SATELLITE METEOROLOGY

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Contents

Summary

This chapter can largely be divided into two parts: 1, a brief review on the theoretical bases for satellite remote sensing of various meteorological parameters, and 2, several selected applications of satellite observations to tropical meteorology. In the theoretical review, the solutions to the radiative transfer equations are described under a variety of conditions, in relation to the physical principles by which certain meteorological parameters can be retrieved. That is, under clear-sky conditions, surface temperature and atmospheric temperature and moisture profiles may be retrieved, respectively, from window and sounding channels in infrared and/or microwave spectrum. Cloud properties, such as optical depth and effective radius, can be retrieved from reflected solar radiation at visible and near-infrared channels. Observations in the microwave spectrum can be used to infer such meteorological variables as precipitable water, cloud liquid water, cloud ice water, rainfall, and ocean surface wind speed. Additionally, active sensors, such as cloud and precipitation radars, can provide the vertical distribution of hydrometeors. Scatterometers, on the other hand, can measure both ocean surface speed and direction. Three topics are selected to demonstrate the applications of satellite observations in the tropics: hurricane studies, tropical rainfall and energy exchange at ocean surface. Studies on tropical cyclone's intensity, structure and water

balance are first introduced. For tropical rainfall, works primarily from Tropical Rainfall Measuring Mission satellite observations are reviewed, including rainfall climatology, horizontal and vertical structures of rain fields, diurnal variation of rainfall and latent heating related to precipitation. Finally, topics on deriving radiative and turbulent fluxes at ocean surface are discussed. Since clouds are an important factor in influencing these fluxes, we also introduced research on satellite-derived cloud properties, with an emphasis on the efforts made by the International Satellite Cloud Climatology Project.

1. Introduction

What happens in the tropical region is vital for understanding and forecasting the global weather and climate since the region provides the "fuel" to the engine of the atmospheric general circulation. However, the vast majority of the tropics are covered by oceans where surface-based observations of the atmosphere and surface are sparse. This makes satellite-based remote sensing an indispensible part of the tropical observation system. Since the first satellite that was completely dedicated to satellite meteorology - TIROS 1 (Television and Infrared Observational Satellite) – was launched in 1960, satellite observation has been playing an increasingly important role in the field of tropical meteorology. An historical overview of important milestones in satellite meteorology is given by Kidder and Vonder Haar (1995). While interested readers may consult that book for details, there are still several developments worth mentioning here: First, since the mid of 1960s, meteorological satellites have become operational (as opposed to experimental) in the United States; their coverage became continuous in time and almost anywhere on globe in space. One important implication of this routine observation is that no more tropical cyclones will go undetected any more, which is a plausible explanation that the number of recorded Atlantic storms jumped in the 1960s. Second, the availability of microwave sensors, particularly SSM/I (Special Sensor Microwave/Imager) since late 1980s, dramatically improved the quantitative estimation of global precipitation. Before this microwave era, rainfall estimates in the tropical oceans were primarily relied on the few measurements from commercial ships and sparsely located atolls; there was no clear consensus on the climatology of tropical rainfall amount. Third, satellite meteorology leaped a large step forward with the introduction of active sensors. The first precipitation radar on TRMM (Tropical rainfall Measuring Mission) and the first cloud radar on CloudSat have proved to be extremely valuable in understanding the vertical structures of clouds and precipitation.

This chapter is in no means to be inclusive of all the important developments in satellite meteorology. Instead, the author decided to focus on two things: laying the physical ground of remote sensing in the first half and then in the second half "cheery-picking" several applications of satellite observations, to which the author deemed important to tropical meteorology. For interested readers, the following books may be found helpful: Stephens (1994), Kidder and Vonder Haar (1995), and Liou (2002). Additionally, the online materials published by University Corporation for Atmospheric Research (UCAR) COMET (Cooperative Program for Operational Meteorology, Education and Training) program at the website:

http://www.meted.ucar.edu/tropical/textbook/ch3/Ch3_Remote_Sensing.pdf are also very informational. Remote sensing is the inverse process of radiative transfer. To perform retrieval of meteorological parameters from satellite measurements, we first have to understand how radiative energy at certain wavelength propagates in the atmosphere under given conditions. Therefore, this article starts in Section 2 with the basic theoretical descriptions of radiative transfer equations, followed by its solution under a specific condition and how the solution is relevant to remote sensing of certain meteorological parameters. In Section 3, we focused on three topics of applications of satellite remote sensing: hurricanes, precipitation and air-sea energy exchange (including the influence by clouds). The reasons to pick up these three topics for tropical meteorology are explained at the beginning of each section. One topic – atmospheric sounding using satellite observations – is not given much space in this article, although it is a very important topic, especially for improving numerical weather prediction models. Radiances from sounding channels have been assimilated in many operational forecasting models since early 1990s. Interested reads may consult Eyre et al. (1993) for more details.

2. Principles of Satellite Remote Sensing

Meteorological satellites have been designed so far to fly either polar or geostationary orbit. A geostationary satellite at 36,000 km altitude over the equator has a traveling speed equaling the angular velocity of the Earth, so that its position relative to an observer on the Earth appears to be fixed. This gives the ability for a sensor on a geostationary satellite to measure a target on the Earth in highly frequent repetition. For example, we can measure a tropical cyclone by a radiometer on a geostationary satellite every 15 minutes to monitor its evolution. However, its high altitude prevents sensors that have large field of view (for example, current microwave radiometers) from being placed on a geostationary satellite in order to obtain a reasonable spatial resolution of measurements. A polar orbiter, on the other hand, overflies higher latitudes on the Earth, normally at an altitude below 2000 km. While the satellite's orbital plane is fixed in space, with the rotation of the Earth, sensors on the polar orbiting satellite can observe different parts of the Earth. A target on the Earth usually can be observed twice daily by a typical meteorological satellite.

Remote sensing refers to as measuring certain features of a target without being in direct contact. It can be divided into two categories – active and passive sensing – depending on whether or not the sensor-received energy is first transmitted from the sensor. A satellite-borne radiometer receives radiative energy from the Earth and its atmosphere. The received energy may be the emission originated from, or the reflection by the Earth and atmosphere, or a combination of both. Therefore, the radiometer-received energy contains the information on the characteristics of the atmosphere and its underlying surface. The task of satellite remote sensing is then to extract meteorologically useful information from the satellite-received radiation; which is termed as "retrieval problem", or, "backward problem". In other words, the information we have (satellite received energy) is a result of complicated interactions between electromagnetic waves and matters in the sensor's viewing volume. Yet, the goal of the retrieval problem is to infer one certain feature of these matters. For example, we are to retrieve rainfall from observations at several microwave channels. The radiation received by the satellite is a combination of surface emission and reflection, emission by atmospheric gases, emission and scattering by hydrometeors at all levels of the atmospheric column. Rain drops near the surface are only one of the many factors that contribute to the upwelling radiation reaching to the satellite. The same surface rainfall rate could result in very different radiative energy under different surface conditions or with different atmospheric/cloud structures. On the other hands, corresponding to the same satellite received radiation, surface rainfall could have many possible intensities depending again on the surface and atmospheric conditions. Therefore, retrieving meteorological parameters by satellite remote sensing is intrinsically an ill-posed problem. To obtain a quality result, a retrieval algorithm developer is generally required to (1) select sensor channels that are most sensitive to the parameter to be retrieved, and (2) use *a priori* knowledge as constraints to the retrieval algorithm so that only the most probable solution is to be inferred from the observations.

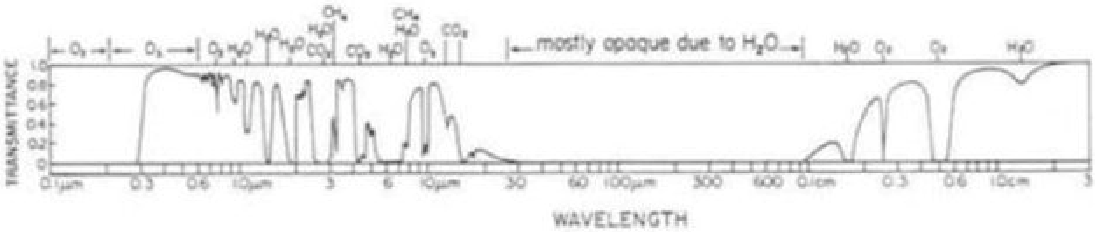

Figure1. Atmospheric transmittance from wavelength from 0.1 μm to 3 cm. (adapted from Kidder and Vonder Haar, 1995, *Satellite Meteorology – An Introduction*. Academic Press)

Figure 1 shows the atmospheric transmittance for wavelength from 0.1 μm to 3 cm. Transmittance is defined varying from 0 to 1. A transmittance close to 1 indicates that an electromagnetic wave at the wavelength can travel through the atmosphere with little absorption (window region). Otherwise, a transmittance close to 0 indicates that the atmosphere at the wavelength is nearly opaque. What wavelength to select for a retrieval algorithm depends on the parameters intended to infer. For example, to retrieve surface feathers (e.g., sea surface temperature, surface wind), it is preferred to avoid the atmospheric influence as much as possible; thus, window wavelength (e.g., 11-12 μm) is preferred. On the other hand, to retrieval atmospheric temperature profile, it is required that the satellite received radiances at several wavelengths originated primarily from different atmospheric levels; thus wavelengths near (O_2 or CO_2) absorption lines (e.g., 15 μm, 0.5 cm) should be selected. It is particularly noted that of the broad spectrum of wavelengths used in satellite radiometry, microwaves convey especially rich information because of their ability to penetrate deep cloud and precipitation layers, so that information beneath the cloud can be accessed from the satellite. For this reason, satellite microwave data have been increasingly utilized in retrieving cloud water and rainfall intensities and in improving numerical weather forecasts, particularly under raining conditions.

2.1. Radiative Transfer in the Atmosphere

While the goal of satellite meteorology is to determine meteorological feature from received radiation, i.e., the backward problem, it cannot be done without first understanding how much radiation would reach to the satellite given a known surface and atmospheric condition, i.e., the forward problem. The radiative energy received by a satellite radiometer is either emitted by the earth-atmosphere system (terrestrial radiation) or first originated from the sun and the reflected by the earth-atmosphere system (solar radiation). Approximately, 99% of terrestrial radiative energy is distributed in the spectra with wavelength longer than 4 µm, while 99% of solar energy is with wavelength shorter than 4 µm. Therefore, in radiative transfer computations, it is common to treat terrestrial and solar radiations separately. For terrestrial radiation, the thermal emission is the fundamental source of the energy while radiation from the sun is ignored (unless the sensor is directly pointing to the sun). For solar radiation, the radiation from the sun is the fundamental source of energy while emission from the earth-atmosphere system is ignored.

The radiative transfer equation for an unpolarized wave at a given wavelength under a plane-parallel atmosphere can be expressed by

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - \frac{\omega_0}{2}\int_{-1}^{+1} I(\tau,\mu,\mu')P(\cos\Theta)d\mu' - (1-\omega_0)B(\tau), \qquad (1a)$$

for terrestrial radiation, and

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - \frac{\omega_0}{2}\int_{4\pi} I(\tau,\mu,\mu')P(\cos\Theta)d\mu' - \frac{\omega_0}{4\pi}F_0 e^{-\tau/\mu_0}P(\cos\Theta_0), \qquad (1b)$$

for solar radiation. In the equations, τ is optical depth defined to be zero at the top of the atmosphere and increases with lowering altitude, μ is the cosine of the emergent zenith angle of the wave, $I(\tau,\mu)$ denotes the radiance at optical depth level τ and emergent direction μ, ω_0 is single-scatter albedo, Θ is the angle between radiation's emergent direction μ and incident direction μ', Θ_0 is the angle between radiation's emergent and sunlight direction, and F_0 is solar flux at the top of the atmosphere. $B(\tau)$ is the Planck's function at optical depth τ. Several methods have been developed for solving the radiative transfer equations, including discrete ordinate method and doubling-adding method, etc. Here we are not going to describe these methods although computed results using them will be shown in later sections. Interested readers may refer to radiation textbooks, e.g., Liou (2002), for detailed descriptions. Instead, we are going to simplify the equation under idealized conditions, in an effort to grasping the physical insight by only extracting the primary signature without regarding to the quantitative details.

2.2. Thermal Radiation under Clear-Sky

At infrared and microwave wavelengths under clear-skies, the scattering (by air molecules and aerosols) is negligible $(\omega_0 = 0)$. Eq.(1a) can be rearranged as

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - B(\tau) \tag{2}$$

The solution for upwelling radiation at the top of the atmosphere is then

$$I(0,\mu) = I(\tau^*,\mu)\exp(-\frac{\tau^*}{\mu}) + \int_0^{\tau^*} B(t)\exp(-\frac{t}{\mu})\frac{dt}{\mu} \tag{3}$$

where τ^* is the atmospheric total optical depth measured at ground. Defining a transmission function $\Im(t,0,\mu) = \exp(-t/\mu)$ and a weighting function $W(t,0,\mu) = d\Im(t,0,\mu)/dt = -\frac{1}{\mu}\exp(-t/\mu)$, (3) becomes

$$I(0,\mu) = I(\tau^*,\mu)\Im(\tau^*,0,\mu) + \int_{\tau^*}^{0} B(t)W(t,0,\mu)dt \tag{4}$$

The solution states that the radiance received by a satellite sensor consists of the contributions of transmitted portion of surface emission and the weighted sum of the atmospheric emission at different levels. This equation becomes important as we retrieve surface temperature and atmospheric temperature and moisture profiles. At window wavelengths the atmospheric contribution is minimal, the main contribution will be from the surface (the first term on right side of the equation), which allows us to derive surface temperature at infrared window channels under clear-skies. On the other hands, if we choose absorbing channels that have weighting functions peaked at different levels, we may combine the observations at these channels to derive atmospheric profiles. A special circumstance is thermal infrared window channel observation over overcast sky, in which cloud top acts the same as a surface, so that the satellite observed signal indicates the cloud top temperature.

2.2.1 Surface Temperature Retrieval

The principle of retrieving surface temperature from measurements of brightness temperatures at split-window (11 and 12 μm) channels is based on Eq.(4). At atmospheric window channels, the absorption by atmospheric gases (primarily water vapor) is minimal, we may further simplify Eq.(4), and express the satellite received radiance at channel i as

$$I_i = B_i(T_\mathrm{s})\Im_i + B_i(T_\mathrm{a})(1-\Im_i), \tag{5}$$

where T_s and T_a are surface and atmospheric mean temperatures, respectively. The transmission function $\Im_i = \exp\left(-\int k_i du\right) \approx 1 - k_i u$, where k_i is the water vapor absorption coefficient and u is the water vapor path. If we use $i=1$ and 2 to denote the split-window channels of 11 and 12 μm, respectively, surface temperature may be approximately expressed by [interested readers may refer Liou (2002) for detailed derivation]:

$$T_s = T_{B1} + \eta(T_{B1} - T_{B2}) \tag{6}$$

where $\eta = \dfrac{k_1}{k_2 - k_1}$, and T_{B1} and T_{B2} are the brightness temperatures observed at 11 and 12 μm channels, respectively. Based on this principle, empirical methods by regressing brightness temperatures observed by NOAA satellite AVHRR (Advanced Very High Resolution Radiometer) split-window channels to buoy-measured sea surface temperatures (SSTs) have been developed (e.g., McClain et al., 1985).

2.2.2 Atmospheric Sounding

In the thermal infrared and microwave spectra, atmospheric molecules absorb radiation by rotational or vibrational-rotational transition, which occurs at certain absorption lines (or bands) with strength and width specific to the gas species. For example, CO_2 has a strong absorption line centered 15 μm and water vapor has a strong line centered 6.3 μm wavelength. Around the absorption line, absorption does not occur at a single wavelength, but rather spreads a wavelength range following a line shape function. Mass absorption coefficient at frequency ν, k_ν, may be approximately described by a Lorentz model (Stephens, 1994):

$$k_\nu = \frac{S\tilde{p}\alpha_{L0}/\pi}{(\nu-\nu_0)^2 + \alpha_{L0}^2\tilde{p}^2}, \tag{7}$$

where ν is the frequency in consideration and ν_0 is the frequency at the absorption line center. α_{L0} is the Lorentz half-width, frequency shift corresponding to half power point of the line, at pressure $p_0 = 1$ atmosphere. S is the line strength, and $\tilde{p} = p / p_0$ is the pressure normalized by p_0. Eq.(7) indicates that the line shape widens with atmospheric pressure, called pressure broadening, so that the absorption is more concentrated near the line center in the upper atmosphere while it expands more toward the wings in the low atmosphere. Consider that the upwelling radiation is measured at multiple wavelengths from the line center to its wings for the absorption line of a vertically well-mixed gas (e.g., CO_2, O_2, …). The radiation measured near the line center corresponds to the temperature of upper atmosphere while radiation measured at the far wing corresponds to the temperature of the lower atmosphere; therefore, the atmospheric temperature profiles may be derived using an inversion algorithm.

Let us derive an approximate expression of the weighting function as a function of height for a vertically well-mixed gas that has a mixing ratio of w_g. The optical depth of a layer between pressure level p_1 and $p_2\left(p_2 > p_1\right)$ in an atmosphere with hydrostatic balance may be written

$$\tau = \frac{w_g}{2p_0 g}\int_{p_1}^{p_2} \frac{Sp\alpha_{L0}/\pi}{(\nu-\nu_0)^2 + \alpha_{L0}^2\tilde{p}^2}dp\,. \tag{8}$$

To simplify the equation, let us consider the absorption in the line wings where $\nu - \nu_0 > \alpha_{\mathrm{L0}}\tilde{p}$, so that optical depth at pressure level p equals

$$\tau \approx \frac{S\alpha_{\mathrm{L0}} w_{\mathrm{g}}}{g p_0 (\nu - \nu_0)^2} p^2 . \tag{9}$$

Assuming that atmospheric pressure decreases with height following a scale height H, i.e., $p(z) = p_0 e^{-z/H}$, then optical depth at altitude level z,

$$\tau(z) = \tau^* e^{-2z/H} , \tag{10}$$

and τ^* is the optical depth for the entire atmosphere. From the definition of weighting function,

$$W(z) = \frac{d\Im(\tau)}{dz} = \frac{d\Im(\tau)}{d\tau}\frac{d\tau(z)}{dz} = \frac{2\tau^*}{H}\exp(-\frac{2z}{H} - \tau^* e^{-2z/H}). \tag{11}$$

It is shown by this simple expression that two factors (the two terms within the exponential function) govern the shape of the weighting function. The first factor leads it to decrease with height manifesting the fact that the density of the absorbing gas decreases with the increase of height. The second factor leads the weighting function to increase with height, which is a result of better transmission of radiation to the space at higher altitudes. The combination of the two competing factors results in a bell-shape weighting function curve peaked at $\frac{H}{2}\ln\tau^*$ (i.e., where τ = 1). Note that when the observing frequency is far from the absorbing line center (τ^* becomes very small), the second factor does not have a measurable contribution, leading to the weighting function peaks at surface. From Eq.(4), the peak of the weighting function is the location where the atmospheric emission contributes the most to the satellite received radiation.

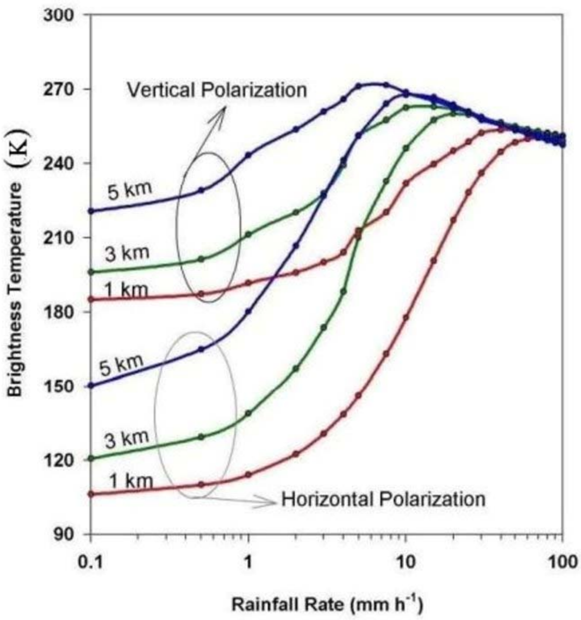

Figure 2. Radiative transfer model simulations of brightness temperatures at 19.35 GHz for rainfall over ocean. A viewing angle of 53° is assumed. The values in km indicated on the curves are freezing level heights.

Ideally, we wish the weighting function to be extremely sharp so that the temperature (or water vapor for measuring at H_2O absorption lines) at a distinctive level may be derived from satellite observation at each frequency. However, in reality weighting functions have commonly broad shapes. To retrieve the vertical profiles of temperature, or water vapor if temperature profile is known, inversion algorithms need to be employed. Physical, statistical and hybrid algorithms have been developed during the past several decades (see, for example, Kidder and Vonder Haar, 1995). A recent development in using sounding channel data is to assimilate the satellite-received radiances directly into numerical weather prediction models (e.g., Eyre et al., 1993), in which case the end products of model fields constitute the retrievals of atmospheric temperature and moisture profiles.

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Biographical Sketch

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