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Vertical profile retrievals with warm-rain microphysics using the ground-based microwave radiometer operated by the Hong Kong Observatory

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ABSTRACT

We present the formulation of a variational-method-based retrieval algorithm for a ground-based microwave radiometer. Absorption by air, water vapor, cloud liquid water and rain water are incorporated into the formulation. The absorption of microwave radiation by air is calculated using a line-by-line method, while that by liquid water is calculated using an empirical formula that models the complex refractive index of liquid water. The root-mean-squared error of the retrieved temperature was no more than 1 °C in the lowest 2000 m of the profiles based on the 1-year verification data. The absorption of microwave radiation by rain water is important for improving the accuracy of the retrieval profiles during rainy conditions.

1. Introduction

Nowcasting of convection is a challenge. Common approaches for nowcasting include radar extrapolation (Yeung et al., 2009), dynamic numerical weather simulations (Sun et al., 2010), combined radar extrapolation and numerical simulations (Wong et al., 2009) and statistical methods (Lin et al., 2012). The last three methods are capable of forecasting the development of a convective system before it forms. However, the methods involving a numerical weather prediction system (NWP) are more computationally costly in real-time operations.

Statistical methods are limited by the available observational data. Statistical models commonly incorporate upper-air observations (Lin et al., 2011) because vertical instability is key for convective development (Adams and Souza, 2009). However, because of the operational cost, both temporal and spatial coverages of upper-air observations are insufficient to provide detailed mesoscale information for nowcasting convective development.

In recent years, real-time measurements of vertical profiles using ground-based microwave radiometers have become popular (Cimini et al., 2011; Cadeddu et al., 2013). The operational cost of ground-based microwave radiometers is much lower than that of radiosondes; thus, radiometers are more promising for improving both the spatial and temporal coverages of upper-air measurements. The accuracy of the vertical profile obtained by radiometers depends on the retrieval, which inverts the radiometer brightness temperature readings to the vertical profile. A major issue with the retrieval of vertical profiles from radiometers is that the profile during precipitation is often less accurate. This inaccuracy is caused by two effects: 1) the accumulation of water, snow (Woods et al., 2005) or ice (Fernández-González et al., 2014) over the radome and 2) the lack of scattering and emission/absorption effects of rain water in the retrieval algorithm. Attempts have been made in the past few years to solve the former problem, such as using a hydrophobic radome and forcing airflow over the radiometer surface to avoid the accumulation of water, snow and ice (Chan, 2009a) or observing the microwave irradiance at an off-zenith angle to avoid thin films of water (Xu et al., 2014). To the authors' knowledge, few attempts have been made to handle the latter problem. The two problems are distinct, but efforts devoted to solving each problem can be applied simultaneously.

There are two classes of retrieval approaches: statistical (Tan et al., 2011) and variational minimization (Hewison, 2007). The second class provides more accurate results, and it is expected to be more skillful in the application of nowcasting convective development. This article describes a vertical profile retrieval algorithm with warm-rain microphysics developed by the Hong Kong Observatory (HKO) and based on the variational minimization approach. The major objective is to address the lack of scattering and emission/absorption effects of rain water in the retrieval algorithm and the use of radar reflectivity to derive upper-air rain water content. The

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impact of incorporating the scattering and emission/absorption effects of rain water is demonstrated.

2. Inputs of the retrieval algorithm

Two radiometers are operated by the HKO. One radiometer was acquired in 2008 for the Hong Kong International Airport (denoted "HKIA radiometer" hereafter), and the other radiometer was acquired in 2013 for King's Park (denoted "KP radiometer" hereafter), where the radiosonde site is located. The horizontal distance between the two radiometers is approximately 26 km. Both radiometers are 14-channel microwave radiometers (model: RPG HATPRO from Radiometer Physics, Chan (2009b)). The frequencies of the 14 channels are tabulated in Table 1. The KP radiometer was out of service for 2 months in its first year of operation. An entire calendar year of data is not available from the KP radiometer during the study period. The performance of the retrieval method was mainly tested with data from the HKIA radiometer; an exception is the analysis of the impact of incorporating rain droplet effects in the calculation, which used data from the co-sited KP radiometer. Temperature and humidity profile retrievals using the HKIA radiometer data at 0000 UTC and 1200 UTC from Sept 2010 to Aug 2011 were compared with the radiosonde data from the KP. There are 653 profiles for the comparison. We used radar reflectivity data from the S-band weather radar located on top of Tai Mo Shan (3 km above sea level) for deriving the upper-air rain water content on rainy days.

The underlying principle of the variation minimization retrieval is similar to the variational assimilation method in NWP. An initial guess of the vertical profile for the retrieval is obtained from the 6-hour forecast of the regional numerical weather prediction system, Meso-NHM, run by the HKO. To speed up the convergence of the variational retrieval algorithm, the lowest 1500 m of the forecast profile from Meso-NHM was first calibrated based on the differences between the surface temperature forecasts by Meso-NHM and the temperatures measured by the automatic weather station (AWS). Such calibration often has insignificant effects on the retrieved profiles, but it speeds up the calculation by reducing the average number of iterations needed in the minimization process by providing a first-guess profile similar to the surface observations. Details on Meso-NHM can be found in Wong (2011).

3. Numerical schemes

The one-dimensional radiative transfer equation is given by

$$\frac{dI}{dx} = -\sum_i \rho_i(\sigma_i^a + \sigma_i^s)I + \sum_i \rho_i\sigma_i^a B(T_i) + \sum_i \rho_i\sigma_i^s J \tag{1}$$

where I is the intensity of the radiation, x is the optical path, i is a label for individual species of scattering/absorbing particles, $\sigma_i^a(\sigma_i^s)$ is the absorption (scattering) cross section of species i, ρ_i is the number density of species i, $B(T)$ is the Plank function at temperature T and J is a source function from scattering. J is related to scattering phase function $p(\Omega)$ by Eq. (2)

$$J = \int_\Omega p(\Omega)I(\Omega)d\Omega \tag{2}$$

Note that I, ρ_i, T and J are explicit functions of x, while σ_i^a and σ_i^s depend on x implicitly through their dependence on T.

Table 1
Frequencies and band widths of the 14-channel radiometer.

Channel	1	2	3	4	5	6	7
Frequency (GHz)	22.24	23.04	23.84	25.44	26.24	27.84	31.4
Band width (GHz)	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Channel	8	9	10	11	12	13	14
Frequency (GHz)	51.26	52.28	53.86	54.94	56.66	57.30	58.00
Band width (GHz)	0.23	0.23	0.23	0.23	0.6	1	2

To solve Eq. (1), we discretize ρ_i and T along the optical path x. We first solve for I at these piecewise domains and join the domains together by requiring I to be continuous at the boundaries of the domains. Within the individual domains, we assume that the thermally emitted radiation is scattered no more than once, i.e.,

$$\rho_i J = \int_\Omega p(\Omega)B(T_i)d\Omega \tag{3}$$

As $p(\Omega)$ is integrated to unity, Eq. (3) further simplifies to

$$\rho_i J = B(T_i) \tag{4}$$

Thus, Eq. (1) simplifies to

$$\frac{dI}{dx} = -\sum_i \rho_i\sigma_i^e I + \sum_i \rho_i\sigma_i^e B(T_i) \tag{5}$$

where σ_i^e is the extinction cross section in individual domains.

The solution of Eq. (5) in the domain spanning x_j to x_{j+1} is

$$I\left(x_{j+1}\right) = \frac{\sum_k \Omega_k B\left(T_{kj}\right)}{\sum_k \Omega_k}\left(1-\exp\left(-\sum_i \Omega_i(x_{j+1}-x_j)\right)\right) + I\left(x_j\right)\exp\left(-\sum_i \Omega_i(x_{j+1}-x_j)\right) \tag{6}$$

where T_{kj} is the temperature in domain (x_j, x_{j+1}) for particle i and $\Omega_i = \rho_i\sigma_i^e$. In this study, we set $I(x_0) = 0$ because the radiometers operated by the HKO never point directly at the sun. Additionally, the radiometers operate at the microwave frequency, and the scattering of the solar-emitted microwave radiation by the atmosphere was negligible.

We assume that microwave radiation is absorbed by dry air (mainly oxygen and nitrogen molecules), water vapor, cloud water droplets and rain water droplets. Solid hydrometeors are not considered because they are not common in the study area in the period analyzed. Eq. (6) simplifies to

$$I\left(x_{j+1}\right) = B\left(T_j\right)\left(1-\exp\left(-\sum_i \Omega_i(x_{j+1}-x_j)\right)\right) + I\left(x_j\right)\exp\left(-\sum_i \Omega_i(x_{j+1}-x_j)\right) \tag{7}$$

when there is a local thermal equilibrium in which the temperatures of all particles in the domain (x_j, x_{j+1}) are given by T_j. The assumption is valid when no rain is present. For rainy cases, we assume that the dry air, water vapor and cloud droplets are in a local thermal equilibrium, while the temperature of the rain droplets is computed from a microphysics scheme that is discussed later. σ_i^e for the gaseous components are obtained from Millimeter-wave Propagation Model (MPM-93) data (Liebe et al., 1993). σ_i^e from liquid water droplets is calculated using the formulas for Rayleigh scattering (for cloud droplets) and Mie scattering (for rain droplets), in which the empirical formula for the temperature and the frequency-dependent complex refractive index of bulk liquid water are the input.

The densities of O_2 and water vapor are determined using the ideal gas law and the mixing ratio, respectively. We assume that the number density of the cloud droplets is $N_c = 1 \times 10^8\ \mathrm{m}^{-3}$, in which the sizes follow a generalized gamma distribution, i.e.,

$$n_c(D) = N_c\frac{\alpha_c}{\Gamma(\nu_c)}\lambda_c^{\alpha_c\nu_c}D^{\alpha_c\nu_c-1}\exp\left(-(\lambda_c D)^{\alpha_c}\right) \tag{8}$$