RETRIEVAL OF MICROPHYSICAL AND OPTICAL CHARACTERISTICS OF MIXED FRONTAL CLOUDS FROM MULTISPECTRAL SATELLITE DATA

Vladimir Bakhanov, Oleksiy Kryvobok, Boris Dorman

Ukrainian Hydrometeorological Research Institute, Prospekt Nauki 37, 03028 Kyiv, Ukraine

Abstract

The paper is devoted to retrieving stratiform mixed cloud characteristics from multispectral radiometric data or in a more narrow sense to the relationship between cloud reflectance in visible and near infrared channels of a satellite radiometer and optical thickness and microphysical characteristics of cloudiness.

At first we realized the consecutive numerical simulation of microphysical and optical characteristics of frontal mixed stratiform clouds with several crystal forms and simulation of the cloud reflectance (satellite signal) in visible and near infrared satellite channels. The simulation is based on the next models: a) the detailed microphysical model of a cloud with 3 crystal forms (needles, plates, columns); b) algorithms of calculations of scattering characteristics for drops (based on the Mie theory) and crystals (based on the geometric optics approximation); c) the discrete ordinate method for simulation of solar radiative transfer in a not uniform cloud.

Results of the simulation were used for improvement of the retrieval procedure of the cloud optical thickness and effective radius of cloud particles. It was developed also the procedure of distinguishing regions with the great liquid water content and nearly crystal clouds. It was made processing of the NOOA images made on 29.12.2002 over Ukraine. Estimations of microphysical and optical characteristics correspond with ground-based precipitation data.

SHORT DESCRIPTION OF NUMERICAL MODELS

1. The simulation of microphysical characteristics of frontal mixed clouds is based on the realistic 1D microphysical model of stratiform mixed cloud with 3 crystal forms (Bakhanov and Dorman, 1992, 1996; Bakhanov et al., 2004; Buykov and Dorman, 1987) consists of equations of heat and vapor transfer and 4 kinetic equations for dimension spectra \[ n_j(r_j, t, z) \] of drops and crystals (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).

The cloud dynamics is parameterized: the updraft velocity \( w = w(z) \) depends on \( z \) parabolically in interval \( z_1 < z < z_2 \) with the maximum velocity \( w_m \) (in this presentation \( w_m = 5 \) cm/s, \( z_1 = 0.3 \) km, \( z_2 \) is varied).

We will consider so called sorbtion (“condensation – freezing”) ice nuclei (IN) which are activated if the supersaturation over water is reached as well as sublimation IN which are activated if the supersaturation over ice is reached. Distribution of the IN concentration by overcooling has the next form (the approximation of empiric data):

\[
-\frac{dN_j}{dT} = \mu_j A_5 \exp\left[ B_5 (T_0 - T)\right],
\]

where \( T \) – temperature, \( T_0 = 0 \) ° C, \( B_5 = 0.2 \) (° C)\(^{-1}\), \( A_5 \) is varied. Table 1 shows model forms of cloud particles and temperature intervals for nucleation of different crystal forms. In these intervals \( \mu_j = 1 \), outside \( \mu_j = 0 \). Needles and columns were approximated with spheroids (\( b \) – the minor semiaxis, \( a \) – major semiaxis, \( a = r_\perp \) – the typical radius of a particle), plates were approximated with thin cylinders (\( h \) and \( r = r_\perp \) – height and radius of cylinders). In the Table 1 \( \rho_j \) – specific density of crystals. Since the share of needles in a total concentration of crystals below 0.1% we will not discuss characteristics of needles.
Table 1: Classification of cloud particle forms.

<table>
<thead>
<tr>
<th>particle type</th>
<th>modeling form</th>
<th>$\rho_j$, g/cm$^3$</th>
<th>$b/a$, (h/r)</th>
<th>temperature interval of nucleation, o°C</th>
<th>$r_j$, µm</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>droplet</td>
<td>sphere</td>
<td>1.0</td>
<td>1</td>
<td>-5 - 10</td>
<td></td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>needle</td>
<td>prolate spheroid</td>
<td>0.9</td>
<td>1/16</td>
<td>-10 - 25</td>
<td></td>
<td>150</td>
<td>1500</td>
</tr>
<tr>
<td>plate</td>
<td>thin cylinder</td>
<td>0.2</td>
<td>1/10</td>
<td>-10 - 25</td>
<td></td>
<td>120</td>
<td>1200</td>
</tr>
<tr>
<td>column</td>
<td>spheroid</td>
<td>0.9</td>
<td>1/2</td>
<td>-5 - 10; &lt; - 25</td>
<td></td>
<td>80</td>
<td>800</td>
</tr>
</tbody>
</table>

2. Algorithms of calculations of light scattering characteristics are based for drops on the Mie theory (Deirmendjian, 1969), for crystals – on the geometric optic approximation (Macke et al., 1996). The expressions of the scattering coefficient $\beta_s$, extinction coefficient $\beta_e$, phase function $P$, the asymmetry factor $g$, the single scattering albedo $\omega = (\beta_s / \beta_e)$ for a mixture of drops and crystals are calculated by summation at all particle species.

We made calculation for the next wavelengths: $\lambda_1 = 0.55$ µm, $\lambda_2 = 0.78$ µm, $\lambda_3 = 1.6$ µm, $\lambda_4 = 3.6$ µm (in accordance with channels of the AVHRR radiometer of NOAA series).

3. Simulation of the satellite signal (cloud reflectance CR) is based on the Discrete Ordinate Method (DOM) for simulation of solar radiative transfer in a uniform cloud (Liou, 1973; Stamnes and Dale, 1981). We used the two-stream approximation in which the solution depends on two parameters: $\omega$ - single scattering albedo and $g$ – asymmetry factor. Thick not uniform clouds were divided into thin sublayers with constant microphysical and optical characteristics.

EXAMPLE OF MIXED CLOUD EVOLUTION

Now we will consider in detail one example of the mixed cloud evolution (sorption IN, $z_2 = 5.7$ km, nucleation rate parameter $A_s = 0.015$ (g · ° C$^{-1}$)).

Fig.1 depicts the time-spatial sections of LWC – liquid water content, (IC)$_3$ – ice content for plates, (IC)$_4$ – ice content for columns. All values are given in g/kg (of air).

Figure 1: Evolution of the model mixed cloud: a – LWC, b – (IC)$_3$ for plates, c – (IC)$_4$ for columns. All values in g/kg.

It has been seen that the thick nearly liquid droplet 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 (IC)$_3$ and especially (IC)$_4$ at $t > 10$ h (near 0.1 g/kg).
Average sizes of columns are more than 150 – 200 µm (see Fig.2) and after 10 h the precipitation rate amounts to 0.4-0.5 mm/h (Fig. 3).

Calculations ($\lambda_d = 3.6$ µm) of the single scattering albedo $\sigma$ in our cloud under study show that $\sigma = 0.85 – 0.89$ in upper cloud layers (where droplets and crystals are present) while $\sigma < 0.81$ in lower layers (where droplets are nearly absent). The asymmetry factor values $g = 0.6 – 0.8$ in upper layers while $g > 0.8$ in lower layers.

Fig. 4 depicts the cross-section of so called local optical thickness LOT or optical thickness of thin 0.3 km sublayers in our model cloud. The section on Fig. 4 corresponds to the wavelength 3.6 µm. It is easy to see from comparison Fig. 1a and Fig.4 that LWC determined LOT sufficiently. It is very interesting that our model gives two layers with higher optical density. The lower layer consists of crystals only. Fig. 5 depicts the integral optical thickness of the cloud (COT), which first increases up to 35-38 (at t = 5 – 7 hours) and then decreases to ~15 (at t = 20 hours) as a result of crystallization and substantial decrease of LWC.

Figure 2: Average sizes (in µm) of plates (a) and columns (b).

Figure 3: Dependence of precipitation rate on cloud evolution time (1 – PR of plates, 2 – of columns, 3 – total PR).

Figure 4: The time-special section of the local optical thickness (LOT), $\lambda = 3.6$ µm.
Fig. 6 depicts results of cloud reflection (CR) simulation (the cosine of the solar angle is equal 0.9, the earth surface albedo is equal zero). Cloud reflections in channels 0.55 µm and 0.78 µm are near, therefore we will use the first channel. Comparison between Fig. 6 and Fig. 5 shows that CR in the channels $\lambda_1 = 0.55 \mu m$ and $\lambda_2 = 1.6 \mu m$ change synchronously with COT. The satellite signal CR in the radiometer channel $\lambda_4 = 3.6 \mu m$ is less sensible to the cloud optical thickness (more to microphysical and optical parameters $\omega, g$).

In the great LWC region ($t = 5$ h) the COT $> 35$ as in the highly developed crystallization region COT $< 20$ ($t > 10-15$ h).

**RESULTS OF CALCULATIONS OF MICROPHYSICAL AND OPTICAL CHARACTERISTICS FOR CLOUDS WITH DIFFERENT PHASE COMPOSITION**

We have realized calculations for different variants in which IN type (sorption, sublimation), nucleation rate ($A_\omega$), cloud top height $z_2$ (or corresponding temperature of the upper boundary $T_{ct}$) were varied. The variant described in detail in the previous section corresponds to $T_{ct} \sim 34^0 C$.

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.

If the cloud top has a height less than 4.8 – 5.0 km (or the cloud top temperature $T_{ct} > -30^0 C$) mainly water-droplet clouds are formed. The predominate form in snowfalls is the plate at that. These clouds have a very large total LWC more than 1mm if the parameter $A_\omega$ is small ($A_\omega < 0.015 (g \cdot ^0 C)^{-1}$). If $A_\omega$ is equal more than 0.05 ($g \cdot ^0 C)^{-1}$ nearly ice clouds are formed.

If the cloud top has a height less than 4.8 – 5.0 km (or the cloud top temperature $T_{ct} > -30^0 C$) mainly water-droplet clouds are formed. These clouds have a very large total LWC more than 1mm if the parameter $A_\omega$ is small ($A_\omega < 0.015 (g \cdot ^0 C)^{-1}$). If a nucleation rate value is enough ($A_\omega = 0.05g \cdot ^0 C)^{-1}$) nearly ice clouds are formed.

If $T_{ct} < -30…-34^0 C$ nearly ice cloud are formed in most cases and the predominate form in snowfalls is column. The high efficiency of precipitation formation and the great value of (IC)$_4$ are typical for these clouds.
Table 2: Ranges of CR and COT values for clouds with different temperatures of the upper boundary

<table>
<thead>
<tr>
<th>$T_{\text{eff}}$, $^\circ$C</th>
<th>mainly liquid water clouds</th>
<th>mainly ice clouds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COT</td>
<td>CR</td>
</tr>
<tr>
<td>-34</td>
<td>20-34</td>
<td>0.90-0.97</td>
</tr>
<tr>
<td>-23</td>
<td>30-200</td>
<td>0.80-1</td>
</tr>
</tbody>
</table>

The calculated ranges of COT and CR (for $\lambda_1 = 0.55\mu m$) are given in the Table 2 for clouds with high and low upper boundaries.

The Table 2 depicts that for clouds with high tops there are more or less sufficient criteria for distinguishing clouds with the great LWQ and of highly crystallization. Nevertheless the diapasons of COT and CR are overlapping.

Overlapping is much more in the case of low clouds. For mainly liquid droplet clouds COT can reach values 100 – 200 and more, CR ($\lambda_1 = 0.55 \mu m$) can reach values ~1 and does not depend on the cloud optical thickness. In the case of mainly ice low clouds COT values can reach values ~45 though on average COT for ice clouds less than for water droplet clouds. The cloud reflectance can reach values till 0.9 but never reach 1.

Thus it is possible to previously conclude that absolute values CR and and their ratios (for different channels) are insufficiently informative for distinguishing mainly water droplet clouds and ice clouds (especially for low clouds).

The simultaneously calculated values of COT and the effective dimension of cloud particles are more informative for our goal. The values of $r_{\text{eff}}$ in water clouds is less than 20$\mu$m as $r_{\text{eff}}$ in ice clouds are equal hundreds microns.

Calculations demonstrate that COT of ice clouds does not depend on the wave length and ratios of COT in the channels 1.6$\mu$m and 0.55$\mu$m satisfy the relationships:
- for ice cloud: \[ \text{COT}(1.6\mu m)/\text{COT}(0.55\mu m) \approx 1, \]
- for mixed clouds: \[ 1.04 > \text{COT}(1.6\mu m)/\text{COT}(0.55\mu m) > 1, \]
- for water clouds: \[ \text{COT}(1.6\mu m)/\text{COT}(0.55\mu m) < 1.04. \]

RETRIEVAL COT AND R$_{\text{EFF}}$ FROM MULTISPECTRAL SATELLITE IMAGES

Some results of the above satellite signal simulation were used: a) for improvement of the procedure of COT and $r_{\text{eff}}$ from measured CR in two radiometer channels, b) for improvement of the method of distinguishing of cloudiness regions with the great LWC and regions of highly crystallization and precipitations.

We have used the channels 0.6 $\mu$m and 1.6 $\mu$m of the radiometer AVHRR on NOAA satellites. The idea of the method of COT and $r_{\text{eff}}$ retrieval from spectrometric data in two channels (Nakajima, King, 1990) is based on the property that cloud reflectance CR depends mainly on COT in the channel $\lambda = 0.6 \mu$m and in the channel 1.6$\mu$m CR depends to a greater extent on microphysical parameters. We will as usual suppose that the cloud layer under study is uniform and contains only one phase. We will also suppose that crystals have only the plate form and the distribution of cloud particles on dimensions has the form of the $\Gamma$-function:

$$ f(r) \sim r^\alpha \exp(-br), \quad b = (\alpha + 3)/r_{\text{eff}}. \quad (2) $$

The next parameters are varied: wave length 0.63 $\mu$m and 1.6 $\mu$m; COT; $r_{\text{eff}}$ of droplets and crystals; zenithal angle of the Sun; sounding angle; azimuth angle. The multidimensional tables of CR (so called LUT’s) were calculated for uniform monophase clouds. Then we have developed so iterative scheme for the retrieval of COT and $r_{\text{eff}}$:

1) From LUT’s we determine COT(0.63 $\mu$m) corresponding to measured CR(0.63 $\mu$m) and some initial $r_{\text{eff,0}}$.
2) Then we calculate COT in the channel 1.6 $\mu$m.
3) Then with the help of LUT’s and COT(1.6 $\mu$m) we determine $r_{\text{eff,1}}$ corresponding to measured CR(1.6$\mu$m).
4) Then we backspace to the first step with the new $r_{\text{eff,1}}$.

We end the procedure when COT and $r_{\text{eff}}$ end to vary.

Let us consider the individual example 29.12.2002. The cyclone was observed over West Ukraine (two fronts), the stationary anticyclone – over the north-east region ( the front in the Chernigiv - Kharkiv region is practically motionless). Heavy precipitation are observed in Uzhgorod (13.4 mm per 14 hours) and over North-East Ukraine (near Chernigiv 10.4 mm per 14 hours).

We have processed the images made with theNOOA-12 (at 14:02 GMT) and NOOA-17 (at 09:46 GMT).
After primary processing of data we began to determine the phase composition of the cloudiness. If $T_{ct} < -30 \, ^\circ C$ ($T_{ct}$ – cloud top radiation temperature) we began the iterative procedure for a crystal cloud and ended it as $COT < 20-25$, $r_{eff} > 80 \, \mu m$.

If $T_{ct} > -30 \, ^\circ C$ we began the iterative procedure for a water-drop cloud and ended this procedure as $\tau > 25 - 30$, $r_{eff} < 20 \, \mu m$. Fig. 7 and 8 depicts the fields of retrieved COT and $r_{eff}$.

Figure 7: Retrieval of COT field using satellite data.

Figure 8: Retrieval of effective radius field using satellite data.
We can see that near crystal cloudiness is observed in west and north-west regions of Ukraine (COT < 20, often COT = 7 – 10, \( r_{\text{eff}} = 200 - 300 \) µm). The rest parts of Ukraine are covered with cloudiness with great LWC (COT ~ 30-35, \( r_{\text{eff}} \approx 7 – 15 \) µm). In the Chernigiv, Sumy regions one can see spots with smaller COT ~ 25 and \( r_{\text{eff}} = 15 \) µm. In these clouds precipitation also form (we saw this in the previous section) because these clouds are mixed in actuality. So estimations of microphysical and optical characteristics are in accord with ground-based precipitation data.

CONCLUSIONS

1. It was developed the realistic microphysical model of mixed stratiform clouds with several crystal forms. It were calculated microphysical, optical characteristics of these clouds including cloud reflectance (satellite signal) of the solar radiation in visible and near infrared channels.
2. Results of numerical simulations of optical characteristic dependence on the cloud phase composition depict that values of the cloud reflectance and the cloud optical thickness vary within wide limits and their diapasons overlap for mainly liquid droplet clouds and nearly ice clouds (especially for clouds with the low top). Therefore the more informative criteria for distinguishing mainly water droplet and nearly ice clouds are proposed. These criteria are based on combined analysis of radiative temperature of cloud top, cloud optical thickness, and effective radius of cloud particles.
3. It has been shown that the ratio of COT for \( \lambda = 1.6 \) µm to COT for \( \lambda = 0.55 \) µm correlate with the cloud phase composition. COT does not depend on wave length.
4. It was improved the procedure of COT and \( r_{\text{eff}} \) retrieval from measured CR values for the satellite radiometric channels 0.63 and 1.6 µm and the procedure of distinguishing mainly water droplet and nearly ice clouds.
5. It was made processing of the NOAA images made at 29.12.2002 over Ukraine. Estimations of microphysical and optical data are in accord with ground-based precipitation data.

REFERENCES