1 Meteorology and radar

If you live in an affluent country, chances are good that one or more radars dedicated to the monitoring of weather take regular measurements of the atmosphere above you. Radar has become a standard instrument in meteorology, joining the thermometer, the radiosonde, and satellite-based imagers as tools used operationally in weather offices. Its images are widely distributed and frequently consulted: in many countries, the web pages showing weather radar images are among the most frequently visited government sites. It is also a key instrument used in research to understand weather phenomena, particularly cloud and precipitation processes. It hence appears that the use of radar in meteorology is here to stay. How and why did this happen?

1.1 How it all started

The year was 1940. World War II raged. The improvement of a decade-old invention, the radar, was being stimulated by the need to detect raiding airplanes and submarines capable of sinking convoys. The radars then transmitted long radio frequency waves and received echoes that bounce off targets, allowing military personnel to detect the enemy at sufficiently long distances to be able to react to the threat. However, at that time, they were huge devices that looked much more like modern-day radio station transmitting antennas, and their angular resolution was poor. A new technological development, the magnetron, provided a solution to this problem by allowing radar to use much shorter wavelengths, microwaves, to achieve the same task; as a result, radar units could become much smaller and be easily moved and installed on aircraft. By the following year, magnetron-based radars were detecting large patches of echoes of unknown origin. It was soon realized that these echoes were caused by precipitation.

War secrecy prevented the publication of such results. Fortunately, during World War II, most meteorological services were part of the military because of the strategic use of weather forecasting. Meteorology personnel were hence shown these images, and immediately realized their potential. Small research groups within the military quickly formed to investigate how this information could be further exploited.

To understand the historical importance of radar as a meteorological tool, it is necessary to remember the state of observing systems at that time. Satellites did not exist, but surface and upper-air observations were taken regularly. This observation network made it possible to map the large- or synoptic-scale patterns of weather systems (>200 km), permitting the detection and the tracking of extratropical cyclones and of anticyclones reasonably well over land, but not as well over oceans. At the other end of the spectrum, human observers at weather stations could

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Figure 1.1. Weather radars then and now. Left: picture of a CPS-9 radar, one of the first radars specifically designed for monitoring weather. This particular unit served as the operational radar for the Montreal area from 1954 to 1968 (photo courtesy of Véronique Meunier). Right: the current radar facility in Montreal.

describe the weather at the local scale (<10 km). There was no way to map and study phenomena occurring between these two scales. Radar closed this gap, and the mesoscale was first defined as the scale that could only be studied by this instrument. After the war, radars were put to use in research to observe and understand thunderstorms and their life cycle, and much of what we know of convective storms has been learned using radar observations. Research also focused on understanding cloud and precipitation mechanisms, on what information this new tool could provide, and on how weather radars could be improved. "Radar meteorology" was born.

At the same time, the ability of radar to monitor rapidly developing events such as thunderstorms as well as to track the speed and direction of movement of precipitation systems made it also very interesting for real-time operations. Radars specifically designed to be used for weather monitoring and forecasting were deployed in the early 1950s (Fig. 1.1). The first radar network in the United States was set up in the late 1950s, one of its main roles being to provide advance warning of hurricanes.

1.2 Why radars now

Much has changed since that era. For instance, many more remote sensors have been developed and are being used in meteorology, particularly satellite-based imagers that can obtain data frequently over large portions of the globe. But at the same time, radars used for weather monitoring have undergone considerable transformations (Fig. 1.1), including the ability to obtain wind information using the Doppler effect and to infer the type of echoes observed by transmitting and receiving waves at more than one polarization.

Radar still continues to be used in meteorology nowadays, probably more than ever. Why?

1. Radar remains the best instrument for monitoring the occurrence and movement of precipitation patterns, and people do care about precipitation. A survey about how the public uses and values weather forecasts revealed that precipitation timing, probability, location, type, and intensity forecasts were judged the most important components of weather forecasts along with maximum temperature (Lazo *et al*. 2009). Radars provide the best information on these specifics in the short term (0–6 h), and this alone explains why radar images are so often consulted by the public.
2. Of equal or greater importance, and not mentioned in the survey, is the fact that radar also remains our best tool to detect or infer the presence of many hazardous weather conditions such as severe thunderstorms, hail, and tornadoes. It is able to do so because it is one of the rare instruments that can obtain weather-related information in three dimensions (x, y, z) as a function of time. It can see within storms, a medium through which most electromagnetic radiation cannot penetrate, and can be used to assess their severity using information from the reflectivity, Doppler velocity, and polarization of echoes. Together with satellite imagers, it generally provides us with our last opportunity to recognize whether a previously issued forecast is proving to be wrong and needs to be corrected.
3. Finally, this information is available immediately, and can therefore be used at once.

As a result, there are now networks of radars in many countries whose sole task is weather surveillance, or round-the-clock monitoring of weather events (Fig. 1.2). In fact, at present, the issuance of severe weather warnings is often based on radar observations. Until recently, the limited maximum range of radars (a few hundred kilometers) has hampered their use for larger scale systems. For those situations, geostationary satellite imagers generally provide a much more complete picture, though of clouds rather than of precipitation. But thanks to our increasingly fast communication infrastructure, it is now possible to combine imagery and information from multiple radars in real time and thus obtain useful precipitation monitoring over much larger areas than before. As a result, there is now room for the expansion of the role of radars in meteorology, particularly over large continents, though not as much for island states (Fig. 1.3).

Operational radars also come in a few flavors. In addition to scanning radars that are used for weather surveillance, there are also wind profilers used primarily to derive wind information, and sometimes temperature, above the radar location as a function of height and time. Originally used exclusively for high-atmosphere work, wind profilers have found their place in the arsenal of tools available to meteorologists to supplement radiosonde information. In many countries, they now monitor the current weather and provide data that can be used to initialize numerical prediction models. Finally, there exist many types of research radars that are as varied in size, shape, and mode of operation as are the applications that stimulated their design.

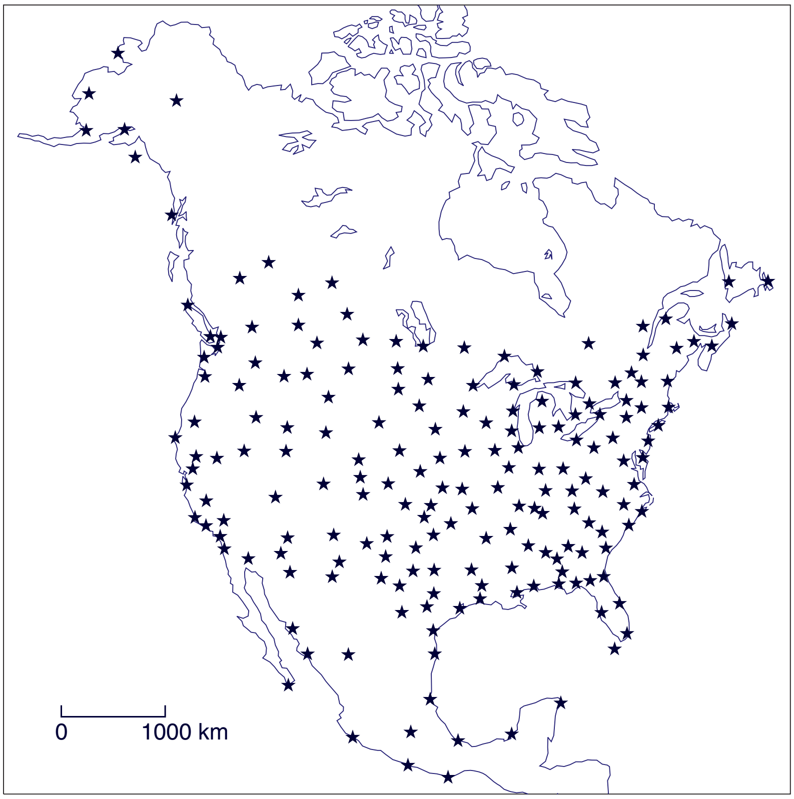

Figure 1.2. North American network of weather surveillance radars circa 2015. Not included in this figure are weather radars dedicated for airport terminal use like the US Terminal Doppler Weather Radars (TDWR) and those owned by nongovernmental organizations such as TV stations.

1.3 Understanding radar observations

The ability of radars to see inside storms and gauge their severity and precipitation intensity makes it a tool of choice for operational meteorologists, researchers, and hydrologists. But radar is also a complex tool, and remote sensing has limitations that must be understood in order to best make sense of the observations. Although considerable progress has been made to quality control the radar data used by meteorologists, radar data processors still cannot succeed in completely removing the many observation artifacts. While detailed technical knowledge of the radar is not required to use its data, a conceptual understanding of the process and limitations of remote sensing measurements is essential to comprehend why things are done the way they are, as well as what problems may arise in the data as a result. This understanding will then help us make the most judicious use of the information.

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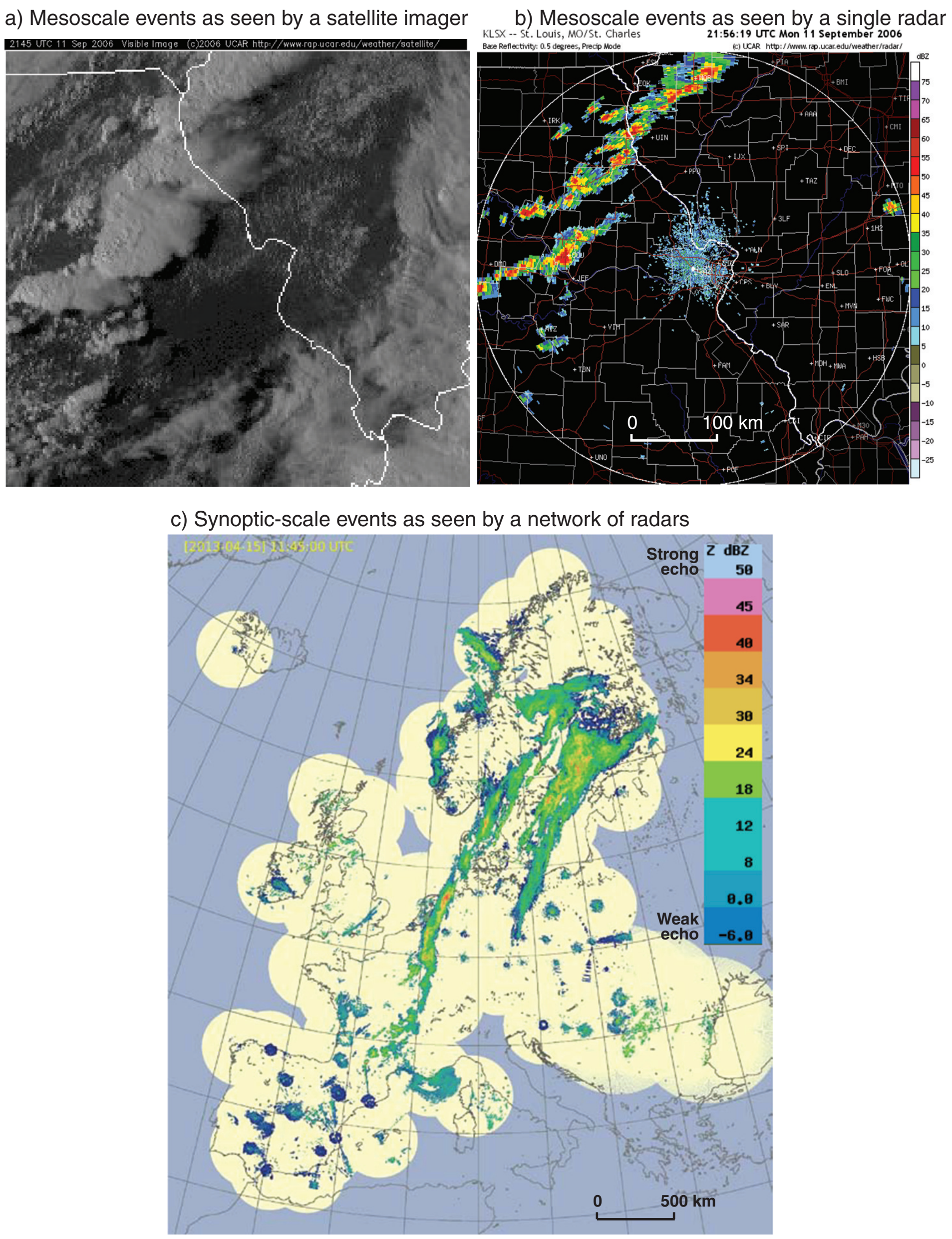

Figure 1.3. Illustration of the information conveyed by radar for mesoscale and synoptic-scale systems. On the top row, the imagery obtained by (a) a satellite-borne visible light imager and (b) a radar is contrasted for mesoscale weather events (© 2006 University Corporation for Atmospheric Research (UCAR), used with permission). On the bottom, a composite image from multiple radars is shown (republished with permission from the American Meteorological Society (AMS) from Huuskonen *et al*. (2014); permission conveyed through Copyright Clearance Center, Inc). For synoptic-scale events, single-radar displays, that generally have diameters of at most 500 km, do not provide a complete picture of weather systems, though this can be achieved by combining multiple radars. At the mesoscale, radar is generally more useful than satellite imagers to determine the location and intensity of convective events.

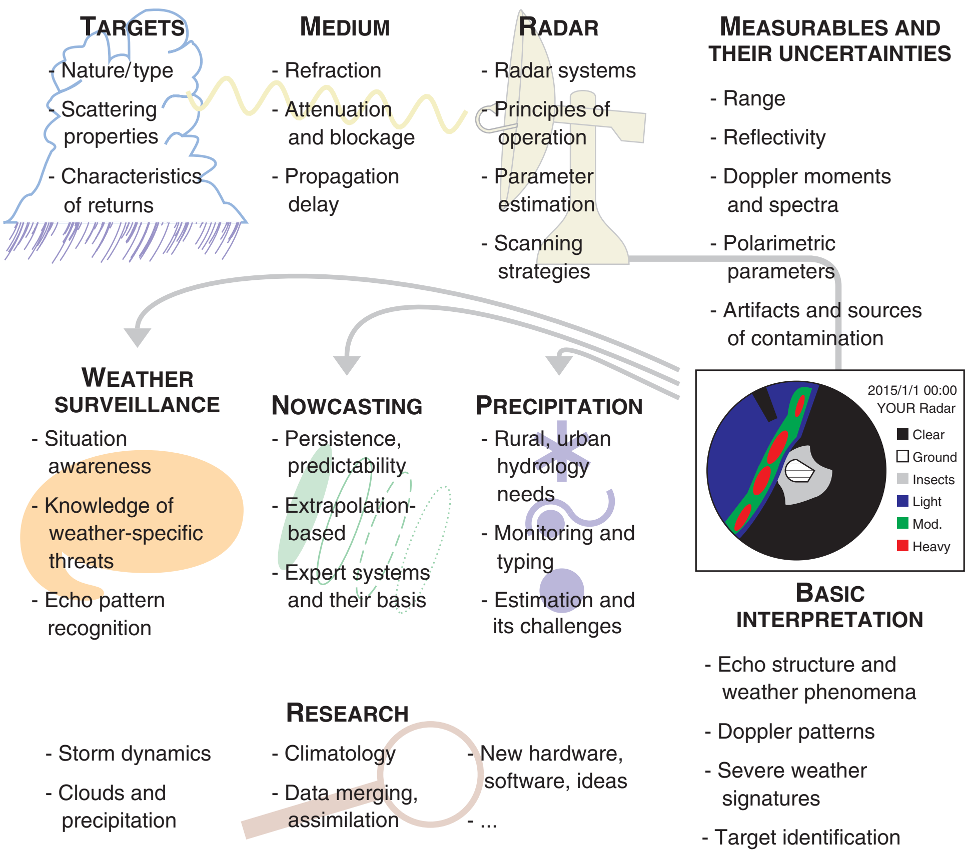

Figure 1.4. Concept map of radar meteorology illustrating the data provided by radars, issues of importance in the interpretation of that data, and the uses of that information in meteorology.

As illustrated in Fig. 1.4, proper understanding of radar data requires some basic knowledge of a variety of topics, including radar operation, propagation, scattering, as well as measurements and their uncertainties. This technical aspect of weather radar measurements has historically been at the center of courses in radar meteorology. But one should keep in mind that the reason we use radars so much is because of the insights they allow us to obtain about weather phenomena. As a result, it is impossible to fully make use of the radar data without understanding both the meteorological phenomena that are observed by this instrument and the value of the information gathered for meteorological or hydrological applications. This is why this book not only presents what radar can observe but also provides some background information on the atmospheric processes shaping the radar imagery and on how we can use the information provided by radar for meteorological and hydrological applications.

The book is structured in three parts. The first section introduces basic radar principles and imagery: what quantities do we measure? How do we recognize different types of targets, or different signatures? On what basis are the inferences made? The second section deals with key applications of radar data, starting with operational uses such as monitoring of convective and widespread systems, precipitation estimation, and short-term forecasting, and progressively shifting to more research-oriented questions including retrievals, cloud and climate uses, and the complicated question of what radar really measures. To provide a support to some of the more technical discussions, an appendix on mathematical and statistical concepts used in radar meteorology completes this book.

1.4 Supplemental readings

For more information on the early years of radar meteorology, the reader is referred to Fleming (1996) that contains many radar-related historical accounts including a chapter on the beginnings of radar meteorology, and other chapters on additional meteorological activities where radar plays a role (e.g., broadcasting). For the most thorough discussion of the history of radar meteorology, Atlas (1990) remains the book of choice: it contains a compendium of knowledge in radar meteorology as of 1990. The early chapters focus on the beginnings of radars at various institutions as well as the historical impacts of radar in various meteorological specializations.

2 Fundamentals of weather radar measurements

2.1 Radar: an active remote sensor

To gather information about the world around us, we rely on a variety of sensing mechanisms. Some, such as touch or taste, are based on *in situ* sensing: the sensor must be in direct contact with an object to gather information about it. Others, such as sight, use remote sensing: the sensor can be some distance away from the object. For remote sensors to work, information must travel between the object and the sensor. Most remote sensors rely on the detection of acoustic waves (sound) or electromagnetic (EM) waves (light, heat, and radio waves, among others) to gather that information.

While the applications of remote sensing are extremely varied, the principles and the process of data gathering are extremely similar. Most remote sensors basically measure the energy received for certain ranges of wavelengths, preferably from a given direction, as a function of time. That energy is either emitted or reflected by the object observed.

Radar, an acronym for RAdio Detection And Ranging, refers to an instrument that emits a strong signal at radio or microwave frequencies and then listens for echoes that occur if the signal reflects off objects known as targets (remember, radar was first a military instrument). And since it provides illumination to the target – like a camera and a flash do, and unlike the way our eyes rely on an external source such as the Sun – it is referred to as an active remote sensor.

Because of the need for an energy source, active remote sensors such as radars tend to be more complex than passive remote sensors such as satellite imagers. But that extra complication comes with benefits. Since we know what was transmitted and when, active remote sensors can make additional measurements compared to passive sensors: How much time elapsed between the transmission of the signal and the reception of the echo? How strong is the signal compared to what was transmitted? Has the frequency or the polarization of the signal changed? These crucial pieces of information give us additional clues on the object being studied, as well as on the medium between the sensor and the object.

From these measurements, and given a model or a mental picture of what we should observe, we interpret the properties measured in order to obtain information on the size, composition, and distance of the object. All remote sensors rely on the combination of detection and interpretation systems. Just as we use our eyes and our brain to understand the scene being observed, artificial sensors use the instrument and the data processing software as a detection–interpretation system. This last step is crucial and poorly recognized: whatever the level of sophistication of the sensor, it is only as good as the assumptions on which the interpretation is based and their implementation in the data processing system. As our eye–brain system can be fooled (optical illusions are proof of that), so can systems based on radar.

What does a radar do?

a. It first generates a strong microwave signal. The task of generating that signal is accomplished by the radar transmitter.
b. It then focuses the signal in one direction, to get information from targets that are located along that specific alone. This is the role of the antenna.
c. It receives the (very) faint echoes from the targets, the intensity of the returned signal being a tiny fraction of what was emitted. The reception of that signal is made possible by the combination of the antenna, which focuses the returns back into the radar system, and the radar receiver.
d. It then extracts as much raw data as possible from the received signals, for example, target range, echo strength, and velocity. Signal processors perform this duty.
e. It processes the raw data to obtain meteorological information. The task of sifting through the large amount of data to produce information of interest to meteorologists is taken care of by the radar product generation hardware and software.
f. It finally displays and disseminates the information, using a radar product display system.

Note that the components involved in the last two functions may or may not be physically located at the radar site; therefore, whether they are considered to be part of the radar system or not is a matter of interpretation. Nevertheless, their existence somewhere is essential to make use of the information obtained. For a quick presentation illustrating what a radar system looks like, consult the electronic supplement e02.1 (figure numbers starting with the letter e refer to electronic material accessible at http://www.cambridge.org/fabry).

After this brief outline of the radar, let us turn our attention to what we intend to use it for: gather information about the atmosphere.

2.2 Microwaves and the atmosphere

We generally are intuitively familiar with many properties of the atmosphere at visible wavelengths. For example, we know that the dry atmosphere is mostly transparent, except for some scattering of blue light that results in the blue sky during the day. We also know that clouds, and to a lesser extent precipitation, scatter light at all wavelengths in the visible part of the spectrum, giving rise to white clouds and thin grayish precipitation trails. However, these properties change considerably with wavelength. The interactions between

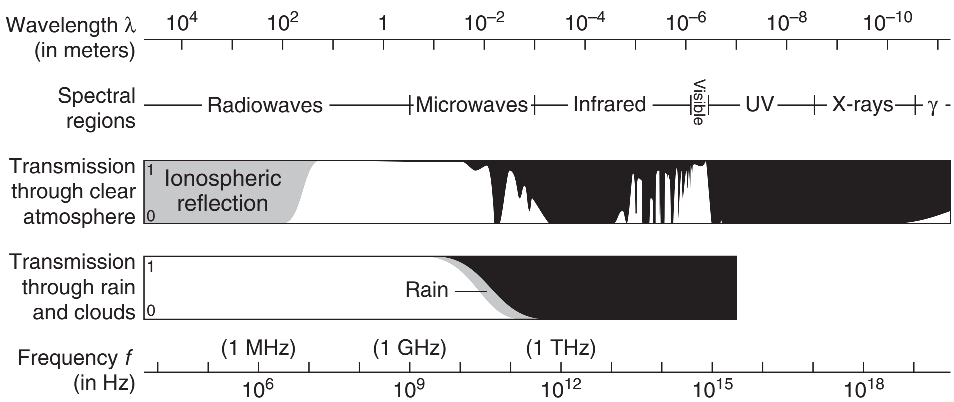

Figure 2.1. The electromagnetic spectrum from radio waves to gamma rays, and the direct zenith transmissivity of the clear atmosphere and of rain and clouds as a function of wavelength. Spectral regions of high transmissivity (all-white areas) are the atmospheric windows.

the atmosphere and microwaves can therefore be very different than those involving radiation at visible wavelengths. Furthermore, both physical and engineering considerations determine what type of information can be obtained by microwave active remote sensing, and they mesh in complicated ways. To understand how remote sensing functions at microwave wavelengths, it then becomes necessary to shed some of our preconceived ideas and try to view the world from the perspective of a radar system.

2.2.1 The radio wave and microwave atmospheric window

For information to travel between an object and a sensor, the medium between the two must allow it. The transparency of the atmosphere to EM waves depends critically on the wavelength of those waves. Figure 2.1 illustrates the direct transmissivity at zenith of the clear and cloudy atmosphere to a variety of EM waves. The atmosphere is transparent only to limited regions of the EM spectrum known as atmospheric windows. These include visible light, narrow regions in the near and thermal infrared, and a large window for the longer microwaves and shorter radio waves (from 1 cm to tens of meters). Radars operate in the latter region, while laser-based systems known as lidars operate in the infrared, visible, and ultraviolet wavelengths. Interestingly, longer microwaves and radio waves will also travel through clouds and most storms without being seriously attenuated. This rare all-weather atmospheric window allows radars to see through storms as well as cover much broader areas than is possible with ground-based optical remote sensing.

The radio wave and microwave atmospheric window covers four orders of magnitude in wavelength, and radars operate over this entire range. In contrast, thermal infrared and visible wavelengths are "only" 1.3 orders of magnitude apart, and this difference is large enough to radically change the atmospheric properties that can be observed and the