SPECTRAL AND ANGULAR PARAMETERIZATION OF SATELLITE IR MEASUREMENTS OF THE OCEAN SURFACE TEMPERATURE

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Inadequacy of the linear theory of the multichannel method (MCM) of the IR measurements of the temperature of the ocean surface (TOS) through the atmosphere is demonstrated. The four–channel parameterization of the IR measurements of the TOS is obtained on the basis of a quadratic approximation of the atmospheric transmission function entering in the radiative transfer equation, from the two spectral measurements at two zenith angles. Different two–channel reductions of this parameterization are tested based on the in situ *measurements of the TOS and the NOAA–10/AVHRR data obtained in the spectral regions near 3.7 and 10.8* μm. *It is concluded that, in order to determine the TOS accurately, the angular IR measurements (or at least a synoptic adaptation of the angular parameter) are needed.*

The multichannel method (MCM) of determining temperature of the ocean surface (TOS) in the atmospheric transparency windows (in the spectral regions 3.5–4.0 and 10–12 μm) employs either spectral or angular differences in order to take into account the distorting effect of the atmosphere.[1] Its two–spectral version is the most widespread, since the available information was taken from the linearly scanning IR radiometers of the AVHRR type, which are not capable, as assumed, to use the angular differences. However, in this case in order to provide an acceptable accuracy (of the order of 0.5–0.7 K), one had to employ only the data obtained at zenith angles $\vartheta < 45°$ (see Ref. 2); this fact significantly limits the body of the useful information. For example, in the GAC format (global atmospheric viewing with spatial resolition 4×4 km^2) ~40% of the measurements were rejected. But even with such a limitation, an error in determining the TOS remained large (greater than 1°C according to Ref. 3) under complicated meteorological conditions (especially in tropics) and, which is the most important, it had a tendency to grow with increase of zenith angle.

The last fact cannot be explained from the standpoint of the existing MCM theory, since after two–spectral correction the angular dependence of the retrieved TOS must be absent. Recently spectral and angular algorithms[4-7] have been proposed for determining the TOS using the additional terms of the form $\beta(\sec\vartheta - 1)$ or $\gamma\,\Delta T(\sec\vartheta - 1)$, where β and γ are the *a priori* fixed parameters while $\Delta T = T_1 - T_2$ is the difference between the radiative temperatures in the channels, in order to account for this effect. All of the proposed spectral and angular algorithms have been obtained either with the help of heuristic premises or empirical fitting based on real or model data. Moreover, although in the latter case they are called theoretical,[7] there is no guarantee at all that the principal factors affecting the accuracy of the TOS determination have been correctly parameterized.

Meanwhile, the possible number of the coefficients for every possible combinations of the spectral measurements and angle-dependent quantities may be quite large. For instance, about ten regression coefficients have been chosen in Ref. 7. For this reason, it is not always clear, if the obtained coefficients are optimal and how stable they are. A theoretically justified scheme for parameterizing the MCM, whose derivation and experimental investigation is the main purpose of this paper, must answer these questions.

As an experimental results we use the AVHRR data obtained in the spectral regions near 3.7 and 10.8 μm, which were received in the ART regime (corresponding to the GAC format) from a NOAA-10 artificial earth satellite during the period from August to October, 1990 carrying out the "Taifun–90" experiment over the Philippine sea. The regions and dates of the viewing, which are listed in Table II, were specially chosen with weak cloudiness and slight variability of the TOS (within the limits of one degree). The latter property makes it possible to ascribe an average ocean surface temperature T_0, which was estimated based on the decade maps published by the Japanese Meteorological Agency and the shipborne meteorological observations, to all measurements of every region. For each turn of the satellite over the given region, histograms of radiative temperatures, incorporating swaths of nine viewing lines whose centers corresponded to the chosen zenith angles, were plotted; after that a threshold cutoff of the cloudy elements was performed. A survey corresponding to a definite period is a summation of such truncated histograms over several turns. For example, the summation was performed over 3 turns of the NOAA–10 satellite during the first viewing period and over 21 turns during the second viewing period. Insofar as the employed method of cloudness filtration does not ensure its total ellimination (this is hardly possible at all[8]), as an average radiative temperature we took its noise–proof estimate, representing the 75 percentile of the sampling quantile function. In order to employ this estimate it is quite sufficient that there exists only a certain degree of uniformity of the sampling[8] that was obtained by the truncation of histograms. An additional check of the degree of uniformity was based on the value of the difference between the 75 and 50 percentiles[9] must be less than 1°C.

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TABLE I. Results of calculations of the MCM parameters from radiosonde data using a LOWTRAN–5 model.

Sonde characteristics	$\sec\vartheta$	τ_1	τ_2	$\overline{T}_{a1}$ (°C)	$\overline{T}_{a2}$ (°C)	δT_0 (°C)	γ_1	γ_2
October 17, 1990 (12GMT) 22°22′ N 136°E	1.24	0.68	0.29	16.1	17.6	–0.9	0.82	0.25
October 18, 1990 (0GMT) 19° N 137°E	1.00	0.74	0.44	14.9	17.8	–1.4	0.89	0.28
October 20, 1990 (0GMT) 15°47′ N 136°47′E	1.00 1.42	0.77 0.69	0.57 0.35	16.8 17.8	20.1 20.8	–1.6 –1.8	1.13 0.91	0.39 0.29

Note: $\overline{T}_{ai}$ is the average atmospheric temperature in the ith channel, δT_0 is calculated from Eq. (1), γ_1 is the spectral parameter of the linear theory of the MCM, and γ_2 is that of the quadratic theory of the MCM.

The choice of the dates and regions of viewing had an additional purpose to provide a wide presentation of both moderate and extreme atmospheric conditions observed in the tropics concerning their effect on the IR radiation of the ocean. Because these conditions are primarily determined by the water vapor density variations at an altitude of ~2 km,[10] its distribution was monitored based on data of temperature and moisture–content sensing (with the use of radar). Thus survey 1 corresponds to an extremely large concentration of water vapor (when the concentration becomes still higher, as a rule, thick cloudiness arose, which interfere with the IR measurements of the TOS). Survey 3 was carried out under conditions of extreme saturation deficit at altitudes of a large zone of air descent. Survey 2 corresponds to moderate conditions, which was provided by monthly averaging of the data.

The fundamental value in the MCM theory has the assumption about a constancy, under given atmospheric conditions, of the mean air temperature[1]

$$\overline{T}_a = [1 - \tau_i(p_0)]^{-1} \int\limits_{p_0}^{0} T_a(p) \partial\tau_i(p)/\partial p dp ,$$

where $T_a(p)$ is the vertical profile of the atmospheric temperature, p is the air pressure (p_0 is the surface pressure), $\tau_i(p)$ is the IR–radiation transmission function of the atmosphere in the ith channel (in what follows, where there is no doubt, $i = 1$ corresponds to the spectral region near 3.7 and $i = 2$ to the spectral region near 10.8 μm in the two–spectral algorithm; $i = 1,2$ corresponds to two different zenith angles ϑ_1 and ϑ_2 in the two–angle algorithm). An estimate of the systematic error for $\delta\overline{T}_a = \overline{T}_{a1} - \overline{T}_{a2} \neq 0$ and $\tau_i = \tau_i(p_0)$ ($\overline{T}_{a1}$ and $\overline{T}_{a2}$ are the mean temperatures of the atmosphere in two measuring channels) can be obtained from the relation

$$\delta T_0 = \delta\overline{T}_a(1 - \tau_1)(1 - \tau_2)/(\tau_1 - \tau_2) . \qquad (1)$$

As one can see from the results of calculations (Table I) based on the data of aerological sensing of the atmosphere (the calculations were made in the Marine Hydrophysical Institute of the Academy of Sciences of the Ukrainian SSR), this error is quite large for the two-spectral method. Moreover, from the results of calculations from the sonde data obtained on November 20, 1990 one can obtain an estimate of δT_0 for two–angle method. It equals 0.9° C in both channels.

From the fact that there are angular and spectral dependences of $\overline{T}_a$ we can conclude about inadequacy of the linear approximation of the transmission function $\tau_i(p)$ in the MCM theory. A necessary refinement can be obtained by an expansion of $\tau_i(p)$ in the Taylor series in a small parameter (the absorption coefficient k_i) directly in the IR–radiation transfer equation[1] written, for the simplicity, in terms of the radiative temperatures

$$T_i = T_0\, \tau_i(p_0) + \int\limits_{p_0}^{0} T_a(p) \partial\tau_i(p)/\partial p\, \mathrm{d}p ;$$

taking into account only the terms of the second order, we have

$$T_0 = T_i + Ck_i m + D(k_i m)^2 , \qquad (2)$$

where $m = \sec\vartheta$,

$$C = T_0\omega(p_0) + \int\limits_{p_0}^{0} T_a(p) \partial\omega(p)/\partial p\, \mathrm{d}p ,$$

$$D = -\left[1/2T_0\omega(p_0)^2 + \int\limits_{p_0}^{0} T_a(p)\omega(p)\partial\omega(p)/\partial p\, \mathrm{d}p \right] ,$$

and $\omega(p)$ is the water content of the atmosphere.

In contrast to T_a, which contains the function $\tau_i(p)$, the new unknown quantities C and D are independent of the choice of the spectral interval and zenith angle. In order to determine them, however, at least three–channel measurements are needed. Employment of the three-angle method in practice[11] is justified only for the error in the IR measurements of the order of 0.01 K (see Ref. 12), which is unreal. As regards the three–spectral solution, system (2) will prove to be very close to degeneration, and an inadequacy of specifying the quantities k_i under these conditions will lead to large errors in determining T_0.

TABLE II. Results of calculation of the parameters of the quadratic MCM from the surveys over the Philippine sea.

Survey No.	Dates & latitudes, *in situ* average TOS	Radiative temperatures as functions of the path length $m = \sec\vartheta$					Angular coefficients		Regression coefficients		
		ϑ deg.	0	45	57	63	β_2 (1.6)	$\beta(\gamma_2{=}0.35)$	β	$\overline{\gamma}+1$	Correlation
		m	1.0	1.4	1.8	2.2	β_1 (1.6)				
1	August 10–12, 1990 15–25° N 29.5°C	T_2	22.5	21.0	19.0	17.5	–4.17	–3.04	–3.14	1.28	0.98
		T_1	25.5	24.0	23.0	21.5	–3.33				
2	August 31–September 29, 1990 20–25° N 28.3°C	T_2	22.5	21.0	20.0	19.0	–2.92	–2.35	–2.46	1.37	0.95
		T_1	25.0	23.5	23.0	22.0	–2.50				
3	October 20–21, 1990 10–20° N 28.8°C	T_2	23.5	23.0	21.5	20.5	–2.50	–1.94	–1.78	1.39	0.99
		T_1	26.0	25.5	24.5	23.5	–2.08				

Note. The parameters of the tilt $\beta_i(m)$ were estimated from the data obtained at the angles 0 and 63°(m = 1.0 and 2.2) and the regression was determined according to the formula

$$x\,\frac{\Delta T}{m} + y\,\frac{T_0 - T_2}{m}\ ,\ \overline{\beta} = \hat{y}\ ,\ \overline{\gamma} = \hat{x} - 1\ .$$

Let us consider a combined scheme, in which C is determined by two–angle measurements while D–by two–spectral measurements. Let us differentiate the system of equations (2) with respect to m and introduce the angular coefficient $\beta_i(m) = \partial T_i(m)/\partial m$. We have $Ck_i = -\beta_i(m) - 2Dk_i^2\, m$. By substituting this into Eqs. (2), we obtain $T_0 = T_i(m) - \beta_i(m)m - D(k_i\, m)^2$. Excluding D from the system for i = 1,2 we finally obtain

$$T_0 = T_1(m) - \beta_1(m)\, m + \gamma_2\left[\Delta T(m) - \Delta\beta(m)\, m\right], \tag{3}$$

where $\Delta\beta(m) = \beta_1(m) - \beta_2(m)$ and $\gamma_2 = k_1^2/(k_2^2 - k_1^2)$.

The results of calculations given in Table I show that the quadratic parameter γ_2 agrees better with the trend toward a decrease of the empirical values of γ in the algorithms, obtained by means of regression analysis of the experimental data: in the MCSST (see Ref. 2) γ = 0.5 and in the CPSST (see Ref. 6) γ = 0.40–0.45. Comparison of the regression estimate $\overline{g}$ (Table II) and the model quantities (Table I) makes it possible to conclude that the fixed value γ_2 = 0.35 can be used for further calculations.

However, it is impossible to use Eq. (3) directly in order to determine T_0, since in practice the measurement of $\beta_i(m)$ corresponds to the chord connecting $T_i(m_1)$ and $T_i(m_2)$ and refers to m which is equal to a half–sum of m_1 and m_2 (in our case m = 1.6). Meanwhile, the summary parameter

$$\beta = \beta_1(m) + \gamma_2\Delta\beta(m) \tag{4}$$

already becomes independent of the angle (the choice of γ_2 balances the curvatures of the plots of $T_i(m)$, which are proportional to k_i^2). For this reason, a practical algorithm can have the form

$$T_0 = T_1(m) + \gamma_2\Delta T(m) - \beta m\ , \tag{5}$$

in which the angular parameter β is constant for the given atmospheric conditions to an accuracy of the second order (the terms of the third order are estimated to be 0.1 K). An estimate of this parameter from Eq. (4) for m = 1.6 and by a regression analysis using *in situ* value of the T_0 (see the note under Table II) yields close results. In this connection, one can conclude that the four–channel method (5) adequately describes the IR measurements of the TOS through the atmosphere for the current level of the instrumentation errors.

It is desireable to consider a possibility for two-channel reductions of this method. If the parameter β in Eq. (4) is assumed to be a universal constant (similar to γ_2), a two–spectral algorithm with a fixed angle–dependent term is obtained. This algorithm describes the principal part of all of the up–to–date spectral–angular algorithms[4-7] and, for this reason, it permits one to estimate their accuracy. As can be seen from Table II, for the pair of spectral regions under consideration the variability of the parameter β under tropical conditions is estimated by the quantity 0.5–0.6. This means that, choosing a universal value of β = –2.5 (in the CPSST format[6] β = –1.97, but with an account of the constant ~0.6°C we have the same resultant value), we obtain the error in determining the TOS under extreme conditions ~1.2°C for m = 2.2 and at the endpoints of the AVHRR viewing line (m = 2.7) it grows up to 1.5°C. (The CPSST algorithm based on the data of survey 1 for m = 2.2 has virtually yielded 28.0°C and 29.5°C for survey 3. In the former case we have an underestimation by 1.5°C and in the latter an overestimation by 0.7°C).

Taking into account so unfavorable estimates of the two–spectral reduction accuracy (the estimates for the pair of the spectral regions near 10.8 and 12 μm are still worse, and this fact, in particular, gave rise to an attempt to introduce the term $\gamma\Delta Tm$ instead of $\beta\, m$ in Refs. 6 and 7), let us consider the method of quadratic extrapolation

$$T_0 = T_1 - \beta_1' m - \beta_1'' m^2 , \quad (6)$$

which follows from Eq. (2) for $\beta_1' = -Ck_1$ and $\beta_1'' = -Dk_1^2$. The spectral and angular parameterization of the IR measurements of the TOS (3) makes it possible to derive the following relations: $\beta_1'' m^2 = \gamma_2[\Delta T(m) - \Delta\beta(m)\, m]$ and $\beta_1' = \beta_1(m) - 2\beta_1'' m$. Table III presents the calculated parameters β_1'', from which it follows that it is quite acceptable to fix $\beta_1'' = 0.29$. Using this quantity and the calculated angular coefficients $\beta_1(m)$ (for $m = 1.6$) we will obtain the required value of the parameter β_1' for this method. Table III also gives the results of testing algorithm (6) on the viewing data over the Philippine sea with these values of the parameters. By way of a comparison, the errors of the four–channel algorithm (5) are also shown in the table; in this algorithm the measurements of angular coefficients corresponding to each viewing were taken as β (Table II). One can see that both algorithms based on the averaged data have approximately identical accuracy characteristics, and this confirms the critical role of angular measurements (or, at least, of an adaptation of the parameter β to the synoptic conditions) in order that the TOS be obtained to an accuracy higher than that currently available amounting to 0.7°C (see Ref. 6).

TABLE III. Calculated parameters of the quadratic extrapolation method.

Survey No. (Table II)	ΔT (1.6)	$\Delta\beta$ (1.6)	β_1''	β_1'	Algorithm errors	
					Eq. (6)	Eq. (5)
1	3.50	0.84	0.295	–4.26	0.0 (0.1)	0.1 (0.2)
2	2.75	0.42	0.284	–3.43	–0.2 (0.2)	–0.2 (0.2)
3	2.75	0.42	0.284	–3.00	0.1 (0.2)	0.1 (0.1)

Note. ΔT 1.6 corresponds to a half–sum of ΔT 1.4 and ΔT 1.8; the errors of the algorithms with adjustable parameter β equal the bias (standard deviation) for each survey.

An advantage of the more complicated algorithm (5) may be manifested in this case owing to a better reconstruction of the local anomalies of the water vapor distribution in the atmosphere using the term $\gamma_2\Delta T$. However, the principal advantage of the four–channel measurements of the TOS is in obtaining an additional information about water vapor, which is an urgent problem.[10] Let us remind that the linear theory of the MCM admits only two–channel IR measurements, with the help of which the unknown instrumentational variable, i.e., the average temperature of the atmosphere $\overline{T}_a$, is excluded (but not determined). Meanwhile in the approach proposed the geophysical parameters C and D in Eq. (2), which can be determined using four measurements channels, carry this information.

A more detailed insight into this problem as well as a treatment of other spectral regions and ways of using the angular measurements in practice must be the subjects of separate papers. In conclusion I express my gratitude to A.M. Ignatov for assistance in formulating the problem and discussions of the obtained results.

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