PHYSICAL METEOROLOGY

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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 more clearly. 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.
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 detains 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 °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 °C. Droplets may remain supercooled while in this state. At temperatures colder than about -40 °C, all supercooled cloud-droplets must freeze spontaneously. This is called homogeneous freezing. Clouds at levels colder than about -40 °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, SO₂, 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 SO₂ onto pre-existing aerosols, and reaction of SO₂ 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 (NO₃). 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 SO₂ 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 10⁵ 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
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.

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**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.