Review of "Characteristics of cloud liquid water path from SEVIRI on the Meteosat Second Generation satellite for several cloud types" by Kniffka, et al.

The above paper examines the (daytime) liquid water path (LWP) diurnal cycles of clouds that have been categorized into different cloud types using the SEVIR instrument. The classification of the clouds into different categories represents a new aspect to diurnal LWP measurements that has not previously been documented. Such information is likely to be useful. However, some of the discussion does not accurately reflect the results and should be changed (see specific points below). Plus, there are some retrieval issues that need to be discussed since they may lead to biases that are likely to be a function of the time of day and thus would distort the retrieved diurnal cycles. Some of the figures are also not very clear and could be improved. Grammar and some additional line by line comments have been annotated in a separate PDF of a Word document.

It will be suitable for publication once the points made here have been addressed.

1. Some discussion on the effects of cloud heterogeneity and 3D radiative effects on the retrieved τ and Reff, and therefore LWP is required. E.g. see Loeb and Coakley, 1998; Loeb and Davies, 1997; Loeb et al., 1998; Marshak et al., 2006; Zhang et al., 2012; Liang and Girolamo, 2013, etc. Some clouds are likely to be more heterogenous than others and thus may be more prone to such biases. It is possible that one type of cloud is affected more than others. It is perhaps beyond the scope of the study to quantify this, but it should be mentioned. Also, are cloud edge pixels used and is this likely to lead to increased biases? What effect might such biases have on the PDFs or on the result that land LWP values are larger than ocean ones? Could land retrievals be more prone to biases? At one point a comparison to the O'Dell LWP dataset is shown and reveals that the SEVIRI retrievals are generally too high – could this be due to such biases? And if not what might be the cause? There also needs to be some discussion of any validation of SEVIRI τ and Reff that has been done – have there been any comparisons to aircraft data? There have been for MODIS (e.g. Painemal, 2011) and the conclusions may be similar if they are the result of the plane parallel assumption. These should be discussed.
2. Is it possible that the restriction to liquid only pixels will give a biased LWP when comparing to O'Dell, since the latter will also include LWP for mixed phase clouds?
3. The alternative formula to equation 1 (for adiabatic clouds that increase in LWC linearly with height) described in Wood and Hartmann (2006) should be mentioned – this reduces the LWP retrieved by a constant factor (uses 5/9 instead of 2/3). This formula is likely to be more realistic given that clouds are more likely to display adiabatic LWC profiles than constant LWC profiles (e.g. Painemal, 2011).
4. Can an approximate optical depth threshold for the cloud mask be given? This would be useful for comparing to e.g. MODIS. Is there any cloud edge removal? Such issues will affect the

comparison to the O'Dell dataset since cloud fraction is required in order to make that comparison.

5. Figure 3 and its discussion – some of the description does not accurately describe the results. For example, for some cloud types the seasonal cycle is greater for the whole region. Perhaps you should calculate the variability and clarify that you mean general month-to-month variability and not e.g. the seasonal cycle (if this is the case).
6. Could there be remaining solar zenith angle (SZA) issues with the diurnal analysis? The comparisons to the O'Dell LWP get worse at sunrise – could this be an SZA effect? The possibility needs to at least be mentioned in the diurnal cycle section.
7. There is no indication of the errors (both instrumental and sampling) for e.g. the diurnal cycle plots. E.g. could it be that the number of samples at high SZA is quite low due to much of the region being above the threshold SZA for retrievals? Also, the value of the threshold SZA needs to be mentioned and discussed.
8. Are clouds with CTT<< -38 degC identified as liquid? This would suggest problems with the retrieval of cloud phase.
9. Some more discussion of the rim errors are required – what is known about them?
10. Line 409 and the discussion of the change of cloud types over the course of the day seems dubious – the diurnal cycle of the number of low clouds is very small, so it is hard to say much about this for low clouds. Plus, the detection of clouds is affected by the presence of higher clouds. Thus anticorrelation between particular cloud types and the clouds overlaying them might be expected. I don't think that this part of the analysis is useful and should be removed.
11. Also, a general discussion on the likelihood of the detection of certain cloud types being affected by the presence of other cloud types needs to be made – e.g. low cloud detection when higher clouds are present.
12. There are a lot of acronymns that have not been defined, or that are defined after they have already been used, etc.
13. Colours in figures – the use of many colours without other means of distinguishing the lines is not clear – especially since some people (like myself!) will be colourblind (or rather colour vision deficient). It would be better to use different line markers (or line style, dotted, dashed, etc.) as well as different colours.

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Manuscript corrections using track changes.

Characteristics of cloud liquid water path from SEVIRI on the Meteosat Second Generation 2 satellite for several cloud types

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Abstract.

In this study the temporal and spatial characteristics of the liquid water path (LWP) of low, middle ~~level~~ and high level clouds are analysed using space-based observations from~~of~~ the Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument onboard the Meteosat Second Generation 2 (MSG2) satel- lite. Both geophysical quantities are part of the ~~dataset~~ CLAAS (CLoud property dAtAset using SEVIRI) dataset and are generated by EUMETSAT's Satellite Application Facility on Climate Monitoring (CM SAF). In this article we focus on the statistical properties of LWP (retrieved during~~at~~ daylight conditions only) associated with ~~the~~ individual cloud types. Our results reveal that each cloud type possesses a characteristic LWP distribution. These frequency distributions are constant with time in the entire SEVIRI field of view, but vary for smaller regions like Central Europe. For low clouds, ~~T~~the average LWP is higher over land than over sea ~~, in case of low clouds~~ by 15 - 27 % for 2009 and the variance of the frequency distributions is enhanced. Also, the average diurnal cycle of LWP is related to cloud type ~~where~~ with the most pronounced diurnal variations ~~were~~ being detected for middle level clouds. With SEVIRI it is possible to distinguish between intrinsic LWP (i.e. the LWP in only cloudy regions) variability and variations driven by cloud amount. The relative amplitude of the intrinsic diurnal cycle ~~can~~ exceeded the cloud amount driven amplitude.

1 Introduction

An essential parameter for monitoring climate variability is the large scale view of the cloud field distribution. Clouds influence strongly the energy budget and water cycle of the Earth and have therefore a major impact on the atmospheric state at shorter time periods as well a~~s~~t climat~~ic~~e relevant timescales. Due to their complexity in both formation mechanisms as well as spatial and temporal variability,

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the knowledge about many cloud aspects is limited. In a recent comparison of General Circulation Models the consistency with observations differed~~s~~ strongly among the models. In ~~P~~particular~~ly~~, low clouds

Comment [D1]: Since you make the distinction between cloudy-only LWP and all-sky LWP (i.e. including the zeros when there is no cloud), you should be clear which one you mean when you talk about the LWP results. I suggest introducing the above concept before the other LWP results.

Comment [D2]: Better to state how often it exceeds it. Does it happen frequently? Which is the largest on average?

accounted for much ~~for~~ of the climate sensitivity in the considered models (Williams andWebb, 2009). Bony and Dufresne (2005) studied in detail the tropical cloud evolution in General Circulation Models and suggest that the representation of marine boundary layer clouds is the main source of uncertainty in tropical cloud feedbacks simulated by the models. Amongst other observations, ~~S~~satellite data can help to improve our understanding~~,~~ ~~amongst others~~ by serving as input for climate models or numerical weather prediction models. Jiang et al. (2013) intercompared 19 climate models in the Cloud model Intercomparison Project (CMIP). They documented the improvement of the description of column-integrated cloud amount in more than half of the models from Phase 3 to Phase 5 of the project. Chlond et al. (2004) modelled the liquid water path of marine clouds with Large Eddy Simulation and Single Column Models and stated~~,~~ that clouds remain the largest uncertainty for assessing the impact of anthropogenic influence on climate change. Naturally, ~~cloud's~~ the complexity of clouds is not only a challenge for modelling, but also for ~~retrieving~~ the retrieval of cloud properties via radiance measurements from satellite. The intercomparability is explored for example in the Global Energy and Water Cycle Experiment, see Stubenrauch et al. (2009). The ~~M~~measured brightness temperatures and reflectance ~~impacted by~~ of clouds depend strongly upon their macro and microphysical characteristics such as ~~like~~ cloud amount and cloud top height;~~, as well as~~ the droplet size distribution;~~,~~ cloud texture; and the thermodynamic phase. They are also affected by the atmospheric conditions and by the respective sun and satellite ~~respective~~ positions. Having a good knowledge of these conditions and positions allows the retrieval of cloud properties from the remaining signal.

The diurnal or daytime cycle of satellite-derived LWP has been well documented in several studies (Wood et al. (2002), O'Dell et al. (2008), Painemal et al., 2012), ~~in detail~~ mainly for specific regions such as the west coast of South America (Painemal et al., 2012). In our study, we go beyond these and and analyse and discuss the relationship between cloud type and liquid water path as they are categorised by CM SAF. Both variables are derived from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the Meteosat Second Generation 2 (MSG2) satellite. Characteristic features of LWP concerning its distribution and diurnal cycle for the individual cloud types are explored. The results of the one year time-frame are put into context with the University of Wisconsin (UWisc) cloud liquid water path climatology derived from 18 years of passive microwave observations, see O'Dell et al. (2008). The general features of LWP, for example frequency distribution, average value and diurnal cycle are specified to serve as characteristic measures in atmospheric numerical modelling. More specifically, they can be used to conduct process studies, assist in the evaluation of microphysical measurement experiments such as the airborne probing of clouds and serve as input for cloud generators and radiative transfer studies on a wide range of spatial scales. The temporal resolution of MSG2 permits assessing the temporal evolution of cloud systems in cloud resolving models and facilitates model evaluation studies such as undertaken in Hanay et al. (2009), Brunke et al. (2010), or the other above mentioned articles.

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The article is structured as follows: in Section 2 the methods of the LWP and CTY retrieval from SEVIRI measurements are described, Section 3 contains the analysis of LWP with respect to cloud type, where the statistical properties are considered first, followed by a subsection on liquid water in high opaque clouds. The analysis is completed with a consideration of LWP diurnal cycle for several regions and a comparison with the climatology of microwave-based LWP observations (O'Dell, 2008). Also the seasonal variations for the considered year are presented in a subsection. In Section 4 the results are discussed taking into account the limitations of a geostationary imager.

2 Generation of LWP and CTY from SEVIRI measurements

Comment [D3]: Why not use the LWP acronym as used elsewhere?

Comment [D4]: Perhaps intercomarpability is not the best word. Also, you will need to reiterate what is being compared here.

Comment [D5]: This needs to be defined in the main text too (as well as the definition in the abstract)

Comment [D6]: This has not been defined yet.

In this study, non-averaged data of LWP and CTY derived from SEVIRI measurements form the basis for the dataset ~~basis~~. Both parameters are part of the ~~dataset~~ CLAAS (CLoud property dAtaset Using SEVIRI) dataset by CM SAF (Schulz et al., 2009) that includes cloud micro- and macrophysical properties, as well as surface albedo, and spans the time period 2004 - 2011. The radiances were measured with the passive optical imaging radiometer SEVIRI. It is equipped with 12 spectral channels at visible and infrared wavebands. SEVIRI is mounted on the geostationary MSG satellites, where MSG 1 and MSG 2 measurements were projected so that the subsatellite point appears to be 0/0 while they are in operational mode. The horizontal resolution of a SEVIRI image is 3 x 3 km at nadir. ~~As input~~ ~~r~~Hourly radiances from the Level 1.5 ~~data from~~ EUMETSAT (2010) data were used as input. ~~in the~~ This was the reprocessed version with updated radiance definitions (EUMETSAT, 2007) ~~were used in hourly resolution~~. More details can be found in Stengel et al. (2013, in preparation) and in Kniffka et al. (2013a). The Level 1.5 radiances were additionally calibrated against MODIS Aqua, see Meirink et al. (2013a). The input radiance fields were processed with the CM SAF algorithms but have not undergone temporal and spatial averaging at that stage. The months considered were January, April, July and October 2009, thus giving one representative month per season~~, in hourly resolution~~.

Macro- and microphysical parameters were created with two independently developed algorithms. The CPP v3.9 algorithm of CMSAF, developed at KNMI (Royal Netherlands Meteorological Institute), was employed to retrieve the cloud liquid water path (Roebeling et al., 2006; see Section 2.2 for retrieval details), while cloud mask and cloud type are dervied with the NWC SAF algorithm v2010 by M´et´eo France (Derrien, 2010, Derrien and Le Gle´au, 2005).

2.1 Cloud type classification

Both macrophysical parameters, CTY and LWP, need the cloud mask as input. The cloud mask is prepared with the NWC SAF algorithm v2010 (Derrien and Le Gl´eau, 2005, Derrien and Le Gl´eau, 2010), which is comprised of a sequence of threshold tests for different combinations of SEVIRI channels at~~in~~ both~~,~~ visible and infrared wavelengths. The algorithm produces 15 cloud classes and~~,~~ from these classes five more general types are derived for the CLAAS dataset. CM SAF categorizes the cloudy pixels

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into the classes: low, medium, high opaque, high semitransparent and fractional, which means that the cloud types are determined from a radiation-based point of view. In general, a threshold technique is applied with a sequence of various tests using the following channels: 1.6 ψ ψ , 3.7 ψ ψ , 3.9 ψ ψ , 8.7 ψ ψ , 11 ψ ψ ψand 12 ψ ψ . For ~~the~~ individual pixels, the employed test sequence depends on the illumination, which can be ~~the conditions can be~~ twilight, ~~or~~ daylight ~~and~~ or night time conditions. Also the geographical location, the viewing geometry, the water vapour content and a coarse atmospheric structure are taken into account, where the latter two are both described by numerical weather prediction data. ~~As input v~~Vertical profiles of temperature, ~~and~~ humidity ~~as well as~~ and water vapour content from ERA interim were also used. ERA interim is part of the ERA reanalysis project of the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011). As a first step, pixels with semitransparent or fractional clouds are identified. ~~,~~ A~~a~~fter that, the low, middle and high cloud classification is performed by using a threshold for the brightness temperature of the 10.8 ψ ψ ψchannel that is related to the cloud top height. ERA interim analysis temperatures at several pressure levels are used to compute the thresholds that allow ~~to separate~~the separation of very low clouds from low clouds, low from medium-~~-~~high clouds and so on. From statistical analysis of the cloud top pressure, ~~that~~ which is assigned afterwards, five cloud top pressure ranges for the different cloud types resulted ~~that are listed in~~ (see T~~t~~able 1). For cloud type, ~~and~~ pressure, ~~as well as~~ cloud liquid water path and NWC SAF's cloud mask are~~is~~ used as input. A type is only dervied for a pixel that was masked ~~to be~~as completely cloudy. Pixels with inherent sub-pixel cloudiness are ascribed to the fractional cloud class without further testing.

From the cloud type algorithm 15 carefully defined cloud types result; CM SAF groups these types

Comment [D7]: What does this mean? Needs some explanation. Is it 0° latitude, 0° longitude? Would be better to write like that if so.

Comment [D8]: Inconsistency with previous "CM SAF"

Comment [D9]: Refer to section 2.2 here.

into 5 more general classes which are:
low level clouds, middle level clouds, high level opaque, high level semitransparent and fractional clouds. Usually
the latter step is done during the spatial and temporal averaging procedure, but since in this study the non-averaged (level 2) data were analysed, the reclassification was done directly after the CTYalgorithm.
Evaluation of the cloud type product is carried out by CM SAF as described in Hollmann (2011). Here the cloud type products from two sensors, SEVIRI and AVHRR, are~~is~~ compared. Since the cloud type classes are not completely equal for the two sensors, two artificial classes are generated, to reduce the data to the least common denominator: high clouds and cirrus clouds. The time series of AVHRR and SEVIRI-based products resemble each other closely in the case of high clouds, though it has to be noted~~,~~ that even with the generation of the artificial classes the two products are not completely based on the same conditions. Both products are also compared against MODIS, which shows 10 - 20 % smaller values (% is to be understood in absolute units, i.e. 10 % cloud fraction of type x). This could be expected, because the MODIS h~~H~~igh clouds IR category defines all clouds detected
above 400 ψψψ, while for the corresponding CM SAF products the reference level is 500 ψψψ. Also the cirrus clouds class is compared against MODIS.~~,~~ F~~f~~or the SEVIRI product, differences between 10 - 20 % occur, ~~where~~ with MODIS giv~~es~~ing a higher fraction. These can partly be explained by the
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differences in the reference thresholds for MODIS and SEVIRI~~, leading to more observed clouds with the MODIS instrument, but naturally~~ since high and thin clouds can be more reliably detected with the~~a~~
spectrally and spatially higher ~~resolved~~ resolution of the MODIS instrument.
For a typical CTY-field with liquid water and ice pixels within~~on~~ the SEVIRI field of view ~~,~~ (also called the SEVIRI disc), see figure 1 on the left hand side. In this snapshot all cloud types are present.~~,~~ A~~a~~t the same time, low and high opaque clouds dominate most of the cloudy regions. The corresponding LWP-values are displayed on the right~~-~~hand ~~-~~side. The LWP-field covers a smaller region due to the restriction of both~~,~~ the viewing zenith angle and the solar zenith angle being smaller than 72 ° (Stengel et al., 2013). Also note that, particularly in the tropical regions, the cloudy pixels are often icy on top.~~,~~ I~~i~~n ~~this~~ F~~f~~ig.~~ure~~ 1 they are not displayed because of the restriction to liquid ~~water~~only pixels. The H~~h~~ighest values
for LWP can be found mainly in cloud bands with high opaque clouds, but also low and middle level clouds can be associated by the retrieval algorithms with high LWP values, e.g. middle Europe.

2.2 Cloud liquid water path derivation

For consistency reasons, CPP v3.9 makes use of the cloud-mask processed beforehand. In principle, the retrieval method relies on the assumption that cloud reflectance, and so SEVIRI's visible channels, are mainly influenced by the cloud's optical thickness (ψ ψ), whereas changes in the near-infrared depend on the effective radius (ψψψψ) of the cloud droplets. The 0.6 ψ ψ ψchannel and the 1.6 ψ ψ ψchannel proved to deliver the most accurate results. ψ ψand ψψψψare determined by comparing simultaneously the radiances for the 2 channels with radiances in look-up tables for various values of ψ ψand ψψψψ. The look-up tables were generated with the radiative transfer model DAK from KNMI, which makes use of a doubling-adding method (De Haan et al., 1987) and Stammes (2001). In the model, clouds are assumed to be plane-parallel and horizontally homogeneous and they are embedded in a vertically
stratified medium allowing for Rayleigh scattering. Surface albedo is assumed to have a constant value of 0.1 over land and 0.05 over ocean for 0.6 ψ ψ ψas well as 1.5 and 0.05 for the 1.6 ψ ψ ψchannel. The droplets themselves are assumed to be spheres with effective radii between 1 and 24 ψ ψ ψand an effective variance of 0.15 in their gamma type size distribution. The cloud liquid water path is finally retrieved via the relation (Stephens, 1978):
ψψ ψψ- -
- -
- -

Comment [D10]: Is this what is meant here?

Comment [D11]: 1.6um is a near-infrared wavelength

Comment [D12]: Is there a reference for this?

Comment [D13]: Radiances or reflectances?

Comment [D14]: Brackets are wrong here.

ψ ψψψψψψ ψ(1)

with ψ ψbeing the density of liquid water. The retrieved particle size values are unreliable for optically thin clouds~~.~~ and so for clouds with COT ψ ψ8 the climatological value 8 ψ ψ ψis used, which is similar to values used by Rossow and Schiffer (1999).

Roebeling et al. (2008) validated the retrieved LWP values with CloudNET data from two measurement sites: Chilbolton and Palaiseau. At the two sites, measurements were taken with microwave radiometers (MWR). One year of MWR-retrieved values w<u>ere</u>~~as~~ compared to the SEVIRI LWP values, retrieved with the algorithm outlined above. The derived accuracy is variable and depends on a number of factors, mainly viewing geometry, collocation uncertainties and <u>the</u> inhomogeneity of clouds. For 5 summer months, daily and monthly derived LWP values agreed within 5 ψψψ - , corresponding to a relative accuracy of 10 %. In winter, the accuracy was found to be 10 ψψψ - , which was caused by the unfavourable viewing geometry and the smaller amount of data ~~values~~<u>available</u>. The diurnal variations of SEVIRI-derived LWP did not differ <u>by</u> more than 5 ψψψ - -from the MWR-measurements.

The dataset CLAAS itself has undergone a careful validation process, whose results are documented in the validation report of CM SAF (Kniffka et al., 2013). The non-averaged cloud phase was validated on <u>a</u> pixel<u>-by-pixel</u> basis with CALIPSO/CALIOP<u>. LWP was also compared against MODIS on a nonaveraged pixel-by-pixel basis;</u> ~~,~~ <u>LWP and CPH were compared using the</u> ~~monthly mean values of the~~ complete time series of<u> monthly mean values.</u>
~~LWP and CPH were validated against MODIS~~. ~~LWP was also compared against MODIS on nonaveraged pixel basis.~~

The 8 years cloud phase time-series of CLAAS was compared to the Modis Optical and the MODIS Infrared dataset (Meirink et al., 2013b in preparation), it agrees generally with both, but best with the MODIS-IR product. When studying the spatial patterns, differences in the higher~~-~~<u>level?</u> liquid cloud fraction over ~~the~~ tropical land and the low<u>-level?</u>~~er~~ liquid cloud fraction in the Sahara and at high solar zenith angles can be noticed.

The liquid water path time-series of CLAAS and MODIS are in very good agreement<u>; in</u>~~,~~ particular~~ly~~ the seasonal cycle is nearly identical. The spatial patterns that are produced by MODIS and SEVIRI are in good agreement, though differences can be found in regions with strongly broken cloud cover (e.g. the South-Atlantic trade cumulus region), where the algorithms have different treatment<u>s</u> of clear-sky restoral and the pixel resolution has a great effect. CPH, LWP and cloud fractional cover including CTY meet the requirements for a qualified dataset of the CM SAF project (Kniffka et al., 2013b).

3 Analysis

This analysis is based on level 2 datasets of CTY and LWP, with CPH (cloud phase) as auxiliary data. Four months of 2009 were analysed instead of averaging over a complete year in order to highlight the effect of the individual seasons. In the following, only those pixel<u>s</u>~~,~~ that were marked as filled with liquid water were considered; ice or mixed phase <u>pixels</u> ~~was~~ <u>are</u> excluded from the discussion. The analysis was restricted to liquid cases since the two branches of liquid and ice retrieval<u>s</u> in the CPP algorithm are not comparable. Ice crystals have a larger variety <u>of</u>~~in~~ shapes, <u>e.g.</u> hexagons and clustered pieces in various forms<u>,</u> as opposed to ~~mere~~ spherical liquid droplets. Therefor<u>e</u> more assumptions have to be made concerning the shape of the particles in the retrieval of ice water content.

All cases refer to the intrinsic variability of LWP. This means we have only <u>taken into account</u> ~~LWP~~<u>liquid</u>-filled pixel<u>s</u> ~~taken into account~~ to eliminate the effect of changes in cloud fractional cover (CFC) in e.g. the diurnal cycle of LWP. The comparison with the LWP climatology of O'Dell (2008) is an exception for the sake of comparability. Here we also took the chance to demonstrate CFC and LWP diurnal fluctuations for a predefined region.

Comment [D15]: You should mention that for vertically adiabatic clouds (or a fraction thereof) the factor here would be 5/9, resulting in lower LWP (see Wood and Hartmann, 2006). Real clouds have been shown to be closer to adiabatic (Painemal, 2011)

Comment [D16]: τ used previously.

Comment [D17]: First definition of this.

Comment [D18]: Do you mean high-level cloud, or that SEVIRI gave a higher cloud fraction? I'm presuming the former here. If it's the latter then this sentence needs to be altered to make that clearer.

Comment [D19]: Need to define this earlier.

Comment [D20]: Will this affect the comparison to the O'Dell LWP, since the latter will detect liquid in mixed phase columns?

3.1 General characteristics of distributions and statistical properties

One objective of the present study ~~was~~ is to explore the potential for parameterisation of LWP in relation to CTY suitable for process studies or model evaluation and testing. From each pair of LWP and CTY fields frequency distributions of LWP were determined for the individual cloud types, where the pixels were sorted with respect to local time. It was found that the shape of the frequency distributions themselves remained constant with time~~, in case~~ when a large~~r~~ area is considered. Bugliaro et al. (2011) evaluated the cloud property retrievals used by CM SAF with simulated satellite radiances based on the output of the COSMO-EU weather model. It was found that CM SAF's algorithms are capable of reproducing the ~~real~~ simulated LWP distribution ~~concerning the form~~ (modal classes and skewness), with a slight overestimation of the histogram peak location and an underestimation of the peak number of occurrences ~~in the considered test data set~~.

The distributions for all points in time and all cloud types are unimodal and positively skewed. With these constant properties it is possible to characterise a cloud type as having ~~with~~ a certain distribution ~~possessing characteristic parameters~~. For a mathematical description either a lognormal distribution or a gamma type distribution has to be chosen. The non-zero skewness ~~that is unequal 0~~ forbids description ~~with the help of~~using a Gaussian distribution. This corresponds to the findings of de la Torre Jua´rez et al. (2011) who derived fitting functions for the probability distributions of LWP, amongst other cloud properties, retrieved from MODIS-Aqua. In their work, the best fit was found to be either a lognormal or gamma type distribution, depending on the considered spatial scale. Unlike in Considine et al. (1997), who proposed G~~g~~aussian distributions in case of very large cloud fractions close to 100 %, a G~~g~~aussian distribution was never found to produce the best fit. The gamma type distribution ~~is also detectable~~ has also been observed from ship-based ~~as well as~~and airborne measurements (McBride et al., 2012).

In general, the distributions can be characterised as such (~~see also~~ figure 2): low clouds show on average a rather narrow highly peaked distribution with small ~~liquid water contents~~LWPs of approximately 67.2 - 86.2 ψψψ - . The averaged variance ranges from 21.9 to 29.7 ψψψ - .

Middle level clouds possess a larger spectrum of LWP, the average values are between 153.8 ψψψ - - in July and 174.8 ψψψ - - in October while the variance li~~ea~~ys between 51.5 ψψψ - - in April and 58.1 ψψψ - - in January.

The distributions with highest absolute values can be found in the high opaque cloud class, ~~at the same time~~ for which the distribution is not as broad as for middle level clouds. For this classs, T~~t~~he average values range ~~for this class~~ from 148.8 ψψψ - - in January up to 187.3 ψψψ - - in April. The variance changes between 50.3 ψψψ - - in October and 59.2 ψψψ - - in July. High semi-transparent clouds again have smaller average values compared to the high opaque class (34.4 ψψψ - - in April - 43.9 ψψψ - - in October) and the most narrow distributions of all (variance: 11.0 ψψψ - - in April - 16.0 ψψψ - - in January). More figures on averages and variances for the complete MSG disc as well as a subset for Europe can be found in table 3.

As a next step, let us consider specified regions. A distinction between land and water pixels leads

to the following observations: distributions appear broader for land pixels than for water pixels~~.,~~ T~~t~~his means that ~~,~~ the variance is greater and more high LWP values are measured. On average LWP is higher over land than over sea: for example low clouds show the following behaviour: in January 98.8 ψψψ - - compared to 84.0 ψψψ - , April: 78.4 ψψψ - - and 65.4 ψψψ - , July: 79.3 ψψψ - , 63.4 ψψψ - , October: 108.6 ψψψ - , 79.2 ψψψ - . In table 2 the average values for all cloud types can be found for the SEVIRI disc, where we also distinguish~~ed~~ between land and water pixels. The enhancement of LWP above land is particularly visible for high opaque and middle level clouds. The difference is more pronounced

Comment [D21]: Which area?

Comment [D22]: Simulated LWP distribution? Even an analysis model might not do a good job with LWP magnitudes.

Comment [D23]: ?

Comment [D24]: Do you mean the SEVIRI observed dsitributions?

for October and January than for April and July. Due to this, the peaks in the distributions have lower values. Nevertheless, they peaks occur approximately at the same LWP bins. The differences in the distributions of LWP between land and water pixels are likely the result of a combination of due toall possibleseveral mechanisms of cloud formation over land or waterfactors. Among those are: The albedo of the land surface is much more variable relative to that over the ocean, which will affect cConvective processes due to solar heating variations. with varying ground albedo exist over land, Also, the formation of clouds over ocean is influenced by the temperature of the underlying sea current that usually fluctuates more slowly than the surface temperatures of land. also Tthe inversion layer height will differ more over land than over the ocean due to a varying availability of water vapour in the atmosphere. In addition, The oorography has an effect on the atmospheric flow and influences the formation of clouds. On the microphysical scale, aerosol over land is of a different type than to that over sea and is, also more variable in composition. Additionally the number density concentration is mostly greater over land than over ocean. Over the Aatlantic ocean, sea salt dominates together with mineral dust from the Saharan desert. The formation of clouds over ocean is influenced by the temperature of the underlying sea current that usually fluctuates more slowly than surface temperatures of land.

The second focus was placed onto analysing a smaller and more heterogeneous region from the SEVIRI disc, where the surface type (land or water) should vary on a comparably small length scale. Middle and western Europe (between 36N and 60N and -10E and 30W) was chosen, to be more precise, a region between 36N and 60N and -10E and 30W, compare (see figure 1). No distinction between land and water pixels wereas made. The frequency of occurrence of different cloud types in the total cloud coverage is slightly different for Europe than for the full SEVIRI disc. The most striking feature is, that the relations are not constant with time, as can be seen in figure 3. In here, the share of the individual cloud types from all cloudy pixels is displayed. On the left hand side the figures for Europe, spatially averaged from the monthly mean data product of CM SAF for the year 2009, areis shown., Tthe full disc data can be found to the right. On the full disc the proportion of the cloud types do not change vigorously during the year 2009. In the summer month the low cloud class fraction increases to exceed the high semitransparent one. In Europe, the monthly variation for all cloud types is generally bigger compared to the results for the full SEVIRI disc. Most noticeable is the increase in fractional clouds during the summer months which that is not visible when considering the full disc and the subsequent raise increase of the high opaque cloud class from September to December. This might indicate that the raise increase is merely caused by seasonal changes in the circulation pattern. A shift of the general circulation, like such as the meridional movement of the polar front, has an observable effect in this small subset of the SEVIRI disc. The differences become much more noticeable when considering smaller time-scales. For October 2009 daily aver-

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ages of LWP were calculated from the non-averaged data for the respective European region. The average is afor daylight-only averageperiods., where the illuminated hours were taken as weighting factor. The time series for low clouds is displayed in the upper panel in figure 4 together with the daily averages. The time series shows a pronounced temporal variation with apparently periodic fluctuations. The repetition period is in the of order of several days, which corresponds to the time scale of synoptic features such as cyclones and anticyclones. The auto-correlation function reveals, that the fluctuations solely appear to be periodic, which can be expected for a single month of data within a chaotic dynamic system. As can be seen from table 3, the monthly mean values show enhanced LWP values (on average) for middle level and high opaque clouds on average enhanced LWP values., Oon the contrary, the LWPs of the high semitransparent and the fractional cloud classes isare smaller in Europe, compared to the full SEVIRI disc. A

Comment [D25]: Is this shown? Which distributions and which has the larger peak? Does this mean that there are more clouds for this distribution (whichever it may be).

Comment [D26]: Is this more the case for land than for the ocean? Are there any references for this? This will depend on a variety of meteorological factors, including solar ground heating and convective development.

Comment [D27]: Again, should provide references for this claim.

Comment [D28]: It looks to me like the time variability is not a great deal larger than for the full SEVIRI disc. Low and high-semitransparent clouds were more variable for the latter for example.

Comment [D29]: See above.

Comment [D30]: Is this actually the case? You could quote the time variance perhaps? This looks to be true for middle, high-opaque and fractional clouds, but not the other two types. The writing here needs to be modified to give a fairer description of the results.

Comment [D31]: What is the definition of daylight only used for SEVIRI retrievals? Is it based upon a solar zenith angle threshold?

Comment [D32]: Not sure if this is necessary – needs some explanation as to what you mean if you think that it is necessary.

typical uncertainty is caused by the viewing geometry of SEVIRI since it is mounted on a geostationary satellite: the cloud amount and also the liquid water path are dependent on the line of sight through the atmosphere, and so the error increases towards the rims of the disc~~,~~ (see the Validation Report for CLAAS, ~~(~~Kniffka et al., 2013).

Comment [D33]: Can you say by how much? Is the sign of the biases known?

The connection between high-semitransparent clouds and liquid water can only be rated as approximate, because of an inconsistency between cloud top temperature from the msgv2012 algorithm and the one used for the derivation of the cloud physical properties. In CPP v3.9, the cloud top temperature is derived from the 10.8 ψ ψ ψchannel where a linear relationship between radiance and CTT is assumed. While this performs well in most cases, it leads to greater differences between the two independently derived CTTs in the case of high semitransparent clouds where a more sophisticated method would have to be used to refine the results.

Comment [D34]: What does this mean for the retrievals (e.g. the results shown so far) for the high semitransparent cloud?

3.1.1 Liquid water in high opaque clouds

~~Some notes about the phase state of the water in the clouds:~~ It may seem a little optimistic to show distributions of liquid water for high clouds, for example high opaque clouds. The majority of those clouds are regarded ~~to have~~ as having a cloud top consisting of ice particles. While this is the case for most cloudy pixels in the analysed scenes, it is not true for all high opaque cloud fields. First of all, measurements of SEVIRI always provide a snapshot of the current state of the atmosphere and therefore contain also clouds that are still in the process of glaciation, which ~~is in the~~ occurs at timescales of the order of a few minutes (Ansmann et al., 2009) or even up to tens of minutes depending on certain atmospheric conditions such as ice nuclei concentration or updraft velocities (Korolev and Isaac, 2003). From the experimental side, supercooled liquid water can be found in clouds down to temperatures of -37.5 ℃, as was experimentally proven by Rosenfeld and Woodley (2000). They conducted in situ aircraft measurements in deep convective clouds and found that most of the condensed water remained liquid until -37.5 ℃. The amounts of detected liquid water content were not negligible with~~,~~ values between 0.4 and 4.0 ψψψ ~~were~~ measured ~~and remained~~ during several passages through the same cloud fields. This suggests, that the large amounts of supercooled water are not transient features.~~,~~ F~~f~~reezing times

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were about 7 minutes. Rosenfeld and Woodley suggest, that in those cases heterogeneous freezing plays a minor role and homogeneous freezing is the main glaciating mechanism. In a further study by Khain et al. (2001), the mechanisms leading to these supercooled cloud water droplets are simulated with the bin microphysics Hebrew University cloud model (HUCM). Supercooled watering ~~effect~~ at low temperatures was most often found for cloud fields with high cloud condensation nuclei number concentrations together with high vertical velocities~~y~~. The authors argue~~,~~ that the existence of large amounts of liquid water ~~also in great~~at heights up to 9 to 10 ψψ ψseems to be a common feature of deep vigorous convective clouds, but is not often modelled by cloud modellers due to gaps in knowledge and a lack of parameterisations for some microphysical processes. Particularly the rate of drop freezing seems to be overestimated significantly, mostly in the temperature range from -32 to -38 ℃.

Another question arises when dealing with multi-algorithm data: could the cloud phase attached to the cloudy pixels that were identified as e.g. high opaque, be erroneous? Both quantities are derived with different algorithms and ~~therewith~~ so are inconsistent in a numerical sense, so it might be possible~~,~~ that the phase "liquid" is attached falsely to a cloudy pixel. Also, the number of high clouds that are flagged as liquid is fairly small compared to the other cloud types. To make our results more plausible, we further restricted the fields for October 2009 ~~with~~ using the corresponding cloud top temperature (CTT).

Comment [D35]: Which quantities?

Cloudy ~~P~~pixels ~~with~~ of liquid phase ~~and cloudy~~ were only considered to be valid if the cloud top temperature was greater than -38 ℃. We found that the pixels are not randomly distributed, but form contiguous areas. Also the pixels are not preferably situated in regions with high viewing angles, where the detection of clouds becomes more complicated~~,~~ due to the slant viewing geometry. High opaque liquid cloud pixels are found both over water as well as over land, as can be seen in the cloudy regions in figure 5. On the left hand side the pixels li~~ay~~e over water, on the right hand side the cloudy patches can be

Comment [D36]: Needs a new paragraph. Also, are we talking about all clouds here, or just high opaque ones? You need to introduce what data you are looking at here and introduce Fig. 5. I.e. single day of data, what region, etc.

found both over water and over land. ~~In this figure, only pixel with the above described conditions are displayed plus the restriction of CTT $\psi\psi$-38 °C.~~ No dependence on the underlying surface could be found.

The number of pixels with high opaque clouds and liquid water and CTT $\psi\psi$-38 °C is much smaller compared to other cloud types for~~at~~ the same conditions. When averaging the data for October 2009, the cloudy pixels ~~belonging to the conditions above~~ that satisfy the above conditions consist of 87.3% low clouds, 3.6% middle level clouds, 0.24% high opaque clouds and 8.8% high semitransparent clouds. So the number of high opaque pixel is approximately 7 % of the number of middle level clouds. Still, the number is not negligible, and ~~approves~~ somewhat corroborates the findings of Khain et al. (2001). A more detailed analysis of this subject can be found in Hogan et al. (2004). The authors measured the global distribution of supercooled water clouds by analysing data from the Lidar In-space Technology Experiment (LITE). The lidar, which was mounted on a space shuttle, had the advantage of providing a view from above, as a satellite instrument does, and so delivers results that are suitable for comparison with our data. In this study, the highest amounts of the coldest supercooled clouds were found in the midlatitudes of the northern and southern hemisphere, but not in the region of the ITCZ. Also Hu et al. (2010), who studied the

occurrence of supercooled water clouds with CALIPSO found supercooled clouds mainly in the mid or high-latitudes, associated with storm-track regions. This corresponds roughly to our findings for October 2009, but a more careful study with a broader database would have to be made.

3.2 Diurnal cycle

Directly from the level2 data, monthly averaged diurnal cycles of LWP were created per cloud type for the northern hemisphere of the SEVIRI disc. The local time of the individual data~~-~~points was taken into account by sorting the pixels into time zones. In figure 6 the results for October 2009 are displayed;~~,~~ it ~~needs to be aware~~ should be noted that the algorithm yields results during daylight only. The LWP shows diurnal variations for all cloud types, ~~whereat~~with the middle level and high opaque cloud types ~~has~~ showing the biggest amplitude.
The LWP of low and high-semi-transparent clouds shows maximal values in the morning hours and around midday, whereas middle level and high opaque clouds peak in the afternoon (local time). The diurnal amplitude of low clouds is very pronounced;~~,~~ not only in Octob~~er~~re, on average it reaches 29.1 % of the mean LWP and at maximum 56 % of the mean LWP value (April). Pfeifroth (2009) analysed the diurnal variation of cloud fractional cover from SEVIRI ~~as it is~~ generated by CMSAF for the year 2008 and found that the average cloud fractional cover (CFC) has a relative diurnal cycle of less than 30 % ~~from~~ of the average CFC for 58.5 % of all considered pixels. In relative terms, this indicates that LWP can be more variable than the cloud fraction from SEVIRI during a day.~~!~~ LWP and CFC fluctuations cannot be compared directly;~~,~~ CFC fluctuations for example result only from variation in the horizontal direction, whereas LWP ~~can vary~~is a result of variability in three dimensions. ~~Nevertheless both kinds of fluctuation cause variations in cloud optical thickness (COT) which again influences the radiative budget~~. ~~Fluctuations in COT for different reasons could directly be compared.~~ Further studies are required to confirm the observations and to analyse the effect on cloud optical thickness or the radiative budget, respectively.
In figure 6, also the number of observations is depicted, to illustrate the dependence of the CPP algorithm on the illumination conditions. For solar zenith angles above 72° no useful information can be retrieved for the liquid water path and so, ~~in conjunction with~~due to the viewing geometry of the geostationary MSG2 satellite, the number of observations is mainly dependent upon the time of day.
Marine boundary layer clouds are a major source of uncertainty for~~in~~ cloud radiative feedbacks, as stated in several publications;~~,~~ see Chlond et al. (2004), Seethala and Horv´ath (2010) or Wood and Hartmann (2006). Therefore, the climate modelling community would greatly benefit from accurate LWP

Comment [D37]: Didn't you already say this?

Comment [D38]: If we are talking about deep convective cores then these will cover only a small area. Convective outflow, anvils and stratiform cloud is likely to dominate in terms of area and this is more likely to be frozen.

Comment [D39]: Would be good to reiterate that you are talking about the "intrinsic" LWP here.

Comment [D40]: The use of 6 different colours in this figure is a little hard to discern. Can different linestyles etc. be used to distinguish between some of them – particularly low clouds and all clouds have very similar colours.

Comment [D41]: Again, how is this defined? Using a certain solar zenith angle?

Comment [D42]: This too shows a similarly large diurnal cycle.

Comment [D43]: Need to introduce Fig. 7 before you quote the results from it. Also, the linestyles in Fig. 7 should be varied to make it clearer.

Comment [D44]: Over Namibia?

Comment [D45]: Not sure what you are trying to say here. Also, from Fig. 7 the October diurnal amplitude looks larger than for April. Or is this "not shown" data?

Comment [D46]: Defined before?

Comment [D47]: τ

Comment [D48]: τ is also affected by vertical variations, so why is it different to LWP? I.e., naturally a cloudy pixel can have a variety of τ values. τ is an in-cloud quantity anyway, so it does not make sense to talk about it here.

Comment [D49]: What effect? Not sure what you're trying to say here.

Comment [D50]: This information needs to be given earlier – see the comments above. Should say that this is because no τ or Reff retrievals are made, if that is the case.

measurements of marine boundary layer clouds. Since those clouds are relatively optically thin, their radiative impact is very sensitive to their vertically integrated liquid water content ~~or liquid water path~~ (i.e. the LWP, Turner et al., 2007). The cloud deck off the coast of Africa, approximately at Namibia and Angola serves as an example ~~for~~ of marine boundary layer clouds that consist mainly of water. This special region shall be considered in more detail. Therefore, a field between 5° W - 15° E and 30° S - 10° S was cut from the MSG data (see ~~compare~~ figure 1) for LWP and CTY. ~~and the l~~Level 2 data from the months of January, April, July and October were averaged to form monthly mean diurnal cycles for

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the respective cloud types.

In figure 7 the average diurnal cycle of low and middle level clouds for the cloud deck is shown. As can be seen on the left hand side, the diurnal cycle of low clouds shows a strong morning maximum, tend~~s~~ings to decrease during the day and then raise again at around ~~2~~14:00 local time. ~~This is valid for the months January, April, July and October. A course~~Diurnal variation ~~of this type~~ similar to this is caused by solar absorption where the cloud ~~cover~~ top is heated during the day-time, which leads to the evaporation of cloud droplets and thinning of the cloud cover. This effect can be simulated for example with a Large Eddy Simulation Model by including shortwave-heating (Chlond, 2004). Wood et al. (2002) propose fitting coefficients for the diurnal cycle of LWP for low clouds; ~~which agree with~~ our findings suggest that this would be a valid approach. ~~These~~ ~~F~~fitting coefficients t~~o~~ for a sinusoidal curve were derived from the microwave radiometer data of the TMI (Tropical Rainfall Measuring Mission Microwave Imager). The middle level clouds on the right hand side do not show such a constant shape of diurnal cycle;~~,~~ in January and April the maximal value is reached in the early afternoon, whereas in July and October the maximal values appear in the morning, ~~but~~although ~~no pronounced maximum can be observed~~the maxima were quite unpronounced.

~~In these considerations we have to take into account~~Here we consider~~, that it is possible for~~ the possibility of particular clouds developing ~~to develop~~ during a day (e.g. through convective development)~~, for example through convection and~~ and changinge ~~the~~ its cloud type class. To illustrate this effect, we analysed this special region, which should provide a temporally stable cloud layer. Stable is meant in a sense that this layer stays in more or less the same geographic location in the time frame of a month. Hence the observed changes in CTY and LWP should result mainly due to internal developments of the cloud deck during daytime. In figure 8, the average diurnal cycle of LWP together with the number of observations is displayed for the cloud deck in April 2009. The LWP of low clouds is highest in the morning hours and decreases during daytime, also the number of observed low clouds decreases until 12:00 UTC and increases afterwards. The numbers of middle level and high semitransparent clouds show a similar development. ~~At the same time t~~The number of fractional clouds increases to reach a maximum at 11:00 UTC, plus the number of high opaque clouds increases until 10:00 UTC before decreasing again. Because ~~of the~~the cloud deck as a whole is ~~spatial stationarity~~ fairly stationary~~of the considered cloud deck~~, this indicates a transition of clouds from one type to another in this region. We are aware that this study can give only a rough impression on the possibility of cloud class transition and that temporally and spatially much higher resolved analysis would be needed to make a more quantitative declaration for this specific region.

For further characterisation, the diurnal cycles of LWP derived from SEVIRI were compared to climatological diurnal cycles derived from passive microwave observations (O'Dell et al., 2008). From this climatology a small subset was processed for our region specified above. In figure 9 a direct comparison between the SEVIRI derived LWP values and the microwave measurements (aggregated from SSM/I, TMI and AMSR-E data) can be found. The microwave data are climatological average values from the years 1988-2008, the SEVIRI data are monthly averages from the year 2009. For a

Comment [D51]: Not sure how much the direct evaporation of droplets plays a role – another aspect is that the additional cloud top heating reduces the temperature gradient within the cloud and reduces the convective overturning. Add refs for this – e.g. Wood stratocumulus review paper.

Comment [D52]: Are you talking about the Wood paper here or your paper?

Comment [D53]: Which region?

Comment [D54]: As well as the position of the cloud deck, does the cloud fraction stay roughly constant too? I.e. is there variability in the number of open cells, etc.

Comment [D55]: LT?

Comment [D56]: Not that similar for middle clouds.

Comment [D57]: This result is very questionable – the diurnal cycle of the number of low clouds is very small, so it is hard to say much about this for low clouds.

Plus, the detection of clouds is affected by the presence of higher clouds. Thus anticorrelation between particular cloud types and the clouds overlaying them might be expected.

I don't think that this part of the analysis is useful and should be removed.

~~better~~ comparability, ~~also~~ cloud-free pixels were ~~averaged~~ includedfor the SEVIRI data and no distinction between cloud types was

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made, although clouds in this region are mostly of low type. As can be seen, the shape of the diurnal cycles derived from SEVIRI corresponds reasonably well with the diurnal cycles derived from the climatology, especially if the times near sunrise are not considered.~~,~~ ~~particularly April and~~ July show a particularly good agreement in terms of both the shape and magnitude for all the times of the day available. The absolute values from the SEVIRI measurements are higher for all months. As can be seen on the right hand side of figure 9, with SEVIRI it is possible to provide ~~also~~ high temporal~~ly~~ ~~resolved~~ resolution diurnal cycles for the whole of a given day~~with SEVIRI~~, ~~so also the temporal fluctuation of the~~ ~~diurnal cycle can be studied~~ ~~, as opposed~~ in contrast to measurements from polar orbiting instruments.

The diurnal cycle of LWP can be caused by either the intrinsic fluctuations of LWP within a cloud field or by the macroscopic change of cloud cover, ~~which means~~ i.e. the absence or presence of clouds ~~in this respect~~. In figure 10 we ~~refined the diurnal cycle description by splitting~~split the average diurnal cycle into contributions from these two parts. The intrinsic share is determined by averaging over all pixels with LWP $\psi\psi$0.0 $\psi\psi\psi$ -. The macroscopic change in cloud cover is assessed by creating masks ~~with the entry~~ for which a value of 1is given for pixels with LWP $\psi\psi$0.0 $\psi\psi\psi$ - and 0 for pixels without clouds or with ice.~~,~~ ~~subsequently t~~The average ~~is formed by including~~ of all of such pixels in the mask is then calculated. For a better comparability, the resulting diurnal cycles are displayed in figure 10 relative to their mean values. The intrinsic diurnal cycle represented by the filled stars can easily be described as sinusoidal with a maximum in the morning hours and ~~the~~ a minimum in the afternoon. The LWP mask contribution (open circles) has two maxima;~~,~~ one in the morning and one in the late afternoon, with ~~the~~ a minimum at midday. As pointed out before, the relative amplitude of the intrinsic fluctuation is greater tha~~e~~n the marcoscopic fluctuation of cloud cover in this region. This example demonstrates~~,~~ that it is possible to distinguish between different sources of variability in the overall LWP diurnal cycle when monitoring with SEVIRI. The analysis of the possible consequences on for example the energy budget or the transformation of cloud cover on longer time scales remains to be elucidated.

3.3 Seasonal variation

To complete the picture, the average diurnal cycles of low, middle level, high opaque and high semitransparent clouds in the northern hemisphere are~~is~~ displayed in figure 11. Contrary to the marine region considered before, the low clouds ~~in~~ here do not possess a pronounced morning maximum, a more striking feature is the second one around midday, which is also the absolute maximum in the considered months.

The seasonal variation is present for all cloud types in the northern hemisphere. ~~Predominantly a shifting of the curves can be detected.~~ The highest mean values are found in October and the lowest in April in the case of low clouds or middle level clouds. High semitransparent clouds show a maximum in July and a minimum in January. But not only the mean values fluctuate with time, but also the shape of the diurnal cycle. High opaque clouds are variable in this respect, which indicates that the cloud formation mechanisms are complex and vary with time. The shape of the diurnal cycle of the other cloud classes is rather constant during the four seasons.

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4 Conclusions

In this study we analysed the occurrence of LWP depending on cloud type. The objective was to find

Comment [D58]: I think that this should be added sinî the shapes are only similar if we ignore the values early in the day.

Comment [D59]: You need to discuss reasons why this discrepancy occurs. Are the retrieved effective radius and optical depth too high for example? Could the derived cloud fraction be too high, so that the weighting produces too high an all-sky average LWP? Could the assumption of a vertically homogeneous cloud be playing a role? I.e. the use of 2/3 rather than 5/9 in equation ? Something else?

Comment [D60]: Better called liquid cloud fraction mask?

Comment [D61]: However, there is the problem that at sunrise (and probably sunset too) there are likely to be LWP retrieval errors due to the high solar zenith angle – as also pointed out by Roebeling 2008. Fig. 9 suggests that such errors are still occurring at SZA<72 degrees.

Comment [D62]: What does this mean? Is it necessary?

Comment [D63]: Even for high opaque clouds the shape does not change that much – I don't think that you can justify this.

characteristic features of LWP for the individual cloud types. The general features of LWP, for example frequency distribution, average value and diurnal cycle are specified to serve as characteristic measures in atmospheric numerical modelling. With these measures, studies for a better description of LWP distribution in models under varying conditions, as for example ~~done~~ performed by de Roode and Los (2008), are facilitated. Other possible applications are process studies or input data for cloud generators (Venema et al., 20) and radiative transfer studies on a wide range of spatial scales. They can also provide verification in microphysical measurement experiments such as the airborne probing of clouds Each cloud type possesses a characteristic average LWP distribution that is rather constant with time for the complete area observed by MSG, but variable for smaller regions, e.g. Europe. The fact, that the distributions do not change with time when considering the full disc shows that the disc is big enough to cover all cases ~~for a cloud to be~~, so the statistics derived from such a large spatial field is robust and general for most applications. Also the two retrieval algorithms are independent enough, so that one scheme does not limit the sample space of the other. LWP is derived by applying the Nakajima and King scheme using the 0.6 and 1.6 ψ ψ ψchannels. The CTY algorithm does not use the 1.6 ψ ψ ψchannel, but together with 6 other channels, the 0.6 ψ ψ ψchannel is needed to distinguish high semitransparent or fractional clouds from the more opaque cloud types. However, for both thin cloud types several tests are applied, which always include the two cases radiance of 0.6 ψ ψ ψbelow or above the same threshold. Hence the use of the 0.6 ψ ψ ψchannel does not influence the frequency distribution of the individual cloud types. We studied the diurnal cycle of liquid water path for the entire year 2009 and found that ~~also~~ the diurnal cycle is dependent on cloud type. It has to be noted that clouds can develop during a day leading to a different type assignment by the retrieval. So clouds can change from one cloud type class into another, i.e. the diurnal cycle of LWP of a certain cloud type should be interpreted as being composed of the liquid water content averaged over all clouds of one type that are existing at the individual points in time.

The diurnal cycle of low clouds in the region of the coast of Angola and Namibia seems to be driven mainly by solar absorption. A numerical verification of cloud development through shortwave heating via Large Eddy Simulation can be found in Chlond (2004). The diurnal cycle of middle level and high opaque clouds ~~follows more a~~ is more characteristic of ~~convectional~~ convecitve development, with the clouds developing during thea day and containing more liquid water in the afternoon. Please be aware that when considering the complete SEVIRI disc only a rough average is provided, which sums up all possible mechanisms of cloud development in just one curve per cloud type. Still we would consider these curves to be a useful approximation that can serve as prototype clouds in large scale numerical process studies or simulations on longer time scales because on the whole, the energy cycle or radiative cycle can be described correctly with these approximations. Another drawback is the typical problem of an imager mounted on a geostationary satellite: the cloud amount and also the liquid water path is dependent on the viewing geometry, and so the error increases towards the rims of the disc.

It is particularly noticeable that the relative amplitude of the LWPs diurnal cycle can exceed that of CFC. This aspect needs further analysis and careful error assessment. Particularly the fluctuations

of cloud optical thickness that result either from fluctuations of LWP or from CFC are of interest, to better quantify the absolute effect caused by fluctuations in the two quantities. Therewith the impact on radiative quantities such as heating rates or cloud radiative forcing will be assessed in future studies. In Wood et al. (2002) the normalised amplitude of the simultaneously retrieved low cloud amount is 50 % less than the LWP amplitude in subtropical regions. But shortwave radiative transfer calculations showed, that the cloud amount diurnal cycle has a 2-3 times larger influence on morning-afternoon differences in top of atmosphere shortwave radiative forcing. In this context, the impact of the diurnal variations of LWP and CFC should be considered in more detail.

In further analysis ice water path will be included, to investigate the effect of phase transition during the development of clouds, particularly convective cloud systems will be of interest.

Acknowledgements. This work was carried out within the framework of EUMETSAT's Satellite Application Facility on Climate Monitoring (CM SAF) in cooperation with the national meteorological institutes of Germany,

Comment [D64]: ?

Comment [D65]: Describe which two you are talking about.

Comment [D66]: ?

Comment [D67]: Is this necessarily a problem?

Sweden, Finland, the Netherlands, Belgium, Switzerland, and the United Kingdom.

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