APPLICATION OF MMCA* ALGORITHMS TO NUMERICAL RETRIEVAL (PREDICTION) OF VERTICAL TEMPERATURE PROFILES IN THE ATMOSPHERIC LAYER BELOW CLOUDS FROM SATELLITE MEASUREMENTS

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A technique is proposed of increasing the efficiency of satellite sounding of temperature under cloudy conditions. It combines satellite measurement data for the atmosphere above clouds with the statistical prediction of temperature profile in the layer below clouds with the latter being based on a modified MCA algorithm.

Study and successful prediction of physical processes occurring within the atmosphere are impossible without the reliable meteorological information obtained over vast areas. For instance, one–two days long weather forecast must employ global (hemispheric) information.[1] But for many reasons the existing observational (and especially aerological) stations are distributed over the globe nonuniformly. Therefore in recent years satellite measurements are used to provide more reliable global meteorological information required for analysis and prediction of the atmospheric physical processes and fields. Combination of ordinary data from aerological–meteorological stations with satellite sensing data made it possible to achieve required spatiotemporal resolution of the information obtained. Problems, however, have arisen connected with a significant reduction of global satellite information because of clouds in the atmosphere.

In the atmosphere there are a lot of clouds at different altitudes (mostly in the troposphere). They are of various types and optical properties, and may cover at any time as much as 50% of the Earth.[2] This factor can make it difficult or sometimes even impossible (e.g., in the case of overcast by lower clouds) to obtain any information on the state of the atmospheric layer below clouds from satellite measurements of outgoing thermal IR radiation $I^{\uparrow}_{\Delta m}$. This suggestion is well illustrated by the relation[3]

$$I^{\uparrow} = N\, I^{o\uparrow}_{\Delta m} + (1 - N)\, I^{\uparrow}_{\Delta m}, \tag{1}$$

where $I^{o\uparrow}_{\Delta m}$ and $I^{\uparrow}_{\Delta m}$ are overcast and clear sky intensities of outgoing radiation, N is the fraction of instrumental field of view obscured by clouds. When $N = 1$, and the field of view is screened by clouds, the outgoing radiation from the under cloud $I^{\uparrow}_{\Delta m}$ cannot be determined since the second term in the right–hand side of Eq. (1) is zero. Therefore, to estimate meteorological parameters (e.g., temperature) of the atmospheric layer below clouds, one needs for certain *a priori* information (either statistical or prognostic).

One possible way to overcome this difficulty in thermal sensing of cloudy atmosphere is the complex approach assuming simultaneous use of sufficiently accurate satellite measurements of temperature in the upper and middle troposphere (with error about 1–2° (see Ref. 3)) and the statistical prediction of temperature in the lower, under–cloud, layer by means of different numerical methods.

Among them, most commonly used is the method of multidimensional extrapolation (see, e.g., Refs. 4 and 5) as well as the correlation method employing the relation of temperature of lower troposphere to the surface temperature, estimated from satellite measurements in the atmospheric transmission window[6] (8–12 μm spectral region).

However, both these methods require preliminary compilation of large arrays of long–term empirical observations to extract statistics for a large number of aerological stations describing the vertical statistical structure of meteorological fields on a global scale with a required accuracy and adequacy. In practice, considerable spatiotemporal variations of vertical structure of meteorological fields (in particular, temperature field[7]) make the global statistical description of this structure impossible.

In this paper we propose an alternative way of increasing the efficiency of thermal sensing of cloudy atmosphere; the idea is in combination of satellite data on temperature stratification of the overcloud atmospheric layer with the statistical prediction of temperature below the upper boundary of clouds by means of MMCA.[8] This method was chosen primarily because

– it is relatively simple, requiring not so much input data and computer time,

– it does not need for a preliminary averaging of long series of empirical data,

– it allows one to synthesize a prognostic model (using an *a priori* information) even when the structure of process being modelled and the character of noise in the data used are partially or completely unknown.

It should be noted that in order to use MMCA algorithms in reconstruction (prediction) of temperature stratification of the under–cloud atmospheric layer one have

– to specify the form and the sampling size of experimental data,

– to fix the class of basis functions (operators), from which the set of prognostic model is constructed,

– to find the methods of the model assessment and minimization of the criteria of excellence.

As in Ref. 8, we use the experimental data of spatiotemporal observations

$$\{Y_{h,t},\ \ h = 0, 1, \dots, h^*;\ \ t = 0, 1, \dots, N\};$$
$$\{Y_{h,t},\ \ h = 0, 1, \dots, \bar{h} \le h^*;\ \ t = N + 1\} \tag{2}$$

* Modified method of clustering of arguments

as input data, where h is the height and t is the time of the observation. But unlike Ref. 8 $h = 0$ corresponds to the initial altitude of satellite measurements, and the basis functions are presented by the biased dynamic–stochastical difference models of the form

$$Y_{h,\,N+1} = \sum_{s=1}^{N^*} A_{h,\,\tau}\, Y_{h,\,N+1-\tau} + \sum_{j=0}^{h-1} B_{h,\,j}\, Y_{j,\,N+1} + \varepsilon_{h,\,N+1} \qquad (3)$$

for $h = \overline{h} + 1, 2, \ldots, h^*$, where N^* is the time delay ($N^* < [N - h - 1]/2$), $A_{h,\,1}, \ldots, A_{h,\,N}$ and $B_{h,\,0}, \ldots, B_{h,\,h-1}$ are unknown model parameters, $\varepsilon_{h,\,N+1}$ is the model discrepancy.

Since the choice of the best model, using methods of directed group sorting out (in order to optimize the model structure) and minimax estimation (for evaluation of model parameters which ensure high quality of prediction) has been described earlier,[9] we omit its detailed discussion here.

Let us analyze some results of assessment of the quality and efficiency of the selected approach to the prediction (reconstruction) of the temperature stratification in the atmosphere under one–layer overcast by low clouds (of St, Sc, or Ns types). Since data of satellite thermal sensing were unavailable, such an assessment was made for winter and summer, using long–term (1961–1975) radiosonde observations at four aerological stations (Keflavik, Vienna, Rome, and Belgrade), representative of different physical and geographical regions of the northern hemisphere. In doing so using Eq. (3) we have reconstructed about 50 vertical profiles for each station and season and thus obtained sufficiently reliable estimates of standard, δ, and relative, $\theta = \delta/\sigma$, %, errors (σ is the rms deviation characterizing temperature variations at a given atmospheric level).

TABLE I. Standard (δ) and relative (θ, %) errors of temperature prediction in the atmospheric layer below clouds (overcast by St, Sc, and Ns clouds) using data on the atmospheric layers above clouds.

Reconstruction altitude, hPa	Keflavik		Vienna		Rome		Belgrade	
	δ	θ	δ	θ	δ	θ	δ	θ
				Winter				
700	0.2	3	0.1	1	0.1	3	0.1	1
750	1.4	26	1.6	32	1.3	32	1.3	25
800	2.5	46	3.2	59	2.1	58	2.5	44
825	3.0	56	3.3	60	2.5	60	3.1	53
850	3.1	58	3.4	62	3.1	96	3.3	58
875	3.2	59	3.8	72	3.7	111	3.4	59
900	3.2	59	4.0	77	4.0	116	5.5	97
925	3.2	64	4.4	85	4.4	125	5.9	106
950	3.7	72	4.6	88	5.0	144	6.5	122
975	4.3	85	5.3	105	5.5	153	7.1	136
Ground	4.6	95	5.7	112	6.0	163	8.1	159
				Summer				
700	0.3	7	0.9	23	0.1	3	0.2	6
750	0.9	26	1.5	39	0.8	22	0.9	26
800	1.5	47	1.9	47	1.5	40	1.7	46
825	1.8	49	2.0	47	1.9	49	2.1	55
850	2.1	59	2.0	47	2.0	51	2.3	56
875	2.1	59	2.0	47	2.0	52	2.5	57
900	2.2	63	2.0	47	2.2	57	2.6	58
925	2.3	65	2.5	56	2.5	63	2.9	63
950	2.7	94	2.8	63	3.0	81	3.5	73
975	3.2	109	3.4	73	3.8	104	3.8	75
Ground	3.5	121	3.9	82	4.3	119	4.1	79

It should also be emphasized that in constructing the matrix of spatiotemporal observations $Y_{h,\,t}$ we used mixed (with respect to the amount of clouds present) statistical samples, each consisting of no less than 16 profiles (with time separation of 12 h). The temperature measurement data were linearly interpolated here to give an isobaric coordinate system with a variable step in altitude and to include the following levels: ground, 975 hPa (~0.25 km), 950 (~0.50), 925 (~0.75), 900 (~1), 875 (~1.25), 850 (~1.50), 825 (~1.75), 800 (~2), 750 (~2.5), 700 (~3), 650 (~3.5), 600 (~4), 500 (~5.5), 400 (~7), and 300 hPa (~9 km). The choice of such a coordinate system is caused by the fact that, according to Ref. 7, these atmospheric levels are most representative.

After an analysis of the results of numerical evaluation of the accuracy of temperature reconstruction in the atmospheric layer below clouds it became evident that

– the MMCA algorithms using data on the overcloud measurements give fairly good estimates of temperature stratification in atmospheric layer below clouds, since almost everywhere in the layer, i.e. at altitudes below 3.5 km (precisely where the dense one–layer clouds of St, Sc, and Ns types normally occur[9]), the values of the prediction error θ are well within the maximum acceptable one, θ_0, whose value commonly used in similar problems is 65%;

– most reliable prediction (reconstruction) of temperature profile in the under–cloud atmospheric layer by MMCA method would be expected to occur in summer period, when it is possible to estimate the profile down to the 925 hPa (~0.75 km) level and even lower;

– the complex approach proposed to reconstruct temperature in the under–cloud atmospheric layer (under overcast by lower clouds) may be nearly successful by employing satellite thermal sensing data on the atmospheric parameters above clouds.

The latter conclusion is supported by the fact that, as noted above, satellite measurements using modern sounding systems in the middle and upper troposphere (between 4 and 9 km) provide an error of 1–2° (see Ref. 3), i.e., nearly as accurate as ground–based sounding.

Useful recommendation that could be given based on the results obtained is that the satellite thermal sensing in cloudy atmosphere (particularly, in the presence of lower clouds of St, Sc, and Ns types) may be essentially improved using a complex approach incorporating satellite data on the middle and upper troposphere (up to 9–km altitude) and the MMCA algorithms allowing fairly reliable reconstruction of temperature stratification in the under–cloud layer to be done. The only problem is the need for prior sampling of vertical temperature profiles for the whole troposphere (including layer below clouds), in order to construct an optimal prognostic model. However, this problem may be easily solved using either data of the closest (to the region sounded) aerological station or the numerical predictions of temperature field supplied by a meteorological forecast centre.

Summarizing the aforesaid we would like to stress that further studies of this problem with the use of the statistical evaluation of temperature profile reconstruction accuracy will be done only in overcast cloudy cases (with cover index of 8–10). In doing so, as in the present paper, the data samples from observations including all cases, under cloudiness or not, will be used as the initial data.

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