Recent Advances in Measuring Cloud Albedo with Satellites

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ABSTRACT

Recent advances in satellite cloud albedo measurements, specifically data-assimilation algorithms, cloud profilers, radiometers, and limitations of each are reviewed. There has been a shift from single-instrument radiance measurements to multi-platform instruments able to probe the full vertical profile of clouds. This paradigm aims to measure a wide range of cloud properties which control cloud albedo. These new developments are necessary to reduce remaining uncertainty in cloud albedo and constrain global climate models. This review found that new developments, such as multi-instrument techniques, are necessary to verify results, and new instrumentation and methods enhance the accuracy of the results.

1. Introduction

Planetary albedo (α), the fraction of solar radiation incident on Earth that is immediately reflected to space, can be altered with changes in Earth's cloud properties, aerosol content, and surface coverage (Wielicki et al. 2005). After accounting for reflection, the amount of incoming solar intensity (S_0) available for the Earth's radiation budget is $S_0(1-\alpha)$. Equations derived from first principles provide an approximate spatially averaged planetary albedo of $\alpha = 0.30 \pm 0.005$ (Seinfeld and Pandis 2006; Curry and Webster 1999; Wallace and Hobbs 2006), of which 50-60% is contributed by clouds. By neglecting other climate feedbacks, these equations show changes of 1% in albedo can alter Earth's surface temperature by 1 K. Furthermore, a 1% change in albedo is equivalent to the effect of doubling the atmospheric concentration of CO_2 (Solomon et al. 2007). Such examples demonstrate the importance of albedo on Earth's climate and the importance of having accurate measurements (Smil 2008).

A conventional planetary albedo (α_p) has been defined with respect to fractional cloud cover (F_{cloud}) in order to divide cloudy and clear sky influences of albedo(A_{cloud} and A_{clear}, respectively) (Cess 1976):

$$\alpha_p = (1 - F_{cloud})A_{clear} + F_{cloud}A_{cloud} \qquad (1)$$

Any planetary albedo definition is incomplete without cloud contribution. Not all clouds contribute equally to albedo; most clouds reflect incoming solar radiation, but some actually enhance the greenhouse effect by trapping the outgoing terrestrial radiation. Large low lying clouds, such as stratocumulous, are the main contributors to cloud albedo. High altitude, thin, icy cirrostratus clouds are responsible for trapping terrestrial infrared (IR) radiation (Halusa 2008).

The 1960 Television Infrared Observation Satellite (TRIOGS-1) was the first successful meteorological satellite and lead to the long running Nimbus program. Numerous satellites have made cloud optical and physical property measurements since NASA's 1964 launch of the first Nimbus satellite (Grayzeck 2003). Remote sensing data is not exclusive to satellites and has, to some extent, been around for decades. Despite the relatively new availability of high quality satellite data, large uncertainties in the measurements make validation of global climate models problematic. Parameterization of micron-sized particles and drops onto planetary scales makes clouds and aerosols the source of largest uncertainty in predicted climate change (Solomon et al. 2007). A series of advanced satellites are now measuring properties of these two critical atmospheric constituents to constrain models. These newer satellites employ more sophisticated technologies, including LIDAR, RADAR, and highly sensitive radiometers. Satellite measurements provide global, consistent, and reliable observations that are unparalleled by ground-based instruments. The most recent and important satellite advances in the measurements of cloud albedo are reviewed, covering algorithms, cloud profilers, radiometers, and their limitations.

2. Algorithms

The advent of multi-platform observation systems requires retrieval algorithms that can translate raw data from a variety of sources into usable properties of clouds. Several satellites carry more than one sensor per platform and other sensors are located on multiple platforms. Radiative budgets are generally calculated as fluxes and changes in temperatures, whereas satellite measurements are measured in radiances. Conversion algorithms are then needed to convert measurements into compatible forms for input into climate models. The Multilayered Cloud Retrieval System (MCRS) is a recent (2004) technique that uses data from multiple satellites to determine the characteristics of multilayer clouds. The older, homogeneous, single-layer assumption introduces large errors in cloud properties and in the resulting albedo due to differences in actual composition (Yi et al. 2007). To overcome the homogeneous, single-layer cloud assumption the MCRS algorithm was designed from the results of a two-layer cloud model (Huang et al. 2004). MCRS was developed to provide a more comprehensive look at cloud structure and is an improvement upon the original single-layer algorithm, Visible Infrared Solar-Infrared Split Window Technique (VISST).

Vertical layering of ice clouds over water clouds presents a large impediment in determining overall cloud optical depth and albedo (Minnis et al. 2007). Ice water and liquid water phases in clouds contribute differently to the overall cloud albedo because they have different reflectivities. The optical depth of a cloud depends on the ice water path (IWP) and liquid water path (LWP), so it is important to accurately measure both. Albedo increases with an increase in the optical depth (Curry and Webster 1999). Optical depth, derived from reflected visible and infrared radiance, also includes a combination of the radiative transfer between cloud layers. This leads to an approximate 40% overestimation when a multilayered cloud is considered to be a single, homogeneous layer (Huang et al. 2004).

Microwave radiance data from satellites is used to directly determine the LWP of clouds (Minnis et al. 2007), defined as the vertical integral of the liquid water mixing ratio (Curry and Webster 1999). In previous methods, cloud IWP was found by subtracting the LWP from the total water path (TWP) (Minnis et al. 2007). MCRS uses a parameterization of the original adding-doubling radiative transfer method. This was a statistical method which assumed a single homogeneous layer, by combining the lower layer cloud with the surface to produce background radiance for the retrieval of the ice cloud properties. The LWP and IWP are determined with the MCRS using a combination of microwave, visible, and infrared data, which has significantly improved the accuracy of the retrieved IWP (Minnis et al. 2007).

MCRS will positively impact the global climate model validation and formulation (Huang et al. 2004, 2006; Yi et al. 2008) due to an improvement in quantifying LWP and IWP. The combination of new satellite technology and MCRS will lead to better characterization of clouds and their impact on the radiation budget.

3. Cloud Profilers

Cloud-Aerosol Lidar (Light Detection and Ranging) and Infrared Pathfinder Satellite Observation (CALIPSO) and CloudSat are the ”first real observational advance in cloud property retrievals in a long time” (Bony 2006). Launched in 2006, these two satellites fly in formation in the NASA satellite constellation known as A-train. They maintain a sun-synchronous orbit, where the sun remains in the satellite’s orbital plane as Earth revolves around it. This makes the orbital plane precess approximately 1 degree/day. As seen in Figure 1, the satellites are 15 seconds apart in orbit and capable of near-simultaneous complementary measurements.

The ability of clouds to scatter light is controlled by the bulk properties (size and chemical composition) of the cloud’s particle constituents. Cloud profilers do not directly measure albedo, but rather they improve the understanding of the micro-scale processes that manifest themselves as macro-scale cloud albedo by quantifying the aerosol scattering effects at different wavelengths.Temporal variation and three dimensional cloud resolution are sources of large uncertainty in cloud cover fraction for radiation model evaluation. Because radiative transfer processes (including changes in cloud albedo) are directly and indirectly affected by aerosol particles (Twomey 1977), many newer satellites measure a combination of cloud and particle properties. Barker et al. (2008) showed systematic cloud fraction resolution errors can lead to a measured top of atmosphere (TOA) forcing of the same magnitude as those predicted by the indirect aerosol effect (i.e., cloud albedo modification due to aerosol components).

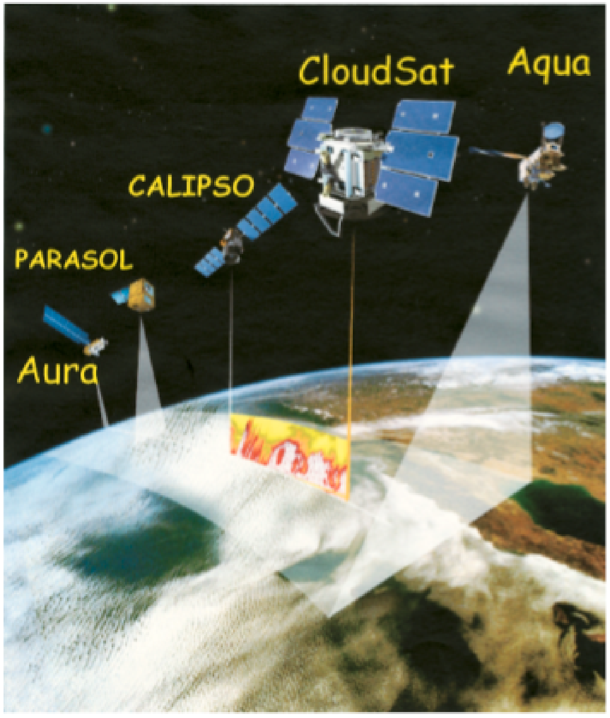

Figure 1: The satellites that make up the NASA A-Train Consellation including CALIPSO and CloudSat (Stephens 2002).

Cloud and related aerosol properties such as altitude, cloud phase and drop categorization have been largely unmeasured with previous passive sensor satellites. The advent of lidar allows CALIPSO to measure these historically unattainable properties. Active remote sensing measures properties of an object by emitting its own electromagnetic radiation, whereas passive remote sensing relies on external sources such as the sun. Instruments on the CALIPSO satellite include the dual wavelength Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), an imaging infrared radiometer and a wide field camera (Winker et al. 2003). A lidar functions similarly to radar except that it uses laser radiation in the IR, visible, and UV range rather than the lower frequency radio band. Because the wavelength of laser radiation is much shorter than that of radar, aerosols and particles in the atmosphere are detectable using a lidar. The most relevant cloud albedo advances will come from CALIOP, which actively detects cloud layers and phase properties along its swath. When this data is used with other simultaneous A-train products, cloud types and their vertical distributions are resolved. Lidar measurements encompass a wide range of albedo values that contrast with the bi-modal, clear sky and cloudy sky albedo categories as required in the 'conventional' planetary albedo definition (Charlson et al. 2007). This is an improvement over climate models that are only able to specify between clear sky and cloudy sky conditions.

The Cloud Profiling Radar (CPR), the main instrument housed on CloudSat, is a 94-GHz cloud backscatter radar. Previous to CloudSat, satellite measurements used centimeter-wavelength cloud radar, which has a minimum detection limit on the order of raindrop sized particles (on the order of 2.5 mm). The new satellite - based millimeter-wavelength cloud radar has the capability to detect smaller particles. By combining the raw radar measurements of the Terra satellite Moderate-Resolution Imaging Spectroradiometer (MODIS) and lidar measurements of CALIPSO, CloudSat obtains processed in-cloud liquid and ice water content profiles. CloudSat's improved sensitivity compares better than that of the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) and allows for more detailed cloud profiling (Stephens 2002). Patterns of cloud and precipitation radar data from CloudSat were used to perform cluster analysis which identified five distinct tropical cloud regimes occurring at varying frequencies (Zhang et al. 2007). For cluster analysis, reflectivity was grouped into seven categories starting from the minimum detectable signal from CPR. Such an analysis wouldn't have been possible without CloudSat's sensitivity. Local radiative profiles may be derived when CloudSat radar data is cross-analyzed with CALIPSO lidar data.

4. Radiometers

Several satellite-based passive radiometers instrument complement these techniques by measuring reflected, solar electromagnetic radiance, including NASA's Clouds and the Earth's Radiant Energy System (CERES) and MODIS. These instruments are aboard the Terra (launched in 1999) and Aqua (launched in 2002) satellites that measure terrestial and solar radiation reflected from the Earth's surface and the atmosphere (Sun et al. 2007). Both CERES and MODIS directly measure radiance via a scanning radiometer sensitive to land, atmospheric, and oceanic variables. CERES measures in the 0.3 - 5.0 μm band while MODIS measures over 0.4-14.4 μm in 36 sub-bands. Terra MODIS and Aqua MODIS complete scans of the entire Earth's surface every two days from a sun-synchronous polar-orbit (Platnick et al. 2003). These two instruments measure cloud properties such as altitude, cloud thickness, and cloud particle size.

CERES does not directly measure shortwave reflected flux, since it only measures the radiation in a narrow viewing angle (Smith 1986). Instead it measures radiance, the radiant energy per unit time in a given solid angle from a specific direction. Conversion from radiance to flux would be trivial if the radiation was isotropic; however, outgoing radiation scatters anisotropically, and is characterized by an angular distribution function. CERES measures the radiance for an element at the top of the atmosphere (TOA) at many different angles and depends on other satellites to make measurements of the angular distribution function. This function depends on many parameters such as solar angle, surface type, and atmospheric conditions (Bertrand et al. 2005). Angular distribution functions require very focused multi-angle measurements from several satellites, and are very sensitive to spatial and temporal differences in the measurements. The validity of the measured angular distribution is the main source of error in determination of flux.

MODIS uses combined IR and visible spectral measurements to derive cloud variables including cloud phase, effective particle size, daytime cloud optical thickness, pressure, emissivity, cloud top temperature and height. Optical thickness and effective particle size are the most significant factors in cloud shortwave radiation behavior, contributing differently to measured properties and influencing albedo. Phase information is inferred from absorption differences in the IR band reflected radiation, while the optical thickness of clouds is inferred from the measured intensity in the visible band (King et al. 1997). To discriminate cloud coverage character, MODIS employs a statistical confidence routine to determine whether a given pixel is obstructed by clouds (Platnick, 2003). Unlike the coarse 20km spatial resolution of CERES, MODIS is able to resolve cloud characteristics to 1km, 500m, and 250m spatial resolution depending on the frequency band (Frey et al. 2008).

Measurements of cloud albedo depend on many parameters and vary extensively by cloud type. Xu et al. (2005) considered four types of clouds over oceans: tropical deep convection, boundary layer cumulus, transition stratocumulus, and solid stratus. From CERES measurements in 1998 and 2000, the distribution of cloud type as a function of cloud albedo was determined, quantifying the albedo distribution for different cloud types. Lin et al. (2004) used CERES data to show that clouds had a higher albedo than previously thought. These new measurements altered the understanding of cloud feedback systems.

5. Uncertainties and Limitations

Satellites must be accurate and stable over the operational lifetime in order to provide useful data. Absolute accuracy is affected by systematic error in the data and is important for model validation and understanding sensitisve climate processes. Stability refers to the change in accuracy over time and is essential to determine long-term climate trends on the order of years or decades. Accuracy and stability are influenced by practical and instrumental considerations. All satellites are limited practically by lifetime, cost of operation and maintenance, physical design, and timely data transfer back to earth. Instruments are also constrained by spatial and temporal resolution, spectral sensitivity, calibration and signal to noise ratios (SNR).

A 2002 workshop at the University of Maryland developed standards for satellite instrument calibration (Ohring et al. 2005). It was decided that albedo measurements should be accurate to 1.5 W/m^2 solar irradiance and the stability must be at least 1% per decade (0.3 W/m^2 per decade). Data from various satellites from 2000-2005 (Loeb 2007) showed that CERES, MODIS, and MISR (Multiangle Imaging Spectro-Radiometer) aboard Terra had relative stabilities under 1% per year with no systematic change in time. It was also determined that 10 to 15 years of satellite data may be needed to detect a statistically significant TOA flux change of 0.3 W/m^2 per decade. Uncertainties and limitations can pertain to algorithms, cloud profilers and radiometers.

a. Algorithms

Parametrized algorithms compound instrumental errors with their own computational limitations. Algorithms for profiles differ from those for radiometers. Modified algorithms are needed to adapt to different target types and measurement techniques. Non-linear inversion algorithms are computationally intensive and numerical errors often lead to unrealistic vertical profiles. Error analysis requires numerical simulations on idealized profiles before measured data can even be compared (Vaughan 2004).

Until 2006, the MCRS algorithm could only be applied to data collected over the ocean. Microwave radiance data over land was inconsistent due to variations of land surface temperature and emissivity (Yi et al. 2008). Radiance measurements at different wavelengths replaced microwave measurements over land (Huang et al. 2006). Surface emissivities detected by CERES and MODIS are now used to determine more accurate water phases over land using MCRS (Yi et al. 2008).

MCRS is an improvement over older algorithms that assumed a homogeneous, single layer cloud. It provides a way of determining the properties of the upper ice cloud layer given satellite measurements of lower liquid cloud layers. Data confirms that single-layer retrievals overestimate the ice content in multilayer clouds and demonstrates the accuracy MCRS (Minnis et al. 2007). Slight overestimation of optical depth increases as a function of liquid water content using MCRS (Huang et al. 2006). Even with this overestimation, MCRS is still more accurate than the other retrieval techniques.

b. Cloud Profilers

Active measurements from space pose more problems than active ground based techniques. The target distance (500-700km in orbit), orbiting speed ($\sim$7 km/s) and change in target along flight path introduce low signal to noise ratios and require spatial averages to account for the large lidar footprint, spatial heterogeneity and nonlinear scattering. CALIPSO has different averaging intervals for different target types. Water clouds require less spatial averaging for retrieval of accurate profiles than do thin aerosol layers.

Different lidar wavelengths have different accuracy. As of 2003, accurate retrievals of the 1064 nm wavelength of CALIPSO were nearly impossible and were found to be sensitive to altitude, SNR and particle size (Vaughan et al. 2002; Vaughan 2004). Early descriptions of CALIPSO retrieval errors were largely qualitative, but recent work shows improvement in the quantification of CALIPSO uncertainty. Accuracy differs considerably between lower troposphere and higher altitude measurements. Both cloud and aerosol profiles have smaller errors above 5 km. The planetary boundary layer presents challenges in quantifying profiles below 5 km (Tao et al. 2008). Biases in the Atmospheric Infrared Sensor (AIRS) radiometric measurements of cloud height against CALIPSO and CloudSat differ considerably between satellites (Kahn et al. 2008). New uncertainty analysis of CALIPSO cloud coverage is relevant to cloud albedo, especially when compared to other cloud measuring satellites.

Cloud albedo by profilers is limited to certain cloud types. CloudSat was able to detect up to 70% of shallow boundary layer clouds over the ocean, but less than 40% over land. Limitations in detection of thin cirrus clouds are also suspected (Stephens 2002). In one case 37% of all thin cirrus were predicted to be below CloudSat's minimum detectable signal. CloudSat's low minimum detectable signal does allow for observations of rain and, for the first time, snowfall from space, yet challenges exist in accurately capturing the transition from cloud to precipitation. Although drizzle can be detected, the LWP during drizzling events has not been quantified. Detection of supercooled liquid water and the quantification of ice water contents remain in question. CloudSat provides reliable liquid and solid precipitation up to 5-8 mmh^{-1}, but is limited by high signal attenuation during high precipitation events. Low frequency radar could have improved sensitivity but physical restraints on the power supply and maximum antenna diameter made such radar implementation unfeasible (Stephens 2002). As an example of high satellite costs and short mission lifetimes, CloudSat, an over $200 million project, is expected to last three years (Hupp 2006).

c. Radiometers

CERES was the first radiometer to meet the climate community's sensitivity goals in terms of accuracy and stability but general radiometer uncertainties still exist. Accurate flux requires radiance measurements at many different angles because TOA point radiation emits in all directions. Orbital constraints make it impossible for radiometers to have perfect angular resolution. Low spatial resolution means CERES and MODIS do not observe outgoing flux from small scale features. Radiometers require constant calibration against onboard control targets. For example, CERES uses an evacuated tungsten lamp to calibrate its shortwave sensors, so the accuracy of TOA flux measurements is limited by the lamp's stability. There is a disagreement between CERES radiometers on the Terra and the Aqua radiometers for tropical ocean TOA fluxes. This is believed to be caused by damage to Aqua's optics by UV radiation. Such malfunctions are difficult to predict ahead of time and to quantify afterwards. Proliferation of observations and data products can be offset by increases in the range and variety of overall uncertainty in measurements from multiple instruments. Many of these can be reduced by cross validation with other instruments.

Degradation of instrument components due to radiation damage are responsible for some uncertainty in measurements. MODIS instruments on-board the Terra and Aqua satellites are monitored monthly to track the stability of the twenty reflective solar bands it measures. Methods to characterize the sensor's radiometric performance are based on lunar observations with the moon serving as a radiometric reference. From launch to 2007, band 8 (412 nm) have demonstrated a degradation of 36% and 17% on Terra and Aqua MODIS instruments; time-dependent corrections to lookup tables are applied accordingly for improvements, which are as large as 14%(Sun et al. 2007).

Surface roughness of ice particles in the atmosphere affect the scattering properties of bulk ice mass used in satellite observation of ice cloud properties. Increasing roughness decreases retrieved cloud optical thickness and increases effective particle size. Compared to near-surface based lidar and aircraft radar methods, satellite measurements tend to overestimate cloud optical depth. This affects the visible and near infrared bands in satellite-based cirrus cloud sensing and results in an underestimate of cirrus cloud-top heights (Yang et al. 2008). Cloud top estimates are crucial in determining cloud temperature and emissivity, and have been shown to be chief contributors to cloud albedo. Since MODIS assumes smooth ice particles in its retrieval algorithm, optical depth bias can be reduced by incorporating surface roughness of ice particles; however, the computational requirements exceed present capability (Yang et al. 2008).

Continuing with cirrus cloud sensing issues, multilayer cloud coverage beneath cirrus clouds makes cirrus clouds difficult to distinguish. Due to the large volume of data managed by satellites imagers, a simplifying assumption that each pixel represents a single cloud layer is employed in retrieval. Attempts to rectify this flattening of the cloud column in regions of overlapping of low altitude water clouds and high altitude, icy cirrus clouds use spectral response differences in the liquid water versus ice phases. Though the mentioned technique shows promise, detection is limited in regions of large cloud coverage because of the algorithm's dependency on clear-sky radiance. Additionally, mid-level clouds appear to be identified as multilayer clouds, and towering, convective clouds are problematic since the algorithm was designed for a binary cloud height distribution scenario unlike the continuous height distribution of a towering cloud (Baum and Menzel 2008). Further progress is needed in isolate upper ice cloud sensing and optical depth retrieval.

Satellite radiometers have biasing in bands important to cloud and aerosol research. Two of the Earth Observing System instruments, MODIS and MISR, on-board Terra show 3% absolute radiometric differences over most of the visible band and in the near-IR spectrum (Bruegge et al., 2004; Thome et al., 2004; Xiong et al., 2005b). The cross-instrument inconsistencies are the primary cause of albedo bias. The MISR albedo is systematically higher than MODIS albedo. The average visible and NIR bias results are +0.014±0.014 in the blue, +0.011±0.007 in the green, +0.002±0.015 in the red, and +0.008±0.010 in the NIR bands. Differences in band-passes and effective band center wavelengths between MODIS and MISR are suspected to cause the blue and red biases, yet the green and NIR are unexplainable. Such biasing and differences in viewing geometry, spectral response functions, and overpass times makes cross-instrument agreement of radiances challenging (Lyapustin et al. 2007). The instruments and methods discussed represent cutting-edge technology and vast improvements from their predecessors, yet limitations and uncertainties still exist. It is essential to recognize these limitations to correctly interpret the data provided and to best design the successors of the current instrumentation.

6. Conclusion

Recent advances in cloud albedo using satellite measurements were examined and compared with previously accepted values. Several new satellites and algorithms have been implemented in the last decade, yet none of their measurements have led to any detectable change in the accepted value of cloud albedo beyond natural variability (Wielicki et al. 2005). Still the advances covered here highlight that measurements have become more accurate and available, validating previously calculated values. A system is now in place with the capability to measure specific changes more accurately and clarify current uncertainties. Satellite measurements are essential to understand cloud albdeo, to monitor trends and changes, to help constrain climate models, and to prepare for geoenginnering decisions. Suggested future work includes satellites located at the equilibrium gravitational point that provide a continuous picture of Earth rather than orbiting. A recent attempt to implement such a satellite, DSCOVR, was made but due to inadequate funding the launch was not carried out (Brand 2007) (Valero and Charlson 2008). This Lagrange point located satellite would be beneficial and enhance current satellite measurements.

Lower layer cloud properties (height, temperature, optical depth, and liquid water path) are obtained from CALIPSO and CloudSat data while upper layer cloud properties are retrieved using the MCRS and validated with CALIPSO, CloudSat, MODIS, and CERES observations (Yi et al. 2008). This combination of techniques provides a unique look at cloud properties and also provides a strong baseline for future cloud property measurements. The most important recent advance is the increase in the number of new multi-instrument measurements and their interdependency. The new satellites reduce the uncertainty in cloud properties by providing self-consistency between results and have filled in the gaps between the 'conventional' clear sky and cloudy sky regimes. The push towards assimilation of active cloud plus aerosol remote sensing is necessary to further reduce uncertainty in cloud albedo and constrain global climate models.

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