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# How well do climate models simulate cloud vertical structure?

## A comparison between CALIPSO-GOCCP satellite observations and CMIP5 models

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[1] The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite provides robust and global direct measurements of the cloud vertical structure. The GCM-Oriented CALIPSO Cloud Product is used to evaluate the simulated clouds in five climate models using a lidar simulator. The total cloud cover is underestimated in all models (51% to 62% vs. 64% in observations) except in the Arctic. Continental cloud covers (at low, mid, high altitudes) are highly variable depending on the model. In the tropics, the top of deep convective clouds varies between 14 and 18 km in the models versus 16 km in the observations, and all models underestimate the low cloud amount (16% to 25%) compared to observations (29%). In the Arctic, the modeled low cloud amounts (37% to 57%) are slightly biased compared to observations (44%), and the models do not reproduce the observed seasonal variation. **Citation:** Cesana, G., and H. Chepfer (2012), How well do climate models simulate cloud vertical structure? A comparison between CALIPSO-GOCCP satellite observations and CMIP5 models, *Geophys. Res. Lett.*, 39, L20803, doi:10.1029/2012GL053153.

### 1. Introduction

[2] Clouds are the primary modulators of the Earth's radiation budget and still constitute the main source of uncertainty in model estimates of climate sensitivity [Randall *et al.*, 2007], and a major limitation to the reliability of climate change projections [e.g., Dufresne and Bony, 2008]. To improve the reliability of climate change projections, it is therefore imperative to improve the representation of cloud processes in models. This first requires evaluating cloud descriptions in climate models. Until recently, this evaluation has been largely based on satellite data of the Earth's radiation budget (the Earth Radiation Budget Experiment, ERBE [Kandel *et al.*, 1994], the Scanner for Radiation Budget, ScaRaB [Barkstrom and Smith, 1986], and the Clouds and the Earth's Radiant Energy System, CERES [Wielicki *et al.*, 1996]). Basic aspects of cloudiness, as fundamental as the vertical distribution of the cloud cover were crucially lacking. Direct robust observations of the cloud amount over highly reflective surface (ice-sheets, deserts, continents) or in sparse shallow cumulus clouds near the surface, and of cloud vertical structure were not available at global scale. This lack of knowledge is

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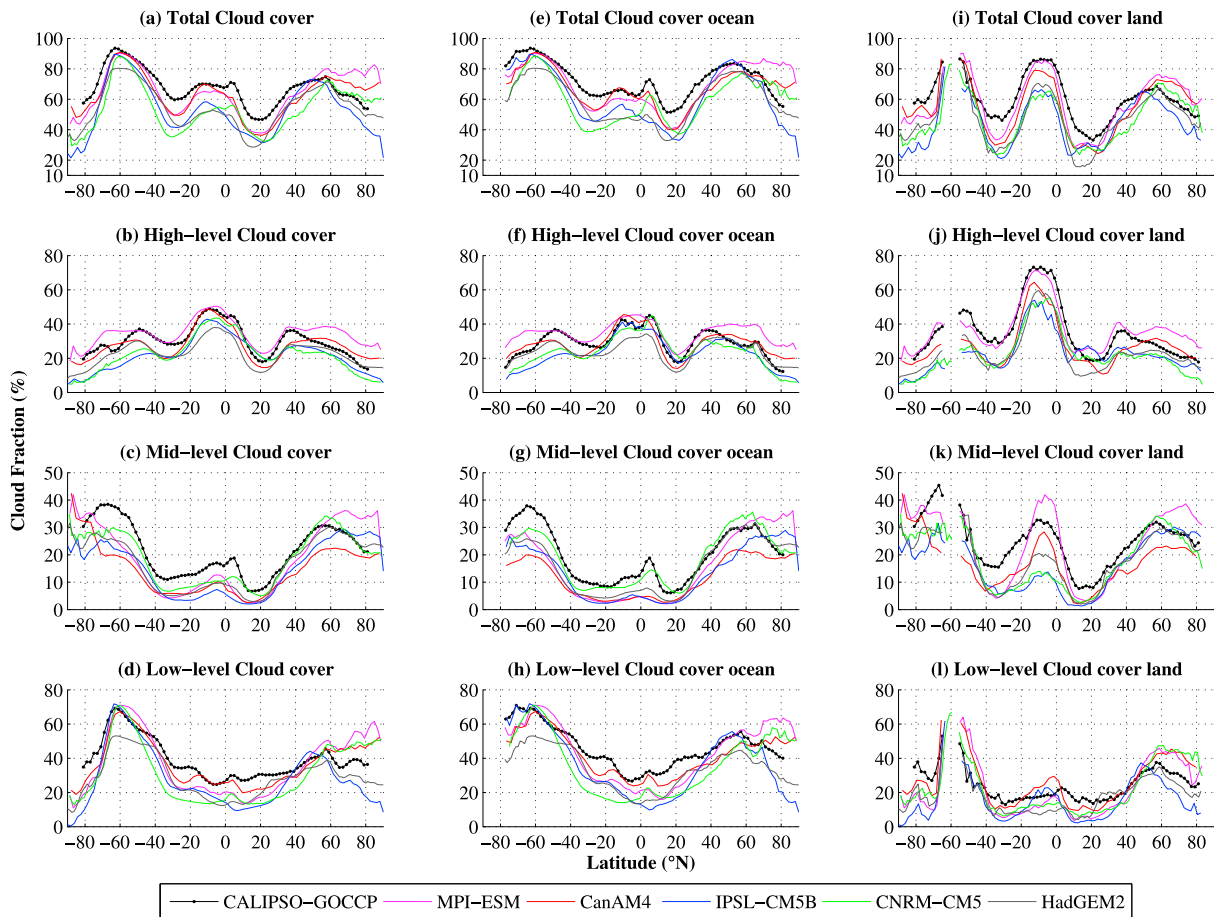
particularly critical in the tropics [e.g., Bony and Dufresne, 2005] and the polar regions [e.g., Winton, 2006; Kay and Gettelman, 2009; Kay *et al.*, 2012], where model-based estimates of future climate have shown to be significantly sensitive to the description of clouds in the models.

[3] The A-Train constellation includes active remote sensing satellites (CALIPSO, launched in 2006 [Winker *et al.*, 2009] and CloudSat [Stephens *et al.*, 2002]) that can observe directly some of the key missing cloud properties like the cloud vertical distribution at high spatial resolution (30 m to 480 m), and to detect clouds over reflective surfaces. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP [Winker *et al.*, 2009]) lidar is specifically well adapted for observing i) clouds with optical depth lower than 3, ii) sparse clouds like shallow cumulus, iii) occurrence of clouds within the two first km above the surface (continent and ocean). Its main limitations regarding clouds, are i) the heliosynchronous orbit of the satellite does not give access to the cloud diurnal cycle (not studied in this paper), and ii) its laser cannot penetrate an optical thickness larger than 3. This precludes the observations of clouds within deep convection along the Intertropical Convergence Zone (ITCZ) and within optically thick storm tracks in mid-latitudes.

[4] This study aims at evaluating the description of the cloud cover and the vertical structure within the Coupled Model Intercomparison Project Phase 5 (CMIP5) [Taylor *et al.*, 2012] climate models using the GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP [Chepfer *et al.*, 2010]). The methodology used for comparing climate models and CALIPSO-GOCCP observations is shortly described in Section 2. Results are primarily shown as averages and over the globe, over oceans and over continents (Section 3). We then focus our study on two regions where predictions of future climate have been shown to be significantly sensitive to clouds: the tropics (Section 4) and the Arctic region (Section 5).

### 2. CALIPSO-GOCCP Observations and Climate Model Outputs

[5] CALIPSO-GOCCP was developed from the CALIPSO level 1 attenuated backscatter measurements for evaluating clouds in climate models [Chepfer *et al.*, 2010]. Here we used six years (2006–2011) of monthly CALIPSO-GOCCP observations including the layered low-level ( $z < 3.36$  km), mid-level ( $3.36 \text{ km} < z < 6.72$  km), high-level ( $z > 6.72$  km), and total cloud cover, as well as the cloud fraction profile at a vertical resolution of 480 m, averaged over a  $2^\circ \times 2^\circ$  horizontal grid. These observations are based on CALIOP lidar footprints which have a diameter of about 70 meters with a center-to-center spacing of 1/3 km. This small footprint



**Figure 1.** Zonal mean cloud covers observed by CALIPSO-GOCCP and simulated by five “climate models + COSP/lidar simulator” in DJF. (a) Total, (b) High, (c) Mid, (d) Low cloud covers, (e) Total, (f) High, (g) Mid, (h) Low cloud cover over ocean, (i) Total, (j) High, (k) Mid, (l) Low cloud cover over continents.

size reduces concerns about partially filled pixels [Pincus *et al.*, 2012]. The CALIPSO-GOCCP cloud climatology has been compared with that from CALIPSO Science Team (CALIPSO-ST) and found significant differences in zonal cloud profiles, because different cloud detection thresholds and horizontal averaging are used in the two algorithms (H. Chepfer *et al.*, Comparison of two different cloud climatologies derived from CALIOP Level 1 observations: the CALIPSO-ST and the CALIPSO-GOCCP, submitted to *Journal of Atmospheric and Oceanic Technology*, 2012).

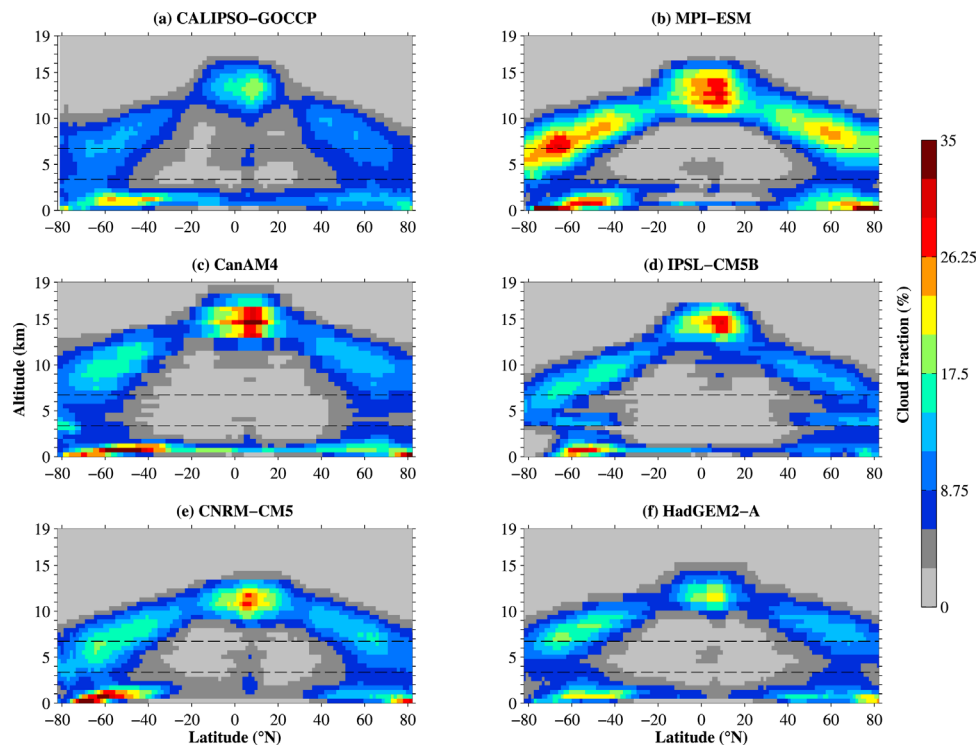
[6] We evaluated model output (AMIP experiment, atmosphere only, monthly time frequency and r1i1p1 ensemble) from years 1979 through 2008) of the CMIP5 experiment [Taylor *et al.*, 2012] by the following climate models: IPSL-CM5B [Hourdin *et al.*, 2012], CNRM-CM5 [Voldoire *et al.*, 2011], HadGEM2 [Jones *et al.*, 2011], CanAM4 [Cole *et al.*, 2011] and MPI-ESM [Jungclaus *et al.*, 2010]. As the definition of a cloud is not the same in models and observations nor between models, the lidar simulator [Chepfer *et al.*, 2008] that is integrated into COSP (Cloud Feedback Model Inter-comparison Project, CFMIP Observational Simulator Package [Bodas-Salcedo *et al.*, 2011]) has been used in each model to simulate the cloud amount that would be observed by CALIPSO above the atmosphere predicted by the model.

Use of a simulator reduces instrument biases and ensures that the cloud covers are defined consistently across the models and with the observations. Nevertheless, even a perfect agreement between CALIPSO-GOCCP and simulator outputs would not guaranty that the model reproduces perfectly clouds, because CALIPSO-GOCCP and COSP do not detect the optically thinnest clouds [Chepfer *et al.*, 2010; also submitted manuscript, 2012].

### 3. Global Scale Analysis

#### 3.1. Zonal Mean Cloud Cover

[7] Figure 1 shows the zonal mean cloud cover observed by CALIPSO-GOCCP and as simulated by the climate models through the lidar simulator. The total, mid and low cloud covers (Figures 1a, 1c, and 1d) are underestimated by most models at all latitudes except north of 50°N, where inter-model spread is significant around the observations (+/− 20% at 80°N). The global underestimation of total cloud cover (51% to 62% in models vs. 64% in observations) was already pointed out [Zhang *et al.*, 2005] in former climate models (CMIP3 [Meehl *et al.*, 2007]) compared to International Satellite Cloud Climatology Project (ISCCP) observations [Rossow and Schiffer, 1999]. The present



**Figure 2.** Zonal cloud fraction profiles (annual mean). (a) observations CALIPSO-GOCCP, (b–f) climate models + COSP/lidar simulator with MPI-ESM (Figure 2b), CanAM4 (Figure 2c), IPSL-CM5B (Figure 2d), CNRM-CM5 (Figure 2e), and HadGEM2-A (Figure 2f). Black dashed lines discriminate between low- and mid-level clouds and mid- and high-level clouds.

evaluation (Figure 1a) suggests that this systematic model defect remains in CMIP5 models. The models do not produce enough clouds, and compensate by making clouds optically too thick, in order to get correct fluxes at the top of the atmosphere [Kay *et al.*, 2012; D. Konsta *et al.*, Evaluation of clouds simulated by the LMDZ5 GCM using A-train satellite observations (CALIPSO-PARASOL-CERES), submitted to *Climate Dynamics*, 2012]. In polar regions, where the observed cloud cover was highly uncertain before active space-based remote sensing, the inter-model spread is significant around the observations (20% to 50%), and all models underestimate the Antarctic cloud cover. The modeled cover of low-level clouds is too low, especially in the tropics (Figure 1d). Mid-level clouds vary a lot between models in the polar regions. Modeled high clouds do not show a systematic bias. Compared to passive remote sensing evaluation used by Zhang *et al.* [2005], the CALIPSO evaluation suggests that the inter-model spread in low, mid, high cloud cover is reduced, the underestimate of mid-level clouds by all models is confirmed, and the high latitude clouds are significantly different than the ones seen by passive remote sensing.

[8] Near 60°S (Figures 1a–1d) where most of the climate models exhibit substantial bias against the flux observed at top of the atmosphere (TOA) [e.g., Cole *et al.*, 2011], the total cloud cover (Figure 1a) is not particularly biased compared to others latitudes. Four of the 5 models reproduce surprisingly well the observed low and total cloud cover. This suggests a model’s ability to produce the right cloud cover may

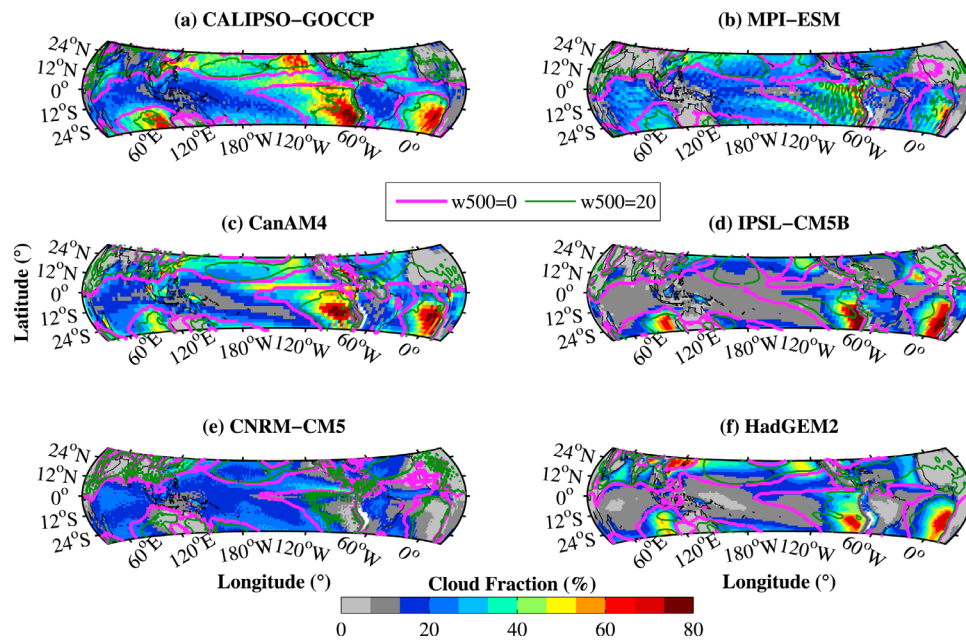
not explain why the modeled TOA flux is too large here. The amount of condensed water (liquid and ice, or the cloud optical depth) is more likely the reason of this discrepancy.

[9] Over continents (Figures 1i–1l), the biases in modeled cloud cover are similar to the previous section. In deep convection along the ITCZ, the observed high altitude cloud cover is higher there (70% Figure 1j) than above ocean (50%, Figure 1f) because the continent is warmer and produces stronger convective motions. The models reproduce roughly this continent/ocean contrast at high altitude, but the simulated mid- and low-level continental clouds (Figures 1k and 1l) spread significantly more than the global/ocean ones (Figures 1g and 1h), especially in the tropics and polar regions. It confirms that the representation of continental clouds remains a challenge for climate models.

### 3.2. Zonal Mean Cloud Profiles

[10] The zonal mean cloud profiles observed by CALIPSO-GOCCP (Figure 2a) illustrate that clouds follow the atmospheric circulation: deep convection along the equator leads to high clouds, the subsidence branches of the Hadley cells around 25° preclude cloud formation in the free troposphere, the mid latitude storm tracks cover the entire troposphere, and boundary layer clouds ( $z < 4$  km) produced by small local convection occur at all latitudes.

[11] Although the models roughly reproduce this structure (Figures 2b–2f), the quantitative comparison with observations (Figure 2a) shows systematic model bias. The highest



**Figure 3.** Tropical low cloud cover (DJF). (a) observations CALIPSO-GOCCP, (b–f) climate models + COSP/lidar simulator with MPI-ESM (Figure 3b), CanAM4 (Figure 3c), IPSL-CM5B (Figure 3d), CNRM-CM5 (Figure 3e), HadGEM2-A (Figure 3f). Green and magenta isolines show respectively  $w_{500} = 0$  hPa/day and  $w_{500} = 20$  hPa/day for each model except in Figure 3a where  $w_{500}$  is from ERA interim.

simulated clouds are between 14 km (CNRM-CM5 and HadGEM2-A) and 18 km (CanAM4) but are near 16 km in CALIPSO-GOCCP. All models generate too many high-level clouds compared to observations, at all latitudes, including in the subsidence branch of the Hadley cells. Most models produce too many boundary layer clouds in mid and high latitudes, and too few in the tropics. This underestimation may, in some cases, be caused by an overestimation of the high clouds, which tends to mask the low clouds in the lidar simulator.

#### 4. Tropics

[12] Exchanges of energy in the tropics influence the climate of the entire Earth, and tropical clouds play a key role in its redistribution. All cloud types influence the tropical climate, but inter-model studies [Bony and Dufresne, 2005] suggest that the representation of low level clouds in subsidence regions (nearly 65% of the tropics) impacts substantially the tropical clouds climate sensitivity.

[13] As describe in Section 1, CALIOP can detect the fractionated and small shallow cumulus in subsidence regions close to the surface [e.g., Konsta et al., 2012]. The observed boundary layer cloud cover is larger than 15% almost everywhere (Figure 3a), with a maximum of 100% in stratocumulus over the East part of oceans, where the subsidence is strong. Figures 3b–3f exhibit the model cloud covers together with the regions of subsidence, identified by a positive mean air mass vertical speed at 500 hPa ( $w_{500}$ ). Stratocumuli are reproduced by most models but their horizontal extent is underestimated, in particular along the Californian and Australian coasts. The shallow cumulus cloud cover is significantly underestimated (10% instead of 25%) by half of the models. Further analysis (not shown) indicates the high

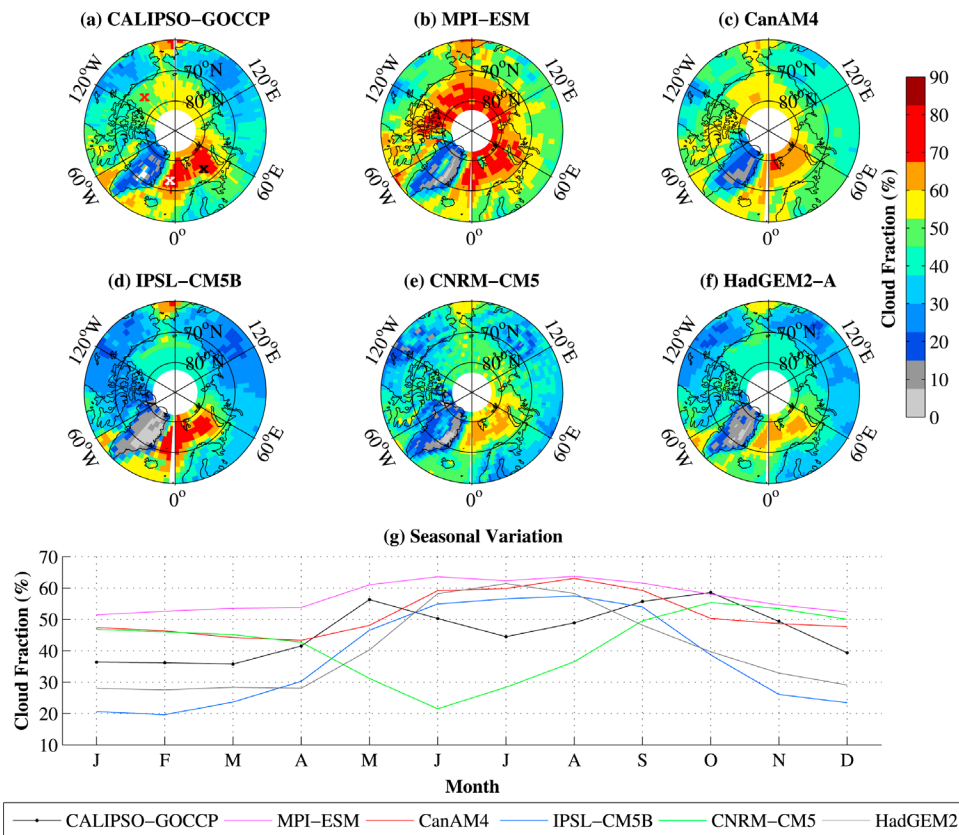
cloud cover in subsidence regions ( $w_{500} > 0$ ) is small in both models and observations, which suggest that the model underestimation of low clouds is not due to masking by higher clouds (Section 3.2).

#### 5. Arctic

[14] Tropospheric polar clouds modulate the radiation reaching the surface and regulate the Arctic climate [e.g., Morrison et al., 2011]. Most reliable observations of Arctic clouds were collected by ground based sites [Shupe et al., 2006; de Boer et al., 2009] that do not provide a complete view of the region. Thanks to its capability to observe clouds above reflective surface, CALIPSO provides relevant information over the polar region equatorward of  $82^\circ$  latitude.

[15] The annual mean low-level cloud cover ( $z < 3.36$  km) observed by CALIPSO-GOCCP in the Arctic (Figure 4a) shows that the dry atmosphere above continents contains a smaller but significant amount of low clouds (30% to 45%), except over Greenland and high altitude regions where it is lower ( $< 30\%$ ). Above ocean, the moister atmosphere produces a larger low-level cloud cover (typically  $> 60\%$  up to 80%). To first order, their significantly asymmetric distribution is related to the sea surface temperature: cloud covers are largest above the warmest Barents and Greenland seas, and smaller (50–60%) above the cold Beaufort sea. All models (Figures 4b–4f) except MPI-ESM, reproduce this asymmetry, but not the correct low cloud cover, and the inter-model spread is large especially in the Arctic sea (between 40% and 70%). Similarly, the models mimic the ocean-continent contrast but the cloud cover is often substantially different from observations.

[16] The annual cycle of the monthly mean low cloud cover in the Arctic is presented in Figure 4g. Observations



**Figure 4.** Arctic low cloud cover. (a) observations CALIPSO-GOCCP (annual mean). The red, white and black crosses show the Beaufort, Greenland and Barents seas, respectively. (b–f) Climate models + COSP/lidar simulator with MPI-ESM (Figure 4b), CanAM4 (Figure 4c), IPSL-CM5B (Figure 4d), CNRM-CM5 (Figure 4e), HadGEM2-A (Figure 4f) (annual mean). (g) Seasonal variation over open ocean ( $60^{\circ}\text{N}$ – $82^{\circ}\text{N}$  without land).

show that it is maximum in May and October ( $>50\%$ ) and minimum in winter between December and March (35%) with a secondary minimum in July (42%). Most of models reproduce the winter minimum cloud cover, but none reproduce the July minimum, except CNRM-CM5 for which it is the only minimum. No model simulated the maximum in fall season. The minimum model cloud cover in winter is strongly variable: between 20% and 50%, vs. 35% in the satellite data.

## 6. Conclusion

[17] In this paper, active remote sensing satellite observations are used to evaluate cloud cover and cloud vertical structure simulated by five climate models. To ensure that differences between model and observations can be attributed to model defects, we used CMIP5 climate models including the COSP/lidar simulator, which mimics the lidar profile that would be observed by CALIPSO over the modeled atmosphere. We compared the “model + simulator” outputs with CALIPSO-GOCCP observations that are consistent with the simulator algorithm.

[18] Results show that all models underestimate the total cloud cover (51% to 62%) against observations (64%) at all latitudes, except in the Arctic. Low- and mid-level altitude clouds are underestimated by all the models (except in the Arctic), while high altitude cloud cover is overestimated by

some models. The discrepancy between models and observations, and the inter-model spread is more pronounced over continents than over ocean. The zonal cloud fraction profiles (every 480 m in the vertical) indicate that some models shift the altitude of the clouds along the ITCZ by 2 km (higher or lower) compared to observations. The models hardly reproduce the cloud free subsidence branch of the Hadley cells, and the high-level cloud cover is often too large. In the tropics, the low-level cloud cover (29% in CALIPSO-GOCCP) is underestimated by all models in subsidence regions (16% to 25%). In the Arctic, the simulated winter low-level cloud cover varies between 20% and 55%. Despite the significant discrepancy between modeled and observed cloud covers, most models roughly reproduce the observed spatial distribution of low clouds over open ocean. The pronounced seasonal cycle observed in low-level Arctic clouds is hardly simulated by some models.

[19] This article shows how CALIPSO-GOCCP observations and COSP/lidar simulator can provide simple and robust benchmark for identifying systematic multi-model deficiencies in the description of the cloud vertical structure at global scale, and in the cloud cover in regions typically hard to observe (e.g. poles, tropical oceans, continents). Future work will include more advanced evaluation using complementary observations from others A-train instruments.

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