The diurnal cycle of cloud profiles over land and ocean between 51°S and 51°N, seen by the CATS spaceborne lidar from the International Space Station

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Abstract.

We document, for the first time, how detailed vertical profiles of Cloud Fraction change diurnally between 51°S and 51°N, by taking advantage of 15 months of measurements from the Cloud and Aerosol Transport System (CATS) lidar on the non-sun-synchronous International Space Station (ISS).

Over the Tropical ocean in summer, we find few high clouds during daytime. At night they become frequent over a large altitude range (11-16km between 10PM and 4AM). Over the summer tropical continents, but not over ocean, CATS observations reveal mid-level clouds (4-8 km Above Sea Level or ASL) persisting all-day long, with a weak diurnal cycle (minimum at noon). Over the Southern Ocean, diurnal cycles appear for the omnipresent low-level clouds (minimum between noon and 3PM) and high-altitude clouds (minimum between 8AM and 2PM). Both cycles are time-shifted, with high-altitude clouds following the changes in low-altitude clouds by several hours. Over all continents at all latitudes during summer, the low-level clouds develop upwards and reach a maximum occurrence at about 2.5 km ASL in the early afternoon (around 2 pm).

Our work also shows that 1) the diurnal cycles of vertical profiles derived from CATS are consistent with those from ground-based active sensors at local scale, 2) the cloud profiles derived from CATS measurements at local times of 0130AM and 0130PM are consistent with those observed from CALIPSO at similar times, 3) the diurnal cycles of low and high cloud amounts derived from CATS are in general in phase with those derived from geostationary imagery but less pronounced. Finally, the diurnal variability of cloud profiles revealed by CATS strongly suggests that CALIPSO measurements at 0130AM and PM document the daily extremes of the cloud fraction profiles over ocean and are more representative of daily averages over land, except at altitudes above 10km where they capture part of the diurnal variability. These findings are applicable to other instruments with local overpass times similar to CALIPSO's, like all the other A-Train instruments and the future Earth-CARE mission.

Outline

1. Introduction

The diurnal cycle of clouds has been documented for decades by ground-based instruments (e.g. Gray and Jacobson, 1977) and geostationary satellites (e.g. Rossow et al., 1989). Even though climatologies give priority on how clouds change with seasons and geography, many studies noted the strong diurnal cycle of boundary layer clouds. During the day, low clouds form in the morning and expand, following the warming of the surface by incoming solar radiation (Stubenrauch et al., 2006). Maximum low cloud amount is often reached in the early afternoon. This sun-driven variation is maximum over continents, where it depends on orography (Wilson and Barros, 2017; Shang et al., 2018), and in summer. It is more limited over ocean and during winter (Rozendaal et al., 1995; Soden, 2000). When night falls, condensation in the boundary layer can create stratiform clouds, which stabilize and expand through nighttime radiative cooling at cloud top and reach maximal cover in the early morning (Greenwald and Christopher, 1999; Eastman and Warren, 2014).

In the Tropics, the near-surface daily increase in water vapor triggered by solar warming (Tian et al., 2004) is transmitted to higher altitudes through deep convection (Johnson et al., 1999). This imposes a diurnal cycle to high clouds, which is delayed by several hours compared to low clouds (Soden, 2000). Their maximum amount is reached in the evening (Rossow and Schiffer, 1999; Stubenrauch et al., 2006). At midlatitudes, without deep convection most of the troposphere is free from surface influence (Wang and Sassen, 2001), and diurnal changes in the distribution of high-altitude clouds are limited. Changes are rather driven by the local atmospheric circulation (e.g. Storm-tracks), leading to less predictable patterns which are more location-dependent.

More recently, geostationary imagery documented the diurnal variations in the composition of cloud cover above Central Africa (Philippon et al., 2016) and cloud top temperatures (Taylor et al., 2017). In any case, the vertically-integrated nature of passive imagery means it cannot resolve the vertical variability of clouds and its diurnal cycle, which is key to better understand the atmospheric heating rate profile (L'Ecuyer et al., 2008). By comparison, active remote sensing instruments, such as radars and lidars, document the cloud vertical distribution with great accuracy and vertical resolutions finer than 500m. Long-running datasets from active instruments operated from ground-based sites have led to useful time series and statistics about clouds (e.g. Sassen and Benson, 2001; Hogan et al., 2003; Protat et al., 2009; Dong et al., 2010; Hoareau et al., 2013; Zhao et al., 2016). From space, Liu and Zipser (2008) were able to derive information on the clouds diurnal cycle from the spaceborne Tropical Rainfall Measuring Mission radar, launched in 1997 (Kummerow et al., 1998), but the instrument was not designed to detect clouds with accuracy. The CALIPSO lidar (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), since its launch into orbit in 2006 (Winker et al., 2010), has provided transformative vertically-resolved data on clouds (Stephens et al., 2017; Winker et al., 2017). Cloud detections from CALIPSO have, among other things, helped pinpoint and improve significant cloud-related weaknesses in climate models (e.g. Cesana and Chepfer, 2013; Konsta et al., 2016), helped improve estimates of the surface radiation budget (Kato et al., 2011) and of the heating rate profile (Haynes et al., 2013; Bouniol et al., 2016). Due to its sun-synchronous polar orbit, CALIPSO samples the atmosphere at either 1:30AM or 1:30PM local time (LT), like the CloudSat radar (Stephens and Kummerow, 2007) and all A-Train instruments (L'Ecuyer and Jiang, 2010). Even though measurements at two times of day can offer insights into the day-night cloud changes (Sèze et al., 2015; Gupta et al., 2018), they are insufficient to fully document the diurnal evolution of cloud profiles. This observational blind spot explains why very little is known so far about how the vertical distribution of clouds changes diurnally in most of the globe, leading to inconsistencies amongst climate models (Yin and Porporato, 2017).

Here we take advantage of measurements from the Cloud Aerosol Transport System (CATS, McGill et al., 2015) lidar on the International Space Station (ISS), to document the diurnal evolution of the vertical distribution of clouds in regions of the globe. As the ISS orbits the Earth many times a day between 51°S and 51°N, CATS measurements cannot track the evolution of individual clouds over a given location and a given day. Instead, cloud detections over a given location at variable times of day can be aggregated over seasons, to create statistics that eventually document the seasonal average diurnal cycle of clouds over that location. Thus far, the CATS dataset is the only one to contain active vertically-resolved measurements made from satellite with variable local times of overpass.

We first describe how data were selected and processed to derive diurnal cycles of cloud Cloud Fraction (CF) profiles and Cloud Amounts (CA) from CATS and all other instruments included for comparison (Sect. 2). Then, using CATS retrievals we document, for the first time, the diurnal cycle of detailed Cloud Fraction profiles in large regions of the globe in two seasons over ocean and land (Sect. 3.1 and 3.2). In Sect. 3.3 we describe CATS-derived diurnal cycles of cloud profiles over selected sites and continents with two goals in mind: (i) to compare them with independent ground-based observations to check the validity of the CATS retrievals, and (ii) to document the diversity of the continental cloud profile diurnal cycles over the globe. In Section 4 we discuss implications of our results: We compare the diurnal cycle of the Low and High cloud covers derived from CATS with ones from geostationary satellites (Sect. 4.1), and discuss the agreement between CATS Cloud Fraction profiles derived at the times of CALIPSO overpass with actual CALIPSO retrievals (Sect. 4.2.a). Finally, we consider CATS profiles at overpass times from current and future sun-synchronous spaceborne lidar missions (Sect. 4.2.b) to understand which part of the diurnal cloud cycle is sampled by these instruments. We conclude in Sect. 5.

2. Data and Methods

2.1 Data

a) Cloud detections from the CATS spaceborne lidar

In this study, our primary data consist of clouds detected during June-July-August (JJA) and December-January-February (DJF) periods using data from the CATS lidar system (Yorks et al., in preparation). CATS operated from the ISS between February 2015 to late October 2017. Although CATS was originally designed to operate at 3 wavelengths (355, 532 and 1064nm) with variable viewing geometries, beginning in March 2015 technical issues limited operation to a single 1064nm wavelength and a single viewing mode. The CATS instrument went on providing single-channel high-quality data (Yorks et al., 2016a) until a fault in the on-board power and data system ended science operations on October 30, 2017.

Being located on the ISS means measurements from CATS are constrained to latitudes below 51°, giving it access to ~78% of the Earth's surface (Figure 1, top). This prevents our study from covering polar regions, but leads to densely distributed overpasses at latitudes above 40°. CATS sampling is particularly good in populated midlatitude regions and above the Southern Ocean.

CATS reports vertical profiles of Attenuated Total Backscatter (ATB) every 350m at 1064nm with a 60m vertical resolution (Yorks et al., 2016a). In the mode 7.2 in which CATS operates since February 2015, each profile is created by accumulating backscattered energy from 200 4kHz pulses, 20 times per second. The CATS vertical feature mask algorithms use these calibrated ATB profiles, averaged to 5 and 60 km, to detect atmospheric layers, discriminate clouds from aerosols, and determine cloud phase (Yorks et al., 2016b and in preparation). The CATS layer-detection algorithms are based on a threshold-profile technique similar to the one used for CALIOP (Vaughan et al., 2009) but, unlike for CALIOP, they rely primarily on 1064nm ATB (Yorks et al., 2016b). CATS cloud-aerosol discrimination algorithm uses a probability density function technique that is based on the CALIPSO algorithm but relies on horizontal persistence tests to differentiate low-level clouds and aerosol because backscatter color ratio, used in the CALIOP algorithms (Liu et al., 2009), is not available in

Mode 7.2. For cloud phase, CATS uses layer-integrated 1064 nm depolarization ratio and mid-layer temperature thresholds based on Hu et al. (2009) and Yorks et al. (2011). Minimum horizontal average was 5km in nighttime and 60km in daytime, a choice that brings the same cloud detection sensitivity to both (Yorks et al., 2016a). This has two consequences: 1) optically thinnest clouds detected during nighttime at 60km horizontal averaging might be absent from daytime detections (these represent roughly ~5% of nighttime clouds) and 2) the horizontal extent and cloud amount of fragmented boundary layer clouds might be overestimated in both daytime and nighttime compared to single-shot detections (as in Chepfer et al., 2013; Cesana et al., 2016). Cloud top and base heights, phase, and other properties are reported in the CATS Level 2 Operational (L2O) products every 5 km along-track. Hereafter we used such cloud properties from CATS L2O data files v2.01 (Palm et al., 2016), including only layers with a feature type score above 5, to avoid including wrongly-classified optically thick aerosol layers near deserts.

To document the diurnal cycle (Sect. 2.2.a), we used CATS cloud detections from JJA and DJF seasons between March 2015 and October 2017. CATS cloud data being still novel at the time of this writing, we document and discuss several of its characteristics in Appendices A and B, including sampling variability and the sensitivity of cloud detection in presence of solar pollution. This exploration of CATS data (and the upcoming comparisons with other instruments) made us confident that its sampling and cloud detections are robust enough to be used for scientific purposes.

b) Cloud detections from ground-based active instruments

Like with any lidar, the CATS laser beam gets fully attenuated when passing through clouds with optical depths larger than typically 3 (e.g., Chepfer et al., 2010). This can lead to the Cloud Fractions being underestimated in the lower troposphere. Meanwhile, horizontal averaging during daytime can lead to Cloud Fractions being overestimated at low altitudes. To estimate how much the CATS Cloud Fraction is biased at low altitudes, we compare CATS detections with independent observations collected from ground-based active instruments.

Ground-based observation sites provide long-term records of atmospheric properties over periods that often cannot be reached by satellite instruments (Chiriaco et al., 2018).

Nowadays such sites are often well equipped with active remote sensing instruments. Data acquisition, calibration and processing are often homogenized in the framework of specific observation networks (e.g. EARLINET, the European Aerosol Research Lidar Network, Pappalardo et al., 2014). Descriptions of the clouds diurnal cycle based on active ground-based measurements are however scarce. In this study, we compare CATS cloud cycles with those derived from active measurements at three ground-based sites, two continental and one oceanic:

- The Site Instrumenté de Recherche par Télédétection Atmosphérique (SIRTA, Haeffelin et al., 2005) is continental, located 20km South-West of Paris at 48.7°N, 2.2°E. From SIRTA we used cloud detections from the Lidar Nuages et Aérosols (LNA, Elouragini and Flamant, 1996), which were curated, packaged and made available in the framework of the SIRTA-reOBS project (Chiriaco et al., 2014, 2018). The LNA requires human supervision and does not operate under precipitation, leading to irregular sampling and almost no nighttime measurements. Thanks to its long operation time, its cloud dataset covers almost 15 years and was used in many studies (e.g. Noel and Haeffelin, 2007; Naud et al., 2010; Dupont et al., 2010). Cloud layers were detected in LNA profiles of attenuated backscatter following a threshold-based approach similar to CATS and CALIPSO.
- The Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site is continental too, at 97°W, 36°N. From ARM-SGP we used the sgparsclkazr1kolliasC1 cloud dataset (DOI: 10.5439/1393437), which contains vertical cloud detection profiles for every second every day based on measurements from the 35GHz Ka ARM Zenith Radar. This instrument has been operating since 2011 (Kollias et al., 2014). Based on these profiles we reconstructed hourly averages of Cloud Fraction profiles over seasons during the CATS operation period. Our results closely match those Zhao et al. (2017) derived from the same instrument, and those Dupont (2011) derived from the ARM-SGP Raman lidar.
- The ARM Eastern North Atlantic (ENA) site is oceanic, located on Graciosa Island in the Azores archipelago (28.03°W, 39.1°N). From ARM-ENA we used cloud detections from the enaarsclkazr1kolliasC1 dataset derived from a 35GHz radar similar to the one found at SGP, which we processed in a similar way.

c) Cloud detections from passive and active spaceborne sensors

In addition to the datasets from CATS, LNA and two ground-based radars, in the upcoming sections we use cloud retrievals from two spaceborne datasets to put CATS cloud retrievals into a referenced context. First, we consider the baseline reference for the description of the clouds diurnal cycle from space: the analysis of data from the ISCCP done by Rossow and Schiffer (1999), hereafter RS99. Their results are based on aggregated and homogenized infrared and visible radiances from imaging radiometers on the international constellation of weather satellites. They are widely considered as the reference for describing the diurnal cycle of the cloud cover at large scales from space measurements. We did not reprocess any ISCCP data for the present study, instead we rely on the description of the diurnal cycle of low and high clouds RS99 documented in their Fig. 11 based on ISCCP, to which we confront CATS retrievals in Sect. 4.1.

Finally, we also confront CATS cloud detections with retrievals based on measurements from the CALIOP lidar, routinely made since 2006 from the sun-synchronous CALIPSO platform at 13:30 and 01:30 LT in Sect. 4.2. To enable comparison with CATS retrievals, we used cloud layers retrieved from CALIPSO measurements during the period of CATS operation (March 2015 to October 2017) and documented at a 5km horizontal resolution in CALIPSO Level 2 V4.10 Cloud Layer Products (Vaughan et al., 2009). We processed both CATS and CALIPSO data alike as described in Sect. 2.2.a.

2.2. Methods

a) Building the diurnal cycle of Cloud Fraction profiles from lidar cloud detections

Analyzing CATS lidar echoes lets one identify at which altitude a cloud is present above a particular location on Earth at a given moment. By aggregating such information over a long period, vertical profiles of Cloud Fraction can be derived. A CF(z) profile documents at which frequency clouds were observed at the altitude *z* over a particular location. Cloud Fractions are conceptually equivalent to the Cloud Amounts derived from passive measurements (next section) but vertically resolved with a 60 meters resolution.

From CATS level 2 data files, we extract profile-based cloud detections and use the measurement UTC time and coordinates to deduce their local time of observation. Using the resulting list of cloud layer altitudes, coordinates and local times of detection, we count the number n of cloud detected within half-hour bins of local time, 2°x2° lat-lon boxes and 200m altitude bins. We also count the number of valid data points n_0 within those bins. Eventually, we derive the Cloud Fraction $CF = \frac{n}{n_0}$, either in individual local time/lat-lon/altitude bin or by aggregating n and n_0 over a selection of bins. Thus, we recreate a statistically accurate representation of the diurnal cycle of Cloud Fractions profiles, over any location between 51°S and 51°N, through the aggregation over long periods of cloud detections made over that location on different days and local times.

CATS reports cloud layers as opaque when no echo from the surface is found in the profile below a detected cloud, following the same methodology as in Guzman et al., 2017. Below an opaque cloud layer, there is no laser signal left to propagate, and clouds potentially present at lower altitudes will not be sampled by the lidar. To account for this effect, we consider the portions of profiles below an opaque layer unsampled, and they do not count in the number of valid data points n_0. This approach limits the influence of laser attenuation on cloud detections but cannot totally cancel it. For very low clouds (top below 2km), we make an exception to this rule and consider the lower part of the profile cloudy, as we found this creates the best agreement with ground-based observations.

To enable comparisons with CATS CF profiles (Sect. 3.3 and 4.2), we followed a similar approach to build CF profiles using cloud detections from SIRTA-reOBS and ARM datasets (Sect. 2.1), and from CALIPSO Level 2 products (Sect. 2.1.c). In both cases, we counted the number of cloud detections and valid (non-attenuated) measurements in hourly local time bins and 200m altitude bins. For CALIPSO, only 01:30AM and PM time bins were filled.

b) Building the diurnal cycle of Low and High Cloud Amounts from CATS data

As ISCCP data are based on radiances, clouds therein are characterized according to their retrieved top pressure P as low ($P > 680$hPa), middle ($440 < P < 680$hPa) or high ($P < 440$hPa). To enable a direct ISCCP-CATS comparison, we derived Cloud Amounts (CA) from CATS data for low and high clouds as defined by altitude: low clouds have their top below 4km ASL, high clouds have their base above 7km, and mid-level clouds are in between. Using the list of cloud layer altitudes, coordinates and local times of detection derived from CATS detections (Sect. 2.2.a), we count the number of occurrences n' of at least part of one cloud layer in half-hour bins of local time, 2°x2° lat-lon boxes and the three altitude ranges (0-4km, 4-7km and higher than 7km ASL). We also count the number of occurrences n'_0 that could possibly be reported given the measurements sampled by CATS within each bin, taking into account the existence of opaque layers. Eventually, we derive the Cloud Amount $CA = \frac{n'}{n'_0}$ for low, mid and high-altitude clouds layers, either in individual local time/lat-lon bin or by aggregating n' and n'_0 over a selection of bins. Like RS99, we separated CATS cloud detections over land and ocean, based on the International Geosphere-Biosphere Programme surface flag present in CATS L2 products on a profile basis (Palm et al., 2016).

3. Results

3.1. Diurnal Cloud Fraction profiles observed at Global scale

Figure 1 shows the global diurnal cycle revealed by CATS during JJA from March 2015 to October 2017 over Ocean and Land (bottom left and right). Low and high clouds are clearly separated, with a band of minimum cloudiness in-between (near 4km ASL). Above both surfaces, CATS data show an increase of high clouds during nighttime. Sassen et al. (2009) explain this increase by the infrared radiative cooling of the upper troposphere. The vertical spread of high clouds is most narrow near noon, at which point their apparent base is the highest. These findings are consistent with CALIPSO retrievals (Sassen et al., 2009; Gupta et al., 2018). The vertical evolution in the fraction of sampled atmosphere due to attenuation by atmospheric components, for these diurnal cycles and all that follow, is documented in Appendix C.

Significant differences exist between the cloud profiles diurnal cycle above land and ocean. Clouds generally extend higher over land during nighttime: high clouds are vertically most frequent near 10km over ocean, while they extend up to 14km above continents until 5AM. Over ocean, high clouds appear to rise late in the afternoon (3-6PM) and fall soon thereafter as the sun sets. Land-ocean differences are most striking at low altitudes: over Ocean low clouds are present almost all day long between 0 and 2km ASL, their CF decreasing from a 20% maximum near 4AM to ~10% between 11AM and 5PM. Over land, low clouds are most significant during daytime: they appear near 2km ASL at 10AM and extends upwards to reach 4km ASL near 4PM. The associated CF remains low, at most 8%. These planetary boundary layer (PBL) clouds are most certainly associated with turbulence and convection activity occurring near the surface. They disappear after 4PM without connecting to the higher layers. The clear-sky band (CF < 2%) near the surface is largest at night (almost 2km) and thinnest in the late morning.

An aside on cloud detection: over the ocean, CATS detects more low and high clouds during nighttime. This means that the increase in high clouds does not prevent the lidar measurements to represent faithfully at least part of the nocturnal increase in low clouds.

During daytime, the decrease in detection sensitivity due to solar pollution could underestimate the retrieved frequency of clouds (low or high). However, CALIPSO cloud detections also reveal a nighttime increase in high clouds, which Sassen et al. (2009) and Gupta et al. (2018) found much too large to be attributed to detection bias from solar noise. Since CATS daytime cloud detection abilities at 1064nm are at least as good as CALIOP's at 532nm (Yorks et al., 2016), it follows that CATS cloud retrievals should provide a reliable qualitative assessment of their diurnal cycle, as comparisons with ground-based measurements will later show (Sect. 3.3). How much solar noise leads to an underestimate of high clouds in CALIOP and CATS datasets still needs to be quantified.

While these seasonal mean results are informative, they mix together unrelated cloud populations from hemispheres with opposite seasons driven by different circulation regimes. We thus describe the daily cycles of clouds in zonal bands in the next section.

3.2. Diurnal Cloud Fraction profiles observed over mid-latitudes and Tropics

In this section, we consider cloud populations over four latitude bands: midlatitude (30°-51°) and Tropics (0-30°), in the North Hemisphere (NH) and South Hemisphere (SH), over land and ocean. We first examine the differences between the diurnal cycles affecting the cloud vertical profiles over ocean and land in JJA (Sect. 3.2.a and 3.2.b, Fig. 2), then we discuss how these cycles are affected by the season by considering DJF results (Sect. 3.2.c, Fig. 3).

a) High clouds

As expected, Fig. 2 shows that high clouds are located at higher altitude in the tropics (12-16km ASL) than in midlatitude (8-12km), following the variation of the troposphere depth with latitude. Also as expected, the occurrence of high clouds is largest (CF > 20%) in deep convection along the Inter-Tropical Convergence Zone (ITCZ), located between 0° and 30°N in JJA, and minimum (CF < 8%) in the subsidence branch of the Hadley cell (0°-30°S in JJA). In mid-latitudes, high clouds (7-9km ASL) are far more frequent (CF ~ 20%) over the Southern Ocean (30°S-51°S) than over the northern ocean (30-51°N).

The CF of oceanic high clouds follows a strong diurnal cycle, with a maximum at nighttime and a minimum at noon, in mid-latitudes and tropics (even in subsidence region). This cycle is more pronounced where the high clouds are more numerous: along the ITCZ (0-30°N) and in the Southern Ocean (30-51°S). In addition to the variation in the high cloud occurrence, the vertical distribution of these clouds also follows a marked diurnal cycle along the ITCZ: detections spread vertically over more than 4km near midnight, but over less than 1km at noon. This spreading out occurs between 5PM and 10PM, and disappears much faster during the morning. A wider spread of detection altitudes can either indicate the presence of geometrically thicker clouds, or a wider distribution of optically thick clouds tops only partially sampled by CATS. By comparison, over the Southern Ocean high cloud detections occur over the same altitude range throughout the day.

Overall, high clouds behave very similarly above land (Fig. 2, right column) and ocean (Fig. 2, left column) at all latitudes, except between 30-51°S where the continental surface is too small to conclude.

b) Low clouds

Over ocean in JJA (Fig. 2), the occurrence of low clouds (0-3km ASL) changes significantly with latitude: The Southern Ocean region (30-51°S) is by far the cloudiest, the mid-latitude north (30-51°N) and the subsidence tropics (0-30°S) are moderately cloudy, and even less low clouds are observed along the ITCZ (0-30°N). The oceanic low clouds show only small variations along the day. A weak diurnal cycle occurs at all latitudes except along the ITCZ (possibly because low clouds there are in part masked by higher clouds affected by an out-of-phase diurnal cycle). Low-level clouds are more numerous in nighttime (CF near 20%) compared to daytime (CF~12%) in subsidence tropics (0-30°S) and mid-latitude north (30-51°N). The southern oceanic low clouds exhibit a very faint diurnal cycle: their CF gets over 20% nearly all day long, with a very small decrease near 2PM.

In contrast to high clouds, the differences between land and ocean are striking for the low and mid-level clouds. Both the occurrences and the diurnal cycles of clouds over land differ significantly from their oceanic counterparts. The low clouds are very few over land (CF~4%) compared to over ocean (>16%), all day long. Moreover, the continental low cloud diurnal cycle exhibits a maximum in the early afternoon (around 2PM) that does not show up over ocean: a maximum CF appears around 2.5 km of altitude in the upper edge (or just above the top) of the atmospheric boundary layer; it is linked to convective activity between 10AM and 5PM.

Another noticeable difference between land and ocean is the presence of well-defined mid-level cloud population over NH tropical land (0-30°N, 2nd row on the right in Fig. 2) in the free troposphere between 5 and 7 km ASL. These mid-level clouds show a diurnal cycle opposite to PBL clouds and similar to the high clouds in that its minimum occurs at midday and its maximum at night, although the magnitude of this cycle is much more limited. This altitude range would be consistent with cumulus congestus (Johnson et al., 1999). Those, however, are present above both land and ocean (Masugana et al. 2005) and CATS finds little clouds at these altitudes over ocean. Rather, the clouds altitudes and location, over land in the summer hemisphere, are consistent with Altocumulus clouds as described by Sassen and Wang (2012) using CALIPSO and CloudSat measurements. Bourgeois et al. (2017) discussed the diurnal cycle of similar clouds observed over West Africa: they found these clouds reach maximum occurrence early in the morning, which is consistent with our results.

c) Seasonal differences

Figure 3 presents diurnal cycles of Cloud Fraction profiles over the same latitude bands as Fig. 2 but based on data collected during the boreal winter (DJF). As seasons switch hemispheres, we anticipate cloud populations to undergo symmetric changes across hemispheres, in agreement with large-scale dynamic processes driving their spatial distribution on seasonal time scales. This is verified for high clouds (Fig. 2 vs. Fig. 3): in the Tropics the ITCZ moves to South and with it the large CF at high altitudes, in midlatitudes the high clouds are more frequent during the winter season, due to more frequent low-pressure conditions.

Interestingly, the mid-altitude clouds visible near 6km ASL in the NH Tropics over land (Fig. 2, 2nd row on the right) also move to the SH Tropics in DJF (Fig. 3, 3rd row on the right). This confirms the year-long persistence of midlevel clouds over continental tropical regions found by Bourgeois et al. (2017).

The seasonal changes in low clouds are less symmetric than in higher clouds, as they are more closely related to surface conditions. Over ocean, in DJF the amount of low clouds increases dramatically in NH midlatitudes compared to JJA (Fig. 2 and 3, top left), but does not change noticeably in the SH midlatitudes: the diurnal cycle that sees a slight decrease in the huge population of low clouds over the Southern Ocean is present in both seasons (Fig. 2 and 3, bottom left). Over land, in the Tropics, low clouds appear similar in frequency and behavior in both DJF and JJA: PBL clouds extend vertically between ~7AM to 5PM (Fig. 2 and 3, rows 2 and 3 of right column). The NH midlatitudes show the strongest seasonal change in low clouds, as they become present all day long: the diurnal cycle associated with PBL development in JJA disappears in DJF (Fig. 2 and 3, top right). SH midlatitude retrievals over land are noisy in DJF and JJA, but the DJF data (Fig. 3, bottom right) suggests that low clouds there extend vertically a lot more than in JJA, up to 4km ASL.

3.3. Diurnal cycle of cloud profiles above selected continental regions

In this section, our first goal is to compare the diurnal cycle of the Cloud Fraction profiles from CATS against independent observations collected by active instruments from ground-based sites (Sect. 3.3.a and 3.3.b). In particular, we want to understand if the behaviors found so far (Fig. 1-3) are valid for low clouds despite the attenuation of the space laser signal (Sect. 2.2.a). Our second goal is to compare, for the first time, the diurnal cycle of the Cloud Fraction profiles over different continental regions all over the globe as observed with a single instrument (Sect. 3.3.c).

It is important to note that since detection sensitivity, penetration depths and algorithmic choices (e.g. averaging times and distances) change significantly from one instrument to the next, we do not expect the various datasets to agree on absolute values of Cloud Fraction profiles or Cloud Amounts. Rather, our interest is in whether different instruments agree on the behavior of the diurnal evolution of clouds when they document the same location. Thus the following comparison focus on the main features of the daily cycles and not on absolute values.

a) Over South of Paris in Europe

Figure 4 shows the diurnal evolution of CF profiles seen by the ground-based LNA lidar (top left) operated on the SIRTA site south of Paris (Sect. 2.1.b) and seen by CATS in a 10°x10° box centered on SIRTA, keeping only profiles sampled over land (top right). Both datasets report a well-defined high-altitude layer, with a clear-cut cloud top near 12 km ASL that rises up a few hundred meters in the morning until 10AM and slowly falls during the afternoon by at most 1 km. In both figures, the bottom of this layer is not sharply defined: the CF decreases almost linearly from 11-12km ASL to near-zero at 4km ASL. Both instruments also report a low-level cloud layer that initiates in the morning and extends upwards from ~1km ASL at 5AM to ~4km ASL near 8PM.

Regarding differences, CATS sees more high-altitude clouds. In the late afternoon (starting near 5PM), in particular, the ground-based lidar instead sees much less high clouds; that instrument, however, suffers from poor sampling at this late hour. CATS reports less boundary layer clouds, particularly in the late afternoon, when the ground-based lidar reports low-level CF above 20% (again, a time of poor sampling). The large number of high-altitude clouds observed by CATS at that time could impair its ability to detect lower clouds, while at the same time the many low clouds observed by the ground lidar can impair its ability to detect high clouds. The absence of precipitating clouds from the LNA dataset could also explain this difference.

b) Over the US Southern Great Plains ARM site

Figure 4 shows the diurnal evolution of CF profiles seen by the SGP-based radar (2nd row, left) and CATS (right) in a 10°x10° lat-lon box centered on the SGP site (Sect. 2.2.b), keeping only profiles sampled over land. During nighttime, both datasets report frequent high-level clouds near 12km ASL, with large CF between 16:00 and 03:00 LT. At night, high clouds are also more distributed vertically, between 9 and 14km ASL. CATS and SGP datasets agree that the importance of high-level clouds strongly drops during daytime (7AM-5PM), with a minimum CF at midday. During daytime, the vertical distribution of high-level clouds is more narrow, from 11 to 12km ASL at its thinnest point (near 10AM). This rather strong cycle of high-level clouds can be explained by possible influence from Tropical dynamics at the 36°N latitude of the SGP site. There are slightly more midlevel clouds (4-8km ASL) at night, with increasing CF between midnight and 7AM. PBL clouds form near the surface at 9AM, rise and thicken almost up to 4km ASL near 4PM.

There are of course differences. The SGP radar detects PBL and midlevel clouds twice more frequently than CATS, even though few high clouds are present. CATS also misses low-level clouds observed by the SGP radar between 6PM and 6AM, probable stratiform clouds that could either be too optically thin for CATS or miscategorized by its cloud detection algorithm.

c) Over the subtropical Eastern North Atlantic ARM site

Figure 4 shows the diurnal evolution of CF profiles seen by the ENA-based radar (bottom row, left) and CATS (right) in a 10°x10° lat-lon box centered on the ENA site (Sect. 2.2.b). The vertical distribution of clouds appears very different over this oceanic site. Both CATS and the ENA radar agree on the day-long persistence of low-level clouds below 2km ASL, and on their slight drop in Cloud Fraction and vertical spread between noon and 6PM. This is consistent with persistent stratiform clouds that are maximum at night. CATS sees more high clouds (8-12km ASL) than the ENA radar (4-12km ASL). CATS also reports a Cloud Fraction minimum between 0300-0500LT that is not present in groud-based dataset.

These three comparisons between CATS and ground-based measurements suggest that, in general, the spaceborne lidar sees more high-level clouds and the ground-based instrument more low-level clouds. This sampling bias affects all space lidar comparisons with ground instruments (e.g. Dupont et al., 2010). Even so, we find similar behavior in the diurnal cycles reported by CATS and ground instruments over the same locations. Dataset discrepancies appear acceptable given the much smaller size of the CATS dataset (infrequent overpasses over 3 seasons compared to daily local measurements) and the instrumental and algorithmic variations already mentioned. It is reassuring to find that CATS results retain the major features of the clouds profile daily cycle, most notably an acceptable representation of the daytime low-level boundary layer clouds at all three sites despite the presence of high-level clouds.

In this section, we have seen that retrievals from ground-based instruments suggest CATS measurements reliably document the clouds diurnal cycle. Due to the distribution of ground-based sites, however, this approach is limited to mostly midlatitudes from the Northern Hemisphere. Next, we compare CATS detections with global spaceborne retrievals.

d) Diurnal cycles of the cloud profiles over continents

Continents are diverse in ground type, orography, latitude, exposition to large-scale atmospheric circulation, and transport of air masses from the local environment. These factors influence the atmosphere above the continent, leading to possible variations in the cloud diurnal cycle profiles. Ground-based observations let us document these different cycles, but differences between instruments and operations in the different ground sites make comparing diurnal cycle observed from ground at different locations difficult. Thanks to CATS data, for the first time we compare here the cloud diurnal cycle profiles observed over different continents by a single instrument and with a relatively large space sampling, compared to single-site ground-based observations. Figure 5 illustrates how the diurnal cycle of CF varies among seven large continental areas across both hemispheres, considering only cloud detections made by CATS over land within lat-lon boxes (defined in the inset map) during the summer seasons (JJA in the NH, DJF in the SH).

During summer most continents share a development of PBL clouds during sunlit hours (with similar Cloud Fractions, hours and vertical extents), except NH Africa where low clouds are almost absent. Most continents also share a nighttime maximum and daytime maximum of high clouds, with an associated narrowing of their vertical distribution during morning and a spreading out during the afternoon. Variations in cloudiness and cloud vertical distribution are particularly intense over South America and SH Africa, while they are minimal over Australia. A mid-altitude cloud layer is present almost all day long, with a faint daytime minimum, over all SH continents and NH Africa.

Note that the present comparison is less robust in the lower troposphere than higher in the troposphere, due to the attenuation of the space lidar signal as it penetrates the atmosphere.

4. Discussion

Hereafter we use our results for answering the following questions: How does the diurnal cycle of low, mid, high cloud covers from geostationary satellites compare with CATS ones? Do the existing lidar space missions document extreme or average behaviors of the cloud profile diurnal cycle? What about upcoming sun-synchronous lidar space missions?

4.1 About the Diurnal cycles of Low and High Cloud Amounts

CATS observations provide an opportunity to compare the cloud diurnal cycle derived from the ISCCP dataset (Sect. 2.1.c) with completely independent observations at near-global scale (excluding latitudes higher than 51°). In particular, we expect cloud retrievals from an active sensor such as CATS to be independent of the surface, even above highly reflective surfaces such as ice and deserts and to include optically thin clouds. Since CATS sampling is constrained between 51°S and 51°N, its data cannot be used to document the diurnal cycle in the polar regions, like ISCCP does: our comparison will extend at most to midlatitudes. Figure 6 shows the diurnal cycle of the Low and High cloud covers observed by the CATS space lidar.

Over ocean CAs are very stable, the diurnal cycle is almost flat (Fig. 6, left column). CATS shows a weak cycle for low clouds, with a maximum in mid-morning and a minimum in early-afternoon, which is also visible in ISCCP data. For oceanic high clouds, CATS exhibit almost no diurnal cycle except in the Tropics where they follow the same cycle as low clouds. ISCCP also shows a weak cycle for high clouds, but opposite to the CATS one. This might be related to the fact that CATS can detect optically thin high clouds better than ISCCP. The optically thicker high clouds seen by ISCCP are thus probably more linked to deep convection activity. CATS can better detect optical thin high clouds, which should be more decoupled from convection and less affected by diurnal cycles.

Over land, between 15°S and 51°N, CATS reports that low-clouds have a pronounced diurnal cycle with a maximum of low-level clouds at midday (+10%) and a minimum at midnight (-5%). This is consistent with ISCCP observations (Figure 11 in RS99), but in the Northern midlatitudes the amplitude of the cycle is weaker for CATS than ISCCP (minimum at -4% instead of -12%). For high-level clouds over land in the Tropics (15°S-30°N) CATS observes a maximum during night-time and a minimum at noon; the timing is consistent with ISCCP but the amplitude is slightly more pronounced with CATS than ISCCP (-12% instead of -7% at midday). In the Southern hemisphere (15°S-51°S) the similarity between CATS and ISCCP gets lost, probably because the land surface is small in those latitude ranges and the observations are not significant.

In summary, CATS confirms the shape of the Low and High cloud diurnal cycles observed by ISCCP except for high tropical clouds. This could be due to the space lidar detecting a larger number of optically thinner clouds not directly linked to deep convection, or to the different day-night cloud detection sensitivities of active and passive measurements. In most cases, the amplitudes of the diurnal cycle observed by CATS differ from those observed by ISCCP.

Both CATS and ISCCP miss some low clouds that are masked by the presence of high thick clouds. So even if CATS and ISCCP diurnal cycles are roughly consistent in low clouds, both results might be biased in the same direction. The high clouds diurnal cycle presented here are more robust than the low clouds ones.

4.2 About the Cloud Fraction profiles observed at fixed local times by space lidars

The CALIOP lidar has provided detailed Cloud Fraction profiles since 2006 at 0130AM and 0130 PM LT. The next spaceborne atmospheric lidar missions ADM-Aeolus, to be launched in late 2018 (Culoma et al., 2017) on a sun-synchronous orbit, will enable measurements at 0600AM and 0600PM LT. After that, the ATLID lidar on the Earth-CARE platform (Illingworth et al., 2015), expected to launch in 2020, will operate at fixed local times close to CALIOP (02:00AM and PM). The CATS dataset may remain for the near future our single source of diurnally distributed cloud profile lidar measurements from space.

a) Comparison between CATS and CALIPSO

In this section, we first check how CATS sees the day/night variation in cloud profiles also documented by CALIOP through its two daily overpasses. Figure 7 shows vertical profiles of

Cloud Fraction reported by both datasets at 0130AM and PM, over ocean (left) and land (right), latitude-weighted and averaged between 51°S and 51°N over JJA between 2015 and 2017. The black lines show the CF obtained when considering all measurements from both instruments. Over land and ocean, we find that both CALIPSO and CATS overall report larger Cloud Fractions at 0130AM (blue) than 0130PM (red), in agreement with the findings of Gupta et al. (2018). Below 2.5 km, this difference is stronger over ocean (+7% in 0130AM CF) than over land. Both datasets report a strong increase in 0130AM CF (almost +7% compared to 0130PM) above 15km over land.

The CF profiles reported by both datasets agree very well over Ocean (left) in both daytime and nighttime conditions. Over land (right) in daytime (red) conditions, CATS reports slightly more low-level clouds (CF~7% near 1km ASL, ~5% for CALIOP). This difference, which is present at all latitudes above land during daytime (not shown), might be due to the so-called single-shot low clouds, for which CALIOP data undergoes a specific processing (Winker et al., 2009). The strongest differences appear for nighttime CF over land (right, blue): CALIPSO CF is larger than CATS CF by a 2-3% throughout the entire profile. A perfect agreement between CF from both datasets should not be expected, as the CATS and CALIOP lidars operate in different configurations – wavelengths, pulse repetition frequencies and signal-to-noise ratios are different, for a start. These technical variations lead to differences in, for instance, how fast the laser pulse energy of both instruments gets attenuated as it penetrates atmospheres of various compositions, or differences in cloud detection performance, e.g. when sampling optically thin clouds in the upper troposphere, or fractionated boundary layer clouds (see Reverdy et al., 2015 for a study of the impact of design choices on lidar retrievals). Both datasets agree quite well on the general vertical pattern of the profile, though. A useful conclusion is that considering CALIPSO observations at both overpass local times (i.e. 0130AM and 0130PM) apparently provides a good approximation of the daily average Cloud Fraction profile.

b) Comparison of Cloud Fraction profiles at various times of satellite overpass

As a final analysis, we represent the range covered by CATS hourly CF profiles over a day (averaged over the globe - white envelope in Fig. 8) and show CF profiles observed by CATS ±1 hour around the fixed local observation times of the three sun-synchronous space lidar missions (CALIPSO, ADM-Aeolus, EarthCare).

Our first aim is to understand how wind observations made at fixed local time by ADM-Aeolus might be impacted by the cloud diurnal cycle. ADM-Aeolus will provide information on wind only in absence of clouds. Figure 8 indicates that ADM-Aeolus overpass times are quite cloudy in both AM and PM compared to the diurnal variability (white envelope). The PM overpass corresponds to the daily maximum in cloud profiles over both ocean and land, while AM observations correspond to a time representative of the daily average Cloud Fraction profile. As more clouds occur in the PM than AM observations, less wind information will likely be provided by ADM-Aeolus in the afternoon than in the morning. For the future, another ADM-Aeolus-like mission around midday (minimum Cloud Fraction profile) would increase the number of wind measurement with respect to the cloud occurrence.

Our second aim is to understand how well observations made at fixed local times by space lidar dedicated to clouds studies (CALIPSO and EarthCare) capture the daily variability of Cloud Fraction profiles. Figure 8 suggests that over land (right), CALIPSO and Earth-CARE retrievals capture only part of the daily CF variability above 8km ASL: the PM measurements overestimate the daily CF minima and the AM measurements underestimate the daily CF maxima. Below 8km ASL they are rather representative of the daily average, except below 5km ASL where PM measurements get close to the daily CF maxima. Figure 8 also shows that over Ocean (left) CALIPSO and Earth-CARE retrievals should be considered as the daily CF maxima during the nighttime (AM) overpass and as the daily CF minima during the daytime (PM) overpass. This has interesting implications: it suggests that not only CALIPSO but all the observations dedicated to cloud studies collected by the instruments within the A-train (CloudSat, CERES, MODIS, PARASOL, etc.) have documented the state of the atmosphere in the extreme states of the cloud profile diurnal cycle over the last 12 years over ocean. These conclusions suggest the A-Train observations are likely relevant and robust to constrain the cloud diurnal cycle extremes in climate models and climate studies.

5. Conclusions

In this paper, we took advantage of the variable local time of overpass of the International Space Station to document the diurnal cycle of the cloud vertical profile as seen by the CATS lidar. This is the first time the diurnal evolution of the vertical cloud profile is documented on that vertical scale on a large part of the globe, between 51°S and 51°N. Our results are based on 15 months of systematic observations (3 boreal summers and 2 austral summers) collected during the 2015-2017 time period, which enable statistically significant results.

The main results follow. We observed that high tropical clouds begin to spread out vertically in the late afternoon (4-5PM). Their vertical distribution is largest (over 5km) near 10PM. This spread-out is particularly large in the Summer Hemisphere in DJF. A mid-level cloud layer (4-8 km ASL) persists all day long over the tropical continent during summer, with a weak diurnal cycle (minimum at noon). Southern Ocean results are quite unique; low clouds (0-2km ASL) cover this ocean all day long in summer and winter. A slight diurnal cycle sees their CF drop by a few percents during the afternoon (from noon to 6PM), but their vertical distribution stays constant. High clouds are also frequent over the Southern Ocean, more so in JJA. They follow a diurnal cycle in summer and winter, with an daytime minimum (from 8AM and 3PM). At all latitudes, continental low clouds are most frequent in the early afternoon (around 2PM) at about 2.5 km ASL. Finally, our results show that in summer the diurnal cycle of continental clouds is similar in both hemispheres: a rapid development of near-surface PBL clouds during sunlit hours, and an increase in cloudiness and wider vertical distributions during nighttime for high-altitude clouds (stronger over the SH and the Tropics). Exceptions are NH Africa, where PBL clouds are very few, and Australia, where high clouds appear only significant between 8 and 11PM.

We evaluated the diurnal cycle derived from CATS against independent ground-based observations and found satisfactory agreement. Moreover, our results suggest that over oceans CALIPSO and Earth-CARE should describe the daily minimum of the Cloud Fraction profile during their PM overpass, and its daily maximum during their AM overpass. This supports the idea that data collected by A-train instruments (not only CALIPSO) are very relevant to document the cloud diurnal cycle. This is also roughly the case over land at altitudes above 8km ASL, although the amplitude of the diurnal variability is quite underestimated.

Questions remain about how several factors could affect our ability to retrieve the vertical variability of clouds from lidar-based measurements through the day. More specifically, the irruption of solar noise in daytime conditions requires increased horizontal averaging to keep CATS detection sensitivity stable. High clouds with very small optical depths (lower than 0.005), which CATS can detect in the nighttime, will be probably missed in the daytime. Meanwhile, the occurrence and extent of fragmented boundary layer clouds might be overestimated. Even though prior work using the similarly-affected CALIPSO data suggests the observed diurnal changes in clouds are too large to be solely due to those effects, their impact on the retrieved cycles needs to be quantified. In the same manner, how extinction by high clouds impacts the retrieved Cloud Fractions at low altitude needs to be investigated.

In the future, it would be possible to consider CATS measurements at smaller scales, to identify regionally consistent cloud populations and diurnal behaviors over specific regions of interest. It would also be possible to use CATS detection of opaque cloud layers to identify the best local time of observation from space to study local cloud radiative effects. We will address these lines of research in upcoming papers.

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Figures.

Figure 1: (top) Number of CATS profiles in 2°x2° lon-lat boxes sampled during JJA 2015-2016-2017, with unsampled latitudes in grey. (bottom) Evolution of the vertical profile of Cloud Fraction as a function of local time of observation over the Ocean (left) and Land (right), using CATS detections made in JJA from 2015 to 2017.

Figure 2. Like Fig. 1, over the North Hemisphere midlatitudes (top row) and Tropics (second row), the South Hemisphere Tropics (third row) and midlatitudes (bottom row) during JJA from 2015 to 2017.

Figure 3: Same as Fig. 2, considering data CATS measured during the boreal winter (DJF, from 2015 to 2017).

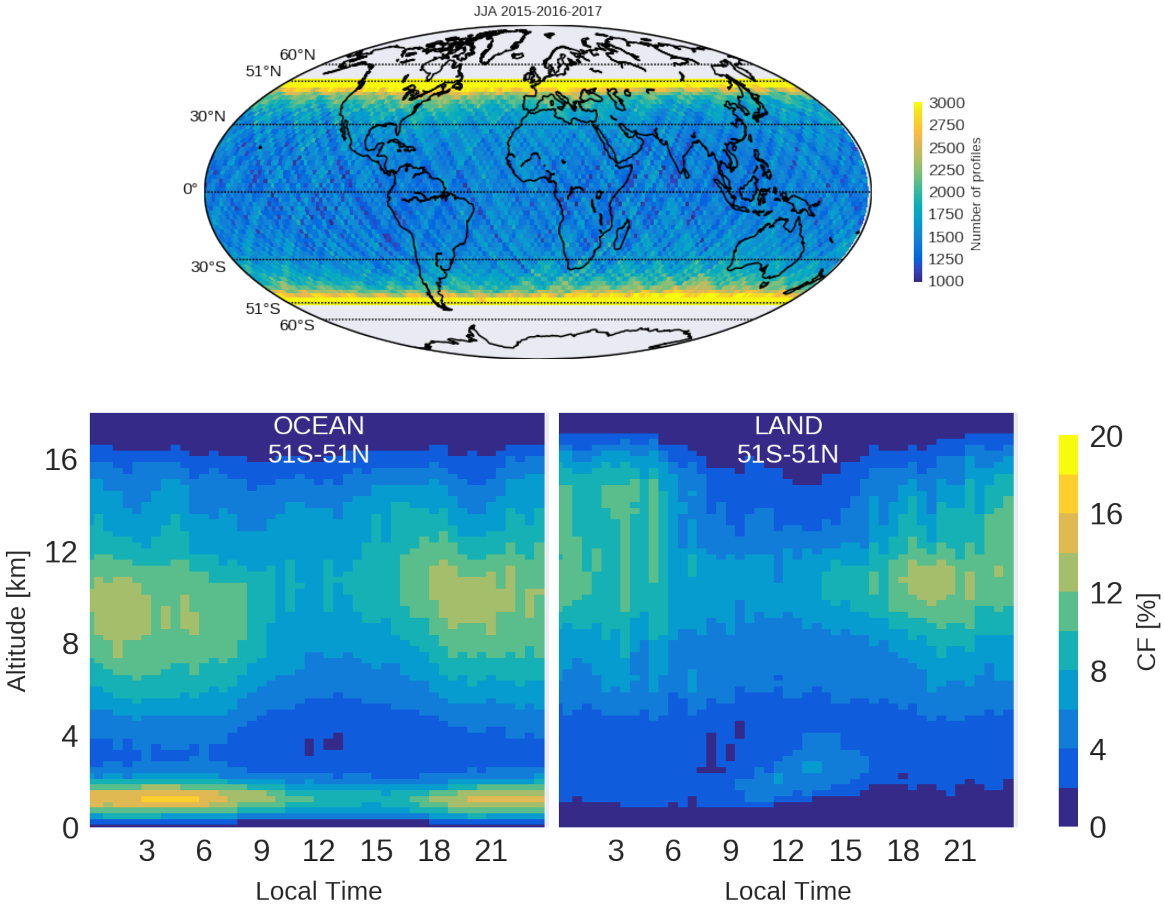
Figure 4: The diurnal cycle of cloud fraction profiles as seen ground-based instruments (see text, left column) and the CATS instrument (right column) during JJA 2015-2017 at or in a 10°x10° lat-lon box centered on (first row) SIRTA, considering only sunlit conditions, (second row) ARM-SGP, (third row) ARM-ENA. Times are local.

Figure 5: Diurnal cycle of the cloud fraction profiles observed by CATS over different continents a) NH America, b) Europe, c) China, d) NH Africa, e) SH America, f) SH Africa, g) Australia, averaged over the summer months (JJA in the North Hemisphere, DJF in the South Hemisphere) from 2015 to 2017. For each region we considered all profiles sampled over land within the boundaries shown by the inset map. CF over Europe do not extend to altitudes as high as the rest, as it is the only region that does not include part of the Tropical band.

Figure 6: Mean diurnal variations of low-level (solid line) and high-level (dotted line) cloud amounts (%) every 3 hours in five zonal bands over ocean (left) and land (right) in JJA from CATS for the period 2015-2017.

Figure 7: Vertical Profiles of Cloud Fraction observed by CALIPSO (full line) and CATS (dashed line) between ±51° around 0130AM (blue), 0130PM (red) and at all times (black), over ocean (left) and land (right). Measurements were weighted based on the latitude at which they were made, to account for the different zonal sampling distributions of both instruments. CALIOP cloud profiles were built using cloud layers from the CALIPSO v4.10 level 2, 5-km cloud layer product. Only layers with a Cloud/Aerosol Discrimination score (CAD_Score) above 0.7 were considered to build the CALIOP profiles, and layers with a Feature_Type_Score above 5 were considered to build the CATS profiles. For both instruments, we used JJA observations from 2015 to 2017.

Figure 8: Mean Cloud fraction profiles observed by CATS at the overpass local time of the sun-synchronous space lidars (CALIPSO and the A-train 01:30UTC, ADM 06:00UTC, Earth-CARE 02:00UTC) compared to the envelope of the whole cloud fraction profile diurnal cycle observed by CATS (white), averaged between ±51° over ocean (left) and land (right). CALIPSO and Earth-CARE are dedicated to clouds an aerosols studies, while ADM is primarily dedicated to wind measurements in non-cloudy conditions. We used CATS observations during JJA from 2015 to 2017.



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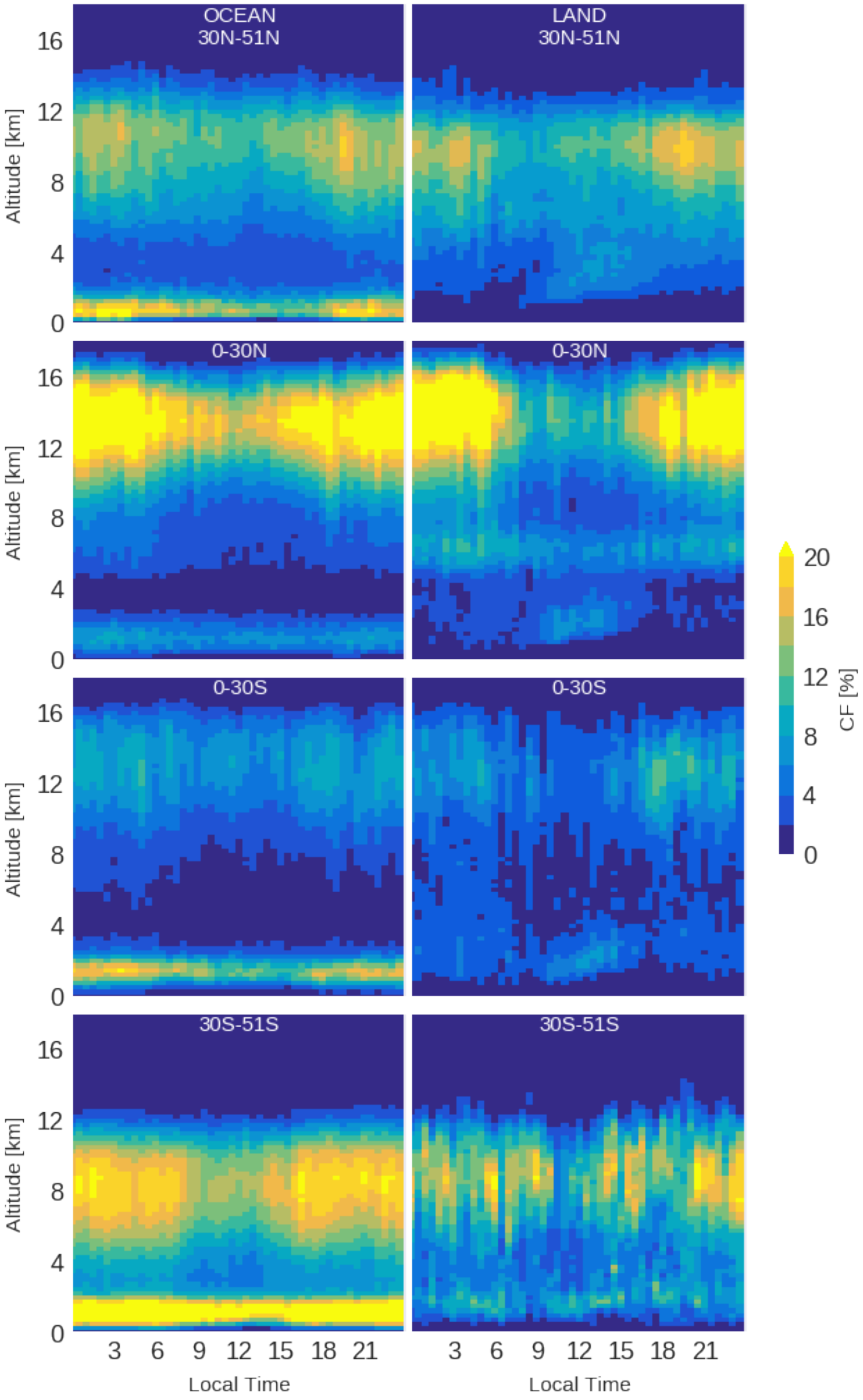

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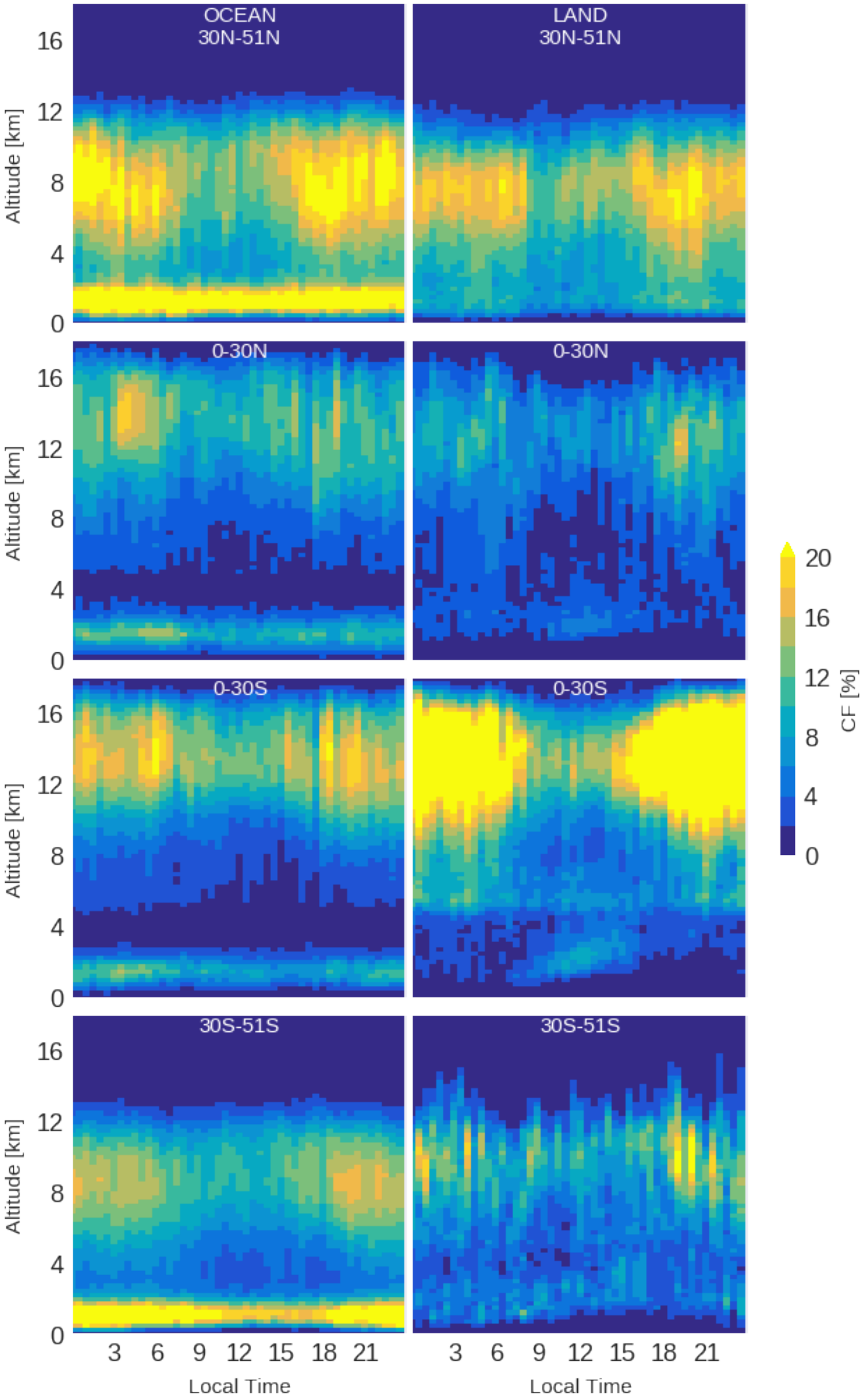

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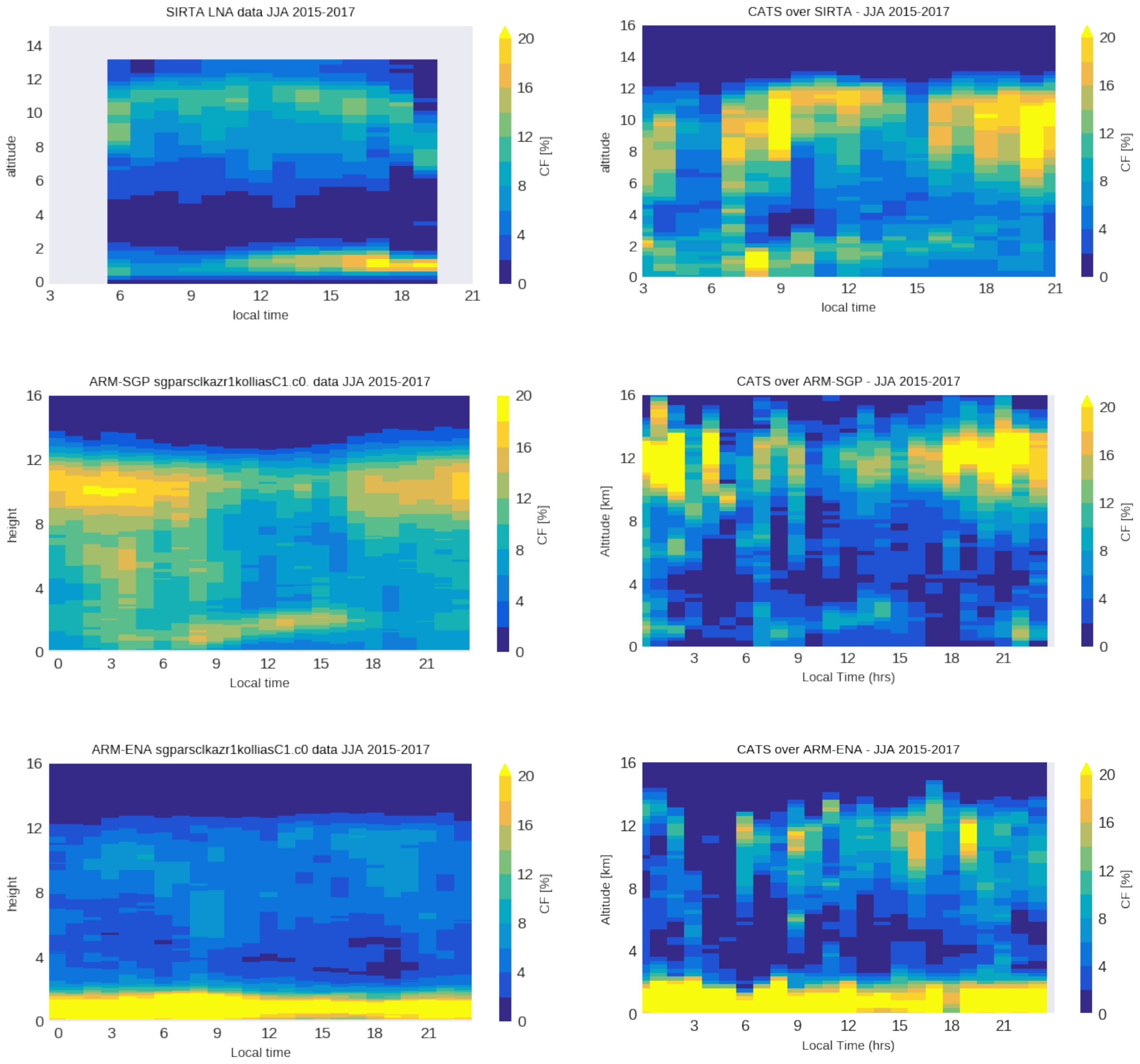

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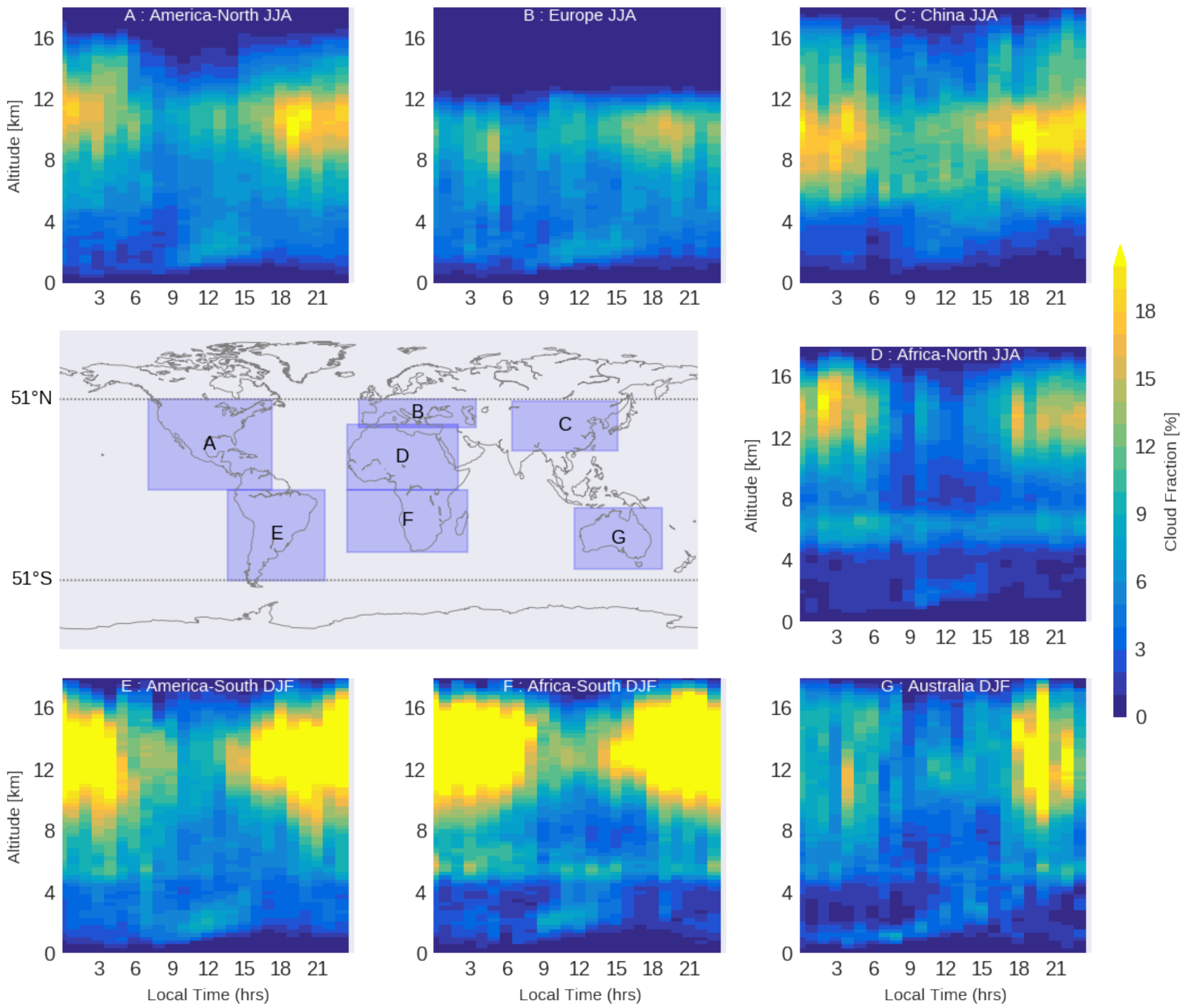

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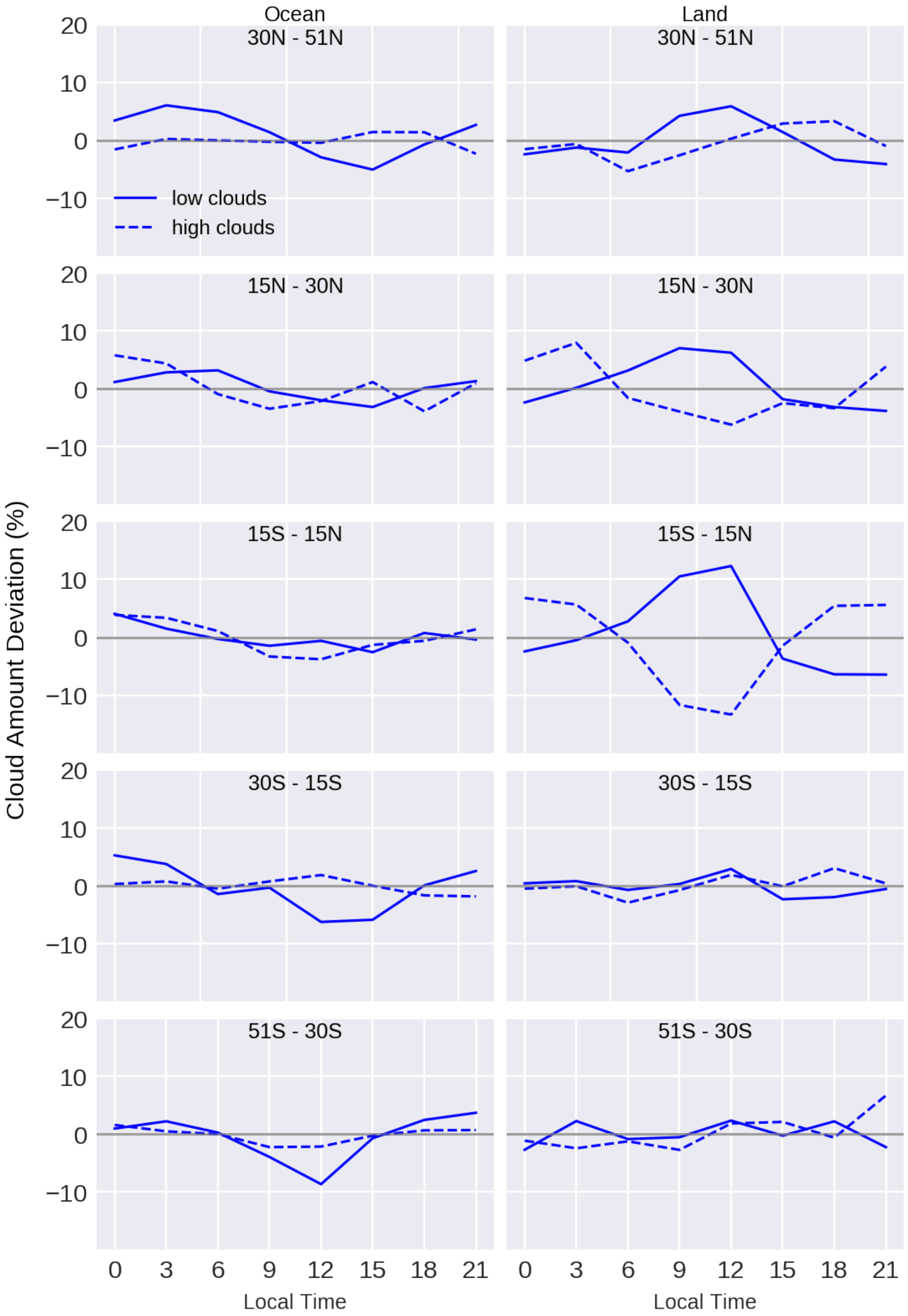

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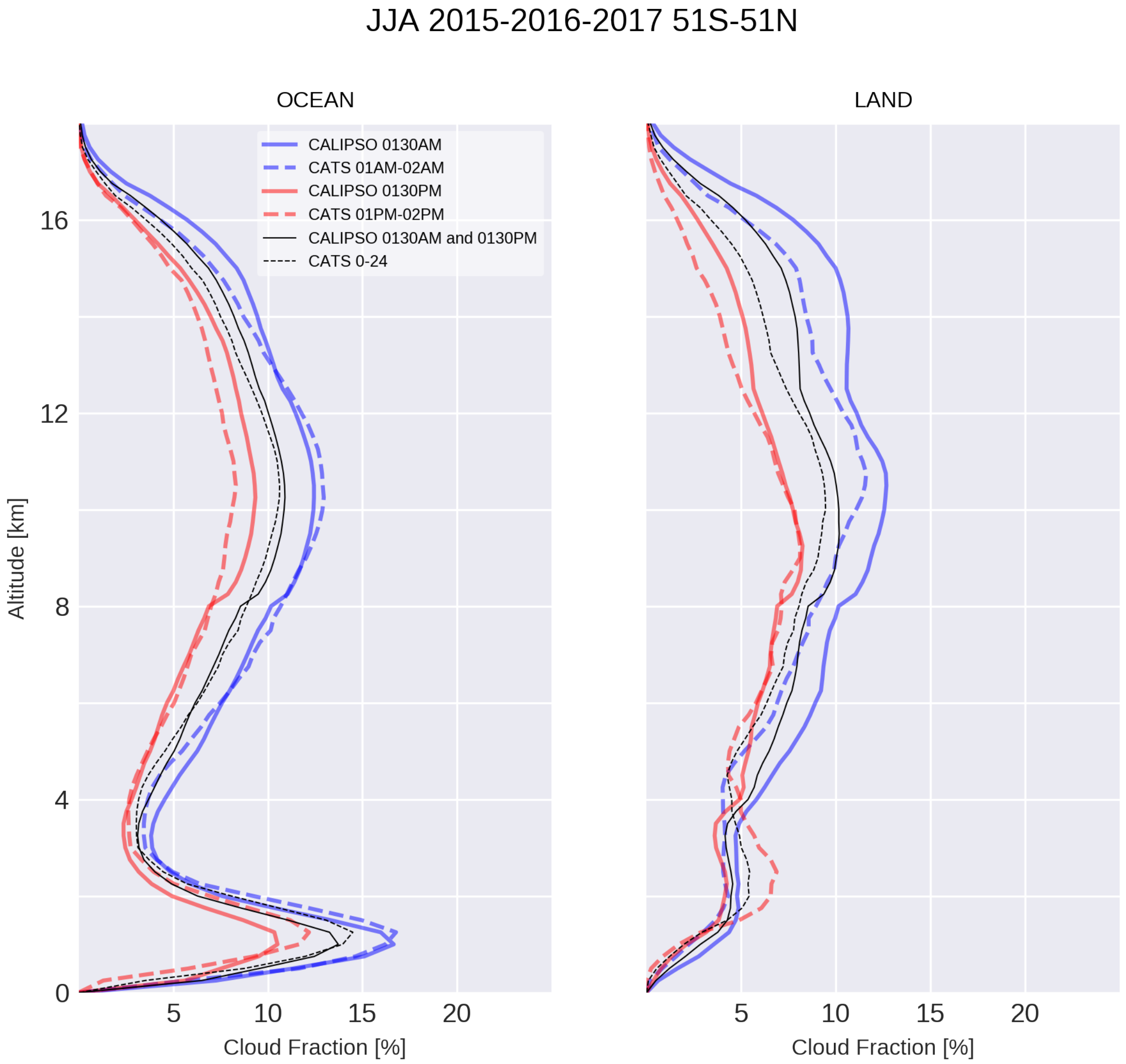

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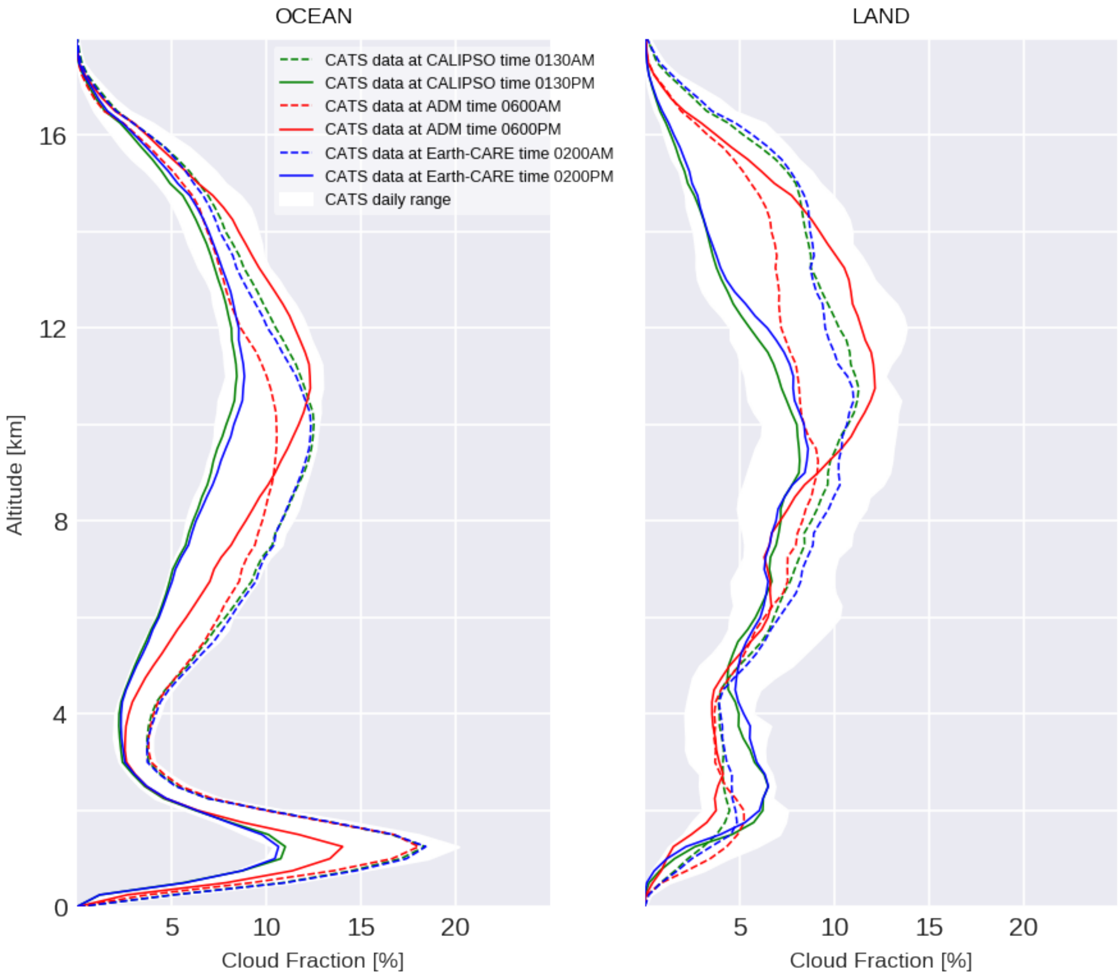

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