INTEGRATED APPROACH TO A SOLUTION OF THE PROBLEMS OF WIND SOUNDING FROM SATELLITES UNDER CONDITIONS OF A CLOUDY ATMOSPHERE

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Feasibility of the modified method of clustering of arguments (MCA) for solving a problem of pre–computation of vertical profiles of zonal and meridional components of wind velocity from satellite data of wind measurements in upper tropospheric layers is discussed. Particular examples demonstrate efficiency of such an integrated approach as well as its prospects for solving the problems of wind sounding under conditions of a cloudy atmosphere with a spaceborne Doppler lidar.

A great progress has been made in the last few years in the field of weather forecast and modeling of general atmospheric circulation (GAC). However, more detailed and reliable meteorological data on the physical state of the atmosphere, cloudiness, and underlying surface are necessary for further improvement of forecast performance and GAC models. These data must not only encompass the whole globe, but also have a rather high spatial and temporal resolution. Obviously, such data may be obtained only with the use of the results of global observations conducted by different ground–based and spaceborne measuring systems.

According to the plans of developing the Global Observation System (GOS) proposed by the World Meteorological Organization, by the turn of the present thousand years the following principles must underlie this System[1]:

– the data obtained by different measurement systems must be used for adequate description of one or another meteorological parameter;

– GOS should incorporate two subsystems: a ground–based subsystem (base synoptical network) and a spaceborne subsystem (remote sounding from satellites);

– the space–based subsystem must be the center of GOS because it will provide the complete encompassing of all regions, including those for which information from the base synoptical network is lacking.

It is well known that wind is an important characteristic of the Earth's atmosphere and plays an essential part in solving the problems of routine forecast and global climate modeling. In addition, it is very important for solving the numerous applied problems. The data of ground–based measurements at hand (obtained with radiosondes, pilot balloons, and rockets) are insufficient for retrieval of comprehensive and reliable information about spatial (including vertical) wind distribution even in the case of observation network extension. The existing approaches to the estimate of global wind field from satellite observations about displacement of cloud systems[2] or temperature, humidity, and cloudiness distributions[3] are characterized by low accuracy and do not meet modern requirements for numerical forecast (presented in Table I) and numerous applied problems.

That is why another approach to wind velocity retrieval from space harnessing modern methods and technical means of remote sounding has been developed in the last few years. The lidar method of wind sounding that allows one to obtain the information about wind on a global scale with high spatiotemporal resolution and rather high accuracy is considered to be most promising and reliable (from the viewpoint of wind field estimation from space).

Recent studies (see, e.g., Ref. 4) demonstrated that a Doppler lidar with a CO_2 laser must be used as a basis for wind lidar.

However, before the advent of a spaceborne Doppler lidar, considerable technical and technological difficulties must be overcome. For this reason this system is still under development. Nevertheless, starting from the results of field ground–based and airborne experiments (see Ref. 1), we can state that spaceborne Doppler lidar is a rather reliable instrument for estimation of wind characteristics from space. For example, according to Ref. 1, the accuracy of measurement of wind characteristics in the troposphere is about 2–5 m/s.

TABLE I. Requirements for wind data measured by spaceborne sounding methods (SSM).[1,3]

Specifications of wind lidar	Reached values	Required values	
		Stratosphere	Troposphere
Horizontal resolution, km	2600	100 (50)	100 (50)
Vertical resolution, km	1.5	3	1 (within the layer 2–15 km), 0.5 (below 2 km)
Measurement accuracy of wind velocity components, m/s	4	2–3	1–2
Number of measurements per twenty–four hours	1	4	4

However, the data on the vertical wind velocity distribution in the entire atmospheric column (from satellite to the Earth's surface) can be retrieved only under cloudless conditions, since continuous low cloudiness (*St*, *Sc*, and *Ns* cloud types) makes it difficult to measure the wind in a subcloud layer of the atmosphere. Considering this fact, we suggest an integrated approach to the solution of the given problem (technique and results of its application are given below). This approach is based on simultaneous use of quite

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accurate spaceborne lidar measurements of wind in the layer above the clouds (above 3–4 km) and results of its statistical forecast in the lower levels, i.e., in the subcloud atmospheric layer.

It should be emphasized that in contrast to the temperature stratification of subcloud layer that can be partially reconstructed from the satellite data by multidimensional statistical extrapolation method (see, for example, Ref. 5), this method cannot be used for pre–computation of the wind parameters in the above–indicated layer, because very weak interlevel correlation is characteristic of them (as examplified by Table II). That is why another method, namely, modified method of clustering of arguments (MMCA) is used in the present paper for statistical forecast of wind field in the subcloud atmospheric layer from the data of satellite wind observations. This method demonstrated its high efficiency for retrieval of zonal and meridional components of wind velocity in the free atmosphere from the data of their measurements in the lower levels.[6,7]

TABLE II. Autocorrelation matrices of temperature (T) and zonal (V_x) and meridional (V_y) components of wind velocity retrieved from the data of the station Rome (winter).

Altitude, km	0	1	2	3	4	5	6	7	8	9
					T					
0	1.00	0.78	0.43	0.31	0.32	0.31	0.29	0.26	0.21	0.07
1	0.78	1.00	0.88	0.68	0.66	0.59	0.54	0.50	0.45	0.25
2	0.43	0.88	1.00	0.91	0.86	0.76	0.69	0.64	0.59	0.35
3	0.31	0.68	0.91	1.00	0.95	0.85	0.77	0.71	0.65	0.37
4	0.32	0.66	0.86	0.95	1.00	0.97	0.93	0.86	0.77	0.41
5	0.31	0.59	0.76	0.85	0.97	1.00	0.99	0.92	0.81	0.41
6	0.29	0.54	0.69	0.77	0.93	0.99	1.00	0.96	0.85	0.44
7	0.26	0.50	0.64	0.71	0.86	0.92	0.96	1.00	0.91	0.52
8	0.21	0.45	0.59	0.65	0.77	0.81	0.85	0.91	1.00	0.82
9	0.07	0.25	0.35	0.37	0.41	0.41	0.44	0.52	0.82	1.00
					V_x					
0	1.00	0.54	–0.25	–0.28	–0.33	–0.32	–0.34	–0.34	–0.37	–0.38
1	0.54	1.00	0.64	0.38	0.29	0.20	0.19	0.22	0.21	0.19
2	–0.25	0.64	1.00	0.87	0.76	0.59	0.59	0.63	0.64	0.61
3	–0.28	0.38	0.87	1.00	0.83	0.61	0.59	0.64	0.64	0.61
4	–0.33	0.29	0.76	0.83	1.00	0.95	0.93	0.77	0.77	0.73
5	–0.32	0.20	0.59	0.61	0.95	1.00	0.98	0.74	0.73	0.69
6	–0.34	0.19	0.59	0.59	0.93	0.98	1.00	0.84	0.83	0.77
7	–0.34	0.22	0.63	0.64	0.77	0.74	0.84	1.00	0.97	0.90
8	–0.37	0.21	0.64	0.64	0.77	0.73	0.83	0.97	1.00	0.98
9	–0.38	0.19	0.61	0.61	0.73	0.69	0.77	0.90	0.98	1.00
					V_y					
0	1.00	0.37	–0.11	–0.09	–0.10	–0.10	–0.11	–0.12	–0.13	–0.14
1	0.37	1.00	0.85	0.65	0.61	0.55	0.50	0.42	0.40	0.37
2	–0.11	0.85	1.00	0.89	0.84	0.77	0.72	0.64	0.64	0.60
3	–0.09	0.65	0.89	1.00	0.95	0.87	0.83	0.77	0.77	0.74
4	–0.10	0.61	0.84	0.95	1.00	0.98	0.96	0.90	0.89	0.86
5	–0.10	0.55	0.77	0.87	0.98	1.00	0.99	0.93	0.92	0.88
6	–0.11	0.50	0.72	0.83	0.96	0.99	1.00	0.97	0.96	0.91
7	–0.12	0.42	0.64	0.77	0.90	0.93	0.97	1.00	0.98	0.92
8	–0.13	0.40	0.64	0.77	0.89	0.92	0.96	0.98	1.00	0.98
9	–0.14	0.37	0.60	0.74	0.86	0.88	0.91	0.92	0.98	1.00

The choice of this method is caused by the fact that the large volume of initial information is not required for its implementation because it operates under conditions of partial or full uncertainty in our knowledge of the structure of modeled process. The length of initial sample is limited merely by the condition

$$M \geq N + 1\ , \tag{1}$$

where M is the length of the initial sample, and N is the number of informative levels in individual profile.

Numerical experiments have demonstrated that for our case the random sample must include about 16 profiles that corresponds to 8 twenty–four hours when measurements are performed every 12 hours. It should be noted that this sample must be formatted differently at the first and next stages of algorithmic implementation. For example, at the first stage we can use:

– the real data obtained for the atmospheric column with a spaceborne wind lidar for conditions of a cloudless atmosphere;

– the data of the nearest reference aerological station or the results of numerical forecast of wind field made at the Center of Meteorological Forecasts for conditions of a cloudy atmosphere.

At the next stages under conditions of cloudiness, combined profiles may be used, i.e., profiles estimated from the satellite data (in the layer above the clouds) as well as retrieved ones (for lower levels).

Now we consider the performance and efficiency of the chosen approach to the forecast (retrieval) of wind in the subcloud atmospheric layer under conditions of continuous single–layer low cloudiness for *St*, *Sc*, and *Ns* cloud type.

In connection with the fact that field experiments with a spaceborne Doppler lidar have not yet been carried out, the forecast performance was evaluated by us on the example of radiosonde observations. For this purpose we used long–term (1961–1975) winter and summer radiosonde observations at four aerological stations: Keflavik (63°51′N, 22°31′W), Rome (41°48′N, 12°38′E), Wien (48°15′N, 16°22′E), and Beograd (44°47′N, 20°32′E), located in different physico–geografical regions of northern hemisphere. In this case 90 vertical profiles were retrieved for every station and season, with the same number of calculated deviations of zonal ($\Delta u = u^* - u$) and meridional ($\Delta v = v^* - v$) components of wind velocity (here u^* and v^* are the retrieved wind parameters, while u and v are the same parameters estimated from the data of radiosonde observations). This allowed us to obtain rather reliable estimates of rms (δ) and relative ($\theta = \delta/\sigma$) errors, expressed in per cent (here σ is the standard deviation characterizing the variability of wind field at one or another level), as well as to calculate the probabilities of deviations Δu and Δv less than ± 1, ± 2, ± 3, and ± 4 and greater than ± 4 m/s.

It should be also emphasized that when forecasting (retrieving) vertical wind profiles, the data of wind measurements in the troposphere (at altitudes up to 9 km) were referred to a standard grid of altitudes, which will be further used in spaceborne lidar sounding of wind, by means of linear extrapolation procedure. For this purpose, according to Table I, the following standard altitudes were used: 0, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, and 9.0 km.

The results of numerical evaluation of performance of the forecast of wind field altitude profiles in the subcloud atmospheric layer from the data of observations at higher levels (these results for two typical stations: Keflavik and Rome, are given in Table III) demonstrate:

TABLE III.

Altitude of retrieval, km	Winter							Summer						
	δ, m/s	θ, %	Probability of errors, m/s					δ, m/s	θ, %	Probability of errors, m/s				
			≤□1	≤□2	≤□3	≤□4	>□4			≤□1	≤□2	≤□3	≤□4	>□4
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Zonal component of wind velocity V_x														
Station Rome														
0	12.8	185	0.03	0.11	0.27	0.34	0.66	7.8	114	0.11	0.28	0.37	0.47	0.53
0.5	9.2	148	0.12	0.20	0.30	0.42	0.58	5.8	83	0.14	0.32	0.43	0.60	0.40
1.0	5.8	106	0.14	0.28	0.46	0.58	0.42	4.6	64	0.16	0.41	0.54	0.69	0.31
1.5	4.1	90	0.14	0.40	0.51	0.72	0.28	4.5	62	0.26	0.48	0.61	0.71	0.29
2.0	2.9	54	0.28	0.51	0.74	0.87	0.13	3.1	43	0.40	0.61	0.73	0.81	0.19
3.0	0.2	2	0.99	1.00	1.00	1.00	0.00	0.4	5	0.98	1.00	1.00	1.00	0.00
Station Keflavik														
0	10.4	186	0.06	0.12	0.18	0.31	0.69	7.1	136	0.09	0.19	0.31	0.44	0.56
0.5	7.1	119	0.10	0.22	0.34	0.43	0.57	5.1	102	0.19	0.29	0.43	0.61	0.39
1.0	5.5	83	0.16	0.31	0.47	0.60	0.40	4.3	91	0.17	0.43	0.53	0.67	0.33
1.5	4.9	79	0.18	0.34	0.49	0.62	0.38	3.9	79	0.23	0.36	0.54	0.74	0.26
2.0	3.8	57	0.29	0.46	0.68	0.79	0.21	3.0	63	0.29	0.54	0.71	0.84	1.16
3.0	0.2	2	0.99	1.00	1.00	1.00	0.00	0.3	6	0.98	0.99	1.00	1.00	0.00

TABLE III (continued).

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Meridional component of wind velocity V_y														
Station Rome														
0	12.8	185	0.03	0.11	0.27	0.34	0.66	7.8	114	0.11	0.28	0.37	0.47	0.53
0.5	9.2	148	0.12	0.20	0.30	0.42	0.58	5.8	83	0.14	0.32	0.43	0.60	0.40
1.0	5.8	106	0.14	0.28	0.46	0.58	0.42	4.6	64	0.16	0.41	0.54	0.69	0.31
1.5	4.1	90	0.14	0.40	0.51	0.72	0.28	4.5	62	0.26	0.48	0.61	0.71	0.29
2.0	2.9	54	0.28	0.51	0.74	0.87	0.13	3.1	43	0.40	0.61	0.73	0.81	0.19
3.0	0.2	2	0.99	1.00	1.00	1.00	0.00	0.4	5	0.98	0.99	1.00	1.00	0.00
Station Keflavik														
0	8.9	155	0.08	0.22	0.28	0.33	0.67	5.4	128	0.21	0.40	0.52	0.63	0.37
0.5	6.4	133	0.12	0.27	0.32	0.42	0.58	4.1	116	0.29	0.51	0.63	0.72	0.28
1.0	3.8	99	0.22	0.39	0.58	0.69	0.31	2.8	101	0.40	0.60	0.76	0.83	0.17
1.5	2.0	74	0.47	0.70	0.86	0.96	0.04	2.5	87	0.44	0.66	0.79	0.91	0.09
2.0	1.5	52	0.52	0.81	0.96	0.99	0.01	1.8	59	0.53	0.77	0.90	0.96	0.04
3.0	0.8	25	0.84	0.93	1.00	1.00	0.00	0.7	21	0.89	0.98	0.99	1.00	0.00

1) Implementation of the modified version of MCA algorithm for solving the given problem gives a rather reliable estimate of altitude profiles V_x and V_y down to a 2 km altitude, i.e., 2 km lower than an initial altitude of 4 km, where the real wind observations are performed and which is always above the top of single–layer *St*, *Sc*, and *Ns* clouds (according to Ref. 8, this top is usually at altitudes below 2.0–2.8 km). In this case, at an altitude of 2 km the rms errors of zonal and meridional wind velocity component forecast do not exceed limiting error

of 65% (it is most often used to estimate different statistical characteristics), and probability of permissible variations of the same wind parameters from their real values, i.e., probability of errors less than a required value of 2 m/s (see Ref. 1) varies from 0.42 to 0.81 here, i.e., is rather high.

It should be emphasized that the probability of errors (≤ 4 m/s) that satisfy practical requirements in most cases[9] reaches already 0.67–0.99 everywhere.

2) Suggested integrated approach to retrieval of wind parameters in the subcloud atmospheric layer also may yield quite reliable results when we use the data of satellite wind measurements at higher altitudes, performed with a spaceborne Doppler lidar, as initial information rather than radiosonde data.

The last conclusion can be drawn proceeding from an assumption that expected measurement errors of developed wind lidars of the given type will be in the same limits (1–2 m/s) as the errors of modern radiosonde observations.

Thus on the basis of obtained results we arrive at a conclusion that to increase the efficiency of a spaceborne wind Doppler lidar under conditions of cloudy atmosphere (with thick single–layer *St*, *Sc*, and *Ns* clouds), it is reasonable to use integrated approach based on combined usage of the given lidar measurements in the middle and upper atmosphere (at altitudes of 9–4 km) and modified version of the MCA algorithms that allow the wind field to be retrieved quite reliably in the subcloud layer (at altitudes below 2 km).

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