GLOBAL–REGIONAL STATISTICAL MODELS OF THE ATMOSPHERE AS AN INFORMATIONAL BASIS FOR SPACEBORNE OBSERVATIONAL SYSTEMS

V.S. Komarov and V.A. Remenson

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
A.F. Mozhaiskii Military Space Engineering Academy, St. Petersburg
Received April 13, 1994

Some calculations by the improved version of regional statistical models of a cloudy and clear atmosphere are discussed. The models are built on an objective classification of the Earth's climates and provide the information for spaceborne observational systems of various purposes.

Long–term functioning of spaceborne systems in optical observations employed to collect various environmental information and to solve specific applied problems (including those of satellite observations of the Earth, as well as navigation, communication among many other) has been a useful practice of applying the data of satellite observations. However, wider and more efficient use of these systems is still problematic for a number of reasons:

– insufficient reliability of the interpretation of satellite radiation measurements in remote optical sensing;

– inadequate account for distorting effect of the atmosphere on optical radiation causing attenuation of signals reaching the satellite and hindering efficient discriminating between an object and the background;

– strong dependence of the system operation on cloudiness, whose presence on the line of sight of onboard instrumentation can completely eliminate the possibility of performing satellite measurements of the Earth's surface.

The latter factor is of most importance for the observation system operation because, as shown in Ref. 1, at any time a half of the Earth can be covered by clouds.

Obviously, for better interpretation of satellite measurements and better estimation of distorting effect of the atmosphere and clouds one needs for a considerable *a priori* information on optically active components of the atmosphere and cloudy conditions. The information must be global in character, but quite adequate to describe the regional features of meteorological fields and meet the requirements of the present and future satellite systems of the Earth's surface observation and remote sensing.

The current practice shows that these requirements are met most fully with a specialized global–regional atmospheric model intended for supplying information to the optical measurement systems at all stages of their development and implementation. Here and below, by global–regional models we understand those which are close to global ones in the spatial coverage, but remain as accurate and representative as regional ones, treating the specific climatic processes over the Earth.

Up to now, many papers can be found in the literature concerning the construction of global–regional models for cloudy and clear atmosphere (see, e.g., Refs. 2–7). Practice, however, shows that those fail to meet all the requirements the satellite systems impose on the *a priori* information about the state of atmospheric optical channel and the conditions of satellite observations of the Earth's surface.

This was a recent motivation for scientists from IAO SB RAS and MSEA to start extensive fundamental and applied research to develop complex and improved global-regional models (including regional models of cloudy and clear atmosphere) as an informational basis for the spaceborne observational systems. General principles and some preliminary results of construction of such models we have discussed in Ref. 8.

In this paper we analyze the earlier results in order to refine the model discussed in Ref. 8.

A new improved version of global-regional atmospheric models, constructed for winter and summer, has been developed using, as before, the results of complex taxonomic classification of the Earth's climates. We used unchanged climatic division according to the many–year regime of cloudiness made using data on occurrence of five gradations of the total cloud cover (0, 1–4, 5–6, 7–9, and 10) and using the method of successive hierarchical clusterization; but the objective classification of climates in the free atmosphere, made by the complex "pressure–temperature–humidity–ozone", was slightly refined to include the analogous classification of wind field in the improved version of regional climatic models of the clear atmosphere. This classification, made by the method of major components for zonal (V_x) and meridional (V_y) components of wind velocity calculated from long–term (1961–1975) observations at sixty aerological stations in the Northern hemisphere, has shown that the quasi-homogeneous regions, inferred from wind regime, are much larger than those found using the set of meteorological quantities: pressure, temperature, humidity, and ozone concentration. As a result, the climate models of vertical distribution of zonal and meridional components of wind velocity were constructed for the same quasi-homogeneous regions of the Northern hemisphere as the models for the meteorological quantities mentioned above.

Additional characteristics included into regional models of cloudy and clear atmosphere were generalized in accordance with the earlier division into regions.

Then let us consider briefly the newly constructed global–regional atmospheric climate models. These models were developed in accordance with the climatic division of the Northern hemisphere and represent the set of the revealed quasi-homogeneous and homogeneous

0235-6880/95/05 386-05 $02.00

cloudy regions, each supplied with the corresponding complex regional cloudy and cloudless models, as well as the set of special algorithms for organizing and searching for the regions according to the prescribed spatial and temporal (latitude φ, longitude λ, and season t) features.

In addition, the regional cloudless climatic models, which are parts of the global–regional models and constructed for individual quasi-homogeneous regions, include such parameters as vertical profiles of the mean values $\overline{\xi}$ and standard deviations σ_ξ of the optically important atmospheric characteristics (pressure p, temperature T, humidity q, partial ozone pressure p_3, and the concentrations of trace gases, such as CO, NO, and NO_2) and wind characteristics (that is the zonal (V_x) and meridional (V_y) components of wind velocity), as well as the autocorrelation and cross-correlation matrices $\|R_{ij}\|$. Noteworthy, the version modified from the earlier models, described in Ref. 8, contains altitudinal model profiles of trace gases (CO, NO, and NO_2) and V_x and V_y.

Unlike the cloudless models, climatic models for homogeneous cloudy regions, included in the quasi-homogeneous region, are significantly extended; first versions of these models contained only average cloud amount ($\overline{n}$), covering the trapezoids 5×5 degs, and the five gradations of cloudiness P_k (with P_1 denoting the occurrence of the cloud cover index gradation 0, P_2 – 1–4, P_3 – 5–6, P_4 – 7–9, and P_5 – 10) while the new version of the cloud model is complemented with not only the large scale cloud characteristics such as the beta distribution of total cloudiness and the temporal matrix of conditional probabilities of cloudiness gradational transitions, but also the statistical characteristics of meso- and microscale cloud structures calculated for different cloud types and their combinations: *Cu hum, Cu med – Cu hum, Cu cong + Cu med, Cb + Cu Cong*, and *Cu + Sc.*

In addition, the statistical characteristics of meso- and microscale cloudiness also include the mean cloud size $\overline{d}_{\rm cl}$, the parameters of the longnormal distribution of cloud diameters, the average intercloud gaps $\overline{l}_{\rm cl}$, the average cloud density $\overline{N}_{\rm cl}$, which is the number of clouds per unit area of the cloud ensemble $S = 10^4$ km^2, the horizontal area of individual cloud $S^*_{\rm cl}$, and the amount of cumulus clouds $N_{\rm cum}$ in the cloud ensemble.

The above listed regional model parameters were obtained using the following input data:

– long–term (1961–1975) radiosonde observations at 120 (or at 60, for wind observations) aerological stations located in the Northern hemisphere;

– observations at 20 ozone stations taken from 1963 to 1990 and regularly published in the Word Meteorological Organization release "Global data on ozone",

– satellite radiometric observations of temperature in the 0–30 km layer for the period from 1973 to 1977; the observations are for 56° squares of 5 by 5 degs in different parts of the Pacific and the Atlantic;

– special altitude observations of the tropospheric and stratospheric trace gases (CO, NO, and NO_2) between 1965 and 1992 (totally 2500 observations for CO, 2800 for NO, and 2560 for NO_2);

– many-year (1976–1990) satellite data on total cloudiness, averaged over 5° trapezoids and taken from the archive of global cloudiness prepared by the All-Union Scientific-Research Institute of Hydrometeorological Information, the World Information Center;

– satellite data on cloud amount averaged over about 25 sea miles (or 46.3 km) as obtained for the period from 1977 to 1979 and reported in the archive of global cloudiness of the US Air Forces Global Center of Weather;

– over 400 automatically processed photos of moderate– and high–resolution TV images of cloudiness from explorative and meteorological satellites.

Let us now describe briefly the regional climatic models of cloudy and cloudless atmosphere.

Table I gives the main parameters of the models as constructed for the typical quasi-homogeneous region, namely the region *3.6* (figure *3* indicates the subtropic zone and *6* is the number of the quasi-homogeneous region in the zone, Fig. 1). Also shown are all homogeneous cloudy subregions contained in the region (they are given by dashed lines and have numbers which correspond to those of histograms of total cloudiness). We note that because of great number of data we do not present correlation matrices $\|R_{ij}\|$ for a given quasi-homogeneous region and the models in Table I are only for summer conditions.

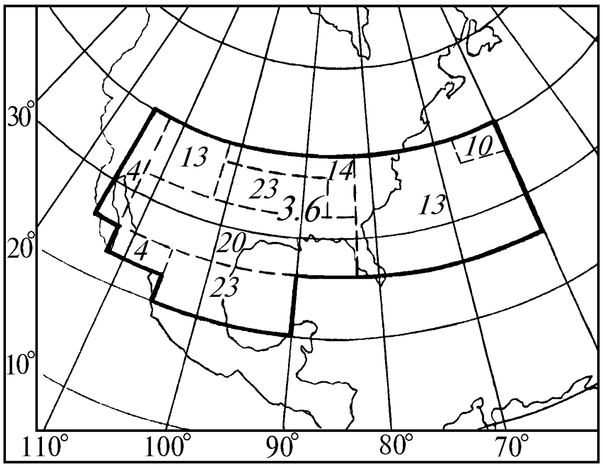

FIG. 1. An example of typical quasi–homogeneous region 3.6 and cloudy subregions involved obtained as a result of dividing the Northern hemispere into climatic zones, summer period (figures denote numbers of cloudy subregions).

TABLE. I. Regional climatic atmospheric model for the typical quasi–homogeneous region in the Northern hemisphere (the region 3.6, summer).

Height h, km	P, hPa	T, K		q, g/kg		P_3, mPa		S_{CO}, ppm		S_{NO}, ppb		S_{NO_2}, ppb		V_x, m/s		V_y, m/s	
	$\bar{P}$	$\bar{T}$	σ_T	$\bar{q}$	σ_q	P_3	σ_{P_3}	$\bar{S}_{CO}$	$\sigma_{S_{CO}}$	$\bar{S}_{NO}$	$\sigma_{S_{NO}}$	$\bar{S}_{NO_2}$	$\sigma_{S_{NO_2}}$	$\bar{V}_x^*$	σ_{V_x}	$\bar{V}_y^{**}$	σ_{V_y}
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Cloudless model																	
0	1013	300.2	3.2	16.100	2.200	3.8	2.1	0.222	0.078	0.074	0.073	3.4	5.6	0.7	2.7	1.1	1.4
2	805	288.7	2.2	8.250	2.100	3.9	1.4	0.187	0.023	0.060	0.007	3.2	2.1	– 0.9	4.3	0.6	2.8
4	633	275.0	1.6	2.910	1.309	3.4	1.1	0.156	0.021	0.049	0.006	3.0	1.6	– 0.2	4.6	0.2	3.0
6	492	261.5	1.7	1.000	0.680	2.9	1.1	0.131	0.028	0.040	0.001	2.6	0.9	0.3	6.0	0.0	4.2
8	378	248.6	1.8	0.410	0.200	2.6	1.0	0.110	0.018	0.138	0.013	2.1	0.7	0.2	7.1	– 0.6	4.4
10	286	231.1	1.7	0.072	0.035	2.6	1.5	0.092	0.018	0.475	0.043	3.9	1.8	1.1	9.1	– 0.8	6.2
12	213	219.8	1.8	0.012	0.007	3.3	2.3	0.077	0.018	1.630	0.167	7.1	5.6	1.0	11.2	– 2.0	7.3
14	156	209.4	2.5	0.004	0.003	3.7	3.0	0.065	0.003	1.230	0.167	9.1	7.2	0.1	10.1	– 2.9	6.3
16	111	205.7	3.1	0.002	0.001	5.1	2.9	0.054	0.003	0.834	0.079	6.0	3.0	– 3.3	7.5	– 3.0	4.2
18	80	211.4	1.9	0.002	0.001	8.7	2.5	0.045	0.003	0.434	0.089	2.2	0.6	– 8.4	4.7	– 2.5	2.2
20	56	216.7	1.5	0.002	0.001	12.3	2.0	0.038	0.003	0.593	0.098	10.1	3.5	– 12.7	3.8	– 1.4	1.7
22	41	219.2	1.5	0.002	0.001	14.1	1.8	0.032	0.003	0.752	0.075	17.9	5.3	– 15.5	3.6	– 0.9	1.8
24	30	222.7	1.9	0.002	0.001	15.0	2.1	0.027	0.003	0.911	0.064	25.7	7.1	– 17.7	3.8	–0.8	2.5
26	22	226.5	1.9	0.003	0.001	13.2	1.6	0.022	0.003	1.070	0.071	33.5	11.2	– 19.0	4.2	– 1.1	2.2
28	16	230.9	2.1	0.003	0.001	12.1	1.3	0.019	0.003	1.660	0.099	41.3	17.5	– 21.0	4.4	– 2.5	2.0
30	12	235.9	2.4	0.003	0.001	9.0	1.1	0.016	0.003	2.580	0.329	49.1	18.6	–23.1	4.6	– 3.4	1.8

2. Cloudy models

Number of cloudy regions	Average cloud amount $\bar{x}$, %	Occurence of gradations, %					RMS deviations within the cloudy region, %						Parameters of β–distribution	
		P_1	P_2	P_3	P_4	P_5	$\sigma_{\bar{x}}$	σ_{P_1}	σ_{P_2}	σ_{P_3}	σ_{P_4}	σ_{P_5}	α	β
2.6.04	40	27	27	15	26	5	0.9	1.5	1.0	0.7	1.5	0.9	1.132	1.630
3.6.10	57	8	23	22	42	5	1.4	2.1	1.1	1.8	1.6	1.8	2.317	2.088
3.6.13	52	11	28	21	35	5	1.9	2.6	1.2	2.4	1.2	1.2	1.925	2.004
3.6.14	44	18	32	20	26	4	1.2	2.0	1.3	0.9	1.2	1.2	1.539	2.024
3.6.20	38	33	22	15	27	3	1.1	1.2	1.6	1.4	0.9	0.9	1.035	1.619
3.6.23	37	26	33	19	20	2	1.4	1.8	1.1	1.4	0.8	0.8	1.186	1.709

* Positive and negative values are for the western and eastern wind components, respectively.
** Positive and negative values are for the northern and southern wind components, respectively.

Some parameters of climatic models in Table I and the following tables need explanations, so we give them now. Thus the parameters α and β of beta–distribution which are usable with the theoretical function of the form

$$f(x) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\,\Gamma(\beta)}\, x^{\alpha-1}\,(1 - x)^{\beta-1}, \qquad (1)$$

where Γ(α) is the gamma-function that can be used to describe the empirical distribution of the probability of cloud amount, with the parameters α and β being evaluated from the formulas

$$\hat{\beta} = (1 - \bar{x})\,[\bar{x}\,(1 - \bar{x}) - \tilde{\sigma}^2_{\hat{x}}]\,; \qquad (2)$$

$$\hat{\alpha} = \bar{x}\,\hat{\beta}\,/\,(1 - \bar{x})\,. \qquad (3)$$

Here $\bar{x}$ is the average cloud amount for homogeneous cloudy regions, $\tilde{\sigma}^2_{\hat{x}}$ is the empirical value of the variance of x, related to the cloud gradations by the relation

$$\tilde{\sigma}^2_{\hat{x}} = \sum_{i=1}^{5} (\,x_i^* - \bar{x}\,)\,P_i\,, \qquad (4)$$

where x_i^* is the middle of the ith gradation, and P_i is the occurrence of this gradation.

Among the basic parameters of regional climatic models of a cloudy atmosphere are also the matrices of conditional probabilities of cloud gradational transitions (one such matrix, as obtained for a typical homogeneous cloudy region 3.6.13, is presented in Table II). The cloud transitions during the time Δτ = 6, 12, ..., 24 h were evaluated once at the initial time τ_0, specifically, at 6:00 p.m., Greenwich mean time, the cloudiness fell within one of the five adopted gradations of the cover index (0, 1–3, 4–6, 7–9, or 10).

The statistics in Tables I and II are mostly for large-scale cloud structures and partly for mesoscale cloudiness. The knowledge of these is quite sufficient for solving many problems employing observational data from spaceborne systems operating in the optical range. A number of them, however, require the knowledge of detailed structure of cloud ensembles and individual clouds. This is especially true in the case of convective clouds whose geometrical characteristics are of erucial importance for design and use of laser observational systems and for scanning opto-electronic systems in the visible and IR ranges. That is why these characteristics were included in regional climatic models of cloudy atmosphere among other supplementary parameters.

TABLE. II. An example of the matrix of conditional probabilities (%) of cloudy gradational transitions during different time intervals for the typical cloudy subregion.

Cloud cover index					
at the initial time τ_0	at the time $\tau_0 + \Delta\tau$				
	0	1 – 3	4 – 6	7 – 9	10
			Δτ = 6 h		
0	33.8	28.6	14.3	20.0	2.6
1 – 3	2.4	34.8	29.6	30.4	2.8
4 – 6	1.9	22.6	28.1	40.6	6.7
7 – 9	1.3	16.7	24.1	43.5	14.4
10	1.8	7.0	13.8	38.3	39.1
			Δτ = 12 h		
0	20.8	18.2	23.4	35.1	2.6
1 – 3	1.5	25.6	29.5	37.8	5.7
4 – 6	3.2	24.9	25.9	38.3	7.7
7 – 9	1.9	20.4	24.1	39.7	13.7
10	1.8	8.9	16.1	39.1	34.1
			Δτ = 18 h		
0	15.8	25.0	19.7	30.3	9.2
1 – 3	4.6	28.6	28.6	30.9	7.4
4 – 6	2.5	26.2	25.1	38.3	7.9
7 – 9	1.2	17.9	26.3	41.7	12.9
10	1.3	7.6	13.5	45.6	32.0
			Δτ = 24 h		
0	9.2	40.8	14.5	28.9	6.6
1 – 3	5.7	40.2	26.3	23.5	4.2
4 – 6	1.4	25.4	36.5	31.9	4.7
7 – 9	1.6	10.8	21.0	50.9	15.7
10	1.8	7.6	12.8	42.6	35.2

TABLE III. Models of mesoscale cloudiness constructed for the typical subregion 3.6.13.

Types of clouds and their combinations	Cloud cover index gradations	Average cloud cover index	$\bar{z}$	$\sigma_{\hat{z}}$	$\mathrm{Me}_{\hat{z}}$	$\bar{d}_{cl}$, km	$\bar{l}_{cl}$, km	$\bar{N}_{cl}$ in an ensemble	S^*_{cl}	N_{cum}
Cu hum	1–4	2.5	–0.21	0.47	0.62	0.82	2.45	4100	$5.3\cdot10^{-1}$	10
	5–6	5.5	–0.10	0.51	0.79	1.48	1.64	4400	$1.7\cdot10^{0}$	9
Cu hum + Cu med	5–6	5.5	0.08	0.58	1.20	2.35	2.05	3500	$4.2\cdot10^{0}$	7
	7–9	8.0	0.12	0.55	1.32	2.49	0.60	3900	$4.9\cdot10^{0}$	7
Cu cong + Cu med	5–6	5.5	0.41	0.35	2.57	3.96	3.35	2300	$1.2\cdot10^{1}$	6
	7–9	8.0	0.57	0.46	3.72	4.70	1.18	2800	$1.7\cdot10^{1}$	6
Cb + Cu cong	7–9	8.0	1.45	0.85	28.18	61.40	15.40	1100	$3.0\cdot10^{3}$	4
Cu + Sc	5–6	5.5	0.20	0.44	1.58	4.28	3.50	1700	$1.4\cdot10^{1}$	3
	7–9	8.0	0.31	0.48	2.04	5.00	1.25	2300	$2.0\cdot10^{1}$	4

As an example, Table III presents all of the above mentioned mesoscale cloudiness parameters as determined for a typical cloudy subregion 13 from the quasi–homogeneous region 3.6. We note, however, that unlike $\bar{d}_{cl}$, $\bar{l}_{cl}$, $\bar{N}_{cl}$, S^*_{cl}, and N_{cum}, which are ready for an immediate use, the parameters $\bar{z}$, $\sigma_{\hat{z}}$, and $\mathrm{Me}_{\hat{z}}$ (the median) are applicable only with the probability density of x (cumuli clouds diameter in our case), given by

$$f(x)=\begin{cases}\dfrac{0.4393}{\sigma\sqrt{2\pi}\,x}\exp\left[-\dfrac{(\log x-\overline{z})^2}{2\sigma}\right] & \text{for } x>0,\\ 0 & \text{for } x\le 0.\end{cases} \quad (5)$$

The mathematical expectation and variance of x are calculated from the analogous estimations for z via the formulas[9]

$$\overline{x} = \exp\,(2.3025\;\overline{a} + 2.6551\;\tilde{\sigma}^2_{\hat{z}}); \quad (6)$$

$$\tilde{\sigma}^2_{\hat{x}} = \overline{x}^2\,[\exp\,(5.3022\;\tilde{\sigma}^2_{\hat{z}}) - 1]. \quad (7)$$

The probability that the random quantity x, distributed lognormally with the mean $\overline{z}$ are variance $\sigma_{\hat{z}}$, lies between a and b is readily determined from the tabulated standard probability distribution, using the relation

$$P\,(a < x \le b) = F\left(\frac{\log b - \overline{z}}{\tilde{\sigma}_{\hat{z}}}\right) - F\left(-\frac{\log a - \overline{z}}{\tilde{\sigma}_{\hat{z}}}\right), \quad (8)$$

and the values of parameters from Table III.

Summarizing, we note that all the parameters for the above regional models of cloudy and cloudless atmosphere have become the basis for constructing a computer version of the climate model informational base. This data base and the algorithm of its functioning are designed in the way that the user just inputs season, coordinates of observation, and the list of required parameters and has the desired characteristics tabulated and explained.

REFERENCES

1. L.T. Matveev, ed., *Global Cloudiness Field* (Gidrometeoizdat, Leningrad, 1986), 279 pp.
2. C.C. Justus, et. al., Four-I Global Reference Atmosphere Technical Description. Part. 1, NASA US C–TMX–64871, Sept. 1974.
3. A. Henderson-Sellers, N.A. Hunges, and M. Wilson, Bull. Amer. Meteorol. Soc. **62**, No. 9, 1300–1307 (1981).
4. N.A. Hunges and A. Henderson-Sellers, Int. J. Remote Sens. **4,** No. 1, 159–173 (1983).
5. V.I. Vorob'yev and V.S. Fadeev, *Characteristics of Cloud Cover of the Northern Hemisphere from Meteorological Satellite Data* (Gidrometeoizdat, Leningrad, 1981), 172 pp.
6. V.T. Bobrovnikov, Issled. Zemlii iz Kosmosa, No. 1, 83–89 (1981).
7. V.E. Zuev and V.S. Komarov, *Statistical Models of the Temperature and Gaseous Components of the Atmosphere* (D. Reidel Publishing Company, Dordrecht–Boston–Lancaster–Tokyo, 1987), 306 pp.
8. V.S. Komarov and V.A. Remenson, Opt. Atm. **1**, No. 1, 3–16 (1988).
9. *Estimation Rules and Confidence Limits for Parameters of Lognormal Distribution.* GOST 11.009–79 (State Committee of Standarts, Moscow, 1980), 30 pp.