ESTIMATION OF OCEAN SKINLAYER THERMAL CHARACTERISTICS WITH A MULTIBAND IR RADIOMETER

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The temperature lapse rate and the average temperature of the water skinlayer are proposed to be estimated by means of the remote two– or three–band detection of its IR radiation. The proposed methods of data processing being effective for airborne and satellite measurements imply rather simple calibration. The required measurement accuracy is calculated to provide the given accuracy of the ocean parameters estimation.

Determination of the vertical temperature profile in the ocean skinlayer is known to be of great importance for the estimation of the ocean–atmosphere energy exchange.[1,2] Temperature measurements carried out by contact methods revealed the type of its vertical profile and main parameters.[1] However, for the solution of meteorological and other problems it is necessary to get the routine information about the ocean temperature regime over large areas that can be obtained by contactless methods only. The IR remote sensing from aircrafts and satellites gives the average temperature of the ocean surface.[3–6,11] But this information is not sufficient for the solution of heat balance equation of the ocean–atmosphere system. Earlier proposed methods of the temperature profiling with IR radiometers[7–10] require rather complicated calibration or imply water stirring.

In this paper the developed IR remote multiband methods of the average temperature and its vertical lapse rate determination based on the approach from Ref. 12 are presented, which are free of the above–mentioned limitations. The capabilities of application of both two– and three–band radiometers are discussed. The required accuracies of measurements and *a priori* data are calculated to provide the given accuracy of the ocean temperature parameters estimation.

I. FORMULATION OF THE PROBLEM AND ITS SOLUTION

The subject of our study is an inhomogeneously heated water layer with the horizontal temperature gradient much smaller than the vertical one, so that the obtained data can be averaged over large areas. Sharp decrease in temperature is known to be observed in water skinlayer caused mainly by surface evaporation. The vertical temperature profile in a 200 μm thick skinlayer can be approximated by a straight line (Fig. 1)

$$T(z) = T_0 + G z , \qquad (1)$$

where G is the vertical temperature lapse rate, axis z is directed vertically from the surface deep into water, T_0 is the temperature of the water layer bordering on the atmosphere.

Thus, for the estimation of thermal regime of the ocean skinlayer down to 200 μm that plays the most important role in the ocean–atmosphere heat exchange processes it is necessary to determine two unknown values: the surface temperature T_0 and the vertical temperature lapse rate G.

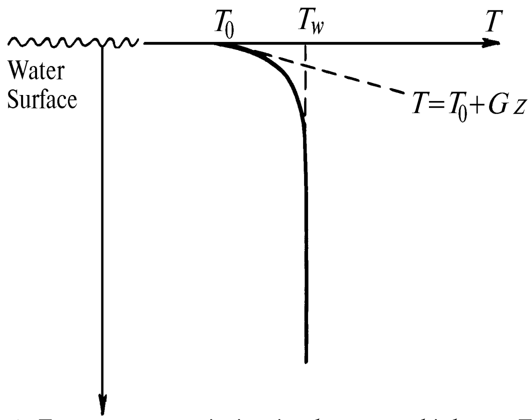

FIG. 1. Temperature variation in the ocean skinlayer: T_0 is the temperature of the thin water layer bordering on the atmosphere; T_w is the temperature in the depth of water.

For solution of this problem significant dispersion of water absorption of IR radiation should be taken into account. As known the depth of the layer effectively absorbing this radiation decreases by more than an order of magnitude (from 60 to 2 μm) as the wavelength increases from 2 to 12 μm. The measurement of the ocean surface radiation at different wavelengths could be considered as if several different objects are studied, for instance, by measuring at 2.5 μm wavelength we detect thermal radiation of a 60 μm thick layer, while by measuring at 5 μm – radiation of a 20 μm thick layer, and at 12 μm – radiation of a 2 μm thick layer. At the same time all these objects have the same surface temperature T_0 and vertical temperature lapse rate G. Just this fact allows us to estimate the thermal parameters of the ocean by means of the multiband passive measurements.

In vertical passive sensing of the ocean surface the signal from the ith operating channel of a radiometer can be described by the following expression:

$$P_i = \Omega_i \int\limits_{\lambda_i}^{\lambda_i + \Delta\lambda_i} d\lambda\, \mu(\lambda)\, \eta(\lambda) \int\limits_0^{\infty} dz \frac{B(\lambda, T(z))}{\overline{z}(\lambda)} \exp[-z / z(\lambda)] , \qquad (2)$$

where Ω_i is an average receiving aperture of the ith channel, $\lambda_i \dots \lambda_i + \Delta\lambda_i$ are the boundaries of ith spectral range, $\eta(\lambda)$ is the spectral response of the radiometer, $\mu(\lambda)$ is the spectral coefficient of the atmospheric transmission along the sight line, $\frac{B(\lambda,T)}{\bar{z}(\lambda)}\,dz$ is the spectral density of radiance of a thin skinlayer of temperature T, $\bar{z}(\lambda)$ is the characteristic penetration depth of radiation at wavelength λ (or characteristic depth of the layer emitting at λ). The radiation from the atmosphere is considered small enough to be neglected.

For the determination of T_0 and G the following approximations were adopted:

1. The water skinlayer emits as black body heated to the temperature of about 300 K. Then in the range from 2 to 12 μm the expression for spectral radiance

$$B(\lambda,\ T) = \frac{c_1}{\lambda^5}\left(\exp(c_2/\lambda T) - 1\right)^{-1} \,|\, \frac{c_1}{\lambda^5}\exp(c_2/\lambda T)\ . \quad (3)$$

may be considered valid.

2. The temperature change in a thin skinlayer, which makes a greater contribution into the ocean surface radiation, is small in comparison with the value of average surface temperature. In fact, the value of the temperature lapse rate is about 10^{-3} K/μm so the relative change in temperature even over a depth of 60 μm is equal to

$$\frac{\Delta T}{T} \sim \frac{G\,z}{T_0} \approx 2{\cdot}10^{-4} \ll 1\ .$$

In this case the exponential argument in Eq. (3) may be easily expanded into a series

$$\frac{c_2}{\lambda\,T(z)} = \frac{c_2}{\lambda\,T_0}\left(1 + \frac{G\,z}{T_0}\right)^{-1} \simeq \frac{c_2}{\lambda\,T_0} - \frac{c_2}{\lambda\,T_0}\,\frac{G\,z}{T_0} \quad (4)$$

It should be noted that the second term here is also much smaller than unity

$$\frac{c_2}{\lambda\,T_0}\,\frac{G\,z}{T_0} \approx 3{\cdot}10^{-3}\ , \quad (5)$$

that will be taken into account in calculation of a logarithm of the irradiance of a receiver input pupit.

Besides, for simplification of calculations all spectral bands of the radiometer were considered to be sufficiently narrow. So the atmospheric transmittance, the spectral response of the radiometer, and the characteristic layer depth are of constant values in every band (μ_i, η_i, and $\bar{z}_i$). This restriction can be removed by means of the methods developed in Ref. 12 for the temperature detection with a wide–band radiometer.

After all these assumptions the expression for ith band signal takes the form

$$P_i = \Omega_i\,\mu_i\,\eta_i\,\Delta\lambda_i \int\limits_0^\infty B(\lambda_i,\ T(z))\ \mathrm{e}^{-z/\bar{z}_i}\,\frac{dz}{\bar{z}_i} =$$

$$= \frac{\Omega_i\,\mu_i\,\eta_i\,\Delta\lambda_i\,c_1}{\lambda_i^5}\exp(-\,c_2/\lambda_i\,T_0)\left(1 - \frac{c_2}{\lambda\,T_0}\,\frac{G\,\bar{z}_i}{T_0}\right). \quad (6)$$

Thus, the dependence of the measured signal on the surface thermal characteristics (T_0 and G) sought, radiometer parameters (λ_i, $\Delta\lambda_i$, Ω_i, and η_i), parameter of the atmosphere (μ_i),, and water parameter ($\bar{z}_i$) is obtained in an explicit form.

II. TWO–BAND METHOD

If all necessary parameters of the atmosphere, water, and radiometer are believed to be known accurately enough, the surface temperature and lapse rate can be determined by measuring the radiometer input pupil irradiance in two spectral ranges. Taking Eq. (6) into consideration let us write a set of equations

$$\begin{cases} \ln P_1 - \ln\left(\Omega_1\mu_1\eta_1\,\dfrac{c_1\Delta\lambda_1}{\lambda_1^5}\right) = -\,\dfrac{c_2}{\lambda_1 T_0} - \ln\left(1 - \dfrac{c_2}{\lambda_1 T_0}\,\dfrac{G\,\bar{z}_1}{T_0}\right); \\ \ln P_2 - \ln\left(\Omega_2\mu_2\eta_2\,\dfrac{c_1\Delta\lambda_2}{\lambda_2^5}\right) = -\,\dfrac{c_2}{\lambda_2 T_0} - \ln\left(1 - \dfrac{c_2}{\lambda_2 T_0}\,\dfrac{G\,\bar{z}_2}{T_0}\right). \end{cases} \quad (7)$$

If written in terms of dimensionless variables

$$\xi = \frac{c_2}{\lambda_1\,T_0}\ ; \qquad \varphi = \frac{G\,\bar{z}_1}{T_0} \quad (8)$$

and dimensionless parameters

$$H_1 = -\ln P_1 + \ln\left(\Omega_1\,\mu_1\,\eta_1\,\frac{c_1\,\Delta\lambda_1}{\lambda_1^5}\right);$$

$$H_2 = -\ln P_2 + \ln\left(\Omega_2\,\mu_2\,\eta_2\,\frac{c_1\,\Delta\lambda_2}{\lambda_2^5}\right) \quad (9)$$

the set of equations (7) takes the form

$$\begin{cases} \xi - \xi\,\varphi = H_1, \\ \dfrac{\lambda_1}{\lambda_2}\,\xi - \dfrac{\lambda_1}{\lambda_2}\,\dfrac{\bar{z}_2}{\bar{z}_1}\,\xi\,\varphi = H_2\ . \end{cases} \quad (10)$$

Here Eq. (5) is taken into account for logarithm transformation. The solution of this set of equations can easily be obtained in an explicit form

$$\xi = \left(-\,\frac{z_2}{z_1}\,H_1 + \frac{\lambda_2}{\lambda_2}\,H_2\right) \Big/ \left(1 - \frac{z_2}{z_1}\right); \quad (11)$$

$$\varphi = \left(H_1 - \frac{\lambda_2}{\lambda_1}\,H_2\right) \Big/ \left(\frac{z_2}{z_1}\,H_1 - \frac{\lambda_2}{\lambda_1}\,H_2\right). \quad (12)$$

Figure 2 shows these two dependences for two different cases: the spectral bands of the radiometer $\lambda_1 = 2.5$ and $\lambda_2 = 5$ μm $\left(\frac{\lambda_2}{\lambda_1} = 2\right)$ with corresponding characteristic depths z_1 and z_2 being equal to 60 and 25 μm $\left(\frac{z_2}{z_1} = 0.4\right)$ and the spectral bands $\lambda_1 = 2.5$ and $\lambda_2 = 12.5$ μm $\left(\frac{l_2}{l_1} = 5\right)$ with $z_1 = 60$ and $z_2 = 2$ μm $\left(\frac{z_2}{z_1} = 0.03\right)$. Positive values of φ

correspond to an increase of the temperature with depth, while negative values describe the case of a warm skinlayer. It is clear that the functions $\xi(H_1, H_2)$ and $\varphi(H_1, H_2)$ are quite convenient for the reliable estimation of the ocean thermal characteristics T_0 and G.

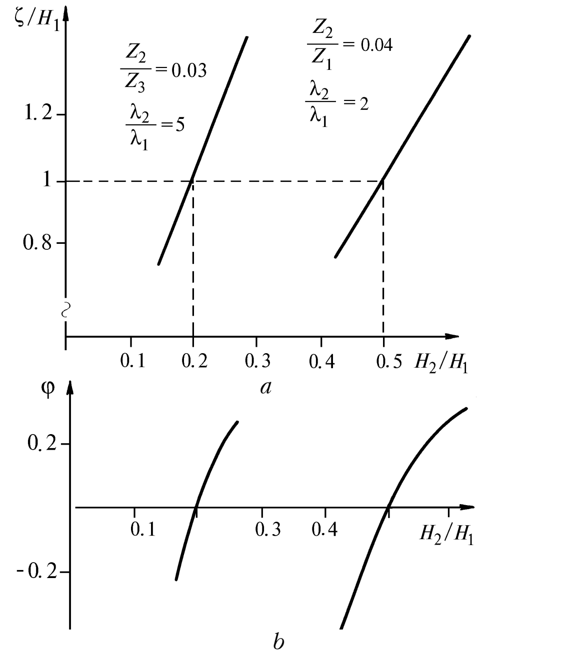

FIG. 2. The dimensionless parameter ξ inversely proportional to temperature T_0 of water on ocean–atmosphere interface (a) and parameter φ proportional to temperature lapse rate G in skinlayer (b) against the parameter proportional to ratio of signals from two–band radiometer.

It should be noted that for the ocean skinlayer $\varphi < 0.01$ and the dependence $\varphi\left(\frac{H_2}{H_1}\right)$ degenerates into a straight line with the slope depending on the ratios $\frac{z_2}{z_1}$ and $\frac{\lambda_2}{\lambda_1}$. That is why the φ–estimate exhibits an error depending on these ratios too $\sigma_z = \frac{\lambda_2}{\lambda_1}\left|1 - \frac{z_2}{z_1}\right|^{-1} \sigma_{H_2/H_1}$ that should be taken into account when choosing the operating spectral bands of a radiometer.

Consider the errors of the surface temperature and lapse rate determination by the proposed method. Returning back from the dimensionless variables to the dimension ones we obtain

$$\sigma_T = \frac{\lambda_1}{c_2} T^2 \sigma_n = \frac{\lambda_1 T^2}{c_2\left|1 - \frac{z_2}{z_1}\right|} \times$$

$$\times \sqrt{\left(\frac{z_2}{z_1}\right)^2 \delta_{p_1}^2 + \left(\frac{\lambda_2}{\lambda_1}\right)^2 \delta_{p_2}^2 + WU + \left(\frac{z_2}{z_1}\right)^2 U_1 + \left(\frac{\lambda_2}{\lambda_1}\right)^2 U_2}\,, \quad (13)$$

where $U = \left(\delta_\mu^2 + \delta_\eta^2\right)$, $U_1 = \left(\delta_{\mu 1}^2 + \delta_{\eta 1}^2\right)$, $U_2 = \left(\delta_{\mu 2}^2 + \delta_{\mu 2}^2\right)$,

$$W = \left(\frac{\lambda_2}{\lambda_1} - \frac{z_2}{z_1}\right)^2 .$$

$$\sigma_G = \frac{T_0}{z_1}\sqrt{\Delta\varphi^2} = \frac{\lambda_1 T_0^2}{c_2 z_1 \,|1 - z_2/z_1|} \times$$

$$\times \sqrt{\delta_{p_1}^2 + \left(\frac{\lambda_2}{\lambda_1}\right)^2 \delta_{p_2}^2 + \left(\frac{\lambda_2}{\lambda_1} - 1\right)^2 U + U_1 + \left(\frac{\lambda_2}{\lambda_1}\right)^2 U_2}. \quad (14)$$

Here δ_{p1} and δ_{p2} are relative errors of the input pupil irradiance determination in both spectral bands; δ_η, $\delta_{\eta 1}$, and $\delta_{\eta 2}$ are relative errors of the response calibration (δ_η is general shift in both channels, while $\delta_{\eta 1}$ and $\delta_{\eta 2}$ are independent ones in each channel), δ_μ, $\delta_{\mu 1}$, and $\delta_{\mu 2}$ are analogous errors in the atmospheric transmittance.

The temperature and lapse rate values vary near 300 K and 10^{-3} K/μm, respectively. The temperature change in the ocean layer under study is about 0.1 K. If based on these data we set the required accuracies of T and G determination as σ_T=2·10^{-2} K and $\sigma_G = 5 \cdot 10^{-4}$ K/μm then relative error of irradiance measurements in each channel at $\frac{z_1}{z_2} = 0.5$ has to be below 2·10^{-4}. It was also belived that the errors caused by calibration and atmospheric distortions are rather small. Under real conditions this, as a rule, is not valid. To avoid these errors, the three–band method was developed.

III. THREE–BAND METHOD

Since measurements of relative values are usually more accurate, let us consider the possibility of ocean thermal parameters estimation by means of such measurements. Let a three–band radiometer (λ_1, λ_2, and λ_3 are the central wavelengths of its three spectral bands, z_1, z_2, and z_3 are the characteristic depths of radiation penetration in water skinlayer at these wavelengths) be used to measure two ratios of the input pupil irradiance $\frac{P_2}{P_1}$ and $\frac{P_3}{P_1}$. Using Eqs. (5) and (6) the set of equations can be written

$$\begin{cases} \ln\frac{P_2}{P_1} - \ln\frac{\Omega_2\mu_2\eta_2\Delta\lambda_2 z_2 l_1^5}{\Omega_1\mu_1\eta_1\Delta\lambda_1 z_1 l_2^5} = \frac{c_2}{T_0}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) - \frac{c_2 G}{T_0^2}\left(\frac{z_1}{\lambda_1} - \frac{z_2}{\lambda_2}\right), \\ \ln\frac{P_3}{P_1} - \ln\frac{\Omega_3\mu_3\eta_3\Delta\lambda_3 z_3 \lambda_1^5}{\Omega_1\mu_1\eta_1\Delta\lambda_1 z_1 \lambda_3^5} = f(c_2, T_0)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_3}\right) - \frac{c_2 G}{T_0^2}\left(\frac{z_1}{\lambda_1} - \frac{z_3}{\lambda_3}\right). \end{cases} \quad (15)$$

Introducing the dimensionless variables ξ and φ and designating

$$A_{21} = \ln\frac{P_2}{P_1} - \ln\frac{\Omega_2\,\mu_2\,\eta_2\,\Delta\lambda_2\,z_2\,\lambda_1^5}{\Omega_1\,\mu_1\,\eta_1\,\Delta\lambda_1\,z_1\,\lambda_2^5}\,,$$

$$A_{31} = \ln\frac{P_3}{P_1} - \ln\frac{\Omega_3\,\mu_3\,\eta_3\,\Delta\lambda_3\,z_3\,\lambda_1^5}{\Omega_1\,\mu_1\,\eta_1\,\Delta\lambda_1\,z_1\,\lambda_3^5}\,, \quad (16)$$

we obtain

$$\begin{cases} \xi\left(1 - \frac{\lambda_1}{\lambda_2}\right) - \xi\,\varphi\left(1 - \frac{\lambda_1\,z_2}{\lambda_2\,z_1}\right) = A_{21}\,, \\ \xi\left(1 - \frac{\lambda_1}{\lambda_3}\right) - \xi\,\varphi\left(1 - \frac{\lambda_1\,z_3}{\lambda_3\,z_1}\right) = A_{31}\,. \end{cases} \quad (17)$$

In the explicit form the solution of this set of equations is similar to Eq. (11) and (12)

$$\xi = \frac{A_{21}\left(1-\frac{\lambda_1}{\lambda_3}\frac{z_3}{z_1}\right)-A_{31}\left(1-\frac{\lambda_1}{\lambda_2}\frac{z_2}{z_1}\right)}{\left(1-\frac{\lambda_1}{\lambda_2}\right)\left(1-\frac{\lambda_1}{\lambda_3}\frac{z_3}{z_1}\right)-\left(1-\frac{\lambda_1}{\lambda_3}\right)\left(1-\frac{\lambda_1}{\lambda_2}\frac{z_2}{z_1}\right)}; \quad (18)$$

$$\varphi = \frac{A_{21}\left(1-\frac{\lambda_1}{\lambda_3}\right)-A_{31}\left(1-\frac{\lambda_1}{\lambda_2}\right)}{A_{21}\left(1-\frac{\lambda_1}{\lambda_3}\frac{z_3}{z_1}\right)-A_{31}\left(1-\frac{\lambda_1}{\lambda_2}\frac{z_2}{z_1}\right)}. \quad (19)$$

The dependencies of ξ/A_{21} and φ on $\frac{A_{31}}{A_{21}}$, e.g., for radiometer operating at 2.5, 5.0, and 12.0 μm wavelengths, are analogous to those in the two–band method and also give the possibility to estimate ξ and φ rather accurately.

Assuming that $\frac{\Omega_1}{\Omega_{2,3}}$, $\frac{\mu_1}{\mu_{2,3}}$, $\frac{\eta_1}{\eta_{2,3}}$, $\frac{\Delta\lambda_1}{\Delta\lambda_{2,3}}$, and $\frac{z_1}{z_{2,3}}$ can be obtained within sufficient accuracy we can arrive the expression for the temperature and lapse rate determination errors

$$\sigma_T = \frac{\lambda_1}{c_2}T^2\left|\left(1-\frac{\lambda_1}{\lambda_2}\right)\left(1-\frac{\lambda_1}{\lambda_3}\frac{z_3}{z_1}\right)-\left(1-\frac{\lambda_1}{\lambda_3}\right)\left(1-\frac{\lambda_1}{\lambda_2}\frac{z_2}{z_1}\right)\right|^{-1}\sqrt{\delta_{p_1}^2\left[\left(1-\frac{\lambda_1 z_2}{\lambda_2 z_1}\right)-\left(1-\frac{\lambda_1 z_3}{\lambda_3 z_1}\right)\right]^2+\delta_{p_2}^2\left(1-\frac{\lambda_1 z_3}{\lambda_3 z_1}\right)^2+\delta_{p_3}^2\left(1-\frac{\lambda_1 z_2}{\lambda_2 z_1}\right)^2}; \quad (20)$$

$$\sigma_G = \frac{\lambda_1}{c_2}T\frac{T_0^2}{z_1}\left|\left(1-\frac{\lambda_1}{\lambda_2}\right)\left(1-\frac{\lambda_1}{\lambda_3}\frac{z_3}{z_1}\right)-\left(1-\frac{\lambda_1}{\lambda_3}\right)\left(1-\frac{\lambda_1}{\lambda_2}\frac{z_2}{z_1}\right)\right|^{-1}\sqrt{\delta_{p_1}^2\left(\left(1-\frac{\lambda_1}{\lambda_2}\right)-\left(1-\frac{\lambda_1}{\lambda_3}\right)\right)^2+\delta_{p_2}^2\left(1-\frac{\lambda_1}{\lambda_3}\right)^2+\delta_{p_3}^2\left(1-\frac{\lambda_1}{\lambda_2}\right)^2}. \quad (21)$$

It is interesting to note that the error coming from each channel depends on the wavelengths and characteristic depths ratios. For example, for $\lambda_1 = 2.5$, $\lambda_2 = 5$, and $\lambda_3 = 12.5$ μm and $z_1 = 60$, $z_2 = 20$, and $z_3 = 2$ μm the errors from each band of radiometer make the contributions into the total variance σ_T^2, which are in the ratio $0.04\,\delta_{p_1}^2 : \delta_{p_2}^2 : 0.64\,\delta_{p_3}^2$. It is seen that the most strict demands should be imposed on accuracy in the second and third channels of the radiometer.

Thus, the proposed methods of the ocean skinlayer temperature and its vertical lapse rate determination by means of two–band and three–band IR radiometers are effective and simple in processing. They can be widely used for passive monitoring of the ocean surface from aircrafts and satellites. Besides, there methods can be used for temperature and its lapse rate estimation in other media with sufficient dispersion of IR radiation absorption.

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