21

Cirrus

The Future

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> Sometime we see a cloud that's dragonish
> A vapour sometime like a bear or lion,
> A tower'd citadel, a pendent rock,
> A forked mountain, or blue promontory,
> With trees upon't, that nod unto the world,
> And mock our eyes with air: thou hast seen these signs;
> They are black vesper's pageants . . .
> That which is now a horse, even with a thought
> The rack dislimns, and makes it indistinct,
> As water is in water.
>
> Shakespeare, *Antony and Cleopatra*

The preceding 20 chapters reveal cirrus in considerable depth. Just as important, however, is what is not revealed. There are many things that we do not know or understand about cirrus. In this final chapter we present the outstanding scientific issues facing the cirrus research community. Our goal here is to produce a guide for students, scientists, policy makers, and funding organizations who wish to quickly grasp the direction and future needs of cirrus research.

The impact of cirrus clouds on climate and how they interact with a climate perturbed by human enterprise is only dimly perceived. Do cirrus clouds, on a regional or global scale, act to cool or warm our planet? By reflecting incoming solar radiation to space, they can cool. Yet as an opacity source in the 10-μm window, they can radiate downward and warm the Earth. Which process dominates, and under what conditions does warming overtake cooling? Does the atmosphere react to cirrus globally or regionally (i.e., can cirrus increase pole-equator temperature differences or mute them)? Are there other mechanisms at work that defeat or amplify temperature changes by cirrus? We do not yet know.

Programs such as SUCCESS, ICE, CRYSTAL, INCA, and FIRE/SHEBA will do much to answer questions about contrails and cirrus variability from one part of the world to another. They also will go a long way toward understanding one of the most difficult problems in meteorology: how convection and turbulence are related to cirrus formation and maintenance. In the meantime, existing capabilities are underused. For example, remote sensing techniques for estimating ice water path now exist but have not been assigned enough priority to achieve the necessary breakthroughs. Considerable progress could also be made in data analysis. As in other fields, analyzing existing data has a lower funding priority than designing and building new hardware and flight systems. Three fields of inquiry need more attention before we can claim a sufficient understanding of cirrus: physical properties, radiative properties, and modeling. These fields are interconnected in often subtle ways.

21.1. Physical Properties

Much of what we do not know about cirrus involves the range of properties and their evolution in time. Cirrus are not one but many types of clouds, a situation that has come about because "cirrus" is a morphological category, not a physical one. Different parts of the same clouds will change in different ways in response to changing environmental conditions, often on time scales of minutes or hours. The precise form of crystal growth is influenced by too many parameters to be reproduced analytically in the foreseeable future. Temperature, humidity, supersaturation, ventilation, existing morphology, and perhaps even trace impurities in the air and nuclei all affect an ice crystal's shape. Shape and size (and orientation) as well as refractive index determine a crystal's radiative properties. The radiative properties determine whether or not a cirrus cloud warms or cools the Earth. Radiative properties even feedback to the cloud itself and influence its evolution.

How are cirrus crystals produced? Is homogeneous nucleation the only means? What is the nature of updrafts and vertical motions associated with cirrus formation? What is the microphysical structure of cirrus in the vertical? What role does aggregation play in the evolution of crystals? Many of these questions can be addressed in the laboratory, but others require in situ studies. More effort should be made to parameterize experimental growth properties and then introduce the results into cloud and climate-modeling codes.

Better in situ (aircraft, balloons, dropsondes) probes are essential for detecting and characterizing small ice particles ($<10\mu m$ across) and for directly measuring ice water content. These probes are necessary for determining optical properties such as phase function and asymmetry parameter, which are vital to modeling codes. A number of new in situ particle-size measuring instruments are undergoing field tests, and these promising devices could translate into major advances, especially when used in aircraft that can reach the tropopause. Remotely piloted vehicles capable of prolonged stays in cirrus could also provide a cost-effective means of gathering detailed information about cirrus.

Many fundamental properties of cirrus clouds can be evaluated from the ground, leading to the creation of site-specific climatologies. This situation can only improve as more advanced (i.e., Raman and high spectral resolution) lidars, lidar-radiometer (LIRAD) combinations, and millimeter-wave Doppler radars are applied to the regular investigation of cirrus clouds to yield more accurate optical extinction and cloud microphysics. For example, by adding a Raman backscatter channel for nitrogen molecules, more reliable measurements of cirrus extinction (and optical depth) can be made; the LIRAD approach combines shortwave (lidar) and infrared radiometer data to measure optical depth accurately; and radar offers the potential for deriving quantitative cirrus microphysical properties using Rayleigh theory. Better cloud-property retrieval algorithms based on multiple active and passive remote sensors will also increase the accuracy of derived cirrus cloud optical and microphysical properties, which are crucial for comprehending their effects on the radiation balance of the earth–atmosphere system. Improving our knowledge of the full gamut of cirrus cloud properties will contribute to our ability to effectively simulate these remote clouds in numerical models, from which a gradual improvement in weather forecasting, general circulation, and climate prediction models can be expected.

Dynamic features and effects of turbulence and cloud-scale vertical motions influence the physical properties of clouds, which in turn affect the clouds' radiative properties. Thus, dynamics should be considered in studies addressing the explicit life cycle of cirrus. Not only are microphysical characteristics important for the cloud–radiation interaction, so too are where, when, and how long cirrus persist. This is because the availability of sufficient water vapor is highly dependent on mixing and advection. Cloud-resolving models need to include the complex interaction between cloud-scale dynamics and larger scale dynamic persist. These links need to be established from observations and experiments. There are two aspects to the problem. The first involves instrumentation and sampling strategies. The influence of turbulence and vertical motions on the development of cirrus must be better quantified and related to the effects of cloud microphysical changes. Optimized sampling strategies must be developed that make use of combined remote sensing and in situ observations to locate the in situ measurements within the three-dimensional cloud field. The goal should be the delineation between cloud-induced phenomena and those associated with the surrounding environment. Multi-aircraft experiments should obtain simultaneous measurements at different heights in neighboring cloud areas to resolve the dynamics of cloud-generating cells in contrast to the more passive parts of the clouds. New experiments should also provide a dense network (space and time) for vertical profiling of wind, potential temperature, and humidity to allow better identification of dynamic regimes and their development during cloud life cycles. The use of dropsondes would be a valuable extension to earlier observational strategies. Global Positioning System (GPS) tracking of sondes might yield the required vertical resolution of the horizontal wind field. A means to map the local three-dimensional wind field would be extremely useful. Real-time, surface-based or airborne active remote sensing should provide a more interactive airborne in situ sampling strategy in response to the observed conditions.

The second aspect involves analysis. Although a significant amount of in situ turbulence data has been analyzed, more quality observations in cirrus clouds are sorely needed. Additional observations would help establish the significance of present findings, an important concern given the existing ambiguities. They would also provide a better sample over the variety of cirrus cloud types and situations. In particular, observations in tropical and anvil cirrus clouds are badly needed. In some instances, a more detailed analysis of existing data by wavelet analysis in combination with a thorough analysis of microphysical and radiation measurements could provide significantly more insight into the processes at work. More studies are needed that combine in situ measurements of turbulence and ice particles with remote sensing data to better comprehend cloud microphysical parameters and macroscopic cloud structure.

Contrails are a special form of cirrus about which there are many unanswered questions: How do persistent contrails evolve with time, and what are their microphysical, morphological, and radiative properties? Which are the most important aircraft parameters controlling the properties of persistent contrails: the number of aircraft cruising; the amount of fuel consumed; the number of condensation nuclei and ice nuclei induced by aircraft; soot, sulfuric acid droplets, and mixed aerosols induced by aircraft; or turbulent mixing induced by aircraft? Which are the most important environmental parameters controlling the properties of persistent contrails: ambient temperature, relative humidity, rising or sinking air motions, wind shear, turbulence, solar and terrestrial radiation, ambient aerosol properties, or preexisting cirrus clouds? Which air masses are conditioned to form persistent contrails, how thick and wide are such air masses, how are these air masses distributed over the globe, and how are these air masses related to large-scale dynamics of the atmosphere? What is the contrail cloud cover over regions other than over Europe and the United States? Is mean contrail cover increasing, and how is this increase related to air traffic properties? What will be the future change in contrail cover? How does the future change in contrail cover depend on parameters of future air traffic and future climate? How do aircraft change background aerosol with respect to cloud-forming properties? What is the impact of aircraft-induced aerosol changes on the microphysical properties, optical properties, areal coverage, and frequency of occurrence of cirrus clouds? Is the mean cirrus cover increasings and which part of this increase is due to aircraft? What are the consequences of cirrus changes for radiative forcing, for the hydrological cycle, for air chemistry, and climate? Is there an observable relationship between aircraft-produced aerosol and cirrus properties? How can one model the contrail–aerosol–cirrus cloud relationships? What is the most efficient strategy to reduce aircraft impact on cirrus clouds? Measurements should be performed to identify the relationship between aerosols and cirrus properties, for example, by measuring in different air masses with low and high aerosol concentrations. Models should be developed to account for the indirect effects of aerosols on cirrus properties for global climate studies. Finally, remote sensing should be applied to identify contrail cover, trends in contrail and cirrus cloudiness, and changes in radiative properties of cirrus clouds.

21.2. Radiative Properties

Although many models predict that cirrus should warm the Earth, they can assume the opposite effect as the optical depth increases. Pivotal factors include cloud height, optical depth, and mean crystal size. Ice clouds possess different solar reflection characteristics from water clouds. Yet cirrus are composed of a mixture of a variety of ice crystal habits and sizes, where one habit may predominate, depending on temperature and saturation. The solar reflection can change depending on the ice crystal habit. These differences have wide implications for climate research. What is required to solve the problem of cirrus–radiation interaction is a two-pronged approach of modeling of ice crystal scattering and carefully designed observational programs.

The asymmetry parameter determines the relative amount of sunlight scattered downward to Earth and upward to space. Recent modeling using different ideal ice crystal shapes has given varying ice crystal scattering phase functions that yield different asymmetry parameters. Ice crystal models have also been run for distorted crystals, thus changing the asymmetry parameters. Such work is crucial to our understanding of energy balance and should be expanded in combination with experimental verification.

The concerted modeling approach should be supplemented by comprehensive aircraft experiments that measure ice crystal shape, irregularity and size, fluxes of solar and infrared radiation, and lidar backscatter intensities. New instruments that are operating will measure asymmetry parameter directly; this will lead to significant advances in understanding how cirrus reflect solar radiation. The experiments should be repeated at many different cirrus temperatures. Lidar backscatter-to-extinction ratios are also affected by ice crystal habit and deformation. Methods for using lidar backscatter to derive the scattering phase function and asymmetry factor would allow resolution of the radiation–cloud interaction problem.

Deriving cloud physical and optical properties in all conditions remains a challenge for cirrus remote sensing, especially from satellites. With better estimates of cirrus optical depth, effective particle sizes, and shapes in all conditions, it will be possible to improve our estimates of ice water path, a quantity fundamentally important in general circulation models. Although substantial improvements were made in the 1990s, much more research is needed to accurately determine the parameters that tie the hydrological and radiative processes together in the upper troposphere. Because reflected solar radiation contains more information about the clouds than emitted radiation, refined techniques are needed for retrieving cirrus properties at night. However, measurements and calculation of infrared properties, for instance by LIRAD, can be related to visible optical depth theoretically. Consistent day–night retrievals of all of the cirrus parameters will enhance our ability to fully understand the radiative and dynamic processes governing cirrus growth and dissipation. Methods need to be developed for identifying cirrus in multilayered cloud fields and isolating their effects during both day and night. Algorithms for systematically using multiangle satellite data, either on a single instrument or on two satellites, should be developed to monitor cirrus properties, especially cloud particle shape, more accurately than possible with current approaches. Satellites with a nearly direct backscatter view would be particularly valuable for estimating particle shape.

The physical thickness of cirrus is an especially elusive quantity for operational cloud monitoring from satellites. Advances in determining cloud thickness will be valuable for a variety of applications, including the computation of atmospheric and surface radiative heating. Future satellite sensors will contain much of the information needed for deriving cirrus properties, but development of a variety of innovative and practical techniques is essential if the host of data from those instruments are to be converted into useful scientific products.

To obtain the global view of the climatic importance of cirrus clouds, measurements from earth-orbiting satellites are a necessity. Although passive, multispectral satellite measurements have shown promise for studying high clouds, and the latest generation of radiometers have recently been launched into orbit, major advances can only be expected after active remote sensing space-borne measurements are added to complement the passive data streams. The physical thickness of cirrus is an especially elusive quantity for operational cloud monitoring from satellites. Advances in determining cloud thickness will be valuable for a variety of applications, including the computation of atmospheric and surface radiative heating. The ability to measure cloud thickness directly from space on a global scale using lidar and radar is of vital importance in understanding and monitoring the global radiation budget.

21.3. Modeling

Cirrus span a wide range of optical thicknesses that encompass both positive and negative net cloud forcing. The processes responsible for their formation, maintenance, and dissipation are not yet adequately understood. Therefore, the role of cirrus in climate change is potentially significant but currently impossible to quantify, even as to the sign of their net feedback. Crucial areas for future investigation include 1) the dynamic scales of motion that are primarily responsible for the transport of water vapor to the upper troposphere that results in cirrus formation; 2) the vapor saturation conditions required to form cirrus at different temperatures and in different dynamic regimes; 3) the global importance of cirrus contrail formation and the potential indirect effect on cirrus of aerosols lofted from the planetary boundary layer into the upper troposphere; 4) factors controlling the small-scale variability statistics of cirrus and their impact on large-scale representations of cirrus radiative effects and microphysical processes; 5) environmental factors determining the strength of convective condensate transport and detrainment into mesoscale cirrus anvils; 6) a global assessment of the relative fractions of supercooled liquid water and ice in the atmosphere as a function of temperature, dynamics, cloud age, and so on, which in turn requires the development and implementation of remote sensing techniques that can measure ice water path; and 7) similarities and differences between mid-latitude and tropical cirrus and between cirrus and winter or polar low-level ice clouds.

Therefore we should promote a close cooperation between the measuring and observing community, on one hand, and the modeling community on the other. The former may be given a better insight into the modeler's request for observational data, while the latter will learn about potentials and limitations in measurements and observations.

21.4. Conclusion

The outlook for making major strides in our understanding of those cirrus cloud properties of importance to climate research is promising in terms of improved in situ probes, satellite and ground-based remote sensing techniques, and numerical modeling. However, some of the problems are so complex that one may ask whether a solution to them is possible at all. For example, given a complete physical description of a parcel of air, it is still difficult to predict the size and shapes of the crystals that actually form. For many other questions, the methods exist at least in principle, but focused research programs for applying them to provide the answers in reasonable time scales are missing. Fortunately, plans are currently being finalized to orbit both a lidar (PICASSO) and 95-GHz radar (CloudSat) and other sensors in formation, along with the latest generation of Earth-orbiting satellites, to profile clouds and aerosols on a global scale. These new satellites represent the first step into a deeper realm of monitoring the clouds, including the tenuous upper tropospheric cirrus. We hope that the importance and beauty of cirrus clouds, as described in this book, will attract further scientists and research programs to promote progress in understanding.

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