The actuality and progress of whole sky infrared cloud remote sensing techniques

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Abstract: Clouds are crucial regulators of both weather and climate. Properties such as the amount, type, height, distribution and movement of them have an impact on the earth´s radiation budget and the hydrological cycle, thus cloud observation is very important. The disadvantages of zenith pointing measuring instruments and whole sky visible imagers limit the application of them. A summary of the actuality and application of ground-based whole sky infrared cloud measuring instruments and analyses of the techniques of radiometric calibrations, removal of atmospheric emission and calculation of cloud cover, amount, type are conducted to promote the automatically observation of the whole sky. Fully considering whole sky infrared cloud sounding theories, techniques and applications, there are still a lot of studies on improving the properties of instruments, enhancing the techniques of cloud base height measurements and establishing instrumental cloud classification criterion before actual operations.

Key words: cloud; whole sky; infrared cloud remote sensing techniques

1 Introduction

The spatial and temporal distribution of clouds contributes to the Earth's radiative balance through reflection and absorption of incoming shortwave and outgoing longwave radiation[1]. It also plays an important role in the earth´s water and energy cycles. Besides, the cloud optical properties and spatial and vertical distribution at any given time will provide a cooling and warming effect on our weather forecasts and globe climate change. The large complexities and uncertainties of parameterizations representing cloud processes and cloud properties in the study of atmospheric science indicate that observations are critical for a better understanding of the role of cloudiness in the present, past and future.

At present, the key parameters of concern on the cloud observation business are cloud amount, form and height. However, the accurate determination of these parameters is still a highly desirable yet rarely attainable goal at many sites. Observations of them have been mainly conducted with visual observation, satellite remote sensing and ground-based remote sensing. Although human observation is still taken as an important aid in clouds observations, it has many significant drawbacks. Traditionally, human observation reports sky conditions featuring low temporary resolution, strong subjectivity, relatively simple records, weather-sensitive load, unaccessible to data at night, uneven distribution of stations around the world, and so on. Besides, the use of human observers is not always feasible due to budgetary constraints[2]. Therefore, human observation can´t completely meet the needs of the atmospheric science research.

Over the years, technological advances in satellite and sensor designs have allowed for greatly improved geometrically and radiometrically processed cloud data products. The major satellite remote sensing instruments consist of Advanced Very High Resolution Radiometer (AVHRR), the latest instrument version of which is AVHRR/3 with 6 channels, Moderate-Resolution Imaging Spectroradiometer (MODIS) and Landsat Multispectral Scanner (Landsat MSS) [3]. Although satellite remote sensing of cloud has made a great contribution to providing global information on cloud properties, it is limited to accurate identification of low clouds and regional clouds. Compared with the present state of satellite remote sensing, more advanced and convenient methods of ground-based measurement need to be explored. Ground-based remote sensing mainly contains active and passive observations. The zenith pointing remote sensing instruments are laser ceilometer, such as CL51, CL31, and so on, Raman lidar (RL) and Micro Pulse Lidar (MPL). The advantages are good monochromaticity, strong directionality, high coherence and small volume. Because all of them are in the adoption of single point measurement, representative of space is poor. The noise of the instruments has an effect on the acquisition of weak signal[4-6]. The millimeter cloud radar (MMCR) systems probe the extent and composition of clouds at millimeter wavelengths. The MMCR is a zenith-pointing radar that operates at a frequency of 35 GHz. The main purpose of this radar is to determine cloud boundaries (e. g., cloud bottoms and tops). This radar will also report radar reflectivity (dBz) of the atmosphere up to 20 km.

The radar possesses a Doppler capability that will allow the measurement of cloud constituent vertical velocities[7]. The remote sensing instruments in visual band represented by the Hemispheric Sky Imager (HSI), Total Sky Imager (TSI), Whole Sky Camera (WSC), All Sky Imager (ASI) are unaccessible to data at night and it is hard to achieve automatic continuous measurement of cloud cover. Besides, measurement accuracy is hard to ensure during the day affected by atmospheric visibility[8-15]. The expensive optics component and complicated engineering design of the instrument in multi band represented by the Whole Sky Imager (WSI) limit its popularity among meteorological researchers[16-17]. However, Sky imagers in infrared band can produce sky-cover measurements at high spatial and temporal resolution and are lower cost, objective and accessible during both day and night. Hence, Sky imagers in infrared band are promising to provide an ideal cloud measurement technique and have been highly concerned. This paper makes a summary of the actuality and application of ground-based whole sky infrared cloud measuring instruments and analyses of the techniques of radiometric calibrations, removal of atmospheric emission and calculation of cloud cover, amount, type to promote the automatically observation of the whole sky in recent years.

2 Instruments description

With the developments of computing technology and digital imaging technology, many ground-based whole sky infrared cloud measuring instruments have been developed in recent years for the purpose of cloud cover estimation and characterization. They mainly contain two types, unit style and focal plane array.

Unit-typed cloud measuring instruments are represented by Infrared Cloud Analyzer (Nephelo) developed by Genkova and Besnard[18]. It operates 7 IR sensors, each with a 6° field of view, to divide the whole sky into 181 pixels. These sensors are based on OMEGA OS 65-V-R2-4-BB model pyrometers. each sensor is mounted at angles 0, 12, 24, 36, 48, 60, and 72 on a semicircular rotating curved band, performing 30 scans, every 12° from 0° (North) to 348° [18]. The downward thermal emission in spectral range 8 ~ 14μm from the clouds and the air column between the clouds and the instrument is measured by IR pyrometers. We can estimate total cloud cover, fractional cloud cover and cloud base height by analyzing these data. But, it will be probably difficult to identify cirrus clouds and the resolution is poor to discriminate cloud type due to much mechanical motion. In order to improve the resolution, more studies on increasing the scan time or IR sensors are necessary.

Focal plane array cloud measuring instruments are mainly represented by the thermal infrared camera, the Infrared Cloud Imager (ICI) and the Whole Sky Infrared Cloud Measuring System (WSIRCMS). Smith and Toumi use a commercially available Thermovision A40 camera developed by FLIR Systems, Inc., which contains an uncooled 320×240 pixels microbolometer array and a 9 mm lens giving it a 60°×80° field of view, to measure radiation in the 7.5 ~ 13 μm wavelengths [19]. Both of the ICI and WSIRCMS adopt ground-based passive sensor that has an uncooled microbolometer focal plane array (FPA), which operates without a thermoelectric cooler element, to obtain a continuous and consistent day-night downwelling atmospheric radiance in the range of 8-14μm with high spatial and temporal resolution. Shaw and Nugent from Montana State University, Bozeman, focus on the development of the ICI for many years. The original ICI uses an uncooled 320×240 pixel FPA and has a relatively narrow field of view of approximately 18°×13.5°, about 1.5% of the overhead sky [20]. The Second-Generation Infrared Cloud Imager (ICI2) is developed to extend the ICI technique to cover an angle of approximately 110°. The ICI2 uses a FLIR Systems, Inc., Photon 320 LWIR camera with an uncooled 324×256 pixel microbolometer FPA. One of the cameras used in these systems is the Photon core with a 14.25-mm focal-length lens which provides a 50° × 38° (62° diagonal) field of view (FOV) allowing for viewing of about 9% of the total sky. The second configuration uses an after-market lens to provide a 86° × 67° (110° diagonal) fov allowing for viewing about 22% of the overhead sky. Monte Carlo modeling has shown that 110° is nearly the ideal field angle for measuring spatial cloud statistics from the ground[21-25]. The ICI2 is a relatively smaller size, lower cost and larger filed-of-view infrared imager. However, it still can't obtain the whole sky images. The WSIRCMS developed by College of Meteorology and Oceanography, PLA University of Science and Technology, also uses an uncooled microbolometer detector array with 320×240 pixels to measure downwelling atmospheric radiance. The WSIRCMS mainly contains optical detector, environmental parameter sensors, controller, power, and terminal unit. The image is obtained at zenith and eight different orientations under the control of the scan servo system and the whole sky image with a resolution of 650×650 pixels is acquired after spelling the nine images. It provides a way to obtain the whole sky cloud distribution, cloud amount, cloud based height, and cloud types every 15 min with no difference in sensitivity during day and night and solves the problem that using wide-angled uncooled microbolometer FPA achieves the quantitative measurement of the whole sky infrared radiation [26-28]. However, due to the limitation of the scan and spelling technique, a high demand for rotating property can't reach and the whole sky image spelled from nine images has one or two gaps. Besides, the instruments in infrared band are influenced by the environment and calibration is found to be necessary for each observation.

3 Key techniques

3.1 Radiometric calibration

The use of ground-based automatic cloud detection instruments offers the potential for understanding and quantifying cloud effects more accurately. However, the raw data stored by the imager cannot be used directly for scientific studies and a series of calibrations representing integrated sky radiance (due to clouds plus atmospheric emission) is necessary.

An in-house calibration of the Thermovision A40 camera mainly uses a reference blackbody. The blackbody which can fill most of the field of view is placed 80 cm away from the camera lens, and uses a combination of liquid nitrogen and electric heaters to control temperature. The study in the charge of Smith indicates a linear relationship exists between the mean pixels measured temperature and blackbody temperature, although there are significant differences exist between the observed and true blackbody temperature when the temperature is below a certain value. The linear equation is applied to all pixels readings and updated annually[29]. Both of ICI and WSIRCMS have a radiometrically calibrated LWIR imaging system, with stable internal calibration achieved without using of onboard or external blackbody calibration sources, and are protected by an environmentally sealed enclosure with a germanium window that has high transmittance in the LWIR (approximately 0.85). The First-Generation ICI mainly uses a two-point linear calibration. A novel internal-shutter-based calibration technique allows radiometric calibration of the ICI2 camera, which operates without a thermoelectric cooler[30-31]. The process used to calibrate these cameras is the following: 1) apply a flat field non-uniformity correction to achieve a spatially constant response for all pixels using the equation (1)

$$DN_c = DN\text{-}DN \times m\Delta T + b\Delta T \quad (1)$$

where DN_c is corrected digital number, DN is the error-containing raw response, ΔT is the difference between the current FPA temperature and the reference temperature, m and b are correction coefficients, 2) record the image of the scene and internal shutter along with the current FPA temperature, 3) convert shutter image to a shutter-based blackbody image, 4) correct the image of the scene and internal shutter using FPA temperature, 5) use laboratory gain k_1 and corrected shutter-based blackbody image to calculate the camera offset k_2, 6) use laboratory gain and calculated offset to calibrate the corrected scene image

$$L(T) = k_1 DN_c(T) + k_2 \quad (2)$$

where $L(T)$ is measured radiance, k_1 and k_2 are correction coefficients. The study results show that this technique produces radiance images with an uncertainty of $\pm 0.45W/(m^2sr)$ in the reading of the integrated radiance at each pixel. The WSIRCMS mainly uses the calibrating data of standard radiant source based on neural network method and linear model method[32-34]. Linear model method based on internal blackbody can be written as

$$\Delta L = K_1\Delta DN + K_2 \quad (3)$$

where ΔL and ΔDN is the radiance and digital number difference between the target and internal blackbody radiance. K_1 and K_2 is the calibration coefficients calculated by least square algorithm. This method is simple but low accuracy. The neural network method can simulate the function of input and output value by designing a right network structure at unknown situation, which can improve the calibration results.

3.2 Cloud detection

The LWIR atmospheric window is an ideal spectrum for continuous cloud detection because of high atmospheric transmission, low atmospheric emission, and relatively high cloud emission. Thermal infrared measurement includes emission of the clear atmosphere and clouds; therefore, cloud detection requires careful removal of the atmospheric emission from the initial measurement. Many studies have been done to use atmospheric radiance models to estimate clear atmospheric emission.

The Nephelo applies Line-by-Line Radiative Transfer Model to calculate the clear sky brightness temperature thresholds with given precipitable water vapor (PWV) and atmospheric profile from independent measurements, and then the measured brightness temperatures are compared to these thresholds to classify a scene as clear or cloudy. Smith and Toumi proposed a new function (4) based on Thermovision A40 camera to estimate the clear sky brightness temperature T between cloud and ground and then compare the measured data with T to detect cloud[37]. The function can be written as

$$T = (T_h\text{-}a)\left(\frac{\theta}{90}\right)^b + a \quad (4)$$

where θ is zenith angle, T_h is the horizon temperature and a and b are fitting parameters which are determined by simulating the function (4) using the brightness temperature data from the SBDART model in different conditions. The ICI2 and WSIRCMS separately use MODTRAN and SBDART to simulate the influence of the atmospheric profiles, PWV, and zenith angle to the radiance and derive the following models,

$$L_{sky} = L_s W_p A + W_p B + L_s C + D \quad (5)$$

$$L_{sky} = a\left(\frac{\theta}{90}\right)^b + c \quad (6)$$

$$L_{sky} = a\theta^2 + b\theta + c \quad (7)$$

$$L_{sky} = a\, W_p^{\,2} + b\, W_p + c \quad (8)$$

Equation (5) derived from MODTRAN relates the band-integrated sky radiance L_{sky} to surface temperature, precipitable water vapor W_p, and zenith angle θ. L_s is the radiance for a blackbody at the temperature of the near-surface air. The coefficients A, B, C, and D are derived from a two-dimension linear regression at each zenith angle and used to determine a modeled clear-sky image. Equations (6) (7) (8) derived from SBDART separately relate L_{sky} to θ or W_p. The coefficients a, b and c in each equation are determined by simulating the equation using radiance data from SBDART model in different conditions. Furthermore, an adaptive algorithm was developed, which allows the atmosphere radiance models to be adjusted to fit the real-time conditions, thereby reducing the uncertainty in the measurements[34]. The approach behind this method is to detect clear-sky regions in the sky mapped by the imager, calculate the atmospheric emission associated with this clear-sky region, build a fit that is used to adjust the calculated clear-sky emission to match the measured data, and then use the emission in other regions of the sky to subtract the properly scaled radiance.

According to the results of cloud detection, cloud cover is estimated from the equation (9)

$$f = \frac{N_{cloudy}}{N_{total}} = \frac{N_{cloudy}}{N_{cloudy} + N_{clear}} \quad (9)$$

where f is total cloud cover, N is the number of cloudy or clear pixels. The field of view of the Nephelo, Thermovision A40 camera, ICI and WSIRCMS can't reach 180°. But, studies indicate that WSIRCMS can obtain the total cloud cover by spelling the nine images. Fractional cloud cover also can be acquired by identifying cloud base height of each pixel to get the family of clouds and then counting the cloud amount of the same family.

3.3 Retrieval of cloud base height

The heights of cloud base can be determined by two methods, bright temperature method and threshold method. The bright temperature method utilizes temperature vertical decrease rate and sky infrared brightness temperature T_b to measure cloud base height (CBH). The sky T_b is observed directly or indirectly by ground-based infrared cloud measuring instruments. ZHANG Wenxing has presented a systematic investigation on the variations of sky T_b with zenith angle of observation for different kinds of aerosol and different visibilities under clear and cloudy sky conditions using MODTRAN 4.0 model[36-37]. The results of simulation and preliminary experiments show that the sky T_b decreases with the CBH and is very sensitive to the variation of CBH for middle and low cloud. Therefore, this method is feasible to derive the cloud base height by measuring T_b, surface temperature and relative humidity. The Nephelo has retrieved the CBHs by using real-time atmospheric profiles and measured T_b. Compared with VCEIL and ARSCL, it is receivable to use the two sensors in the middle of the instrument to measure CBHs. Qin Chao[38] also uses this method to retrieve the CBHs after converting the downward infrared radiation on the basis of the atmospheric correction to brightness temperature T_b. The results show that the algorithm has high accuracy for low cloud. Disadvantages of this method are that it is unavailable to clouds in higher layers, all clouds on observations are treated as blackbody which will make an over estimation of the CBHs, and exact atmospheric correction is needed sometimes, thereby errors exist significantly. Sun Xuejin, etc, propose a threshold method to estimate the CBH based on SBDART. The theory of this method is that there is a monotonic relationship between CBH and downward atmosphere infrared radiation[39]. The algorithm can be written as

$$\begin{aligned} H &= \frac{L_M - L_r}{L_M - L_H} \times (h_H - h_M) + h_M, L_M > L_r \gg L_H, \\ H &= \frac{L_L - L_r}{L_L - L_M} \times (h_M - h_L) + h_L, L_L > L_r \gg L_M, \quad (10) \\ H &= \frac{L_S - L_r}{L_S - L_L} \times h_L, L_S > L_r \gg L_L, \end{aligned}$$

where h_H, h_M, h_L is altitudes at 11 km, 6 km, 2.5 km, respectively; L_H , L_M , L_L is separately the corresponding radiance of the altitudes calculated from equation (8), L_s is the radiance of surface temperature, L_r is the measured radiance from WSIRCMS. Large amount of experimental data have been analyzed and validated by comparing with the laser ceilometer and human observation data and the results prove a high-end accuracy. The primary advantage of this approach lies in the fact that it needs no atmospheric correction. However, the relationship assumption that clouds are supposed to be blackbody will make an over estimation of the CBHs derived by comparing infrared cloud imagers with the actuals.

3.4 Classification of cloud

At present, cloud classification on business traditionally is observed by humans. The study of cloud classification has focused on the whole sky visible images in recent years, while the study of cloud classification based on ground-based infrared images is still underway. Three major methods have been proposed to classify clouds.

Firstly, Structure Feature Method is applied toaddress clouds by extracting the structural features of the segment image and edge image. Several structural features based on zenithal images taken by the WSIRCMS, such as cloud gray mean value (ME), cloud fraction (ECF), edge sharpness (ES), and cloud mass and gap distribution parameters, including very small-sized cloud mass and gaps (SMG), middle-sized cloud gaps (MG), medium-small-sized cloud gaps (MSG), and main cloud mass (MM), are explored and found by Liu Lei to be suitable to distinguish cirriform, cumuliform, and waveform clouds[40]. SUN Xuejin and LIU Lei proposed another method of fuzzy uncertainty texture spectrum (FUTS) based on cloud images obtained from the WSIRCMS, to be used as the texture feature within texture analysis process. The results show that the accuracy rates of five simplex sky conditions (stratus, cumulus, altocumulus, cirrus and clear sky) are relatively high, while the complex sky conditions are still difficult to be classified only by using the FUTS method compared with human observations[41]. Secondly, the Local Binary Patterns (LBP) combining with the local cloud image texture (VAR signal) is used to classify sky conditions. Sun Xuejin has done the studies using this method and the classification correct rates for the five classes of stratus, cumulus, undulatus, cirrus clouds and clear sky, which can reach an average accuracy of 87.2%[42]. However, this method still can't meet the needs of the automatic measurements of all sky conditions. Third, Gray-level Cooccurrence Matrix (GLCM) Approach is presented in recent years. Han Wenyu provides a new way for the automatic identification of infrared cloud images using compress sensing based on GLCM theory[43]. The method mainly applies principal component analysis (PCA) and typical cloud samples to construct redundant dictionary firstly, then use Gradient Projection for Sparse Reconstruction (GPSR) and Orthogonal Matching Pursuit (OMP) algorithm to solve the problem of $l1$ paradigm, and final discriminate cloud using the residual method and sparse proportion method. The results show that the average recognition rate of waveform, stratiform, cumuliform, cirrus, and clear sky can reach 82.8% [45]. This method avoids the feature extraction process and acquires relatively high accuracy, while the process of dimension reduction in building up redundant dictionary will bring non-ignorable errors.

4 Instrument application

In the aspect of application, we compare the products from ground based whole sky infrared cloud measuring instruments with products from other ground based instruments, human observation, satellite measurements. Besnard, et al.[18], contrast the results of cloud cover using the Nephelo, TSI and human observation and find a better corresponding relationship. LIU Lei[46] makes a comparison of cloud cover, CBH and cloud type from the WSIRCMS and ceilometer CL51. Cloud cover, CBH in the lower, and cloud-type, like cumulus and cirrus, show a generally good correspondence, while CBH up to the height of about 6 km and cloud-type, like stratocumulus and altocumulus are not. Qin Chao compares the CBH from the WSIRCMS, CT75K and human observation. Liu Lei contrasts the CBH using the WSIRCMS, CL31 and CL51 and significant differences can be found due to the different measurement principles and CBH retrieval algorithm[44-45]. In the view of present instruments, it is very difficult to classify the cloud into 29 varieties of 10 genera in four families with high, mid-, and low levels and clouds of a significant depth which takes cloud shape as the basic factor, together with considering the cause of its development and the interior microstructure. This manual cloud classification is defined by considering the convenience of human observation and is not suitable for instruments. Therefore, a new cloud classification criterion is the premise to achieve the automatic identification of clouds. At present, Liu Lei, Sun Xuejin, etc, have adopted a new criterion that clouds are classified to five classes of stratus, cumulus, undulatus, cirrus clouds and clear sky and get a high precision.

Cloud measuring instruments not only can obtain the whole sky images, but also can be used to do many other studies. Besnar proposes that UVB can be studied by the data from CIR. Smith and Yang Shuchen uses ground-based thermal imaging to observe cloud forcing [47-48]. Nugent utilizes wide angle ICI for measuring cloud statistics in support of earth space optical communication Optical Communication. Zhao Shijun applies the continuous observation of cloud images from WSIRCMS to detect the upper altitude wind[49]. With the development of the ground based whole sky cloud measuring instruments, studies on the spatial and temporal distribution of clouds and the relationship between climate change, temperature, humidity, landscape and clouds are needed and have broad application prospect.

5 Conclusion and discussion

Due to the poor resolution of unit-type infrared cloud measuring instruments, it is very hard to classify clouds. Infrared cloud measuring instruments using focal plane array detector can acquire continuous and consistent day-night downwelling atmospheric radiance with relatively high resolution. But it demands higher technical content and stabilization. The cloud cover and distribution of clouds have become mature basically, while cloud base height and cloud classification are still at the exploration stage. Therefore, according to the analysis of actuality and progress of whole sky infrared cloud measuring techniques, many works are still needed to be done.

1) The stabilization and environment adaptability of the instruments and more accurate correction methods are needed to further enhance. The instruments mentioned in the article have advantages and disadvantages at the same time and need further verification to meet the needs of long time field observations. Accurate correction methods are the premise of the studies of cloud properties and should carefully implement on business application.

2) Removal of atmospheric emission for ground based whole sky infrared instruments is necessary to extract cloud information. Although cloud has been detected automatically and accurately, high error rates exist at the edge of the sky. More accurate algorithms are urgent to estimate the emission of atmospheric profiles, PWV, and aerosol in infrared band. Besides, a research on using a certain range of zenith angle which guarantees the continuity of data to represent the whole sky needs to be discussed.

3) The whole sky cloud base height measurement technology needs further experiment. The fact that clouds can not be supposed as blackbody using brightness temperature method and threshold method to determine CBHs needs to be taken into account. The accuracy of the temperature vertical decrease rate, surface temperature and relative humidity needs to be improved using brightness temperature method to determine CBHs. More other studies on the cor-

rection of CBHs using active zenith pointing measurements or the overlapping region measured from two-station type cloud measurement instruments are required.

4) Instrumental cloud classification criteria and technique need to be discussed as soon as possible. The lack of guidance of instrumental cloud classification criteria poses difficulties for automatic cloud classification. There is no need to classify the cloud into 29 varieties of 10 genera in four families as far as the present cloud data from ground-based instruments or satellites. In recent years, new criterion that clouds are classified to five classes of stratus, cumulus, undulatus, cirrus clouds and clear sky has been tested. The theory of this classification criterion is that it regards the sky as a whole and then chooses the code which can represent typical weather as a type. The new classification standard can be established using this theory by combining the other cloud data from radar, satellite, ground-based and aerological instruments. At present, the technique used to classify the skies has a high accuracy for simple but not complex sky conditions. Therefore, more advanced techniques are urgent in needs.

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