Annex C

METEOROLOGICAL DATA FOR HEMISPHERIC MODELS

This annex to the report provides a brief description of the preparation of meteorological data for modeling.

Meteorological information for the pollution long-range transport modeling is prepared by a special system developed at Hydrometeorological Centre of Russia. This System of Diagnosis of the lower Atmosphere (SDA) is based on the experience gained in the development and maintaining of the system of meteorological information supply for regional HM and POP transport models of EMEP/MSC-E [*Frolov et al.*, 1994; *Rubinstein et al*., 1997,1998; *Frolov et al.*, 1997a,b,c]. Below we will briefly describe main features of SDA and its main units.

Description of SDA basic principles

SDA provides meteorological information for the Northern Hemisphere on the basis of the objective analysis of meteorological fields and data on the oceanic surface temperature fields. The horizontal resolution of SDA system is 2.5ºx2.5º. The vertical structure of SDA output information is presented by 9 layers in σ-coordinates (Table C.2). The list of meteorological parameters produced by SDA is presented in Table C.1.

Table C.1. *List of meteorological parameters on longitude-latitude grid for the Northern Hemisphere with resolution of 2.5ºx2.5º*

Element	Type	Levels	Purpose
1. Wind velocity (zonal component)	Instantaneous	9 levels	atmospheric transport
2. Wind velocity (meridional component)	Instantaneous	9 levels	atmospheric transport
3. Analogue of vertical velocity in sigma-coordinate system (at the upper boundary of the layer)	Instantaneous	9 levels (at layer boundaries)	atmospheric transport
4. Temperature	Instantaneous	9 levels	reaction rates
5. Water vapour mixing ratio	Instantaneous	9 levels	volumes of gridcells, conversion of mixing ratios to volume concentrations
6. Large-scale cloudiness	Mean 6 hours	9 levels	wet scavenging
7. Convective cloudiness	Mean 6 hours	9 levels	wet scavenging
8. Precipitation	Accumulated during 6 hours	9 levels	wet scavenging
9. Coefficient of vertical turbulence	Instantaneous	4 lower levels (at layer boundaries)	mixing along the vertical
10. Monin-Obukhov length	Instantaneous	Surface	dry deposition
11. Friction velocity	Instantaneous	Surface	dry deposition
12. Surface pressure	Instantaneous	Surface	transport along the vertical, volumes of gridcells
13. Surface temperature	Instantaneous	Surface	natural emissions, soil-atmosphere exchange
14. Roughness length	Instantaneous	Surface	dry deposition
15. Soil moisture of surface	Instantaneous	Surface	POP transport in soil, atmosphere-soil exchange processes
16. Snow cover height	Instantaneous	Surface	natural emissions

Table C.2. *Level numbers and σ values in the middle of the layers used in the SDA*

N	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
σ	0.99	0.96	0.91	0.85	0.775	0.68	0.56	0.39	0.19

SDA technological scheme

In the developed system the preparation of data is made according to the following steps:

- The preparation of an annual set of initial information. Gridded data obtained by objective analysis made by Hydrometeorological Centre of Russia are used as initial information. These data include horizontal wind components, temperature, and humidity on the standard isobaric surfaces with 12-hour interval. Initial data can have some gaps and errors. The data of NCAR/NCEP reanalysis are used as additional input. For this case a special procedure is developed for the control and correction of possible errors in initial data.
- As the next step the hydrodynamic prognostic model of Hydrometeorological Centre of Russia (version T40L15) is run for 36-hour period with the initial data based on the previous step results and data of weekly analysis of the sea surface temperature and sea ice distribution. Modeling results are recorded for each 6-hour interval.
- To obtain the initial data for the next model run the prognostic fields produced by the model are mixed with results of the objective analysis. Weighted multipliers for each type of the field are specially selected by a number of numerical experiments.
- Computed meteorological parameters are interpolated to the required spatial structure (horizontal and vertical).
- In the new spatial structure diagnostic calculations of the analogue of vertical velocity and of all the parameters of the boundary layer are performed.
- The data are aggregated according to periods (4 periods round the clock) with possible subsequent compression.
- At the final step the analysis and control of the output meteorological information is performed.

The main units of SDA technological system are the following:

- unit of initial data preparation including the control and correction of errors,
- unit of preparation of boundary conditions,
- computational unit with the use of the hydrodynamic prognostic model,
- post-processing unit including the computations of the boundary layer parameters.

Brief description of SDA units

Hydrodynamic prognostic model

There are two main aims of the use of the prognostic model in SDA. First of all, every 6 hours model fields of meteorological parameters are mixed up with diagnostic fields thus forming the initial data for the subsequent 6-hour model run. In addition to this, the major part of the parameters in Table C.1 are not measurable and hence are not included in the results of the objective analysis. Therefore, these parameters are computed by the model.

This model described in work [*Kurbatkin et al.*, 1994] is based on numerical integration of a set of hydrodynamic equations for baroclinic atmosphere in hydrostatic approximation. Along the vertical σ co-ordinate is used, where $\sigma = P/P_S$, P is atmospheric pressure and P_S is surface pressure. The set of equations is as follows:

$$\frac{\partial \bar{v}}{\partial t} + \bar{v} \cdot \nabla \bar{v} \sigma \frac{\partial \bar{v}}{\partial \sigma} + f \cdot \bar{k} \times \bar{v} + \nabla \Phi + RT_v \nabla \ln p = \bar{P}_H \qquad \text{(C.1)}$$

$$\frac{\partial \Phi}{\partial \sigma} = -\frac{RT_v}{\sigma} \qquad \text{(C.2)}$$

$$\frac{\partial T'}{\partial t}\left(\frac{\partial p}{\partial \sigma}\right) + \nabla \cdot (\bar{v}\frac{\partial p}{\partial \sigma}) + \frac{\partial}{\partial \sigma}(\sigma \frac{\partial p}{\partial \sigma}) = 0 \qquad \text{(C.3)}$$

$$\frac{\partial T'}{\partial t} + \nabla \cdot (\bar{v} T') - (\nabla \cdot \bar{v}) T' + \sigma \frac{\partial T_v}{\partial o} - \frac{\chi \omega}{p} T_v = P_T \qquad \text{(C.4)}$$

$$\frac{\partial q}{\partial t} + \nabla \cdot (\bar{v} q) - (\nabla \cdot \bar{v}) q + \sigma \frac{\partial q}{\partial \sigma} = P_q \quad , \qquad \text{(C.5)}$$

where $\bar{v}$ is wind velocity vector; p is pressure; $\bar{k}$ is unit vector; Φ is geopotential; R is gas constant for dry air; q is water vapour mixing ratio. T_v is virtual temperature, T' is deviation of temperature from standard profile $T_0(\sigma)$. Terms *PH, PT* and *Pq,* stand for non-adiabatic or subgrid processes. These terms are derived by means of parameterizations. Term σ means analogue of velocity in vertical direction.

The equation set is solved by the spectral method with triangle truncation on the hemispheric scale in the atmospheric layer between the Earth surface ($\sigma = 1$) and the upper level ($\sigma = 0$).

The computations are carried out by T40 version of the model corresponding to the spatial resolution 2.5 degree on Gaussian (non-uniform along latitude) grid. Along the vertical the atmosphere is divided into 15 layers. Basic prognostic and diagnostic variables of the model are calculated for the middle of each layer. Values of vertical velocity analogues and radiation fluxes are calculated at the layer boundaries. Specific σ values at the basic model levels are presented in Table C.3. As the scheme of integration over time, the semi-implicit scheme of Nemchinov-Sadokov-Rober is used. This model considers basic physical processes within the atmosphere and at the underlying land surface important for large-scale numerical weather forecast and atmospheric circulation modeling. Below a brief description of these processes will be given.

Table C.3. *Level numbers and σ values in the middle of the layers used in the hydrodynamic prognostic model*

N	15	14	13	12	11	10	9	8
σ	0.99	0.96	0.91	0.85	0.77	0.68	0.59	0.5
N	7	6	5	4	3	2	1	
σ	0.45	0.34	0.26	0.19	0.15	0.07	0.05	

Horizontal macroturbulence. For the parameterization of horizontal turbulence processes a linear scheme of a fourth order is used. In this model version it is assumed that the horizontal diffusion coefficient has the following value: $K_H = 8\text{x}10^{14}$ m^2/s.

Vertical diffusion transport. In the free atmosphere fluxes of the impulse, enthalpy and moisture are calculated on the basis of *K*-theory. The coefficient of vertical turbulence is determined by the hypothesis on mixing length. It is supposed that this coefficient depends on the wind shear and static stability. The parameterisation for the surface layer is based on Monin-Obukhov similarity theory.

Large-scale condensation. The parameterization is based on the fact that precipitation takes place when the humidity exceeds critical values which for “warm” clouds (with the temperature at the upper boundary higher than -12^{0}C) is 2 g/kg. In subcooled clouds all the condensed moisture precipitates. Besides the effect of rain drops evaporation is taken into account and corrections for negative humidity values resulted from approximation errors are made.

Convective processes. In the parameterization of wet convective processes the scheme of Kuo penetrating convection is used. Vertical and horizontal convective turbulent fluxes of the momentum, enthalpy and moisture are not considered in this version of the model, since it is supposed that their impact on the atmospheric circulation is negligible.

Solar radiation. The parameterization scheme for radiation processes considers main effects of solar radiation on the atmosphere and ground surface. The effect of cloudiness and aerosol are considered in detail. The lower troposphere is the field of main interest in view of supplying the models with the data for computation of pollutant transport. For the lower troposphere the diurnal variation plays an essential role in the reproduction of circulation. It inflicts a considerable impact on near surface processes and therefore it is introduced in diurnal and annual variations of short-wave length radiation.

Calculations of land surface temperature. Temperature of the land surface is a prognostic variable. It is assumed that land is represented by a thin layer (0.42 m) of soil where the local exchange of moisture and heat with the atmosphere takes place. Temperature is calculated on the basis of heat balance conditions, including long-wave and short-wave radiation fluxes, latent and sensible heat turbulent fluxes and heat flux to the surface. Energy transfers because of water freezing or snow melting are considered as well.

Parameterisation of land hydrology. It is assumed that soil is divided into two layers. While calculating moisture variations in the upper soil layer, snow melting, moisture input due to precipitation and its diminishing due to evaporation as well as diffusive exchange with the lower layer are taken into account. The horizontal transport of moisture in soil is absent.

Boundary conditions

At the upper and lower boundaries kinematic conditions are prescribed:

$$\sigma = 0 \text{ at } \sigma = 0 \text{ and } \sigma = 1$$

and at $\sigma = 0$ the condition of absence of heat, moisture and impulse fluxes is also used.

As lower boundary conditions we use fields of the surface temperature (recalculated in the computation process), ocean surface temperature (prescribed), *sea ice distribution (prescribed)*, temperature at the depth of D = 0.42 m (T_D) (prescribed), soil moisture content (recalculated in the computation process), snow cover height (prescribed). In addition, fields of the roughness height and surface albedo (corrected for ice and snow in the course of computations) are used. Fields of sea ice distribution and ocean surface temperature were provided by National Centre of Environmental Predictions (the USA NCEP/NOAA).

Computation of boundary layer parameters

The main task of computation of boundary layer parameters is the definition of vertical structure of meteorological variables inside the atmospheric boundary layer (ABL), up to the height about 1500 m and computation of vertical turbulent diffusion coefficients on four lower levels, friction velocity, and Monin-Obukhov length scale.

The problem is to determine the vertical structure of ABL on the basis of meteorological variables (horizontal wind speed components (*u,v*), air temperature *T* and its specific humidity *q*) at the prescribed boundaries:

ABL upper boundary:

$$z = h \sim 1500 \text{ m } (\sim 850 \text{ hPa}): \quad u = u_h, \quad v = v_h, \; T = T_h, \; q = q_h \tag{C.6}$$

underlying surface,

$$z = 0 \;\; (\text{or } z = z_0 - \text{roughness level}) \quad u = 0, \; v = 0, \; T = T_0, \; q = q_0 \tag{C.7}$$

It is assumed that fields of wind speed, temperature and air humidity are statistically stationary and statistically uniform along the horizontal. It is also assumed that within ABL it is possible to neglect vertical variations of radiation heat flux. On these assumptions all point statistical characteristic of meteorological fields (mean values of *u*, *v*, *T*, *q* and characteristic of turbulence) should be directly dependent only on the height above the underlying surface. Functional expressions for these dependencies are determined from equations for momentum, heat and moisture transport. Hence the formulated model can be interpreted as a hydrodynamic interpolator of meteorological variables within ABL [*Zilitinkevich et al*., 1978]:

$$f(v - v_g) + \frac{1}{\rho}\frac{\partial \tau_x}{\partial z} = 0, \tag{C.8}$$

$$-f(u - u_g) + \frac{1}{\rho}\frac{\partial \tau_y}{\partial z} = 0, \tag{C.9}$$

$$\frac{\partial F_T}{\partial z} = 0, \tag{C.10}$$

$$\frac{\partial F_q}{\partial z} = 0. \tag{C.11}$$

where $\tau_x = -\rho\overline{u'w'}$ and $\tau_y = -\rho\overline{v'w'}$ are the components of vertical momentum flux;

$F_T = \rho c_p \overline{T'w'}$ and $F_q = \rho\overline{q'w'}$ are vertical turbulent fluxes of heat and moisture, respectively;

u, *v*, and *w* are wind velocity components;
T is air temperature;
q is specific humidity;
ρ is air density;
c_p is air specific heat capacity at constant pressure;
u_g and v_g are geostrophic wind components;
f is Coriolis parameter;
P is atmospheric pressure. The prime sign indicates turbulent fluctuations and the bar above means statistical averaging.

In order to close the equation set (C.8 – C.11) first order closure scheme is used. First order closure schemes determine the link between vertical gradients of substances and their vertical fluxes:

$$\left.\begin{aligned}\tau_x / \rho &= -\overline{u'w'} = k_m \partial u / \partial z \\ \tau_y / \rho &= -\overline{v'w'} = k_m \partial v / \partial z\end{aligned}\right\}, \tag{C.11}$$

$$F_T /(\rho c_p) = \overline{T'w'} = -k_T (\partial T / \partial z + g / c_p), \tag{C.13}$$

$$F_q / \rho = \overline{q'w'} = -k_q \partial q / \partial z . \tag{C.14}$$

where g/c_p is adiabatic lapse rate;
g = 9.8 m/sec^2 is gravity acceleration;
$c_p = 1 \cdot 10^{-3}$ is specific air heat capacity at constant pressure, J/(kg·K);
k_m, k_T and k_q are turbulent mixing coefficients for momentum, heat and moisture, respectively.

Following commonly accepted practice, it is assumed that turbulent mixing coefficients for heat and moisture are equal:

$$k_T = k_q \equiv k_H , \tag{C.15}$$

Formulas used for calculation of the coefficients in Ekman layer are as follows [*Smith,* 1993]:

$$k_m = l_m{}^2 f_m (Ri) \left|\frac{\partial \mathbf{u}}{\partial z}\right|, \tag{C.16}$$

$$k_H = l_m l_H f_H (Ri) \left|\frac{\partial \mathbf{u}}{\partial z}\right|, \tag{C.17}$$

where Ri is the local Richardson number,

$$Ri = \frac{\partial B / \partial z}{\left|\partial \mathbf{u} / \partial z\right|^2} = \frac{g\,[(1/T)(\partial T / \partial z + g / c_p) + 0.61 \partial q / \partial z]}{\left|\partial \mathbf{u} / \partial z\right|^2}, \tag{C.18}$$

Stability functions f_m and f_H are computed according to the formulas:

$$f_m = f_H = 1/(1 + c_1 Ri) \qquad \text{at } Ri \ge 0, \tag{C.19}$$

$$\left.\begin{aligned} f_m &= 1 - c_1 Ri / [1 + (c_1 / c_2)(l_m / l_H)(-Ri)^{1/2}] \\ f_H &= 1 - c_1 Ri / [1 + (c_1 / c_3)(l_m / l_H)(-Ri)^{1/2}] \end{aligned}\right\} \qquad \text{at } Ri < 0. \tag{C.20}$$

Here l_m and l_H are mixing lengths at neutral stratification, derived from the work [*Blackadar,* 1962]:

$$l_m(z) = \kappa z /(1 + \kappa z / \lambda_m), \tag{C.21}$$

$$l_H(z) = \kappa z /(1 + \kappa z / \lambda_H), \tag{C.22}$$

where $c_1 = 10$, $c_2 = 4$, $c_3 = 25$ are empirical coefficients;
$\kappa = 0.4$ is von Karman constant;
and λ_m and λ_H are the asymptotic values of mixing length, proportional to the boundary layer depth. In this work it is assumed that $\lambda_m = \lambda_H = 0.2 \cdot h = 0.2 \times 1500$ m = 300 m.

The surface layer is described on the basis of Monin-Obukhov similarity theory. According to the theory vertical gradients of wind velocity $\partial \mathbf{u}/\partial z$, of potential temperature $\partial\theta/\partial z$ and specific humidity $\partial q/\partial z$ are described by dimensionless functions of dimensionless height $\zeta = z/L$:

$$\frac{\partial \mathbf{u}}{\partial z} = \frac{\mathbf{u}_*}{\kappa z}\varphi_m(\zeta)\,, \tag{4.1}$$

$$\frac{\partial \theta}{\partial z} = \frac{\partial T}{\partial z} + \frac{g}{c_p} = \frac{T_*}{\kappa z}\varphi_T(\zeta)\,, \tag{C.23}$$

$$\frac{\partial q}{\partial z} = \frac{q_*}{\kappa z}\varphi_q(\zeta)\,, \tag{C.24}$$

where $\mathbf{u}_*$, T_* are q_* are the scaling parameters for velocity (friction velocity), temperature and air moisture.

Traditionally equations for ABL refer to z-coordinate system where vertical distances are determined in geometrical units. At the same time the system supplying pollution transport models with meteorological information uses σ-levels. In this connection ABL equations are rewritten in the σ-system. The problem is solved by the iteration method with subsequent determination of coefficients dependent on the solution of the system. The iteration process is continued until the difference between solutions on the two subsequent iterations is less than a small threshold level.

Correction of precipitation fields

Precipitation amounts in SDA are computed by the hydrodynamical model. At the same time there is a network of more than 4000 synoptic stations measuring precipitation amounts. Special procedure was developed in order to use these station data for correction of modeled precipitation amounts. The procedure includes the following stages:

- Control of station data and distribution of them within equal temporal intervals
- Objective analysis of atmospheric precipitation
- Correction of vertical distribution of precipitation amounts.

Objective analysis is based on approach of optimal interpolation. The details of the correction procedure one can find in work [*Rubinstein et al*., 2002].

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