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The thin border between cloud and aerosol: Sensitivity of several ground based observation techniques

Josep Calbó[a,*], Charles N. Long[b,c], Josep-Abel González[a], John Augustine[c], Allison McComiskey[c]

[a] Departament de Física, Universitat de Girona, Girona, Spain
[b] Cooperative Institute for Research in the Environmental Sciences, University of Colorado Boulder, CO, USA
[c] National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division, Boulder, CO, USA

A B S T R A C T

Cloud and aerosol are two manifestations of what it is essentially the same physical phenomenon: a suspension of particles in the air. The differences between the two come from the different composition (e.g., much higher amount of condensed water in particles constituting a cloud) and/or particle size, and also from the different number of such particles (10–10,000 particles per cubic centimeter depending on conditions). However, there exist situations in which the distinction is far from obvious, and even when broken or scattered clouds are present in the sky, the borders between cloud/not cloud are not always well defined, a transition area that has been coined as the "twilight zone". The current paper presents a discussion on the definition of cloud and aerosol, the need for distinguishing or for considering the continuum between the two, and suggests a quantification of the importance and frequency of such ambiguous situations, founded on several ground-based observing techniques. Specifically, sensitivity analyses are applied on sky camera images and broadband and spectral radiometric measurements taken at Girona (Spain) and Boulder (Co, USA). Results indicate that, at these sites, in more than 5% of the daytime hours the sky may be considered cloudless (but containing aerosols) or cloudy (with some kind of optically thin clouds) depending on the observing system and the thresholds applied. Similarly, at least 10% of the time the extension of scattered or broken clouds into clear areas is problematic to establish, and depends on where the limit is put between cloud and aerosol. These findings are relevant to both technical approaches for cloud screening and sky cover categorization algorithms and radiative transfer studies, given the different effect of clouds and aerosols (and the different treatment in models) on the Earth's radiation balance.

1. Introduction

The Earth's atmosphere contains suspended particles, i.e. particles that because of their size have terminal fall velocities of the order of centimeters per second at most, so they have atmospheric residence times on the order of hours, days, or much longer in some cases. These particles vary in their chemical composition, have concentrations that vary in space and time, are present in both the solid and liquid phases and have sizes ranging over several orders of magnitude. In gross aggregate, the suspension of particles receives two names: either cloud or aerosol. Simplifying, a cloud is an aggregate of a number of particles formed mainly of water, in liquid or solid state (i.e., hydrometeors) of sizes between a few microns to some millimeters and in sufficient concentration to be perceived by human vision from the Earth's surface. Any other aggregate of particles is called, generically, atmospheric aerosol, and generally contains less liquid water than clouds. This includes wind-borne dust, sea spray particles of salt, sulfate and organic particles, or ash and soot arising from combustion. Precipitating particles such as rain, snow or hail (which have terminal fall velocity of the order of meters per second) are excluded from this discussion.

Despite the above differences in origin and composition, clouds and aerosol could be considered two manifestations of the same phenomenon. However, their description, characteristics, and – in particular – interactions with solar and terrestrial radiation have historically been studied separately. Indeed, the study of clouds extends back to ancient times whereas the study of atmospheric aerosol is much more recent. In fact, the term was proposed in the early 20th century, and has become popular within the atmospherics science community only after the 1960s or so, as previously unspecific names (dust, smoke, etc.) or more technical designations (lithometeor, etc.) were used. The interactions between clouds and aerosols are known, although their climatic significance is far from being fully quantified (see the reviews of

* Corresponding author.
E-mail address: josep.calbo@udg.edu (J. Calbó).

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Heintzenberg, 2012; Rosenfeld et al., 2014; Seinfeld et al., 2016). The presence of different types or concentrations of aerosols has impacts on clouds, as some particulate matter (cloud condensation nuclei or ice nuclei) are more amenable for water vapor to condense into droplets or crystals to form clouds. These effects, especially in the field of energy balance, have been known as aerosol indirect effects (Albrecht, 1989; Twomey, 1974) to distinguish from the direct (purely radiative by absorption and scattering) effect that aerosols have on the radiative energy transfer in the atmosphere.

Broadly speaking, there are two features that distinguish a cloud from other suspension of particles in the air: i) the content of water in droplets and/or ice crystals, and ii) the visibility, i.e., the appearance of a more or less clearly delimited form of (usually) white/grey colour, which is possible to see evolve (it should be noted that some aerosol suspensions are also clearly visible, for example, a smoke plume). Both features allow quantification, i.e. one can propose a threshold for the concentration of droplets or ice crystals (or for the amount of condensed water), and also for the optical effect (the optical thickness at a certain wavelength). Dupont et al. (2008) showed that solar irradiance and sky imagery retrievals tuned to reflect human observations allow up to a visible optical depth of 0.15 to 0.2 of primarily high ice haze to be traditionally classified as “cloud free” sky. But historically the decision on whether a volume of air is cloud or not (leaving no room for intermediate cases) has been based on the judgment of a human observer on the ground. This does not seem very scientific, since it can happen that the same volume of air containing aqueous particles are labeled as cloud or not depending on the contextual conditions in which the observation is made, subject to the judgment and perception of the observer. Similar difficulties arise when clouds are observed from satellites (Koren et al., 2008).

Consequently, fundamental questions remain: What is the limit of visibility from which a suspension of droplets must be considered cloud? Should this limit be set for an “average” human eye, or can it be objectively established for some instrument as in Dupont et al. (2008)? Or is it even reasonable to consider such a limit given that the aerosol/cloud particle suspension could be considered as a continuum and not a dichotomic phenomenon. How does one define visibility when observations are performed in a wavelength outside the visible range of the human eye? Droplets form on soluble hydrophilic particles whereas many ice particles form on insoluble hydrophobic particles so how does one decide if the suspended particles are aerosol particles or hydrometeors? When observation is performed by automated instruments, trying to reduce to a three level classification (cloud/aerosol/clear sky) is even more difficult (Tapakis and Charalambides, 2013). Subsequently, this classification has consequences for climate studies (Charlson et al., 2007), including trend analysis, as derived trends may depend on the instrument and/or methodology used to infer cloud amounts (Wu et al., 2014).

A good example of the difficulties of defining cloud and aerosol is found regarding sky images taken by “all-sky” cameras (they “see” an entire 180° sky view from a particular point at the surface). The digital images are analyzed to obtain information on the state of the sky, in particular cloud cover and cloud type (Calbó and Sabburg, 2008; Heinle et al., 2010; Kazantzidis et al., 2012; Long et al., 2006b). The problem is what thresholds to set to distinguish between the “clear” and “cloudy” pixels. Even if more complex approaches are adopted (Li et al., 2011; Saito and Iwabuchi, 2016), they rely on the initial human decision taken on the training images. In fact, sky cameras have also been proposed as devices to observe and characterize the atmospheric aerosol (Cazorla et al., 2008).

This is not unique for cloud observations by ground-based imaging in the visible. For example, the difficulties in trying to distinguish clouds and aerosol in sunshine duration records have been pointed out elsewhere (Sanchez-Romero et al., 2014). In addition, many works focus on removing cloud “contamination” from aerosol observations performed with sunphotometers or shadowband radiometers (Alexandrov et al., 2004; Kassianov et al., 2013; Michalsky et al., 2010). The problem further expands when considering other views (satellite) or other wavelengths (ceilometers in the infrared, microwave radiometers, weather radars). All these difficulties have consequences in both meteorological and climatological studies (e.g. Boers et al., 2010; Várnai and Marshak, 2011; Sanchez-Lorenzo et al., 2009; Wu et al., 2014).

In general the distinction between a cloudy and a cloudless sky, and the separation between cloud and aerosol, is appropriate for attribution studies and modeling radiative effects of different climate forcing mechanisms, but imposing this classification may be unnecessary (or inconvenient) in relation to new and advanced methods of observation and measurement. If so, the distinction could also be unnecessary in radiative transfer models, or in future parameterizations included in weather and climate models. This approach of a continuous treatment of aggregates of particles in the atmosphere is relatively new, although some previous works have already pointed in this direction.

For example, Charlson et al. (2007) highlighted the importance that has been given to the separation between the “cloud” and “clear” regimes in various fields of study including the radiative forcing by clouds and the quantification of direct effects and indirect radiative forcing by aerosols. The paper questioned the separation between the two regimes, and suggested the desirability of treating the phenomenon as a continuum. Similarly, Koren et al. (2007) described a transition zone (“twilight” zone) around the cloud in which the optical properties are close to those of the cloud itself. The authors estimated that an appreciable fraction (between 30 and 60%) of the part of the globe at any given time considered free of clouds could correspond to that area of transition, a fact that could have important climate implications. The question of the climatic importance of clouds that are considered “small” in size was addressed by Koren et al. (2008), as well as the effect of the aerosol in the regions between clouds (Koren et al., 2009). Also, Bar-Or et al. (2010) introduced the concept of cloud field as an area that includes detectable clouds and twilight zone, and found that the cloud field fraction could be as large as 97% in an area where the detectable cloud fraction is 53%. In the cited works, several methodologies were used: spectral radiometry from the surface in the visible and near infrared, satellite measurements, and modeling. Also longwave spectral radiometry is being used for the purpose of studying the properties of thin clouds and the transition region (Hirsch et al., 2014; Hirsch et al., 2012).

Other researchers have studied radiative effects occurring in the vicinity of the clouds. Thus, the question of increased reflectivity and the “bluish” aerosol in the vicinity of the visible clouds has been attributed to the Rayleigh scattering of the radiation reflected by the cloud; that is ultimately a three-dimensional effect (Eck et al., 2014; Kassianov et al., 2010; Marshak et al., 2008; Várnai and Marshak, 2009; Wen et al., 2008). They have also studied the transition region from satellite measurements and stated its important radiative effects (Várnai and Marshak, 2011) and have explored the combination of data from two different satellites with the goal of obtaining detailed information on aerosols near clouds (Várnai and Marshak, 2012). Recently, Ten Hoeve and Augustine (2016) confirmed from ground-based and satellite measurements that the aerosol optical depth increases in the vicinity of a cloud; Jeong and Li (2010) had previously found that aerosol humidification effects could explain one fourth of a reported correlation between cloud cover and aerosol optical depth. Moreover, Chiu et al. (2009) and Marshak et al. (2009) addressed the description of the continuum from measurements of zenith spectral radiance in the visible and near infrared, with the high temporal resolution that the rapid transitions between cloud and clear sky require. Chiu et al. (2010) successfully replicated these results by radiative modeling.

The goal of the current paper is to quantify the importance and frequency of situations where ambiguity between clouds and aerosol occur; in other words, situations where the suspension of particles depend on subjective definition to be classified as either cloud or aerosol.