\text{K}$ at the vertical direction. As the atmosphere bounded by the ocean surface (see Table 3(b)), it was found from the computations that ΔT ranges from 2.7°K to 3.8°K , for clear and hazy conditions, respectively. Hence ΔT is approximately less than a half in comparison with the case without emission in the atmosphere (6.3°K and 7.6°K for clear and hazy conditions, respectively). Therefore the atmospheric emission is very important for the investigation of SST. For the scatterings by aerosols, the deviation increases to an extent of 1.428°K from clear (0.593°K) to hazy (2.021°K) condition in attenuation calculations, whereas the deviation differs 1.07°K as a result of interaction of radiation. The reason of this difference comes from the fact that most of radiation is scattered to the forward direction by aerosols. Hence attenuation by aerosols tends to be over estimated if the Beer's law is simply adopted. In fact the asymmetry factor ranges from 0.70 to 0.73 in the $3.7\text{ }\mu\text{m}$ window region in our computations. Therefore this value of deviation is also exaggerative.

Table 3(b) Temperature deviation (ΔT) from the atmosphere bounded by the ocean surface. Where θ denote for the direction of observation.

wavelength (μm)			3.5	3.6	3.7	3.8	3.9	4.0	AVHRR
$\theta=0^\circ$	c	1 m/sec	2.64	2.54	2.36	2.28	3.67	2.98	2.71
		5 m/sec	2.63	2.52	2.35	2.27	3.65	2.97	2.69
		15 m/sec	2.63	2.53	2.35	2.27	3.65	2.97	2.69
	h	1 m/sec	3.75	3.63	3.45	3.36	4.69	4.01	3.78
		5 m/sec	3.74	3.62	3.43	3.34	4.68	4.00	3.76
		15 m/sec	3.74	3.62	3.44	3.35	4.68	4.00	3.77
$\theta=19.3^\circ$	c	1 m/sec	2.77	2.66	2.47	2.39	3.85	3.13	2.84
		5 m/sec	2.76	2.65	2.46	2.38	3.84	3.12	2.83
		15 m/sec	2.76	2.65	2.47	2.38	3.85	3.13	2.83
	h	1 m/sec	3.93	3.80	3.61	3.52	4.92	4.21	3.96
		5 m/sec	3.92	3.79	3.60	3.51	4.91	4.20	3.95
		15 m/sec	3.93	3.80	3.61	3.51	4.92	4.21	3.95
$\theta=40.6^\circ$	c	1 m/sec	3.36	3.22	3.00	2.90	4.71	3.82	3.45
		5 m/sec	3.36	3.23	3.00	2.91	4.72	3.83	3.46
		15 m/sec	3.41	3.27	3.05	2.96	4.76	3.88	3.50
	h	1 m/sec	4.72	4.57	4.34	4.24	5.97	5.11	4.77
		5 m/sec	4.73	4.57	4.35	4.24	5.97	5.11	4.77
		15 m/sec	4.78	4.62	4.39	4.29	6.02	5.16	4.82
$\theta=60.0^\circ$	c	1 m/sec	5.15	4.96	4.66	4.57	5.64	6.01	4.97
		5 m/sec	5.21	5.02	4.72	4.63	7.31	6.07	5.41
		5 m/sec	5.31	5.12	4.83	4.74	7.41	6.19	5.52
	h	1 m/sec	6.93	6.71	6.42	6.33	8.88	7.70	7.08
		5 m/sec	6.98	6.76	6.48	6.39	8.93	7.76	7.13
		15 m/sec	7.07	6.86	6.58	6.49	9.04	7.87	7.23

From another point of view, the effect of absorbent constituents can not be derived with the simple sum of the effect of the individual constituents under the condition that these behave independently without interaction of radiation, particularly in existence of scatterers. The effect of the individual constituents can be derived, therefore, in comparison of the computations with and without the specific constituent in the atmosphere. Table 3(c) shows the computational results that if the atmosphere is composed of aerosols only in the absence of absorbent constituents, where τ_a represents the aerosol optical thickness, ΔT is 1.10°K and 2.38°K for clear ($\tau_a=0.0272$) and hazy ($\tau_a=0.0931$) conditions with wind speed of 1 m/sec at the vertical direction, whereas if the atmosphere is composed of absorbent constituents only in the absence of aerosols, where τ_{abs} represents the optical thickness of the

absorbent constituents, ΔT is 1.86°K ($\tau_{\text{abs}}=0.2207$). As a function of optical thickness, the scatterings by aerosols affect the temperature deviation more than twice in comparison with that of absorbent constituents. In another word, aerosols affect the temperature deviation more than twice in comparison with the absorbent constituents if their optical thicknesses are the same. This is mainly due to the fact that the emitted radiation in the lower troposphere compensates the temperature deviation.

As the atmosphere is composed of both aerosols and absorbent constituents bounded by a perfect black surface, it results that ΔT is 1.95°K for a clear condition at the vertical direction and 3.69°K for a nadir angle of 60° . With the comparison of this deviation with that of the case that emissivity of the surface is taken into account, it shows that independent calculation

Table 3(c) Temperature deviation ($^{\circ}\text{K}$) in the case that the atmosphere is composed of either aerosols or absorbent constituents at the $3.7\text{ }\mu\text{m}$ window region. The results of a perfect black surface are also shown.

			0°	19.3°	40.6°	60.0°
aerosols only	clear	1 m/sec	1.10	1.13	1.37	2.57
		5 m/sec	1.08	1.12	1.38	2.64
		15 m/sec	1.08	1.13	1.44	2.76
	hazy	1 m/sec	2.38	2.49	3.03	4.94
		5 m/sec	2.37	2.48	3.04	5.00
		15 m/sec	2.37	2.49	3.09	5.12
absorbent only	1 m/sec		1.86	1.94	2.37	3.81
	5 m/sec		1.85	1.93	2.38	3.86
	15 m/sec		1.85	1.94	2.42	3.97
black surface	clear		1.95	2.06	2.52	3.69
	hazy		3.05	3.21	3.88	5.49
as a system	clear	1 m/sec	2.36	2.47	3.00	4.66
		5 m/sec	2.35	2.46	3.00	4.72
		15 m/sec	2.35	2.47	3.05	4.83
	hazy	1 m/sec	3.45	3.61	4.34	6.42
		5 m/sec	3.43	3.60	4.35	6.48
		15 m/sec	3.44	3.61	4.39	6.58

Table 3(d) The comparison of temperature deviation due to the surface emissivity. The first row and the second row show the difference between the case of black surface and that of the surface emissivity with wind speed of 1 m/sec for clear and hazy condition, respectively. The third row shows the independent deviation due to the surface emissivity at $3.7\text{ }\mu\text{m}$.

	0°	19.3°	40.6°	60.0°
clear	0.41	0.41	0.48	0.97
hazy	0.40	0.40	0.46	0.93
$\Delta T(\epsilon)$	0.56	0.56	0.67	1.54

of ΔT due to surface emissivity is 0.56°K with wind speed of 1 m/sec at the vertical direction, whereas the deviation difference between black surface and the surface where emissivity is taken into account, becomes 0.41°K (see Table 3(d)). This difference of 0.15°K is thought of as the contribution of the atmospheric radiation reflected directly by the surface. In other words, ΔT due to the surface emissivity is partly compensated by the presence of the atmospheric constituents. The difference becomes smaller with the increase

of the aerosol optical thickness, but the contribution of the reflected radiation by the surface is very small for the optical thickness of 0.3. It is only 0.01°K and 0.04°K at the vertical direction and 60° , respectively in terms of temperature deviation.

(c) Deviation from the ocean surface temperature in the daytime

Fig. 2 shows the intensity of the reflected solar radiation at $3.7\text{ }\mu\text{m}$ under the clear condition, where temperature of the sun is assumed to be 5800°K . The ordinate shows the intensity of the reflected radiation ($\text{watts cm}^{-2}\text{ }\mu\text{m}^{-1}\text{ st}^{-1}$) from the atmosphere bounded by the ocean surface in case of the sun nadir angle of 30° (wind = 1 m/sec), whereas the abscissa does the nadir angle of observation to the sun direction ($\phi=0$) and to the anti-sun ($\phi=180$) in the sun vertical. Intensity of the radiation in two other different azimuth from the sun vertical are also shown. Intensity at the specular direction is about $1.75 \times 10^{-4}\text{ watts cm}^{-2}\text{ }\mu\text{m}^{-1}\text{ st}^{-1}$. It decreases rapidly when the observation direction is away from the specular direction. It is less than $0.5 \times 10^{-5}\text{ watts cm}^{-2}\text{ }\mu\text{m}^{-1}\text{ st}^{-1}$ when the observation direction is 20° away from the specular direction. These computational results were confirmed by the following flux computation emerging from the atmosphere bounded by the ocean surface. For a pure specular surface, the flux of the reflected solar radiation is approximately $1.46 \times$

Fig. 2 Intensity of the reflected radiation at $3.7\text{ }\mu\text{m}$ under a clear condition ($\theta_0=30^{\circ}$, wind=1 m/sec), where θ_0 denotes for the nadir angle of the incident sun for different azimuth angles (ϕ).

10^{-5} watts $\text{cm}^{-2} \mu\text{m}^{-1}$ in case of the sun nadir angle of 30° , under the assumption of $\tau (=0.248)$ and the constant surface emissivity of 0.974, where the attenuation due to the atmosphere is taken into account, but emission and scattering are neglected. The flux of the reflected solar radiation at the wind speed of 1 m/sec can be obtained by the use of the results in Fig. 3(a) according to the computations of hemispherical integration of the reflected radiation,

$$\int_{2\pi} I(\Omega) d\Omega .$$

Roughly speaking,

$$\int_{2\pi} I(\Omega) d\Omega = 1.32 \times 10^{-5} \text{ watts cm}^{-2} \mu\text{m}^{-1}$$

where the solid angle $d\Omega$ is undertaken inside the conics defined by the direction of 20° away from the specular direction, where the rest of the energy outside the conics is assumed to be zero. The figure thus obtained is slightly lower than that of the specular case (1.46×10^{-5} watts $\text{cm}^{-2} \mu\text{m}^{-1}$). But allowing the amount of the reflected radiation outside the conics, the computational results are in good agreement.

This intense radiation reflected by the surface causes directly the sun glint at the $3.7 \mu\text{m}$ window region. Hence it is difficult to obtain the ocean surface temperature in the daytime by the use of remote sensing techniques from space. For a hazy condition ($\tau_{\text{tot}}=0.3138$ & $\tau_a=0.0931$), the intensity to the specular direction is reduced to the amount of 0.2×10^{-4} watts $\text{cm}^{-2} \mu\text{m}^{-1} \text{st}^{-1}$ in comparison with that of the clear condition, whereas it increases slightly outside the sun glint region. This is due to the scatterings by aerosols. The incident solar flux is scattered and transferred to the other directions than the specular direction. The amount of the scattered radiation is more for a hazy condition than for a clear condition. For wind speed of 5 m/sec, in the specular direction, the intensity is decreased to 0.5×10^{-4} watts $\text{cm}^{-2} \mu\text{m}^{-1} \text{st}^{-1}$ for a clear condition. The intensity of the reflected radiation decreases rather smoothly in comparison with the case of wind speed of 1 m/sec when the observation direction is away from the specular direction. So far computational results show that the change of intensity along the observation direction depends mainly upon the ocean surface wind. It decreases with the increase of wind speed.

Fig. 3(a) shows temperature deviation (ΔT) from the ocean surface temperature in the sun vertical. It is positive in the case of over-esti-

Fig. 3(a) Temperature deviation from the ocean surface temperature in the sun vertical at $3.7 \mu\text{m}$ under a clear condition. The symbol θ_0 denotes for the nadir angle of the sun.

Fig. 3(b) Temperature deviation from the ocean surface temperature in the azimuth plane ($\phi=20^\circ, 160^\circ$) at $3.7 \mu\text{m}$ under a clear condition.

mation of temperature, whereas negative in the case of under-estimation. The abscissae denotes for the scanning direction of observation toward the sun ($\phi=0^\circ$) and the anti-sun ($\phi=180^\circ$). For a comparison, ΔT is also shown in the absence of the sun's flux. Computations were carried out for the sun nadir angle of $8.5^\circ, 40.6^\circ$ and 60.0° at $3.7 \mu\text{m}$. For a wind speed of

1 m/sec ($\theta_0=8.5^\circ$ & 40.6°) under the clear condition, brightness temperature measured by a satellite is approximately 50 degrees higher than the ocean surface temperature in the specular direction due to the intense reflection of the solar radiation. With the increase of the surface wind speed, ΔT reduces dramatically in the sun glint region. It becomes 22°K and 10°K in the specular direction with wind speed of 5 m/sec and 15 m/sec, respectively at $\theta_0=8.5^\circ$. In the sun glint, therefore, the radiation received by a satellite is mainly due to the solar flux which is transmitted, directly reflected by the ocean surface and transmitted again through the atmosphere. Thus the characteristics of the ocean surface is one of the important parameters for the radiation emerging from the atmosphere. In this region, the contribution of the thermal energy emitted by the ocean surface is relatively small. In other words, SST does not affect the reflected radiation. In the atmosphere, the optical

thickness of aerosols is small (0.1 for hazy condition) in the $3.7\text{ }\mu\text{m}$ window region. Therefore the effect of multiple scatterings due to aerosols is small, thereby the data analysis being simple. This condition make it easy to analyse the optical thickness in the atmosphere.

Therefore, the sun glint region is suitable for deriving the optical thickness, provided that the wind speed is given by some other means or vice versa. In the direction of about 15° away from the specular direction, the dependence of the surface wind upon the reflected radiation is less than that in the specular direction, and yet the reflected radiation is strong enough in the region, whereas the contribution of the thermal radiation emitted by the ocean surface is still small. Hence the reflected radiation depends mainly upon the atmospheric condition. In other words, it is suitable for deriving the optical thickness in this region. Outside the sun glint region, the effect of the sun's flux reflected by the surface becomes

Table 4 Comparison of temperature deviation from the ocean surface temperature in the daytime with at night. The nadir angle of the sun is 40.6° at $3.7\text{ }\mu\text{m}$ for clear and hazy conditions.

(a) clear										
wind		8.5	19.3	30.1	40.6	50.6	60.0	68.6	76.1	82.2
1 m/sec	night	2.38	2.47	2.66	3.00	3.60	4.66	6.51	9.38	12.88
	day	2.03	2.09	2.26	2.53	3.09	4.00	5.70	8.31	11.35
	difference	0.35	0.38	0.40	0.47	0.51	0.66	0.81	1.07	1.53
5 m/sec	night	2.37	2.46	2.65	3.00	3.62	4.72	6.56	9.19	12.51
	day	1.98	2.07	2.25	2.53	3.11	4.06	5.75	8.14	11.01
	difference	0.39	0.39	0.40	0.47	0.51	0.66	0.81	1.05	1.50
15 m/sec	night	2.37	2.47	2.67	3.05	3.71	4.83	6.50	8.83	12.20
	day	0.94	1.78	2.22	2.57	3.20	4.16	5.69	7.79	10.72
	difference	1.43	0.69	0.45	0.48	0.51	0.67	0.81	1.04	1.48
(b) hazy										
wind		8.5	19.3	30.1	40.6	50.6	60.0	68.6	76.1	82.2
1 m/sec	night	3.48	3.61	3.88	4.34	5.12	6.42	8.54	11.53	14.60
	day	2.34	2.37	2.58	2.82	3.46	4.31	6.02	8.43	10.91
	difference	1.14	1.24	1.30	1.52	1.66	2.11	2.52	3.10	3.69
5 m/sec	night	3.46	3.60	3.87	4.35	5.15	6.48	8.58	11.37	14.35
	day	2.28	2.34	2.57	2.83	3.48	4.36	6.07	8.30	10.69
	difference	1.18	1.26	1.30	1.52	1.67	2.12	2.51	3.07	3.66
15 m/sec	night	3.47	3.61	3.89	4.39	5.23	6.58	8.52	11.06	14.13
	day	1.33	2.06	2.52	2.85	3.56	4.45	6.02	8.03	10.50
	difference	2.14	1.55	1.37	1.54	1.67	2.13	2.50	3.03	3.63

small. This is mainly due to the fact that the optical thickness of aerosols is too small to affect the entire radiation field by scatterings. Therefore the main contribution to the upwelling radiation at top is due to the radiation directly reflected by the surface. Hence it is limited in the sun glint region. The intense reflection of the sun glint is approximately limited within 30° from the specular direction (Figs. 3(a) & (b)). For $\theta_0=40.6^\circ$, for example, in the nadir angle of observations beyond 10° on the other side of the sun glint ($\phi=180^\circ$), the effect of the incident solar radiation is less than one degree in terms of temperature deviation for a clear condition. Table 4 shows the comparison of apparent temperature of the ocean surface in the daytime with that at night on the other side of the sun glint region ($\phi=180^\circ$), where all parameters adopted in the daytime are assumed to be these at night, but for the existence of the incident solar radiation at top. The nadir angle of the sun is 40.6° at $3.7\ \mu\text{m}$. ΔT does not show any appreciable difference with regard to the surface wind speed in the observation directions beyond 30° (see Table 4). Moreover in this region ΔT is less in the daytime than at night. For example at the observation direction of 50.6° , ΔT is 3.60°K at night, whereas it is 3.09°K in the daytime with wind speed of 1 m/sec under a clear condition. This is mainly due to the fact that the effect of the solar flux diffusely scattered by aerosols in the atmosphere, rather than diffusely reflected by the surface, compensates the effect of the surface emissivity which is less than 1, in addition to the atmospheric attenuation. It should be noted that the deviation does not show any appreciable difference for wind speed. In other words, the contribution of the radiation diffusely reflected by the surface is negligible. This reason becomes much clear if the optical thickness of aerosols becomes larger. In Table 4 for a hazy condition, ΔT is less in the daytime than at night. For example, at $\theta=50.6^\circ$, ΔT is 3.46°K in the daytime, while it is 5.12°K at night. The difference is 1.66°K . For a clear condition, this difference is 0.51°K . This result suggests that there is possibility to separate the effect of aerosols from the total optical thickness if sequential measurements of the ocean surface temperature both in the daytime and at night are undertaken, provided that all parameters keep constant in time, both in the daytime and at night, but for the existence of the incident solar radiation at top.

(d) *Estimation of optical thickness in the sun glint*

Fig. 4 shows temperature deviation from the ocean surface temperature in the sun vertical at $3.7\ \mu\text{m}$ (ordinates), where the surface temperature is assumed to be 294°K . The nadir angles of the incident sun are 40.6° and 8.5° , respectively. The abscissae denotes for the scanning direction of observations toward the sun ($\phi=0^\circ$) and anti-sun ($\phi=180^\circ$). Three cases were computed for different amount of the atmospheric constituents by keeping the mixing ratio constant. Total optical thicknesses of these three cases are (1) 0.12, (2) 0.24 and (3) 0.36, respectively. For a wind speed of 1 m/sec at $\theta_0=8.5^\circ$, ΔT increases with the decrease of the optical thickness. In the specular direction, the difference becomes 13°K between the cases of (1) and (3). This is mainly due to the fact that the incident solar radiation is absorbed in the atmosphere, reflected by the surface and absorbed in the atmosphere again, before reaching the satellite. The ratio of the attenuated energy to the incident solar radiation is 78 percent in the case of (1), whereas 47 percent in the case of (3). The difference becomes 31 percent. For different wind speed, the similar trend was noted. So far the intense radiation received by a satellite to the specular direction depends upon the surface characteristics as well as the effect of the atmospheric interference. Fig. 5 shows temperature difference between in the specular direction and in the direction of 30° away from the center of the peak (ordinates).

Fig. 4 Temperature deviation in the sun vertical under a clear condition with wind speed of 1 m/sec at $3.7\ \mu\text{m}$. $\tau_{\text{tot}}=(1)$ 0.12, (2) 0.24 and (3) 0.36.

Fig. 5 Temperature difference due to the sun glint with the wind speed in the sun vertical at $3.7\mu\text{m}$. $\tau_{\text{tot}}=(1) 0.12$, (2) 0.24 and (3) 0.36.

The abscissae denotes for the wind speed. ΔT increases with the decrease of wind speed and with the decrease of the optical thickness. For example, at $\theta_0=40.6^\circ$, ΔT decreases about 11°K with the increase of wind speed from 2 m/sec to 4 m/sec, whereas it decreases about 5°K with the decrease of the optical thickness from 0.24 to 0.12. If the wind speed is provided by the other means, the total optical thickness could be approximately derived by the use of Fig. 5 or vice versa. Once the total optical thickness is derived, ΔT can be calculated by extending it to the scanning directions operating by the satellite radiometer. Furthermore, the comparisons of data in the daytime with that at night might yield the separation of the aerosol optical thickness as

mentioned earlier. This information can be used for the further improvement of the accuracy of the ocean surface temperature.

(e) Data of the AVHRR (channel 3)

The NOAA-6 satellite passes a local point twice a day, that is in daytime and at night. Fig. 6(a) shows a scanning cross section of AVHRR channel 3 ($3.7\mu\text{m}$) and 4 ($11\mu\text{m}$) on NOAA-6 in mostly cloud free area at 6:49 a.m. (JST) on Aug. 2, '79 (daytime). The high temperature region of the channel 3 corresponds to the sun glint. The points sharply changed in temperature might be due to emission and reflection by clouds. Figs. 6(b) and (c) show the cross sections at nearly the same region of Fig. 6(a), but for data taken at 12 hours before and after, respectively (night orbit). The scanning and orbiting directions of the NOAA satellite at night differ from these in daytime. For comparison of data in daytime with that at night, the data at night is resampled to adjust the pixels to the scanning line in day time. The NOAA-6 passes at about 7:30 p.m. in local time, so that during summer, the west side of Figs. 6(b) and

Fig. 6(a) Apparent temperature by AVHRR. One scanning line cross section of AVHRR ch. 3 and ch. 4 on NOAA-6 at 6:49 JST on Aug. 2, 1979 (daytime). The ordinate represents apparent temperature, whereas the abscissae does the azimuth ($\phi-\phi_0$), zenith angle of the sun (θ_0) and zenith angle of observations (θ).

Fig. 6(b) The same as Fig. 6(a), but for data taken at 12 hours before.

Fig. 6(c) The same as Fig. 6(a), but for data taken at 12 hours after.

(c) includes the solar reflection partly. As the sun is below the horizon, the east side might not be affected by the solar radiation.

Ten days mean sea surface temperature map during early in August, '79 is shown in Fig. 7(a), in which the rectangular indicates the scanning area of AVHRR in this study. Fig. 7(b) shows the surface weather chart at 9:00 a.m. (JST) on Aug. 2, '79, about 2.5 hours after the NOAA-6 pass. The scanning area is shown by the

Fig. 7(a) Ten days mean sea surface temperature map (Aug. 1-10, '79). The scanning area is shown by the rectangular.

Table 5(a) Comparison of sea surface temperature. Brightness temperature is taken by the AVHRR (ch. 3) along the scan lines on August 2, 1979. Temperature reported by ship is the average sea surface temperature from August 1 to August 10. Visibility is reported to be 20-50 km. Sun glint region is defined by the observational directions ranging from 8.5° to 60.0° on the same side of the sun glint. τ represents the optical thickness adopted in the computations, whereas $0.8^*\tau$ does the optical thickness reduced by 0.8 times.

sub-satellite point	region	ship ($^\circ\text{K}$)	AVHRR ch. 3	model computations (clear)			model computations (hazy)		
				τ , 5 m/sec	$0.8^*\tau$, 5 m/sec	τ , 4 m/sec	τ , 5 m/sec	$0.8^*\tau$, 5 m/sec	τ , 4 m/sec
33 $^\circ\text{N}$	peak	300-301	316.50	304.41	302.20	303.49	306.10	303.62	305.23
	sun glint	300-301	305.63	301.86	300.43	301.85	302.87	301.29	302.84
	outside	299-301	298.01	299.45	299.08	299.45	300.10	299.61	300.11
28 $^\circ\text{N}$	peak	301-302	310.80	302.49	300.62	302.50	303.72	301.67	303.66
	sun glint	301-202	307.11	302.63	301.43	302.99	303.36	302.05	303.63
	outside	301-302	296.28	301.20	300.83	301.19	301.87	301.37	301.87

Table 5(b) The same as Table 5(a), but for the data taken 12 hours after.

sub-satellite point	ship ($^\circ\text{K}$)	AVHRR	model computations (clear)			model computations (hazy)		
			τ , 5 m/sec	$0.8^*\tau$, 5 m/sec	τ , 4 m/sec	τ , 5 m/sec	$0.8^*\tau$, 5 m/sec	τ , 4 m/sec
33 $^\circ\text{N}$	299-301	296.30	299.32	298.83	299.32	301.05	299.59	301.05
28 $^\circ\text{N}$	301-302	296.71	300.27	299.79	300.26	301.55	300.89	301.55

by ship is the average sea surface temperature from Aug. 1 to Aug. 10, which represents temperature of a bulk of water near surface. The sun glint region is defined by the zenith angle of observations ranging from 8.5° to 60° on the same side of the sun glint. The parameter τ represents the optical thickness adopted in the computations (see Table 1), whereas $0.8^*\tau$ does the optical thickness reduced by 0.8 times. In the region of 33 $^\circ\text{N}$, sea surface temperature measured by a satellite is 316.50 $^\circ\text{K}$ at the peak value, which is 16 $^\circ\text{K}$ higher than that measured by ship. This is mainly due to the intense sun radiation directly reflected by the ocean surface. This high temperature decreases rapidly when the observational direction is away from the center of the peak value. In the sun glint region, it is 305.63 $^\circ\text{K}$ on an average, which is 5 $^\circ\text{K}$ higher than that of ship data. Outside the sun glint, on the other hand, temperature measured by the AVHRR is 1-2 $^\circ\text{K}$ lower than that of ship data. This is partly due to the absorption of radiation by the atmosphere and partly due to the emissivity of the ocean surface which is less than 1.0. The emerging radiation from the atmosphere bounded by the ocean surface was evaluated for six different sets of data in mid-latitude in summer. The cases of the optical

thickness τ under the clear condition result 304.41 $^\circ\text{K}$ and 303.49 $^\circ\text{K}$ at the peak values with wind speed of 5 m/sec and 4 m/sec, respectively. The temperature deviation from the ship data is about 3-4 $^\circ\text{K}$. It was found from the same computations under the hazy condition that temperature deviation is 3 $^\circ\text{K}$, 5-6 $^\circ\text{K}$ for the case of $0.8^*\tau$ with 5 m/sec and that of τ , respectively. The case of the optical thickness of $0.8^*\tau$ with wind speed of 5 m/sec under the clear condition simulates the sea surface temperature within the accuracy of 1-2 $^\circ\text{K}$, allowing the fact that the peak value of temperature in the sun glint region is disturbed by the presence of clouds (see Fig. 6(a)). It is 302.20 $^\circ\text{K}$. These computational results provide the good correspondence to the visibility reported by ship (20-50 km). When the optical thickness derived by the simulation in the sun glint region is extended to the other region, the expected temperature is 301.86 $^\circ\text{K}$ and 301.85 $^\circ\text{K}$ on the average for the case of the optical thickness τ with 5 m/sec and with 4 m/sec, respectively under the clear condition. These values are still 1-2 $^\circ\text{K}$ higher than that of ship data, whereas the case of the optical thickness of $0.8^*\tau$ with 5 m/sec under the clear condition agree with the result of ship data. In this region, the emergent radiation at top does not show any

appreciable dependence on the surface wind speed. This is mainly due to the fact that the peak value of temperature measured by the AVHRR is not at the center of the specular direction, but it is measured at 16° (28°N) and 13° (33°N) away from the specular direction, where the dependence of the wind upon the reflected solar radiation is much less than that at the specular direction. Outside the sun glint, where the wind speed is not an essential parameter to the temperature investigation, these model atmosphere-ocean surfaces simulate the ship data both under the clear and hazy conditions.

Table 5(b) shows the same as Table 5(a), but for the data taken 12 hours after (night orbit). As the west side of the data is affected by the solar reflection of radiation, the east side of the data is used for analysis. Temperature by the AVHRR (channel 3) is $3\text{--}4^\circ\text{K}$ lower than that of ship data on the average. The model computations of the case of the optical thickness τ under the clear condition agree with that of ship data in the region of 33°N , whereas the case of the optical thickness τ under the hazy condition agree in the region of 28°N .

(g) The other discussions

Throughout the investigations of the surface temperature, the effect of the atmospheric constituents was estimated by the use of climatological data on water vapor, pressure and temperature profiles of the U.S. standard atmosphere. In the sample computations of the case that temperature in the layer between 1 km and 2 km height is 5°K higher than that of the U.S. standard atmosphere, which corresponds to an existence of the inverse layer in the lower troposphere, ΔT at top was evaluated 0.3°K less than that of the U.S. standard atmosphere in the observation direction ($\theta \leq 30^\circ$), both in the daytime and at night. This is due to the fact that the more energy contributes to the total energy at top by the emitted radiation in the inverse layer. It is 0.5°K and 1.2°K at the observation directions of 60° and 80° , respectively. Therefore for a precise analysis of temperature, these profiles should be derived simultaneously on a real time with the measurements of sea surface temperature.

The size of the sun glint region is about 30° in radius (400 km to the horizontal direction). On deriving the optical thickness in the sun glint, the vertically inhomogeneous, but horizontally homogeneous, plane-parallel atmosphere was as-

sumed, where all parameters involved in the computations are assumed to be constant. The optical thickness thus obtained was used in the region outside the sun glint region. Therefore it should be kept in mind that this method is limited to some extent. Beside these problems, the microstructure of vertical temperature profile a little above and below the ocean surface shows a complicated pattern. It is easy to have a 0.5°K difference, whereas the sea surface temperature reported by ships is temperature of a bulk of water. Therefore for the further improvement of measurements, it is essential to obtain the radiometric measurements of SST by ships.

4. Conclusion

In the infrared window region ranging from $3.5\text{ }\mu\text{m}$ to $4.0\text{ }\mu\text{m}$, the deviation from the ocean surface temperature (SST) was investigated by the use of the AVHRR data on board the NOAA-6. It was found from the computations that outside the sun glint, ΔT is less in daytime than at night. This is partly due to the fact that the scattered radiation by aerosols compensates the brightness temperature measured by satellite. The surface wind does not show any appreciable difference upon ΔT in this region. In the specular direction, ΔT reaches more than 50°K , but it is possible to evaluate this deviation by simulation. In the sun glint, the total optical thickness can be derived, provided that the surface wind speed

Fig. 8 Histogram in temperature (ch. 3) in daytime and at night approximately in the same region (28°N , 148°E) within $\pm 10^\circ$ of zenith angle of observations. The time difference is about 12 hours between daytime and night after.

is known by some other means (ship data). Furthermore it was found that it is suitable for deriving the optical thickness in the direction of about 15° away from the specular direction. For a sample analysis (33°N , 147°E on Aug. 2, '79), the very clear atmosphere simulates SST within the accuracy of $1\text{--}2^\circ\text{K}$ at the center of the sun glint and within the accuracy of 0.5°K in the rest of the region. This atmospheric condition agreed with the ship data of visibility. To discuss the accuracy further, a knowledge of the vertical temperature and the mixing ratio profiles is essential. The radiometric measurement of SST by ship is also necessary. Finally computational results suggest that the comparison of temperature in daytime with that at night make it possible to separate the effect of aerosols from the total optical thickness. In fact a sample comparison of the AVHRR data shows the definite difference in temperature measurements (1°K) even if the pattern of the histogram at night is to that in the daytime at channel 4 ($11\text{ }\mu\text{m}$ window region) (see Fig. 8), but a further study is required to have any conclusion.

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リモートセンシングによる $3.7\mu\text{m}$ 窓領域における 海面温度推定について

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赤外 $3.7\mu\text{m}$ 窓領域 (NOAA-6 号衛星搭載 AVHRR 放射計の第3チャンネル) において、海面温度と計算によって得られた衛星での輝度温度との差を中緯度帯の夏の場合について求めた。

ここで大気を plane-parallel と仮定し、そこから出てくる放射を昼および夜の場合に計算によって求めた。この波長帯では太陽光の影響が大きいので昼間はこの点を考慮した。またデータの中で雲の影響はないと仮定した。大気中では水蒸気、窒素、酸化窒素、炭酸ガス、メタン、エアロゾルによる影響を考慮した。海面は、傾きがガウス分布している素面から成立しているとし、その傾きは表面風に等方的に依存しているものとした (Cox and Munk, 1955)。海面とエアロゾルの屈折率は水のそれと仮定し Hale and Querry (1973) によるものを用いた。大気中の吸収物質の透過率は Weinreb and Hill (1980) による方法を用い 20 cm^{-1} の幅で計算した。大気-海面系の放射伝達の計算は Takashima et al. (1977) の方法によった。

計算結果から $3.7\mu\text{m}$ 帯の昼間の観測によると鏡面反射方向から約15度離れた観測方向で大気の光学的厚さを求められることが判った。これは $11\mu\text{m}$ 帯の窓領域1チャンネルでは大気の影響を直接評価できなかったが、 $3.7\mu\text{m}$ では観測データより直接補正できる利点がある。事例として1979年8月2日の NOAA 衛星データ (30°N , 147°E) を用いて船による風のデータをもとに光学的厚さを求めたところ、船の視程観測と一致した結果を得た。またこの光学的厚さを他の観測域に適用して海面温度を求めると Sun glint の中心で $1\sim 2^\circ\text{K}$ 、他の領域で 0.5°K の測定精度を得た。なお、海面温度測定より高い精度の評価には船での放射観測による表皮温度との比較が不可欠である。