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From the single-scattering properties of ice crystals to climate prediction: A way forward

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ABSTRACT

Cirrus is composed of non-spherical ice crystals, and against the blue background of the sky, they appear as tenuous wispy clouds, usually located at altitudes greater than about 6 km. Their spatial and temporal distribution about the Earth's atmosphere is significant. With such distributions, their contributions to the Earth's natural greenhouse effect and hydrological cycle are important. Therefore, it is important that climate models are able to predict the radiative effect of cirrus, as well as their contribution to the total amount of ice mass that occurs in the Earth's atmosphere. However, cirrus is composed of ice crystals that can take on a variety of geometrical shapes, from pristine habits such as hexagonal ice columns, hexagonal ice plates and bullet-rosettes, to highly randomized habits, which may have roughened surfaces and/or air cavities. These habits also aggregate together, to form chains of aggregates and compact aggregates. The sizes of these habits may also vary, from about less than 10 μm, to several cm, with the smaller ice crystals usually existing toward cloud-top and the larger ice crystals existing toward the cloud-bottom. Due to this variability of geometrical complexity, size, and ice mass, predicting the magnitude of the cirrus greenhouse effect has proven problematic. To try to constrain these radiative and hydrological uncertainties, since about 2006 there is now available the A-train constellation of satellites, which attempt to quantify the radiative and hydrological contributions of cirrus to the Earth's atmosphere. The A-train obtains nearly simultaneous measurements of cirrus from across the electromagnetic spectrum. Such simultaneous measurements pose challenges for theoretical scattering models of cirrus, as these models must conserve ice mass and be physically consistent across the electromagnetic spectrum.

In this review paper, the microphysical properties of cirrus are summarized. The current idealized habit mixture models that have been proposed to represent the observed variability in ice crystal shape, size and mass are discussed. The theoretical light scattering methods that are currently applied to the idealized habit mixture models to solve for their scattering and absorption properties are discussed. The physical inconsistency of the current approach to parameterize the bulk scattering and absorption properties of cirrus in climate models is highlighted. An alternative parameterization, which couples cloud physics more directly with radiation, is proposed. Such a coupling is required, if climate models are to be physically consistent and radiatively interactive.

Contents

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1. Introduction

Cirrus or ice crystal cloud, viewed against the blue background of the sky, takes on a ghostly appearance to the naked eye; it appears tenuous as it stretches across the sky. This tenuous cloud type can give rise to colourful displays of optical phenomena, such as halos and sun dogs. The manifestation of cirrus to the naked eye may leave one with the impression that cirrus, because of its wispy, ghostly appearance, is not an important component of the Earth's radiation budget and hydrological cycle. However, this is untrue, as cirrus is very important to both these components of the climate system. This review article will explore the importance of cirrus to the Earth's radiation balance and hydrological cycle, through its microphysical and macrophysical properties, its fundamental bulk scattering properties and the impact of these properties on a global climate model.

Cirrus is a cold cloud, which implies that its constituent particles are ice crystals, and so it must occur over certain altitudes. The altitudes at which cirrus occurs are usually greater than about 6 km, and pure ice clouds exist at temperatures less than about 230 K (Guignard et al., 2012). The spatial and temporal distributions of cirrus about the Earth's atmosphere are determined by space-based measurements. These space-based measurements reveal that cirrus covers about 30% of the mid-latitudes at any given time, while in the tropics; the coverage can be 60%–80% at any given time (Wylie and Menzel, 1999; Stubenrauch et al., 2006; Sassen et al., 2008; Nazaryan et al., 2008; Lee et al., 2009; Guignard et al., 2012). More recent space-based infrared measurements analyzed by Guignard et al. (2012), also reveal that semi-transparent cirrus make up about 25% of all high clouds and occur mainly in the tropics and mid-latitudes during the winter period. Moreover, visible space-based measurements studied by Heidinger and Pavolonis (2005), show that the daytime distribution of cirrus during January and July, between 60°N and 60°S, with cloud beneath, occurs about 40% of the time. Clearly, with such spatial and temporal distributions, cirrus is an important cloud type, that significantly contributes to the Earth's climate system. Indeed, the most recent fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007) concluded, that understanding the coupling between *all* clouds and the Earth's atmosphere remains one of the largest uncertainties in climate prediction. Cirrus is one such cloud type, where the coupling between it and the Earth's atmosphere is still poorly understood. Fig. 1 illustrates the difficulties that current climate General Circulation Models (GCMs) have in predicting the Earth's top-of-atmosphere (TOA) reflected short-wave flux.

Fig. 1 shows the differences in TOA reflected short-wave flux between a climate GCM and spaced-based measurements, averaged over 10 years, during the winter period (December, January and February combined). The figure shows that, in the tropics, the GCM simulation of the Earth's TOA reflected short-wave flux is underpredicted. Indeed, in the Indonesian region, the differences in the 10-year winter mean TOA reflected short-wave flux can be as large as $-40\ \mathrm{W\,m^{-2}}$. The Indonesian region is important, as this is where vigorous convection can produce significant amounts of cirrus (Sassen et al., 2008). It should also be noted here, that in Fig. 1, the differences in the TOA reflected short-wave flux, in the Southern Hemisphere over the ocean, is also significant. This is because, in general, GCMs do not predict sufficient mid-level cloud in that region (Williams and Webb, 2009; Bodas-Salcedo et al., 2011). The GCM deficiencies, illustrated by Fig. 1, are common to all current climate models used in the IPCC reports (Williams and Webb, 2009). Although, GCMs tend to underestimate the amount of cirrus, some, however, may satisfactorily predict its occurrence (Delanoë et al., 2011).

Although current GCMs cannot as yet predict the 10-year mean TOA reflected short-wave flux (the same is also true for the 10-year mean TOA long-wave flux, but not shown here for reasons of brevity), as illustrated by Fig. 1. There have still been, however, numerous GCM studies, which illustrate the importance of cirrus to the earth-atmosphere radiation balance, see for example Mitchell et al. (1989), Donner et al. (1997), Zhang et al. (1999), Kristjánsson et al. (2000), Stephens et al. (2002), Hartmann et al. (2001), Ringer et al. (2006), Edwards et al. (2007), Fu (2007), Kahnert et al. (2008), and Gu et al. (2011). Unfortunately, such studies have demonstrated large uncertainties in the net radiative effect of cirrus. The net radiative effect of cirrus is defined as follows; it is the sum of the short-wave radiative effect and long-wave radiative effect. The short-wave radiative effect is the difference between the cirrus reflected short-wave flux and the clear-sky reflected short-wave flux, and the long-wave radiative effect is similarly defined. In general, the short-wave radiative effect is generally negative (*i.e.*, cirrus has a cooling effect), while the long-wave radiative effect is generally positive (*i.e.*, cirrus has a warming effect). The net radiative effect of cirrus can therefore be positive, neutral or negative.