Cloud physics from space

Cloud Physics from Space[1]

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Abstract

A review of the progression of cloud physics from a subdiscipline of meteorology into the global science it is today is described. The discussion briefly touches on the important post-war contributions of three key individuals who were instrumental in developing cloud physics into a global science. These contributions came on the heels of the post-war weather modification efforts that influenced much of the early development of cloud physics. The review is centered on the properties of warm clouds primarily to limit the scope of the paper and the connection between the early contributions to cloud physics and the current vexing problem of aerosol effects on cloud albedo is underlined. Progress toward estimating cloud properties from space and insights on warm cloud processes are described. Measurements of selected cloud properties, such as cloud liquid water path are

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now mature enough that multi-decadal time series of these properties exist and this climatology is used to compare to analogous low cloud properties taken from global climate models. The too wet (and thus too bright) and the too dreary biases of models are called out underscoring the challenges we still face in representing warm clouds in Earth system models. We also provide strategies for using observations to constrain the indirect radiative forcing of the climate system..

1. Introduction

It can reasonably be argued that meteorology began as a scientific discipline with the study of clouds when formalized by their naming in 1802 by Luke Howard (e.g. Hamblyn, 2001; Stephens, 2003). Inklings about the importance of cloud physical processes was contemplated even earlier by Franklin in 1789 who suggested that "*much of what is rain, when it occurs at the surface of the earth, might have been snow, when it began its descent*." While the association of clouds with weather is obvious, the post-war modern era of meteorology, with its focus on quantitative numerical weather prediction and forecast analysis, relegated the study of clouds more or less to the background. Although we have made substantial progress in weather prediction on sub-seasonal to seasonal time scales (eg. Bauer et al., 2015), we now recognize the need to better represent all moist processes in the atmsophere, all ultimately involving clouds, as a leading challenge not only for weather prediction and on time scales up to seasonal and beyond but also also for understanding longer term climate change (Bony et al., 2015).

Our desire to predict changes in weather and climate associated with the build up of greenhouse gases in the atmosphere return the subject of clouds to the forefront of the atmospheric and climate sciences. Although the focus on weather prediction remains, we now embrace more fully the broader problem of the prediction of the evolving, moist atmosphere as foretold more than 40 years ago by Lorenz (1969):

> "*The previous generation was greatly concerned with the dynamics of pressure systems and talked about highs and lows. Today we have not lost interest in these systems but we tend to look upon them as circulation systems. This change in attitude has led to a deeper understanding of their dynamics. Perhaps the next generation will be talking about the dynamics of water systems*."

If we are to advance our understanding of the physics of water within the giant atmospheric circulation systems and significantly improve on our ability to model the '*dynamics of water systems*' and predict the evolution of these sytems then we need to be able to make observations of cloud physical properties and make inferences about cloud processes on a very large scale from the global vantage point of space. This paper underscores how our abilty to observe clouds from this vantage point has evolved considerably since the beginning of the era of satellite meteorology.

A number of interwoven activities have occurred during the current 'modern era' of meteorology that advanced cloud physics to the science discipline of today. Highlights of these activities are summarized in the review of Hobbs (1999). Here we briefly introduce the contributions of three iconic figures of our science who set us on a path to expand the perspective of cloud physics from the laboratory to the cloud scale and now to the global scale. Our discussion is centered on the properties of warm clouds primarily to limit the scope of the paper. This focus also provides a link between the topic of cloud seeding and the problem of aerosol indirect effects on clouds that is discussed in section 6. Contemplating this link is most relevant to the discussion of this paper because in many respects cloud seeding propelled the modern science of cloud physics to its current form as discussed in the next section. This is followed by a discussion of measurements of selected cloud properties that are now mature and provide multi-decadal time series of these properties. The paper concludes with a discussion on the challenges we face in understanding the influence of low clouds on the climate system.

2. Post war era of weather modification

Weather modification has a long and colorful history (Fleming, 2010) being motivated by the immense societal value to be reaped in making rain. Even today weather modification continues to gain interest with desperate attempts to increase precipitation in times of severe drought over the parched food basket regions of the world.

The modern era of weather modification really began in the early post war era with cloud seeding experiments conducted by General Electric (GE) scientists. In November 1946, GE announced to the world that it made snowflakes in the laboratory (Schaeffer, 1946; Figure 1) followed with the discovery that silver iodide was an efficient nucleator of ice (Vonnegut, 1947). At that time it was hypothesized that nucleating ice particles in super-cooled clouds by injections of silver iodide would produce rapid growth of ice particles and subsequently enhanced precipitation. It is argued below that current challenges in climate science surrounding the aerosol-cloud-interation (ACI), for example, evolved in a parallel way and from similar governing hypotheses to cloud seeding in that one only has to make small changes to cloud microphysics to bring about a desired macro-physical response in the cloud. Many cloud seeding experiments were subsequently conducted (NRC, 2003) but results were overwhelmingly inconclusive, in part because the link between cause and effect could not be established. Even today, no convincing scientific proof of the efficacy of intentional weather modification exists (NRC, 2003).

The need to establish a connection between cause (seeding) and effect (enhanced precipitation) and thus provide credibility to seeding gave birth to modern numerical models of clouds (Simpson and Wiggert, 1969; Cotton, 1972) and an early example of such a cloud model simulation is provided in Figure 2. Simpson and Wiggert (1969) note that differences in the microphysics between maritime and continental cumulus clouds, known from earlier studies such as Squires(1958), encouraged numerical experimentation on whether one type of cloud could be converted into the other and whether precipitation could be significantly altered between cloud types. The seeding experiment of Simpson and Wiggert (1969) illustrated in Figure 2 is significant for a number of reasons. It demonstrated how precipitation can be changed by manipulating the microphysics of clouds as postulated and it was the first study of the second indirect effect in that adding small particles to maritime type clouds reduces precipitation from these clouds making them more continental in character. It became evident early in such experiments, however, that simply changing the microphysics of modeled clouds did not necessarily produce the response originally hypothesized. Simpson and Wiggert conclude

> *"that the main effect of seeding supercooled tropical cumuli is through the alteration of the cloud dynamics, which in turn alters the water carried and precipitated."*

What subsequently emerged was a deeper appreciation for the importance of the interaction between dynamical and microphysical processes on the production of precipitation of individual cumulus clouds. Cloud seeding became dependent upon use of these numerical cloud models (Cotton, 1976; Cotton, 1982) despite the recognition of the problems in using them. At that time computer limitations meant modelers had to make decisions between performing accurate simulations of the microstructures of small cloud volumes versus accurate detailed depictions of the dynamics of the clouds on a larger scale. These decisions ultimately compromise the utility of these numerical tools for their purpose (e.g. Arakawa et al., 1975). We face the same challenges and compromises today in modelling aerosol cloud effects on the global scale.

Cloud seeding and the ACI problem with its associated radiative forcing of climate have many common parallels. Both primarily involve a variety of processes that connect clouds with their environment. As a consequence, understanding the physical basis of the aerosol influences on clouds has proven to be more complex than expected of a purely microphysical response that was the original hypothesis behind both problems. Whereas cloud dynamics played a defining role in the deeper understanding of cloud seeding (e.g. Figure 2), cloud dynamics similarly now plays a defining role in understanding ACI (Stevens and Feingold, 2009;Wood, 2012).

There are also a few noteworthy differences between cloud seeding and ACI that differentiates these two problems. Cloud seeding primarily focused on effects on a scale of individual clouds with experiments performed being small-scale in nature and too few in number to build clear statistical consensus of cause and effect (NRC, 2003). There are no obvious simple ways to contrast the observed behavior of seeded and unseeded clouds. By contrast and as discussed later, more direct ways to observe effects of aerosol on clouds exist providing a larger body of data for potentially understanding responses to specific changes of aerosol in clouds. Ship tracks are observed localized changes in clouds due to large injections of aerosol from emissions from ship stacks (Conover, 1966; Scorer, 1987). These emissions create localized perturbations to boundary layer clouds.

Cloud differences between regions immediately influenced by these emissions and adjacent cloud regions free of the immediate influence suggest an observational framework for understanding aerosol cause and effect on clouds. Whereas ship tracks provide a cloud-scale perspective of aerosol influences, the effects of volcanic emissions on clouds (Schmidt et al., 2012; Ebmeier et al., 2014; Gettelman et al., 2015 and Malavelle et al., 2017) offer another potential natural test case and thus a possible way for constraining models on a much larger scale. This topic is returned to below.

3. The influences of three giants in shaping the science

It can be reasonably argued that the modern discipline of clouds physics evolved from the need to understand how seeding of clouds might affect the precipitation produced by them. Cloud physics evolved from that point into a more global science today and the foundations that advanced the science from the study of individual clouds ultimately to large scale cloud systems were laid by the important contributions of three iconic individuals (Figure 3).

3.1 Sir (Basil) John Mason (1923-2015)

Much has been written about the life and career of Sir John Mason (e.g. Browning, 2015). He will be forever remembered for building the Meteorological Office into a leading centre of excellence on the international stage. He is also remembered for establishing cloud microphysics as a coherent discipline within atmospheric sciences and became the leader of that science. In his early career, Mason was apparently strongly influenced by the cloud seeding work being performed at GE by Irving Langmuir and his research team and realized that there were several threads of this work that could be brought together in what seemed to be an area of research ripe for scientific development. He knitted these threads together to articulate cloud physics as a formal science endeavor in a form we recognize today.

3.2 Verner Suomi (1915–1995)

Vern Suomi's legacy and the shadow he caste across our science perhaps extends even further than that of Mason. He is broadly regarded as the founder of satellite meteorology as we know it today. The paths of Suomi and Mason undoubtedly crossed. They were contemporaries who had a vision that the science of weather prediction would advance with the marriage of satellite observations with numerical weather prediction. A biography of the life of Suomi and his contributions to our science are described in Lewis et al., 2010. That biography describes how the seeds for satellite meteorology began with the energy balance instrumentation Suomi had developed for its application to agricultural meteorology. It was a question posed to Suomi during his doctoral exam at Chicago by Herbert Riehl "*So now you've examined the energy budget over a cornfield, how would you go about examining the heat budget for the Earth and its atmosphere*?" This ultimately led Suomi to design radiation budget instruments that flew on Earth orbiting satellites in 1957. An obvious result today, but one that was subsequently influential to the development of weather satellites, was the appearance of weather patterns in Suomi's early radiation budget measurements. Thus the new discipline of satellite meteorology was born.

3.3 Sean Twomey (1927–2012)

The influence of Sean Twomey on cloud-related science is pervasive, even today. Twomey was an enigmatic character and a genuine polymath of our science. He made significant and lasting contributions to a number of areas including to the mathematics of inverse theory with methodologies that bear his name (Twomey 1963), pioneering work on cloud nucleation (Twomey 1959), the development of radiative transfer tools that ultimately formed the basis of cloud property retrievals from reflected sunlight (Twomey and Seton, 1980) now widely used and the discovery of a critical climate forcing that also bears his name, the so called Twomey-effect (Twomey 1974,1977), that today looms large over our ability to project climate change. These latter contributions are returned to below in both the next section and in section 6. In many respects Twomey's contributions fused the cloud physics of Mason to the satellite approaches of Suomi leaving us to ponder whether observations from space might offer hints of cloud physical processes observed on an unimagined global scale.

4 Warm Cloud physics from space: I the early period

The relation between the optical depth of clouds (τ) and their vertically integrated cloud water contents (liquid water path, hereafter LWP), or equivalently ice water path, was introduced by Stephens (1978),

$$\tau = \frac{3}{2}\frac{LWP}{\rho_l r_e} \quad (1)$$

where ρ_l is the density of liquid water and r_e is droplet radius that expresses the ratio of the volume to area of the droplet size distribution. This relation was significant for a number of reasons. It provided a tangible connection between cloud physical properties, like LWP, and radiative processes that are distinct functions of τ like the albedo of clouds. This connection then led to a number of conjectures about cloud feedbacks associated with water content changes of warm clouds in a warming world (Paltridge, 1980, Somerville and Remer, 1984; Tselioudis et al., 1992) and ice clouds (Stephens et al., 1990 among others). Underlining the importance of the cloud LWP in this way was also notable because approaches were developing around use of satellite microwave measurements to deduce the water path of clouds (e.g. Staelin et al., 1976). Furthermore, the relation opened the pathway to estimate the LWP from different measurement approaches based on reflected sunlight measurements that too were in a nascent stage at that time. At the same time Twomey (1977) introduced a relation

$$\tau = 2\pi N_c r_A^2 H \quad (2)$$

that connected cloud optical depth to droplet number concentration N_c thus ultimately providing a direct link to aerosol influences on cloud radiative properties. H is the geometric depth of cloud and the droplet radius r_A that appears in (2) represents the area mean radius. As discussed below, this expression serves as the basis for estimating N_c from satellite measurements.

4.1 Cloud LWP

The joint estimation of the LWP, column water vapor and precipitation from the differential emission of microwave radiation is now mature (e.g. Stephens and Kummerow, 2007). More than 29 years of observations of LWP from a constellation of 15 low-Earth orbiting satellites exist and have been compiled into a climatology of cloud LWP (e.g. the multi-sensor advanced climatology of LWP, MAC-LWP, Elsaesser et al 2017). Figure 4 summarizes this 29 year LWP climatology and provides the ratio of LWP to total water to underscore an important challenge of the approach. Estimating the total water (cloud plus precipitation) water path is complicated because the sensitivity of the microwave emission to these modes of water differ fundamentally though the effect of drop sizes on emission confounding microwave signals. Microwave-based estimates of LWP have to account for the presence of rain and drizzle as this is a significant source of uncertainty in estimating LWP and the simplest way to deal with this complication is to screen out cases where precipitation is present. Methods to separate the rain from cloud water are now developing, aided by measurements of drizzle as described in the next section.

4.2 Cloud optical properties

The use of measurements of sunlight reflected by clouds to deduce their optical properties, expressed in term of cloud optical depth (τ) and radius r_e, also has a relatively long history. Sagan and Pollack (1967), for example, introduced the concept in the study of the clouds of Venus. Hansen and Pollack (1970) employed the observations of spectrally reflected sunlight made by Blau et al. (1966) to study terrestrial clouds. Twomey and Seton (1980) introduced a bi-spectral reflectance method to estimate cloud optical depth and effective particle radius (r_e). This bi-spectral approach was later popularized by Nakajima and King (1990) and today it is applied to many other types of satellite and aircraft measurements.

The bi-spectral method is based on measurements of narrow-band reflectances in two spectral regions (or spectral channels), one at visible wavelengths where water is non absorbing and reflection varies principally as a function of τ and a second located within the near infrared region in which solar radiation is both absorbed and scattered being influenced by both τ and r_e. This combination of measurements thus yields information on the pair of optical properties, τ and r_e. We refer to these as optical properties as they are both a consequence of and an expression for the solar radiative transfer characteristics of clouds. Whether the optical property r_e has deeper meaning for cloud physics is a topic returned to below. The choice of the near-IR channel also has an important influence on the droplet sizes retrieved and thus for the LWP obtained according to (1). For example, warm cloud drop sizes obtained globally using the 3.7 μm channel are about 20% smaller than those derived using the 2.1μm channel (Nakajima et al., 2010). These differences arise from the vertical profile of particle size in clouds and in part to intrinsic differences in the absorption properties of water between these two wavelengths where the effective penetration depth of 2.1μm radiation though a homogeneous slab of water is approximately four times that of 3.7μm radiation. These factors result in different effective depths of representation of the measurements. As a consequence, particle sizes from 3.7μm reflectance are nearer cloud top and influenced by entrainment mixing at cloud top whereas the 2.1μm particle size represents a deeper layer average (e.g. Nakajima et al., 2010; Platnick 2000). Differences in the vertical representation provided by different channels have been exploited, for example, to infer vertical profiles of particle size (e.g. Chen et al. 2008). Except for the column radius defined and discussed in reference to Figure 8, all values of r_e referred to in this study are based on the use of reflection measurements at wavelengths characterized by the 2.1 μm radiometer channel.

Figure 5 is the annual mean global distribution of liquid cloud τ and r_e derived from the average of 12 years of MODIS data (MODIS collection 6 level 3 monthly data from 2003 to 2014). A cloud top temperature above freezing criterion was applied to the data to restrict the data to liquid only clouds. Ocean and land differences in τ and r_e are notable and emphasized by the distributions presented in Figure 5c and d. Warm clouds over land are more optically deep (mode values of 13.5 compared to 7.5 over oceans) and possess smaller particles (13.5 μm compared to 17.5 μm). This particle size difference between land and ocean is one factor in producing the optical depth differences shown and further reflects the existence of more prevalent drizzle in clouds over ocean. Warm clouds over land are also typically deeper (Takahashi et al, 2017) than over oceans, which is another factor that contributes to the larger optical depths of warm, land-based clouds.

The degree to which r_e in Figure 5b reflects an actual cloud physical entity has been debated over the years. As Figure 5b shows, the magnitude of the particle sizes, especially over oceans are typically much larger than the expected sizes of cloud droplets. Explanations for this perceived high bias in retrieved drop sizes have in part revolved around not properly accounting for 3D radiative transfer effects in retrievals (e.g. Zhang and Platnick, 2011, Painemal et al., 2013) but this explantion does not fully account for the magnitude of the drop size bias over oceans where large areas of cloud possess r_e that exceed 16 μm (Figure 5b) and the relative lack of bias in retrieved drop sizes over land. As described below, these large drops in oceanic clouds align specifically with the existence of drizzle and rain thereby suggesting that r_e indeed reflects this cloud process. This debate, however, will continue as the existence of drizzle is also often associated with a more cellular cloud structure (e.g Cho et al.,. 2015) which in turn induce these 3D radiative biases associated with drizzle scenes.

4.3 Cloud droplet number concentration (N_c)

Cloud drop number concentration is of elemetary relevance to many cloud processes and the need to provide global measurements of it is widely recognized (e.g. Wood 2012). Although a number of studies report on approaches to estimate N_c (see review of Grosvenor et al., 2017), these are inevitably framed around a simple adiabatic model of cloud properties that require gross assumptions about those factors in (2), like the cloud depth H, that are not readily observed. For example, a simple relation between LWP, and cloud depth H

$$LWP = \frac{1}{2} f_{ad} c_w H^2 \qquad (3)$$

follows from the adiabatic assumptions where c_w depends to first order on temperature and the factor f_{ad} <1 accounts for the degree to which the cloud deviates from an adiabatic water profile due to effects like mixing of dry air into clouds evaporating cloud water and the loss of cloud water by drizzle and rain. With this model of water content, and further assumptions about the relation of r_A to r_e and r_e to the depth of cloud H, among others, it follows that $N_{c\,c}$ can be expressed as a function of both τ and r_e according to,

$$N_c = \frac{\sqrt{5}}{2\pi k} \left(\frac{f_{ad} c_w \tau}{Q_{ext}\, \rho_l r_e{}^5} \right)^{1/2} \qquad (4)$$

where ρ_l is the density of water, and k is a factor that relates the volume droplet radius to r_e and is assumed constant within a cloud. It well recognized that as this simple model ignores effects of drizzle, cases that contain drizzle and rain need to be screened out before applying the methodology (e.g. Bennartz, 2007). The uncertainties of the many factors in (4) and assumptions underlying them are difficult to quantify. Depsite these difficulties, Grosvenor et al. (2017) suggest that the combination of all sources of error provides an overall uncertainty of about 80% and comparison to airctraft measurements (e.g. McCoy et al.,2017) seems to support the credibility of these uncertainties.

It is curious though that the approach to estimate N_c based on (4) completely overlooks the influence of drizzle. Reference to Figure 6 underscores why drizzle and rain are important. This figure, modified from Wood et al (2012), presents the longitudinal profile of MODIS-derived N_c along the 20S latitude stretching from the remote Pacific to the Chilean coast. These MODIS retrieved values of N_c are compared to aircraft observations of N_c collected during the VOCALS field experiment (Bretherton et al., 2010) and estimates derived from a simple drop budget model that uses as input the observed precipitation profile derived from CloudSat observations as shown. The figure also presents concentrations of cloud condensation nuclei (CCN) that varies with longitude. For comparison, model calculations that assume fixed values of CCN with and without precipitation are also presented. These model results illustrate the basic importance of the drizzle as a process controlling N_c, a key conclusion of the study of Wood et al. (2012). The similarity of the longitudinal variation of the MODIS-based N_c esentially determined from (4) to the observations of VOCALS and also to the N_c derived from a budget model driven using precipitation as input is obviously misleading given that the effects of precipitation are not explicit in (4) and it is not known how much exclusion of drizzle effects bias existing retrievals of N_c.

5 Cloud physics from space: II The A-Train era

The A-Train satellite constellation is a successful demonstration of an integrated approach to observe clouds from multiple perspectives (e.g. Stephens et al., 2018).

5.1 Warm rain and drizzle occurrence

The occurrence of drizzle in warm clouds is fundamental to many of the cloud properties that influence Earth's climate system. Before the measurements of CloudSat, the only way we could identify drizzle was to employ very approximate and indirect methods (Masunaga et al. 2002; Liu and Daum, 2004). The highly sensitive radar of CloudSat now offers a definitive measure of the occurrence of all modes of precipitation (Stephens et al. 2018) including the occurrences of rain and drizzle from warm clouds.

Figure 7, taken from Christensen et al (2013), is the zonally averaged occurrences of drizzle and rain in all low warm clouds for the JJA and DJF seasons based on the radar analysis approach defined in Haynes et al., (2009). This occurrence applies to detection within a column and does not correspond specifically to occurrences of rain and drizzle at the surface. Although CloudSat detects the presence of drizzle and rain in the column unambiguously, as represented in this figure, it is not possible to determine how much of this rain reaches the surface with certainty. The CloudSat product used in Figure 7 also includes corrections for sub-cloud evaporation (Lebsock and L'Ecuyer, 2011) to provide the best estimate of rainfall occurrence at the surface. The approach to include these effects has been tested against ship-based observations, (Kalmus and Lebsock, 2017). Because radar reflection by drizzle is large compared to cloud reflection, the drizzle that occurs on finer scales that only partially fill the radar footrpint are also detected. The observations represented in Figure 7 indicate that drizzle exits over a range of spatial scales, from the footprint scale more typical of the cellular cloud structure (e.g. Comstock et al., 2005, van Zanten and Stevens, 2005) to much longer spatial scales characteristic of drizzle in more stratiformn clouds. On average, oceanic warm clouds produce drizzle or rain about 18% of the time with 6.7 % determined to be raining and 11.3 % containing drizzle. The occurrence of these two modes of precipitation however varies significantly with latitude being higher in both lower latitudes and the winter hemisphere while drizzle and precipitation is more suppressed in the summer hemisphere.

5.2 Droplet growth process

The underlying basis of remote sensing is that variables that relate to observable consequences of a given physical process can be acquired by inverting a model of that process. The potential exists, however, for using remote sensing to probe the process itself when different variables related to the same inherent process are extracted from measurements sensitive to different aspects of the process. Suzuki and Stephens (2008) showed that joint relationships between cloud layer-mean radar reflectivity Z and columnar effective particle radius r_e of warm clouds differentiates the process of condensational growth and drop growth by coalesence. In this case, the columnar effective particle radius r_e is obtained using (1) with a combination of microwave derived LWP from the AMSRE instrument on Aqua matched with the cloud optical depth from MODIS. Global statistics developed from seasonally aggregated data presented in Figure 8 reveals that radar reflectivities Z< -10 dBZ tend to relate to the effective radius via a sixth-power dependency and corresponds to particle growth under conditions of constant number concentration implying that the condensation particle growth process mainly takes place within these cloud layers (Figure 8a). For Z > -10 dBZ, Z exhibits an approximate cubic dependence on r which correspond to particle growth conditions under a constant mass concentration thus implying coagulation as the dominant particle growth process for these clouds (Figure 8b). These microphysical regimes are also consistent with CloudSat-inferred rainfall occurrence as highlighted in Figure 8c showing the occurrences of the cloud only free of precipitation. The regions of higher frequency of these clouds near west coasts of continents, for example, align with the much smaller cloud drops that also occur in this region (Figure 5b) and as we now describe consistent with the lack of coalescence occurring there. This analysis offers one way of defining cloud physical regimes and it is argued below that aerosol influences on clouds differs according to these different growth regimes.

5.3 Observing the formation of warm rain

A second illustration of the value of combining multiple A-Train sensor information focuses on warm rain production by the coalescence. Measures of visible cloud optical depth τ, an expression of the vertical integral of the cross section area of scatterers, is a measurement that relates more directly to the smaller droplets being collected in the coalescence process. The local volume scattering measured by a radar at millimeter wavelengths, expressed in terms of radar reflectivity *Z*, is more indicative of the larger collector droplets. Together these two pieces of information provide direct insight on the coalescence process as exemplified by the relation derived from a simple model of the coalescence process (Suzuki et al., 2010)

$$\frac{d \ln Z}{d\tau} \approx \frac{\alpha}{6} E_c \qquad (5)$$

where E_c is the collection efficiency which is an important factor in the process. The value of α is associated with what variable is conserved in the course of the process. As discussed above in relation to Figure 8, α=6 when number concentration is conserved whereas α=3 when mass concentration is conserved. Since the former and latter situations correspond to condensational growth and coalescence processes, respectively (Suzuki and Stephens,2008, and also Figure 8), it may be natural to assume α=3 for the collection process examined here. On the other hand, inherent in the continuous collection model is the assumption that all the collector drops grow at same continuous rate, which implies a constant number concentration of the collector drops, leading to α=6. These arguments imply we can assume that the value of α ranges between 3 and 6. It is relevant to note in the following illustrations that a zero gradient in $lnZ\text{-}\tau$ implies no droplet collection and thus no warm rain formation. Figure 9 is a graphical portrayal of (5) presented from both an observational and global model perspective. The observations are from the A-Train and these are compared to the simulations from one global model (the UKMO HadGEM2) (Suzuki et al., 2015) to which to the Cloud Feedback Model Intercomparison Project Observation Simulation Package (COSP) version 2.0 (Swales et al., 2018) is coupled. Both the observations and model data are grouped by the 2.1μm r_e for reference. It is striking how the model example presented in the same way as the observations reveals a propensity to drizzle even for clouds mostly formed by small droplets whereas drizzle is only observed to develop when droplet r_e exceeds 10μm. This observation lends furhter creedence to the argument that the larger retrieved drop sizes presented in Figure 5b for example is indicative of the existence of drizzle drops in clouds. The cause and consequence of the too frequent light rain bias that exists within global models (Stephens et al., 2010) is an active area of research and one consequences of it is examined in the next section.

5.4 Cloud liquid water path

The joint combination of microwave, MODIS and cloud radar made possible by the A-Train provides a more meaningful basis of comparison between sunlight-based LWP methods framed around (1) and microwave methods based on emission processes. Matching the microwave observations to the CloudSat rain and drizzle information also provides a way of assessing the effects of rain on estimating LWP. Hilburn (personal communication) used A-Train observations to separate the microwave observations of raining clouds from non-raining clouds testing a simple microwave rain detection method that could be applied to non A-Train data. Their analysis is highlighted in Figures 10a and b where the MODIS-MAC LWP differences between rain and non-rain are presented as a function of matched CloudSat rain rate. Without accounting for rain, the differences can be substantial exceeding -40 gm^{-2} especially for heavier rain rates above 1mm/hr. Although the simple microwave rain screening method they developed fails to remove all rain contaminated pixels in the estimate of LWP, especially for the lighter rains detected by CloudSat, the screening developed substantially improves the retrieval of LWP and brings the two types of LWP data (those from solar reflection measurements of MODIS and those from the microwave measurements of AMSRE) into closer agreement.

The availability of a global, multi-decadal record of cloud LWP together with a better understanding of the limitations of the approaches used to derive it provides the means to assess the ability of global models to reproduce this observed property of warm clouds.

Such an assessment is given in Figure 11. This assessment is of the historical simulations of thirteen models that contributed to CMIP5 (Taylor et al., 2012) and uses the multi-year MAC-LWP data screened for precipitation as described above (Figure 11) and also the observed MODIS low cloud amount for producing the cloud weighted LWP. Data from both the model and observations were limited to regions of downward motion at 500 hPa and averaged over the region defined by the latitudes and longitudes of 40N/S and 120W-60E. Restricting the analysis to regions of subsiding air in this way largely confines the analysis to regions of low stratiform clouds over the eastern Pacific. The observed LWP data were divided by the observed cloud amount and the modeled LWP data were similarly divided by the modeled cloud amount below 500 hPa as a way of representing the in-cloud values of LWP in both. The results of this LWP analysis reveal substantial positive multi-model bias of 53%. This is one of the factors of the 'two few - too bright' model bias noted in previous studies (e.g. Nam et al., 2012).

Table 1 summarizes the oceanic mean values of low cloud properties derived from A-Train observations (adapted from Christensen et al., 2013). For this summary, A-Train data are grouped into four categories: all low clouds (all), clouds that contain neither drizzle nor rain (cloud only and also highlighted in Figure 7c), clouds that contain drizzle but no rain (drizzle), and clouds that contain rain (rain). The LWP data provided are those derived from MODIS observations applied to (1) where r_e is based on 2.1um channel reflection measurements . The difference between the all category and cloud-only category thus provides some indication of the effect of drizzle and rain on the global mean statistics of low cloud properties. In addition to these LWP values, the MAC values of LWP (ocean only) based on the microwave observations and corrected for rain is also given. The ocean-mean MAC-corrected LWP (82 gm^{-2}) is similar to the ocean mean MODIS LWP (85.3 gm^{-2}) underscoring the earlier point that these two different estimates of LWP agree when data are properly conditioned. The mean LWP of all low clouds, slightly larger than the low cloud LWP data reported in Lin and Rossow [1996], is approximately 30% higher than the respective cloud-only values. The mean r_e of all clouds is also about 10% larger than the respective cloud-only values, and drizzling and raining clouds are deeper than non raining clouds by up to a kilometer in the mean. Although the r_e of drizzling and raining clouds is almost 50% larger than the particle sizes of the clouds-only category (20 and 22 μm compared to 15 μm), these larger particle sizes do not offset the effects of the increased water path on optical depth [e.g., Stephens et al. , 2008] such that the oceanic mean optical depth of drizzling or raining low clouds is increased by approximately 25% over the cloud-only values. This suggests that the presence of drizzle and rain coincides with larger mean LWP, mean particle size, optical depth, and albedo of all low clouds. The extent that rain water enhances the optical properties of low clouds has not been systematically studied although Lebsock et al (2011b) suggests the contribution of rain water to warm cloud optical depth is less than

5%. By contrast, the contribution of snow water to ice cloud radiative properties is significant (Li et al., 2017).

6 The Aerosol-Cloud Interaction Problem (ACI)

The cloud properties introduced above are also central to our understanding of the problem aerosol-cloud-interactions (ACI) and the radiative forcings associated with them. ACI-related radiative forcings, the most uncertain of all known forcings acting on the global climate system over the past century (Myre et al., 2013) , are commonly thought of as a consequence of reduced cloud droplet radii in low warm clouds in the presence of increased aerosol concentrations. On the one hand, this aerosol 'indirect effect' opposes the forcing due to increased concentrations of greenhouse gases providing a cooling mechanism for the planet by enhancing the albedo of low clouds (Twomey, 1977) while on the other hand future removal of aerosol from the atmosphere can expose the Earth system to greater levels of warming. As we show, simply changing assumptions about warm cloud physical processes dramatically impact this negative forcing and result in global model simulations that either mimic the observed 20th century warming of Earth or not (e.g. Golaz et al., 2013).

6.1 A space-based ACI perspective

That droplet radius decreases in the presence of elevated amounts of aerosol is a robust finding, supported by our advanced understanding of cloud physics (Wood et al., 2009), ground-based and airborne observations, detailed numerical modeling of clouds (Feingold et al., 2016) and many years of satellite observations of differing types (Chen et al., 2012; Durkee et al., 2000; Christensen and Stephens, 2012; Nakajima et al., 2001; Breon et al., 2002; Quaas et al., 2009). Figure 12a presents a correlation between changes to satellite-derived r_e and changes in aerosol optical depth (AOD) also derived from satellite observations. These satellite observations of reduced r_e under elevated level of AOD have subsequently been applied to estimate the ACI radiative forcing (Chen et al., 2014; Quaas et al., 2008) . The use of such data as an explicit constraint on model-derived forcings is widely rejected because of (i) an inability to assign cause and effect uniquely to the observational results like in Figure 12a due to co-variability of meteorology that also influences cloud changes, (ii) doubts about the use of column integrated aerosol information like the AOD as a proxy for condensation nuclei entering clouds (Nakajima et al., 2001), (iii) inappropriateness of present-day observed geographical differences of aerosol as indicative of aerosol differences between preindustrial and present day (Penner et al., 2011; Gryspeert et al., 2017; Hamilton et al., 2014) and (iv) insensitiveness of current satellite measurements to tenuous aerosols, to which model clouds are the most susceptible, so that the correlation statistics offer only weak constraint on model cloud susceptibility (Ma et al., 2018). Direct observational constraints of the radiative forcing, while sorely needed, are fundamentally not possible. It is suggested here that a more process-oriented viewpoint that uses of observations that include variability and correlations between variables and that exploit emerging advances in aerosol analysis is a more fruitful approach toward ultimately constraining model processes that govern estimates of these highly uncertain radiative forcings of Earth's climate.

Many processes provide the natural system with several degrees of freedom capable of mitigating the effects of aerosol perturbations on clouds making the ACI complex. Stevens and Feingold (2009) refer to such mitigating effects as buffering. Macroscopic processes can alter the amount of liquid water in clouds and thus the albedo of cloud which is also controlled by their LWP. Figure 12b is the correlation of LWP with AOD changes over global oceans. This correlation suggests a complicated pattern of environment influences on observed LWP changes. For example, the LWP decreases generally in the marine stratus regions off the west coasts of major continental regions where air above clouds is excessively dry and where condensational growth is domonant (Figure 8c). A number of studies hypothesize that reduced r_e together with dry air above are ingredients for enhanced evaporation and reductions in cloud LWP in these regions (e.g. Ackermann et al., 2004). As we will show below, simply inferring a forcing from a cloud droplet size change is misleading producing exaggerated estimates of the forcing.

6.2 A cloud process viewpoint

Figure 13 is an example of how global satellite data, cloud-scale process data from ship tracks, aircraft data from field experiments and model-calculated cloud responses to aerosol might be combined to explore and then test the physical processes underlying cloud-aerosol indirect effects. Figures 13a and b group the satellite observations of Figure 12 into two-dimensional histograms of the cloud albedo sensitivity with AOD correlated with the r_e-AOD sensitivity (Figure 13a) and LWP-AOD sensitivity (Figure 13b) respectively. Conditions of enhanced aerosol indeed reduce the r_e in most all regions (Figure 13a) but this is not always associated with increased cloud albedo with albedo decreases occurring in approximately 28% of oceanic low clouds. By contrast, changes to the LWP more directly correlate to the change in cloud albedo (Figure 13b) and thus can be viewed as the more defining parameter of the cloud albedo.

Figures 13a and b also contains observations of ship tracks that are superimosed on the satellite data. These ship track observations have been assembled into a global data base (Christensen and Stephens, 2011) and analyzed in the same way as the satellite data. The senstivities derived from ship track observations credence to the interpretation that the correlations derived from the global satellite data suggest cause and effect responses. About 30% of all ship track data analyzed showed reductions in albedo (Chen et al., 2012) similar to the 28% of satellite data that negatively correlate cloud albedo to aerosol . In both cases, these sensitivities are associated with reductions in cloud LWP. When oceanic data are averaged globally, the integrated effect of cloud LWP is small with large negative regional responses being offset by similarly opposing large positive regional responses. The Holuhraun volcano (Iceland) data analyzed by Malavelle et al.(2017) behave similarly with a small net LWP response averaged over the region influenced by the volcano which similarly results as a compensation of large regional positive and negative changes in LWP. These data together suggest the buffering expressed by Stevens and Feingold (2009) whereby enhanced injections of aerosol results in dynamical and microphysical responses that collectively change the water balance of clouds that in turn govern cloud albedo changes.

The model data are presented in Figures 13b–g are taken from two sources of simulations. One source of four models is the Coupled Model Intercomparison Project phase 5 (CMIP5) aerosol forcing experiments (sstClim and sstClimSulfate, Taylor et al., 2012) which were specifically designed to diagnose aerosol-radiation interactions and aerosol-cloud interactions. These experiments are 30 year fixed sea surface temperature (SST) and sea-ice experiments, using prescribed repeating annual cycles of climatological SSTs and sea-ice as derived from each GCMs coupled atmosphere-ocean pre-industrial control run. The control uses pre-industrial natural and anthropogenic forcing levels, while the perturbation run is identical except for year 2000 emissions of anthropogenic sulfate aerosol. Although the need for cloud droplet effective radius limits analysis to just 4 models (CSIRO-Mk3-6-0, HadGEM2-A, MIROC5 and MRI-CGCM3), these four models largely span the range of aerosol-cloud-interaction diversity (~ -1.0 to -

0.2 Wm^{-2}) reported for a the wider set of CMIP5 models (Zelinka et al., 2014). The cloud liquid water path was calculated as the difference between the condensed (clwvi) and ice (clivi) water path diagnostics, normalised by the total cloud fraction (clt) and the cloud top effective droplet radius was deduced from (1) from the LWP and optical depth diagnostic.

The second set of model experiments summarized in Fig. 13c -g are from the AeroCom aerosol indirect effect experiment (for details see https://wiki.met.no/aerocom/indirect). Data from the ECHAM6-HAM, NCAR_CAM5.3_CLUBB_MG2, and SPRINTARS.IND3 models used are the same selected models reported in Ghan et al.(2016). As an additional step to improve collocation with the satellite data we interpolate the output using the model time steps according to the A-Train equator-ward crossing time of 1:30 pm local time.

The contrast between the observations and models revealed in Figures 13c-g suggests there is a large bias associated with the model representation of low cloud processes. The models all produce a reduced cloud droplet radius although twice that observed (as exemplified by comaprison of model points to background satellite data in Figure 13c and more clearly evident in the comparison presented in Figure 13f). The multi-model average LWP response is 3 times the observed response (Figure 13g). Only 6% of the model regions experience reductions in LWP (not shown) in contrast to the approximate 30% in the observations. As a result, global models produce an effect where processes largely reinforce resulting in a larger aerosol indirect effect (exemplified by an enhanced cloud albedo change, Figure 13e) than might be expected of the real world. This reduced LWP response to aerosol, however, is more realistically captured in cloud resolving model simulations (Satoh et al., 2018).

The results of Figure 13 underscore the importance of these processes that define the water budget of low clouds because of the principle influence of cloud water path on cloud albedo. Jing and Suzuki (2018) and Jing et al (2019) explore the specific effects of the drizzle process as a prime factor in determing cloud LWP and thus its influence in estimating preindustrial to present-day aerosol indirect radiative forcing. They incorporate five different autoconversion schemes into a single GCM to evaluate the warm rain formation processes by a systematic comparison to satellite observations. The GCM used in both studies is the Model for Interdisciplinary Research On Climate version (MIROC5.2) (Watanabe et al. 2010). Full aerosol-cloud interactions are represented through a coupling to the GCM of the Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS) (Takemura et al. 2000; 2002). The wet scavenging rates of the various aerosol species are parameterized in SPRINTARS as functions of precipitation fluxes and aerosol microphysical properties such as number concentration and radius (Takemura et al., 2000), making the wet scavenging efficiencies highly amenable to precipitation changes. The five auto-conversion schemes incorporated into the MIROC5.2 are those of Berry (B68, 1968), Tripoli and Cotton (T-C, 1980), Liu and Daum (L-D, 2004), Khairoutdinov and Kogan (K-K, 2000) and Beheng (Be94,1994). COSP was implemented in MIROC5.2 to facilitate comparison with the satellite observations

The results of the Jing et al (2019) study are synthesized in Figure 14 and presented in the form of a comparison between model simulated observations and observations of the A-Train. These comparisons are in the same format as discussed above in relation to Figure 9 in which cloud optical depths and radar reflectivities are matched to provide insight into the warm rain process and a perspective on how this process varies with cloud top droplet radius. Their study found that the drizzle bias problem can be mitigated via altering the autoconversion process so as to inhibit rain formation under conditions of a large cloud number concentration and small droplet sizes. Three of the five schemes (L-D, K-K and Be94) inhibit warm rain formation in the manner that more closely resembles both the observations shown Figure 14. Wood (2005) also showed that L-D and KK schemes compare well with *in-situ* measurements. When the L-D, K-K and Be94 schemes are used, little rain is associated with those clouds composed of smaller drop radii (5-10 μm) at cloud top. In these three cases, as in the observations, the occurrence of precipitation systematically increases as the cloud drop radii increase as indicated by the tendency for reflectivity to increase with increasing optical depth as droplet radii increase. The remaining two schemes (T-C and B68) produce precipitation too readily, a common feature of global models referred to as dreary by Stephens et al (20100, regardless of cloud drop radius, reflecting a drizzle bias in these two model configurations which is also typical of GCM models more generally (Suzuki et al., 2015).

The effect of this rain process on the ACI radiative forcing is also assessed. The forcing is calculated as the difference in the reflected solar radiative fluxes between experiments performed with pre-industrial and present-day aerosol emissions. The results shown in Figure 14 demonstrate how the choice of auto-conversion scheme in the MIROC model has a substantial influence on the radiative forcing varying in range between the 5 models by approximately a factor of six. As Golaz et al (2013) and Suzuki et al. (2013) had also previously shown with a different model, schemes that produce the least physical production of warm rain with copious drizzle (e.g. Be68, T-C) produce a forcing that is small and similar to the AR5 estimate (Myhre et al., 2013) (gray solid fill). Conversely the three schemes that produce precipitation less frequently and more consistent with observations induce a negative forcing that is large enough to cancel much of the observed warming trend in the past century. This enhanced radiative forcing occurs as a consequence of the relation between changing cloud droplet size and drizzle and in turn changes to the cloud water path. This relation between aerosol and existence of drizzle is weak in the version of the model with Be68 or T-C schemes because these schemes produce drizzle regardless of changes to cloud drop sizes making drizzle production in these models is insensitive to drop size. The schemes that provide a drizzle sensivity to drop size also produce a sensitivty of LWP to drop size and in turn a larger ACI forcing. This pronounced cloud-water response to aerosol perturbations is further amplified through the wet scavenging feedback that also depends on precipitation-formation parameterization (Jing and Suzuki, 2018).

The results of Figures 13 and 14 serve to underscore the importance of those processes that control the water balance of low clouds as also controlling ACI related radiative forcings. On the one hand, the results of Figure 13 suggest aerosol cloud interaction in models produce exaggerated cloud LWP responses that exaggerate the radiative forcing (Figures 13c-d). We hypothesize that process like cloud top entrainment and evaporation that induce a negative or reduced cloud water feedbacks are more likely in clouds in which the condensational growth is predominant (e.g. Figure 8c). On the other hand, the model sensitvity results of Figure 14 illustrate the importance of the warm rain process suggesting that models that produce drizzle too frequently lack a process by which aerosol can positively influence the water balance of clouds resulting in an underestimate the cloud-aerosol related forcing. This latter influence is most likely to occur in those regions where clouds are identified as being under the influence of coalescence. The net global ACI radiative forcing is thus a combination of both reponses that appear to compnesate globally but not regionally.

7. Summary

This paper offers a brief discussion the progression of cloud physics from a subdiscipline of meteorology into a global science today. The discussion briefly touches on the important post-war contributions of three key individuals who were instrumental in developing cloud physics into a global science. These contributions came on the heels of the post-war weather modification efforts that influenced much of the early development of cloud physics. The connection between this early contribution to cloud physics and the current vexing problem of aerosol effects on cloud albedo is discussed.

Discussion focuses on low, warm clouds and underscores the advances made in both observing low cloud physical properties from space and in understanding global-in-scope processes such as condensaational growth and warm rain formation among other processes that shape cloud aerosol interactions. These advances include:

(i) The retrieval of optical properties of low clouds in the form of a pair of properties of cloud optical depth and cloud drop effective radius (τ, r_e). The interpretation of r_e more as a cloud physical property than a cloud optical property has been made possible with the advent of the A-Train observations.

The magnitude of r_e derived from MODIS observations is everywhere much larger than cloud mode droplet sizes over oceans (Figure 5b) except near coastal areas and is indicative of the ubiquitous existence of large drizzle drops in low marine clouds.

(ii) An alternative interpretation of the (τ,r_e) pair of optical properties in the form of the pair (τ,N_c) is described where N_c is the column mean droplet number concentration. This latter property, however, requires a number of significant but difficult to quantify assumptions about the vertical structure of clouds including assumptions of the cloud being drizzle free. The latter is problematic given the existence of drizzle is a first order influence on N_c (Wood et al., 2012) and that drizzle sized drops are a ubiquitous feature of marine clouds (Figure 5b). Although screening for drizzle is well recognized Bennartz, 2007), a more comprehensive approach for estimating N_c in the presence of drizzle is needed.

(iii) Global climatologies of cloud LWP, based on multi-decadal microwave observations, now exist. This LWP climatology requires that precipitation be screened from the product because the emission signal from precipitation introduces a bias when interpreted as LWP. This climatology is now an important source of information to assess global models and a preliminary assessment is given.

(iv) The combination of the cloud optical properties (τ,r_e) and radar reflectivity provides a way of diagnosing the warm rain process in clouds. This analysis, discussed in relation to Figure 8, now offers a process centric way of determining the sources of model drizzle bias (e.g. Suzuki et al., 2015) as well as a way to constrain model derived aerosol indirect forcings (Figure 14).

Comparison between the observed LWP of low clouds and analogous low cloud properties taken from global climate models reveal a significant level of model bias (~53% for the multi-model mean) and is indicative of a too-wet (and bright) bias of model low clouds, a bias that has existed in models for some time. When combined with the drizzle occurrence bias exemplified in Figure 9 and further in Figure 14 for one model but also called out in previous studies (e.g. Stephens, 2010; Suzuki et al., 2015) for other models, these together suggest shortcomings in the way low cloud processes are resprestented in global models today.

The particular challenges around representing low clouds in global models discussed in this paper also project onto the specific problem of understanding the influence of aerosol on cloud properties. An important but as yet unmet challenge in doing so is the need to develop an observational strategy to constrain model derived ACI radiative forcings. One approach to constrain this forcing with observations is described. This approach uses obervations to test specific processes that govern the water balance of clouds. The result of Figures 13 and 14 serve to illustrate the importnce of these processes for determining the aerosol-indirect radiative forcing.

We can expect to see further advances in the measurement of cloud physics from space in the coming decade. The EarthCARE mission of ESA (Illingworth, 2015) offers the potential to add cloud vertical motion to the suite of cloud properties described in this paper. The recent US National Academy survey study that defines the Earth observations plan for the next decade (NAS, 2018) also recommends NASA emphasize cloud dynamics in future mission designs. Remarkable advances in miniaturization of sensors has also occurred making it now possible to consider more distributed lower cost observing strategies that can be applied to address cloud physical processes from spaceborne measurements. Figure 15 is one highlight of such progress showing about 130 kms of radar profiles through a large stratiform rain system observed on 25th of January, 2019 near Prince Edward Island observed by a miniature rain radar flown on a 10X60 cm in size (6U) cubesat with a deployable 0.5m antenna. This small, low cost observatory is referred to as RainCube with a radar that operates at a frequency of 35 GHZ (in the Ka -band). The remarkable performance of the RainCube Ka-band radar is underscored by the comparison to the observations of the same raining scene observed within 9 miniutes of RainCube by the Global Precipitation Mission (GPM) dual frequency precipitation radar

(DPR). This is one of a number of examples of developments in minaturization of Earth sensors that are presently occurring that are beginning to open the way for entirely new approaches for observing Earth's cloud systems (e.g. Stephens et al., 2019).

8.References

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Cloud Physics from Space[1]

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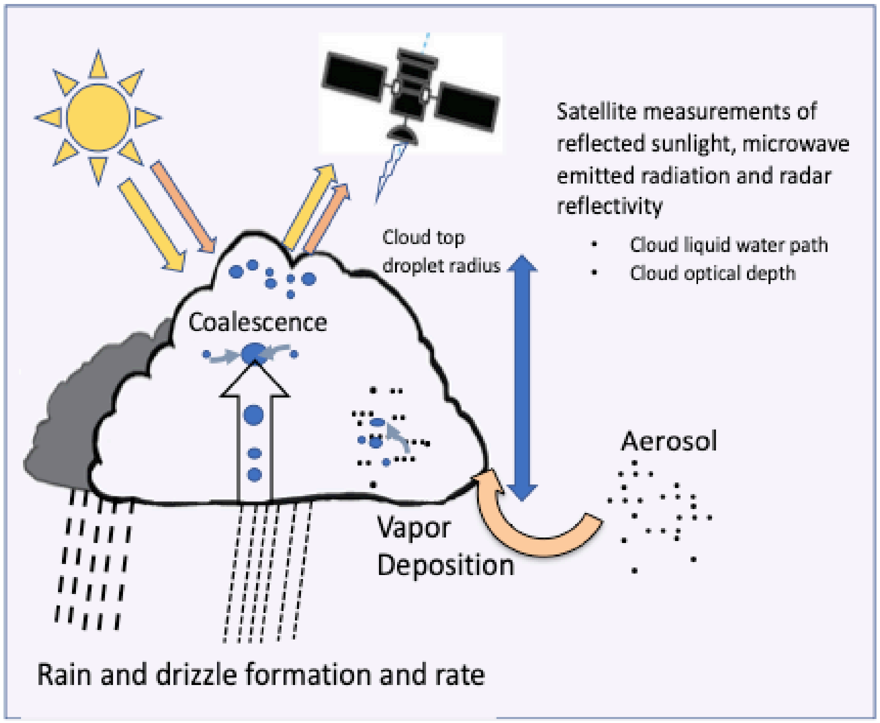
Key findings

This paper reviews the progression of cloud physics from a subdiscipline of meteorology into the global science it is today. The paper also briefly describes the important post-war contributions of three key individuals who were instrumental in developing cloud physics into a global science. These contributions came on the heels of the post-war weather modification efforts that influenced much of the early development of cloud physics. A review of advances made in observing warm clouds and processes that define them from the vantage point of space is provided. Earth observations interpreted in the form of cloud properties are now mature and offer multi-decadal time series of cloud properties that are also described. Approaches that combine different types of observations to reveal droplet process growth are highlighted. The parallels between weather modification and the current challenge in understanding and modelling aerosol cloud interactions are also highlighted.

Graphic illustrating scope of study

[1] The 2018 Mason Gold medal lecture



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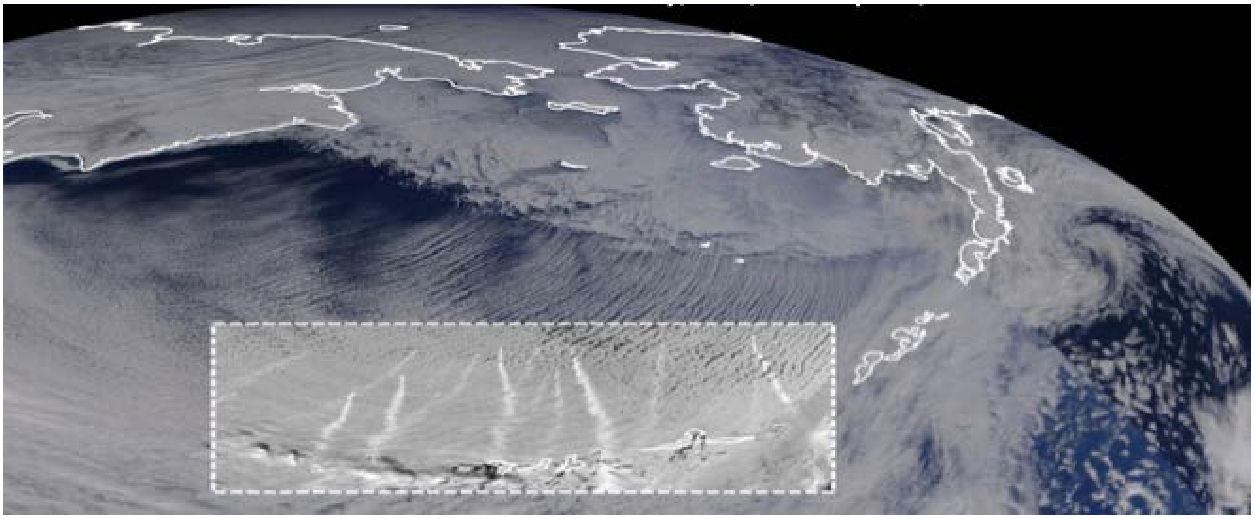

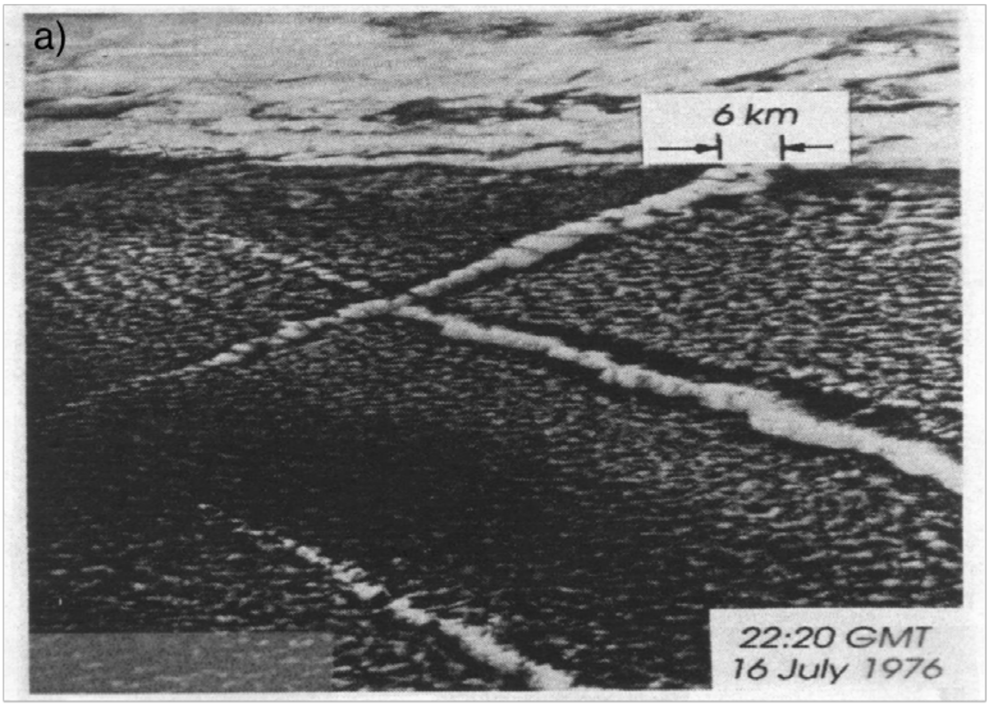

These are different views of ship tracks – a phenomena that expresses the effects of aerosol on l clouds, a topic explored in the paper. The lower image, more grainy, is a more historical view of ship tracks from Apollo-Soyuz on 16 July 1975 at 2221 GMT obtained from Porch et al. (1990). This image emphasizes that more is going on than simply brightening the cloud locally with regions of suppressed albedo and mesoscale process at play. Adding aerosol to clouds does not always result in an icnrease in the albedo of cloud fields.