Report for Tutorial of Numerical Modelling of Weather and Climate

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Contents

List of Figures

1 Model description

In the tutorial, we are developing a isentropic model, in which the vertical coordinate is given by the potential temperature:

$$\theta = T(\frac{p_0}{p})^{\frac{R}{c_p}} \tag{1}$$

where p_0 is a reference pressure, normally p_0=1000 hPa, R=287 J/(K·kg) the gas constant for dry air, and c_p= 1004 J/(K·kg) the specific heat of dry air at constant pressure.

There are several assumptions in our adiabatic models:

- Neglect earth's rotation
$$f = 0 \tag{2}$$
- Adiabatic flow
$$\frac{D\theta}{Dt} = 0 \tag{3}$$
- Two-dimensional flow in (x, z) plane
$$\frac{\partial}{\partial y} = 0 \qquad , \qquad v = 0 \tag{4}$$
- Lower boundary is an isentropic surface
$$\theta(z = z_s) = \theta_s = const \tag{5}$$

As the vertical wind velocity is then defined as

$$\theta' = \frac{D\theta}{Dt} \tag{6}$$

from the assumption, we can see that in adiabatic flow, the potential temperature is conserved, as seen in Equation 3, which implies a vanishing vertical wind in isentropic coordinates which reduces the 3-dimensional system to a stack of 2-dimensional θ-layers.

Apart from Equation 1, we also implement other atmospheric dynamics equations:

1. Horizontal momentum equation in x-direction
$$\frac{Du}{Dt} = -\left(\frac{\partial M}{\partial x}\right)_\theta \tag{7}$$
with
$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\left(\frac{\partial}{\partial x}\right)_\theta \tag{8}$$
2. The Montgomery potential:
$$M = gz + c_pT \tag{9}$$

3. Equation of continuity in 2D:

$$\frac{\partial \sigma}{\partial t} + \left(\frac{\partial \sigma u}{\partial x} \right)_\theta = 0 \tag{10}$$

where σ is the isentropic density, defined as:

$$\sigma = -\frac{1}{g}\frac{\partial p}{\partial \theta} \tag{11}$$

4. Hydrostatic relation:

$$\pi = \frac{\partial M}{\partial \theta} \qquad with \qquad \pi = c_p \left(\frac{p}{p_0} \right)^{R/c_p} \tag{12}$$

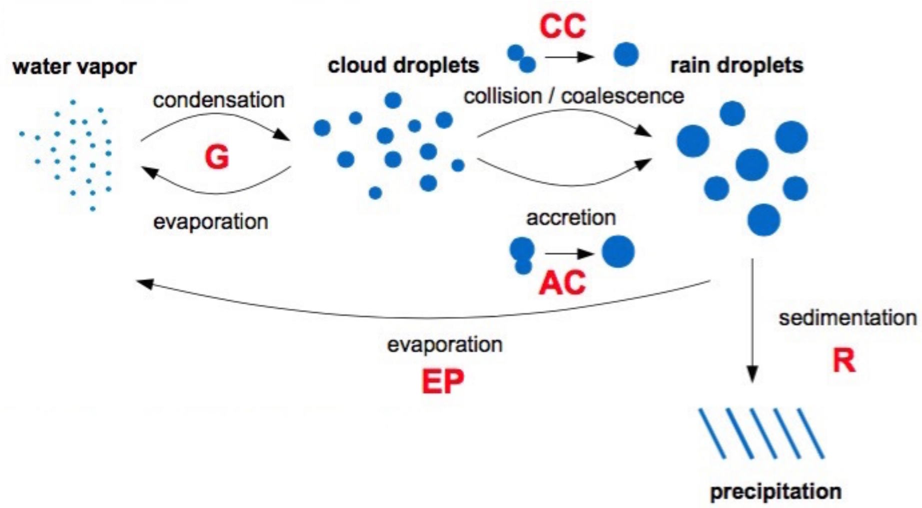

Figure 1: Microphysical processes in the model

However, up till now, those equations could just describe dry and adiabatic flow without any microphysics processes like evaporation and condensation. Hence we induce the microphysics processes to the model to present processes that have something to do with latent heat, as shown in 1. In the model, we add five scalars: water vapor mixing ratio q_v, cloud liquid water mixing ratio q_c, rain droplets mixing ratio q_r, cloud droplet number density n_c and rain droplet number density n_r. Those scalars are described as:

$$\frac{\partial q_v}{\partial t} + u\frac{\partial q_v}{\partial x} = -G_1 + EP_1 \tag{13}$$

$$\frac{\partial q_c}{\partial t} + u\frac{\partial q_c}{\partial x} = G_1 - CC_1 - AC_1 \tag{14}$$

$$\frac{\partial q_r}{\partial t} + u\frac{\partial q_r}{\partial x} = CC_1 + AC_1 - EP_1 \tag{15}$$

$$\frac{\partial n_c}{\partial t} + u\frac{\partial n_c}{\partial x} = -CC_2 - AC_2 + G_2 \tag{16}$$

$$\frac{\partial n_r}{\partial t} + u\frac{\partial n_r}{\partial x} = CC_2 + SC_2 - EP_2 \tag{17}$$

This process in the tutorial is called 'Two Moment Scheme', whereas the first three equations in the tutorial is called 'Kessler Scheme'.

Then we couple the microphysical processes to dynamics. The horizontal momentum equation in x-direction miss a term in the operator shown in Equation 8. If we couple the microphysical processes to dynamics, then the new one is:

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\left(\frac{\partial}{\partial x}\right)_\theta + \theta'\frac{\partial}{\partial \theta} \tag{18}$$

We also implement relaxed lateral boundaries and absorbing boundary at the top of the domain, hence we can avoid the reflection of upward-propagating waves and finally obtain an undistorted atmosphere at lower levels. We therefore choose a smooth sin^2-type transition from D_0 to D_{abs}, which can be described as following,

$$\tau(k) = D_0 + (D_{abs} - D_0)sin^2\left(\frac{\pi}{2}\frac{k-(nz-nab)}{nab}\right), \qquad (nz-nab) < k \leq nz \tag{19}$$

Finally, as mentioned above, the isentropic model developed in the tutorial includes both dynamics and microphysical processes, with relaxed lateral boundaries and absorbing boundary at the top of the domain.

2 Case Study: Qin Mountains

The Qin Mountains (2000-3000m a.s.l.) are a major east-west mountain range in southern Shaanxi Province, China. The mountains provide a natural boundary between the North and South of the country, as shown in Figure 2. In January, the mean temperature in the northern side of Qin Mountains is below 0 °C, whereas in the southern side of Qin Mountains, it is above 0 °C. For annual precipitation, in the southern side, it is more than 800 mm, whereas in the northern side, it is less 800 mm. In the northern side, the type of climate is Temperate monsoon climate, whereas in the southern side, it is Subtropical monsoon climate. Hence Qin Mountains are considered to be a geographical mark in China.

Figure 2: Qin Mountains

In this study, I pick up a city called Han Zhong in the southern side of Qin Mountains, and 30km to the peak of the mountains. Han Zhong belongs to Subtropical monsoon climate, but as it is near the mountains, it is not the typical Subtropical monsoon climate and influenced by the mountain climate. I will exam the precipitation in the city and gravity wave generated in the mountain region. As from Wikipedia, the annual precipitation of Han Zhong is 852.7 mm, and annual mean temperature is 14.3 °C. I run the model with all the processes mentioned in Part 1, for the moisture process, I use the 'Two Moment Scheme'. For simplicity, I set the height of mountain as 3000 m, half width as 100 km. The initial wind velocity is 15 m/s, relative humidity is 79.3 % as shown in Wikipedia. Other parameters are kept as default. Integration time is 24h.

2.1 Dynamics

Before running the model, I test the relaxation routine mentioned in the Tutorial 3 and it works very well. In this test, as indicated in the Figure 3, the gravity wave is also generated. But it seems that 24h integration time may not be enough to determine the wavelenght of the gravity wave. From the figure, we can see the gradient is very large in the sky of the right side of the mountain, it might because of the short integration time in this case or because of the height and the shape of the mountain. I integrated for more time, 120h this time, we can see from the Figure 4, at t=120h, x=1400 km, the wavelength of this gravitiy wave is at least 20 km. The wavelength very large maybe because the topography of the mountain.

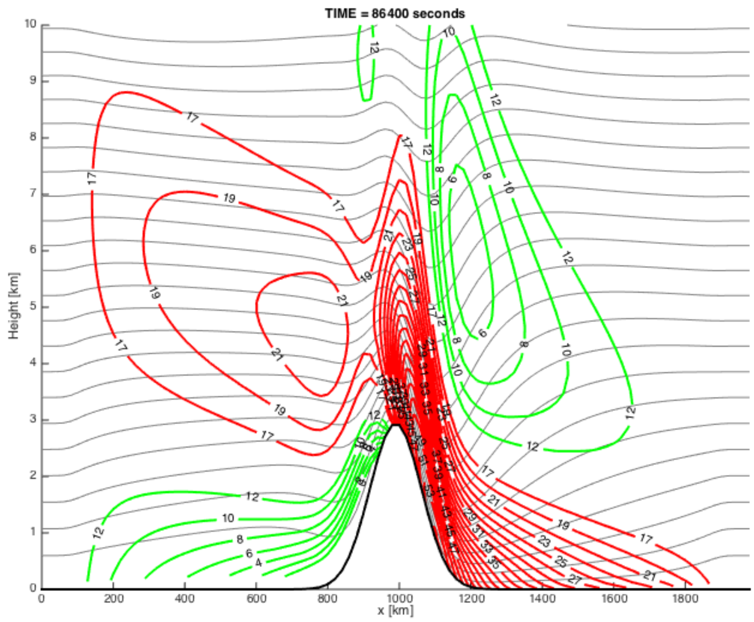

Figure 3: Gravity Wave generated in the Qin Mountained Region

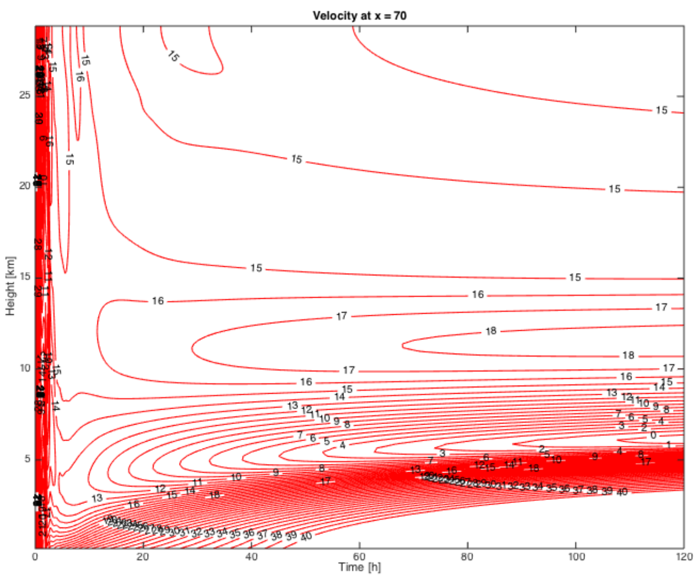

Figure 4: Velocity at x=1400km as time goes by

2.2 Precipitation

As Han Zhong locates in the southern side of the Mountains, and the direction of the wind is from south to north (in the plot, from left to right), the wind carries the moist air, climbs along the mountains and is cooled as altitude increases. Since the temperature decreases with increasing height, the relative humidity of the air parcel increases and the air parcle would be saturated after a critical height. After homogeneous or heteregeneous nucleation (mainly the heter. nucleation), droplet will form. After accretion and collision-coalescence processes as mentioned in the Figure 1, rain droplet will be precipitated.

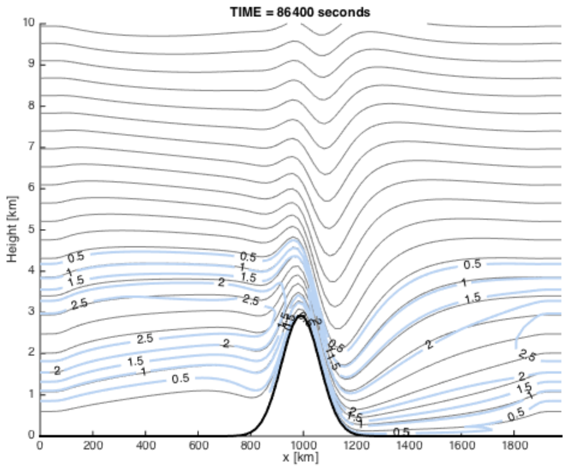

Figure 5: Water Vapour Mixing Ratio of the air in the domain

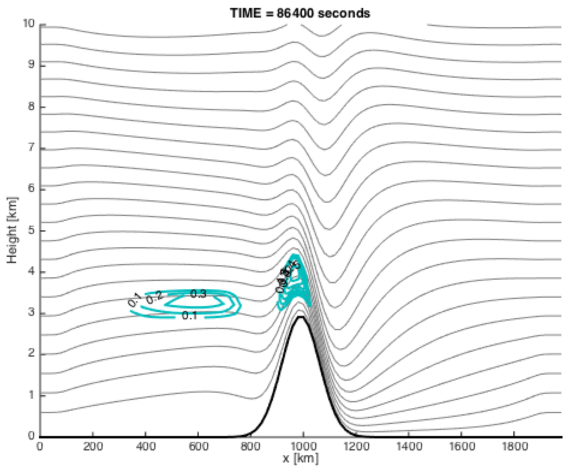

Figure 6: Cloud Liquid Water Mixing Ratio of the air in the domain

From the Figure 5 and Figure 6, we can see at the level of 3km, the water content peaks. From Figure 5, the Water Vapour Mixing Ratio peaks at 3km in front of the mountain and decrease as altitude increases and decreases. From the Figure 6, Cloud Liquid Water Mixing Ratio peaks at the top of the mountain, indicating precipitation may form there, whereas at x=600km, height=3km, another peak is formed, but the reason is unknown (beyond my knowledge, so I cannot explain the peak there).

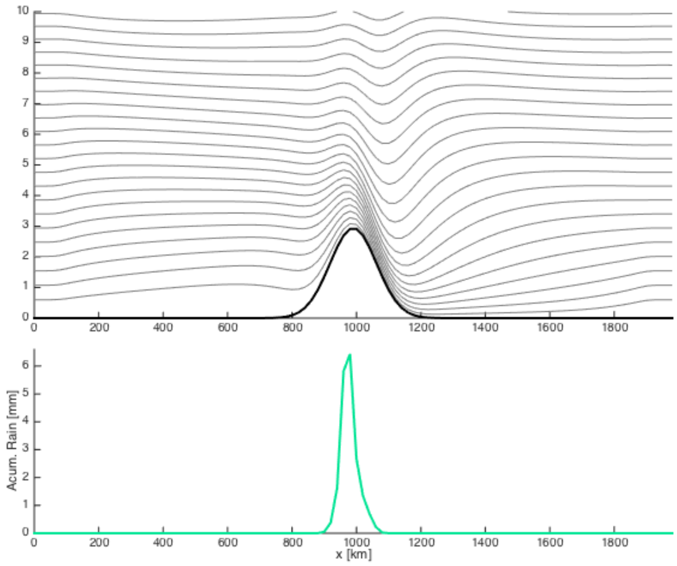

Figure 7: Rain Droplet Mixing Ratio in the domain (upper panal) and Accumulated Precipitation in the mountain region (lower panal) at t=24h

In the Figure 7, we can see the precipitation occures in the mountain region, starting from the height nearly 600m in the southern side of the mountain, and peaking at the top of the mountain, which quite fits the processes I mentioned in the Part 2.2. As we can see from Figure 8 and Figure 9, at t=0.5h, there is no precipitation in the mountain and the Rain Droplet Mixing Ratio is large on the top of the mountain. Whereas at t=1h, there is precipitation in the mountain region while the the Rain Droplet Mixing Ratio is lower than when it was at t=0.5. As time goes by, the Rain Droplet Mixing Ratio is lower and lower, and vanishes finally. So at t=24h as indicated in Figure 7, there is no Rain Droplet Mixing Ratio. The changes of the Rain Droplet Mixing Ratio and the precipitation prove the processes in the Part 2.2.

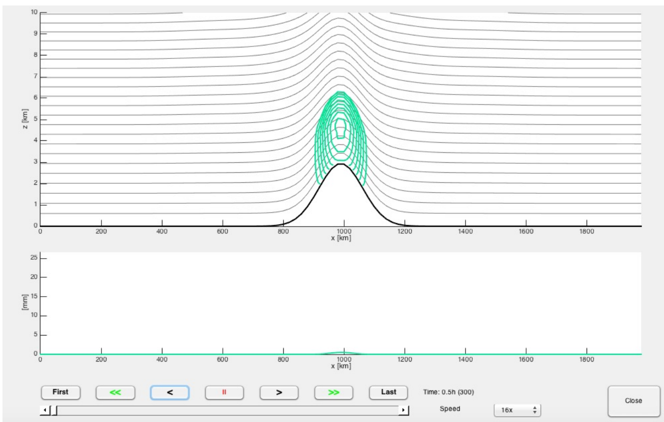

Figure 8: Rain Droplet Mixing Ratio in the domain (upper panal) and Accumulated Precipitation in the mountain region (lower panal) at t=0.5h

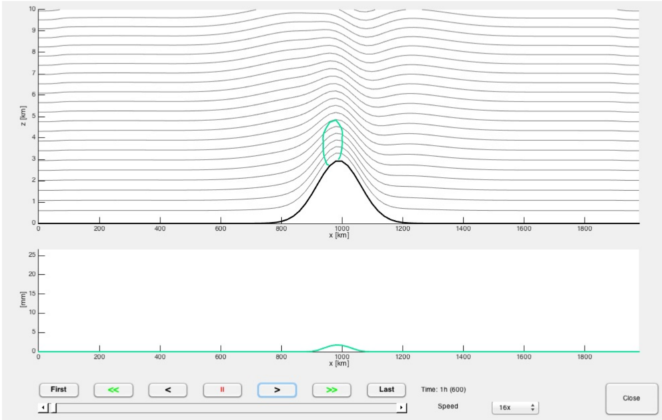

Figure 9: Rain Droplet Mixing Ratio in the domain (upper panal) and Accumulated Precipitation in the mountain region (lower panal) at t=1h

As the city locates 30km south to the peak of the mountains, we can read from Figure 7, the accumulated rain in a day is about 6mm, hence the daily precipitation is 6mm/day. Using the data from Wikipedia, the average precipitation days in Han Zhong from 1951 to 2010 is 117.9 days, hence the total precipitation per year is about 708mm whereas the statistic data for the annual precipitation in the past 60 years is 852.7mm.

3 Conclusion

As we can see from the case study, the simulated precipitation in the city is 708mm, much lower compared to the statistic data 852.7mm, so the simulation is not that precise. However, this model only includes the simple dynamics and microphysical processes, but topography, vegetation, and other processes may influence the precipitation. That may explain the difference of the precipitation. Also meteological conditions may influcence it. The data I used in the model, e.g. RH, temperature, are the annual mean data. And 708mm is from the simulated daily precipitation multiplying the numebr of raining days in a year. In the model, topography is simplified, I only change the height of the peak and the width of the mountain. So those reasons may explain the difference.

I understand the content of the tutorial, and I want to do more complicated case study. For example, I should have implemented more detailed topography in Qin Mountains Region, more detailed climate data and compared the simulated data with the longer time period climate data of Han Zhong, which I can only get in China. I know case study is not that quantitatively, but I have learned what should be included in a meteological model, how to run the model and how to understand the weather processes with the help of the model from the tutorial.

4 Acknowledgement

I hereby should thank the tutors in the tutorial class for helping me with the code, explaining me about the processes included in the model and providing the exercise sheets on the website. Also, I should thank Ari, Annika, Ryan and Prisco for cooperation.