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LETTER

On the properties and radiative effects of small convective clouds during the eastern Mediterranean summer

Eitan Hirsch[1,2], Ilan Koren[1], Orit Altaratz[1] and Eyal Agassi[2]

[1] Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot 76100, Israel
[2] Department of Environmental Physics, Israel Institute for Biological Research, Nes-Ziona, Israel

E-mail: ilan.koren@weizmann.ac.il

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Abstract

A ground-based field campaign was conducted over the summer of 2011 in Israel to measure the properties of small warm clouds. The horizontal size distribution for cloud sizes of 50–3000 m is presented, with a special focus on the properties of the smallest clouds (liquid water path <10 g m^{-2}, cloud thickness $<\sim 50$ m) and their estimated radiative effect. We show that these small clouds dominate the cloud radiative properties during the summer over the studied region. The average daily cloud cover of the small cloud subset throughout the field campaign was $81 \pm 21\%$ (corresponding to $30 \pm 14.3\%$ of the total measured time), and they contributed $83 \pm 19.4\%$ of the clouds' reflectance. Their average daily radiative effect was estimated at -3.6 ± 2.1 W m^{-2}.

1. Introduction

Shallow cumulus clouds play a key role in the Earth's radiation budget. Due to their low-altitude location in the atmospheric column, their emitted thermal radiation is comparable to the surface blackbody emission. Therefore, their radiative effect is determined mainly by the reflection of shortwave radiation and it is usually considered to be cooling, although the exact radiative effect is still uncertain. Ramanathan *et al* (1989) estimated the global radiative effect of all clouds to be -13.2 W m^{-2}, whereas recent estimations based on satellite data and models stand at -21 W m^{-2} (Allan 2011). Focusing on cumulus clouds, Chen *et al* (2000) estimated their global annual mean radiative effect to be -4.6 W m^{-2} at the top of the atmosphere. These radiative estimations agree well with Rossow and Schiffer (1999), who reported that shallow cumulus clouds (less than ~3 km in depth) cover 11–12% of the Earth's surface and are one of the most dominant cloud types on the surface radiation flux budget.

The properties and formation processes of shallow cumulus clouds have been studied extensively by observation, *in situ* measurements and modeling. Attempts to analyze the size distribution of shallow cumulus clouds have been made since the 1960s. Plank (1969), using airborne photographs of Florida, USA, reported that the number size density of shallow cumulus clouds decreases nearly exponentially with increasing cloud size. Sengupta *et al* (1990), using Landsat imagery, found that the distribution of shallow cumulus cloud sizes can be represented by a power–law relationship with a power exponent of 1.4–2.3 for clouds smaller than 1 km. The larger clouds were represented by another power–law relationship with a power exponent of 2.1–4.75. Lane *et al* (2002) analyzed 16 days of ground-based measurements of shallow cumulus clouds over the Southern Great Plains, USA, with sizes ranging between 200 m and 4000 m, and reported a size distribution that followed an exponential decay of -3.6. Rodts *et al* (2003) reported case studies of shallow cumulus clouds over Florida where the cloud fraction was dominated by the smallest clouds observed. Gryschka *et al* (2008) analyzed spaceborne images and large eddy simulations of shallow cumulus fields and reported that the cloud size distribution follows a power–law relationship with scale breaks at 1 and 7 km. Zhang and Klein (2013) reported shallow cumulus statistics collected from the ground during the summertime for 13 years in the Southern Great Plains. They showed an average cloud-chord length for thin clouds (geometrical depth <300 m) of 780 m, while 41% of the cloud-chord lengths were shorter than 400 m. Other ground-based measurements of summer continental shallow cumulus clouds (>100 m) in the Southern Great Plains showed that the cloud-chord length distribution fits an exponential distribution, and that clouds with a cloud-chord length of 1 km contribute most of the observed cloud fraction (Berg and Kassianov 2008).

All of the aforementioned studies demonstrate that cumulus cloud size distribution obeys an exponential decrease or power–law, dictating that the small clouds are numerous compared to their larger counterparts. Nevertheless, the terms 'small' or 'thin' cloud are vague, as they are defined differently in different studies. Koren *et al* (2008) studied the question of 'how small is a small cloud?' and showed that the cumulative radiative effect of small clouds (area <1 km^2) can be substantial. They showed that in some cases, this power–law relationship implies that a significant portion of the reflectance of a sparse cumulus cloud field originates from the small clouds (area <1 km^2) rather than from big ones. Specifically, 15–50% of the reflectance of the cumulus cloud field originated from these small clouds. From a global perspective, and accounting for all cloud types, Wood and Field (2011) found that the horizontal size distribution of cloud-chord lengths is represented by a power–law relationship with a power exponent of 1.66, in the range of 100 m–1500 km. They defined clouds with cloud–chord length shorter than 10 km to be small clouds and estimated that these clouds contribute ~15% to the global cloud cover.

The smaller the cloud is, the harder it is to detect and to retrieve its physical properties. Therefore, most measurement techniques are biased toward larger clouds. Small clouds fall below most of the sampling rates and sensitivity of the *in situ* measurement instruments, and they are smaller than the spatial resolution of most climate-oriented remote-sensing sensors. Small cumulus clouds are usually optically thin and contain small amounts of liquid water content (LWC), posing an additional challenge for most retrieval methods. Turner *et al* (2007) showed discrepancies between different remote-sensing methods which were assigned to retrieve the properties of thin stratocumulus clouds with liquid water path (LWP) <100 g m^{-2}. Their analysis emphasized the need for specific methods when dealing with small, thin clouds. These technical difficulties and the fact that the radiative effects of small clouds are significantly important, suggest that special care should be given to studying small clouds' properties. The LWC of a convective cloud with 1 km depth is usually below 1 g m^{-3}, while that of shallower clouds (100 m depth) usually reaches up to 0.2 g m^{-3} (Wallace and Hobbs 2006). This can give us a scaling factor for the cloud-thickness range. Clouds with LWP in the range of 1, 10 and 100 g m^{-2} typically scale to cloud thicknesses of 1–10 m, 10–50 m, and 100–500 m, respectively.

Moreover, detailed studies of the formation of small convective clouds may shed light on interesting boundary layer processes. Hirsch *et al* (2014) recently showed cases with certain meteorological conditions for which small, warm, convective clouds (typically on the order of hundreds of meters in size with a lifetime of a few minutes) can be characterized as an interim state between haze pockets and more developed cumulus clouds. Such clouds were defined as 'transition-zone' clouds and were shown to be highly sensitive to the magnitude of the initial perturbation that created them. On the same note, previous studies have shown that the cloud inter-region (also known as the 'cloud twilight zone', Koren *et al* 2007) is characterized by unique optical properties. The nature of the 'twilight zone' is still uncertain, although several mechanisms have been suggested to explain its optical properties: undetected clouds, humidified aerosols, and scattering of solar radiation by nearby clouds, are only some of the suggested explanations (Koren *et al* 2009, Wen *et al* 2007, Marshak *et al* 2008, Yang *et al* 2012). Insights into the formation and properties of small clouds can improve our understanding of the twilight zone's nature and relevant microphysical processes.

In this study, we analyze measurements of small warm clouds that were obtained during a ground-based field campaign. The campaign was conducted during the summer of 2011 in Israel, which is characterized by the presence of small, warm, convective clouds (Goldreich 2003). In the summer, the eastern Mediterranean region is influenced by a large-scale subsidence produced by the subtropical highs with a well-defined inversion layer; this decouples the upper warm air and the cooler marine air layer near the surface. Due to these stable conditions, only shallow clouds can develop in the boundary layer and there is an evident diurnal cycle in the clouds' properties due to changes in temperature near the surface throughout the day. More vertically developed clouds are expected during the morning and evening hours when the temperature near the ground is significantly lower than at noon. The typical cloud sizes during this season are 10–100 s of meters. Such clouds are usually overlooked by cloud remote sensing studies. Space-borne remote sensors usually lack the spatial resolution to detect such small clouds, and most ground-based retrievals are designed to retrieve the properties of well-developed clouds. To the best of our knowledge, it is the first attempt to characterize the optical, microphysical and morphological properties of such small clouds. We use a newly developed retrieval method (Hirsch *et al* 2012) to analyze the horizontal size distribution of the clouds and their LWP distribution. In addition, we estimate their contribution to the total zenith reflectance and their radiative effect.

2. Methods and field campaign

A field campaign was conducted during the summer (June–August) of 2011 in Nes-Ziona, Israel, focusing on the microphysical, optical and spatial properties of small, thin, warm convective clouds. The measurements were conducted over 45 days, for a total of 528 h (daily average of ~12 h, usually between 08:00 and 20:00 local time (LT)).

The measurement setup consisted of a calibrated spectroradiometer (SR5000, CI-Systems, Israel) in the range of 2–14 μm (Cabib *et al* 2006), which was pointed to the zenith and acquired data every 2 s. The acquired signals were analyzed by a ground-based hyperspectral technique in the longwave IR (Hirsch *et al* 2012), which enabled retrieval of the optical (cloud optical depth (COD)), and microphysical (droplet effective radius (r_{eff}), and LWP) properties of the passing clouds. The method was specifically designed to be sensitive to thin warm clouds and it relies on three elements: detailed radiative-transfer calculations in the longwave-IR regime, signal enhancement by subtraction of a clear sky reference, and a spectral matching method that exploits fine spectral differences between water droplets of different radii. The retrieval is at its highest sensitivity for thin clouds, and the error is estimated to be ±0.5 μm for $r_{eff} \approx 2$ μm and for LWP <10 g m^{-2}. The theoretical limitations of the methodology are estimated to be LWP in the range of 0.065–49.26 g m^{-2}, and a lower limit of about 0.01 visible optical depth. The method is particularly efficient for clouds with r_{eff} of up to 4 μm, while it gradually losses sensitivity (regarding the effective radius) for larger r_{eff} (see Hirsch *et al* 2012 for more details). This lost of sensitivity does not pose substantial difficulty, since the studied clouds are small and thin. Such clouds are expected to be characterized by small effective radius. Past studies (Liu *et al* 2003 for example) reported positive correlation between LWP and r_{eff}, suggesting that small LWP values (thin clouds) are expected to be characterized by small effective radius. Furthermore, Hirsch *et al* (2014), studied the microphysical processes which lead to the formation of 'transition-zone' clouds under similar meteorological conditions, and showed that such clouds are characterized by short lifetime and small r_{eff} (in the order of 1–2 μm). The aforementioned considerations coincide well with the fact that merely 8.7% of the r_{eff} readings in our study were above 4 μm. To retrieve the chord lengths of clouds passing over our sensors, we used complementary information regarding the cloud base height and the horizontal wind speed. The cloud base height was measured by a ceilometer at the Israeli Meteorological Service (IMS) Bet-Dagan station, which is located approximately 10 km north of the cloud-measurement system, and a similar distance from the coast. The similar distance from the coast assures that the clouds properties at the IMS station and at the cloud-measurement system are similar. The IMS provided the average 10 min readings of the ceilometer. It also measured atmospheric conditions twice a day by releasing a radiosonde from the Bet-Dagan station (at 03:00 LT and 15:00 LT). The data were downloaded from the University of Wyoming website (http://weather.uwyo.edu/upperair/sounding.html). The radiosonde provides information on temperature, pressure, humidity, and horizontal wind speed profiles. Assuming that the velocity of the clouds is identical to the wind velocity at the same height (see Hirsch *et al* 2011), we combined the ceilometer readings with the horizontal wind profile to retrieve the velocity of the passing clouds. Multiplying the cloud speed by the time period at which it was measured in the zenith produced the chord length of the cloud as it passed above our sensors. Our retrieval algorithm does not depend on any external information and determines automatically (based on IR spectral information) when the measured signal originates from water droplets.

3. Results

We open with a description of the general characteristics of all of the clouds that were measured during the 45 days of the field campaign in terms of distributions of cloud-chord length and LWP. Then we focus on the small clouds and present an analysis of the daily and seasonal contribution of two subsets of smallest clouds (LWP <10 and 1 g m^{-2}) to the total reflection of the cloud field, and the radiative effect imposed by them.

3.1. Horizontal size, optical depth and LWP distributions

Based on the data collected during the field campaign, the chord lengths of the clouds that passed over our sensors were calculated (figure 1, right). As previously mentioned, many studies (especially those making use of ground-based measurements) calculate the chord length of a cloud as it passes over the sensors. This methodology assumes that over long measurement durations, the chords fairly represent the statistics of the passing clouds. Assuming clouds with a spherical horizontal projection, the average chord will be ~20% less than the maximal (twice the radius) chord.

Chord lengths in the range of 50–3000 m were measured and a single power–law relationship with an exponent of 1.74 ± 0.09 (95% confidence) was found to represent the size distribution. Figure 1 reveals a very low number of cloud-chord lengths longer than 1000 m documented during the 45 measurement days (7.4% of the measured clouds). This means that the clouds of the Israeli summer are mostly small clouds with a characteristic horizontal scale of tens to hundreds of meters. The left panel of figure 1 presents the retrieved LWP values

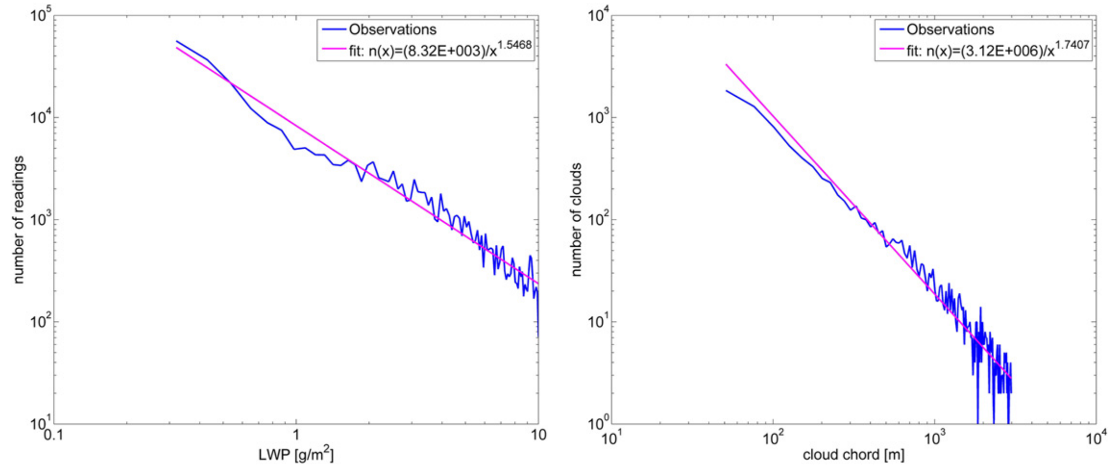

Figure 1. Left: liquid water path (LWP) distribution during the field campaign. A power–law relationship with an exponent of 1.55 ± 0.075 represents the LWP distribution. Right: cloud-chord length distribution. During the field campaign, chord lengths in the range of 50–3000 m were measured. A single power–law relationship with an exponent of 1.74 ± 0.09 was found to represent the size distribution.

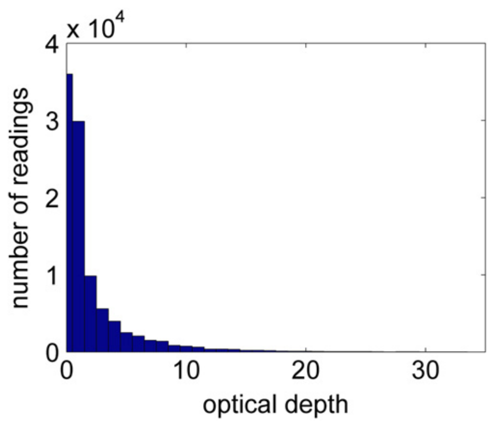

Figure 2. Optical depth histogram of the measured clouds during the field campaign.

during the field campaign for LWP $<10\ \mathrm{g\ m^{-2}}$, since most of the measured clouds were very thin and the frequency of LWP values $>10\ \mathrm{g\ m^{-2}}$ was small during the campaign (only 18% of the LWP readings). Therefore, and to avoid small numbers fluctuations in the large LWP values, we restricted the LWP analysis to values up to $10\ \mathrm{g\ m^{-2}}$. The LWP values in the range of 0.3–$10\ \mathrm{g\ m^{-2}}$ can be described by a power–law relationship with an exponent of 1.55 ± 0.08 (95% confidence). This analysis already suggests that small clouds are significantly more numerous than large clouds, and might make a significant contribution to the reflectance and radiative effect of the cloud fields.

The histogram of the COD measured during the campaign (figure 2) shows that most of the clouds had small optical depth (<10), as expected from the low measured LWP values.

3.2. Daily and seasonal estimation of the radiative effect and the contribution of small clouds to the zenith cloud reflectance

On 12 Jun 2011, a sparse shallow cumulus cloud field was present in the studied region. Based on the retrieved optical depth, a radiative transfer model was used to estimate the reflectance and radiative effect of every measured cloud (Corti and Peter 2009). The model uses the retrieved COD in the visible and IR regions combined with parameters for the Earth's albedo, solar flux, and temperatures of the cloud and ground. Since the daily measurement duration varied throughout the field campaign, and to enable a comparison of different days, we analyzed the radiative effect of the clouds under the same solar and thermal conditions. The daily atmospheric radiosonde profiles were used to calculate the average ground and cloud temperatures during the field campaign (30.23 °C and 19.75 °C, respectively). To examine the possible effect of these clouds, we used common solar and planetary constants. The earth's albedo was taken as 0.3 (Wallace and Hobbs 2006), and the solar conditions were set as the daily mean equinox at the equator (Corti and Peter 2009), i.e. a solar constant of $435\ \mathrm{W\ m^{-2}}$ and a solar zenith angle of 50.51°. The calculated radiative forcing is imprecise due to the use of these constants, but a good approximation is provided.

Following Koren *et al* (2008), we analyzed the clouds' contribution to the normalized cumulative cloud reflectance, sorted by the clouds' LWP (blue line in figure 3, left) and by the clouds chord length (figure 3 right, in blue line). Note that clouds with LWP $<10\ \mathrm{g\ m^{-2}}$ contributed more than 70% to the zenith cloud reflectance. The importance of these clouds is further demonstrated by their contribution to the total radiative effect imposed by the clouds (red line in figure 3, left). While the total radiative effect stands at $-8.55\ \mathrm{W\ m^{-2}}$, clouds with LWP $<10\ \mathrm{g\ m^{-2}}$

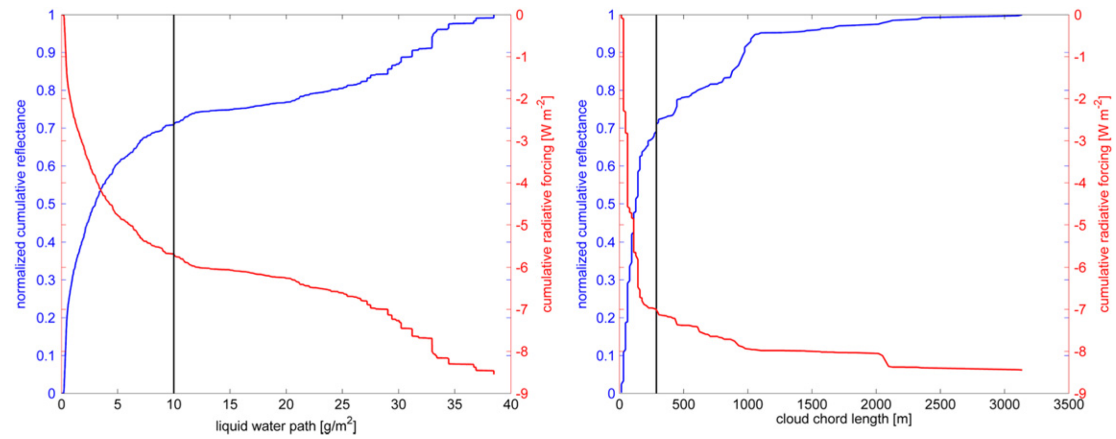

Figure 3. Analysis of 12 June 2011. Left: the graph presents the cumulative contribution of the clouds to the normalized zenith cloud reflectance sorted by the liquid water path (blue), and the cumulative radiative effect introduced by the clouds (red). Notice that the contribution of clouds with LWP <10 g m^{-2} to the zenith cloud reflectance exceeds 70%. In addition, these clouds form a radiative effect of −5.68 W m^{-2} (~66% of the daily radiative effect of all of the clouds). Right: the same analysis, sorted by the cloud-chord length. Notice that 70% of the reflectance is contributed by clouds with cloud-chord length smaller than 300 m.

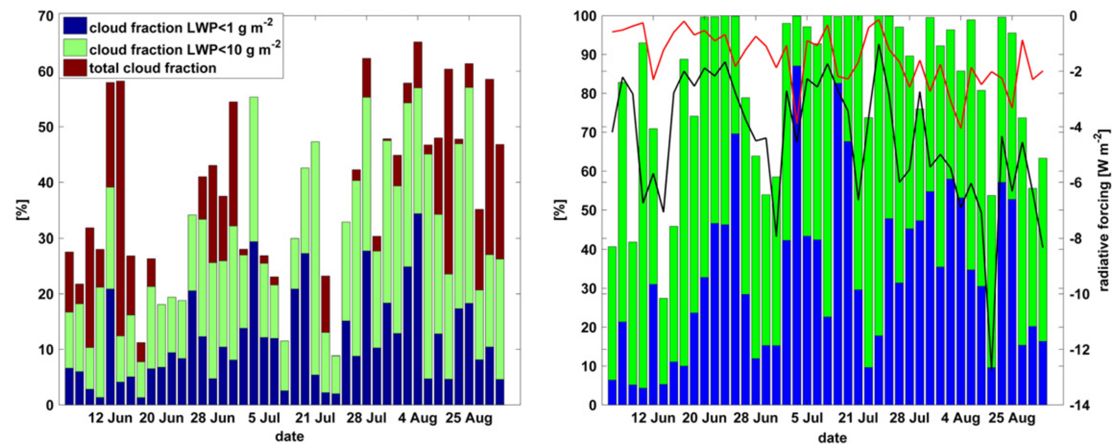

Figure 4. Left: coverage of clouds with LWP <1 g m^{-2} (blue bars), coverage of clouds with LWP <10 g m^{-2} (blue and green bars), total cloud fraction (blue, green and brown bars). Right: contribution of clouds with LWP <1 or 10 g m^{-2} to zenith cloud reflectance (blue and green bars, respectively), and daily radiative forcing of thin clouds with LWP <1 g m^{-2} (red) and clouds with LWP <10 g m^{-2} (black).

contributed ~66% of that effect (−5.68 W m^{-2}). The cloud-chord length analysis shows that 70% of the reflectance and radiative effect were contributed by clouds with horizontal extent smaller than 300 m.

In a similar manner, we analyzed the thin clouds' coverage and their contribution to the zenith cloud reflectance and radiative effects for the whole campaign. We define here the daily cloud fraction as the percentage of time during which clouds were present above our sensors. Figure 4 presents the temporal total daily cloud fraction and the contribution of thin clouds to the cloud fraction and zenith reflectance, as well as the imposed radiative forcing. In the following analysis, the daily standard deviation was used to estimate the range of every parameter. During the measurement period, clouds with LWP <1 g m^{-2} were present for 11.5 ± 8.4% of the total measurement time (figure 4, left, blue bars), but they contributed 30 ± 17% to the total cloud cover and 35.1 ± 21.6% to the zenith cloud reflectance (figure 4, right, blue bars), and created a daily average radiative effect of −0.94 ± 0.64 W m^{-2} (figure 4, right, red line). It should be noted that since the cloud reflection's dependence on LWP is not linear, the relative contribution of small clouds to the reflection might be larger than their proportion of the cloud fraction. Clouds with LWP <10 g m^{-2} were detected 30 ± 14.3% of the time (figure 4, left, green bars), but contributed 81 ± 21% to the total cloud cover, and 83 ± 19.4% (figure 4, right, green bars) to the zenith cloud reflectance. The average daily radiative forcing of clouds with LWP <10 g m^{-2} was −3.6 ± 2.1 W m^{-2} (figure 4, right, black line).

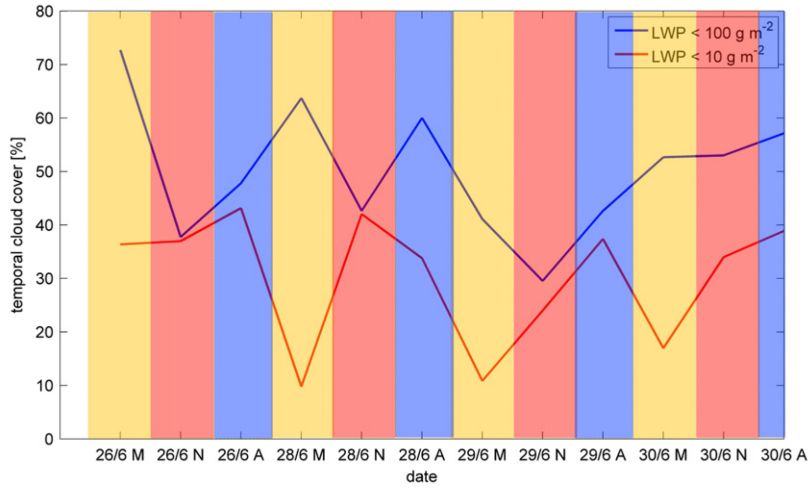

Figure 5. An example of the cloud properties' diurnal cycle over four days during the field campaign. The temporal cloud cover is shown for two distinct liquid water path (LWP) ranges. Orange background ('M') represents morning hours (08:00–11:00 LT), red background ('N') represents noon hours (11:00–15:00 LT) and blue background ('A') represents afternoon hours (15:00–19:00 LT). Note the decrease in total cloud coverage (blue line) around noon, and the simultaneous increase in the relative contribution of clouds with LWP <10 g m^{-2} (red line).

4. Summary and discussion

During the eastern Mediterranean summer, typical atmospheric conditions favor the formation of small convective clouds (tens to hundreds of meters). In this paper, we study the properties and radiative effects of such clouds, measured in a field campaign performed during the summer in Israel. Similar atmospheric conditions are quite common in other locations around the globe (specifically coastal areas along the subtropical belt), in which a persistent synoptic-scale subsidence exists. In such places, similar clouds are expected to form.

We show that the size distribution of the small clouds obeys the same mathematical description of deeper cumulus clouds (a single power–law relationship with an exponent of 1.74 ± 0.09), that were reported previously by Wood and Field (2011). To the best of our knowledge, not many studies have described the LWP distribution of clouds in general, and of cumulus clouds in particular. Taylor and Wood (2001) found that the LWP distribution of marine stratocumulus clouds follows a power–law relationship with an exponent of 1.5, which is very similar to the power exponent that we found here in our study (1.55 ± 0.08).

We also analyzed the contribution of the small cloud subsets to the reflectance of the total cloud field. We showed that the subsets of clouds with LWP <10 g m^{-2} and LWP <1 g m^{-2} (with typical thicknesses of hundreds and tens of meters, respectively) contribute ~80% and 35% of the daily cloud reflectance, while imposing an average radiative effect of -3.6 ± 2.1 W m^{-2} and -0.94 ± 0.64 W m^{-2}, respectively. Chen *et al* (2000) reported a global annual mean radiative effect of cumulus clouds of −4.6 W m^{-2} at the top of the atmosphere. Our analysis suggests that the contribution of the very small cloud subset to the total forcing can be significant. There are times during a typical Israeli summer day that the small clouds (LWP <10 g m^{-2}) are almost the only clouds in the field. Figure 5 presents an example of the diurnal cycle detected over four days in the field campaign. The figure presents the partial cloud coverage for different ranges of LWP values. Note that the proportion of small clouds out of the total cloud cover increases at noon (red regions) when it is almost equal to the total cloud coverage.

Currently, remote-sensing methods classify sky conditions as clear or cloudy scenes. Such classification is prone to error, since the signal that originates from small clouds is either ignored or wrongly attributed to aerosols retrieved in a cloud-free area. Our study demonstrates that more effort should be invested in developing (1) holistic approaches that do not require deterministic detection of each and every cloud in the field to answer important climate questions and (2) measurement techniques and retrieval methods to correctly analyze the contribution of small clouds.

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