COMPARISON OF SPECTRAL AND ANGULAR METHODS FOR DETERMINING THE TEMPERATURE OF THE OCEAN SURFACE FROM REMOTE MEASUREMENTS OF IR RADIATION

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The problem of atmospheric corrections in determining the temperature of the ocean surface (TOS) is studied based on computer modeling taking into account the regional variability of vertical temperature and moisture content profiles in the atmosphere. We used our developed approach, which enables one to analyze physical factors affecting the errors in determining the TOS and to obtain the substantiated objective estimates of these errors. In addition to the two–angle scheme of measurements described earlier (Atmospheric Optics **2***, No. 7 (1989), ibid.* **4***, No. 8 (1991)) the spectral scheme is studied for measuring in the atmospheric transparency window within two spectral intervals* 10–13 μm. *As the calculation results show, the accuracy in determining the TOS under conditions of real errors in recording the IR radiation varies within the limits from* 0.1 *to* 0.7 K, *depending on the regional characteristics of the atmosphere. The angular scheme accounts for the atmospheric noise slightly better, however, it is more sensitive to the instrumental errors. Under extreme condition of the moist tropical regions, the angular scheme of measurements gives the advantage even in the presence of instrumental errors.*

Nowadays two alternatives of the method for determining the temperature of the ocean surface (TOS) from remote measurements of IR radiation from space, both spectral and angular, are widely accepted. Their efficiency was experimentally evaluated in the case of interpretation of measurements made for methodological purposes onboard the Kosmos–1151 satellite.[1–3] The first method has been implemented in the AVHRR device onboard the NOAA satellites, the second – in the ATSR radiometer onboard the European satellite ERS–1 orbited in July, 1991.

There is a great number of theoretical investigations of different processing algorithms applied for atmospheric correction of IR measurements from space. A new approach to the problem of TOS determination is developed in Refs. 3–7 based on local linearization of the IR radiation transfer equation. Its specific feature consists in taking into account the variability of the vertical profiles of the temperature and moisture content of the atmosphere which is considered as multifactor noise in determining the TOS. In this case the number of acting variable factors essentially exceeds the number of measured values specified by the number of measuring channels. Hence it follows that the problem of the TOS retrieving is an incorrect problem and the use of some *a priori* information is needed to solve it unambiguously. As is done, for example, in the case of remote determination of vertical profiles of the atmospheric parameters using the multi–channel IR sensors. At the same time, such an approach was not applied earlier to the study of the methods for determining the TOS which provide for the use the minor number of measuring channels.

The scheme of the analysis is based on the representation of the variances of errors σ^2 in determining the TOS as a sum of two terms, the former is conditioned by variations of vertical profiles of the temperature and moisture content of the atmosphere (multifactor atmospheric noise) and the latter is related to the errors in recording the IR radiation onboard a satellite. This enables one to choose correctly a set of measuring channels of the satellite IR radiometer and to find the optimal parameters of linear algorithm for the TOS calculation taking into account the specific features of atmospheric conditions in different regions of the Global Ocean.

It is shown in Refs. 5–7 that when using the two–angle measurement scheme in the spectral range 900–920 cm^{-1} the angles $\Theta_1 = 0$ and 55° (the angles are counted off from the local vertical at the point in which a viewing ray intersects the surface with the sphericity of the Earth taken into account) are approximately optimal for the entire range of the variability of atmospheric conditions (with regard to the errors in recording the radiation temperature at the level 0.05–0.10 K in each channel). An exhaustively justified way of choosing the number and set of channels of a measuring scheme including all spectral regions being candidates for the TOS determination (among them the 3.7 μm transparency window) and taking into consideration local features of the atmospheric noise, has not been yet described in the literature. Such an analysis similar to that being fulfilled in Refs. 6 and 7 as applied to the angular scheme is of great interest but it is beyond the scope of the present paper. We consider here a spectral scheme for vertical observations (at the nadir) within two spectral ranges 900–920 and 790–810 cm^{-1} (the wavelengths are 11.0 and 12.5 μm, respectively). As the preliminary estimates show this combination of channels can be considered close to optimal if only measurements within the atmospheric transparency window 10–13 μm are used.[3] The main goal of this paper includes analysis of this scheme based on the procedures, which were employed to analyze two–angle scheme in Refs. 5–7, and in comparison of their most considerable properties.

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All the procedures including the initial assumptions and the basic notation are identical to those described in Refs. 6 and 7. Therefore we restrict here ourselves only to the minor explanations for understanding the further description.

Let us denote the exact values of the radiative temperatures in the first and second channels by T_1 and T_2, and the errors in their recording by ε_1 and ε_2. The temperature of the ocean surface T is determined by the formula

$$T = \alpha_0 + \alpha_1 (T_1 + \varepsilon_1) + \alpha_2 (T_2 + \varepsilon_2) . \tag{1}$$

The minimum of the variance of the total error in the TOS determination is provided with the optimal coefficients α_1 and α_2. The value of α_0 depends strongly on the absolute average values of T_1 and T_2 for each season and region and does not affect the component of the error in the TOS determination caused by the principal multifactor nature of the problem. Therefore, we do not analyze the effects associated with α_0 (some aspects of this problem have been discussed in Refs. 3 and 4). Thus, our attention now focuses on the study of values α_1, α_2, and σ pertaining to different two–channel schemes of measurements.

To make the calculations it is necessary to prescribe the average vertical profiles of the atmospheric parameters, the statistical nature of their variations (the matrix G), the matrix H defining the sensitivity of the values T_1 and T_2 to variations of the atmospheric parameters at different altitudes and the properties of the measurement errors ε_1 and ε_2. The last errors are considered to be the random values being uncorrelated in the channels with the identical variances σ_n^2 and zero average values. The matrix H was calculated using the program LOWTRAN–5 for the cloudless and aerosol–free atmosphere. The values of its columns correspond to the derivatives of the radiative temperature over the atmospheric parameters at different altitudes and the values of its rows – to different channels. The ocean surface was considered to be smooth and reflecting according to Fresnel.[7] The data on average vertical profiles of the atmospheric parameters and statistical characteristics of their variability were taken from Ref. 8.

Solving the numerical problem of determination of the TOS in Refs. 5–7 we used the statistical characteristics of all 48 atmospheric situations described in Ref. 8 and corresponding to different seasons and geographical regions of the Northern hemisphere. At the same time it will suffice to consider only a few most typical situations to span all the variety of the situations being important in practice. First of all, it is warranted to eliminate from the analysis the atmospheric columns typical of the continents and of the sea regions, where the surface is covered by ice. The remaining 22 atmospheric cases are shown in Table I. In addition, if one does not take into account the geographical difference and proceeds from a comparison of the results of determination of α_1, α_2, and σ in both spectral and angular methods, then the number of essentially different atmospheric situations becomes still less. In Table I the rows contain the number (according to notation from Ref. 8) of regions which can be considered as nearly identical according to the above–indicated criterium. In each row one region is underlined which can be treated as a typical representative of the entire group as a whole. Note, that from this point of view the spring and fall seasons separated for a tropical zone in Ref. 8 give practically no additional information as compared with summer and winter seasons. Therefore they are not included in Table I.

TABLE I. Groups of regions with similar properties from Ref. 8.

N	Winter	Summer
1	(2.1) (2.2)	–
2	(2.7)	–
3	(3.1)	(2.2) (3.1) (3.2) (3.5)
4	(3.3) (3.4)	(2.3)
5	(4.1) (4.3) (4.4) (4.5)	(4.4) (4.5)
6	–	(3.4)
7	–	(3.6)
8	–	(4.1)
9	–	(4.3) (4.6)

The results of determining the optimal values of α_1 for nine atmospheric situations indicated in Table I are shown in Fig. 1 (Q denotes the total content of water vapor in the atmosphere). It is possible to show only α_1 for all the cases under consideration, because the pair of coefficients in both angular and spectral methods are with a reasonable accuracy related by the formula $\alpha_1 + \alpha_2 = 1$ (see Table II, where the examples of optimal α_2 for three most characteristic atmospheric situations are also given). Below we discuss the physical mechanisms responsible for this relationship. However, before it is instructive to pay attention to some most essential peculiarities of α_1, and α_2 shown in Fig. 1 and Table II.

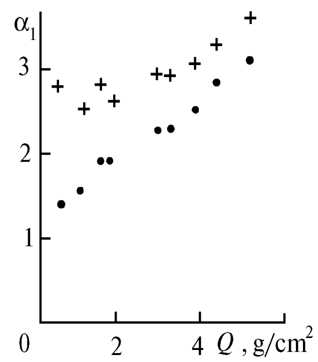

FIG. 1. Optimal values of the coefficient α_1 for the spectral (dots) and angular (pluses) methods, $\sigma_n = 0$.

TABLE II. Comparative characteristics of spectral (above the line) and two–angle (under the line) methods.

Regions	Season	Q, g/cm^2	σ_n, K	α_1	α_2	σ, K
4.3 (The Indian Ocean)	Summer	5.2	0	3.23 / 3.64	– 2.25 / – 2.57	0.54 / 0.26
			0.1	3.22 / 3.61	– 2.21 / – 2.52	0.66 / 0.52
3.3 (Subtropical zone of the Pacific Ocean)	Winter	1.7	0	1.94 / 2.84	– 0.97 / – 1.87	0.27 / 0.20
			0.1	1.93 / 2.73	– 0.95 / – 1.74	0.34 / 0.39
2.7 (Temperate zone of the Pacific Ocean)	Winter	0.63	0	1.47 / 2.83	– 0.48 / – 1.84	0.08 / 0.07
			0.1	1.44 / 2.00	– 0.44 / 0.99	0.17 / 0.28

In all cases $\alpha_1 > \alpha_2$ and $\alpha_2 < 0$. In the case of the angular method α_1 (and evidently the sum $\alpha_1^2 + \alpha_2^2$) is somewhat higher than in the case of the spectral method. As a consequence, in the spectral method the effect of errors in recording the radiation (at $\sigma_n < 0.1$ K) on the optimal coefficients is almost indistinguishable, and in the angular method it is noticeable only for atmospheric situations with small content of water vapor ($Q < 0.5$ g/cm^2). For both methods of measurements the coefficients α_1 and α_2 are strongly changed depending on the region. The maximum values of α_1 exceed 3.0–3.5 in this case.

To understand the causes of such a behavior of the coefficients it is appropriate to refer to the simplified ways of substantiation of two–channel methods for determining the TOS. It enables one, in particular, to establish the relation between our results of determining the optimal values of α_1 and α_2 and those obtained by other authors.[9–11] We will only base ourselves on the most general points of these papers and combine the various ways of considerations without posing the problem of discussion of all the approaches described in these papers in detail. In addition, for the purpose of the greater clarity of presentation we will ignore a number of details of secondary importance such as the errors in recording the IR radiation and the variation of the degree of blackness of the ocean surface from unity.

The radiative temperature of the ocean–atmosphere system being measured in the ith channel (i = 1, 2) can be given in the form

$$T_i = T\tau_i + T_{ai}(1 - \tau_i), \qquad (2)$$

where τ is the atmospheric transmittance and T_a is the effective temperature of the atmosphere. An important feature of the measuring channels under consideration is the fact that the quantity T_a is virtually independent of an angle and spectral range.[9,10] By writing Eq. (2) for two channels (i = 1, 2) and eliminating T_a we obtain an expression for the TOS coincident with Eq. (1), when

$$\alpha_0 = 0\ ,\ \alpha_1 = (1-\tau_2)/(\tau_1-\tau_2)\ ,\ \alpha_{12} = -(1-\tau_1(/(\tau_1-\tau_2). \qquad (3)$$

These values of coefficients satisfy the evident relations: $\alpha_1 + \alpha_2 = 1$ and $\alpha_1\tau_1 + \alpha_2\tau_2 = 1$. Note that α_1 and α_2 are uniquely determined by these conditions which are, consequently, equivalent to two Eqs. (2) with additional equality $T_{a1} = T_{a2}$.

In our approach, the optimal values of α_1 and α_2 are determined on the basis of *a priori* data separately for different seasons and regions which are characterized by uniform properties of variability of the atmosphere. In doing so the condition $\alpha_1\tau_1 + \alpha_2\tau_2 = 1$ is considered as an initial one and provides the valid reconstruction of contrasts in the field of the TOS.[3–7] Nevertheless, the relation $\alpha_1 + \alpha_2 = 1$ holds in this case with rather high accuracy. As a result, we achieve almost the same values of α_1 and α_2 according to formulas (3). This is supported by the result of calculations using our model with the absolutely black water surface and $\sigma_n = 0$. Thus, the coefficients of both angular and spectral methods are varied from region to region, and the peculiar features of these variations are caused by the properties of transmittance in channels (see Fig. 2). Note that in practice the variability of coefficients α_i is most frequently ignored or they are approximately expressed in terms of the integral water content of the atmosphere Q (see Fig. 2).[10, 12–14] To prescribe Q, the supplementary information, in its turn, can be used. Some authors propose, in particular, to use the approximate functional relation of Q with the difference $T_1 - T_2$ which leads to a nonlinear algorithm of the TOS calculation.[13]

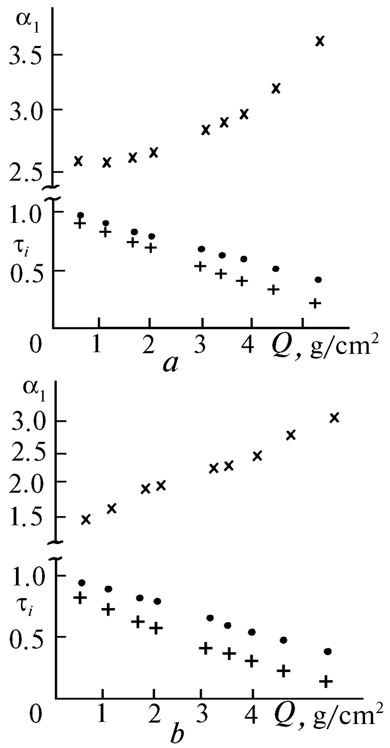

FIG. 2. Dependences of the values τ_1 (dots), τ_2 (pluses), and α_1 (crosses) on Θ calculated from Eq. (3) *for the angular* (*a*) *and spectral* (*b*) *methods.*

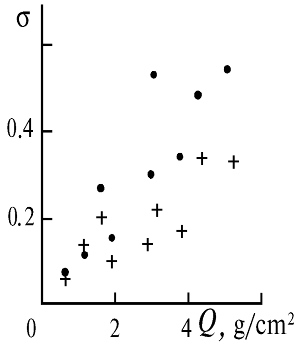

FIG. 3. Optimal values of estimates of errors in determining the TOS by the angular (crosses) and spectral (dots) methods for nine regions presented in Table I.

The most essential distinctive feature of our approach is associated with additional (as compared with Refs. 10, 12–14) possibilities for establishing the physical mechanisms affecting the errors in determining the TOS and in obtaining the substantiated objective estimates of these errors. Within the framework of the used model they are determined by the multifactor character of the variability of the vertical temperature and moisture content profiles of air and by instrumental errors in recording IR radiation.

The estimates of errors in determining the TOS for nine situations presented in Table I are shown in Figs. 3 and 4 (see also Table II). σ_{dv} and σ_{ds} are the standard deviations of errors in determining the TOS using the two–angle and two–channel spectral methods, respectively. The most essential peculiarities of the results are as follows.

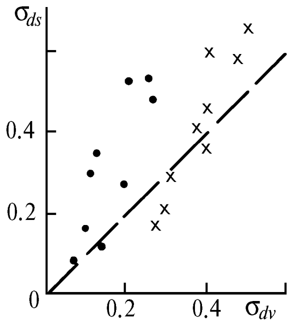

FIG. 4. Comparison of errors in the TOS determination by the angular (σ_{dv}) and spectral (σ_{ds}) methods, at $\sigma_n = 0$ (dots) and $\sigma_n = 0.1$ K (crosses) for nine regions presented in Table I.

Both in the case of the two–angle and two–channel spectral methods the errors in determining the TOS are noticeably changed from one region to the other, with the more pronounced trend for the case of the spectral method. For $\sigma_n = 0$ the maximum values of σ_{ds} run to 0.53–0.54 K, and for $\sigma_n = 0.1$ K these values run as high as 0.60–0.66 K. The Indian Ocean and the Golf Stream region belong to a number of regions with the lowest accuracy of retrieving the TOS (regions 4.3 and 3.6 according to the classification from Ref. 8) in summer.

If the errors in recording the radiation are not taken into account (i.e., when $\sigma_n = 0$), the accuracy of the two–angle method under all atmospheric conditions is higher than that of the spectral method. When σ_n increases up to 0.1 K, this trend is violated for the atmospheric conditions with small moisture content, because in these cases the contribution of the instrumental errors into σ^2, which is equal to $(\alpha_1^2 + \alpha_2^2)\sigma$, plays a leading role, whereas in the case of angular method $\alpha_1^2 + \alpha_2^2$ is somewhat higher than in the case of the spectral one. At the same time this advantage of the spectral scheme of measurements is insignificant and is of interest from the point of view of the method, because the errors in determining the TOS in high and temperate latitudes ($Q < 1.5$–2.0 g/cm^2) do not exceed 0.2–0.3 K. For example, in the Black and Mediterranean Seas the values σ_{dv} and σ_{ds} run as 0.32 and 0.28 K in summer and 0.30 and 0.21 K in winter at $\sigma_n = 0.1$ K, respectively. In the tropical Atlantic zone $\sigma_{dv} = 0.48$ and $\sigma_{ds} = 0.59$ K in summer and $\sigma_{dv} = 0.38$ and $\sigma_{ds} = 0.41$ K in winter.

Note that despite the general trend in degradation of the accuracy of retrieving the TOS with increase of the moisture content of the atmosphere there is no unambiguous correlation between these characteristics. Thus, for example, at $Q \approx 3$ g/cm^2 the quantity σ_{ds} can take the values being different from each other almost by a factor of two.

A generalization of the two studied schemes of remote measurements is the combined two–channel spectral–angular scheme in which the measurements in the first channel are carried out in the more transparent spectral range λ_1 at the nadir (or at the small angle Θ_1 to the vertical), and in the second channel – in the range λ_2 with the stronger absorption of radiation in the atmosphere at the angle $\Theta_2 > \Theta_1$. In principle, the higher efficiency of the use of remote measurements could be expected due to simultaneous implementation of advantages of both the angular and spectral schemes of the TOS determination. To verify this assumption, the calculations were made using the same procedure for $\lambda_1 = 11$ μm, $\Theta_1 = 0$, $\lambda_2 = 12.5$ μm at different values of Θ_2. The results obtained show that such a scheme line gives no essential gain as compared with spectral scheme (for which $\Theta_2 = 0$).

Summing up the comparisons of angular and spectral methods we can say that in extreme situations the first has a certain advantage (for example, at $\sigma_n = 0.1$ K in the Indian Ocean $\sigma_{dv} = 0.52$ K and $\sigma_{ds} = 0.66$ K in summer), however, in other cases there are almost no differences between them. Note that this conclusion cannot be considered as the ultimate one because the radiation model used in this paper does not take into account the atmospheric aerosol. At the same time, according to certain estimates (see, for example, Ref. 15), the spectral scheme of measurements can be subjected to the influence of the aerosol to a large extent as compared with the aerosol angular scheme. This question, however, is beyond the scope of this paper and calls for further investigations.

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