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GEWEX Cloud Assessment: A Review

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Abstract. Clouds cover about 70% of the Earth's surface and play a dominant role in the energy and water cycle of our planet. Only satellite observations provide a continuous survey of the state of the atmosphere over the entire globe and across the wide range of spatial and temporal scales that comprise weather and climate variability. Satellite cloud data records now exceed more than 25 years; however, climatologies compiled from different satellite datasets can exhibit systematic biases. Questions therefore arise as to the accuracy and limitations of the various sensors. The Global Energy and Water cycle Experiment (GEWEX) Cloud Assessment, initiated in 2005 by the GEWEX Radiation Panel, provides the first coordinated intercomparison of publicly available, global cloud products (gridded, monthly statistics) retrieved from measurements of multi-spectral imagers (some with multi-angle view and polarization capabilities), IR sounders and lidar. Cloud properties under study include cloud amount, cloud height (in terms of pressure, temperature or altitude), cloud radiative properties (optical depth or emissivity), cloud thermodynamic phase and bulk microphysical properties (effective particle size and water path). Differences in average cloud properties, especially in the amount of high-level clouds, are mostly explained by the inherent instrument measurement capability for detecting and/or identifying optically thin cirrus, especially when overlying low-level clouds. The study of long-term variations with these datasets requires consideration of many factors. The monthly, gridded database presented here facilitates further assessments, climate studies, and the evaluation of climate models.

Keywords: Cloud properties, Satellite observations, Climate data record.

PARTICIPATING DATASETS AND DATABASE

The International Satellite Cloud Climatology Project (ISCCP [1]), which is the GEWEX cloud project, uses multi-spectral imager data from a combination of polar orbiting and geostationary weather satellites to achieve the necessary sampling. During the past decade, other global cloud data records have been established from various instruments, mostly onboard polar orbiting satellites. New sensors such as MODIS, POLDER, CALIPSO and CloudSat have expanded the cloud measurement capabilities. It is imperative that the longer time series such as ISCCP products be compared to recent instruments to assess the accuracy and error sources relevant for climate studies and for evaluation of general circulation models (GCM). The GEWEX Cloud Assessment was focused on the intercomparison of global Level-3 (L3) cloud products (gridded, monthly statistics), retrieved from measurements of *multi-spectral imagers* (ISCCP, PATMOS-x [2, 3], MODIS-ST [4, 5], MODIS-CE [6]), *multi-*

angle multi-spectral imagers (ATSR-GRAPE [7], MISR [8], POLDER [9], the latter also using polarization), *IR sounders* (HIRS-NOAA [10], TOVS Path-B [11, 12], AIRS-LMD [13, 14]) and *active lidar* (CALIPSO-ST [15], CALIPSO-GOCCP [16]). Discussions during four workshops led to the creation of the GEWEX Cloud Assessment L3 database, in common format and available at <http://climserv.ipsl.polytechnique.fr/gewexca/>, allowing for the first time an inter-comparison of L3 cloud essential climate variables (ECVs) of twelve ‘state of the art’ datasets.

KEY RESULTS

In addition to self-assessments (see references and Annex I of [17]) which show the maturity of the various datasets, the analyses have shown how cloud properties are perceived by instruments measuring different parts of the electromagnetic spectrum and how their averages and distributions are affected by instrument choice as well as some methodological decisions. **These satellite cloud products are very valuable for climate studies or model evaluation:** Even if absolute values, especially those of high-level cloud statistics depend on instrument (or retrieval) performance to detect and/or identify thin cirrus, relative geographical and seasonal variations in the cloud properties agree very well (with only a few exceptions like over deserts and snow-covered regions). Probability density functions of optical and bulk microphysical properties also agree well, when one considers retrieval filtering or possible biases due to partly cloudy samples and to ice-water misidentification. The study of long-term variations with these datasets requires consideration of many factors, which have to be carefully investigated before attributing any detected trends to climate change.

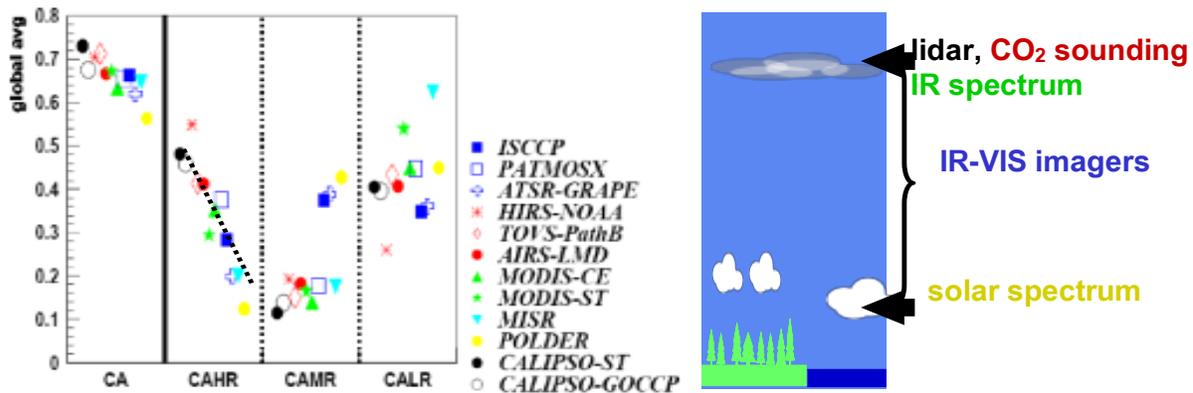


FIGURE 1. Left: Global averages of total cloud amount (CA), and fraction of high-level, mid-level and low-level cloud amount relative to total cloud amount (CAHR+CAMR+CALR = 1). Statistics are averaged over daytime measurements (1:30 – 3:00 PM LT, except MISR and ATSR-GRAPE at 10:30 AM LT). Right: Sketch illustrating cloud height interpretation in the case of thin cirrus overlying low-level clouds (less than 20% of all cloudy scenes according to CALIPSO) when using different instruments.

Total Cloud Amount

Global total cloud amount (fractional cloud cover) is about 0.68 (± 0.03), when considering clouds with optical depth > 0.1 . The value increases to 0.74 when considering clouds with optical depth < 0.01 (e.g. CALIPSO) and decreases to about 0.56 when clouds with optical depth > 2 are considered (e.g. POLDER). Global effective cloud amount (cloud amount weighted by cloud emissivity) is about 0.50 (± 0.05).

According to most datasets, there is about 0.10 – 0.15 more cloudiness over ocean than over land. HIRS-NOAA and MISR detect a difference of 0.30, which can be attributed to uncertainties in cloud detection over land (low-level clouds for HIRS and thin cirrus for MISR) and to sampling time of 10:30 AM local time for MISR in the presence a strong diurnal cycle difference between land and ocean.

Cloud Height

Cloud top height can be accurately determined with lidar (e.g. CALIPSO). Apart from the MISR stereoscopic height retrieval for optically thick clouds, passive remote sensing provides a ‘radiative height’. It was found that the ‘radiative cloud height’ may lie as much as a few kilometers below the ‘physical height’ of the cloud top, depending

on the cloud extinction profile and vertical extent. Especially high-level clouds in the tropics have such ‘diffusive’ cloud tops, for which retrieved cloud top temperature may be up to 10 K larger than cloud top temperature. In general, the ‘radiative height’ lies near the middle between cloud top and ‘apparent’ cloud base (for optically thick clouds height at which the cloud reaches an optical depth of 3). When cloud height is determined via O₂ absorption (e.g. POLDER), it corresponds to a location even deeper inside the cloud.

Global uncertainties in retrieved cloud pressure are estimated to 100 hPa for ISCCP, compared to about 50 hPa for IR sounding. During night, ISCCP may misidentify thin cirrus as mid-level cloud, because only one IR radiance is measured, leading to a positive bias of about 75 hPa, in comparison with IR sounder retrievals.

Height-stratified Cloud Amount

Clouds in all datasets are vertically stratified according to their pressure into high-level, mid-level and low-level clouds. Separation levels are at 440 hPa and 680 hPa (corresponding to altitudes of about 6 km and 3 km, respectively). We consider height-stratified cloud amounts relative to total amount, because these values are less influenced by differences in cloud detection.

About 42% of all clouds are high-level clouds with optical depth > 0.1. The value increases to 50% when including subvisible cirrus, and it decreases to 20% when considering clouds with optical depth > 2.

About 16% ($\pm 5\%$) of all clouds correspond to mid-level clouds with no other clouds above. Values from ISCCP are 27% (day: IR and VIS information) and 40% (day and night: night only one IR channel), respectively. These biases are due to semi-transparent cirrus overlying low-level clouds during day and in addition due to semi-transparent cirrus during night.

According to the majority of datasets, about 42% ($\pm 5\%$) of all clouds are single-layer low-level clouds. Outliers are HIRS-NOAA with 26% (only one IR channel for low-level clouds) and MODIS-ST with 53% (misidentification of optically thin cirrus).

Global effective cloud amount of high-level clouds (0.15) is very similar for the different datasets, because a smaller cloud amount due to missing optically thin clouds is compensated by a larger average cloud emissivity.

Most datasets show similar latitudinal variations in total and height-stratified cloud amount. Exceptions are polar latitudes and relative low-level cloud amount from HIRS-NOAA (underestimation of low-level clouds with minimal thermal contrast). Geographical maps show some differences in total cloud amount over deserts and land areas which may be linked to aerosols. Regional anomalies (difference between regional averages and global average cloud properties) agree better between the datasets than regional absolute values. The spread in regional cloud amount anomaly is less than 0.10 and in relative high-level cloud amount anomaly varies between 10 to 20% (polar regions and regions with frequent cirrus). Most datasets agree on the seasonal cycle. In general, seasonal variations are smaller than latitudinal variations, except for the transition of the InterTropical Convergence Zone (ITCZ). The seasonal cycle is generally larger over land than over ocean.

Cloud Optical Properties

Cloud optical depth is in general determined from reflectances in the solar spectrum and therefore only available during daytime conditions. The datasets provide global average cloud optical depth between 4 and 9. However, given that the global mean cloud amount is larger than 0.65, we know that the average cloud optical depth has to be smaller than 5 to give a consistent planetary albedo. The larger values in some datasets are produced by retrieval filtering.

Probability density functions of cloud optical depth agree for cloud optical depth between 1 and 10. The relative contributions outside this range (< 1 and > 10) essentially reflect differences in retrieval filtering and limits (< 10) due to conversion from cloud emissivity.

Bulk Cloud Microphysical Properties

Remote sensing determines an effective particle size by assuming particle shape and size distribution within the cloud. The height contributions in the retrieval of the effective particle size depend on the absorbing spectral band used: in general, absorption increases with increasing wavelength. However, with increasing cloud optical depth the retrieved particle size corresponds more and more to particles near the cloud top, leading typically to overestimates for liquid clouds and underestimates for ice clouds.

Global effective droplet radius of liquid clouds is about 14 μm ($\pm 1 \mu\text{m}$). Global effective ice crystal radius of high-level ice clouds is about 25 μm ($\pm 2 \mu\text{m}$). Effective cloud droplet radii are on average about 15 – 20% larger over ocean than over continents, whereas the difference in effective ice crystal radius is only about 5%.

Global cloud water path varies from 30 to 60 gm^{-2} for liquid clouds and from 60 to 120 gm^{-2} for clouds with ice tops. Retrieval filtering of ice clouds leads to smaller (25 gm^{-2} for semi-transparent cirrus) or larger values (225 gm^{-2} for clouds with optical depth larger than 1) of average cloud water path.

Differences in probability density functions have been identified due to thermodynamic phase misidentification (leading to larger droplet radii or smaller ice crystal radii, respectively), partly cloudy samples (leading to slightly smaller particle sizes and water path) and retrieval filtering.

CONCLUSIONS

The GEWEX Cloud Assessment L3 database, available at <http://climserv.ipsl.polytechnique.fr/gewexca/>, allowed for the first time an inter-comparison of L3 cloud essential climate variables (ECVs) of twelve ‘state of the art’ datasets. It has revealed its usefulness in the interpretation of cloud properties from different satellite instruments and facilitates further assessments, climate studies and the evaluation of climate models. Detailed results of the GEWEX Cloud Assessment can be found in [17], also available at the GEWEX cloud assessment website.

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