NUMERICAL SIMULATION OF FRONTAL MIXED CLOUD SYSTEMS AND CLOUD MICROSTRUCTURE EFFECT ON SATELLITE SIGNAL

V. Bakhanov, O. Kryvobok, B. Dorman

Ukrainian Hydrometeorological Research Institute, Avenue of Science 37, 03028 Kyiv, Ukraine

ABSTRACT

This paper presents some results of consecutive numerical simulation of the satellite signal (SS, cloud reflectance in visible and near-infrared part of spectrum) for frontal mixed clouds with several forms of crystals. The simulation is based on the next models: a) the microphysical model of clouds, b) models of computation of light scattering characteristics by drop and crystal systems, c) the simulation of radiative transfer in non-uniform thick mixed clouds. Simulations have shown that the main contribution to the integral optical thickness makes the liquid water content. SS at $\lambda_2 = 1.6 \ \mu\text{m}$ and $\lambda_3 = 3.6 \ \mu\text{m}$ are very different in a great liquid water content region but become close in a region of significant crystallization and precipitation.

Considered in the next table is the block-diagram of the satellite signal simulation:

<table>
<thead>
<tr>
<th>Initial and boundary conditions for the numerical cloud model. Thermodynamical and microphysical parameters of atmosphere</th>
<th>Numerical microphysical model of a mixed stratiform cloud with several forms of crystals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength, complex index of refraction</td>
<td>Evolution of thermodynamical, geometrical and microphysical characteristics of model clouds (including size spectra of droplets and crystals of several forms)</td>
</tr>
<tr>
<td>Geometry of observations, surface reflectance</td>
<td>Calculations of light scattering characteristics for droplets and crystals</td>
</tr>
<tr>
<td></td>
<td>Phase functions, extinction coefficients</td>
</tr>
<tr>
<td></td>
<td>Simulation of satellite signal</td>
</tr>
<tr>
<td></td>
<td>Reflectance of model clouds</td>
</tr>
</tbody>
</table>
1. NUMERICAL MICROPHYSICAL MODEL OF FRONTAL CLOUDS

The numerical 1D time-dependent microphysical model of stratiform mixed cloud with several crystal forms (needles, columns, plates) was described in our previous papers (Bakhanov et al. 1991, 1996). Here we will give only brief description of our model.

The model equation system consists of equations of heat and vapor transfer and 4 kinetic equations for size distributions of drops and crystals \( f_j(r_j, t, z) \) (\( j = 1 \) – for drops, \( j = 2 \) – for needles, \( j = 3 \) – for plates, \( j = 4 \) – for columns; \( r_j \) – the characteristic dimension of particles; \( t \) – time; \( z \) – height). Functions \( f_j \) are normalised on \( n_j \) – concentration of particles (in air mass unit). The cloud dynamics is parameterized: the updraft velocity \( w = w(z) \) depends on \( z \) parabolically in an interval \( z_1 < z < z_2 \) with the maximum velocity \( w_m \) at \( z_3 = \frac{z_1 + z_2}{2} \) (\( z_1, z_2, w_m \) were varied). We will consider in this presentation so called sorbtion ("condensation – freezing") ice nuclei (IN) which are activated if the supersaturation over water is reached. Distribution of the IN concentration by overcooling has the next form (the approximation of empiric data):

\[
-(dN_j/dT) = \mu_j A_s \exp[ B_s (T_o - T)],
\]

where \( T \) – temperature, \( T_o = 0 \degree C \), \( B_s = 0.2 \((\degree C)^{-1}\) \( A_s \) was varied in the range \( 0.002 - 0.05 \((\degree C)^{-1}\) \. Temperature intervals for nucleation of different crystal forms are different: for needles \(-10 < T < -5 \degree C\), for columns \( T < -25 \degree C\) for plates \(-25 < T < -10 \degree C\). In these intervals \( \mu_j = 1 \), outside \( \mu_j = 0 \). Since the share of needles in a total concentration of crystals below 0.1% we will not discuss characteristics of needles. Needles and columns were approximated by prolate spheroids with the minor and major axes equals \( 2b \) and \( 2r \) respectively, plates were approximated by cylinders with radius \( r_3 \).

Numerical simulation has been shown that the dynamical structure of a front under study (especially heights and thicknesses of updraft cells) determines the phase composition, crystal form spectra and efficiency of precipitation formation. The predominate form in snowfalls is plate if the top cloud boundary height less than 4.8 – 5.0 km. These clouds have a very large total liquid water content (TLWC) to 1 mm. If the top boundary has height as isotherm - 34...-35\degree C the predominate crystal form is column, these clouds have the high efficiency of precipitation formation and high ice content (IC).

We will consider in this presentation in detail only one example of the mixed cloud evolution \( (w_m = 5 \text{ cm/s} \), \( z_1 = 0.3 \text{ km}, z_2 = 5.7 \text{ km}, A_s = 0.015 \((\degree C)^{-1}\) \). Figure 1 depicts the time-spatial sections of LWC – liquid water content, \((\text{IC})_3\) – ice content for plates, \((\text{IC})_4\) – ice content for columns. All values are given in g/kg (of air).

\[ \text{a} \] LWC \[ \text{b} \] \((\text{IC})_3\) for plates \[ \text{c} \] \((\text{IC})_4\) for columns. All in g/kg.

It is seen that the thick mixed cloud has been formed in 3-5 hours of evolution, maxima LWC are more than 0.1 g/kg at 5 h. The further crystallization process leads to abrupt decrease of LWC, increase of \((\text{IC})_3\) and especially \((\text{IC})_4\) at \( t >10 \text{ h} \) (near 0.1 g/kg). Average sizes of plates are more than 600 – 800 \( \mu \text{m} \) (see Figure 2) and after 8-10 h the precipitation rate amounts to 0.4-0.5 mm/h (see Figure 3).
2. LIGHT SCATTERING CHARACTERISTICS OF MIXED CLOUDS

Simulations of scattering characteristics of liquid drops are based on the Mie theory (Deirmendjian, 1969). Simulations of scattering properties for randomly oriented ice crystals are based on the geometric optics and the far-field diffraction approximation (Macke et al., 1996).

We will depict further some optical characteristics of cloud mixture of drops and crystals in our model cloud. The expressions of the scattering coefficient $\beta_s$, the extinction coefficient $\beta_e$, the single scattering albedo $\sigma$, the asymmetry factor $g$ have so forms:

$$\beta_s = \sum_{j=1}^{4} \beta_s^{(j)} , \quad (2)$$

$$\beta_e = \sum_{j=1}^{4} \beta_e^{(j)} , \quad (3)$$

$$\sigma = \frac{\beta_s}{\beta_e} , \quad (4)$$

$$g = \frac{1}{\beta_s} \sum_{j=1}^{4} \beta_s^{(j)} g^{(j)} , \quad (5)$$
where summation \((j = 1,2,3,4)\) is carried out all particle species.

Figure 4a and 4b depict correspondingly the time-spatial section of \(\sigma\) and \(g\) in the cloud under study. In upper cloud layers (droplets and crystals are present) \(\sigma = 0.7-0.8, \ g = 0.6-0.7\). Values essentially raise in lower cloud layers where LWQ is nearly absent and only plates and columns are present: \(\sigma > 0.9, \ g > 0.8\).

Figure 4. Time-spatial sections of single scattering albedo (a) and asymmetry factor of cloud particles (b), \(\lambda_3 = 3.6\ \mu m\).

Figure 5a depicts the time-spatial section of local optical thicknesses (LOT) or else optical thicknesses of thin 300 m layers in our model cloud under study:

\[
\Delta \tau_k = \int_{z_k}^{z_k + \Delta z_k} \beta_\tau(\zeta) d\zeta.
\]  \hspace{1cm} (6)

The section on Figure 5a corresponds to the wave length of satellite radiometer \(\lambda_3 = 3.6\ \mu m\). Figure 5b depicts the dependence of the integral optical thickness of the whole model cloud under study on time (\(\lambda_3 = 3.6\ \mu m\) also). Dependences of IOT on time for three wave lengths (\(\lambda_1 = 0.55\ \mu m, \lambda_2 = 1.6\ \mu m, \lambda_3 = 3.6\ \mu m\)) under study are close with each other.

Figure 5. a –Time-spatial section of the local optical thicknesses \((\lambda_3 = 3.6\ \mu m)\), b –Dependence of the cloud integral optical thickness (IOT) on time \((\lambda_3 = 3.6\ \mu m)\).

It’s easy to see from comparison Figure 1a and Figure 5a that LWC determines LOT sufficiently. IOT runs up maximum value \(\sim 18\) at \(t = 5\ h\) and then decreases as a result of crystallization of the cloud and considerable decrease of LWC.
3. SIMULATION OF SATELLITE SIGNAL

Discrete Ordinate Method (DOM, Liou, 1973; Stamnes et al., 1988) was used for simulation of solar radiation transfer in non-uniform clouds and calculation of measured reflected intensity on satellite. We have used the two-stream approximation for radiative transfer. This method was slightly modified by one of authors (Kryvobok, 1988). Thick clouds were divided into thin layers with constant microphysical and optical characteristics. The cosine of the solar angle is equal 0.9, the earth surface albedo is equal to zero. We will determine SS (satellite signal) as a cloud reflectance of solar radiation in visible and near-infrared part of spectrum. Figure 8 depicts results of SS simulation for the cloud under study in this presentation.

![Figure 6](image)

*Figure 6. Satellite signal from the model cloud, 1 - $\lambda_1 = 0.55 \, \mu m$, 2 – $\lambda_2 = 1.6 \, \mu m$, 3 – $\lambda_3 = 3.6 \, \mu m$."

Comparison Figure 5b and Figure 6 shows that reflectances for satellite radiometer channels $\lambda_1 = 0.55 \, \mu m$ and $\lambda_2 = 1.6 \, \mu m$ change synchronously with IOT. The abrupt decrease of IOT and SS at $t > 7h$ is connected with crystallization process and LWC decrease. SS in the radiometer channel $\lambda_3 = 3.6 \, \mu m$ is less sensible to the optical thickness (more sensible to microphysical and optical characteristics of single scattering). The important result: $SS_{\lambda_2}$ and $SS_{\lambda_3}$ are very different in a great LWC region: $(SS_{\lambda_2} / SS_{\lambda_3}) \sim 3$, but these signals get close values in a region of significant crystallization and precipitation.

4. CONCLUSIONS

a) The numerical model of mixed frontal clouds with several forms of crystals shows that the phase composition, the crystal form spectra and precipitation formation efficiency are dependent on dynamical structure of front and ice nuclei properties.

b) Simulations of satellite signal (cloud albedo) show that $SS_{\lambda_1}$ and $SS_{\lambda_2}$ change synchronously with the integral optical thickness of a cloud. The main contribution to IOT makes LWC.

c) The channel $\lambda_3 = 3.6 \, \mu m$ is less sensible to the optical thickness. SS at $\lambda_2 = 1.6 \, \mu m$ and $\lambda_3 = 3.6 \, \mu m$ are very different in a great LWC region but become close in a region of significant crystallization and precipitation.

The preliminary conclusion: the comparison of $SS_{\lambda_1}$, $SS_{\lambda_2}$, $SS_{\lambda_3}$ gives the possibility to distinguish regions with thick LWC layers and regions of highly developed crystallization and precipitation.
5. REFERENCES

BAKHANOV, V. P., and DORMAN, B. A., (1992) Natural and seeded precipitation formation in frontal stratiform clouds with several crystal forms. Proceedings of the UHRI (Kyiv, in Russian), 243, pp 8-23


