



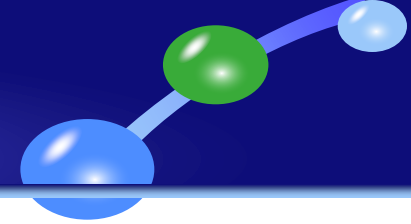
# 水凝物对强降水演变影响的数值试验

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中国气象科学研究院，灾害天气国家重点实验室

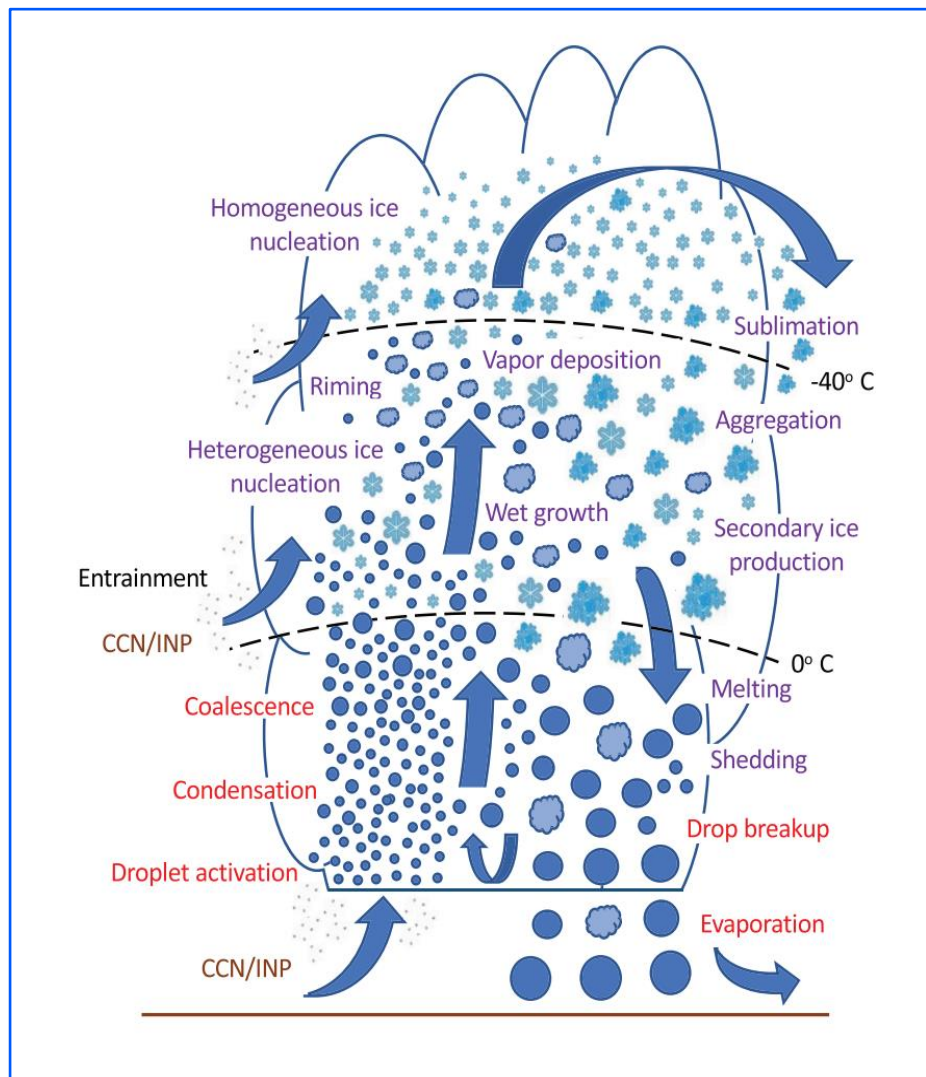
2023. 08. 10

# 内 容

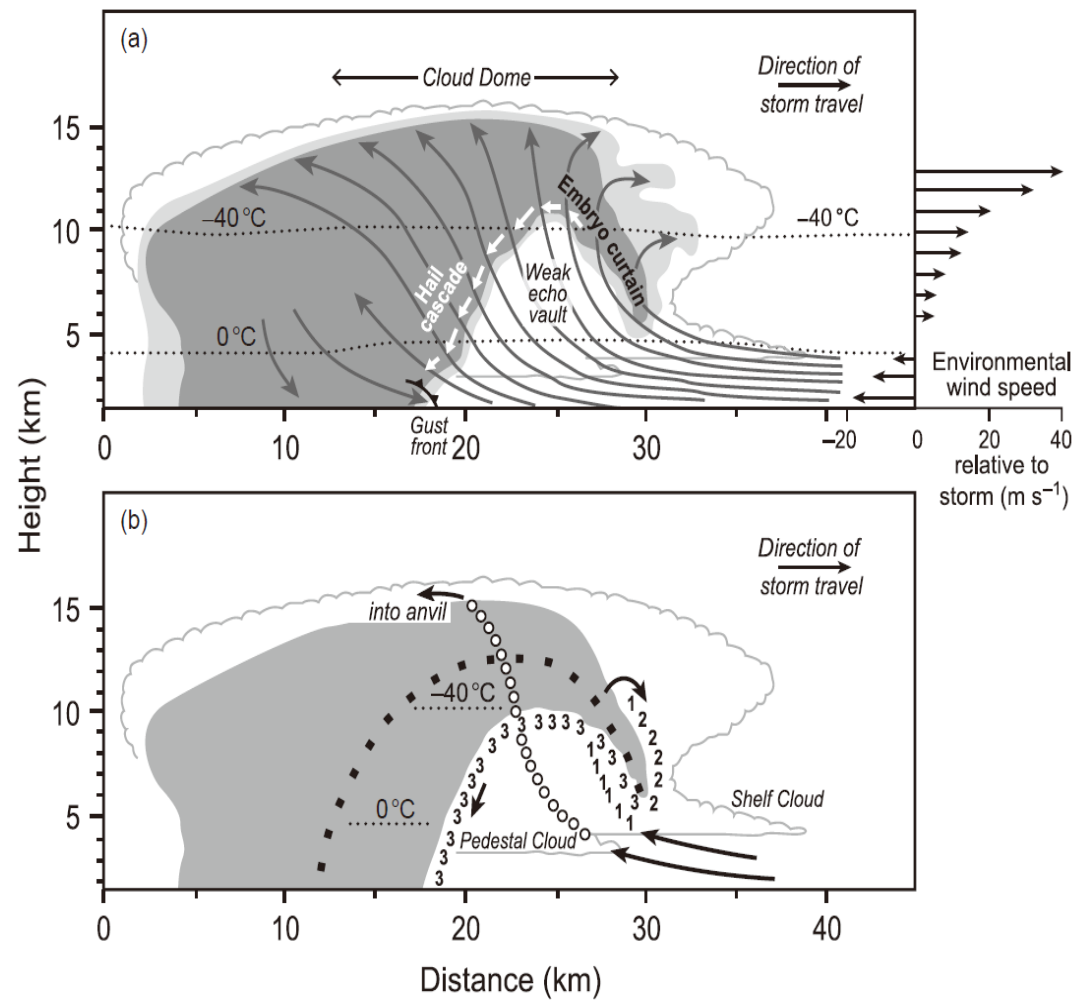


1. 水凝物相关过程对强降水的贡献
2. 云中热动力特征及演变
3. 相变潜热敏感试验

# 云微物理过程



(Morrison et al., 2020)



(Houze, 2014, Cloud Dynamics)

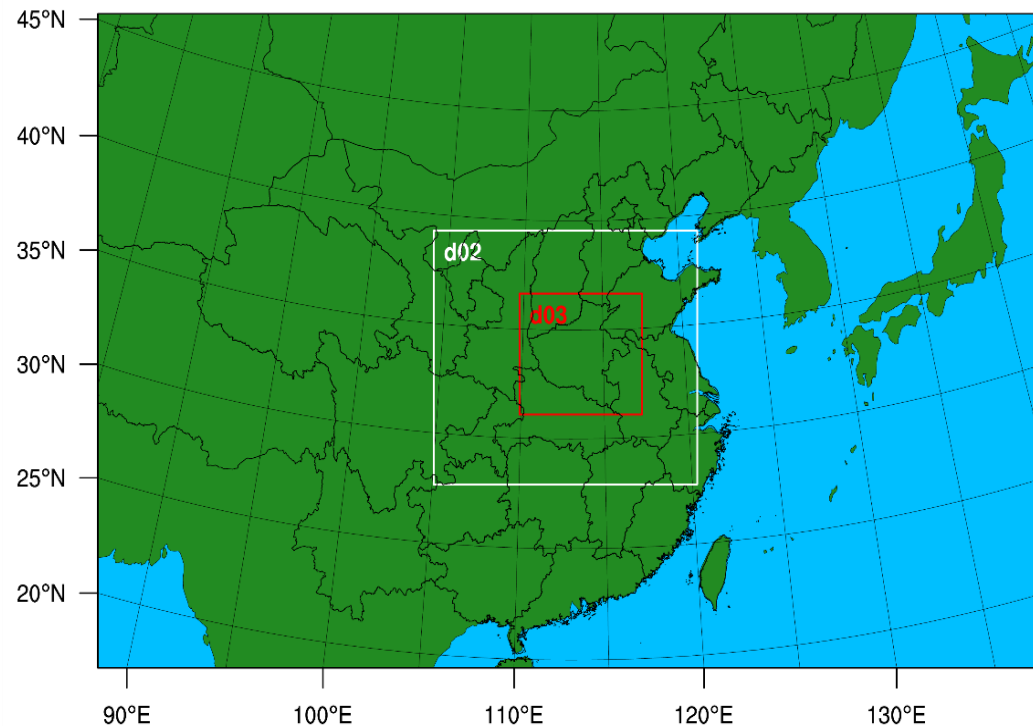


# 1. 模式设置及验证

WRF物理过程设置:

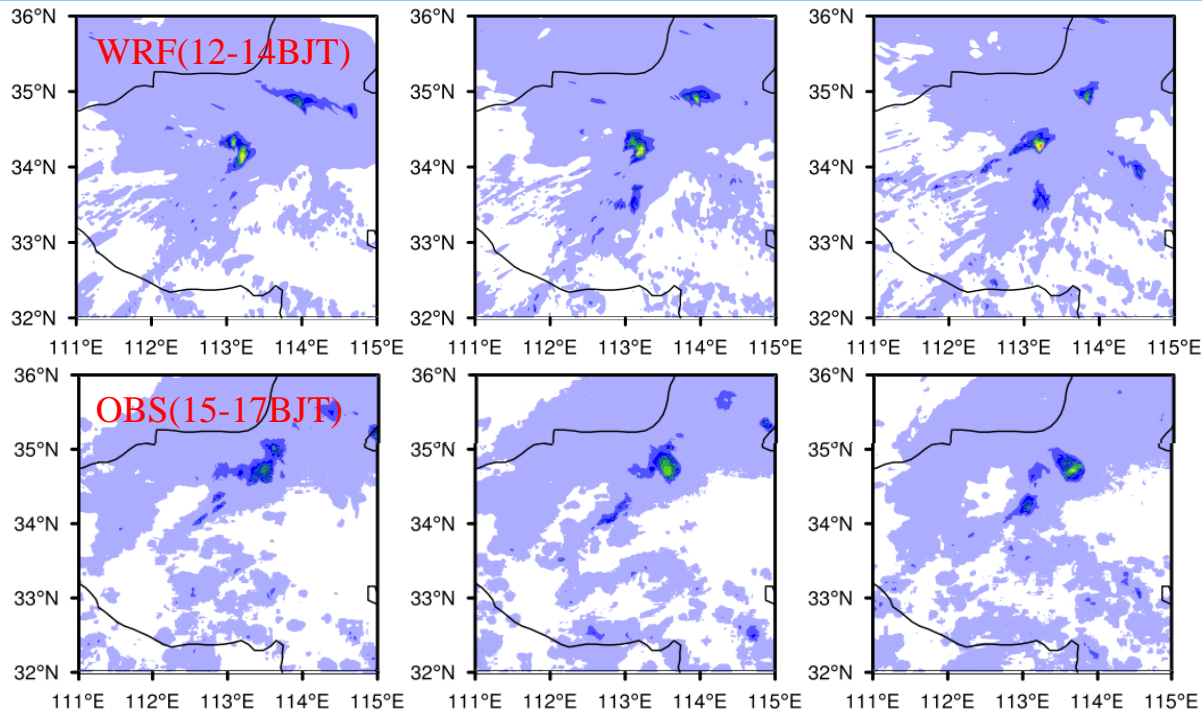
名称	描述
云微物理方案	NSSL-1 moment
长波辐射方案	RRTMG
短波辐射方案	RRTMG
边界层方案	MYJ
陆面方案	Noah
积云对流方案	GF (最外层)
初边界条件	ERA5
积分时间	2021.07.19-18:00, 24h

21.7 郑州暴雨

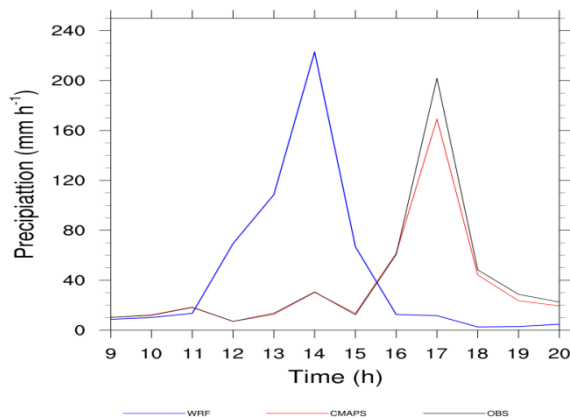
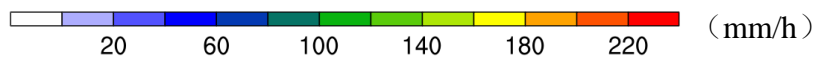


3层嵌套模式域 (水平分辨率9、3、1-km)

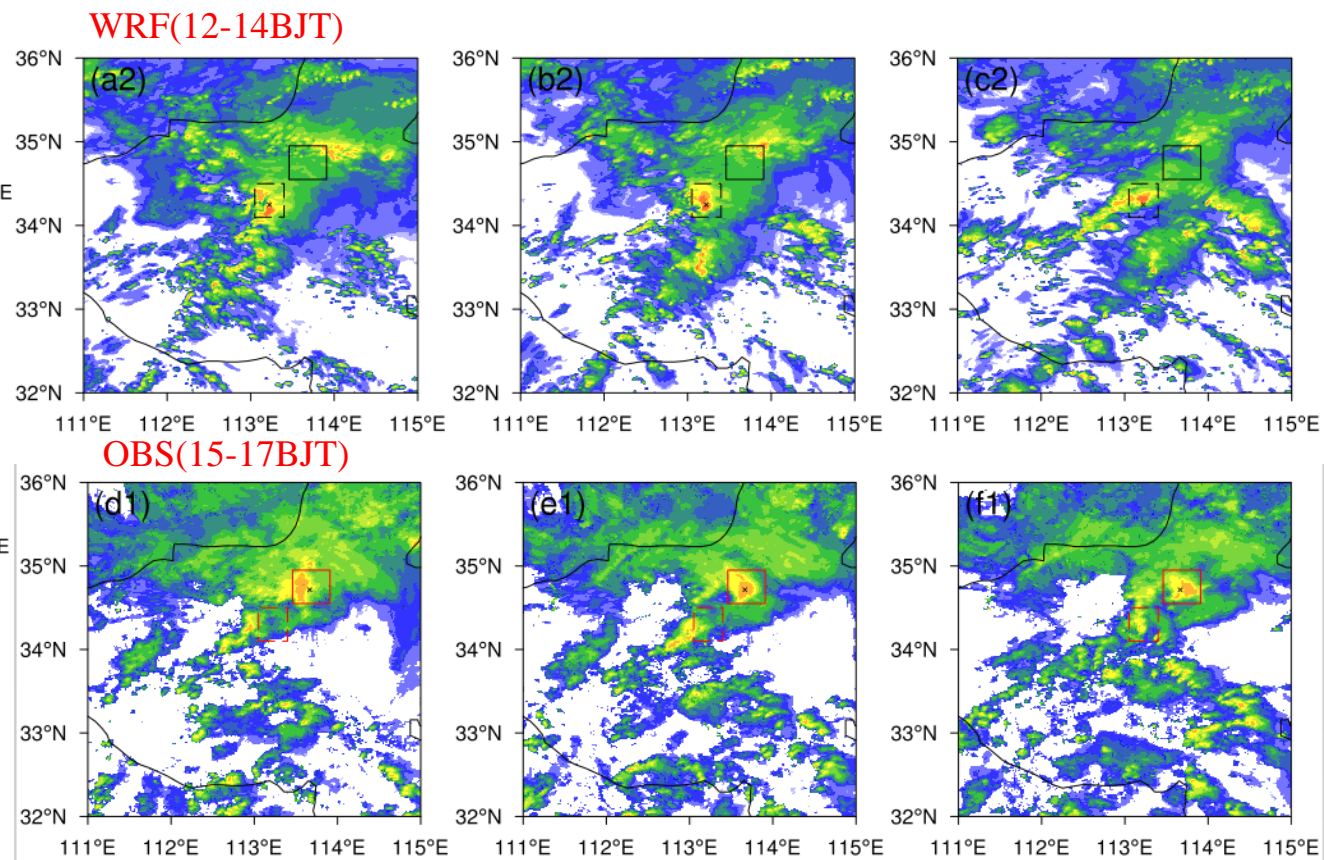
# 1. 模式设置及验证



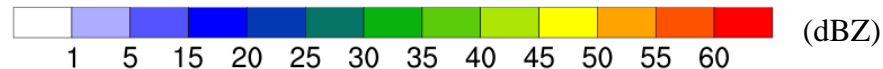
小时降水



最大累积降水点的小时降水率时间演变

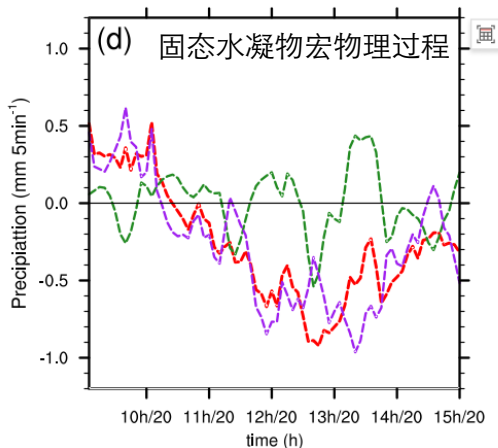
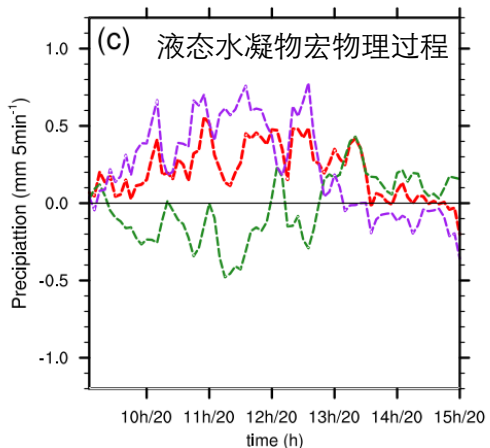
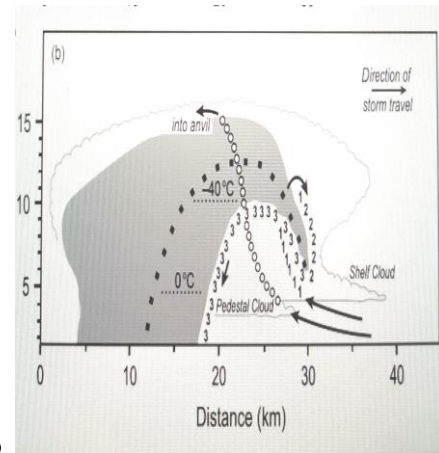
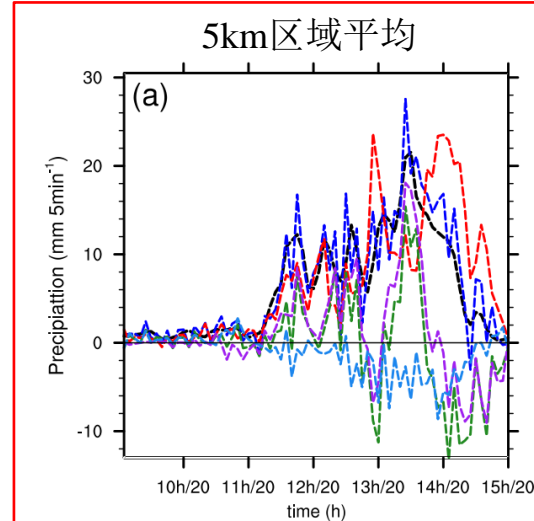
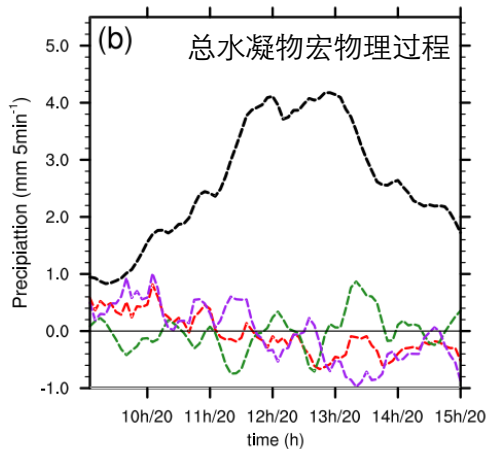
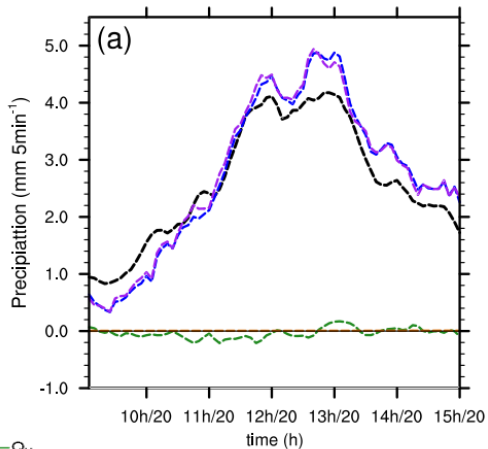
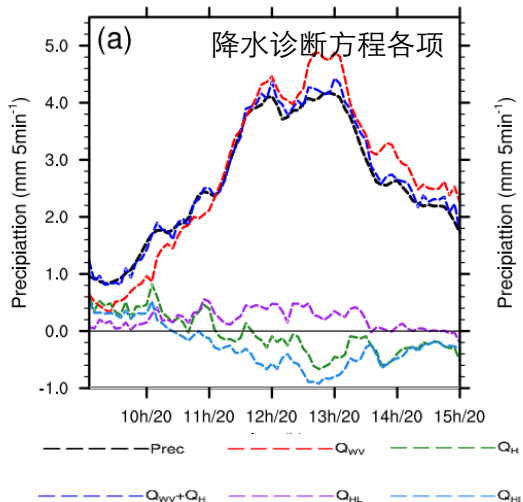


组合雷达反射率



$$g \frac{\theta - \bar{\theta}}{\bar{\theta}} + 0.61(q_v - \bar{q}_v) - q_H$$

## 2. 水凝物过程对降水的贡献



$$P_s = \int_{pb}^{pt} -\frac{\partial q_v}{\partial t} dz + \int_{pb}^{pt} -\nabla(q_v \vec{V}) dz + Es - MP_{qv} - MP_{qcr} + MP_{qisg}$$

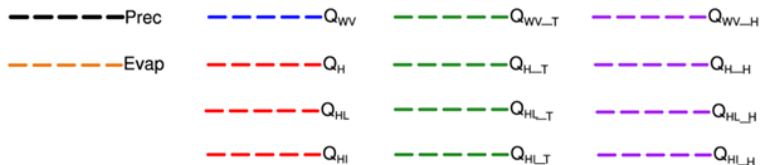
水凝物微物理过程  $Q_{WV}$

液态水凝物宏物理过程  $Q_L$

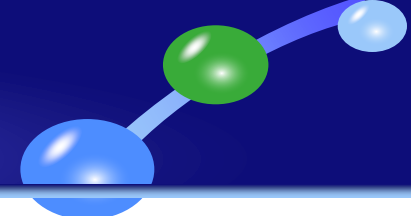
固态水凝物宏物理过程  $Q_I$

(Huang, Cui, et al., 2016, 2019)

最强降水时段，水凝物微物理过程的贡献超过100%，降水早期水凝物宏物理过程占比可达30%-50%。11:30前，总水凝物局地变化为负，通量辐合，表示不断有水凝物输送到研究区域，云系处于合并增长阶段。液态水凝物始终起着促进降水的作用，而固态水凝物随降水的增强转负。这里研究区域为主降水区  $0.4^\circ \times 0.35^\circ$ 。



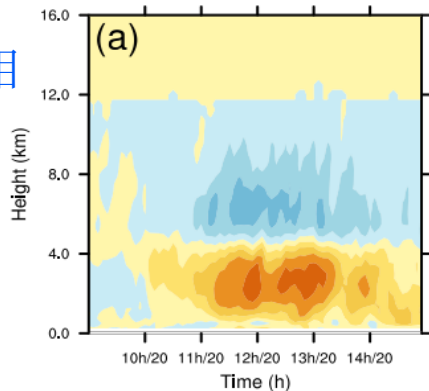
## 2. 水凝物过程对降水的贡献



风场散度

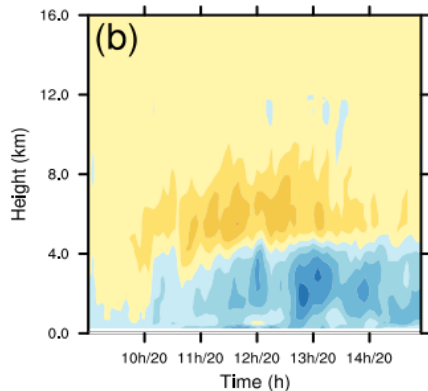
$$-q_x \left( \frac{\partial u}{\partial X} + \frac{\partial v}{\partial Y} \right)$$

液相



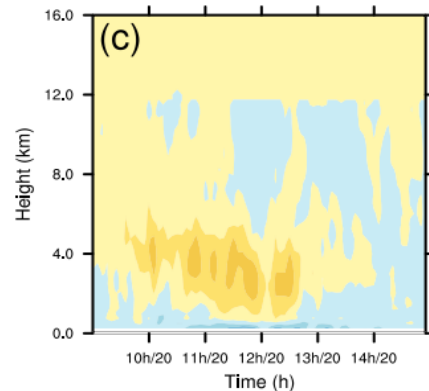
水凝物平流

$$-(u \frac{\partial q_x}{\partial X} + v \frac{\partial q_x}{\partial Y})$$

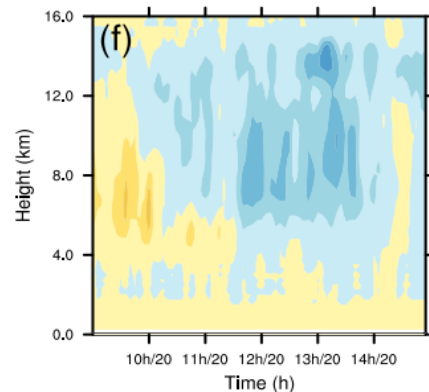
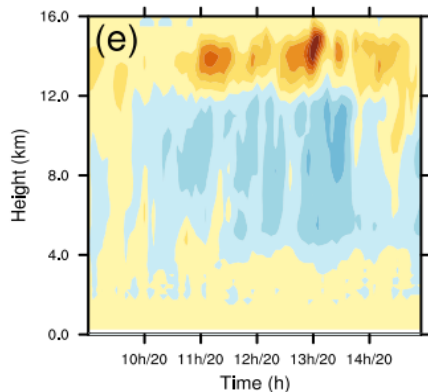
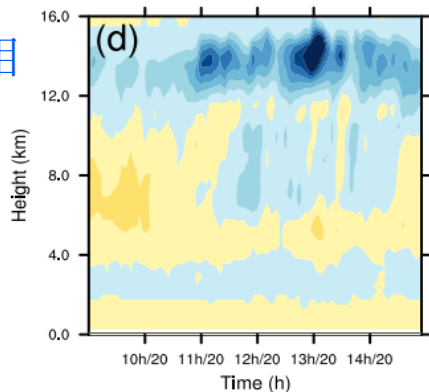


水凝物通量散度

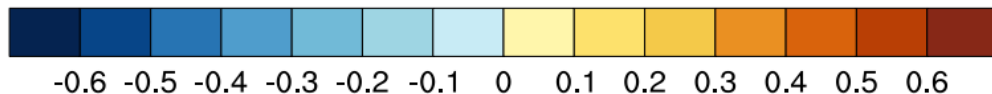
$$-\left( \frac{\partial u q_x}{\partial X} + \frac{\partial v q_x}{\partial Y} \right)$$



冰相



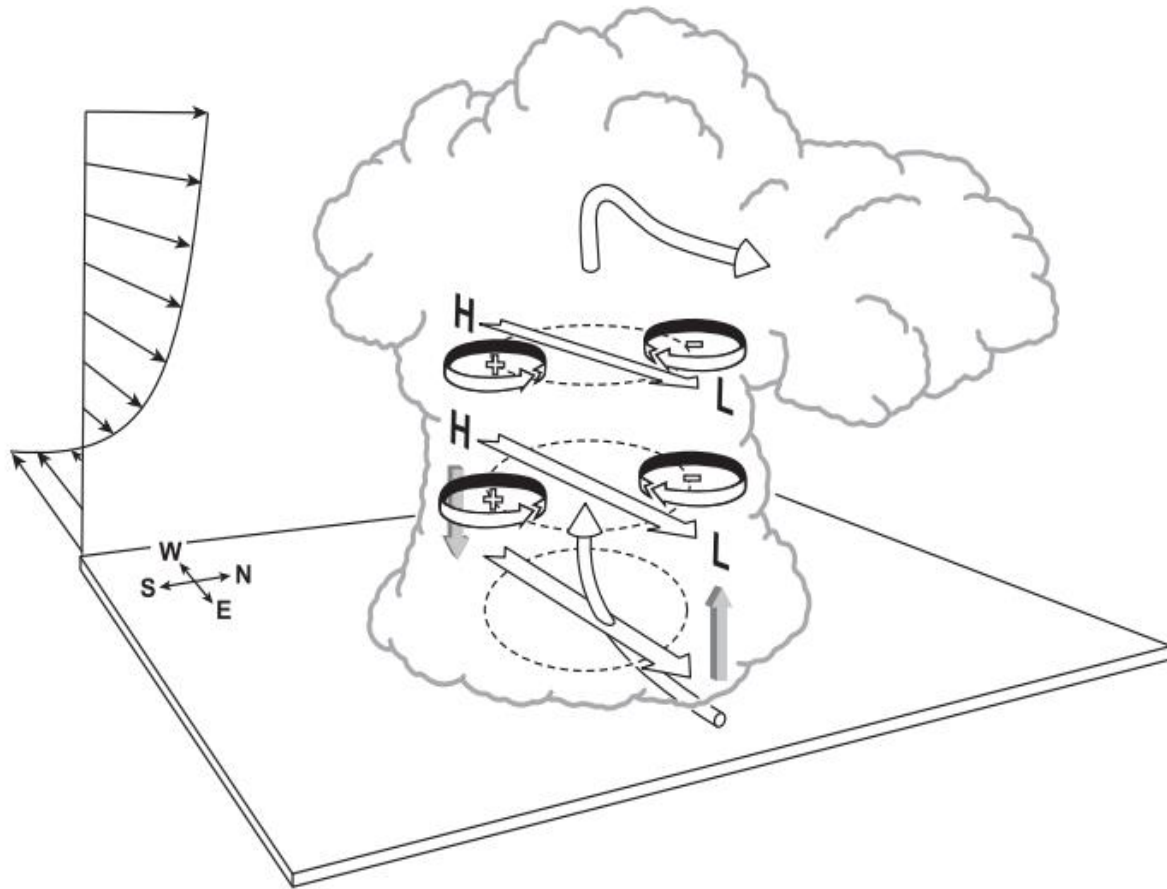
10h后，低层风场明显正辐合，同时液态粒子由于分布不均被平流出研究区域。12h左右4km以下液态水凝物宏物理过程的正作用最大，即在这个时间点，液态水凝物最显著增加降水。固态水凝物宏物理过程相反，高低层风场散度是导致两者对降水贡献不同的主要原因。





### 3. 云动力过程

对流发展的动力、热力、云微物理机制  
核心问题：垂直速度与浮力



$$\frac{dw}{dt} = -\frac{1}{\rho_0} \frac{\partial p'_d}{\partial z} + \left( -\frac{1}{\rho_0} \frac{\partial p'_b}{\partial z} + B \right)$$

$$B \approx g \left[ \frac{\theta'}{\bar{\theta}} + 0.608(q_v - \bar{q}_v) - q_H \right]$$

$$\nabla^2 p'_b = \frac{\partial(\rho_0 B)}{\partial z} \quad \nabla^2 p'_d = -\nabla \cdot (\rho_0 \mathbf{v} \cdot \nabla \mathbf{v})$$

$$p' \propto e'_{ij}{}^2 - \frac{1}{2} |\boldsymbol{\omega}'|^2 + 2\vec{S} \cdot \nabla_h w' - \frac{\partial B}{\partial z}$$

可得到各环境动力场及云微物理过程对垂直速度的定量贡献。

(Klemp, 1987)



# 诊断浮力

WRF中垂直速度方程:

$$\partial_t W + m_x [\partial_x(Uw) + \partial_y(Vw)] + \partial_\eta(\Omega w) - m_y^{-1} g (\alpha/\alpha_d) [\partial_\eta p' - \bar{\mu}_d (q_v + q_c + q_r)] + m_y^{-1} \mu'_d g = F_W$$

扰动垂直气压梯度力、拖曳力、扰动密度浮力，  
(基于干空气的静力平衡)

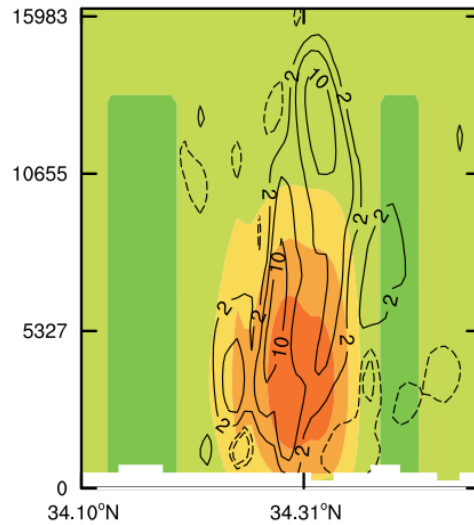
Boussinesq近似:

$$\frac{Dw}{Dt} = -\frac{1}{\rho_0} \frac{\partial p'}{\partial z} - \frac{\rho'}{\rho_0} g$$

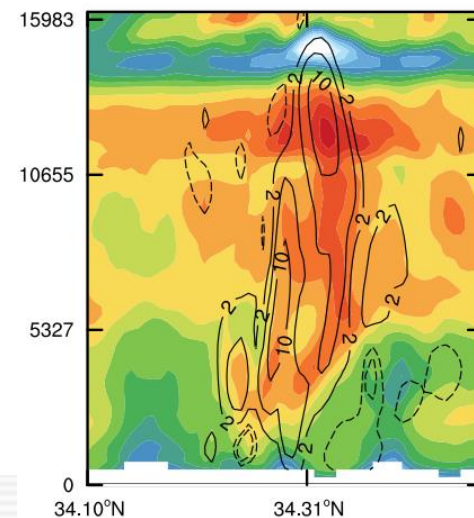
$$B = -\frac{\rho'}{\rho_0} g \approx g \left[ \frac{\theta'}{\bar{\theta}} + 0.608 (q_v - \bar{q}_v) - q_H \right]$$

(目前文献多是通过一定区域的平均作为参考态, 具有较大随意性)

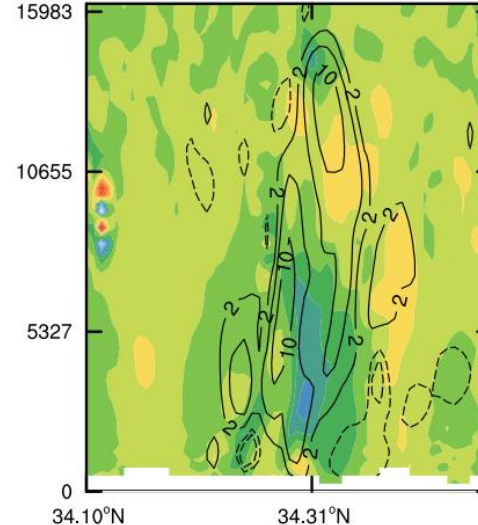
WRF: 浮力



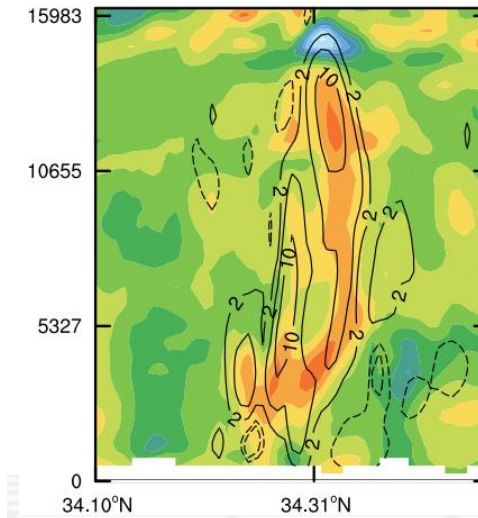
诊断浮力1



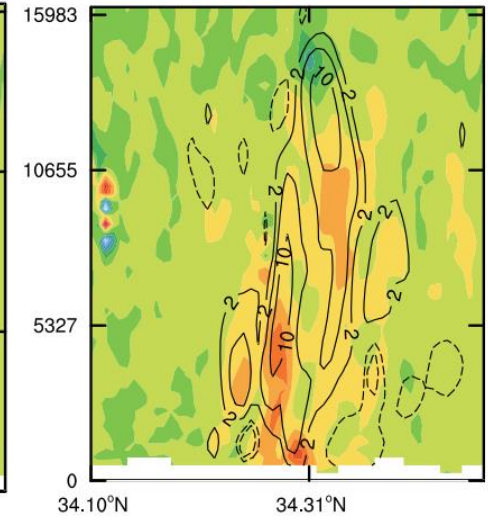
气压梯度力



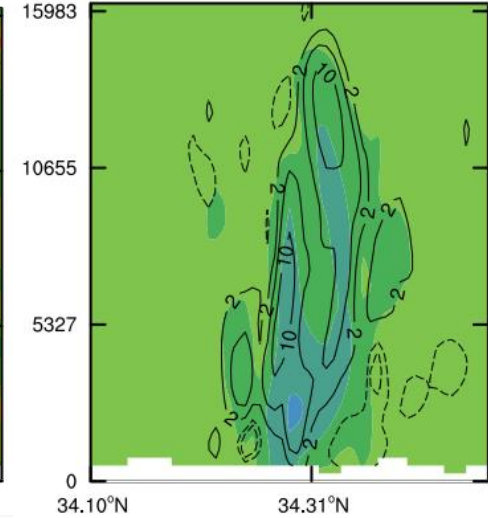
诊断浮力2



气压梯度力+浮力



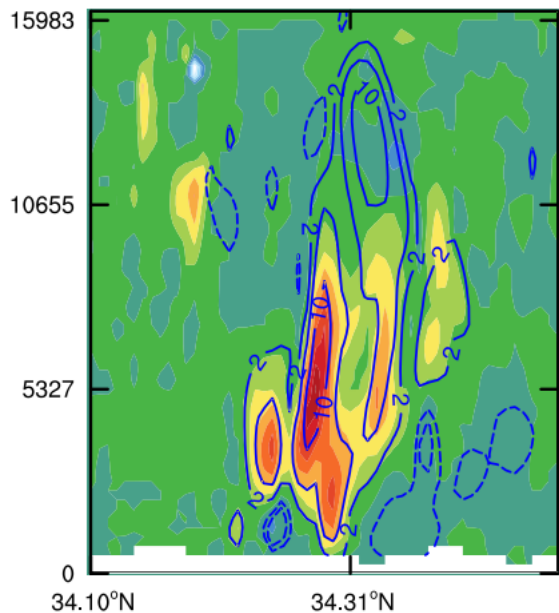
水凝物拖曳力



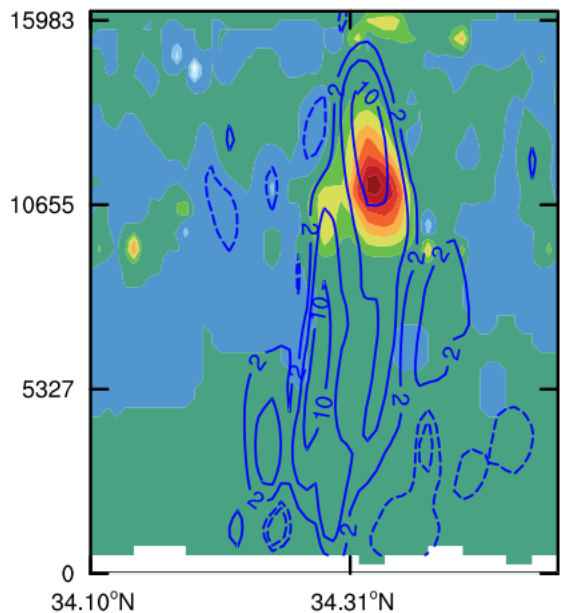
# 3. 云动力过程

T=14:00

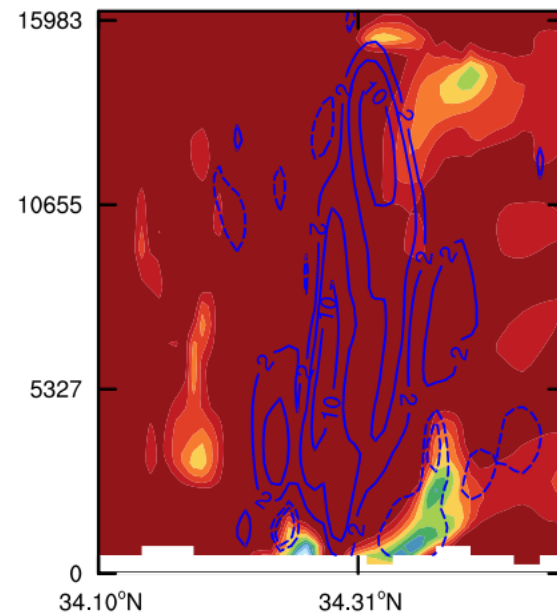
强降水时的浮力主要由云微物理的相变潜热引起，而降水早期主要为动力驱动（边界层辐合、低空急流等）



水汽凝结



水汽凝华



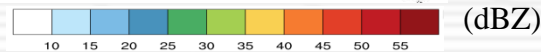
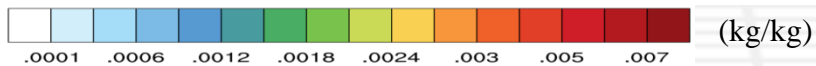
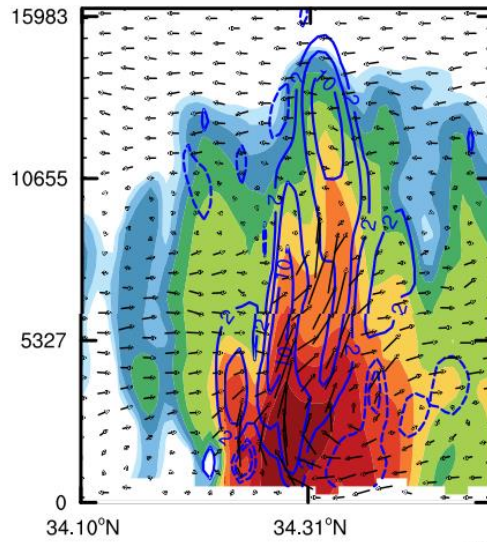
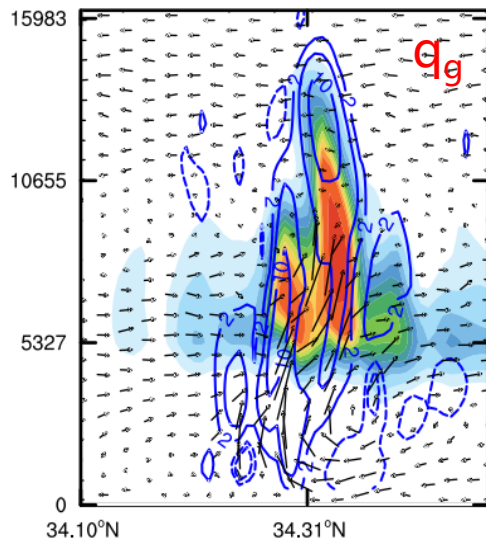
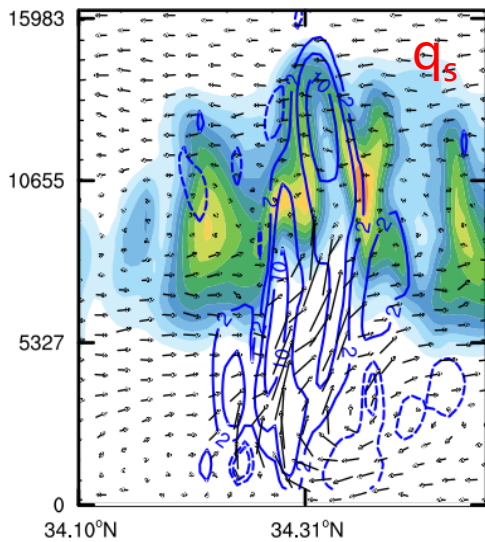
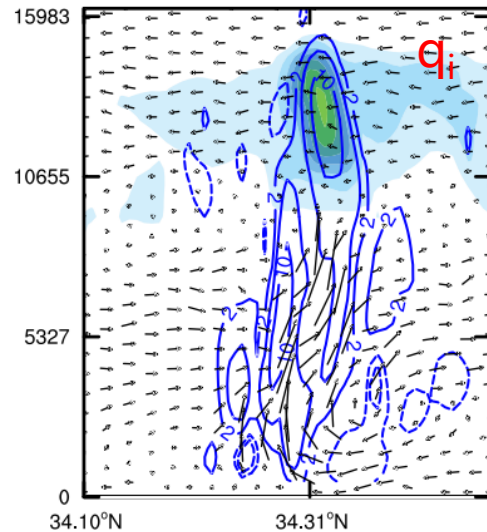
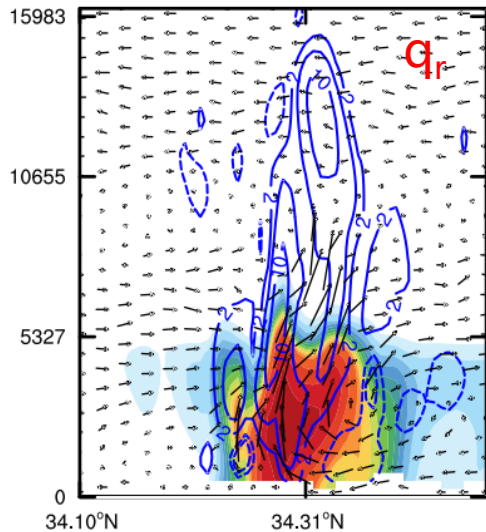
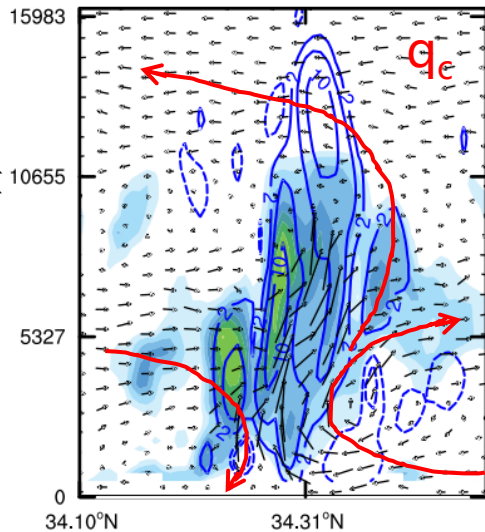
雨水蒸发

(g/kg/s)

# 3. 云动力过程

T=14:00

蓝线: 垂直速度  
填色: 水凝物含量



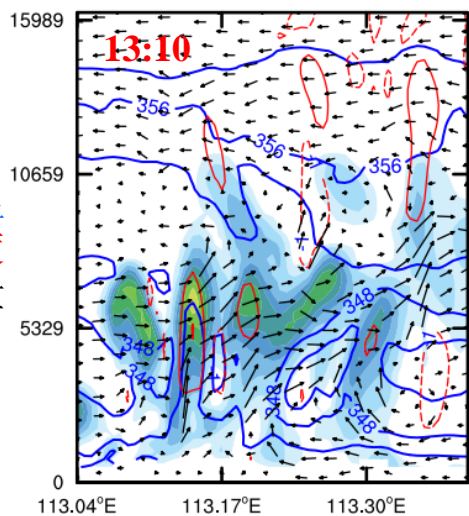
引发强降水的特征:  
γ尺度动力场稳定,  
上升速度中心与小  
粒子的云水、云冰  
中心对应, 雨水随  
高度呈现一定倾斜,  
雪霰有V字型结构。



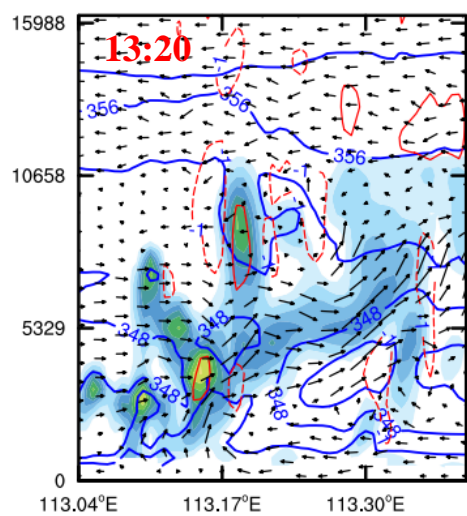
# 3. 云动力过程

$q_c$

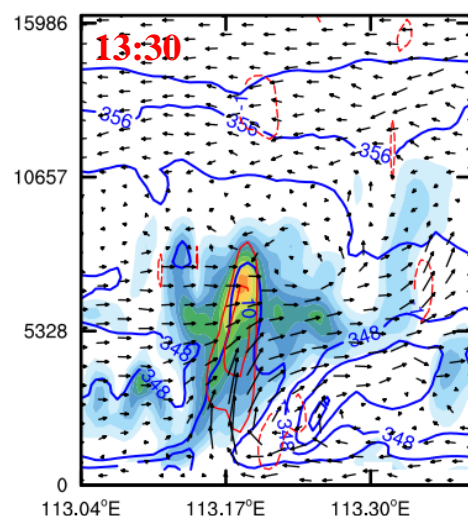
蓝线: 等效位温  
 红线: 垂直速度  
 填色: 云水含量



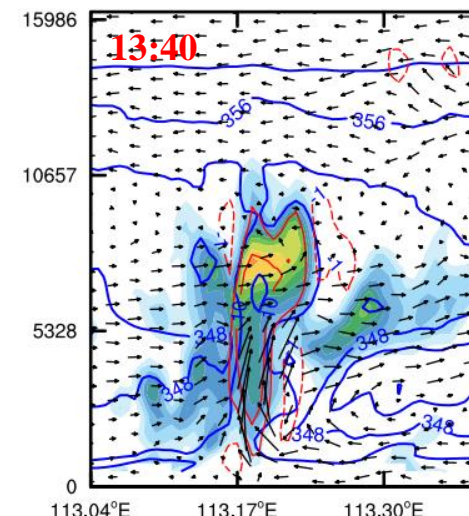
25.2 mm/5min



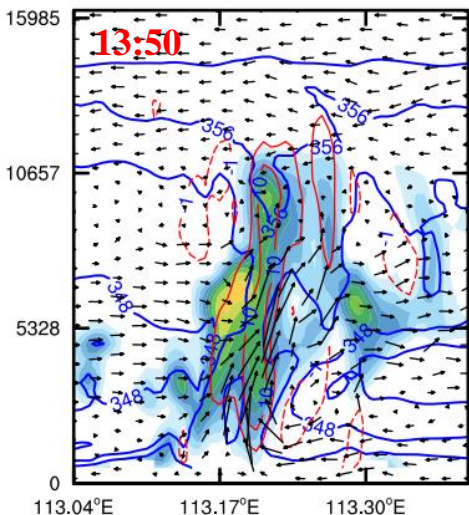
32.7



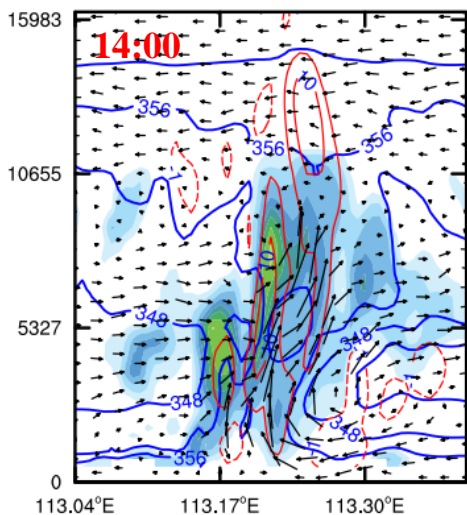
28.6



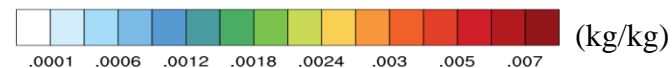
23.0



28.9

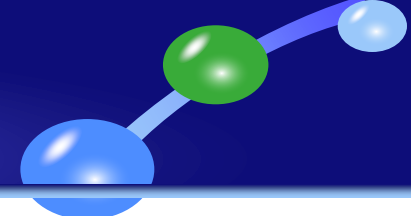


27.6

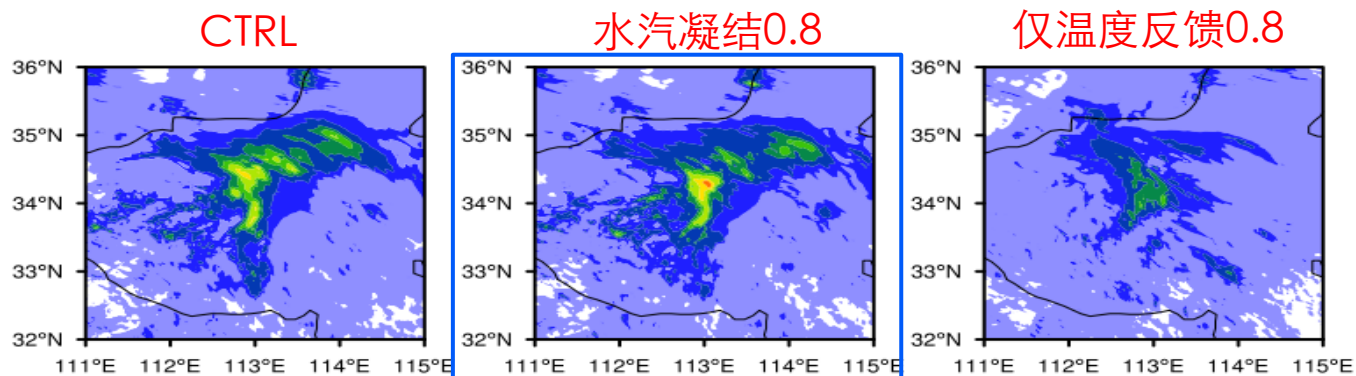


RKW理论延展, 在水凝物的参与下, 形成倾斜状态下的新动态平衡 (对流并非最强), 暖雨过程剧烈, 导致了最强降水。

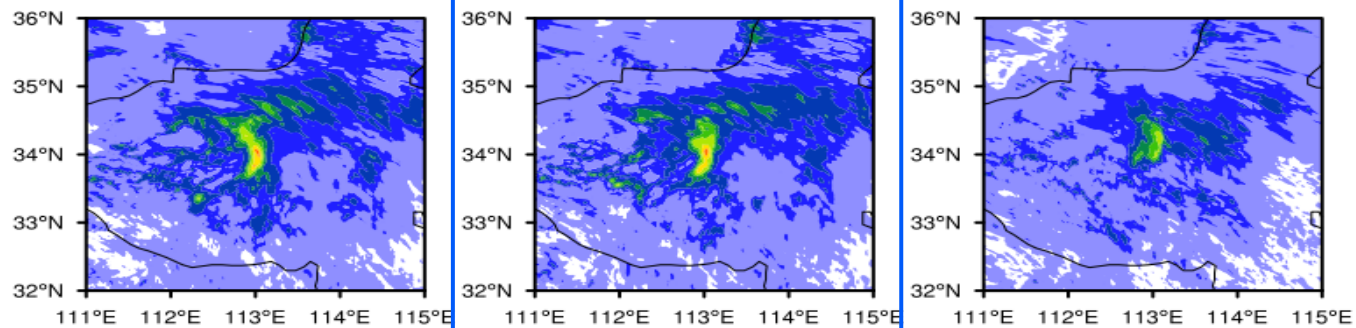
# 4. 相变潜热



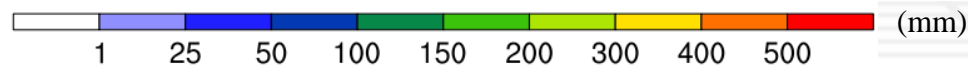
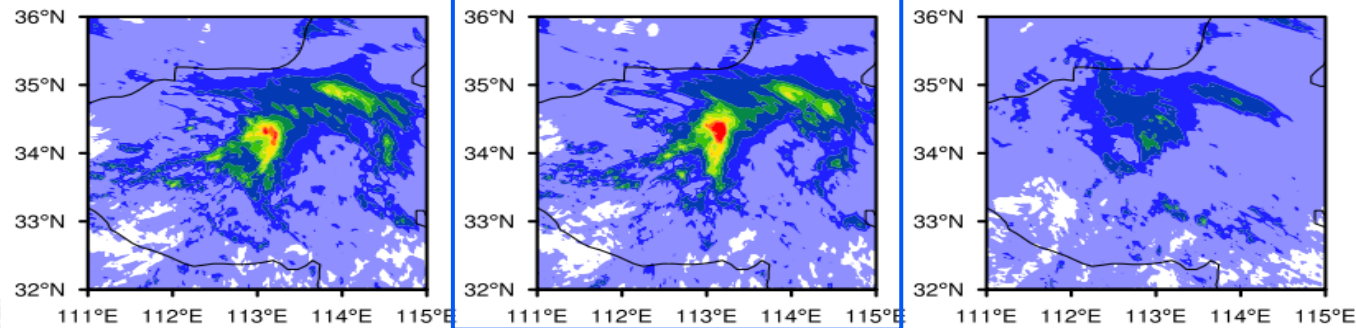
Morrison



Thompson



NSSL-1m



虽然相变潜热支配着云中的浮力演变，但其微物理参数化的不确定性（增减 $\pm 20\%$ ）并不会显著影响对流降水，这是因为水汽过饱和度与水汽凝结之间存在自调节机制。而当相变潜热的增减试验仅影响温度反馈时，其对降水的作用巨大。

08-20h累积降水量

# 5. 结论

- 降水由水凝物微物理过程（即水凝物的所有微物理源汇项，其值与水汽通量辐合相当）和宏物理过程（即水凝物的局地变化及通量散度）决定。水凝物微物理过程是产生强降水的关键，水凝物宏物理过程贡献一般小于10%，但在降水早期可达30%-50%。
- 热浮力是中小尺度对流系统发展的主要驱动力，而目前研究多是通过任选一给定区域的平均位温来计算，存在较大误差，建议选取与对流尺度接近的区域为宜。
- 强降水阶段水凝物相变潜热与云中浮力及垂直速度中心分布基本一致，表明相变潜热主导着浮力变化。在水凝物参与下，形成了倾斜状态的新动态平衡（对流并非最强），暖雨过程剧烈，导致了最强降水。
- 虽然相变潜热支配着云中的浮力演变，但其微物理参数化的不确定性（增减 $\pm 20\%$ ）并不会显著影响对流降水过程，这是因为水汽过饱和度与水汽凝结之间存在自调节机制。



An aerial photograph showing a vast expanse of white, fluffy clouds covering a landscape. The clouds are dense and appear to be made of cotton or wool, with some shadows cast between them. The sky above is a clear, deep blue. The overall scene is bright and airy.

谢谢!