PHYSICAL METEOROLOGY

Vaughan Phillips
Department of Meteorology, University of Hawaii at Manoa, Honolulu, USA

Keywords: Deep convection, aerosol, cloud-particle, graupel, charge separation

Contents

1. Introduction
2. Clouds and Aerosols in the Tropics
2.1. Aerosols and their Sources
2.2. Aerosol Growth and Atmospheric Processing
2.3. Initiation of Cloud Particles
2.3.1. Heterogeneous Nucleation of Droplets by Soluble Aerosol
2.3.2. Heterogeneous Nucleation of Ice by Insoluble Aerosol
2.3.3. Homogeneous Freezing
2.3.4. Secondary Ice Nucleation
2.4. Initiation of Precipitation
2.4.1. Warm Rain Process
2.4.2. Ice-Crystal Process
2.5. Deep Convection and Associated Layer-Cloud
2.5.1. Cloud Dynamics
2.5.2. Microphysics
2.5.3. Tropical Cloud Systems
2.5.4. Electrification and Lightning
3. Atmospheric Radiation in the Tropics
3.1. Electromagnetic Radiation
3.2. Role of the Tropics in the Climate System
3.2.1. Climate Forcings
3.2.2. Climate Feedbacks
3.2.3. Climate Responses
3.3. Aerosol Indirect Effects on Tropical Climate
3.3.1. Impacts on Cloud Albedo and Emissivity
3.3.2. Cloud Lifetime Effects
4. Conclusions
Glossary
Bibliography
Biographical Sketch

Summary

A salient aspect of the tropics is the prevalence of deep convection. It spans much of the depth of the troposphere, due to the positive buoyancy of cloudy updrafts warmed by latent heating from condensation. Cells of deep convection transfer heat, moisture and momentum to upper levels. They are crucial for the large-scale atmospheric circulation. Most precipitation from tropical systems is from deep convection. The most vigorous deep convection is lit up by lightning, especially over land.

Deep convection, certain sources of aerosol and of greenhouse gases, certain aspects of climate feedbacks, and some mesoscale cloud systems (e.g. hurricanes) are more common in the tropics than elsewhere. The tropics have a unique role in atmospheric radiative transfers, with their excess energy from radiation driving large-scale flows. However, the nature of many of the small-scale processes in the area of physical meteorology differs little qualitatively between the tropics and extra-tropics, although their frequency of occurrence may be different. For example, aerosols activate by the same set of mechanisms in the tropics as elsewhere.

In the rest of this chapter, aspects of the science of aerosols, clouds and radiation are outlined, with a mention of any phenomena particularly common or different in the tropics. Some highlights from the latest research in the broad field are mentioned.

1. Introduction

The tropics are where the majority of the solar energy entering the earth's system is absorbed by the surface. Latent heat release is the primary energy source of synoptic-scale tropical disturbances, due to the weakness of the Coriolis force and to the associated horizontal homogeneity of temperature fields there. Much of this latent heat release occurs in systems of deep convection. Convective cells are convective-scale circulations (< 20 km) embedded in large-scale circulations. There is a two-way interaction between the deep convection and the large-scale circulations. In fact, much of the ascent of large-scale circulations occurs inside the updrafts of deep convective clouds in the tropics. So, the tropical clouds must be represented in models of numerical weather prediction for adequate forecasts to be made in the tropics.

Yet large-scale or global models have inaccuracies in predicting tropical precipitation, the El Nino Southern Oscillation and the Madden-Julian Oscillation (MJO). Such biases may be attributed mostly to the treatment of small-scale processes, such as tropical convective clouds. In such models, small-scale processes can only be represented approximately in terms of their interaction with the large-scale flow (e.g. by latent heat release in clouds). This linkage is not completely understood. For instance, an open question is how cloud cover and properties respond to climate change, altering the reflection of sunlight to space and modifying the surface warming. Clouds are inherently difficult to model, especially the convective ones.

In the tropics, convective clouds are common and can be very deep. They are a response of the troposphere to intense heating and moistening, preferentially at lower levels, by the warm surface. They are often electrified, especially over land, as convective ascent can be very rapid. Their microphysics is coupled to their dynamics, partly though latent heat release and *via* the ascent-dependent supersaturation, which governs processes of nucleation and diffusional growth. Microphysics consists of a web of interactions between different types of ice and liquid (e.g. cloud-droplets, pristine crystals, aggregates or “snowflakes”, graupel, raindrops, hail).

In nature, aerosols, clouds, turbulence and radiation are tightly coupled. Cloud-related processes occur on widely varying spatial scales and are inter-dependent. Droplet activation by aerosols occurs on the submicron-scale; prolonged condensation leading to rain formation occurs on the kilometer-scale; mesoscale cloud systems that alter the atmosphere's radiation budget occur on the scale of many 10s or 100s of kilometers. Clouds may be viewed as large sets of aerosol particles made visible by their mass activation in saturated conditions, and so cloud properties tend to be related to environmental aerosol loadings. This multi-scale nature and inter-relatedness of diverse physical processes is one reason why clouds are so difficult to treat in large-scale forecasting models.

Models simulate the large-scale flow by predicting momentum, heat and moisture at discrete points on a 3D grid throughout the atmosphere. The problem is how to forecast meso- or synoptic-scale tropical disturbances adequately, if small-scale processes are crucial, as noted above, and if they exist on scales too small (e.g. < 10 km, down to less than 1 micron) to resolve on such a grid. The modern strategy for development of climate models is to understand small-scale processes first with separate "process-level" models and then to create simplified or statistical representations of these processes (e.g. "parameterizations") for the large-scale or global models.

This focus on small-scale processes illuminates the interactions between components of climate, which were previously studied in isolation. Aerosol science and cloud physics were once studied as if they were almost disparate disciplines. For instance, the composition of natural ice nuclei in the atmosphere used to be a mystery, as only their final, combined effects on ice concentration could be measured. But now, with better observational instruments, it is appreciated that ice nuclei (IN) are particular species of insoluble aerosols in certain size ranges, so the linkage between ice-clouds and aerosols is being seen moreclearly. Similarly, in-cloud turbulence and cloud microphysics are now seen as inextricable. It is now appreciated that the time for rain to form in warm clouds is shortened by in-cloud turbulence.

Fields such as cloud physics, turbulence, radiation, aerosol science and now even electrification are starting to merge, as the understanding of their inter-dependence in nature grows. Improved parameterizations of small-scale processes are emerging, for example with new schemes for cloud microphysics. With this trend and with higher resolution afforded by faster computers, the quality of forecasts of tropical severe weather, which has major socio-economic and humanitarian impacts, will likely improve in future.

2. Clouds and Aerosols in the Tropics

Clouds are central to physical meteorology. They consist of many cloud-particles so small (< 0.1 mm) that they fall very slowly (see Figure 1) and are effectively suspended in the air. Yet cloud-particles are large enough to be visible and store much mass of condensate. Their mass is derived from diffusion of vapor onto cloud-particles. The growth of cloud-particles (< 0.1 mm) to become precipitation-sized (> 0.1 mm) is required if a cloud is produce any precipitation that falls to the surface. Clouds determine the distribution of precipitation, which consists of particles large enough (e.g. > 0.1 mm) to fall to the surface without totally evaporating away, and govern the radiative fluxes that drive the climate system.

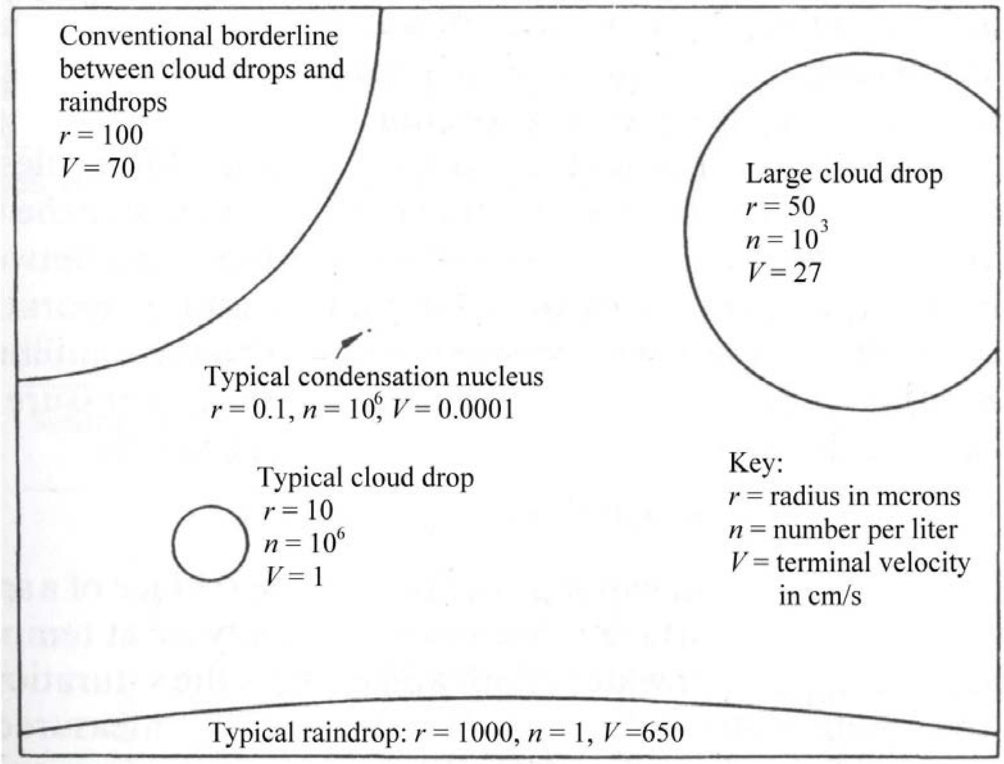

Figure 1. Relative sizes, and fall-speeds of CCN aerosols, cloud-droplets and raindrops (reproduced from McDonald (1958); see Rogers and Yau (1991, Figure 6.1 therein)). Note that the fallspeed of a drop increases monotonically with its size.

Warm clouds are produced by condensation, which can only occur at vapor pressures near or above water saturation. Atmospheric air 'parcels' have a variety of possible routes for attaining saturation. However, a common route involves the chilling of air by expansion during ascent to levels of lower ambient pressure, until it becomes saturated. Precipitation production requires prolonged chilling and condensation after saturation has been reached, which only sustained ascent usually provides. Consequently, characteristics of clouds, such as their extent, precipitation production and lifetime, are all closely related to the nature of the ascent.

Such ascent is produced by dynamical instabilities in the atmosphere. In the tropics, buoyancy forces cause these instabilities, because the Coriolis force is very weak. If warm moist air is located beneath relatively cold air, such that the atmosphere is unstable, then buoyant convection acts to stabilize the atmosphere by vertically re-distributing heat and moisture. Warmer (less dense) and colder (more dense) air is transferred to upper and lower levels respectively, while latent heat is released by condensation of the moisture. A convective cloud is generated. Conditional instability is an example of this type of instability.

There are many different types of clouds. The characteristics of clouds are defined by environmental conditions, such as temperature, instability and shear. Clouds may be grouped into three broad types: *convective* (or ‘*cumulus*’ or ‘*cumuliform’*), *stratiform* and *cirriform*. Convective clouds are vertically developed with a depth comparable to their width and are driven by buoyancy forces due to an unstable environment (warm moist air below cold dry air). The deepest type of convective cloud is cumulonimbus, which is so deep that its outflow near cloud-top forms a trail of cirriform cloud consisting of ice, the outflow being called an anvil. Stratiform clouds occur in buoyantly stable environments, often where there is large-scale ascent (e.g. near fronts), and are much wider than they are deep. They resemble a grey cloud-layer, taking up the entire sky. Nimbostratus is the deepest type of stratiform cloud, producing significant precipitation. Stratocumulus cloud is common in the boundary layer (e.g. in sub-tropical subsidence regions over the oceans) and consists of shallow convection that detrains condensate, creating a stratus layer and being a hybrid of two of the above types. Often such shallow convection is organized in cells that have cloud-free regions (e.g. pockets of open cells), and more marked drizzling. Cirriform clouds (e.g. cirrus) are similarly wide except that they occur at temperatures colder than about -30 ^{o}C, and usually consist only of ice. For each of these three types, there are shallow and deep clouds, with the latter producing substantial precipitation.

Most types of cloud occur from time to time at most latitudes. Nevertheless, in the tropics, the high degree of instability causes deep convective clouds to be relatively common. Cumulonimbus clouds can span almost the depth of the troposphere, which is deeper at lower latitudes. Deep convective clouds are glaciated at upper levels, if they extend well above the freezing level (about 5 km altitude in the tropics). In the sub-tropical regions of large-scale subsidence, low cloud confined in the marine boundary layer covers a large area. It often consists of shallow convection and layer-cloud (e.g. stratocumulus).

Liquid water has a meta-stable state at temperatures between 0 and almost −40 ^{o}C. Droplets may remain supercooled while in this state. At temperatures colder than about −40 ^{o}C, all supercooled cloud-droplets must freeze spontaneously. This is called homogeneous freezing. Clouds at levels colder than about -40 ^{o}C consist only of ice. This is why cirrus from the anvils of cumulonimbus clouds has a fibrous appearance and usually consists only of ice. Anvils consist of the outflow of ice from the updraft of the cumulonimbus, and this anvil outflow forms cirriform cloud.

Aerosols are particles of solid and liquid material suspended in the air of the atmosphere. Aerosols are always sufficiently abundant to allow clouds to form, acting as sites for condensation or vapor deposition. Vertical motions and large-scale supply of heat and moisture determine whether there is saturation for clouds to form. However, the aerosol content of the local environment can influence rain production, glaciation and other properties of a cloud. In nature, there is a myriad of physical mechanisms for conversion of aerosols to cloud-particles (`heterogeneous nucleation' of cloud-droplets or crystals). Soluble aerosol material (`cloud condensation nuclei' or CCN) can activate to become cloud droplets. Droplets and crystals making up clouds are usually referred to as hydrometeors (> about 1 micron), rather than as aerosols. At levels in the mixed phase region (0 to almost −40 ◦C), the nucleation of ice in supercooled water (or in a supersaturated environment) is promoted by the presence of foreign surfaces. This is called heterogeneous ice nucleation and is caused by IN, which are insoluble aerosols > 0.1 mm that nucleate crystals at high enough supercooling and humidity.

In a sense, the distinction often made between aerosols and cloud-particles is quite artificial. Aerosols *become* cloud-particles, by growing to be visible, the process of activation. Cloud-particles (except for secondary crystals) may be viewed as a subset of the extended population of activated and un-activated “aerosols”. Cloud properties, such as albedo, rain production and even phase, emerge from the microphysical interactions between diverse hydrometeors and vapor, and are defined by aerosol-sensitive numbers, sizes and phase of cloud-particles. Cloud properties are influenced by the chemistry and loadings of environmental aerosols. That is the motivation for considering aerosols and clouds together in the same section here.

2.1. Aerosols and their Sources

Aerosols containing hygroscopic and water-soluble material can serve as centers for condensation, and are called condensation nuclei (CN). Almost all aerosols are CN. They are essential for formation of clouds, because without them surface tension effects would tend to prevent the survival of embryonic droplets of pure water formed by chance collisions (homogeneously). In the absence of aerosols, droplets would form only when the relative humidity is several hundred percent, which is never seen in the atmosphere.

As soon as a CN aerosol is generated in the sub-saturated environment, some water condenses onto it, dissolving its material. Consequently, throughout the atmosphere, CN are present as submicron- or micron-sized solution droplets. They have a wide range of sizes between about 10^{-3} and 10 microns and each size of CN in a given chemical species has a unique critical supersaturation at which it can form a droplet. The larger the CN, the lower its critical supersaturation. For all CN in a typical air sample to be transformed into droplets, an extremely high supersaturation would be needed because most CN are very small (e.g. 10s of nanometers or less). For supersaturations seen in real clouds, the small fraction of the CN that activate as droplets are called cloud condensation nuclei (CCN).

A subset of the aerosol population contains water-insoluble material and can act as centers for ice formation. Such aerosols are called IN. Dust/metallic, black carbon, and insoluble organic aerosols are the key groups of IN. Usually, IN particles are coated with soluble material, so IN tend to be a subset of CCN.

About 75% of the total mass of aerosol material is directly from primary sources at the Earth’s surface. In the tropics, forest fires are important sources, especially during the biomass-burning season, as are industrial sources. Deserts in the sub-tropics are a source of much dust. Recent research has shown that the precise sources of dust are extremely localized. The other 25% of total aerosol mass is from secondary sources involving chemical conversions from the gaseous phase (SO_2, N_2O, NH_3 ...).

The smallest aerosol (< 0.2 microns) can originate from combustion processes, such as forest fires, volcanoes and human activities. But also, natural conversion of trace gases in the atmosphere can create them. Such conversions may be enhanced by high relative humidity, liquid water and sunlight. Evaporation of cloud-droplets can leave behind sulfate particles, boosted with sulfate material from the reaction of SO_2 and ammonia in droplets.

Large and giant aerosols > 0.2 microns are caused by:

- erosion of the land surface in arid regions, generating dust;
- pollen, pollen fragments, spores from plants, bacteria, leaf litter;
- the bursting of air bubbles from wave-breaking over the oceans, emitting salt particles.

In most of the tropics, surface winds are usually weak, so sea-salt aerosols are scarce. However, tropical cloud systems, such as hurricanes, can generate them, influencing cloud properties.

The aerosols generally contributing most to the reflection of sunlight are sulfate aerosols. The main source of sulfate aerosols is the gas, SO_2, emitted by fossil fuel use (about 70%) and dimethyl sulfide (about 20%) emissions from plankton. This occurs by reactions within cloud-droplets that then evaporate, condensation of SO_2 onto pre-existing aerosols, and reaction of SO_2 with OH in the air. Much sulfate material exists as ammonium sulfate in the atmosphere. Organic aerosols consist of many different chemical compounds and are directly emitted into the troposphere (e.g. by combustion, biomass-burning, natural biogenic emissions) or are formed by condensation of gases. Chemical properties of organic aerosols change after emission, due to reactions with ozone, OH and the nitrate free radical (NO_3). After sulfate, organic aerosols make the next largest contribution to aerosol optical depth in pollution plumes, as seen in a recent field experiment over the Indian Ocean in the tropics.

Black carbon results from incomplete combustion and its emissions are mostly anthropogenic. It is emitted as complex chain structures that collapse and aggregate as the particles age. It acts as a site for condensation of sulfate from SO_2 gas. It strongly absorbs solar radiation. Most mineral dust is also absorbing of solar radiation and is naturally emitted from deserts. Dust has major anthropogenic sources. Finally, ammonium nitrate aerosol is formed from excess ammonia not neutralized by formation of sulfate.

2.2. Aerosol Growth and Atmospheric Processing

Large aerosols (> 0.2 and < 2 microns) are partly caused by coagulation of the smaller aerosols < 0.2 microns. The peak in the aerosol size distribution for such large aerosols is termed the accumulation mode. All aerosols are subject to a wide range of transformations: condensation, coagulation, scavenging, wash-out, sedimentation, dispersion, mixing. Some of these alter the aerosol size distribution. Particles formed by condensation are roughly spherical but other types of particles may be irregular, crystalline or fiber-shaped. The majority of aerosols are Aitken particles (e.g. at concentrations of about 10^5 cm^{-3} for polluted air). However, the critical supersaturation for Aitken particles is so high that very few are activated in the real atmosphere. Also, giant particles fall out rapidly from the troposphere, and so, their scarcity limits their importance. This leaves the large aerosols as the most important ones for natural cloud formation. The large particles are formed by the tendency of the numerous Aitken particles < 0.1 microns to collide, due to their Brownian motion, and to clump together. This coagulation causes a peak in the aerosol size distribution in the range of 0.2-2 microns.

Recent aircraft observations in several field campaigns over the Pacific ocean, especially at low latitudes, have revealed that in the upper troposphere near outflow from deep convection there is nucleation from the gas phase (e.g. SO_2 from the outflow) of extremely numerous (e.g. > 10,000 cm^{-3}) and small (3-10 nm) soluble aerosols. They are typically sulfate particles in the Aitken size range. During transport and subsidence of the ambient air, these aerosols grow, with condensation of gases (e.g. SO_2) and coagulation. This very fine mode of sulfate extends down to the boundary layer. Its average particle size increases with decreasing height throughout the free troposphere. Sampling of aerosol pollution from Asia that flows out across the Pacific has shown that it consists of much insoluble carbonaceous material internally mixed with soluble material (e.g. sulfate), partly deposited at its combustion-related source.

Another secondary source of sulfate aerosol is from gases formed by reactions of dimethyl sulfide emitted by plankton in the ocean. This can happen when mixing (e.g. near the top of the boundary layer) boosts the supersaturation of sulfur-containing gas, for instance by reducing the surface area of existing aerosol onto which sulfate material condenses. In the boundary layer, cloud processing may cause the bimodal sulfate distribution typically seen there, with Aitken and large modes.

Some aerosols are initiated naturally in the troposphere. Their life-cycle may take them through the boundary layer, with cycles of droplet activation and evaporation before being rained out. Cloud processing can generate bimodal aerosol size distributions and involves:- (1) aqueous-phase reactions in cloud-droplets converting gases in the ambient air (e.g. SO_2) into extra solute; and (2) evaporation of cloud-droplets re-generating the aerosols at a larger size. Another new view is that chemical processing of aerosols, involving condensation of soluble chemical species from the gas phase, occurs during long-range transport in the environment. Such soluble coatings have been recently found to alter the aerosols ability to nucleate ice and activate droplets in many ways. For instance, organic coatings can reduce soluble particles' hygroscopicity and surface tension, and may slow down their condensational growth to an equilibrium size. This alters the critical supersaturation at which they become cloud-droplets, affecting how many aerosols activate at cloud-base.

-
-
-

Bibliography

Albrecht, B. A., (1989). Aerosols, cloud microphysics, and fractional cloudiness. *Science*, 245(4923), pp. 1227-1230 [Description of aerosol indirect effects on clouds and climate.]

Andreae, M. O., Rosenfeld, D., Artaxo, P., Costa, A. A., Frank, G. P., Longo, K. M., and M. A. F. Silvas-

Dias, (2004). Smoking rain clouds over the Amazon. *Science*, 303, 1337–1342 [Description of aerosols' impact on cloud properties].

Annan, J. D., and J. C. Hargreaves (2006). Using multiple observationally-based constraints to estimate climate sensitivity. *Geophys. Res. Lett*., 33, L06704, doi:10.1029/2005GL025259 [Estimates of equilibrium global warming for CO2 doubling.]

Archuleta, C. M., DeMott, P. J., and S.M. Kreidenweis, (2005). Ice nucleation by surrogates for atmospheric mineral dust and mineral dust/sulfate particles at cirrus temperatures. *Atmos. Chem. Phys*., 5, 2617-2634 [Laboratory observations of artificial dust.]

Baker, M. B., Blyth, A. M., Christian, H. J., Latham, J., Miller, K. L., and A. M. Gadian, (1999). Relationships between lightning activity and various thundercloud parameters: satellite and modelling studies. *Atmos. Res*., 51, 221-236 [Role of quantities like updraft speed for lightning]

Bauer, H., Kasper-Giebl, A., L¨oflund, M., Giebl, H., Hitzenberger, R., Zibuschka, F., and H. Puxbaum, (2002). The contribution of bacteria and fungal spores to the organic carbon content of cloud water, precipitation and aerosols. *Atmos. Res*., 64(1-4), 109-119 [Observations of biological aerosols].

Bertram, A. K., Koop, T., Molina, L. T., and M. J. Molina, (2000). Ice formation in (NH4)(2)SO4-H2O particles. *J. Phys. Chem. A*, 104(3), 584-588 [Description of soluble coatings on IN particles altering their nucleating ability].

Black, R. A., and J. Hallett, (1999). Electrification of the hurricane. *J. Atmos. Sci*., 56, 2004-2028

Blyth, A. M., and J. Latham, (1993). Development of ice and precipitation in New Mexican summertime cumulus clouds. *Q. J. R. Meteorol. Soc*., 119, 91-120 [Observations suggesting the ubiquitous occurrence of the Hallett-Mossop process of ice multiplication].

Blyth, A. M., and J. Latham, (1997). A multi-thermal model of cumulus glaciation via the Hallett-Mossop process. *Q. J. R. Met. Soc.*, 123, 1185-1198 [Description of simulations of ice multiplication in deep convective clouds]

Blyth, A. M., Christian, H. J., Driscoll, K., and J. Latham, (2001). Determination of precipitation rates and thunderstorm anvil ice contents from satellite observations of lightning. *Atmos. Res*. 59–60, 217–229.

Blyth, A.M., Benestad, R. E., Krehbiel, P. R., and J. Latham, (1997). Observations of supercooled raindrops in New Mexico summertime cumuli. *J. Atmos. Sci*., 54, 569–575. [Observations suggesting a role for raindrop-freezing in cumulus glaciation].

Bony, S., and J. L. Dufresne, (2005). Marine boundary layer clouds at the heart of cloud feedback uncertainties in climate models. *Geophys. Res. Lett*., 32(20), L20806 [Observed decrease in reflection of sunlight in subsidence regions of low cloud at low latitudes during global warming in the 20^{th} century]

Bringi, V. N., Knupp, K., Detwiler, A., Liu, L., Caylor, I. J., and R.A. Black, (1997). Evolution of a Florida thunderstorm during the Convection and Precipitation/Electrification Experiment: the case of 9 August 1991. *Mon. Wea. Rev*., 125, 2131–2160 [Observed raindrop-freezing in deep convective updraft]

Brooks, I. M., Saunders, C. P. R., Mitzeva, R. P., and S. L. Peck, (1997). The effect on thunderstorm charging of the rate of rime accretion by graupel. *Atmos. Res*., 43, 277-295 [Laboratory observations of charge separation.]

Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. [Concise description of the functioning of the climate system]

Chisholm, A. J., 1973: Alberta Hailstorms. Part I: Radar Case Studies and Airflow Models. *Meteor. Monograph*, 14(36), 1-36 [Observations of the life cycle of deep convective clouds].

Christian, H. J., and J. Latham, (1998). Satellite measurements of global lightning. *Q. J. R. Meteorol. Soc*., 124, 1771-1773 [Description of lightning's preference for land.]

Clarke, A. D., and V. Kapustin, (2002). A Pacific aerosol survey. Part I: A decade of data on particle production, transport, evolution, and mixing in the troposphere. *J. Atmos. Sci.,* 59, 363-382 [Field observations of production of numerous, ultra-fine aerosols in the outflow aloft from deep convection at low latitudes].

Clarke, A. D., McNaughton, C. M., Kapustin, V., Shinozuka, Y., Howell, S., Dibb, J., Zhou, J., Anderson, B., Brekhovskikh, V., Turner, H., and M. Pinkerton, (2007). Biomass burning and pollution aerosol over North America: organic components and their influence on spectral optical properties and humidification response. *J. Geophys. Res.,* 112, D12S18, doi:10.1029/2006JD007777.

Clarke, A. D., Shinozuka, Y., Kapustin, V. N., Howell, S., Huebert, B., Doherty, S., Anderson, T., Covert, D., Anderson, J., Hua, X., Moore, K. G. II, McNaughton, C., Carmichael, G., and R. Weber, (2004). Size distributions and mixtures of dust and black carbon aerosol in Asian outflow: Physiochemistry and optical properties. *J. Geophys. Res*., 109, D15S09, doi:10.1029/2003JD004378 [Aircraft observations of aerosols consisting of insoluble particles, soot or dust, coated with soluble material in pollution plumes].

DeMott, P. J., Chen, Y., Kreidenweis, S. M., Rogers, D. C., and D. Eli Sherman, (1999). Ice formation by black carbon particles. *Geophys. Res. Lett*., 26, 2429-2432. [Laboratory observations of soot acting as IN]

DeMott, P. J., Cziczo, D. J., Prenni, A. J., Murphy, D. M., Kreidenweis, S. M., Thomson, D. S., Borys, R., and D. C. Rogers, (2003). Measurements of the concentration and composition of nuclei for cirrus formation. *Proc. Nat. Soc. Sci*., 100, 14655-14660 [Atmospheric observations of chemical composition of IN]

Durant, A. J., and R. A. Shaw, (2005). Evaporation freezing by contact nucleation inside-out. *Geophys. Res. Lett*., 32, L20814, doi:10.1029/2005GL024175 [Laboratory observations of a new type of heterogeneous ice nucleation].

Dusek, U., Covert, D. S., Wiedensohler, A., Neususs, C., Weise, D., and Cantrell, W.: Cloud condensation nuclei spectra derived from size distributions and hygroscopic properties of the aerosol in coastal south-west Portugal during ACE-2 (2003) *Tellus Series B-Chemical and Physical Meteorology*, 55, 35–53

Elsner, J., Kossin, J. P. and T. H. Jagger, (2008). The increasing intensity of the strongest tropical cyclones. *Nature*, 455, 92-95 [Observed correlation between surface warming and intense tropical cyclones]

Ervens, B., Feingold, G., and Kreidenweis, S. M. (2005). The influence of water-soluble organic carbon on cloud drop number concentration. *J. Geophys. Res*., 110, D18211, doi:10.1029/2004JD005634 [Description of effects of organics on droplet activation]

Facchini, M. C., Decesari, S., Mircea, M., Fuzzi, S., and G. Loglio (2002). Surface tension of atmospheric wet aerosol and cloud/fog droplets in relation to their organic carbon content and chemical composition. *Atmos. Environ*., 34, 4853–4857

Facchini, M. C., Mircea, M., Fuzzi, S., and R. J. Charlson (1999). Cloud albedo enhancement by surface-active organic solutes in growing droplets. *Nature*, 401, 257–259

Feingold, G. and P. Y. Chuang (2002). Analysis of the influence of film-forming compounds on droplet growth: Implications for cloud microphysical processes and climate. *J. Atmos. Sci*., 59, 2006–2018

Feingold, G., Cotton, W. R., Kreidenweis, S. M., and J.T. Davis (1999). The impact of giant cloud condensation nuclei on drizzle formation in stratocumulus: implications for cloud radiative properties. *J. Atmos. Sci*., 56, 4100–4117 [Modeling study of the effects from giant CCN on cloud properties].

Feingold, G., Eberhard, W. L., Veron, D. E., and Previdi, M. (2003). First measurements of the Twomey indirect effect using ground-based remote sensors. *Geophys. Res. Lett*., 30, doi:10.1029/2002GL016 633

Field, P. R., Mohler, O., Connolly, P., Kramer, M., Cotton, R., Heymsfield, A. J., Schnaiter, M., and H. Saathoff, (2006). Some ice nucleation characteristics of Asian and Saharan desert dust. *Atmos. Chem. Phys*, 6, 1539-1577 [Laboratory observations of ice nucleation by dust sampled from the ground]

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. [Description of climate forcings and sources of various greenhouse gases and aerosol species]

Ghan, S., Laulainen, N. S., Easter, R. C., Wagener, R., Nemesure, S., Chapman, E. G., Zhang, Y., and L.-Y. R. Leung, 2001). Evaluation of aerosol indirect radiative forcing in MIRAGE. *J. Geophys. Res*.,106(D6), 5295–5316.

Ginoux, P., Chin, M., Tegen, I., Prospero, J. M., Holben, B., Dubovik, O., and S.-J. Lin, (2001). Sources and distributions of dust aerosols simulated with the GOCART model. *J. Geophys. Res*., 106, D17, 20255-20274

Greenwald, T. J., Stephens, G. L., Christopher, S. A., and T. H. Vonder Haar, (1995). Observations of the global characteristics and regional radiative effects of marine cloud liquid water. *J. Clim*., 8, 2928–2946 [Sensitivity of clouds' liquid content to global warming]

Griggs, D. J., and T. W. Choularton, 1983: Freezing modes of riming droplets with application to ice splinter production. *Q. J. R. Meteorol. Soc*., 109, 243-253 [Laboratory observations of mechanism for H-M process]

Hallett, J., and S. C. Mossop, (1974). Production of secondary ice particles during the riming process. *Nature*, 249, 26-28 [Laboratory observations of ice particle multiplication].

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., and A. Friend, (2005). Efficacy of climate forcings. *J. Geophys. Res*., 110, D18104, doi:10.1029/2005JD005776 [response of Hadley cell and other tropical climate changes due to aerosol indirect effect]

Held, I.M., and B.J. Soden, (2000). Water vapor feedback and global warming. *Annu. Rev. Energy Environ*., 25, 441– 475.

Heymsfield, A. J., Miloshevich, L. M., Schmitt, C., Bansemer, A., Twohy, C., Poellot, M. R., Fridlind, A. and H. Gerber, (2005). Homogeneous ice nucleation in subtropical and tropical convection and its influence on cirrus anvil microphysics. *J. Atmos. Sci*., 62, 41-65 [Importance of homogeneneous freezing of cloud liquid in anvil updrafts]

Heymsfield, A.J., A. Bansemer, P.R. Field, S.L. Durden, J.L. Stith, J.E. Dye, W. Hall, and C.A. Grainger, (2002). Observations and parameterizations of particle size distributions in deep tropical cirrus and stratiform precipitating clouds: results from in situ observations in TRMM field campaigns. *J. Atmos. Sci*., 59, 3457–3491. [Description of aircraft observations of glaciated clouds, associated with deep convection, from a field experiment near Kwajalein atoll in 1999]

Hirano, S. S., Baker, L. S., and C. D. Upper, (1985). Ice nucleation temperature of individual leaves in relation to population sizes of ice nucleation active bacteria and frost injury. *Plant Physiol*., 77(2), 259-265.

Holton, J. R. (1979) *An introduction to dynamic meteorology*. Academic Press [Discussion of the role of deep convection in the large-scale circulation in the tropics]

Houghton, (1986) *The Physics of Atmospheres*. Cambridge University Press [Description of atmospheric radiation, its role for climate, and the greenhouse effect]

Houze, R. (1993). *Cloud dynamics*. Academic Press [Discussion of various cloud types and tropical cloud systems]

Jaenicke, R., (2005). Abundance of cellular material and proteins in the atmosphere. *Science,* 308(5718), p. 73 [Biological aerosols ivserved in the real atmosphere]

Khain A. P., Pinsky, M. B., Shapiro, M., and A. Pokrovsky, (2001). Graupel-drop collision efficiencies. *J. Atmos. Sci*., 58, 2571-2595 [Data for simulation of the riming process].

Khain, A., BenMoshe, N., and A. Pokrovsky, (2008). Factors Determining the Impact of Aerosols on Surface Precipitation from Clouds:: an attempt of classification. *J. Atmos. Sci*., 65, 1721-1748

Khain, A., Cohen, N., Lynn, B., and A. Pokrovsky, (2008). Possible aerosol effects on lightning activity and structure of hurricanes. *J. Atmos. Sci*., 65, 3652–3677

Khain, A., Pokrovsky, A., Pinsky, M., Seifert, A., and V. T. J. Phillips, (2004). Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixed-phase cumulus Cloud model. Part I: Model description and possible applications. *J. Atmos. Sci*., 61, 2963-2982 [Simulation of how aerosols alter the microphysics and latent heating, invigorating the dynamics, of deep convection]

Khain, A., Rosenfeld, D., and A. Pokrovsky, (2005). Aerosol impact on the dynamics and microphysics of deep convective clouds. *Q. J. R. Meteorol. Soc*., 131, 2639-2663 [Simulation of how aerosols invigorate the dynamics of deep convection]

Koop, T., Luo, B. P., Tsias, A., and T. Peter, (2000). Water activity as the determinant for homogeneous ice nucleation in aqueous solutions. *Nature*, 406, 611-614 [New theory for homogeneous aerosol freezing]

Kristjansson, J. E., (2002). Studies of the aerosol indirect effect from sulfate and black carbon aerosols. *J. Geophys. Res*., 107, doi:10.1029/2001JD000 887 [Assessment of the impact from aerosol pollution on global climate].

Latham, J., (1981). The electrification of thunderstorm. The Symons memorial lecture 1979. *Q. J. R. Meteor. Soc.*, 107, 277-298 [role of non-inductive charge separation in storm electrification]

Latham, J., and J. E. Dye, (1989). Calculations on the electrical development of a small thunderstorm. *J. Geophys. Res*., 94, D12, 13141-13144 [Discussion of role of non-inductive charge separation in storm electrification]

Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson and M. Prather (2007). Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z.

Levin, Z., and S. A. Yankofsky, (1983). Contact versus immersion freezing of freely suspended droplets by bacterial ice nuclei. *J. Clim. Appl. Meteorol*., 22(11), 1964-1966 [Laboratory observations of ice nucleation by bacteria].

Liou, K. N., (2002) *An introduction to atmospheric radiation*. Academic Press [Cloudiness patterns worldwide described, and radiative properties of clouds].

Lohmann, U. (2004). Can anthropogenic aerosols decrease the snowfall rate?, *J. Atmos. Sci*., 61, 2457–2468

Lohmann, U. and Feichter, J. (1997). Impact of sulfate aerosols on albedo and lifetime of clouds: A sensitivity study with the ECHAM GCM. *J. Geophys. Res*., 102, 13685–13700

Lohmann, U. and Feichter, J. (2001). Can the direct and semi-direct aerosol effect compete with the indirect effect on a global scale?, *Geophys. Res. Lett*., 28, 159–161

Lohmann, U., (2002). A glaciation indirect aerosol effect caused by soot aerosols. *Geophys. Res. Lett*., 29, doi:10.1029/2001GL014 357

Lohmann, U., and J. Feichter, (2005). Global indirect aerosol effects: a review. *Atmos. Chem. Phys*., 5, 715-737

Lyons, W. A., Nelson, T. E., Williams, E. R., Cramer, J. A., and T. R. Turner, (1998). Enhanced positive cloud-to-ground lightning in thunderstorms ingesting smoke from fires. *Science*, 282, 77–80 [Observations of lightning enhancement when aerosols are numerous].

Marcolli, C., Gedamke, S., Peter, T., and B. Zobrist, (2007). Efficiency of immersion mode ice nucleation on surrogates of mineral dust. *Atmos. Chem. Phys*., 7, 5081–5091 [Validated reformulation of classical theory to account for observed singular character of artificial dust IN]

McDonald, J. E. (1958). The physics of cloud modification. *Advances in Geophysics*, 5, 223-303. Academic Press [Microphysical species of liquid condensate in clouds]

McFiggans, G., Artaxo, P., Baltensperger, U., Coe, H., Facchini, M. C., Feingold, G., Fuzzi, S., Gysel1, M., Laaksonen, A., Lohmann, U., Mentel, T. F., Murphy, D. M.,O'Dowd, C. D.. Snider, J. R.,and E. Weingartner (2006). The effect of aerosol composition and properties on warm cloud droplet activation. *Atmos. Chem. Phys*. 6, 2593-2649 [Description of effects of organics on droplet activation]

Michalon, N., Nassif, A., Saouri, T., Royer, J. F., and C. A. Pontikis, (1999). Contribution to the climatological study of lightning. *Geophys. Res. Lett.*, 26(20), 3097-3100 [Possible dependencies of lightning on aerosol conditions]

Ming, Y., Ramaswamy, V., Donner, L. J., Phillips, V. T. J., Klein, S. A., Ginoux, P. A., and L. H. Horowitz, 2007: Modeling the interactions between aerosols and liquid water cloud with a self-consistent cloud scheme in a general circulation model. *J. Atmos. Sci*., 64, 1189-1209 [Flux change at top of atmosphere due to aerosol emissions affecting clouds since pre-industrial times predicted to be almost 2 W m^{-2}, less than but comparable to the forcing due to greenhouse gas emissions]

Mircea, M., Facchini, M. C., Decesari, S., Fuzzi, S., and Charlson, R. J. (2002) The influence of the organic aerosol component on CCN supersaturation spectra for different aerosol types, *Tellus Series B-Chemical and Physical Meteorology*, 54, 74–81

Mohler, O., Buttner, S., Linke, C., Schnaiter, M., Saathoff, H., Stetzer, O., Wagner, R., Kramer, M., Mangold, A., Ebert, V., and U. Schurath, (2005a). Effect of sulfuric acid coating on heterogeneous ice nucleation by soot aerosol particles. *J. Geophys. Res*., 110, D11210, doi:10.1029/2004JD005169. [Effect of internal mixing on ice nucleating ability]

Mohler, O., Linke, C., Saathoff, H., Schnaiter, M., Wagner, R., Schurath, U., Mangold, A., and M. Kramer, (2005). Ice nucleation on flame soot aerosol of different organic carbon content. *Meteorol. Zeit*., 14(4), 477-484 [Effect of internal mixing on ice nucleating ability]

Mohler, O., P. R. Field, P. Connolly, S. Benz, H. Saathoff, M. Schnaiter, R. Wagner, R. Cotton, M.Kramer, A. Mangold, and A. J. Heymsfield (2006). Efficiency of the deposition mode ice nucleation on mineral dust particles. *Atmos. Chem. and Phys. Disc*., 6, 1539-1577 [Laboratory observations of dust as an IN]

Morris, C. E., Georgakopoulos, D. G., and D. C. Sands, (2004). Ice nucleation active bacteria and their potential role in precipitation. *J. Phys. IV France*, 121, 87-103 [Review of ice-nucleating bacteria].

Murray, N. D., Orville, R. E., and G. R. Huffines, (2000). Effect of pollution from Central American fires on cloud-to-ground lightning in May 1998. *Geophys. Res. Lett*, 27, 2249–225 [Observations of aerosol and lightning].

Naccarato, K. P., Pinto Jr., O., and I. R. C. A. Pinto, (2003). Evidence of thermal and aerosol effects on the cloud-to-ground lightning density and polarity over large urban areas of Southeastern Brazil. *Geophys. Res. Lett*., 30 (13), 1674, doi:10.1029/2003GL017496 [Observations of correlations between aerosol/stability and lightning activity].

Niemeyer, L., Pietronero, L., and H. J. Wiesmann, (1984). Fractal dimension of dielectric breakdown. *Phys. Rev. Lett*., 52, 1033– 1036. [Theory of lightning discharge].

Orville, R. E., and J. M. Coyne (1999). *Cloud-to-ground lightning in tropical cyclones (1986-1996).* Preprints, 23rd Conf. on Hurricanes and Tropical Meteorology, Dallas, Amer. Meteor. Soc., 194 pp.

Orville, R. E., and R. W. Henderson, (1986). Global distribution of midnight lightning: September 1977 to August 1978. *Mon. Wea. Rev.*, 114, 2640-2653 [Observations of lightning's preference for land].

Penner, J. E., Quaas, J., Storelvmo, T., Takemura, T., Boucher, O., Guo, H., Kirkev, A., Kristjansson, J. E., and Ø. Seland, (2006). Model intercomparison of indirect aerosol effects. *Atmos. Chem.. Phys*., 6, 3391-3405 [Influence of aerosol pollution on clouds and climate, as simulated by a variety of models].

Petersen, W. A., Christian, H. J., and S. A. Rutledge, (2005). TRMM observations of the global relationship between ice water content and lightning, *Geophys. Res. Lett*., 32, L14819, doi:10.1029/2005GL023236 [Observations of how lightning is closely correlated with the mass of ice precipitation aloft in deep convection].

Petters, M. D., and S. M. Kreidenweis (2007). A single parameter representation of hygroscopic growth and cloud condensation nucleus activity. *Atmos. Chem. Phys*., 7, 1961-1971 [A reformulation of Kohler theory for droplet activation in terms of the hygroscopicity parameter]

Phillips, V. T. J., Blyth, A. M., Choularton, T. W., Brown, P. R. A., and J. Latham (2001). The glaciation of a cumulus cloud over New Mexico. *Q. J. R. Meteorol. Soc*., 127, 1513–1534 [Ice microphysics of convective clouds]

Phillips, V. T. J., Choularton, T. W., Illingworth, A. J., Hogan, R. J., and P. R. Field (2003). Simulations of the glaciationof a frontal mixed-phase cloud with the Explicit Microphysics Model (EMM). *Q. J. R. Meteorol. Soc*., 129, 1351-1371 [Study of the microphysics of glaciated nimbostratus cloud].

Phillips, V. T. J., DeMott, P. J., and C. Andronache, (2008). An empirical parameterization of heterogeneous ice nucleation for multiple chemical species of aerosol. *J. Atmos. Sci*., 65, 2757-2783 [A model of ice initiation by insoluble aerosol species].

Phillips, V. T. J., Donner, L. J., and S. Garner, (2007). Nucleation processes in deep convection simulated by a cloud-system resolving model with double-moment bulk microphysics. *J. Atmos. Sci*., 64, 738-761 [Study of the various pathways by which cloud-particles are initiated in mesoscale cloud systems].

Phillips, V. T. J., Pokrovsky, A., and A. Khain, (2007). The influence of time-dependent melting on the dynamics and precipitation production of maritime and continental storm clouds. *J. Atmos. Sci*., 64, 338-359 [Modeling study of the role of melting in deep convection].

Phillips, V. T. J., Sherwood, S. C., Andronache, C., Bansemer, A., Conant, W. C., DeMott, P. J., Flagan, R. C., Heymsfield, A., Jonsson, H., Poellot, M., Rissman, T. A., Seinfeld, J. H., Vanreken, T., Varutbangkul, V., and J. C. Wilson, (2005). Anvil glaciation in a deep cumulus updraft over Florida simulated with an Explicit Microphysics Model. I: The impact of various nucleation processes. *Q. J. R. Meteorol. Soc*., 131, 2019-2046 [Study of how cloud-particles are initiated in a cumulonimbus updraft].

Phillips, V.T.J., Choularton, T.W., Blyth, A.M., and Latham, J (2002). The influence of aerosol concentrations on the glaciation and precipitation of a cumulus cloud. *Q. J. R. Meteorol. Soc*., 128, 951-971 [Modification of microphysics of convective clouds by aerosol]

Pinsky, M., Khain, A. P., and M. Shapiro, (2001). Collision efficiency of drops in a wide range of Reynolds numbers: effects of pressure on spectrum evolution. *J. Atmos. Sci*., 58, 742-764

Pruppacher, H. R., and J. D. Klett, (1997). Microphysics of clouds and precipitation. Kluwer Academic Publishers [homogeneous freezing and dependence of drop size; aerosol sources; microphysical processes]

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A., and K. E. Taylor, (2007). Climate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. [Discussion of feedbacks and climate sensitivity, and an account of simulations of severe weather, such as tropical cyclones.]

Rogers, R. R., and M. K. Yau, (1991). *A short course in cloud physics*. Pergamon Press. [Discussion of routes to saturation, aerosol activation, conditional instability as well as microphysical species and processes]

Rosenfeld, D., (2000). Suppression of rain and snow by urban and industrial air pollution. *Science*, 287, 1793-1796 [Observations of reduced precipitation by aerosol pollution].

Rosenfeld, D., and I. M. Lensky, (1998). Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. *Bull. Am. Meteorol. Soc*., 79, 2457–2476

Saunders, C. P. R., and S. L. Peck, (1998). Laboratory studies of the influence of the rime accretion rate on charge transfer during crystal/graupel collisions. *J. Geophys. Res*., 103, 13949-13956 [Laboratory observations of charge separation.]

Saunders, C. P. R., Keith, D., and R. P. Mitzeva, (1991). The effect of liquid water on thunderstorm charging. *J. Geophys. Res.*, 96, 11007-11017 [Laboratory observations of charge separation.]

Schnell, R. C., and G. Vali, (1972). Atmospheric ice nuclei from decomposing vegetation. *Nature*, 236, 163-165 [Observations of biological IN].

Schnell, R. C., and G. Vali, (1976). Biogenic ice nuclei. I - Terrestrial and marine sources. *J. Atmos. Sci*., 33, 1554-156 [Observations of biological IN].

Shao, X. M., Harlin, J., Stock, M., Stanley, M., Regan, A., Wiens, K., Hamlin, T., Pongratz, M., Suszcynsky, D. and T. Light, (2005). Katrina and Rita were lit up with lightning. *EOS*, 86, No.42, 398-399.

Shaw, R. A., Durant, A. J., and Y. Mi, (2005). Heterogeneous surface crystallization observed in undercooled water. *J. Phys. Chem. B*, 109, No. 20, 9865-9868 [Laboratory observations of modes of heterogeneous ice nucleation.]

Sherwood, S. C., Phillips, V. T. J., and J. S. Wettlaufer, (2006). Small ice crystals and the climatology of lightning. *Geophys. Res. Lett*., 33, L05804, doi:10.1029/2005GL025242 [Analysis of global satellite data for multiple dependencies of lightning].

Soden, B. J., and I. M. Held, 2006: An assessment of climate feedbacks in coupled ocean-atmosphere models. *J. Clim*., 19, 3354–3360

Steiger, S. M., and R. E. Orville, (2003). Cloud-to-ground lightning enhancement over southern Louisiana. *Geophys. Res. Lett*., 30(19), 1975, doi:10.1029/2003GL017923. [Observed spatial correlation between aerosol emissions and lightning]

Stevens, B., Vali, G., Comstock, K., Wood, R., van Zanten, M. C., Austin, P. H., Bretherton, C. S., and D. H. Lenschow, 2005: Pockets of open cells and drizzle in marine stratocumulus. *Bull. Amer. Meteor. Soc*., 86, 51-57.

Takahashi, T., (1978). Riming electrification as a charge generation mechanism in thunderstorms. *J. Atmos. Sci.*, 35, 1536–1548

Takahashi, T., (1984). Thunderstorm electrification – A numerical study. *J. Atmos. Sci*., 41, 2541–2558 [Simulation of aerosol influences on charge separation].

Toracinta, E. R., Cecil, D. J., Zipser, E. J., and S. W. Nesbitt, (2002). Radar, passive microwave, and lightning characteristics of precipitating systems in the Tropics. *Mon. Wea. Rev*., 130, 802-824 [Remote observations (e.g. from satellite) of how lightning occurs when precipitation is abundant in vigorous updrafts of deep convective clouds above the freezing level]

Twomey, S. A., (1977). The influence of pollution on the shortwave albedo of clouds. *J. Atmos. Sci*., 34, 1149–1152. [Description of aerosol indirect effect]

Vali, G., (1971). Quantitative evaluation of experimental results on the heterogeneous freezing nucleation of supercooled liquids. *J. Atmos. Sci*., 28, 402-409

Vali, G., (1994). Freezing rate due to heterogeneous nucleation. *J. Atmos. Sci*., 51, 1843-1856 [Evidence for the singular character of IN particles, which freeze very soon after their characteristic freezing temperatures are reached.]

van den Heever, S. C., Carrio, G. G., Cotton, W. R., DeMott, P. J., and A. J. Prenni, (2006). Impacts of nucleating aerosol on Florida storms. Part I: mesoscale simulations. *J. Atmos. Sci*., 63, 1752-1775

Vrbka, L., and P. Jungwirth, (2006). Homogeneous freezing of water starts in the subsurface. *J. Phys. Chem. Lett. B*, 110(37), 18126-18129, doi:10.1021/jp064021c [results from molecular dynamics simulations showing how surface of liquid favors freezing]

Williams, E. R., Mushtak, V., Rosenfeld, D., Goodman, S., and D. Boccippio, (2005). Thermodynamic conditions favorable to superlative thunderstorm updraft, mixed phase microphysics and lightning flash rate. *Atmos. Res.*, 76, 288– 306

Williams, E., and G. Satori, (2004). Lightning, thermodynamic and hydrological comparison of the two tropical continental chimneys. *J. Atmos. Solar-terr. Phys.*, 66, 1213-1231

Williams, E., Rosenfeld, D., Madden, N., Gerlach, J., Gears, N., Atkinson, L., Dunnemann, N., Frostrom, G., Antonio, M., Biazon,B., Camargo, R., Franca, H., Gomes, A., Lima, M., Machado, R., Manhaes, S., Nachtigall, L., Piva, H., Quintiliano, W., Machado, L., Artaxo, P., Roberts, G., Renno, N., Blakeslee, R., Bailey, J., Boccippio, D., Betts, A., Wolff, D., Roy, B., Halverson, J., Rickenbach, T., Fuentes, J., and E. Avelino, (2002). Contrasting convective regimes over the Amazon: implications for cloud electrification. *J. Geophys. Res*., 107, D20, 8082, doi:10.1029/2001JD000380

Willis, P. T., and A. J. Heymsfield (1989). Structure of the melting layer in mesoscale convective system stratiform precipitation. *J. Atmos. Sci*., 46, 2008-2025 [Field observations of the melting layer and its thermodynamic profile].

Zipser, E. J., and K. R. Lutz, (1994). The vertical profile of radar reflectivity of convective cells—A strong indicator of storm intensity and lightning probability? *Mon. Wea. Rev*., 122, 1751–1759

Zobrist, B., Marcolli, C., Koop, T., Luo, B. P., Murphy, D. M., Lohmann, U., Zardini, A., Krieger, U. K., Corti, T., Cziczo, D. J., Fueglistaler, S., Hudson, P. K., Thomson, D. S., and T. Peter, (2006). Oxalic acid as a heterogeneous ice nucleus in the upper troposphere and its indirect aerosol effect. *Atmos. Chem. Phys.*, 6, 3115-3129 [Observations of OAD acting as an IN]

Zuberi, B., Bertram, A. K., Cassa, C. A., Molina, L. T., and M. J. Molina, (2002). Heterogeneous nucleation of ice in (NH4)2SO4-H2O particles with mineral dust immersions. *Geophys. Res. Lett.*, 29(10), 1504, doi:10.1029/2001GL014289. [Dust as an IN]

Biographical Sketch

Vaughan Phillips is an Assistant Professor at the Department of Meteorology in the University of Hawaii at Manoa, in Honolulu. He is a meteorologist by training, specializing in cloud physics.

His educational background includes a physics degree (BSc) with honors from Bristol University, England, in 1990, and degrees from Reading University, England (MSc, 1993) and Paris University VI, France (Diplome des Etudes Approfondies [DEA], 1997). His PhD degree is in cloud physics at Manchester University, England (2001). He was a post-doctoral visiting scientist at Princeton University in the Atmospheric and Oceanic Sciences program (2001-2006) before arriving in Hawaii as a faculty member. He has lectured at Princeton University on cloud physics and at University of Hawaii on physical meteorology.

He participated in two of NASA’s (CRYSTAL-FACE, TCSP) field campaigns in 2002 and 2005. He serves as a peer-reviewer for “Science”, “Journal of the Atmospheric Sciences” and other journals in atmospheric science, as well as for federal agencies that fund research. His current research is focused on modeling the initiation of cloud-particles, ice multiplication, and aerosol impacts on glaciated clouds, as well as on storm electrification. He has published ways to simulate heterogeneous ice nucleation that include dependencies on aerosols’ chemistry and total surface area, in 2007 and 2008. In 2009, he published the first assessment of effects from biological aerosols on mesoscale ensembles of clouds. He has authored about 30 refereed publications in scientific journals. Since 2005, he has received three research grants from NASA, National Science Foundation (NSF) and the Department of Energy in the USA.