EVALUATION OF THE DIURNAL CYCLE OF MODEL PREDICTED CLOUD LIQUID WATER PATH WITH MSG-SEVIRI OBSERVATIONS

R. A. Roebeling, E. van Meijgaard and A. J. Feijt

Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201, 3730 AE De Bilt, The Netherlands

ABSTRACT

The evaluation of diurnal cycles of cloud Liquid Water path (LWP) in climate models receives relatively little attention. This is partly due to the lack of reference data to evaluate these cycles. The Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard METEOSAT-8 is the first instrument with the potential to provide accurate information on diurnal cycles of LWP over land and ocean surfaces. This paper evaluates diurnal cycles of LWP in the Regional Atmospheric Climate Model (RACMO) over Europe, using corresponding SEVIRI retrievals. The results show that diurnal cycles of LWP from SEVIRI show large spatial variations in their mean values, time of daytime maximum and daytime normalized amplitude. Over Europe RACMO overestimates LWP by about 75% as compared to SEVIRI. In general, the SEVIRI observed spatial variations in normalized amplitude and daytime maximum of LWP are well captured by RACMO. The best agreement between SEVIRI and RACMO is found over Ocean. Most differences are found in Mediterranean and Continental climates, where RACMO tends to predict maximum convection about two hours earlier than SEVIRI. Moreover, RACMO predicts different diurnal cycles than SEVIRI in regions with frequent changes in surface type or weather conditions. In conclusion, the results of this study show that SEVIRI retrieved diurnal cycles of LWP provide a powerful tool for identifying climate model deficiencies.

1. INTRODUCTION

The representation of diurnal variations of cloud properties in present-day climate models is relatively poor, and therefore limits the predictability of cloud feedbacks in a changing climate. Accurate information on the diurnal cycles of LWP over land and ocean would provide a key test of many aspects of the physical parameterizations in weather and climate prediction models, such as the representation of convection, turbulence and cloud processes.

In order to capture the spatial and temporal distributions of cloud properties various methods have been developed to retrieve LWP from satellite measurements. Passive imagers, such as the Advanced Very High Resolution Radiometer (AVHRR) onboard the National Oceanic and Atmospheric Administration (NOAA), are one way to retrieve LWP over land and ocean surfaces from visible (0.6 or 0.8 μm) and near-infrared (1.6, 2.1 or 3.8 μm) reflectances (Nakajima and Nakajima 1995; Platnick et al. 2003; Roebeling et al. 2006).

Over ocean, Microwave Imagers such as TRMM-TMI or Special Sensor Microwave/Imager (SSM/I) are another way to retrieve LWP (Weng et al., 1997, Wood et al. 2002). There has been good progress in quantifying the accuracy of LWP retrievals from passive imagers. Several studies compared ground-based LWP retrievals from Micro Wave Radiometers (MWRs) with LWP retrievals from NOAA/AVHRR (Han et al. 1995; Jolivet and Feijt 2005) and the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard METEOSAT-8 (Roebeling et al. 2007). The accuracies (biases) of the satellite retrieved LWP values are better than 15 g m^{-2}. The precisions (variances) of these retrievals are better than 30 g m^{-2} for thin clouds, whereas lower precisions were found for thick clouds (up to 100 g m^{-2}). The accuracy of model predicted LWP values is considerably lower that those from satellite or ground-based MWR observations. During the FIRE Artic cloud experiment, Curry et al. (2000) compared large-scale model LWP values to MWR inferred LWP values. They found for the Artic region that all models underestimate mean LWP values by about 20 to 30 g m^{-2}, which corresponds to relative differences larger than 60%. For non-precipitating water clouds Van Meijgaard and Crewell (2005) found that MWR inferred and model predicted LWP values may differ as much as 50 g m^{-2}.

This paper presents the evaluation of diurnal cycles of LWP from the Regional Atmospheric Climate Model (RACMO) using SEVIRI derived diurnal cycles of LWP. The study area covers large parts of Europe and comprises land and ocean surfaces within various climate regions. The LWP values are retrieved with the Cloud Physical Properties algorithm (CPP) that has been developed at the Royal Netherlands Meteorological Institute (KNMI) within the Climate Monitoring Satellite Application Facility (CM-SAF) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The evaluation of RACMO predicted diurnal cycles of LWP over Europe with SEVIRI observations is carried out by comparing the daily mean, the daytime normalized amplitude, and the daytime maxima of the LWP diurnal cycles. Finally, the diurnal cycles of LWP are evaluated in greater detail for four subdomains in Europe, which are located in four different climate zones. The outline of this paper is as follows. The measurements and methods used in this study are briefly presented in Section 2. In Section 3, the diurnal cycles of LWP from RACMO are evaluated with SEVIRI observed diurnal cycles, both over entire Europe and over selected subdomains in different climatologic regions. Finally, results are discussed in a broader context and conclusions are drawn in Section 4.

2. MEASUREMENTS AND METHODS

a. Measurements

The satellite measurements were collected from the first Meteosat Second Generation (MSG) satellite (METEOSAT-8). METEOSAT-8 is a spinning stabilized satellite in a geostationary orbit, which carries the 12-channel SEVIRI instrument with three channels at visible and near infrared wavelengths between 0.6 and 1.6 μm, eight channels at infrared wavelengths between 3.8 and 14 μm, and one high-resolution visible channel.

b. Methods

The CPP algorithm is used to retrieve LWP from SEVIRI reflectances at 0.6 and 1.6 μm (Roebeling et al. 2006). For cloudy pixels, the CPP algorithm retrieves cloud optical thickness, particle size and cloud phase in an iterative manner by simultaneously comparing satellite observed reflectances at visible (0.6 μm) and near-infrared wavelengths (1.6 μm) to Look Up Tables (LUTs) of simulated reflectances for given values of optical thickness, particle size and surface albedo. The LUTs have been generated using the Doubling Adding KNMI (DAK) radiative transfer model (De Haan et al. 1987; Stammes 2001). The algorithm to separate cloud free from cloud contaminated and cloud filled pixels originates from the Moderate Resolution Imaging Spectroradiometer (MODIS) cloud detection algorithm (Ackerman et al. 1998; Platnick et al. 2003), but has been adapted for SEVIRI to account for differences in spectral channels and resolution and make it independent from ancillary information (J. Riédi, private communication). The optical thicknesses range from 1 to 256. The particles of water clouds are assumed to be spherical droplets with effective radii between 1 and 24 μm. For ice clouds imperfect hexagonal ice crystals (Hess et al. 1998) are assumed with effective radii between 6 and 51 μm. The retrieval algorithm assigns the phase “ice” to pixels for which the 0.6 μm and 1.6 μm reflectances correspond to simulated reflectances of ice clouds and the cloud top temperature is lower than 265 K. The remaining cloudy pixels are considered to represent water clouds. Finally, the LWP is computed from the retrieved cloud optical thickness and effective radius.

The climate model runs are done with version 2 of the RACMO model (RACMO2), which is a hydrostatic limited-area model used for regional climate modeling (Lenderink et al., 2003) The model has been developed at KNMI by porting the physics package of the ECMWF-NWP, release cy23r4, into the forecast component of the HIRLAM-NWP, version 5.0.6 (de Bruijn and van Meijgaard, 2005). Cloud processes in RACMO are described by prognostic equations for cloud fraction and cloud liquid water and cloud ice. Cloud forming and dissolving processes are considered sub-grid-scale and hence parameterized, however large-scale transport of cloud properties is accounted for on the resolved scale. Sources and sinks of cloud fraction and cloud condensate are process oriented and physically based, in contrast to the more commonly applied statistical approach. The formulation explicitly distinguishes contributions from convective processes, boundary-layer turbulence, stratiform condensation processes, rate of evaporation of cloud water/ice, and rate of reduction of cloud area due to evaporation, dissipation of cloud water/ice by cloud top entrainment, and production of precipitation from cloud water/ice. Total 2D cloud cover is obtained from the vertical profile of cloud fraction by assuming random-maximum overlap within a model grid box.

3. EVALUATION OF RACMO DIURNAL CYCLES OF LWP

The diurnal cycles of LWP from RACMO are compared to corresponding cycles from SEVIRI over Central Europe and Northern Africa (20°W to 20°E and 30°N to 60°N). These diurnal cycles have been generated for the period 15 May 2004 to 15 September 2004, using hourly cloud properties retrievals from SEVIRI and predictions from RACMO during daylight hours for solar zenith angles smaller than 72°. Hence, the diurnal cycles only include daytime information, approximately covering the period between one hour after sunrise and one hour before sunset. Unequal lengths in daytime period related to the north-south extent of the domain of interest and to the seasonal effect within the observation period are accounted for by sorting the data with respect to the fraction of the day, which is defined here as the normalized time between sunrise (fraction = 0) and sunset (fraction = 1). The SEVIRI retrieved LWP values are aggregated onto the RACMO grid of 0.25x0.25°. These values are compared to RACMO predicted vertically integrated liquid water and ice sums, considering both the cloud free and cloud filled grid boxes. The diurnal cycles are analyzed for the mean, the 75th (P75) and 90th (P90) percentiles of the LWP values. These values are calculated for each fraction of the day. In addition, the fraction of the day that corresponds to the occurrence of the daytime maximum LWP (t_{LFmax}) is identified. To determine this maximum a 2nd order polynomial is fitted through the actual LWP values:

$$Y(t) = a + bt + ct^2 \tag{1}$$

where t is the time given as fraction of the day, Y is the approximated observation, and a, b, c the constants of the polynomial fit. The first and second derivatives are then used to determine the daytime maxima (t_{LFmax}) and minima (t_{LFmin}). Finally, to quantity the size of the daytime variation the normalized amplitude is calculated:

$$A = \frac{Y_{\max} - Y_{\min}}{Y_{\max} + Y_{\min}} \tag{2}$$

where Y_{max} and Y_{min} are the daytime maximum and minimum values, respectively.

c. Diurnal cycles over Europe

Figure 1 presents the mean values and normalized amplitudes of SEVIRI retrieved and RACMO predicted LWP values over Europe for the observation period. In general, there is good agreement between the spatial patterns of LWP from SEVIRI and RACMO, with high LWP values over the United Kingdom, South Sweden and the Alps and low LWP values in the Mediterranean region. However, the magnitude of the LWP values differ significantly between RACMO and SEVIRI, with about 75% larger values LWP values from RACMO than from SEVIRI. The largest differences are found over the UK, Ireland and the Northern Atlantic Ocean, where LWP values from RACMO are up to 120 g m^{-2} larger than those retrieved from SEVIRI. A possible reason for this discrepancy is that the weather in this region is dominated by frontal systems. In such conditions RACMO predicts very large LWP values, ranging from 100 to 250 g m^{-2}, whereas the SEVIRI retrieved LWP values ranges from 75 to 150 g m^{-2}. Note that the comparison of SEVIRI and RACMO inferred

LWP is done for the water condensate values, which include both water droplets and ice crystals. As mentioned by Roebeling et al. (2007) the validation of SEVIRI retrieved LWP is restricted to water clouds with LWP values smaller than 800 g m^{-2}. The LWP values have not yet been validated for the thick cloud systems, such as over the Northern Atlantic Ocean, that occasionally consist of both water droplets and ice crystals. In the Mediterranean region the differences between SEVIRI and RACMO do not exceed 30 g m^{-2} over both sea and land surfaces. The weather in the Mediterranean region in summertime is dominated by long spells of fair weather interrupted by convective systems. For these systems, LWP from RACMO agree reasonably well with the SEVIRI retrieved values. Over Spain, RACMO predicts smaller amplitudes in LWP than SEVIRI observes, which suggests that RACMO predicts weaker convection than SEVIRI observes. Over North Western Europe, amplitudes from SEVIRI and RACMO are found similar, with values of about 0.25.

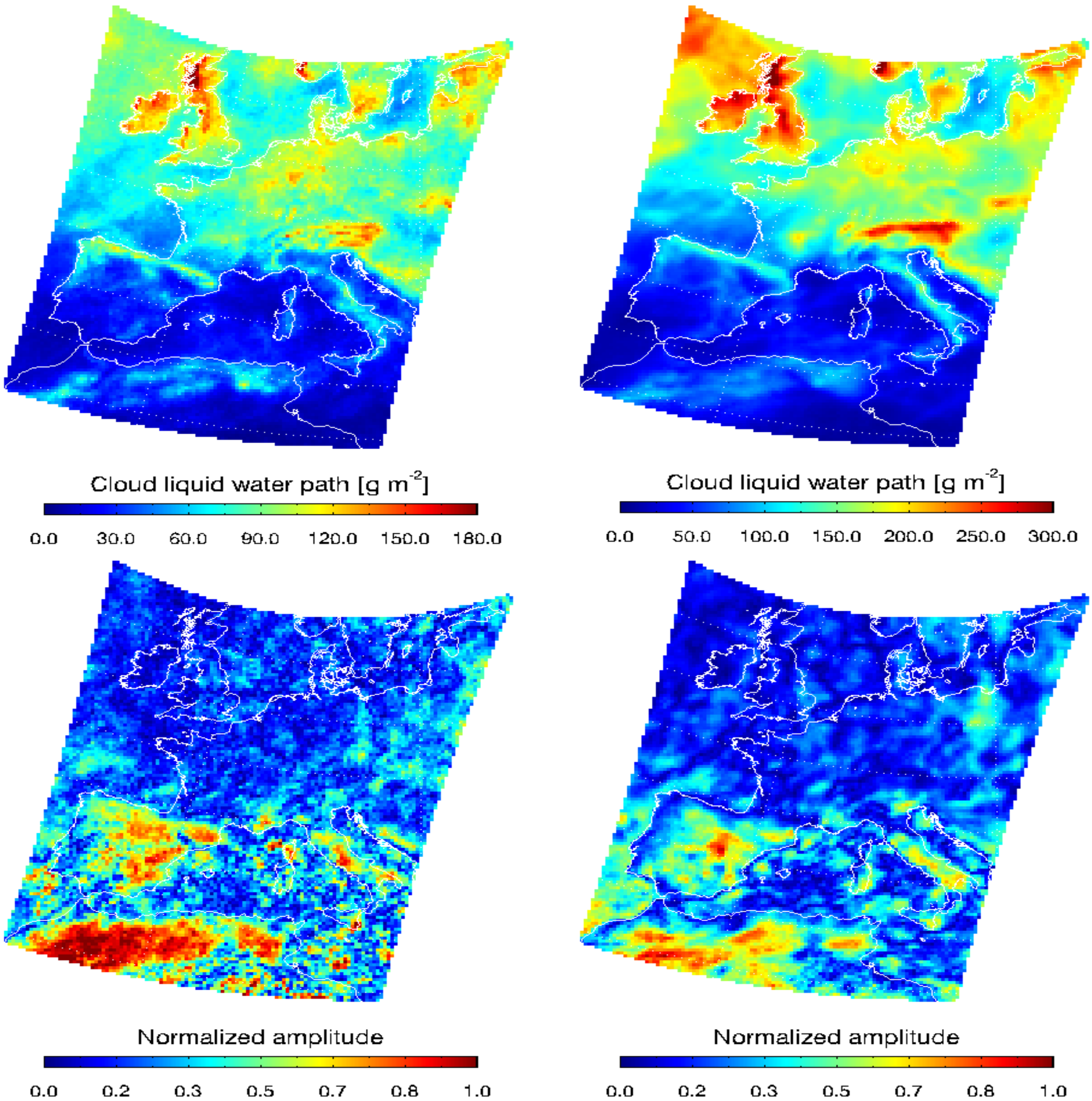

Fig. 1. *SEVIRI retrieved (left) and RACMO predicted (right)* mean LWP and its normalized amplitude of the diurnal cycle for Europe during the period 15 May to 15 September 2004 using cloudy and cloud free grid boxes. Note the large difference in color scale between the LWP values from SEVIRI and RACMO

Figure 2 shows images of the daytime maxima of LWP (t_{Lfmax}) from SEVIRI and RACMO over Europe. The LWP images show that there is a distinct difference between the t_{LFmax} values over land and ocean. The t_{LFmax} values over ocean are about 0.3, which corresponds to early morning observations. Over land the daytime maximum LWP is generally found after local solar noon (t_{LFmax} > 0.5). However, the t_{LFmax} values over land show considerable differences between climate regions. In the Mediterranean region the t_{LFmax} values are close to 0.8 (late afternoon), whereas the t_{LFmax} values in the Maritime and Continental climates exhibit large regional differences and are closer to 0.5 (local solar noon). Remarkable differences are found in the transition zones between land and ocean. For example, along the Portuguese coast or Italy the t_{LFmax} values from SEVIRI are about 0.7 (afternoon), whereas the t_{LFmax} values from RACMO are about 0.5 (local solar noon) over these areas. Over Spain, the t_{LFmax} values from RACMO (t_{LFmax} ~ 0.65) are slightly lower than from SEVIRI (t_{LFmax} ~ 0.75), which indicates that maximum convection is predicted earlier by RACMO than is observed by SEVIRI.

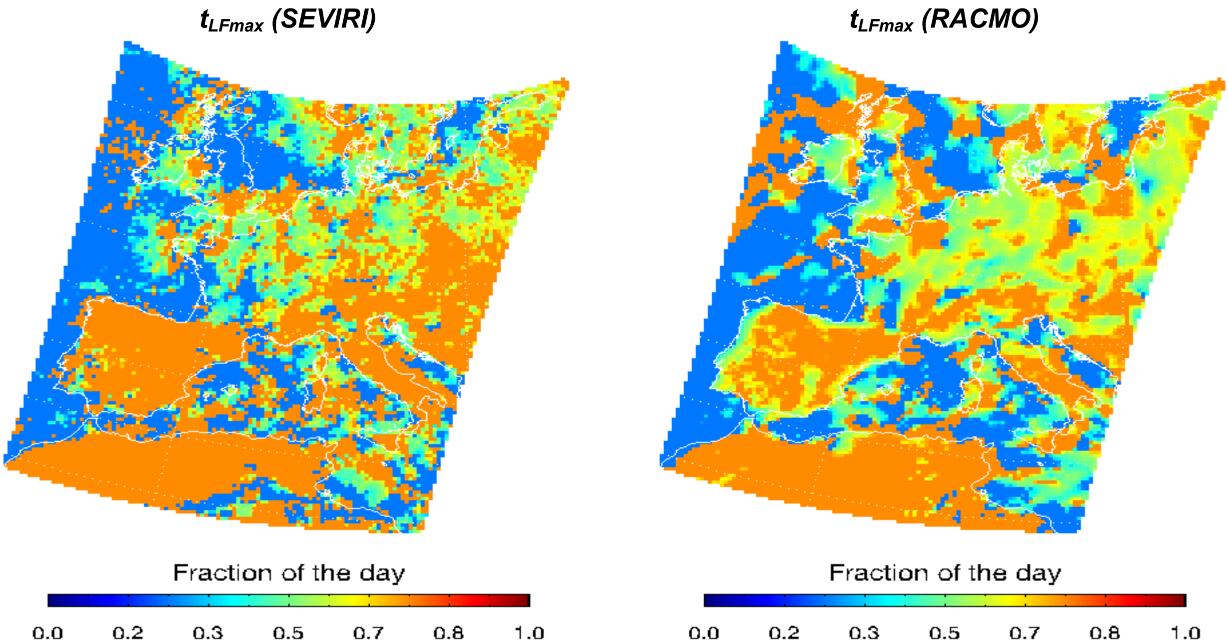

Fig. 2. SEVIRI retrieved (left) and RACMO predicted (right) t_{LFmax} for Europe during the period 15 May to 15 September 2004 for all grid boxes.

d. Regional differences

In order to examine the diurnal cycle in relation to prevailing atmospheric conditions, we focused the study to four different subdomains that are representative for four different climate zones, namely the Ocean, Maritime, Continental and Mediterranean climate, which cover an area equivalent 10x10 RACMO grid boxes (~250x250 km^2). The four subdomains are labeled Biscay Ocean (BOC), Maritime Europe (MEU), Continental Europe (CEU), and Mediterranean Spain (MSP). For each subdomain the diurnal cycles of the 75th and 90th percentile of SEVIRI and RACMO inferred LWP are evaluated, for which the graphs are presented in Figure 3.

In the Mediterranean climate, the summertime diurnal cycles of LWP are dominated by convective clouds that strongly respond to the diurnal cycle of the land surface temperature. During daytime, the surface starts to heat and convective processes start to develop. The strongest convection is typically found in the afternoon. During nightime, the land surface cools down and convective cloud systems collapse. In the MSP-subdomain the diurnal cycles of the P75 and P90 values of LWP from SEVIRI and RACMO are similar, and reveal the largest LWP values during late afternoon. Around midday the difference between SEVIRI observed and RACMO predicted LWP values are largest, when the P90 values from RACMO are about 75 g m^{-2} larger that the corresponding values from SEVIRI. Also maximum LWP in RACMO is found to occur distinctly before the end of the daytime period (t_{LFmax} = 0.65), whereas SEVIRI indicates that LWP continues to rise until at least t=0.75. We suggest that the overestimation of LWP by RACMO is caused by too early onset of the convection scheme. This is consistent with the results of Lenderink et al. (2004), who found that LWP simulations from Single Column Models (SCMs), such as RACMO, are too active. In the BOC-subdomain, the dominating cloud type is stratocumulus, for which the diurnal cycle is characterized by a cloud layer which gradually thickens during the night and thins during the day due to short-wave radiative absorption and decoupling from the surface layer. Although the diurnal cycles of LWP from SEVIRI and RACMO are very similar for the BOC-subdomain, the LWP values from RACMO are 30 to 50 g m^{-2} larger than the corresponding values from SEVIRI. In North Western Europe, the diurnal cycles of LWP are the combination of different cloud systems. These can be frontal systems, which do not have a distinct cycle, or convective systems. The synoptic conditions in maritime regions (e.g. UK, France and the Netherlands) are very diverse and difficult to generalize, because the weather is influenced both by frontal and convective systems. For the MEU-subdomain the diurnal trends in LWP from both SEVIRI and RACMO are rather weak, and show maximum LWP values close to local solar noon. Again, RACMO predicts significantly larger LWP values than those observed by SEVIRI, with P75 and P90 LWP values from RACMO that are about 100 g m-2 larger than the SEVIRI values. There is a slight asymmetry between the LWP values before and after local solar noon (fraction = 0.5), with somewhat larger LWP values in the afternoon than in the morning. In the CEU-subdomain, convection dominates the climate during summer, whereas frontal systems occur less frequently. However, convection in continental Europe is weaker than in the land area of the Mediterranean due to the less pronounced heating of the surface during the day. On the other hand, it may be stronger due to high moisture contents in the vertical profile. Both SEVIRI and RACMO exhibit a strong diurnal cycle in LWP for the CSU-subdomain, with low LWP values in the early morning and high values in the late afternoon. RACMO predicts the maximum values of LWP earlier than SEVIRI. The t_{LFmax} values for P90 are about 0.6 for RAMCO and 0.75 for SEVIRI. Similar to the results for the MSP-subdomain the differences are smallest for early morning observations, when the P75 LWP values from RACMO are about 50 g m^{-2} larger than the SEVIRI values, and largest in the afternoon, when these differences increase to about 100 g m^{-2}. These daytime differences may be explained by too early onset and too early decay of the parameterized convection in RACMO.

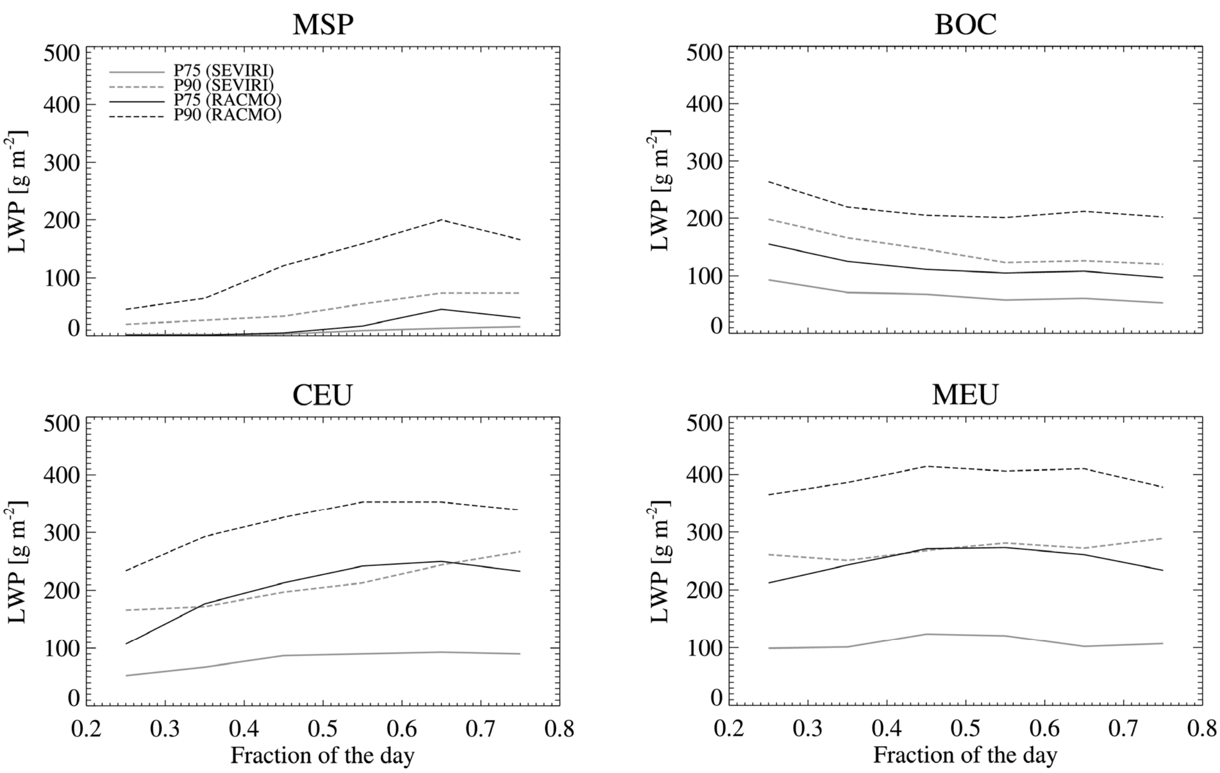

Fig. 3. Diurnal variations of SEVIRI and RACMO inferred 75th and 90th percentile of LWP values for the four subset areas.

4. CONCLUSIONS

This paper presents the evaluation of diurnal cycles of LWP predicted in the Regional Climate Model (RACMO) with SEVIRI observations. Due to the use of SEVIRI observations, this evaluation could be performed, for the first time, over both land and ocean surfaces. Over Europe, RACMO predicts about 75% larger LWP values than the corresponding SEVIRI retrievals. However, the spatial variations in the normalized amplitude and the fraction of maximum LWP predicted by RACMO and retrieved by SEVIRI are similar. From a more detailed evaluation per climate zone it is concluded that RACMO overestimates convection in Mediterranean and Continental climate zones as compared to SEVIRI. Moreover, the SEVIRI observations indicate that RACMO predicts maximum convection about two hours too early in these climate zones.

Over Europe, the LWP values from RACMO are about 75% larger than the SEVIRI values. The differences between SEVIRI retrieved and RACMO predicted LWP values are largest in North Western Europe, where the weather is dominated by frontal systems rather than by convective cloud systems. The LWP differences tend to be smaller (about 25%) in the Mediterranean, where the weather is dominated by convective cloud systems. Despite the differences in magnitude, the spatial patterns of LWP values from SEVIRI are quite well reproduced by RACMO. This is also seen for the spatial variations in the normalized amplitudes and the fractions of daytime maxima of LWP, which are reasonably similar for SEVIRI and RACMO. The largest normalized amplitudes are found in the Mediterranean region, where the values are about 0.7 for LWP. The daytime fractions of maximum LWP differ considerably over the different climate zones, with early morning maxima of LWP over oceans and late afternoon maxima over Mediterranean land. The t_{LFmax} values observed from SEVIRI and predicted from RACMO are found to differ most in the coastal regions or in regions with diverse weather conditions, for example around Italy or The Netherlands. In case of diverse weather conditions, RACMO has to switch frequently between different physical parameterization schemes, for example between the stratiform and the shallow or deep convection schemes, which poses a model challenge.

The comparison over the selected subdomains reveals that RACMO predicts maximum convection about three hours after local solar noon (t_{LFmax} ~0.65) for the subdomains in continental Europe and in Spain, while SEVIRI observes these maxima around sunset ($t_{LFmax} > 0.75$). The diurnal cycles of LWP from SEVIRI and RACMO correspond best for the Biscay Ocean and Maritime Europe subdomains, where the t_{LFmax} values are about 0.25 and 0.50, respectively. However, also over these regions the LWP values from SEVIRI are considerably smaller than the corresponding RACMO values, with the largest differences for the LWP values after local solar noon.

In conclusion, this study shows that satellite retrieved diurnal cycles of cloud properties provide a powerful tool for identifying climate model deficiencies. With four years of SEVIRI data now available, the evaluation of diurnal cycles can be repeated for different years. Such a studied would further increase our understanding on the response of climate models to switches between surface types and weather conditions, which are in particular important for North- Western Europe.

5. ACKNOWLEDGEMENT

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