Examining the Impact of Microphysics Parameters in Simulations of a January 2019 Vermont Winter Storm

Michael L. Wasserstein

Department of Physics, Middlebury College, Middlebury, VT

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Abstract

Using the Weather Research and Forecasting (WRF) model, we conduct simulations of a major winter storm that produced up to 50 centimeters of snow to parts of Vermont on 20-21 January 2019. In WRF simulations, different microphysics schemes yield different model outputs. We employ a sensitivity test using the Thompson (THOM), Morrison 2-moment (M2M), WRF Double Moment 6-class (WDM6), Goddard (GODD), and Milbrandt–Yau Double Moment (MILL) schemes to analyze snowfall during the Vermont storm at a near sea level location in Middlebury, VT and at a mountain location in Rochester, VT. We analyze radar reflectivities produced by WRF, mixing ratios of the hydrometeor species, and accumulated snowfall totals. We find that the THOM and GODD microphysics parameterization predicts snowfall totals that fall most in line with observed snowfall from the storm, while WDM6 and M2M schemes slightly overpredict snowfall, and the MILL simulation grossly underpredicts snowfall.

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I Introduction

Vermont (VT), located in the northeast of the United States, is a state susceptible to major winter storms that have significant implications for the state, both good and bad. In the present study, we consider one of these storms that impacted the state in January 2019 by analyzing the physics of the clouds throughout the duration of the storm.

I. (i) The Storm

During the period from January 20 to January 21, 2019, a major winter storm produced up to 20 inches of snow in parts of Vermont. [1] At Burlington International Airport (BTV) in South Burlington, VT, where the state's primary first order weather station is located, 18.6 in. of snow fell from this storm, making it the 18th largest storm on record at BTV and the 5th largest in January. At the storm's peak intensity during the morning on January 20, the snowfall rate reached 2.4 in. per hour. Temperatures were unusually cold for a snowstorm of this magnitude, falling below 0 degrees F for much of the day on January 20 through January 21. Despite the arctic air that was in place for this storm, snow-to-liquid ratios were near 10:1 for the majority of the time, though they did increase towards the storm's end. Impacts of the storm were primarily travel related, as the storm coincided Martin Luther King Jr. Day weekend, a popular weekend for New Enlgand skiers to travel to Vermont. With nearly 20 inches of snow falling in a 24 hour period in spite of low snow-to-liquid ratios, the microphysical conditions of the clouds were ripe and contributed to the heavy snowfall rates that occurred. Past research on microphysics of Vermont winter storms is scarce, which provides the motivation for this study.

I. (ii) Cloud microphysics

Clouds contain water droplets and ice particles that are suspended in air [2]. Cloud microphysics is the study of the microscale processes occurring within the small particles that make up clouds. The dynamics of cloud microphysics begins with a cloud condensation nuclei (CCN), a particle with a diameter on the order of 1 µmthat provides an ideal surface for other water droplets to stick to. As more water particles coalesce to the original CCN, a cloud particle forms, and more particles combine until a rain drop or snowflake is formed, as shown in Fig. 1. For rain drops to fall, the saturation ratio,

$$S = \frac{e}{e_S}, \tag{1}$$

where e is the water vapor pressure and e_S is the saturation vapor pressure, must equal 1. When S = 1, the atmosphere is saturated and it cannot hold any more water particles, and the particles fall as rain drops or snow flakes. Cloud microphysics has important implications on the weather that we experience.

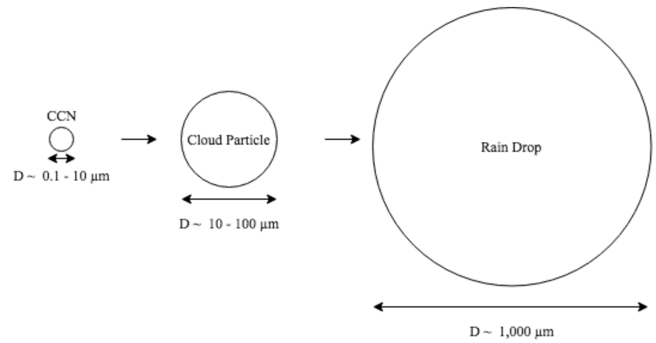

Fig. 1. The dynamics of cloud microphysics. A cloud condensation nuclei (CCN), a tiny water particle, provides a surface to which other water particles can stick, causing that initial CCN to grow until it forms a cloud particle and ultimately a rain drop. When the atmosphere becomes saturated, these rain drops fall and cause precipitation on Earth

In numerical weather prediction (NWP), cloud microphysics is one of the many components that we must take into account when predicting precipitation, and there are many ways to parameterize cloud microphysics. Microphysical modeling consists of bulk microphysics schemes and bin schemes. Bin schemes, while computationally more expensive and complex, can be much more effective because they divide cloud particles into thousands of bins and model the particle sizes based on each individual bins. [3] On the flip side, bulk microphysics schemes, which are used more widely in operational weather models, use an empirical gamma or exponential distribution to determine particle sizes based on a predicted number concentration N and/or mixing ratio q atmosphere. [3] [4] While a bin scheme individually determines particle sizes, a bulk scheme uses a distribution to make this determination. A gamma function for the determination of a particle size distribution a bulk scheme can take the form

$$N(D) = N_0 D^u e^{-\lambda D}, \tag{2}$$

where D is the particle diameter, and N_0, λ, and μ are the intercept, slope, and shape parameters of the size distribution. [5]. The parameters N_0 and λ can be determined by predicted values for N and q in the bulk scheme, while μ depends on the type of particle being examined. Within bulk schemes, there are double-moment schemes that predict N and q as well as single-moment schemes that only predict q, thus predicting N_0 in Eq. 2. Based on the determined particle size distribution in Eq. 2, the bulk scheme will predict the particle size, underpinning cloud microphysics modeling in NWP.

The Advanced Research Weather Research and Forecasting Model (WRF) is a community atmospheric modeling system that allows users to model many physical, dynamical, and chemical processes in the atmosphere through real or idealized simulations. [6] In WRF, users can choose between many microphysics parameterizations (MPs) that use either empirical gamma or exponential distributions to determine particle size for different hydrometeors based on assumptions about mixing ratios (see Eq. 2). In previous simulations of real winter storms, common MP choices include the Thompson (THOM) scheme, the WRF Double Moment 6-class (WDM6) scheme, the Millbrandt-Yau Double Moment (MILL) scheme, the Goddard (GODD) scheme, and the Morrison 2-monent (M2M) scheme. [4] [7] [8] [9] [10] [11] [5] Table I summarizes the characteristics of these 5 MPs. As shown

Table I. An overview of the Thompson (THOM), WRF Double Moment 6-class (WDM6),Millbrandt-Yau Double Moment (MILL), Goddard (GODD), and Morrison 2-monent (M2M) microphysics schemes in the Weather Research and Forecasting Model. For each scheme, the moment, prognostic mass variables q, and prognostic number variables N_0 are listed. The subscripts c,r,i,s,g,h, and n correspond with cloud, rain, ice, snow, graupel, hail, and cloud condensation nuclei, respectively.

	Moment	Mass variables q ($kgkg^{-1}$)	Number variables N_0 (kg^{-1})
THOM	hybrid	Q_c,Q_r,Q_i, Q_s,Q_g	N_i,N_r
WDM6	2	Q_c,Q_r,Q_i, Q_s,Q_g	N_n,N_c,N_r
MILL	2	Q_c,Q_r,Q_i,Q_s,Q_g,Q_h	N_c,N_r,N_i,N_s,N_g,N_h
GODD	1	Q_c,Q_r,Q_i,Q_g Q_s,Q_h	
M2M	2	Q_c,Q_r,Q_i,Q_s, Q_g	N_r,N_i,N_s,N_g

in Table I, each of these 5 schemes makes unique predictions about q and N_0 for all hydrometeors, and these predictions are used in Eq. 2 to predict particle sizes for the hydrometeors. THOM, while primarily a single-moment MP, does predict number concentrations for ice and rain particles. By making unique predictions about q and N_0 for each hydrometeor, when chosen as a MP in WRF each of these bulk schemes should yield different outputs when the model is run. In this paper, we seek to examine the model outputs for these 5 microphysics schemes, using the January 2019 Vermont winter storm as our case study.

II Methods

To analyze the cloud microphysics of the January 2019 Vermont we use the Advanced Research Weather Research and Forecasting Model version 4.2.1. The model is configured with 10 km grid spacings for 38 levels in the atmosphere above mean sea level (MSL). We run WRF simulations for a the two days in which the storm took place, 20 January 2019 - 21 January 2019, beginning each simulation at 0000 UTC 20 January 2019. Each simulation is initialized using Global Forecast System (GFS) analysis data with a 0.5° grid increment obtained from the National Centers for Environmental Information (NCEI) GFS database. The GFS analysis data sets the initialized conditions for the land surface, atmosphere, and boundary at 3 hour intervals.

Table II summarizes the physics options that we used for each simulation. For an overview of each of these parameterizations, see the WRF users guide (`https://www2.mmm.ucar.edu/wrf/users/docs/user_guide_v4/v4.2/users_guide_chap5.html#summary`). With the WRF config-

Table II. Summary of WRF configurations for our simulations. While long-wave radiation, shortwave radiation, surface-layer exchange coefficient, land surface, and planetary boundary layer parameterizations all remained unchanged, the microphysics we used varied for each simulation.

Physics	Parameterization
Long-wave radiation	RRTMG Longwave
Shortwave radiation	RRTMG Shortwave
Land surface	Noah-MP Land Surface Model
Planetary boundary layer	Yonsei University

uration as described in Table II, we varied MPs, using THOM, WDM6, MILL, GODD, M2M, which are described in greater detail in Table I. For each simulation, we ran WRF for 48 hours from 0000 UTC 20 January 2019 to 0000 UTC 22 January 2019. Although there were sparse snow accumulations on 21 January 2019, the focus of the data analysis was on 20 January 2019, when the brunt of the snow in this storm fell. We focused data analysis on the entire region shown in Fig. 2 To compare

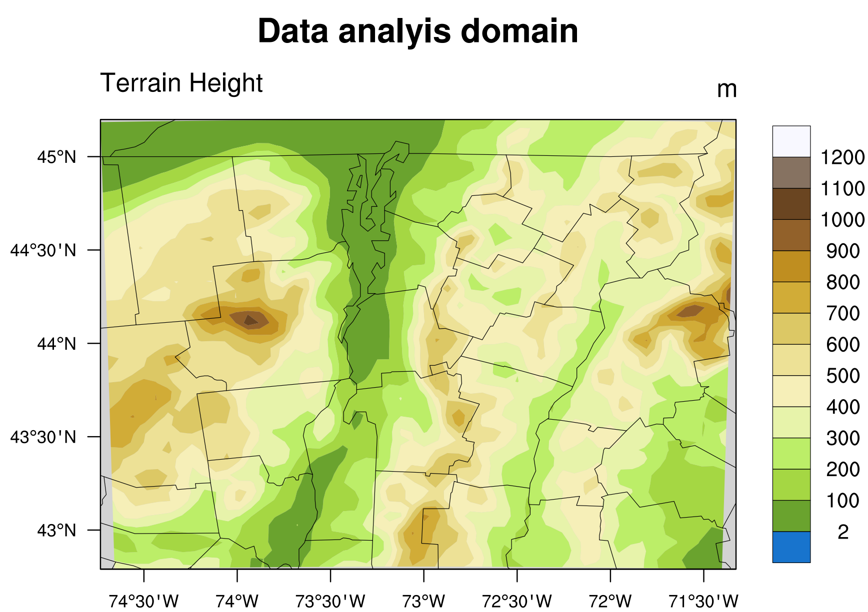

Fig. 2. This figure certainly needs lots of work to improve it - but its the idea that I'm shooting for. Also, it is the incorrect domain - the correct one looks a little different

each simulation, we analyzed estimated radar reflectively data, mixing ratio data for all hydrometeors at different levels of the atmosphere, and accumulated snowfall. We used the radar relectivity data and mixing ratio data to make predictions about accumulated snowfall, and we compared snowfall to real observations from the storm from Community Collaborative Rain, Hail & Snow (CoCoRaHS) Network sites in Middlebury, VT (MSL 113 m) and Rochester, VT (MSL 527 m).

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