RADAR METEOROLOGY IN THE TROPICS

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Contents

Summary

Radar technology has provided an unprecedented view of storm structure in the tropics. Beginning in the late 1960s, radar deployments during field campaigns have highlighted all aspects of tropical convection, including its distribution and vertical structure, how it organizes, and how it interacts with the large-scale circulation via transports of moisture, heat, and momentum.

In addition, radar observations from operational aircraft have provided exceptional details on tropical cyclone structure and evolution. Finally, spaceborne radars have allowed a tropics-wide view of precipitation and clouds.

1. Introduction

Tropical storm systems provide on the order of 1-2 m of rain across the tropics each year. In some locations, annual rainfall exceeds 3 m. This rain is essential to the livelihoods of people that live in the tropics and is also a main driver of the global circulation. Radar provides a good measure of rainfall over large areas (typically a 150 km radius from the radar itself). In addition, radar is a unique tool in that it can observe the internal structure of storms.

Most insight on tropical weather using radars has come from field campaigns. Large field experiments provide the infrastructure necessary for the deployment of radars, whether they are on the ground, on ships, or on aircraft. A few longer-term ground radar datasets exist, but since most of the tropics are ocean there are limited locations to host a long-term ground site. Within the past decade, a precipitation radar and cloud radar have been launched in space, thus providing consistent radar coverage of tropical cloud systems over both land and ocean.

Section 2 provides a brief introduction on radar technology and capabilities. Section 3 highlights radar insights about tropical convection from important field campaigns over the past 40 years, while Section 4 focuses on insights about tropical cyclones using airborne radar. Section 5 discusses satellite-based radar observations of the tropics.

2. Radar Background

Radar is an acronym that stands for “Radio Detection and Ranging”. The technology grew from the idea of using pulses of energy for target detection during World War II. After the war, research into the uses of radar for weather studies (i.e., the detection of a volume of precipitation-size particles instead of the detection of individual ships and planes) blossomed.

A radar consists of a transmitter that generates an electromagnetic signal and an antenna to send out the signal and receive echo back from a target. The total received radar power, P, can be expressed as:

$$P = Z - 20 \log r - C$$

where P is measured in decibels referenced to 1 milliwatt (dBm); Z is the reflectivity factor referenced to 1 $\mathrm{mm}^6\ \mathrm{m}^{-3}$ (dBZ) and is determined by the number, size, and composition of the target; r is the range of the target from the radar in km; and C is a radar constant measured in decibels (dB) that is dependent on the hardware of the system such as wavelength and beamwidth.

When measuring rain or cloud, a radar receives power from many targets in a sample volume. Assuming all of the scatterers are water, the effective radar reflectivity factor, Z_e, can be expressed as:

$$Z_{\mathrm{e}} = \int_{0}^{\infty} N(D) D^{6} dD$$

where D is the diameter of the hydrometeor and N is the drop concentration. Note the D^6 dependence, which places a heavier weight on the size rather than the number of hydrometeors.

Precipitation ranges in size from 0.5-6 mm (or even larger for hail); electromagnetic wavelengths of 2-10 cm (or frequencies of 3-15 GHz) are used to detect these size particles. Thus, radars that operate at these wavelengths are often called precipitation or weather radars. The most commonly used weather radar wavelengths are 10 cm (S-band), 5 cm (C-band), and 3 cm (X-band). See Table 1 for a full list of radar bands, wavelengths, and frequencies. More recently, efforts have been made exploring the meteorological uses of mm-wavelength radars (or frequencies of 35-94 GHz). Radars that operate at these wavelengths are called cloud radars because they are more sensitive than precipitation radars and can see cloud-size particles. However, they attenuate in moderate and heavy rain. The most commonly used cloud radar wavelengths are 8.6 mm (K_a-band) and 3.3 mm (W-band). Most of the following discussion will focus on our understanding of tropical meteorology via cm-wavelength radars, but mm-wavelength technology offers a nice complement to precipitation radars when studying tropical cloud systems.

Radar Band	**Frequency (f)***	**Wavelength (λ)***
L	1 – 2 GHz	15 – 30 cm
S	2 – 4 GHz	8 – 15 cm
C	4 – 8 GHz	4 – 8 cm
X	8 – 12 GHz	2.5 – 4 cm
K_u	12 – 18 GHz	1.7 – 2.5 cm
K	18 – 27 GHz	1.2 – 1.7 cm
K_a	27 – 40 GHz	0.75 – 1.2 cm
W	40 – 300 GHz	1 – 7.5 cm

* Note: $\lambda f = c$

Table 1. Radar Bands (Adapted from Rinehart 2004)

Beyond sensing the power returned from a volume of precipitation or cloud particles, many radars also have the ability to determine the speed and direction of the particles (i.e., Doppler capabilities). Doppler radars measure the speed of a target toward or away from the radar (also called the radial velocity) using a shift of the return frequency. When two Doppler radars view the same region of a storm, dual-Doppler analysis can be done to better constrain horizontal and vertical air motions.

Some radars can send and receive electromagnetic radiation with different orientations (i.e., polarimetric capabilities). This ability allows radars to receive information about the polarization of the scatterers, which can then be used to tell something about a particle’s shape, size, and composition. For example, as rain drops grow they become more oblate such that the horizontal reflectivity (Z_{HH}) will be larger than the vertical reflectivity (Z_{VV}). Small rain drops (< 1 mm in diameter) are spherical and will return equal Z_{HH} and Z_{VV}. Hail, which by definition is > 5 mm in diameter and often tumbles when it falls, will also return nearly equal Z_{HH} and Z_{VV} but with a larger magnitude of Z_{HH} because of its large size. Common polarimetric variables are differential reflectivity (ZDR), which is the ratio of Z_{HH} and Z_{VV}, and differential propagation phase (K_{DP}), which is determined based on a phase shift of the radar wave and provides an indication of the liquid water content along the path of the radar beam. Polarization diversity allows improved hydrometeor classification and rain estimation.

Radars typically scan in azimuth and in elevation. A scan in azimuth with a fixed elevation is called a plan position indicator (PPI) and provides a horizontal view of a storm. A scan in elevation with a fixed azimuth is called a range-height indicator (RHI) and provides a vertical view of a storm. Multiple PPIs at different elevations allow the radar to scan the full volume of a storm. A cross-section of a storm at a constant height can be interpolated from the full volume data and is called a constant altitude PPI (CAPPI). Figure 1 shows an example radar scan strategy with 16 tilts ranging from 0.5° to 33° in elevation. The curvature of the earth causes the beams to curve upward relative to the surface. The refractivity of the atmosphere can also affect the slant range of a radar beam. Because the lowest tilt becomes progressively higher in height away from the radar, a data gap occurs near the surface that can be quite pronounced (e.g., the center of a 0.5° beam will be located 2.5 km above the surface 150 km from the radar assuming a standard atmosphere). Thus, a radar can only observe "near-surface" reflectivity.

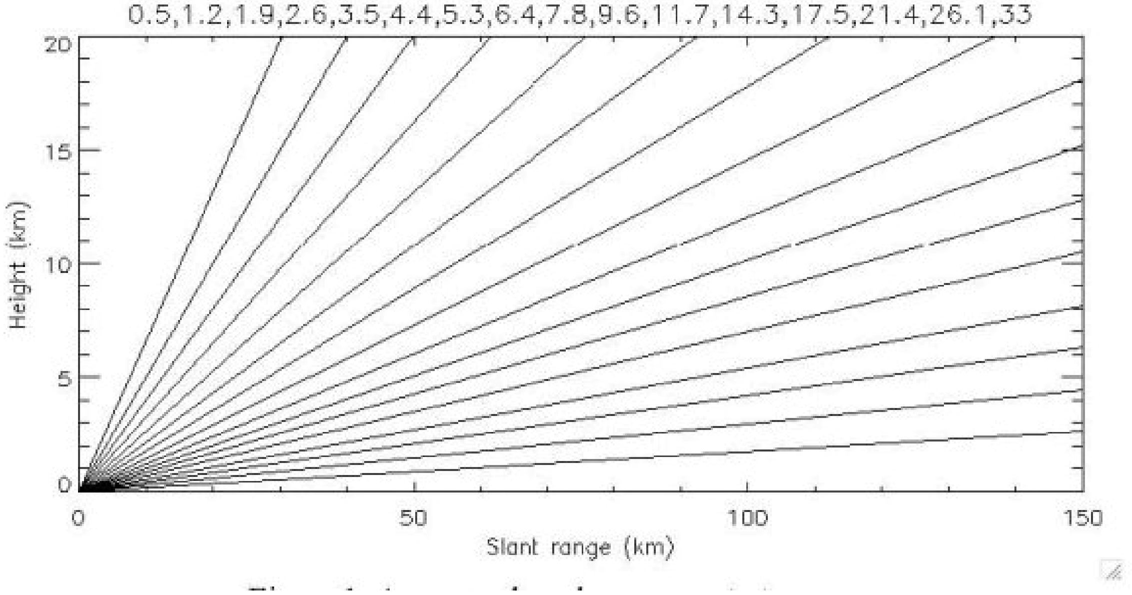

Figure 1. An example volume scan strategy.

Reflectivity near the surface is useful in order to calculate surface rainfall. The most common method to convert reflectivity (Z) to rain rate (R) is to use a *Z-R* relation. *Z-R* relations proliferate the literature but Table 2 lists some representative Z-R relations measured during tropical field campaigns. Implicit in this list is the fact that multiple rain rates can be associated with the same reflectivity because of variations in the drop-size distribution. For example 40 dBZ is equal to 23.2 mm h^{-1} using the GATE *Z-R* relation, while it equal to 10.9 mm h^{-1} using the EPIC *Z-R* relation. Variations in the drop-size distribution (and thus *Z-R* relation) can be temporal and geographical so it is hard to know if an instantaneous rain rate calculated with a fixed *Z-R* relation is necessarily correct, but overall accumulations should be reasonable if an appropriate climatological *Z-R* relation is used. In addition, one must take into account a host of other potential issues that may affect rain rate estimation from near-surface reflectivity (e.g., evaporation, horizontal advection, vertical air motions, attenuation, partial beam filling, and bright band contamination). Despite these issues, radar is an excellent tool with which to measure rain over large spatial domains, as well as to investigate vertical storm structure.

Campaign	***Z-R***	**Reference**
GATE	$Z=230R^{1.2}$	Hudlow et al. (1979)
COARE	Convective $Z=139R^{1.43}$ Stratiform $Z=367R^{1.3}$	Tokay and Short (1996)
MCTEX	$Z=411R^{1.22}$	Keenan et al. (2000)
TRMM-LBA	$Z=465R^{1.08}$ $Z=238R^{1.43}$	Carey and Rutledge (2000) Cifelli et al (2002)
KWAJEX	$Z=175R^{1.5}$	Houze et al. (2004)
EPIC	$Z=218R^{1.6}$	Pereira and Rutledge (2006)
TCs	$Z=300R^{1.35}$	Jorgensen and Willis (1982)
TRMM PR	Convective $Z=147R^{1.55}$ Stratiform $Z=276R^{1.49}$	Iguchi et al. (2000)

Table 2. Reflectivity-rain rate (*Z-R*) relations.

3. Field Campaigns

3.1. Hot towers and mesoscale convective systems (MCSs)

Riehl and Malkus (1958) introduced the idea that undilute cumulonimbus towers (or “hot towers”) are necessary to export the net energy gain at the surface in equatorial regions toward higher latitudes. Riehl and Simpson (1979) revisited Riehl and Malkus (1958) and used radar observations to support the concept that the vertical energy transport in cumulonimbus clouds is important in maintaining the tropospheric energy balance. In particular, they used radar echo top information to indicate the deep vertical extent of the hot towers and used radar observations to help quantify the number of hot towers needed to maintain tropospheric energy balance by overcoming the mid-tropospheric minimum of moist static energy (i.e., 1500-5000 in the equatorial trough zone). In the past 50 years, a large body of research has been focused on the nature of tropical convection and how models capture it. Toward this goal, radar has played an important role in physical process studies and model parameterization and validation.

The tropics are also home to larger, more organized convective systems. These mesoscale convective systems (MCSs) contain both deep convective cells and a more horizontally uniform precipitating anvil cloud (also called the stratiform rain region). Tropical squall lines, which are fast moving MCSs with an arc-shaped leading convective edge, were initially inferred from conventional meteorological observations by Hamilton and Archbold (1945). It wasn’t until field campaigns in the late 1960s and early 1970s that tropical squall lines and other types of MCSs were documented using radar. These radar observations laid the foundation for understanding the importance of convective organization in tropical cloud systems. In particular, the mesoscale portion of these storms was shown to have its own kinematic structure and to be significant in terms of rain production. In addition, organized convective systems were shown to be important in the source and transport of heat, moisture, and momentum, which in turn affect the large-scale atmospheric circulation.

The rest of this section will discuss insights gleaned from the use of radar data in tropical field campaign settings. The locations of some of the campaigns to be discussed are shown in Figure 2. Field campaigns associated with tropical cyclone research will be covered in the following section.

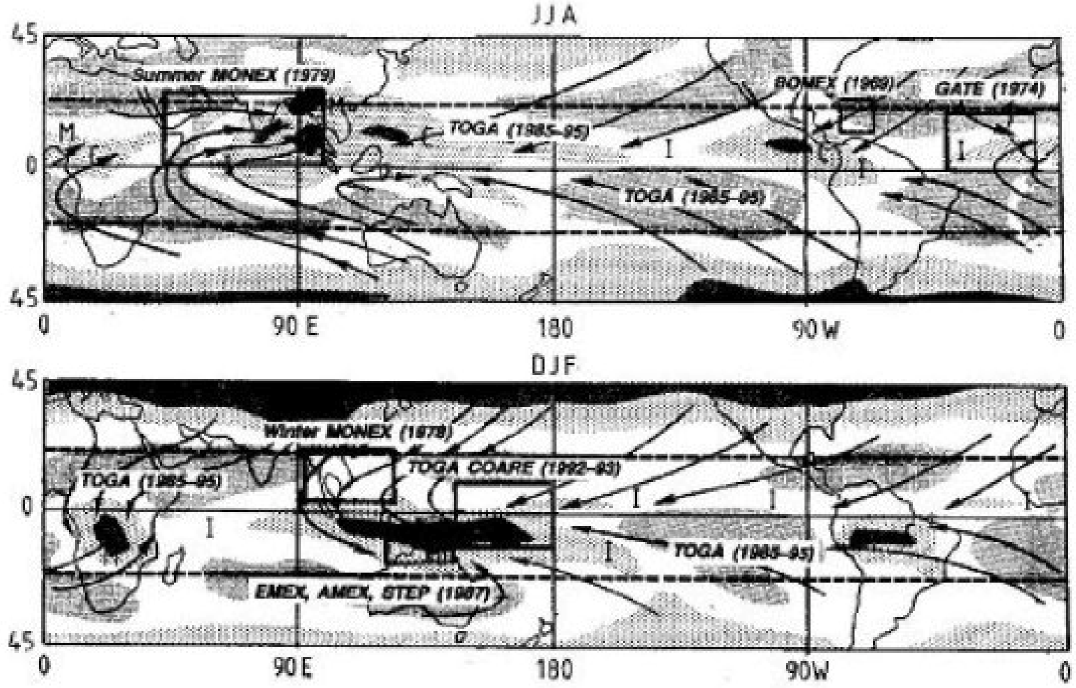

Figure 2. Schematic view of surface circulation of the tropics for the boreal summer (upper panel) and winter (lower panel). Contours show the long term mean long-wave radiation to space (Wm^{-2}). Low radiating regions (OLR<220Wm^{-2}) are stippled and represent regions of persistence and intense convection. The solid dashed lines indicate the monsoonal and near equatorial flow, respectively. The experimental domains of GATE, Summer MONEX, Winter MONEX, and AMEX/EMEX are shown as enclosed areas. The location of planned TOGA COARE is also indicated. Adapted from Webster and Houze (1991).

3.2. Barbados Meteorological Experiment 1968

Using aircraft radar observations made during the 1968 Barbados Meteorological Experiment, Lopez (1973) analyzed the lifetimes of individual convective cells within about a dozen tropical cloud clusters that occurred in July and August. The ultimate goal of this analysis was to use the radar-observed cloud properties in conjunction with a numerical cloud model to investigate the effects cumulus clouds have on their synoptic environment. The scope on the S-band radar onboard the US Navy's Weather Reconnaissance Squadron Four aircraft was photographed every other scan. From the picture sequences, Lopez (1973) found that the average echo lifetime was 14.5 min, with the distribution skewed toward shorter-lived echoes.

Lopez (1976) revisited the 1968 Barbados Meteorological Experiment radar observations and extended the radar analysis to include echoes besides just isolated convective cells (see Figure 3 for an example composite radar map from 22 July). He also examined echo area and height statistics. Lopez (1976) showed that, like echo duration, echo area is positively skewed; and while small (< 100 km^2) echoes are most common, large (> 1000 km^2) echoes contribute more to the total rain area and thus accumulation. Echo heights were observed by an APS-45 (3 cm) radar operating in RHI mode. The echo heights were also positively skewed, with an average echo height of 4.9 km. Lopez (1976) generalized his findings to state that the distribution of echo area and height is lognormal and showed the importance of cell merging in determining the observed convective cloud distributions. Lopez (1977) further showed that these lognormal distributions seem to be universal based on radar analysis from other tropical and mid-latitude locations. Lopez (1976) also postulated that the large population of small, short-lived convective clouds are likely important in moistening the environment for the relatively infrequent but larger and longer-lived deep convective cells. These scale interactions remain an area of active research in tropical meteorology.

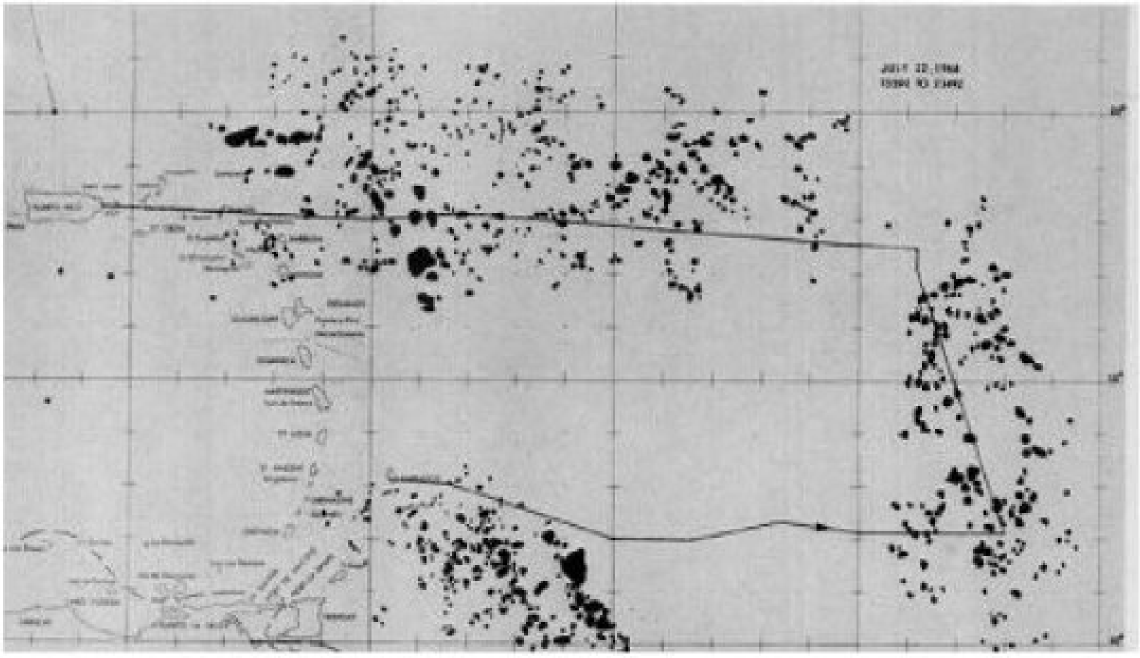

Figure 3. Composite radar map for 22 July 1968. C-scale echoes predominate. Adapted from Lopez (1976).

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Biographical Sketch

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