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The Clouds Observation and Classification Based on Satellites' Data

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Abstract: Recently, there has been a strong focus on understanding how greenhouse gases contribute to rising global temperatures. However, greenhouse gases are not the only element influencing climate; clouds also play a crucial role in regulating global temperatures. Clouds affect the wave path of different wavelengths of radiation, which in turn impacts temperature and weather patterns. Additionally, the complex microphysics within clouds, such as interactions between water droplets and ice crystals, make cloud modeling extremely challenging. This passage will share some basic models of clouds, explore the evolution of cloud models, examining why these models contain high levels of uncertainty and discussing the latest advancements in cloud science, along with unresolved questions that continue to challenge researchers. Furthermore, the passage will outline methodologies that may help reduce uncertainties in cloud modeling, including advanced cloud classification systems and the use of satellite technology for more accurate cloud observation and data collection. These tools are critical in improving our understanding of clouds and their role in climate change.

Keywords: Clouds, Climate Modeling, Aerosols, Cloud classification, Satellites.

1. Introduction

There are many factors which cause the high inaccuracy of clouds models. "Since preindustrial time, the effect of difference in atmospheric aerosol concentrations on the radiative properties and distribution of clouds has been the most uncertain effect of the overall global radiative effect[1]." Aerosol are small particles dissolved in the air, and they are a key factor of cloud formation. With these Aresols, water particles tend to gather together and form water droplets, and thus form clouds. However, the distribution of aerosol on horizontal level over the earth as well as on vertical level is hard to calculate. There are also many kinds of aerosols molecules, each of them have different attraction to water molecules. These integrated small difference brought by aerosols can have a great impact on the distribution and albedo of clouds. Furthermore, they can influence General Circulation Model(GCM) from many aspect, including the climate sensitivity(how the earth temperature will rise when people input unit amount of CO2). That is the uncertainty inducted differences in scale between GCM and individual cloud processes. Another type of uncertainty is the change in the state of aerosols from the pre-industrial era to the present, which is a problem on the time scale. Scientists have proposed some solution to these problems. They have build Process-scale models (e.g. LES and CRM), but these models have a common problem: they cannot be reply on a large scale model.

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Another factor that cause the high inaccuracy of clouds models is the complexity of mixed phase clouds. Mixed phase plays an important role in global radiation budget. It has a global net radiative effect of -3.4 W m−2.a[2] The negative sign means that they prevent global warming. They are widely distributed in high latitude area, and they can influence the atmospheric circulation and oceanic circulation through influencing the temperature. Mixed phase clouds contain both ice and water particles. The water and ice proportion in each mixed phase clouds makes them have deferent albedo which enhance its uncertainty. Besides, mixed phase clouds themselves are unstable with respect to time. That is, when summer comes and temperature raise, the ice particles melt and convert to water triplets. Scientists have also developed some models to stimulate the mixed phase clouds. However, it is difficult to fully describe its vertical structure and microphysical properties from the existing observational data.

With the global temperature raising, the low level clouds will rise, causing their albedo to decrease, and thus enhance global warming[3]. Tropical low clouds, such as Stratus, Stratocumulus, and Cumulus will also raise. This will result on changes of atmospheric stability, surface fluxes, convection, and turbulence. Also, changes in tropical convective cloud area may upset the balance of their long- and short-wave radiative effects, producing positive or negative feedback[4]. All the consequence and phenomenon are related to each other, so we should protect our planet.

2. Some basic models of clouds

Clouds form because of the decrease in the saturation specific humidity of air, which is a function of temperature and pressure $q^*(T,P)$. With a small parcel of air(we assume it has a unit mass 1 kilogram) rises, its pressure would decrease because there are fewer gas above them. Then according to the ideal gas law $PV = nRT$ the temperature will also be influenced, and force some water vapor to come out and form clouds. The condensation of water vapor will provide extra heat to the parcel of air, and thus make the parcel of air rise again[5].

The Moist Static Energy(MSE), which represents the different forms of energy in the parcel of air and follows the conservation of energy, can be represent as $MSE = c_pT(z) + Lq(z) + gz$. The first term is the internal energy of the parcel of air. The second term is energy released or gained by the change in form of H_2O, and the third term is a representation of gravitational potential energy. On the surface, the relative humidity $RH_s = q_s/q^*(T_s,P_s) < 1$, which means the humidity is not greater than the saturation specific humidity so no water vapor are forced to come out. So MSE is reduced to Dry Static Energy(DES), which eliminate the second term. $DSE = c_pT(z) + gz$. On the surface, the temperature can be represent as T_s, so the conservation of energy tells us $DSE_s = c_pT_s = DSE = c_pT(z) + gz$ and we can calculate $T(z)$.

After calculation $T(z)$, we can take in to the MSE formula. If we consider the saturation of humidity of the air parcel, we can change the formula into $MSE = c_pT(z) + Lmin(q_s, q^*(T(z),p(z))) + gz$, where q takes each one depends on whether the humidity is saturated or not.

Based on the formula, scientists can build a graphical solution.

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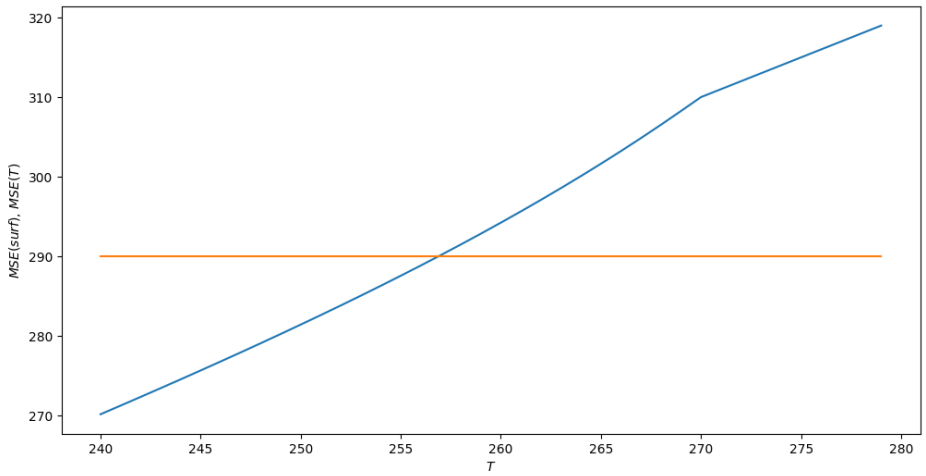

Figure 1: a graphical solution of $MSE/c_p$with respect to T

In this graph, the orange line represent MSE_s/c_p with respect to a specific T(z) and the blue line represent $MSE(T)/c_p$. The initial temperature is set to be 280K. The RH_s is setted to be 80%, and the T is calculated at where z is 3000 meters. As people predict, the tangent of oringe line equal to 0 because there T is not the independent variable of this function. The tangent of the blue line changed at one point where the temperature is about 270T. This point is where RH_s reaches 1 and the minimum value of q begins to take $q^*(T,P)$.

The above graph did not consider the change in pressure. The pressure function with respect to z $p(z)$ can be calculated as $p(z) = p_s e^{\frac{-gz}{R\bar{T}}}$ where p_s is the surface pressure and $\bar{T}$ is the proper temperature(between 220K to 300K) that people choose.

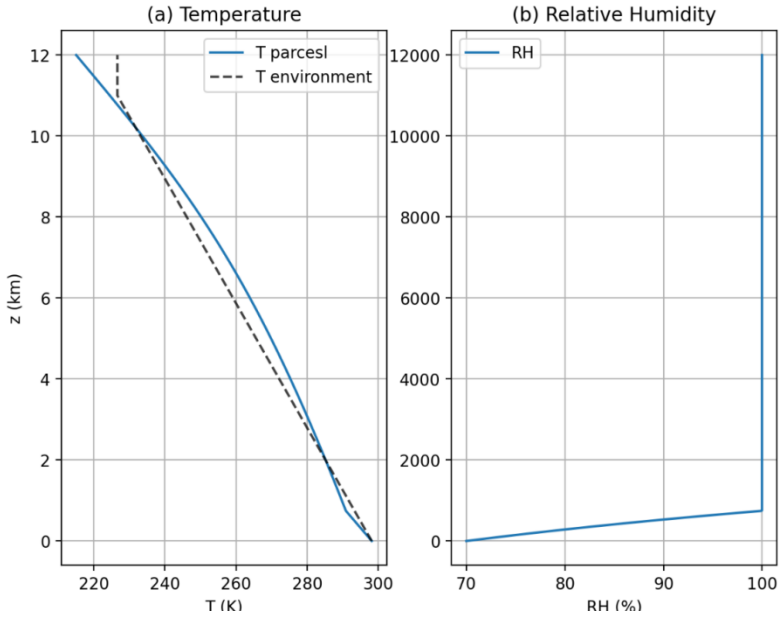

Figure 2: A graphic solution of T with respect to z

In this figure, we see that the difference between temperature of the parcel of air and the temperature of environment various. The point where the water vapor begin to come out at about 1km is called Lift Condensation Level(LCL). At this point people can clearly see that the temperature of the parcel of air begins to rise fast. The point where the temperature of the parcels exceed T

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environment is called the Level of Free Convection. At this point the parcels begins to be free and go up spontaneously. At point level of neutral buoyancy, the parcels is finally trapped again.

3. Classification and formation mechanism of clouds

There are many methods that scientists classify clouds. The first method of classifying clouds is called as Dynamic Regimes(DR)[6]. The essence of DR actually is not a classification of clouds, instead, it is a classification of atmospheric motion. However, because atmospheric motion has a strong relationship with clouds(It is an necessary condition for cloud forming), we can also consider it as a method of classifying clouds. The Dynamic Regimes is very flexible. There is not an uniform classification: people can divide atmospheric motion mode into different types base on the situation they are facing. For instance, in JGR Atmospheres - 2018 - McDonald - A Comparison of Cloud Classification method, the pressure vertical velocity(ω) profile data in the ERA-Interim reanalysis data is selected as the main variable since it is believed that it can effectively distinguish between twelve different cloud types. Then, the author uses SOM algorithm to do cluster analysis for different type of clouds. Through this method, scientists are able to classify cloud radiative effect, since cloud radiative effect is directly related to atmospheric vertical motion[7].

Dynamic Regime was derived from the traditional classification through cloud top pressure and the optical thickness of the cloud which was initiated by the ISCCP project in 1979. Form 1980s to 1990s, some researchers gradually linked the atmospheric motion with cloud formation[8]. That was the rudiment of DR. After 2000, some researchers began to analyse the kinetic characteristics of clouds through ω. Some of them even began to associate their classification with cloud radiative effect. They have also used other data (for instance data from ISSCP and CloudSat) to test DR[9]. Since 2010, scientists have been trying hard to add more variables such as temperature, moist and aerosol other than just consider atmospheric motion. Moreover, they have tried to combine other classifications with DR, because they have found that it is sometimes invalid and inaccurate to just use DR[10].

Another method used to classify clouds was Cloud Regimes(CR)(the data is provided by MODIS). This classification divide clouds into ten categories(2014 version) base on their different top pressure and optimal thickness observed by calculator[6]. Thus, this is a Pixel-based cloud classification algorithm. The categories are named CR1 to CR10.

This form shows the basic information of each type of CRs:

Here is a traditional classification (which is classified base on the clouds shape and how the clouds are formed)

Table 1: Traditional cloud classification. (More details in World Meteorological Organization website[11])

Clouds name	Properties
Cirrus (Ci)	These high-altitude clouds are composed of ice crystals and appear delicate and fibrous.
Cirrostratus (Cs)	A high-altitude cloud layer made of ice crystals, often covers the entire sky without precipitation.
Cirrocumulus (Cc)	Small, white ice crystal clouds at high altitudes, often in rows or clusters.
Altostratus (As)	A mid-to-high altitude cloud layer that can obscure the sun or moon, typically producing light precipitation.
Altocumulus (Ac)	Mid-level clouds with a ragged appearance, capable of light precipitation along their edges.

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Table 1: (continued).

Nimbostratus (Ns)	A thick, low-to-mid level cloud cover that can bring continuous rain or snow.
Stratus(St)	Ground-level clouds that reduce visibility and can cause light precipitation.
Stratocumulus(Sc)	Low-to-mid level clouds that can blanket the sky and produce light rain or snow.
Cumulus (Cu)	Low-level clouds with a flat base and bulging top, usually forming after clear weather.
Cumulonimbus (Cb)	Enormous clouds with significant vertical growth, capable of severe weather like thunderstorms and tornadoes.

Table 2: the CRs classification

Cloud name	**Relationship with traditional classified cloud**
CR1	High clouds like cirrus and cumulonimbus with high cloud top pressures and optical thickness, associated with tropical and frontal storms.
CR2	Cumulus and cumulonimbus clouds with cirrus, similar distribution but lower optical thickness.
CR3	Altostratus and altocumulus clouds, linked to mid-latitude frontal systems.
CR4	Thinner parts of mid-latitude storms with thinner cloud optical thickness.
CR5	Mid-latitude storm clouds with shallower cloud tops, mainly over land.
CR6	Many stratocumulus clouds, including thicker marine stratocumulus.
CR7	Subtropical stratocumulus extending to mid-high latitude oceans.
CR8	Thinner, more broken boundary layer clouds with low optical thickness.
CR9	Fair-weather clouds across latitudes, less frequent high clouds.
CR10	Most common cloud system, early or late stages of others, less cloud cover with significant precipitation.

Among CR1 to CR10, CR1,2,3 have a higher top pressure relative to their bottom pressure, so they are at the top of troposphere. They also have a higher cloud optimal thickness, meaning that they contain a lot of water droplets. CR7,8,9,10 have a lower top pressure relative to their bottom pressure, so most of them are located at subsidence area. From the another perspective, CR1,2,3 have net atmospheric radiative warming effect and CR6,7,8,9 have net atmospheric radiative cooling effect. Through this classification, scientists can focus only on the physical and climate properties of clouds. Thus, this classification is more convenient for scientists to build models.

CR model through MODIS was firstly developed by Jakob and his peers in 2003. They used atmospheric circulation model to identify global cloud patterns and analyzed their radiative and precipitative properties. They also applied clustering techniques to objectively identify different type of clouds. In 2013, Tselioudis and his peers posed a more specific classification criteria of CR. In 2016 version, which is the version showed above, Leinonen used MODIS dataset and announced the regional variability of CR, which can cause different cloud structures. In the same year, McDonald applied Self-mapping organizations to make CR more refined. In the future, people can increase the algorithms to get more precise, shorter-time-span data, as well as save cost. In this way, people can also get aware of how clouds interact with other systems more precisely. With the fast development of machine learning algorithms, cloud models based on CR classification will be benefit a lot.

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4. Application of Satellite Observation Technology in Cloud Research

If scientists want to do research thoroughly on clouds or classify clouds, they need to be familiar with the structure of the clouds. They need to know the vertical and horizontal structure of the clouds, as well as specific information such as precipitation and are sols condition in clouds. Thus, large amount of data available for them are very necessary. satellites can provide them with those data they need. For instance, MODIS is a satellite which support the CR classification.

There are three major types of cloud observation satellites. The first type are satellites which are specialist in cloud observation. This means that these observing clouds is the only function of these satellites. As a result, they usually have a larger capacity and various functions on observing clouds. This type of satellites include Cloudsat, which is the first satellite for cloud observation and is emitted in 2006, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO).

Cloudsat is an almighty satellite to observe clouds. It is generally used to observe the vertical structure and precipitation of clouds. CloudSat carries a 94 GHz Cloud Profiling Radar (CPR), which can provide information on cloud thickness, height, and liquid water content. CloudSat provide various data product, including cloud profile data, cloud mask data, precipitation data[12]. As a result, its data can be applied to do researches on the vertical structure of clouds, the mechanism of precipitation, and the relationship between clouds and climate. CALIPSO is also a satellite of high status. It is mainly used to detect the content and also the vertical structure of clouds. CALIPSO carries a 532 nm and 1064 nm Cloud-Aerosol Lidar with Orthogonal Polarization(CALIOP) that provides information on the vertical profiles of clouds and aerosols, optical thickness. It offers a variety of data products, including cloud and aerosol profile data, optical thickness data, cloud mask data, and more[13]. Actually, scientists often combine the data from Cloudsat and CALIPSO and analyze them together. The data from Cloudsat and CALIPSO have common in the vertical structure of clouds. However, Cloudsat's data focus more on precipitation rate while CALIPSO's data focus more on the structure of aerosols, so scientists can use data from both satellites and analyze the information form each satellite base on the vertical structure of clouds.

There are some common problems with these two satellites: their rotation cycle is 16 days, which means their observation frequency is very low and they can observe a single location only 22 or 23 times per year. Also, Cloudsat and CALIPSO both have narrow observation ranges for only about 1 kilometer around them. These would make it difficult for both of them provide dynamic informations[14].

The second major type of satellites are Earth Observing System(EOS) series. This type include satellites Terra and Aqua, which both carry Moderate Resolution Imaging Spectroradiometer (MODIS). "Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths.[15]" MODIS include series of device that can enhance cloud detection.

Table 3: the CRs classification

The subsystem or abilities MODIS have	Its utility in cloud detection
1,000-m, 500-m, and 250-m resolution spectral bands	Bandpass filters with different resolutions allow scientists to study cloud characteristics from macro to micro levels
Atmospheric, land, and ocean imaging in a single instrument	Allow scientists to combine those information with cloud distribution around the world and figure out the relationship between them

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Table 3: (continued).

Custom-tailored spectral bands from 0.4 to 14.4 μm; low out-of-band response	Various wavelength bands can detect different physical properties of clouds, such as water vapor content, height of cloud top, and particle type. The low out-of-band response ensures the accuracy of the measurements.
Continuously rotating double-sided Scan Mirror Assembly for long life	directs light from the Earth's surfaces onto the Focal Plane Assembly.
Advanced Focal Plane Assembly (FPA) technology for unsurpassed sensitivity	The large number and variety of detector pixels are what make the wide variety of MODIS data possible. High-sensitivity focal plane arrays (FPAs) are capable of detecting faint signals, which is crucial for observing cloud properties under thin cloud or low cloud cover conditions. This sensitivity allows for more accurate and detailed measurements of cloud characteristics, even when the clouds are not optically thick or are less abundant in the scene, thereby enhancing our ability to study and understand the atmosphere.
Electronics System (Space-Viewing Analog Module, Forward-Viewing Analog Module, Main Electronics Module)	The electronic systems can receive instrctions from ground, which means that scientists can adjust MODIS's utility whenever they want.
On-Board Calibration System (IR calibration, Solar Diffuser, Blackbody, SRCA)	IR calibration is performed with each scan to reduce noise and improve the measurement accuracy of cloud parameters in the infrared bands. The Solar Diffuser and the Solar Diffuser Stability Monitor (SDSM) provide calibration for the visible and near-infrared bands, assisting in determining cloud albedo. The Blackbody is used for calibrating the thermal infrared bands to accurately measure cloud top temperatures. The Spectro-Radiometric Calibration Assembly (SRCA) provides spectral radiance calibration, ensuring accurate measurement of the spectral characteristics of clouds. Also, MODIS can detect deep space and the moon which help it build spectrum more precisely.

The third type of satellites are Geostationary orbit satellites. The main purpose of these satellites is monitoring climate changes and doing some whether forces. Since cloud is a very important factor which can influence these, Geostationary orbit satellites also carries some equipment's that can help

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them oberve clouds. Geostationary Operational Environmental Satellites(GOES) is one series of Geostationary orbit satellites.

Since Geostationary orbit satellites are static relative to earth, it is necessary to emit more than one satellites to observe earth comprehensively. GOES series satellites include 4 satellites: GOES-R which was emitted in 2016, GOES-S which was emitted in 2018, GOES-T which was emitted in 2022, and GOES-U which was emitted recently, in 2024.

Here is a picture took by GOES, which shows the Category 5 Hurricane Iota seen from GOES-R (GOES East) on November 16, 2020[16].

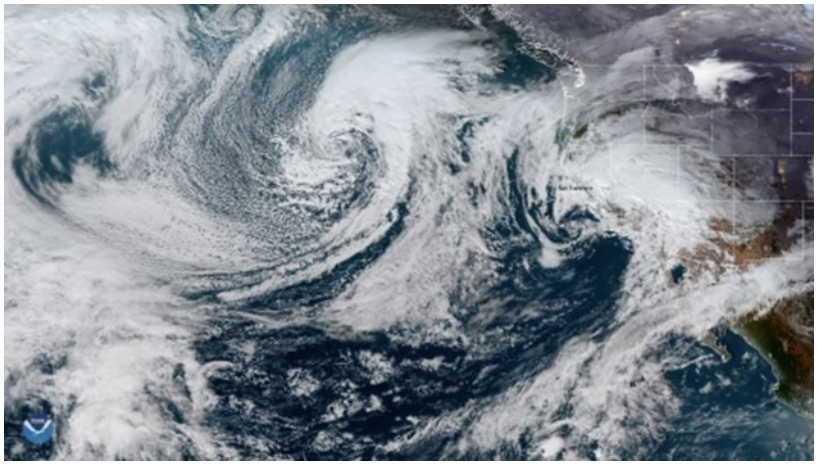

Figure 3: The Category 5 Hurricane Iota seen from GOES-R (GOES East) on November 16.

In real life, scientists usually use the data from all types of satellites introduced previously, so they can carry forward strengths. For instance, Cloudsat has a high vertical resolution, and its radar can work for 24 hours per day. However, it has some probloms: it cannot clearly detect the low clouds or very thin liquid clouds because it can be disturbed by the radiation reflect by the earth. To solve this problem, scientists use the sub adiabatic model since the sub adiabatic model are relatively precisely in modeling the water content in a low or thin liquid clouds.(Richard M. Schulte1). People defined some formulas to help them model the clouds in the sub adiabatic model.

Liquid Water Content function is defined as

$$l = \frac{4}{3}\pi\rho_1 \int r^3 n(r) dr$$

where n(r) is the water droplet size distribution function

The Effective Radius is defined as $r_e = \frac{\int r^3 n(r) dr}{\int r^2 n(r) dr}$

Extinction Coefficient which represent the degree of attenuation of light is defined as $k_{ext} = \int Q_{ext} \pi r^2 n(r) dr = \frac{3Q_{ext} l}{4\rho_1 r_e}$

So people can obtain the Optical Depth by simply intergrading the Extinction Coefficient: $\tau = \frac{3Q_{ext}}{4\rho_1} \int_0^H \frac{1}{r_e} dh$ [17]

Bring the data from MODIS into these formula, we can know the water content and finally the optical thickness of a very low or thin cloud. Despite of getting data from satellites or from observatories on the ground, analyzing data is also a very important step if people want to build cloud models. Some satellites have some automatic data analysis function; for example, Cloudsat has flag method which can read some basic information of clouds and classify them. There are also products for docking with satellites. For instance 2B-CLDCLASS-LIDAR is an algorithm product for analyzing the data from Cloudsat and other satellites. People can input radar reflectance factor profile, cloud mask, geographic location, radar range height, surface range number, cloud layer information

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(from Cloudsat) and CALIOP LiDAR Attenuation Backscatter Coefficient, Cloud Mask, MODIS Radiance Data, ECMWF Temperature Profile, Coastline Map, Topographic Map (Ancillary data which are not from Cloudsat). This algorithm can first perform a cloud clustering analysis to group individual cloud profiles into clusters, and then calculate the cluster characteristics and classify them into one of the standard cloud types. More details on CloudSat 2B-CLDCLASS-LIDAR Product Process Description and Interface Control Document[18].

5. Conclusion

This passage has emphasized that many factors can cause the high uncertainty of clouds models, and has showed how scientists tried to deal with these problems through data from satellites and cloud classification. Some properties of clouds only affects the radiation balance and energy exchange of the earth, but also plays a key role in the global climate feedback mechanism. As a result, these problems are unavoidable, and scientists need to improve their approaches continuely. Fortunately, the fast development of machine learning algorithm brings dawn to this problem: if scientists apply artificial intelligence to analyze or obtain data, building cloud models be much more efficient. Applying machine learning algorithm, the existing accuracy of observation can be improved, since satellites can distinguish between small difference more effectively. The cloud classification algorithms can also be improved since computers will be better at classifying clouds. Machine learning algorithms can further reveal the deep connection between cloud and climate change, and provide stronger scientific support for global climate change prediction.

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