Understanding the Role of Aerosols Distribution in the Thompson Microphysics Scheme for Marine Fog

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Abstract

Many studies on marine fog have shown that different models overestimate the liquid water content (LWC) in the fog layer, resulting in thicker layers and reduced visibility compared to observations. The Weather Research and Forecasting (WRF) model uses different parametrization schemes for different physical processes in the atmosphere. In this report, I investigated the two Thompson microphysics schemes as they are relevant to the formation and evolution of marine fog.

For the Thompson (2008) scheme, I understood that the cloud droplet number concentration, N_c, was preset and kept constant, so based on your specific case it should be changed. It was found that changing N_c from 100 cm^{-3} to 75 cm^{-3} successfully decreased the LWC by roughly 7 %. For the Thompson Aerosol-Aware scheme (2014), they suggested that aerosol distribution can have a large impact on N_c, so they resolved N_c with time and the LWC decreased by approximately 55 %. Those findings show that having a good understanding of the cloud droplet distribution is important to running the WRF model for marine fog studies.

Contents

Chapter 1

Rationale

The project's main purpose is to investigate the liquid water content (LWC) in marine fog layer modeling. Many atmospheric models have been able to predict fog occurrence but the cloud mixing ratio inside the fog layer has always been overestimated. This implies that the LWC inside the fog is much higher than actual and as a result, those models predict much thicker fog layers. This will impact the formation of the fog, how it evolves, and might also delay its dissipation. The real-world implications could be delays in flight departures, landings, or even sailing for sea fog because actual observations might not be as foggy as predicted. The formation of fog and its evolution depends on various climate processes, including cloud microphysics, longwave and solar radiation, turbulent boundary layer mixing, advection and surface interactions.[1]

We are using the Weather Research and Forecasting (WRF) model for this project and it is an atmospheric model used for meteorological research and numerical weather prediction or forecasting. WRF has various physical parametrization schemes that interact with each other, namely the cumulus scheme, the microphysics scheme, the radiation scheme, the planetary boundary layer scheme, and the surface layer scheme.[2] We will be using the WRF- Single Column model (WRF-SCM), which is an ideal case in WRF. The ideal case in WRF uses idealized inputs rather than observational data like in real cases. The SCM-WRF runs on a 3x3 domain with boundary conditions on X and Y. There is no horizontal gradient and each variable runs through the single column. The initial conditions are given in the input_sounding and input_soil files.[3] The reason we chose to use the SCM-WRF ideal case is that when you run an ideal case, it has fewer variables to worry about and we can really access the performance of any changes being made to specific physical parametrizations. We chose the single-column model because most of the physical processes mentioned above mostly interact vertically.[4]

1.1 Surface Deposition of Marine Fog Paper

This project is based on a previous study from the "Surface Deposition of marine fog and its treatment in the Weather Research and Forecasting (WRF) model" paper. The paper also suggests that many weather models, including WRF, overestimate LWC in fog layers. Their main idea was to investigate the surface layer parametrization in WRF. Since we are investigating marine fog, one needs to take into account the sea surface in the weather model but there does not seem to be a deposition of fog droplets to the surface. They hypothesized that the sea surface is an effective sink for the fog droplets and turbulence within the fog layer will increase the probability of the droplets colliding and coalescing with the water surface. This will decrease the LWC near the surface and effectively decrease the thickness of the layer. They decided to use the Mellor–Yamada–Nakanishi–Niino (MYNN) surface scheme and they introduced a turbulent deposition velocity variable inside the MYNN scheme module in WRF. They parametrized the deposition velocity by the roughness length variable which will be dependent on the fog-cloud droplets and the equation is given below:

$$V_d = \frac{ku_*}{ln(\frac{z1+z0c}{z0c})}, \tag{1.1}$$

where k is the Karman constant (=0.4), u_* is the friction velocity, z0c is the roughness length and z1 is the lowest vertical level.[1]

1.2 Thompson Microphysics Schemes

1.2.1 Thompson Microphysics Scheme 2008

In the paper, they also used the Thompson microphysics scheme which deals with moisture tendencies and atmospheric heat of water vapor, cloud droplets, rain, ice, and graupels. It deals with the different processes for each of those aerosols, such as for cloud droplets there will be collision and coalescence, for water vapor there will be condensation or evaporation which are relevant to clouds. For this project, we wanted to investigate the cloud droplet number concentration (N_C) as varying this number will impact the formation and evolution of clouds.

Before doing the modifications, we needed to investigate the Thompson microphysics scheme. For this scheme, we observed that each aerosol (except for snow) follows a generalized gamma function instead of the exponential distribution.

$$N(D) = \frac{N_t}{\Gamma(\mu+1)}\lambda^{\mu+1}D^{\mu}e^{-\lambda D}, \tag{1.2}$$

where N_t is the total number of particles in the distribution, D is the particle diameter, α is the distribution's slope, and μ is the shape parameter.

The idea behind the Thompson microphysics scheme is that instead of doing double moment schemes, they concentrated their efforts on understanding the fault in the other previous single moment schemes and improving on them. The Thompson scheme then, being a single moment, can behave as accurately as a double-moment scheme. For the cloud droplet number concentration, $N_t = N_c$ and it is a constant in this scheme, that is, it is preset in the code and does not vary with time and the default value is 100 cm^{-3} which represents relatively clean air.[5]

1.2.2 Thompson Aerosol-Aware Paper

From the Thompson Aerosol-Aware Paper, it is understood that aerosols play a role in cloud formation and microphysics through heterogeneous nucleation of cloud and ice particles. When aerosol concentration increases, liquid water content increases and will often lead to a larger number of liquid droplets, which are smaller in size which increases the cloud albedo, called the first indirect effect.[6] The second indirect effect of having smaller cloud droplets is that rain droplets are reduced or even take more time to develop, causing a delay in precipitation and both of those effects may affect the fog layer. Different regions will have different aerosol types and distribution, which can impact some weather phenomena. For example, continental regions have relatively dry air while maritime regions have relatively moist air. Those aerosols are important for different cloud properties such as radiation, precipitation, and dynamics which in turn is important for weather applications such as fog formation and other applications sensitive to LWC or ice content.

In contrast to the older scheme, N_c is solved prognostically, that is, it is made to vary with time in the simulation and is a predicted variable. The equation to calculate the cloud droplet number concentration is given below:

$$\begin{aligned}\frac{dN_c}{dt} = &-(\text{rain, snow, graupel collecting droplets})\\ &-(\text{freezing into cloud ice})\\ &-(\text{collide/coalesce into rain})\\ &-(\text{evaporation})\\ &+(\text{CCN activation})\\ &+(\text{cloud ice melting})\end{aligned} \tag{1.3}$$

, where we observe different processes that will either contribute to or decrease the N_c. This is why the Thompson Aerosol-Aware is a two-moment scheme for the cloud droplet whereas the Thompson scheme is a single-moment scheme.[7]

Chapter 2

Methods and Results

2.1 Method

To run the SCM-WRF ideal case, we needed the same input variables as the ones in the Surface Deposition paper. They were initialized in the input_sounding file which contained the initial speed u and v in ms^{-1}, potential temperature in Kelvin, and water vapor mixing ratio in kg^{-3}/kg^{-3}. The input_soil had the input for skin temperature. The files can be found: input_sounding and input_soil. Then, we simulated for four days, from August 15^{th} to August 19^{th} 2018 by inputting the days in the namelist.input file. This file gives all the necessary inputs, from the grid sizes, and timesteps to all the relevant physical parametrizations. The MYNN surface layer scheme was used with the z0c modifications, and no radiation schemes were used as we wanted to mainly investigate the microphysics scheme. Also, to generate fog at the surface, we introduced a 6-hour surface cooling of 3 K/hr. I have uploaded the namelist.input file here: namelist.input. After investigating the Thompson microphysics scheme, we identified that the N_c is a constant and can be changed in the code, so we changed the cloud number from 100 cm^{-3} to 75 cm^{-3} which is more suitable for maritime cases.[5] The code block that was changed is inside the WRF and is called the module_mp_thompson.F and the important part of the code is given below:

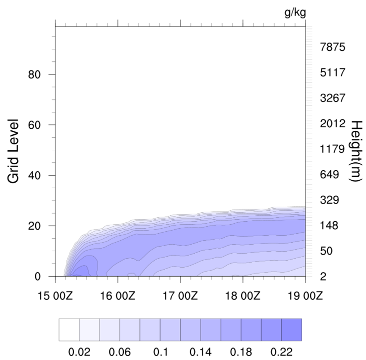
```
!..Prescribed number of cloud droplets.  Set according to known data or
!.. roughly 100 per cc (100.E6 m^-3) for Maritime cases and
!.. 300 per cc (300.E6 m^-3) for Continental.  Gamma shape parameter,
!.. mu_c, calculated based on Nt_c is important in autoconversion
!.. scheme.  In 2-moment cloud water, Nt_c represents a maximum of
!.. droplet concentration and nu_c is also variable depending on local
!.. droplet number concentration.
      REAL, PARAMETER, PRIVATE:: Nt_c = 100.E6
      REAL, PARAMETER, PRIVATE:: Nt_c_max = 1999.E6
```

We can see that the parameter Nt_c can be easily changed to 75 cm^{-3} and the run can be recompiled for that case.

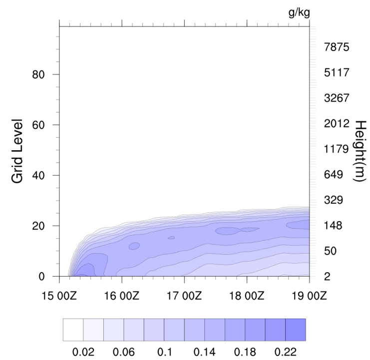
Now, we wanted to investigate the Thompson Aerosol-Aware scheme and this change is made in the namelist.input file, where in the physics part we change the microphysics from mp_physics = 8 to mp_physics= 28 which indicates the aerosol-aware. Then, we rerun the simulation for this case.

2.2 Results

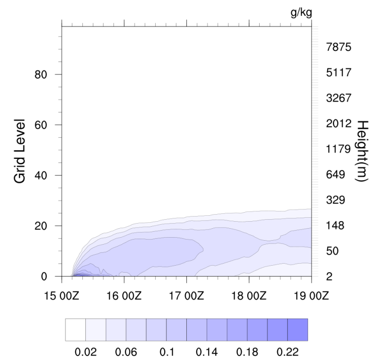
For the first graph, we decided to compare the first figure in the 'Surface Deposition' Paper. We plotted the cloud mixing ratio varying with height against time for each case, that is, the default N_c= 100 cm^{-3}, when N_c= 75 cm^{-3} and with the varying N_c. We had the MYNN



(a) N_c= 100 cm^{-3}



(b) N_c= 75 cm^{-3}



(c) Varying N_c

FIGURE 2.1. Plotting Q_c against Height for 4 days with a 6 hr surface cooling at the start of the simulation. Fig 2.1 a) The Thompson scheme with N_c= 100 cm^{-3}, b) The Thompson scheme with N_c= 75 cm^{-3} and c) The Thompson Aerosol-Aware scheme which has N_c as a predicted variable.

surface layer with z0c = 0.01 m, the surface cooling of 3 K/hr which decreased the skin temperature to 282 K.

From Fig 2.1, we observe that there are no upper layer clouds and the cloud/fog layer develops after the 6-hour cooling. The fog layer seems pretty stratified and steadily increases with time to reach a height of about 315 m for all of the three cases. This may be due to no radiation schemes being introduced but this also simplifies accessing the performance of our changes. We can see there is a slight decrease in LWC when we change the cloud droplet concentration to 75 cm^{-3} and there is a significant decrease in LWC when we use the Thompson Aerosol-Aware.

When doing the comparison between Fig 2.1 a) and 2.1 b), it is quite hard to distinguish the decrease in LWC content, so we decided to plot each day ($16^{th}, 17^{th}, 18^{th}, 19^{th}$) instead of continuously. For example, we plotted the cloud mixing on the 16^th at 00:00 UTC against height for the original case and then for the maritime case. The figure is given below:

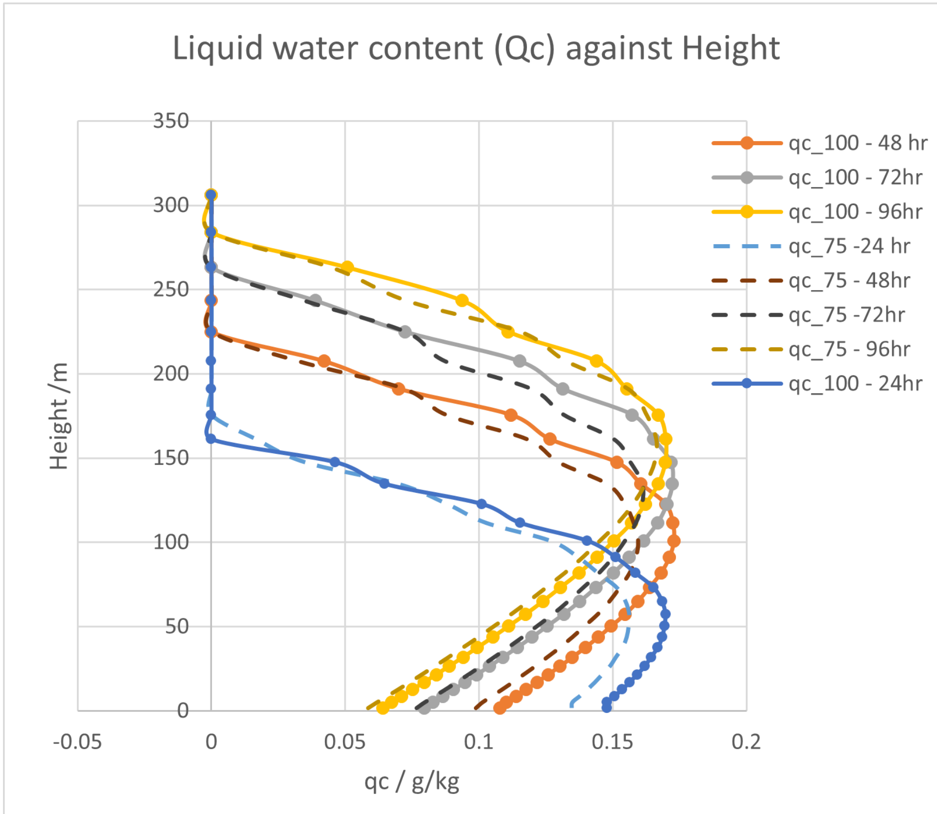


FIGURE 2.2. Qc against Height Comparison between N_c=100 cm^3 and 75 $cm^3$for Thompson (2008) microphysics scheme.

From Figure 2.2, we observe that when we change the N_c to 75 cm^{-3}, there is indeed a slight decrease in LWC. The plots for the default case are in full lines and for the maritime case are in dotted lines. We also plotted a comparison between the default Thompson case and the Thompson Aersol-Aware scheme which is given below:

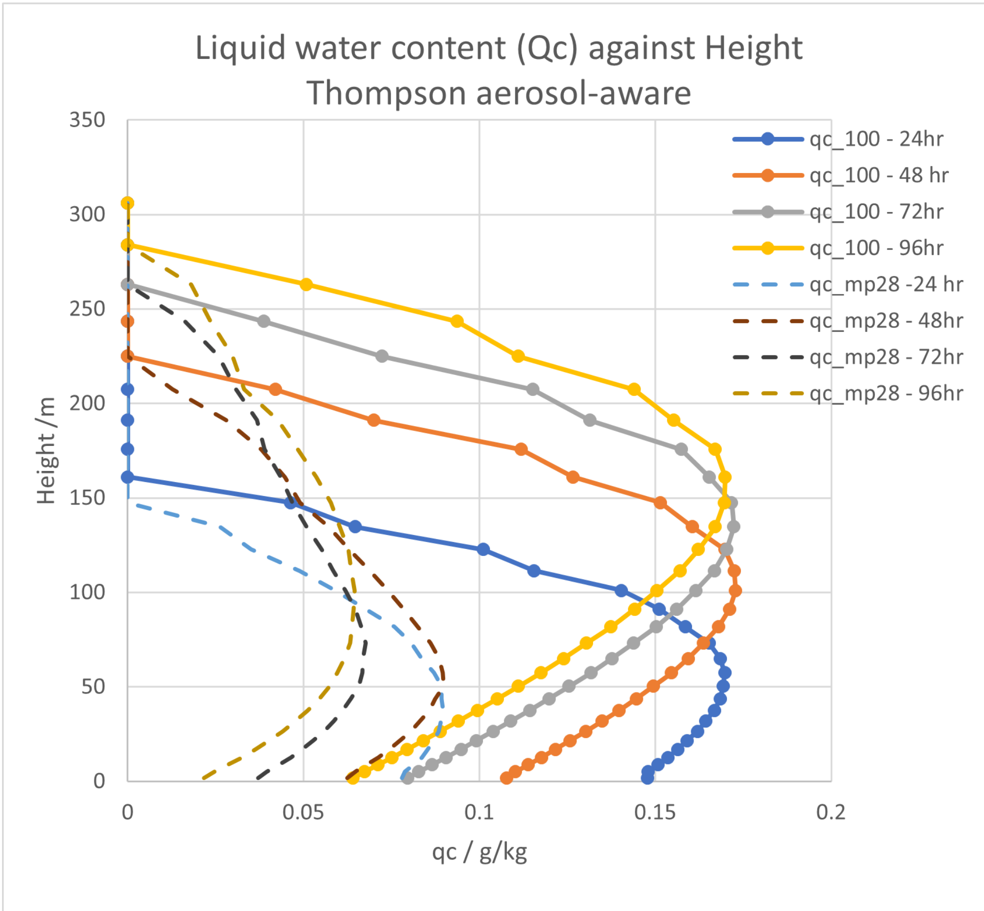


FIGURE 2.3. Qc against Height Comparison between Thompson (2008) microphysics and Thompson (2014) aerosol-aware.

From Fig 2.3, we can see that for the Thompson Aerosol-Aware, there is a significant decrease in LWC which is in agreement with Fig 2.1. Now that we identified that cloud droplet number concentration does affect LWC, we need to know how much the LWC decreases for each case compared to the original case.

Chapter 3

Discussion

We decided to calculate the LWC decrease for each day to fully understand the contribution of changing the cloud droplet number and the Thompson Aerosol-Aware scheme. To be able to calculate the % decrease for each day, we simply used the % decrease formula given below:

$$\% \text{ decrease} = \frac{N_{c100} - N_{c75}}{N_{c100}} * 100 \tag{3.1}$$

We extracted the eta levels for each day till the LWC was 0 and then plugged in the values for N_{c100} and N_{c75}. Then, we calculated the percentage decrease at each vertical level for one day and did an average for that day. This was done for the $16^{th}, 17^{th}, 18^{th}$, and 19^{th}.

From the tables below, we observed that in the Maritime case (N_c = 75 cm^{-3}), there is a 9% decrease in LWC on the first two days and a 6% decrease on the last two days. For the Thompson Aerosol-Aware, there is a 50% decrease on the first two days and a 60% decrease on the last two days.

Maritime Case (75)	After 24hrs	After 48hrs	After 72hrs	After 96hrs
% decrease	9.432596823	9.014164921	5.978218141	5.558809289

Table 3.1. Table of mean percentage decrease for each day comparing original with N_c=75 cm^{-3} for the Thompson scheme.

Aerosol-Aware	After 24hrs	After 48hrs	After 72hrs	After 96hrs
% decrease	50.305688666	49.876277120	57.604611702	59.554538955

TABLE 3.2. Table of mean percentage decrease for each day comparing original with the Thompson Aerosol-Aware scheme.

Now, that we verified that the LWC did decrease by changing the cloud droplet number concentration, the next objective is to find the implications of the changes in the real world. We decided to calculate the visibility inside the fog layer and do a comparison between the three cases. By the Glossary of Meteorology standards, a fog layer is identified when the visibility is reduced below 1 km.[8]

We decided to calculate the visibility for each day again at 00:00 UTC. To be able to calculate the visibility, we used the daytime visibility equation based on the 'Characterizing and Predicting Marine Fog Offshore Newfoundland and Labrador' paper. We used the daytime visibility equation for simplicity, given below:

$$V_k = \frac{1.24\rho_w^{2/3}}{LWC^2 N^{1/3}} \tag{3.2}$$

, where V_k is the visibility in m, ρ_w is the density of water, LWC is the cloud mixing ratio and N is the cloud droplet number concentration.[9]

To calculate visibility, we chose to use LWC at the lowest eta level which corresponded to z $\approx$ 1.6 m. For the cloud droplet concentration, for the original case and the maritime case, it was set as a constant and that number was simply used for the calculations. However, for the Thompson Aerosol-Aware, as the cloud droplet number was varying, we got the values for each day from the WRF run as it is a predicted variable and plugged that value in equation 3.2. All the data was collected and analyzed in Excel and can be found here: Cloud Physics Project.xlsx. The table below gives a comparison of visibility between the three cases:

Visibility/m	After 24hrs	After 48hrs	After 72hrs	After 96hrs
Nc=100	37.44445	46.22861	56.55745	65.40787
Nc=75	39.85451	48.97966	58.00246	69.36349
Aerosol-Aware	224.83444	235.82130	401.35534	491.91817

TABLE 3.3. Table containing visibility at 00:00 UTC for each day of the simulation at height z= 1.6m for each case (original, when N_c is changed to 75 cm^{-3} and Thompson aerosol-aware).

In a general overview, for all three cases, visibility was reduced below 1 km which is considered fog. For the original case (N_c = 100 cm^{-3}), visibility was around 50 m. For the maritime case (N_c = 75 cm^{-3}), visibility was around 60 m, and for the first three days, visibility increased by 2 m while on the last day, it increased by 4 m. Now for the Thompson Aerosol-Aware, we did see a significant decrease in LWC and as we see in Table 3.3, there was a great increase in visibility. Visibility was around 350 m and for the first two days, visibility increased by 200 m, on the third day there was an increase of 350 m, and finally, on the last day, it increased by 400 m. It is also important to note that generally, fog visibility is in the order of hundreds of meters, so one might assume that the Thompson Aerosol-Aware is giving a more accurate depiction of the fog layer.

Chapter 4

Conclusion

4.1 Summary and Conclusions

By changing the cloud droplet number concentration to be more suitable for a maritime case in the Thompson microphysics scheme, that is changing the N_c from 100 cm^{-3} to 75 cm^{-3}, we were able to decrease the cloud mixing ratio or LWC by 7 %. This increased visibility by approximately 3 m. When we changed the Thompson microphysics scheme to its newer version, the Thompson Aerosol-Aware microphysics scheme, which has N_c varying with time, we saw the LWC decrease by 55 %. The resulting increase in visibility was around 300 m.

4.2 Future work

To be able to validate the comparison, we need to run the real case in WRF and see which one is closer to actual observations. This aligns well with the Fog and Turbulence Interactions in the Marine Atmosphere (FATIMA) project which collects data around places that have a lot of fog occurrence (Sable Island or Yellow Sea). We need to also investigate the Thompson Aerosol-Aware scheme to fully understand why it differs that much from the older scheme. Finally, we need to implement the radiation scheme as it plays a major role in the growth of the fog layer (longwave radiation) and its dissipation (shortwave radiation).[10]

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