Estimating cloud field coverage using morphological analysis

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Abstract

The apparent cloud-free atmosphere in the vicinity of clouds (‘the twilight zone’) is often affected by undetectable weak signature clouds and humidified aerosols. It is suggested here to classify the atmosphere into two classes: cloud fields, and cloud-free (away from a cloud field), while detectable clouds are included in the cloud field class as a subset. Since the definition of cloud fields is ambiguous, a robust cloud field masking algorithm is presented here, based on the cloud spatial distribution. The cloud field boundaries are calculated then on the basis of the Moderate Resolution Imaging Spectroradiometer (MODIS) cloud mask products and the total cloud field area is estimated for the Atlantic Ocean (50°S–50°N). The findings show that while the monthly averaged cloud fraction over the Atlantic Ocean during July is 53%, the cloud field fraction may reach 97%, suggesting that cloud field properties should be considered in climate studies. A comparison between aerosol optical depth values inside and outside cloud fields reveals differences in the retrieved radiative properties of aerosols depending on their location. The observed mean aerosol optical depth inside the cloud fields is more than 10% higher than outside it, indicating that such convenient cloud field masking may contribute to better estimations of aerosol direct and indirect forcing.

Keywords: cloud, aerosol, cloud field, spatial analysis, remote sensing

This letter is dedicated to the memory of Yoram J Kaufman, a dear friend and a brilliant scientist.

1. Introduction

Clouds and aerosols play main roles in the climate system. Clouds have an important role in the Earth radiative energy budget and distribution (Trenberth et al 2009) and in the hydrological cycle (Ramanathan et al 2001). Aerosols affect the climate system directly by interacting with the solar radiation (Hansen et al 1997), and indirectly by changing clouds’ properties. Clouds and aerosols interact and therefore influence one another’s properties. The concentration of aerosols serving as cloud condensation nuclei (CCN) and ice nuclei (IN) determines the droplet and ice particle size distribution in the cloud, and hence cloud optical properties (Twomey 1977, Coakley et al 1987, Kaufman et al 2005), precipitation patterns (Levin and Cotton 2009), cloud size (Khain et al 2005), and lifetime (Albrecht 1989, Jiang et al 2006). Likewise, cloud microphysical processes change aerosol size, distribution, and both chemical and optical properties (Feingold and Morley 2003). Light absorbing aerosols reduce the energy reaching the surface and warm the atmosphere. The warming of the aerosol layer stabilizes the atmosphere beneath it, reduces heat and moisture fluxes from the surface and consequently reduces shallow cloudiness (Koren et al 2004, Feingold et al 2005).

To infer the atmospheric optical properties from space-based observations, it is customary to classify the atmosphere as either cloudy or cloud-free; this is done in order to evaluate the radiative forcing of aerosols, clouds, and aerosol effects on clouds.

Nevertheless, it was shown that the apparent cloud-free atmosphere within a cloud field, namely ‘the twilight zone’, has unique optical properties—suggesting optical contributions from undetected clouds and humidified aerosols (Koren et al 2007, Charlson et al 2007, Twohy et al 2009).
The properties of the twilight zone, located between cloudy and cloud-free atmosphere, depends on the presence of nearby clouds and on the aerosol loading. It extends over tens of kilometres from detectable clouds and it is better described as a property of the cloud field. This inter-cloud region is characterized by a number of different phenomena that affect radiation: (1) aerosols at various stages of uptake of water vapour (Feingold and Morley 2003), (2) cloud fragments at various stages of evaporation (Koren et al. 2008), (3) incipient clouds—i.e., clouds that are forming but do not yet exist as stable entities, (4) decaying clouds, (5) hesitant clouds—pockets of high humidity that oscillate near saturation (Feingold and Morley 2003, Koren et al. 2009), and (6) an enhancement in the radiative forcing of suspended particles between clouds due to photons reflecting off neighbouring clouds (a 3D effect) (Podgorny 2003, Wen et al. 2007, Marshak et al. 2007).

These findings raised the need for a robust detection of the cloud-affected area (i.e. the cloud field). Such definition will enable a clear separation between observations of different environments inside and outside cloud field areas. The aim of this study is to introduce a morphological algorithm for defining cloud field boundaries and to demonstrate the significance of cloud field coverage.

2. The method

A new metric for the determination of cloud field boundaries and classification of an observed region into cloud field or cloud-free is presented in this work. Here, cloud field is an area that includes detectable clouds and twilight zone. Detectable cloud is a pixel that was identified as cloudy by the MODIS cloud mask algorithm (Ackerman et al. 1998); for simplicity the data are represented here by a binary matrix (0 for a cloud-free pixel and 1 for a detected cloud).

The cloud field boundaries are defined by the distance-from-the-nearest-cloud parameter, in our case the nearest detectable cloud. The cloud field area \( A \) is the sum of all the pixels whose distance from the nearest cloud is smaller than an independent distance parameter \( r \). \( A \) therefore depends on \( r \) \( (A = A(r)) \).

The cloud field area \( A(r) \) is a monotonically growing function. When examining the behaviour of \( A(r) \) for increasing values of \( r \) a transition point clearly appears as a change in the growth rate of \( A(r) \), enabling the determination of the cloud field boundaries. In order to normalize the results into unitless variables the cloud field fraction (CFF) is defined as the fraction of cloud field area out of the whole domain area \( A_D \):
\[
\text{CFF}(r) = \frac{A(r)}{A_D}. 
\]

The cloud field fraction is analogous to the familiar cloud fraction parameter and it is limited to the range between 0 (absolute cloud-free area) and 1 (total cloud field area). A domain’s CFF will always gain a value equal to or higher than its cloud fraction, since cloud fields contain both detected clouds and their nearest environment. The growth behaviour of \( \text{CFF}(r) \) is used in order to find the cloud field distance parameter \( (R_0) \)—the cloud field boundary distance from detectable clouds. Figure 2 demonstrates the \( \text{CFF}(r) \) function of a synthetic cloud field presented in figure 1, along with the first derivative \( \frac{d}{dr} \text{CFF}(r) \); this simple theoretical cloud field contains pixel size clouds, randomly distributed in a round cluster.

The rapid growth of \( \text{CFF}(r) \) in the range of small \( r \) values is mostly due to merging of clouds inside the cloud field. The turning point of the \( \text{CFF}(r) \) curve represents the minimal \( r \) value of which the dominant geometry is the whole cloud field; hence, this point is the point of transition from the inner part to the outer part of the cloud field. For higher values of \( r \), as areas far from the detectable clouds are included in the CFF, the function \( \text{CFF}(r) \) is similar to that of a single giant cloud.

2.1. The boundary detection algorithm steps

Step 1—creating the distance map. The first step is the calculation of the distance from the nearest cloud of each cloud-free pixel (Koren et al. 2007)—as demonstrated in figure 1. This calculation requires a preliminary projection of the observed domain to a uniform equal-area grid.

Deeper mathematical discussion and further synthetic examples of the distance field distribution can be found in Ripley (1981).

Figure 1. (a) A synthetic disc shaped cloud field of randomly distributed one-pixel clouds, and (b) its distance map (logarithmic scale).
A data set of the calculated distance from the nearest detectable cloud will be added to the next MODIS atmosphere level 2 standard products (emphasizing its importance to climate research).

Step 2—extracting the field distance parameter and cloud field boundaries. Calculating \( CFF(r) \) and \( \frac{\partial}{\partial r} (CFF(r)) \) as a function of \( r \) enables the determination of \( R_0 \). The transition point from the field’s inner area morphology to the field’s outer area is found as a scale break in \( CFF(r) \) or as a local minimum of \( \frac{\partial}{\partial r} (CFF(r)) \) as shown in figure 2. The cloud field’s characteristic distance parameter value is \( r = R_0 \) (the field distance parameter).

A simple example for two different cloud spatial distributions can be found in figures 1 and 2; these demonstrate the difference in \( CFF(r) \) behaviour between randomly distributed cloud fields (the synthetic field that is used for this figure), and a single circular cloud (from \( R_0 \)—the point where the field is starting to behave as a giant single cloud).

This comparison also reveals a limitation of this algorithm, which cannot extract any field distance parameter for the (theoretical) case of a field that contains one cloud only. In this case, the \( CFF(r) \) function will exhibit a uniform behaviour without the inner field distances part. However, the monotonic increase of the distance parameter distribution with no local maxima and minima will reveal such cases, and the mean \( R_0 \) of the neighbouring cloud fields can be assigned to them.

3. Results and discussion

3.1. The Atlantic cloud field fraction

The Moderate Resolution Imaging Spectroradiometer (MODIS) level 2 products were used for this research. The data retrieved by MODIS platforms is stored every 5 min in a subset (i.e. data granule).

The CFF over the Atlantic (50°S–50°N) is estimated on the basis of 329 granules, containing only daylight granules over the Ocean. In order to study the possible dependence of the field distance parameter on the cloud type, several cloud fields in each granule are manually classified into four categories: stratocumulus (Sc), shallow cumulus (Cu), cirrus (Ci), and deep convective (DC). This classification is done using the MODIS provided true-colour images on the basis of the familiar spatial morphology of these types of clouds.

This study covers 874 selected cloud fields that were observed by MODIS during July 2008. The field distance parameter of each field is calculated using the algorithm described; it is done in a similar way for all cloud types.

In addition to the use of the exact algorithm, the total CFF is also calculated using a constant distance parameter \((R_0 = 10 \text{ km})\). This distance is a rough estimate of the minimal value of the distance parameter, based on the estimated exponential
Figure 3. Comparison of AOD values inside and outside cloud fields: AOD map (left) and cloud field calculated boundaries over the cloud mask map (right) using field distance parameters of $R_0 = 30$ km (orange line), and of $R_0 = 10$ km (yellow line).

decay of the reflectance, of the aerosol optical depth (Koren et al. 2007), and of the relative humidity (Twohy et al. 2009) in the twilight zone, when increasing the distance from the nearest cloud.

The results for the CFF and for the field distance parameters of the examined cloud fields over the Atlantic during July 2008 are presented in table 1.

The results show an average field distance parameter for the whole Atlantic of 30 km, which agrees with the observations of Koren et al. (2007), that found a reflectance signal effect up to 30 km from the nearest cloud edges. The comparison between the field distance parameters of different cloud field types shows that Sc fields have the smallest distance parameter, probably because of their relatively high inner field spatial density and sharp transition to clear atmosphere at their edges. The deep convective cloud fields’ class includes many variations and shapes of convective clouds spanning the spectrum between local convective cells and a hurricane. Therefore, the retrieved distance parameter for this class exhibits the highest standard deviation (34 ± 12 km). Cirrus cloud fields are a special case in this analysis due to the possibility that a cirrus field is located above a wider field of different type. Such a setting would give that specific cirrus field the distance parameter of the underlying field. All field distance parameter values are of the same order of magnitude in the range of 19–37 km.

The Atlantic cloud field fraction for July 2008 is 97% when using the detailed analysis and counting every pixel closer than the calculated field distance parameter $R_0$, and 87% when using the constant $R_0 = 10$ km. Twohy et al. (2009) found that only 8% of the detected cloud-free area above oceans is located in a distance larger than 20 km from the nearest detected cloud. Koren et al. (2007) found a global coverage of 81% when adding a 30 km belt around all clouds, given a global cloud fraction of 51%, including deserts and dry land areas. Therefore, taking into account the 30 km average field distance parameter found here, an estimated Atlantic cloud field fraction of 97% agrees both with the observations of Koren et al. (2007) and with those of Twohy et al. (2009).

3.2. Aerosol retrieval and cloud fields

Past research showed that retrievals of aerosol optical properties are different near clouds. The differences in aerosol optical properties may be a result of aerosol humidification (Feingold and Morley 2003, Twohy et al. 2009), the signal contribution of undetected clouds (Koren et al. 2007, 2008, 2009) or cloud 3D radiative effects (Marshak et al. 2006, Wen et al. 2007).

Here this effect is demonstrated using 13 granules of the level 2 MODIS aerosol retrievals (Remer et al. 2005, Levy et al. 2007) over the Atlantic Ocean (50°S–50°N) during June and July 2008/2009. Figure 3 presents a map of the AOD retrieval and of the calculated cloud field boundaries of one of the sampled regions.

One cloud field type was excluded from this analysis—cirrus cloud fields. These fields are usually located higher in the atmosphere than the typical aerosol layers, and may also appear above other lower altitude cloud fields (e.g. stratocumulus or cumulus); hence, including this type in the analysis may add noise and unphysical contributions to the trend of mean AOD as a function of distance from the nearest cloud.

The filtering of cirrus cloud fields from the data was done carefully by comparing true-colour MODIS images of the selected granules with the matching cloud top temperature and cloud mask MODIS products. Only cloud fields that had the cirrus spatial signature and typical cirrus cloud top temperature were manually marked out.

The mean AOD values show an exponential decay as the distance from the nearest cloud increases (figure 4; see also
a fit to the exponential function). Furthermore, it is shown that the mean AOD is nearly constant (in its lower values similar to the background values) only for distances larger than 30 km from the cloud edges. These results emphasize the significant differences between the retrieved AOD values inside and outside cloud fields; the mean AOD inside cloud fields is significantly higher than the mean AOD outside cloud fields.

4. Summary

This study introduces new estimations of the cloud field coverage above the Atlantic Ocean using a robust morphological algorithm for defining cloud field boundaries. The cloud field fraction (CFF) is measured using the MODIS cloud mask for one month of observations (July 2008) over the Atlantic Ocean (50°S–50°N, 874 cloud fields in 329 granules).

The algorithm presented estimates the characteristic distance \( R_0 \) from the nearest cloud which bounds the field, and determines where, outside of it, the measured optical properties of the atmosphere would not be affected by clouds.

When adopting the ‘conservative approach’, using the accurate distances calculated using the algorithm for the Atlantic Ocean, the cloud field fraction reaches 97%, suggesting that the likelihood of finding an area that will not be affected by clouds over this region is very small; however, using a smaller distance parameter of \( R_0 = 10 \) km, roughly \( \frac{1}{3} \) of the cloud optical effects due to the neighbouring cloud field are eliminated, and the estimated cloud field fraction is 87%.

The classification for cloud types reveals the relatively low field distance parameters of Sc fields, as expected considering their high spatial density, and a large variety of values for the deep convective cloud fields, probably because of including different kinds of cloud fields in this type (see section 3.1). Such parameters are offered for use in future cloud classification algorithms. Furthermore, a preliminary analysis of the influence of cloud fields on the AOD retrieval is examined for 13 granules, excluding cirrus cloud fields. An exponential decay of the mean AOD is found when the distance from the nearest cloud is increased. This finding reveals a significantly higher mean AOD inside cloud fields.

The above results emphasize the need to study cloud fields as a major and important entity in the atmosphere. It is suggested here that the atmosphere should be classified into two classes: cloud fields, and cloud-free, while the cloud class should be a subset of the cloud field class. The algorithm presented is suggested to be robust and useful for such classification, supporting future aerosol–cloud–climate studies.

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Figure 4. The mean aerosol optical depth (AOD) as a function of the distance from the nearest cloud of all field types, excluding cirrus cloud fields, based on 13 granules above the Atlantic (blue dots), and its exponential fit (red curve). The highlighted distance parameters (vertical green lines) are the suggested independent value for a good first approximation \( R_0 = 10 \) km and the calculated value \( R_0 = 30 \) km; see section 3.1.
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