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To cite this version:

Hélène Chepfer, Vincent Noel, Dave Winker, Marjolaine Chiriaco. Where and when will we observe cloud changes due to climate warming?. Geophysical Research Letters, 2014, 41 (23), pp.8387-8395. 10.1002/2014GL061792 . hal-01082640

HAL Id: hal-01082640

https://hal.science/hal-01082640v1

Submitted on 24 Aug 2020

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Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL061792

Key Points:
- Cloud vertical distribution is sensitive to climate warming
- Spaceborne lidar can measure forced cloud change
- Forced trends in cloud profiles occur at altitudes above 5 km

Supporting Information:
- Readme
- Figure S1
- Figure S2
- Figure S3

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Citation:
Chepfer, H., V. Noel, D. Winker, and M. Chiriaco (2014), Where and when will we observe cloud changes due to climate warming?, *Geophys. Res. Lett.*, *41*, 8387–8395, doi:10.1002/2014GL061792.

Received 18 SEP 2014
Accepted 6 NOV 2014
Accepted article online 11 NOV 2014
Published online 2 DEC 2014

Where and when will we observe cloud changes due to climate warming?

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Abstract Climate models predict that the geographic distribution of clouds will change in response to anthropogenic warming, though uncertainties in the existing satellite record are larger than the magnitude of the predicted effects. Here we argue that cloud vertical distribution, observable by active spaceborne sensors, is a more robust signature of climate change. Comparison of Atmospheric Model Intercomparison Project present day and +4 K runs from Coupled Model Intercomparison Project Phase 5 shows that cloud radiative effect and total cloud cover do not represent robust signatures of climate change, as predicted changes fall within the range of variability in the current observational record. However, the predicted forced changes in cloud vertical distribution (directly measurable by spaceborne active sensors) are much larger than the currently observed variability and are expected to first appear at a statistically significant level in the upper troposphere, at all latitudes.

1. Introduction

Both models and theory predict that clouds will adjust in response to climate warming. This adjustment implies changes in the top of the atmosphere cloud radiative effects, referred to as cloud radiative feedbacks, and represents one of the largest source of uncertainty in model-based estimates of climate sensitivity [e.g., *Dufresne and Bony*, 2008]. One reason for this large uncertainty is that 25 years of satellite records have so far proven unable to constrain the diversity in cloud feedbacks. One reason is that the predicted changes in clouds are small, even on multidecade timescales. In Coupled Model Intercomparison Project Phase 5 (CMIP5) experiments, regional changes in cloud fraction over the 21st century are predicted to be 2–3%, at most, under the RCP4.5 scenario and 5–6% under the RCP8.5 scenario (AR5, chapter 12, see Figure 12.17). The interannual variability of cloud amount in the existing satellite record is 2–3%, as reported by the recent Global Energy and Water Cycle Experiment (GEWEX) Cloud Assessment [*Stubenrauch et al*., 2013]. Interannual variability of the observational record is similar whether one considers the global mean cloud fraction, tropical or hemispheric means, or the variability in the relative amounts of high-, middle-, and low-level clouds.

Numerous difficulties are involved in observing the cloud response to climate warming. First, very small changes in cloud properties must be observed, requiring measurements which are accurate and stable over multiple decades. Current observation systems, initially designed for the needs of weather forecasting, are not well suited [*Norris and Slingo*, 2009]. Second, observing signatures of forced cloud change requires targeting a cloud parameter which can be measured with random and systematic uncertainties significantly smaller than the variation associated with natural climate variability and significantly smaller than the expected forced change. Moreover, it is helpful, if the expected variation induced by climate warming is larger than the natural variability.

Our current understanding of the cloud feedback problem ties shortwave feedbacks to the behavior of shallow marine clouds and longwave (LW) feedbacks to deep convective clouds [e.g., *Bony and Dufresne*, 2005; *Soden and Vecchi*, 2011]. While the LW cloud feedback is robustly positive in CMIP5 models, tied to increases in the altitude of tropical deep convection [*Zelinka et al*., 2012], the magnitude of the predicted LW feedback varies significantly between models. Increases in the height of tropical high clouds as the climate warms have been noticed in climate simulations for decades, going back at least as far as papers by *Hansen et al*. [1984] and *Wetherald and Manabe* [1988] and appearing in cloud-resolving models [*Kuang and Hartmann*, 2007] as well as in general circulation models (GCMs). *Hartmann and Larson* [2002] explained this

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tendency as a consequence of the approximate radiative-convective equilibrium which must be maintained in the tropics (the Fixed Anvil Temperature hypothesis). Increases in extratropical high-cloud altitude are tied to the rise in the extratropical tropopause height with climate warming [e.g., *O'Gorman and Singh*, 2013]. Because increases in cloud top height under climate warming are expected to exceed natural variability, cloud vertical distribution is a good candidate for an observable cloud response to anthropogenic forcing.

A major challenge in the detection of climate trends in global satellite data is the extreme measurement stability required over multidecadal timescales [*Wielicki et al*., 2013]. Uncertainties due to calibration drifts and sampling errors, as well as natural variability of the climate system, mask the small changes due to anthropogenic forcing. Retrievals of cloud top height from passive sensors are based on forward models involving a number of assumptions, which are often violated. This leads to uncertainties that depend on the cloud type, location, and cloud optical depth, among other factors and can lead to systematic errors in cloud height of as much as several kilometers and misclassification of cloud types [*Holz et al*., 2008; *di Michele et al*., 2013; *Mace and Wrenn*, 2013]. These differences have also been reported and explained in the GEWEX cloud assessment report [*Stubenrauch et al*., 2013]. Cloud top altitude retrieved from passive remote sensing instruments is also sensitive to satellite calibration drifts that can lead to trends in cloud top altitude of opposite sign (e.g., *Davies and Molloy* [2012] versus *Evan and Norris* [2012]). As a consequence, passive cloud observations have not yet provided unambiguous evidence of the evolution of the cloud vertical distribution over time.

Since 2006, global cloud profiling has been performed by spaceborne active remote sensors flying in the A-train constellation [*Stephens et al*., 2002; *Winker et al*., 2010]. These recent active spaceborne observations of vertically resolved cloud distribution at global scales have shown how clouds redistribute in the vertical in response to natural interannual perturbations of the large-scale atmospheric circulation such as El Niño, in the tropics [*Zelinka and Hartmann*, 2011; *Loeb et al*., 2013; *Su and Jiang*, 2013], and exceptionally warm polar winters in the Arctic [*Kay and Gettelman*, 2009]. For lidar, cloud altitude is measured directly from the time of flight of laser pulses from the satellite to the cloud and back. In clear skies or when clouds are optically thin, the lidar also measures the time of flight to the ocean surface. Because cloud altitude is derived from time-of-flight mea surements referenced to the ocean surface, long-term stability of a few meters can be obtained, even over multiple decades. The principles of radar detection are similar, but with coarser vertical resolution.

Given the accuracy and stability possible with spaceborne lidar profiling, we focus in this paper on cloud properties which can be directly measured by spaceborne lidar and consider three questions:

1. Because different vertical cloud distributions and heating rates profiles can lead to the same cloud cover and TOA (top of atmosphere) radiative effects, is the vertically resolved cloud distribution more sensitive to climate warming than vertically integrated variables?
2. Can properties directly measured by spaceborne lidar—the vertical profile of clouds and the penetration depth—be used as metrics of forced cloud change?
3. In a warming climate, in what regions and at what altitudes will a change in cloud properties be observable and where will we first be able to detect these changes?

We first present the observational and simulation data sets used (section 2). In section 3, we compare the change in vertically integrated variables (cloud cover and TOA radiative effect) expected in response to anthropogenic forcing with the variability observed between 2006 and 2012. In section 4, we compare the change in the vertically resolved cloud distribution expected from anthropogenic forcing with the observed variability. In section 5 we examine profiles of optically thick clouds to estimate, based on model simulations, where and at what altitudes lidar observations will first be able to observe a cloud response attributable to climate warming. Section 6 draws the main conclusion and perspective.

2. Tools: Satellite Observations and Model Simulations

2.1. Observations

We first use the *cloud radiative effect* at the top of the atmosphere (CRE_{TOA}) derived from Clouds and the Earth's Radiant Energy System (CERES)-Energy Balanced and Filled [*Loeb et al*., 2009] to characterize the amount of cooling or warming produced by clouds. $CRE_{TOA} = CRE_{TOA,SW} + CRE_{TOA,LW}$ with $CRE_{TOA,SW} < 0$ cooling the system and $CRE_{TOA,LW} > 0$ warming it.

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Then, we analyze the *total cloud cover* and the *low-* (altitude $z < 3.8$ km), *middle-* ($3.8 < z < 7.4$ km), and *high-level cloud covers* ($z > 7.4$ km) from CALIPSO-GOCCP (GCM Oriented CALIPSO Cloud Product) nighttime data [*Chepfer et al*., 2010] over 2006–2012.

Finally, we examined the profiles of *optically thick and optically thin cloud fraction* (480 m resolution) derived from CALIPSO-GOCCP lidar observations (see the supporting information).

1. The *optically thin cloud fraction profile* is based on clouds where the lidar signal is able to penetrate to cloud base. These clouds typically have integrated visible optical depths less than 2.5 for water clouds, and less than 5 for ice clouds. Most ice clouds are transparent to the lidar, while most water clouds are opaque to the lidar.
2. The *optically thick cloud fraction profile* is based on clouds where the lidar signal is completely attenuated before reaching cloud base. The altitude where the cloud becomes opaque to the lidar signal (i.e., where the shortwave radiation field becomes completely diffuse) is a quantity which can be directly and accurately measured. This altitude roughly defines the region of the cloud which is coupled to the TOA in the thermal infrared and so has important implications. As an example, in an atmosphere where the temperature profile remains constant, a shift of the optically thick cloud fraction profile to higher altitudes means the emission temperature of the optically thick clouds and the amount of longwave radiation emitted upward decreases. This implies an increased cloud warming effect ($CRE_{TOA,LW}$ becomes more positive).

2.2. Simulations

We synthesized virtual observations of these quantities from CMIP5 [*Taylor et al*., 2012] and Cloud Feedback Model Intercomparison Project 2 (CFMIP-2) [*Bony et al*., 2009] climate model results. We used the CFMIP Observation Simulator Package (COSP) [*Bodas-Salcedo et al*., 2011] lidar simulator [*Chepfer et al*., 2008], which mimics the observations that would be observed from the spaceborne Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) if it was overflying the atmosphere predicted by a climate model. We refer to these virtual data sets as lidar-like cloud profiles hereafter. CMIP5/CFMIP-2 simulations for the current climate (Atmospheric Model Intercomparison Project (AMIP)) and simulations forced by a sea surface temperature associated with a global mean Earth temperature increase of +4 K (AMIP + 4 K, "+4 K scenario" in figures) were used. The available lidar simulator output is limited, with complete outputs only for 1 year (2008) from the HadGEM2-A model [*Collins et al*., 2008] and 2 years (2008–2009) from the CanAM4 model.

Numerous studies [e.g., *Zhang et al*., 2005; *Klein et al*., 2013; *Cesana and Chepfer*, 2012, 2013; *Nam et al*., 2012] have identified weaknesses in model predictions of clouds in the current climate. *Cesana and Chepfer* [2012], for example, showed that the optically thin cloud fraction profile is overestimated by most of the models as are the optically thick clouds fraction profiles (Figure S3 in the supporting information). Here we do not focus on the cloud properties themselves but on how we expect them to change in a warming climate relative to the present day.

3. Vertically Integrated Variables

3.1. Cloud Radiative Effect

Figure 1a shows the CRE_{TOA} change predicted by CMIP5 climate models in a +4 K scenario (blue shading) superimposed on the change observed by CERES between 2006 and 2012 (green shading). The zonal mean CRE_{TOA} observed by CERES varies less than ± 2 W m^{-2}. This record includes the CRE_{TOA} anomaly due to natural events such as El Niño (-0.6–0.7 W/m^2 as shown in *Su and Jiang* [2013]). Considering a longer period (2001–2012) leads to similar results (not shown) as in previous work [e.g., *Loeb et al*., 2013].

In Figure 1a, thus, the CRE_{TOA} +4 K change predicted by CMIP5 models cannot be unambiguously attributed to anthropogenic change, except perhaps in the Southern Ocean. It suggests that the zonal mean CRE_{TOA} may not change significantly in a warming climate.

The HadGEM2 and CanAM models predict moderate CRE_{TOA} change in a warming climate relative to the ensemble of CMIP5 models.

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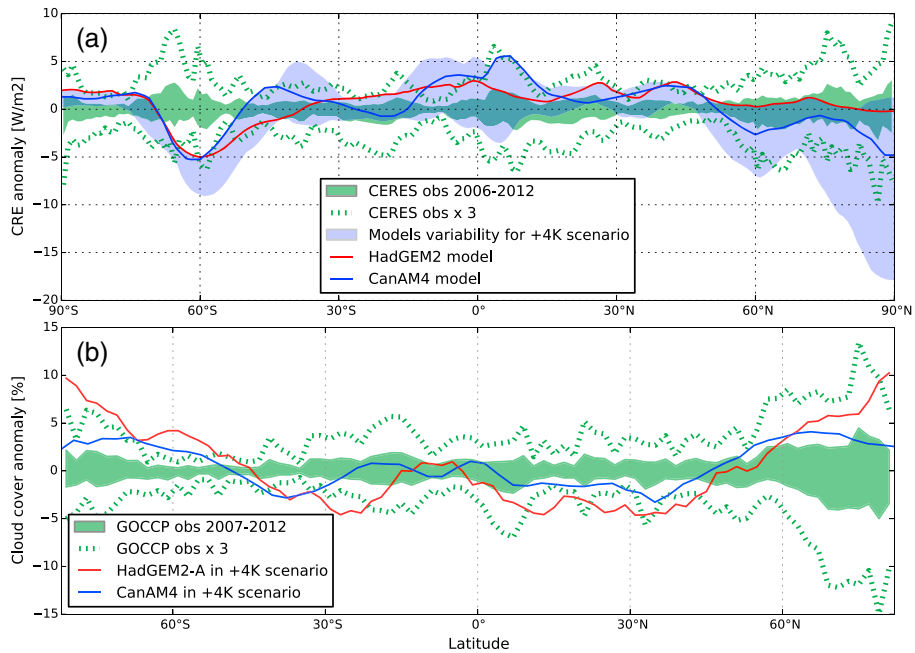

Figure 1. Zonal mean cloud radiative effect and cloud covers. (a) CRE_{TOA} from CERES observations and CMIP5 models. (b) Total cloud cover from CALIPSO-GOCCP and two CMIP5 models using COSP/lidar. In Figures 1a and 1b, the green area contains 6 years (2007–2012) of observed annual zonal mean anomalies. These anomalies are calculated as the interannual deviation of annual and zonal means of CRE_{TOA}. The green dotted line represents 3 times this envelope. The solid lines are the differences in the annual and zonal mean CRE_{TOA} averaged over the durations of the AMIP/AMIP + 4 K predicted with CanAM4 (blue) and HadGEM2 (red) models. The blue area in Figure 1a indicates the intermodel range in this quantity (CanAM, MPI-ESM-LR, CNRM-CM5, MIROC5, IPSL-CM5B-LR, and HadGEM2-A).

3.2. Cloud Covers

The annual variability in total cloud cover from CALIPSO-GOCCP between 2007 and 2012 (Figure 1b, green area) is somewhat less than 2%, in agreement with the GEWEX cloud assessment report. The difference between the lidar-like mean cloud cover expected in a +4 K scenario and the one predicted in the current climate remains close to the variability observed since 2006. The relative predicted change of the cloud cover and the observed interannual variability are of the same order of magnitude: about 3% (±2.5% out of 65% [e.g., *Chepfer et al.*, 2010]). The expected change in total cloud cover falls outside the observed variability in two regions: the Southern Hemisphere subsidence regions where the atmosphere is expected to get slightly less cloudy in a warming climate, and around 60°S, where it is expected to get a little more cloudy.

To get more insight into these changes, we examined the variability when partitioned into high, middle, and low cloud covers (Figure S2). The observed variability of clouds is larger at low altitudes (±5%) than at higher altitudes (±3% max), but this may be a sampling artifact as the detection of low clouds is modulated by high opaque clouds. The change expected in the +4 K scenario is more significant in high-level clouds (up to 10%) than in low-level clouds (5%). The observed variability in middle-level clouds is moderate, as is the change in middle-level cloud expected in a +4 K scenario. At latitudes higher than 50°, the future upper troposphere is predicted to become more cloudy. Based on these two models, the change is significantly larger than the variability observed during recent years in the southern polar region; and the high-level cloud cover is more sensitive than the total cloud cover to climate warming.

4. Detailed Cloud Vertical Structure

We examine the change in synthetic lidar-like cloud profiles (480 m vertical resolution) expected in a warming climate (Figure 2). While the shapes of the optically thin and thick cloud fraction profiles remain stable in a +4 K climate, the values themselves are shifted upwards by about 1 km compared to profiles for the current climate. This result is found in all regions for both models (Figure S3), with the largest shift in the

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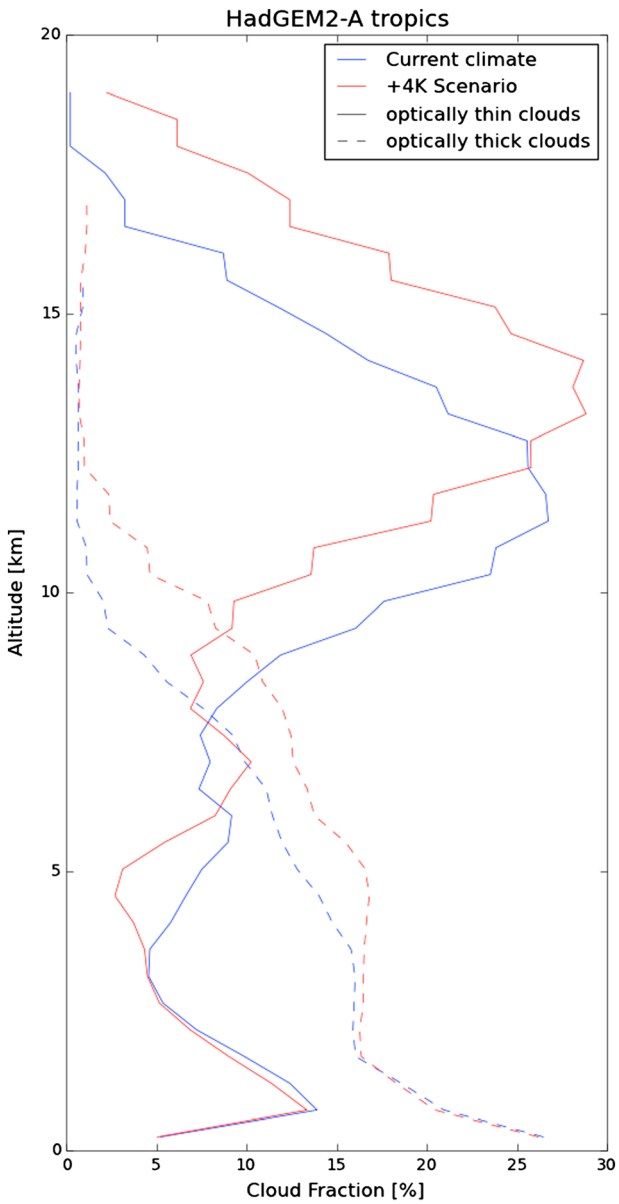

Figure 2. Synthetic lidar-like cloud fraction profiles for optically thin and thick clouds, based on output from the HadGEM2-A model + COSP/lidar for the current climate and the +4 K scenario in the tropics (30°S–30°N).

tropics (+1.7 km) and the smallest in northern midlatitudes (+0.7 km). In the tropics, the upward shift of optically thin clouds is consistent with the behavior predicted by the Fixed Anvil Temperature hypothesis of *Hartmann and Larson* [2002] and consistent with analysis by *Soden and Vecchi* [2011] and *Zelinka et al.* [2012], as well as *O'Gorman and Singh* [2013]. At lower altitudes, the frequency of occur rence of opaque clouds (Figure 2) is also predicted to shift upward.

In the observations, the interannual variability of the cloud fraction vertical profiles is less than ±2% (Figure 3) for cloud fraction values of 5% to 10% (Figure S3), at all latitudes and altitudes over the last 6 years (Figure 3). This corresponds to an interannual relative variability of about 10% (not shown). As a consequence, the observed relative interannual variability of the detailed cloud vertical structure (10%) is larger than the vertically integrated cloud cover one (3%, see section 3).

The relative predicted changes in optically thin and thick cloud fraction profiles in a +4 K scenario are larger than 100% (e.g., +15% in Figure 3 out of 15% in Figure S3), whereas they are of the order of 3% for the vertically integrated cloud cover (section 3). As a consequence, the detailed cloud vertical distribution is significantly more sensitive to climate warming than vertically integrated variables.

Corresponding with the rising cloud profiles (Figure 3), the global mean outgoing TOA flux change is +6.7 and +6.9 W/m^2, depending on the model, and the associated CRE changes are 0.67 and 0.42 (with 1.11 and 2.15 in the LW). Assuming a simple linear trend over 94 years, this corresponds to a TOA flux change of 0.71 W/m^2 per decade (respectively 0.73) which is larger than the current observations (+0.5 W/m^2 in *Loeb et al.* [2013]).

5. Consequences for Observation of Cloud Changes in a Standard Emission Scenario

Our results show the zonal mean CRE_{TOA} and cloud cover are predicted to remain quite stable in a warming climate, and these variables are poor choices to look for signatures of climate change. On the other hand, cloud vertical structure is predicted to change significantly with climate warming. Spaceborne lidars and radars (CALIPSO and CloudSat since 2006, Earthcare in a few years, and hopefully other afterward) provide direct measurements of cloud vertical distribution, and these measurements can be very stable on decadal timescales.

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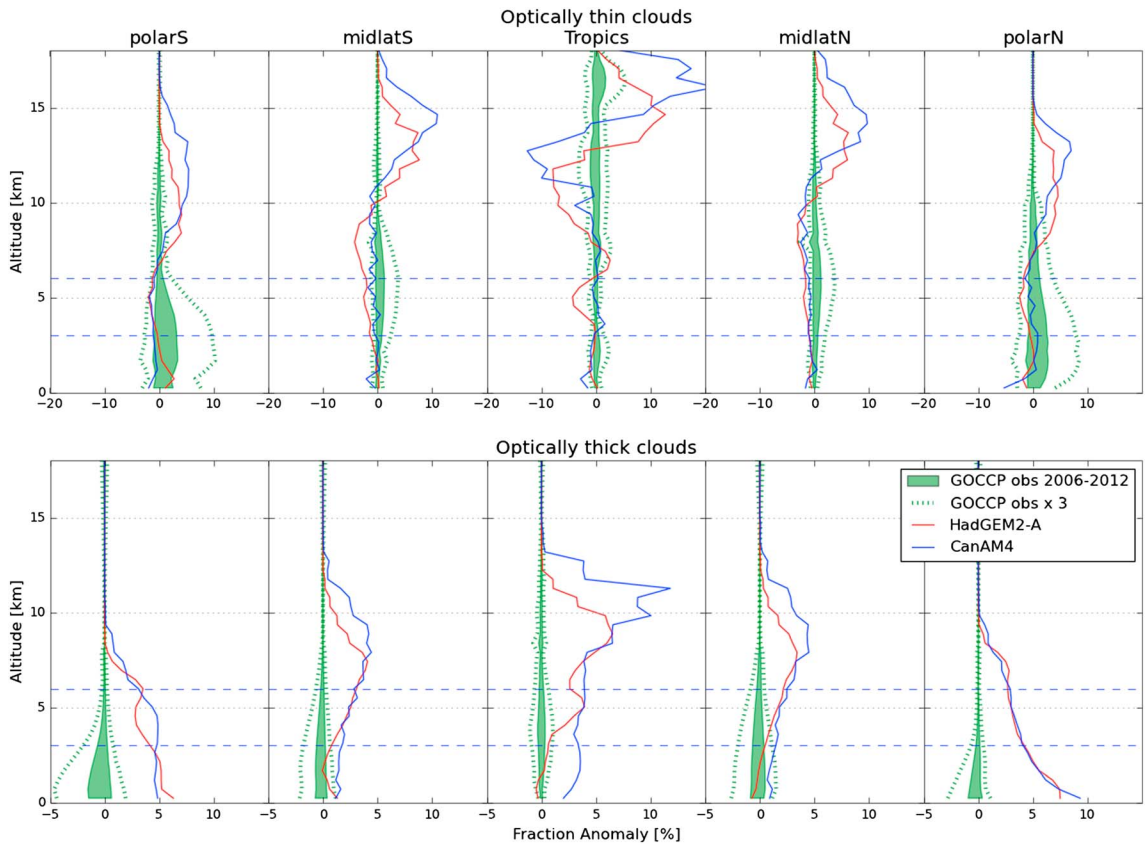

Figure 3. Cloud fraction profiles for (top) optically thin and (bottom) optically thick clouds that fully attenuate the laser. The green area and dotted line are defined as in Figure 1b but for cloud fraction profiles. The solid lines represent the difference between the CALIPSO-like profiles in the future climate (+4 K) compared to the current climate as predicted with CanAM4 model (blue line) and HadGEM2 model (red line) using COSP/lidar. Horizontal dashed lines divide altitudes of low-, middle-, and high-level clouds.

The results shown in Figure 4 indicate where robust signatures of forced climate change may likely first occur. The CMIP5 RCP8.5 CO_2 emission scenario produces a roughly +4 K increase in the global mean surface temperature (+3.8 K ± 1 K depending on the CMIP5 model considered) between 2006 and 2100. Assuming a linear evolution of the thick cloud fraction profiles between 2006 and 2100, we computed the number of years required to observe a change equal to three times the observed variability. As an example, in the tropics (Figure 3), at $z = 5$ km, 3 times the observed variability is ±0.92%, and the expected change in a +4 K climate is +4% for the CanAM4 model (red line). In this emission scenario, it would take $0.92 \times 94/4 = 22$ years for this change to be observed. Figure 4 shows the time required to produce a change of 3 times the observed variability, as a function of altitude, assuming the Earth temperature increases +4 K in 94 years.

The results shown in Figure 4 represent lower bounds on the time required to detect a change in cloud occurrence, due to anthropogenic forcing, and where such change may first be detectable. Changes in opaque cloud profiles possibly attributable to anthropogenic forcing would be observable more quickly at altitudes higher than 5 km at all latitudes. The first observable change would be in the polar northern regions. Observable changes would occur last in northern midlatitudes at low altitudes.

The results shown in Figure 4 can be used to make relative comparisons about the time needed to detect signals using different variables or locations but should not be used in an absolute sense because of the following:

1. The AMIP + 4 K experiment does not fully depict the cloud changes that will result from greenhouse gas-induced warming. Results from a coupled-ocean atmosphere model would be more reflective of what to expect in the future climate, both because the sea surface temperature changes will not be uniform and

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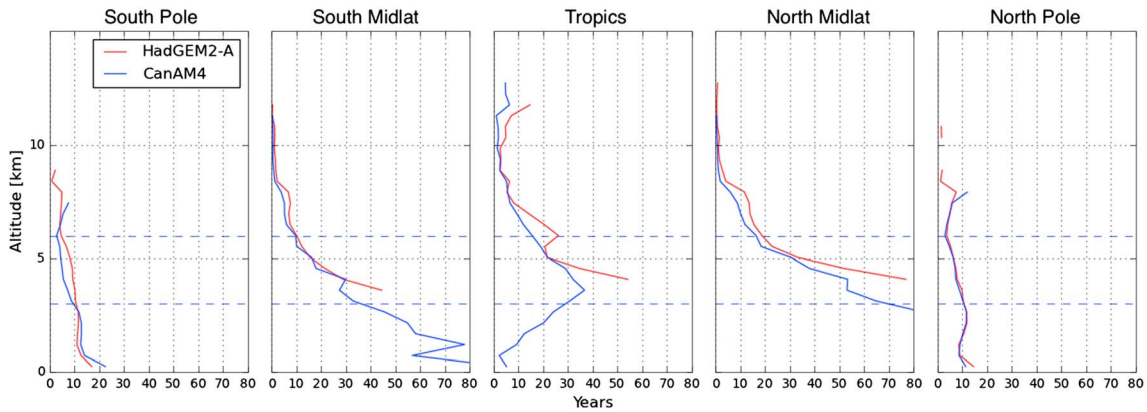

Figure 4. Number of years required to observe a change in optically thick cloud profiles corresponding to 3 times the natural variability found in CALIPSO-GOCCP since 2007, at each altitude level, assuming the RCP8.5 CO_2 emission scenario. Altitudes where the predicted fraction change is small (<1%) are hidden.

because the direct response of clouds to the greenhouse gas changes (i.e., rapid adjustments) may be important. Neither of these effects is included in the AMIP + 4 K experiment. We expect these differences would affect the details of our results but not the overall conclusions as to the observability of vertical changes in cloud occurrence.

2. A future observed change larger than 3 times the current observed variability cannot be unambigously attributed to anthropogenic forcing as the current CALIPSO record is too short to capture the full magnitude of the natural interannual variability.
3. The time estimates given in Figure 4 depend on the CO_2 emission scenario. The magnitude of simulated cloud changes scales with the amount of warming: if the warming were 8 K instead of 4 K, then the magnitude of the cloud changes would be even larger. Conversely, a more moderate emission scenario would lead to a longer time period required for detection.
4. The linear assumptions made in computing these results are simplistic as most of the temperature evolutions in the RCP scenarios are not exactly linear in time.
5. The time estimates in Figure 4 depend on the climate models. Figure 4 is based on two climate models (HadGEM2 and CanAM4) for which +4 K scenario detailed COSP/lidar outputs are currently available. It is likely that adding more models would lead to larger uncertainties in the results. The spread in CRE_{TOA} change (Figure 1a) between six models shows that the two models used here have moderate cloud sensitivity to anthropogenic forcing compared to the others. Moreover, Figure 4 depends on the reliability of model prediction which remains uncertain.

6. Conclusion

In this paper we examined using satellite observations to detect changes in cloud properties attributable to climate warming, and where these changes might be first detectable by a highly accurate and stable sensor.

We used observations (TOA fluxes and lidar profiles) collected by A-train instruments (CERES and CALIOP) since 2006, and equivalent virtual observations simulated by CMIP5 models for the current climate and a warming climate (+4 K). We compared the variability of radiative fluxes and lidar profiles observed from satellite during the last 6 years with the change expected in a warming climate. Results indicate the profile data equivalent to that collected by CALIOP would be able to detect future predicted cloud changes, whereas vertically integrated variables (cloud cover and cloud radiative effect) will likely remain within the variability observed over recent years.

Current climate models predict the frequency of optically thin clouds will increase between 5% and 15% in the upper troposphere at all latitudes in a +4 K climate. Simultaneously, the altitude where optically thick clouds occur is expected to rise by 1 km on average at all latitudes, and by 1.7 km in the tropics. The amplitude of these model-predicted changes is significantly larger than the variability observed over the last 6 years, which contains large-scale events such as El Niño/La Niña and anomalous warm winters in the polar regions. A simple linear interpolation in time of these predicted changes suggests that lidar observations

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could detect forced trends in cloud profiles at altitudes above 5 km at all latitudes on relatively short timescales, if the amplitude of the model-predicted changes are reliable. Observing the predicted upward shift in altitude (typically 20 m/yr in the tropics for a strong CO_2 emission scenario) requires an observing system which is highly stable over multiple decades.

CALIPSO, launched in 2006, is expected to collect observations into 2017. The EarthCare mission [*EarthCARE Mission Advisory Group,* 2006] is expected to launch in 2017/2018, with a lifetime of 4 years. A third lidar mission, following EarthCare, would extend the record of lidar cloud profiles to provide a more complete picture of how clouds redistribute in the vertical under the influence of natural variations in the large-scale atmospheric circulation. This longer lidar record would also provide a better chance of separating natural variability from forced changes and test whether clouds respond to climate warming in the way predicted by models.

Acknowledgments
Thanks are due to the two anonymous reviewers who helped to significantly improve this manuscript. We acknowledge NASA and CNES for CERES and CALIPSO data and ClimServ/Icare. We acknowledge the WCRP/WGCM, and the climate modeling groups (HadGEM and CanAM4) for producing and making available their model outputs, and the DOE PCMDI. The model data are available at http://esgf-node.ipsl.fr/esgf-web-fe/live, and the observation data are available at http://climserv.ipsl.polytechnique.fr/cfmip-obs.

Geoffrey Tyndall thanks two anonymous reviewers for their assistance in evaluating this paper.

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