Extracting the Relationship of Visible Cloud Features and Atmospheric Conditions

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Some topics of interest in cloud meteorology include interactions between clouds and aerosols, cloud evolution in different atmospheric conditions, etc. Most of these cloud relations are better observed from the earth surface. Local or regional cloud variations are much larger and faster than the variations of global cloud systems observable from space. We make use of the resources of ground-based observations by means of digital photography for detecting the fine variations in cloud visible properties. Variations of some macro physical characteristics of clouds such as shape, thickness, motion, etc. are well displayed in series of photographs. The rates of changes of these characteristics are related to cloud microphysical properties that are determined by atmospheric conditions and cloud interactions with near-ground aerosols.

Physical basis

Among many others, the important terrestrial factors that influence the radiation budget and hydrological cycle of the planet are the atmospheric aerosols and clouds. Atmospheric aerosols influence climate in two main ways, referred to as direct forcing and indirect forcing. The indirect effect of aerosols on climate involves aerosol particles acting as cloud condensation nuclei. Aerosol particles are carried into the cloud by air motions. The number of cloud particles whose growth is initiated depends on the number and characteristics of these aerosols as well as the rate at which the air parcel cools. Cloud properties are sensitive to aerosol size, chemical composition, and meteorological conditions. In humid air, aerosol potential for hygroscopic growth controls the size distributions of aerosols and the cloud at its initial formation. The hygroscopic growth of the aerosol particles influences heterogeneous reactions, light extinction and meteorological visibility [1]. Clouds, in turn, influence the vertical distribution of the air humidity due to the fact that the cloud pumps water vapor from the boundary layer into the cloud. With the associated downdrafts at the sides the water vapor is transported downward toward the surface. It is further found an important upward and downward transport of aerosol particles across the boundary layer caused by the cloud [2].

A delay or acceleration in raindrop formation does not automatically lead to a decrease or an increase in the accumulated rain because of strong dynamical feedbacks induced by the changes in the precipitation-forming processes. The evolution of clouds, precipitation formation, and the radiation properties of clouds highly depend on environmental conditions, such as the atmospheric instability, wind shear and atmospheric humidity [3].

The role of clouds remains a major uncertainty in current-day climate change simulations. Validation of these model simulations requires increasingly comprehensive observations of clouds and their precursors - aerosols and water vapor [4].

Computing the details of cloud microphysics requires a detailed understanding of the dynamical processes moving water vapor through the atmosphere, and the physical mechanisms involved in the formation and growth of cloud particles, including heating and cooling by solar and terrestrial radiation [5]. Understanding both the cloud radiation and the cloud water feedbacks on the climate also requires understanding how atmospheric motions determine cloud properties and how cloud systems form, evolve and decay in different meteorological regimes [6]

Research grounds and approach

The best way for studying the relationship of cloud properties and surface atmosphere conditions is from ground-based observations. The nearness to the object of investigation when clouds are observed from the ground gives circumstantial information about some important characteristics such as: the vertical structure of clouds that is particularly diagnostic of the motions producing the clouds, 3D shapes, horizontal/vertical inhomogeneity, and so on. As far as the most aerosols are situated near the earth surface, the continuous ground-based observations serve adequately to carry out research on the complex aerosol-cloud interactions in relation with the surface and atmosphere properties. The net mass inflow and outflow through the other cloud boundaries is small compared to what enters via the cloud base [2] that is observable only from earth surface. Ground-based remote sensing observatories have a crucial role to play in providing data to improve our understanding of atmospheric processes, to test the performance of atmospheric models, and to develop new methods for future space-borne observations [4]. Together with the space and airborne, the ground-based remote sounding of the atmospheric constituents is an essential additional data provider for research in atmospheric physics and climate change. The short-wave (or visible) flux is more sensitive than the IR (or long wave) flux to variability in the water content and base and top heights of observed clouds [7].

In the present study, the affordable tool such as the ground-based conventional digital photography of clouds is used to establish some relations between the variations of visible cloud features and atmospheric parameters in very short time intervals. Because of their high resolution in space and time, ground-based series of cloud photographs allow for quantitative and detailed analysis of cloud development in different meteorological regimes detecting the fine changes of the cloud motion, thickness, shapes and borders.

The objectives of the present study include self training activities for extracting from ground-based visible images the representative features of clouds, that correspond to the specific surface and atmospheric meteorological conditions; looking for criteria that allow the interpretation of cloud visible characteristics as indicative of cloud physical properties in relation with dynamical atmospheric processes; study of the complex atmospheric aerosol-cloud interactions revealed by the variations of cloud optical properties in visible images taken from earth's surface. An attempt to find out the necessary visible features for assessment and interpretation of cloud properties and evolution on the base of some morphological features is made. Tracking analysis may be applied to determine the velocity of air motions aloft, to scrutinize the evolution of the convective cloud systems; texture analysis may be applied to automatic classification of cloud types. Analysis of the variations of cloud visible features then may be used for making some inferences about current atmospheric conditions.

The most important radiation characteristic of clouds that is investigated is the optical thickness (or depth). In the present study specially developed software tools for assessment the variation in cloud optical thickness are used. The geometry of observations is such that the measured cloud brightness corresponds predominantly to the transmitted light, i.e. the darker clouds the greater optical thickness of cloud. The variations of cloud brightness are interpreted as variations of its optical depth. The rate of changes of the optical thickness is expressed by the relative change of cloud brightness, determined from consecutive digital images with account of the specific settings of the camera. In order to set the correspondence between digital image codes and values of brightness, the camera specific settings, such as shutter speed, aperture value and focus are taken into account. We have restricted ourselves to the average black & white brightness, though the spectral radiance in the R, G and B channels could also be considered in principle. As far as we examine only the variations of cloud appearance and brightness in short time intervals, the need for an absolute calibration of the camera is avoided.

The radiance of transmitted light is directly related to the light extinction in clouds that is governed mostly by values of effective radius and liquid water content independently of the particle-size distribution [8]. The high time resolution in observable variations of cloud properties such as optical thickness allows for assessing the rates of microphysical processes in clouds.

Ground-based observations of clouds are strongly influenced by the distribution of the solar illumination due to the light scattering by the atmosphere and by the clouds themselves. Steady state cloud conditions such as stratus clouds and overcast sky allow reliable assessment of changes of their optical thickness. The broken cloud conditions, when clouds do not obscure the instrument, complicate the assessment of the variability of their radiance because of the edge scattering effects. Only fast changes at practically identical illumination conditions are reliably interpretable. Cumulus clouds, however, allow observations of the behavior of cloud edges, which display the transition processes between cloud and adjacent air related to the cloud-aerosol reversible interactions.

The fine visible changes of cloud appearance described by the variations of the optical thickness, of the shape and cloud edges, are juxtaposed to the current local meteorological parameters refreshed every half an hour available at the website:
http://bulgarian.wunderground.com/global/stations/15614.html. The atmospheric dynamics is accounted for by means of the values of the atmospheric pressure (P), temperature (T), wind velocity (W), etc., observed at the earth's surface. The size and number concentration of aerosols determine the volume scattering coefficient of the atmosphere that is in well-known practical relation to the meteorological visibility (V). The variations of the relative humidity (RH) and the horizontal visibility are considered to be representative of the variations of the type (natural/manmade) and amount of the atmospheric aerosols near the earth surface, and potentially, the cloud drop number concentration. Some evidences for the complex atmospheric aerosol-cloud interactions revealed by the variations of cloud optical properties in visible images taken from earth's surface are found. Also the influence of the mountain lay and the coexistence of multiple cloud layers are taken into consideration.

Data analysis and interpretation

Usually, our photographs include the sky in south hemisphere over the city of Sofia – the capital of Bulgaria. Sofia is situated at an average altitude of 550 m, but the given data about the pressure P refer to the sea level. Our site of observations is at a beeline distance of approximately 10 km to the summit of the nearest Vitosha Mountain.

We first outline the general distinction between cloud appearances in visible images acquired under different weather conditions. The left picture in Fig.1 presents remote white clouds over the summit of the Vitosha Mountain. They are a common occurrence associated with fine weather. The skies aloft are clear. Dark clouds like the one in the upper half of the 2nd picture in Fig.1 are usually associated with precipitations. In this case, however, the dark cloud is residual from a rainy one. The brightening of its upper part is a sign of its depleted precipitation efficiency due to already increased pressure to value above norm. The small clouds in the lower part of the picture are an evidence of the high RH and the worsened V of the air, i.e. the presence of abundant quantity of large size surface aerosol as a result of the passed rainfall.

Next we shall illustrate the observed variations of cloud properties in relation with the usually fast variable meteorological parameters in March. The influence of the mountain lay is also considered. The 6 consecutive digital photographs (Figures 2.1, 2.2, 2.3 - left and right, correspondingly) are taken within an hour.

In the first two images (Fig.2.1), an immediate visible effect on the cloud behavior during the slight fall of the low pressure by 1 hPa, and the drop of the wind speed W from 22 km/h to 7 km/h is observed. When the wind speed from the mountainside is stronger, the dark clouds remain pressed in the lee of the mountain. The drop of the wind speed releases the movement of clouds already formed at pressure below the norm. In short time of 5 minutes the clouds start to rise up, looking higher and larger, and reveal the mountain contour. The pictures are taken during further decreasing of the relative humidity RH of the dry air below the clouds from 47% to 39% that may be ascribed to the pumping effect due to the growth of the cloud droplets. The increasing of the temperature T at 4 p.m. (from 13°C to 15°C) also may point to thr the fact of coming rainfall due to the fast water vapor condensation on growing cloud droplets.

Fig.1. Fine weather clouds over the summit of Vitosha Mountain, the skies aloft are clear; P=1017 (norm), RH=39%, V=10 km (left). Depressive overhanging rainy cloud; P=1022 hPa (>norm), RH=72%, V=8 km (worsened) (right)

Fig.2.1. Δt = 5 min (from left to right), P = 1010< norm, falling to 1009; W = 7 km/h, S-W, dropping from 22 km/h; T – increases ($13^o \rightarrow 15^o$C) at 4:00 p.m.; RH - decreases (47%→39%)

Fig.2.2. Δt = 4 min (left-right), time delay 30 min from Fig. 2.1, W = 22 km/h.

Fig.2.3. Δt = 2 min (left-right), time delay 12 min from Fig. 2.2, W = 18 km/h

The meteorological conditions characterized by pressure that is not too much lower than the norm, and by depleted water supplies of the dry air beneath due to the redistribution of the air humidity by clouds themselves, lead to the loss of precipitation efficiency of these broken clouds. The inference may be drawn that the moderate or strong blowing wind promotes the evaporation of small cloud droplets. The effect of passing cloud dissipation finds expression in the slight increase of the RH and to fall in the T. The moderate or strong blowing W promotes the formation of cloud at the upwind side but keeps clouds in the lee of the downwind side of the mountain.

The next example illustrates the development of secondary stratocumulus cloud and the effect of primary upper cloud layer on the secondary lower clouds. Early in the morning a high altitude thin bright cloud layer is formed. During the process of primary cloud formation, the depletion of the near surface water supplies (RH decreases from 80 to 20%) accompanied with improvement of the horizontal visibility V to 25 km for a short time are registered. Later in the afternoon, secondary clouds appear from the lee of the mountain. Bit by bit, they stack into a steady state stratocumulus observed in the background of the primary cloud layer.

The two pictures in Fig. 3.1 show that in 40 minutes the observed low cloud gets thicker and accumulates vertical power. Opposite to the effect on surface atmosphere during formation of the primary cloud layer, now slight increase of RH and lowering in the T by a degree are registered. The situation may be explained with the transition of new air masses by the wind, if no other changes occur. But the base height of the primary cloud layer H_1 descends drastically from 6096 to 3048 m above ground level. More likely, a stronger wind at the upper levels moves water droplets and ice downwind fostering their fall through warmer dry air and their evaporation and sublimation. Downdraughts caused mainly by evaporation, sublimation and melting may explain the lowering of the temperature and the air moistening. The resulting replenishment of the water supplies below the higher cloud fosters the formation of the observed secondary low cloud.

The image features that may be extracted from the comparison of these two pictures are the descending and strengthening of the higher cloud layer expressed by its darkening; the increasing of the optical thickness and the changes of the base contour of the observed low cloud that has become heavy, smooth and well outlined, which is quite characteristic for early formation of the most nimbostratus-cumulus.

Further we consider the evolution of the low stratocumulus cloud expressed by the redistribution of cloud optical thickness and changes of the shape in relation with the registered meteorological conditions.

Half an hour later the base of the observed cloud does not look so smooth, but it breaks down. The visual comparison of the two pictures taken in 3 minutes (Fig. 3.2) clearly shows this tendency. Such changes of cloud appearance are assumed to be indicative of the complex transient interactions of cloud base with the air below the cloud. During still blowing wind leading to descending of cloud base heights and temporal dissipation in the dry air beneath, slight decreasing in the T and moistening of the cloud free air are noted. Thus the feedback – the effect of clouds on the atmospheric dynamics is displayed.

The quantitative assessment indicates that the mean brightness of rarifying cloud base increases by 2.5%. At the same time the mean transmitted brightness of the central part of the cloud "body" decreases by 53%. Even though observations of steady state clouds at dynamical equilibrium conditions show that cloud appearance varies little, quantitative assessments of cloud properties from digital images give useful information. The variations of cloud edges and base reveal the interactions with the adjacent air - droplets continually grow and evaporate by local moisture

Fig. 3.1: $\Delta t = 40$ min (left-right), $P = 1004 <$ norm, slight decrease; $W = 22$ km/h from S-SW (Vitosha mountain); T – decreases ($16 \rightarrow 15^{o}C$) at 3:30 p.m.; $RH < 60\%$ (dry air) - increases ($31 \rightarrow 34\%$); $H_2 = 1981$ m, slight rise; H_1 – descends ($6096 \rightarrow 3048$ m)

Fig. 3.2. $\Delta t = 3$ min (left-right), time delay 25 min from Fig.4.1 (right): $W = 22$ km/h from S-SW (Vitosha mountain); T – decreases ($15 \rightarrow 14^{o}C$); $RH < 60\%$ (dry air) - increases ($34 \rightarrow 41\%$); $P = 1004 <$ norm, steady; H_2 – descends ($2011 \rightarrow 1828$ m); H_1 – descends ($3048 \rightarrow 2438$ m)

Fig. 3.3: $\Delta t = 3$ min (left-right), time delay 30 min from Fig.4.2. $P = 1004$ hPa $<$ norm, slight falling; W – drops ($22 \rightarrow 4$ km/h); T – increases ($12 \rightarrow 14^{o}C$), few raindrops reach the ground; RH - increases ($31 \rightarrow 44\%$); $H_1 = 2438$ m, steady; V improves to 25 km for a while

variations. However, the steady thickening of the cloud in such short time intervals of a few minutes, detectable only by means of quantitative ground-based observations, is in line with the future precipitating cloud evolution.

In the next two pictures (Fig. 3.3) taken an hour later, the relationship of cloud appearance with variable meteorological conditions is shown. Under the slight falling of the pressure and the drop of the wind, fast formation of new secondary (rather tertiary) low clouds (areas denoted by ellipses) is initiated. The new just forming clouds rise up and join the base of the considered stratocumulus cloud. The activation of surface aerosols to give rise to droplet formation is often accompanied by temporal improving of the horizontal visibility. Due to the pumping effect during cloud formation, a short time improving of the V to 25 km that is much above the typical value of 10 km goes before the appearance of these new low clouds.

The mean brightness of cloud base near the area of merger (rectangles) decreases by 16%, while the decrease of the brightness of the remaining part of the cloud is slowing down - by 7%. Light rain showers begin half an hour later, continuing for some hours. While the blowing wind fosters spreading of drops and ice downwind and leads to higher loss in precipitation, the drop of the wind speed favors the growth of raindrops. The rate of final thickening slows down during the growth of the large raindrops at the expense of small ones.

These pictures are a visible corroboration of some model predictions (for example in [3]) that the formation of secondary clouds turns out to be dependent on the properties of primary clouds and the continental secondary clouds develop into a deeper cloud giving rise to squall line formation, but in dry air the precipitation efficiency of clouds is lost to some extent.

Many other observations indicate that the primary cloud formation is determined from meteorological preconditions, mainly by the availability of high air humidity ($RH > 60\%$) and/or worsened visibility. However, at high pressure the primary clouds are usually thinner and unstable. They tend to dissipate and the residual abundance of larger in size surface aerosol stipulates the formation of new low clouds but rarely is a sufficient condition for the growth of cloud droplets to raindrops. At $P >$ norm secondary clouds have longer lifetime and poorer precipitation efficiency (See Fig. 1 (right)).

Results and conclusions

The results show that the variations of visible features of clouds closely reflect meteorological conditions and their dynamics displayed in the relatively fast (compared to satellite observations) variability of cloud appearance. The high time resolution in observable variations of cloud properties such as redistribution of optical thickness allows for assessing the rates of microphysical processes in clouds. There are evidences that time intervals between measurements as short as several minutes may be indicative of the trend of evolution of certain types of clouds. Some complex atmospheric interactions based on physical processes in the atmosphere are established by means of quantitative analysis and visual interpretation of the acquired images of clouds. The remote sensing of the variations of cloud optical properties by means of visible images taken from earth's surface can improve our knowledge of the climatologic importance of atmospheric aerosols and clouds.

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