



中国科学院大气物理研究所 云降水物理与强风暴重点实验室

# 一种可用于雨区识别的双偏振雷达计算参数—— 降水粒子轴比均匀性指数

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中国科学院大气物理研究所

Institute of Atmospheric Physics, Chinese Academy of Sciences



# 报告提纲

- 1、研究背景
- 2、新参数的推导
- 3、新参数的特征
- 4、新参数的应用

# 1、研究背景

## 研究背景

- **原始探测变量不足以完全客观反映微物理特征**
- **云中降水粒子的相态识别算法仍然存在很大局限性**

### Hydrometeor Classification (HC)

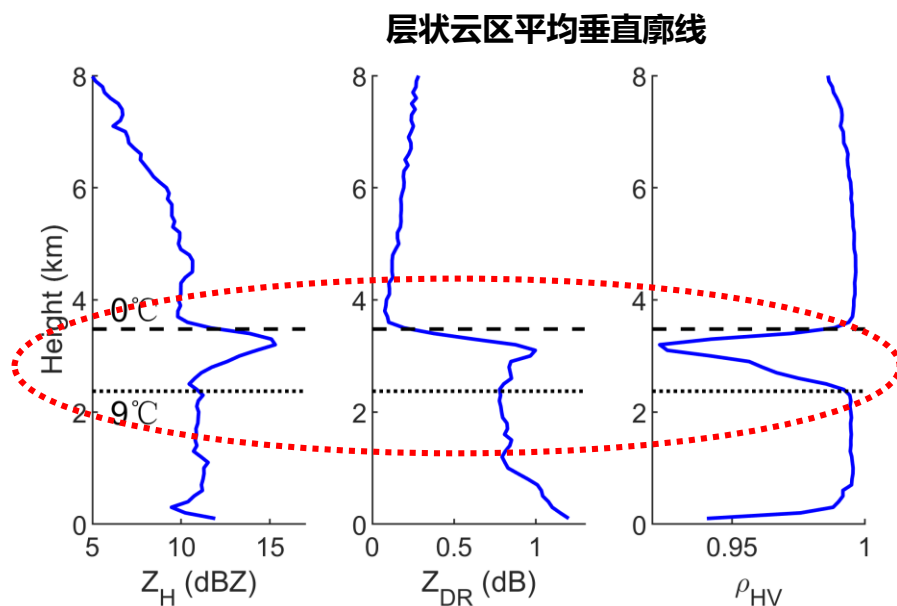
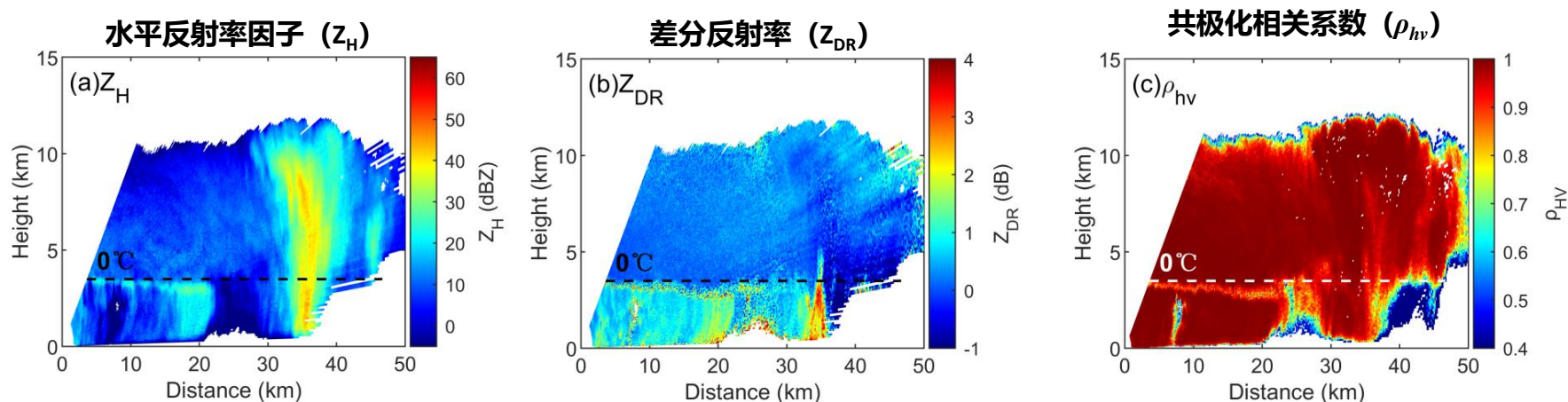
- 算法本身的经验性和主观性 (Zhang et al. 2019, AAS)
- 应用在理论研究和实际业务中的逻辑相反, 进一步应用于理论研究的潜力有限

### 融化层识别

- 只能应用于大范围三层结构的层状云, 无法应用于对流云
- 与HC一样很大程度上都取决于温度廓线

# 1、研究背景

## 原始变量/传统分析



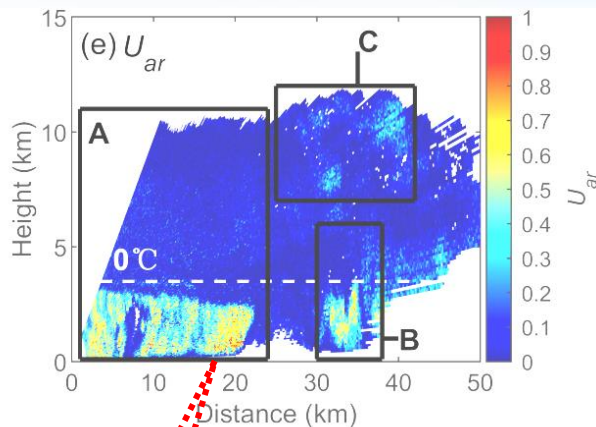
➤ 层状云区的融化层具有可目视特征和可自动识别潜力

- 但是，依赖于水平大范围平均统计
- 依赖于外部输入的温度廓线
- 很难应用于对流云区

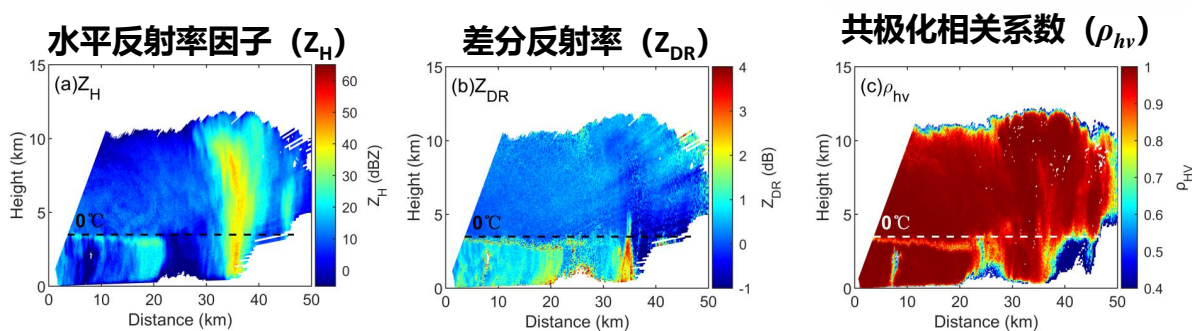
# 新参数 Quick Look

## 新参数 ( $U_{ar}$ )

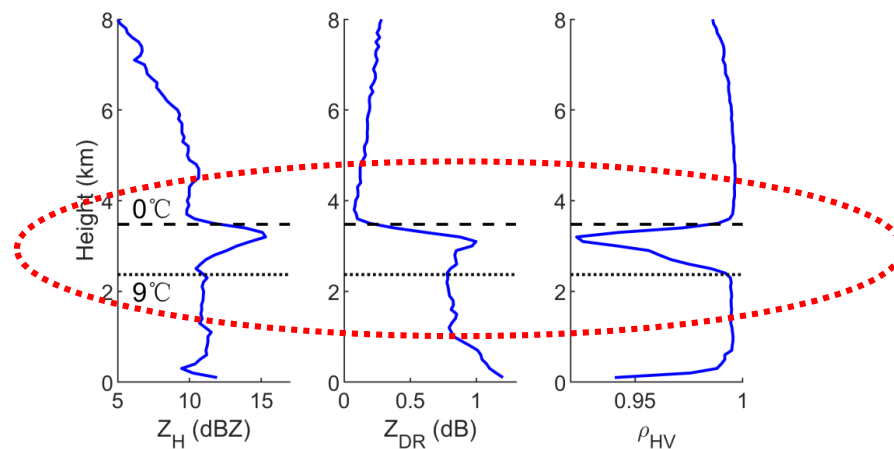
$$U_{ar} = \frac{(\rho_{hv}\sqrt{Z_{dr}} - 1)^2}{Z_{dr} - 2\rho_{hv} \cdot \sqrt{Z_{dr}} + 1}$$
$$= \frac{(\bar{r} - 1)^2}{(r - 1)^2}$$



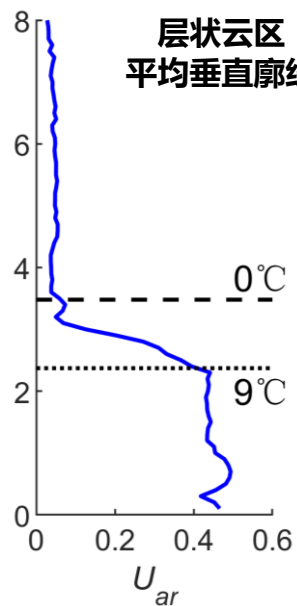
## 原始变量/传统分析



### 层状云区平均垂直廓线



### 层状云区 平均垂直廓线



➤ **层状云区:**  
 $U_{ar}$  呈阶梯性突变,  
从冷层的接近0突变  
到暖层平均0.4以上

➤ 传统变量只在融化层内具有大范围水平平均的峰值特征, 不易精细化应用, 无法应用到对流云区

## 2. 新参数的推导

### 粒子相态的参数化

#### 单个粒子的近似关系

单个粒子的轴比 ( $r$ )、相态指数 ( $E$ ) 和反射率比 ( $\eta_{dr}$ ) 的近似关系

#### 粒子群的近似关系

共极化相关系数 ( $\rho_{hv}$ ) 和单个粒子水平/垂直反射率 ( $b_h/b_v$ ) 的近似关系

新参数  
( $U_{ar}$ )

# 新参数的推导：1. 参数化的水凝物相态指数

## 粒子相态的参数化

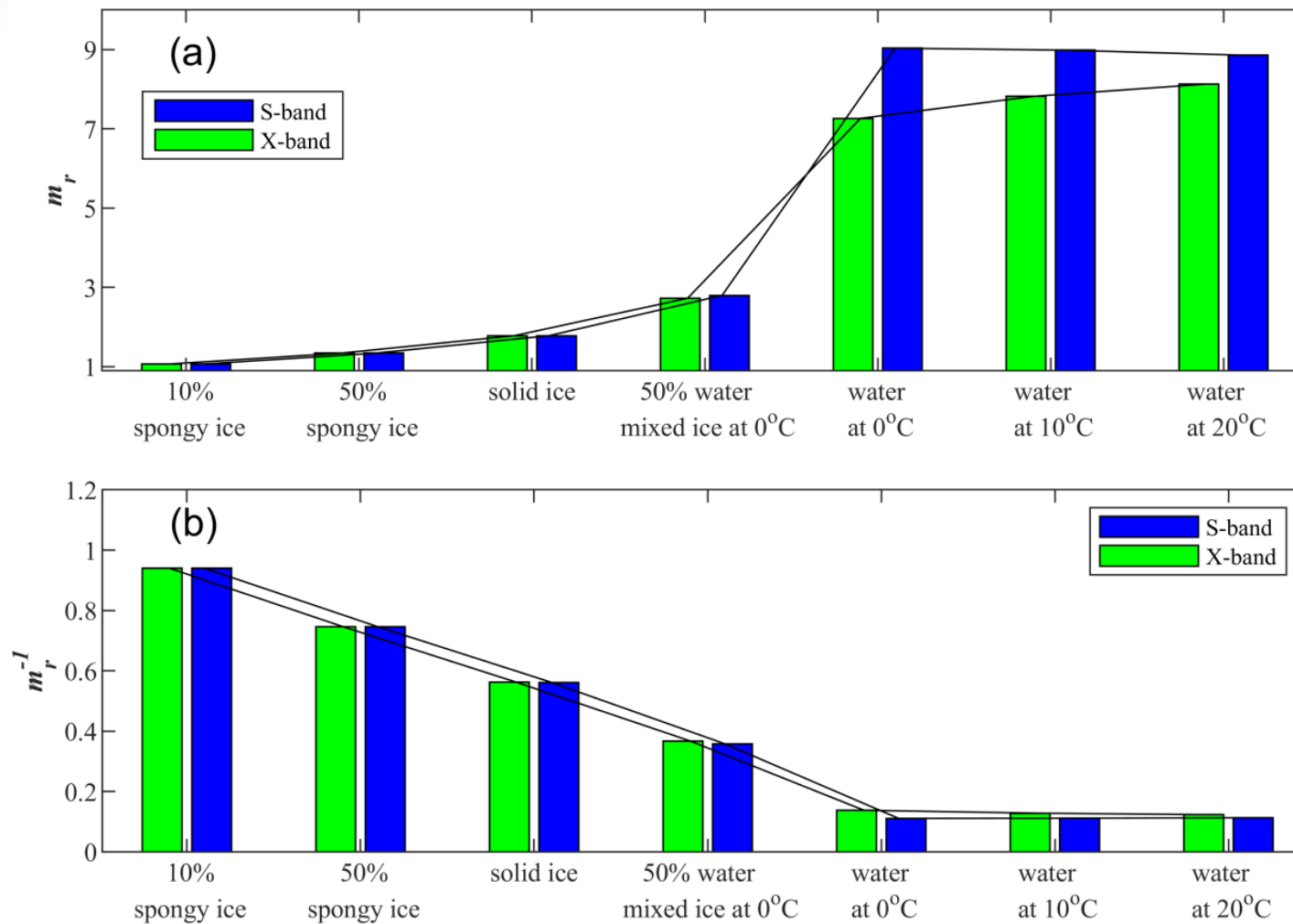
负折射指数  $m_r$ :

- 随温度、相态、雷达波段变化
- 非线性、非单调

取  $m_r$  的倒数:

- 线性反映蓬松冰、实心冰、冰/水混合、纯水

$$E = a_1/m_r + a_0$$



Dielectric property parameters: (a)  $m_r$  and (b)  $m_r^{-1}$  of hydrometeors at different phases and temperatures

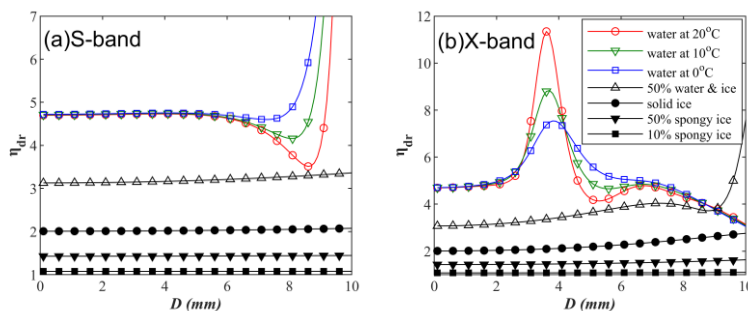


# 新参数的推导：2. 针对单个粒子的近似关系

单个粒子的轴比 (r)、相态指数 (E) 和反射率比 ( $\eta_{dr}$ ) 的近似关系

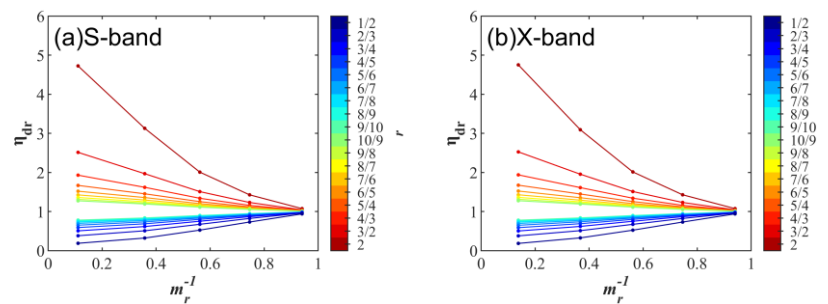
( $\eta_{dr}$  代表单个粒子的线性单位下的  $Z_h$  和  $Z_v$  之比)

- 轴比 (r) 不变时, 反射率比 ( $\eta_{dr}$ ) 总体随相态参数 (E) 增大
- 介电特性对反射率比具有放大作用

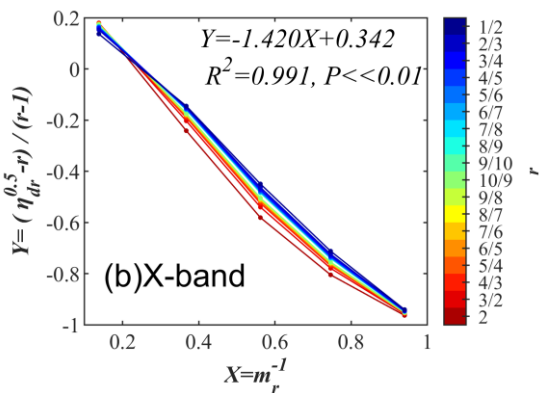
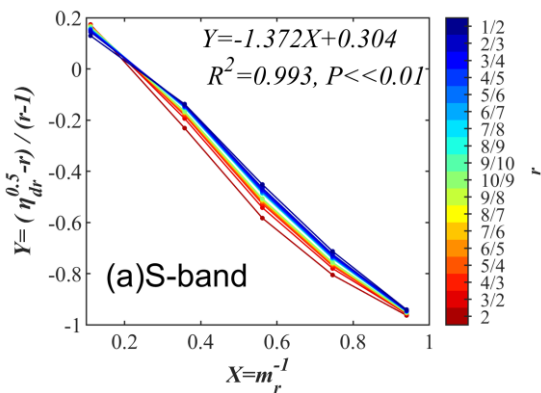


Variation of  $\eta_{dr}$  with the spherical equivalent diameter  $D$  for a single ellipsoid water particle with an axial ratio  $r = 2$  under different phase conditions. (a): S-band, (b): X-band.  $\eta_{dr}$  represents the  $Z_{dr}$  of a single particle.

- 相态参数 (E) 不变时, 反射率比 ( $\eta_{dr}$ ) 总体随轴比 (r) 增大



Variation of  $\eta_{dr}$  with  $m_r^{-1}$  for a single ellipsoidal water particle with different axial ratios (colors of the lines) when  $D=1$  mm. (a) S-band, (b) X-band.



$$\sqrt{\eta_{dr}} = E \cdot (r - 1) + r$$

➤ 得到新的近似关系



# 新参数的推导：3. 针对粒子群的近似关系

**共极化相关系数 ( $\rho_{hv}$ )**  
**和单个粒子水平/垂直**  
**反射率 ( $b_h/b_v$ ) 的近似关系**

➤ 利用雨滴谱模型测试  
 新的近似  $\rho_{hv}$

➤ 理论的:

$$\rho_{hv}^{(Ideal)} = \frac{\langle S_{hh}^* S_{vv} \rangle}{\sqrt{\langle |S_{hh}|^2 \rangle \langle |S_{vv}|^2 \rangle}}$$

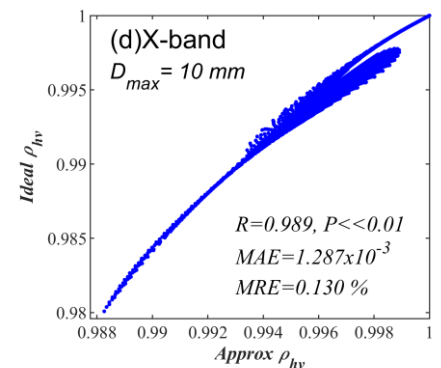
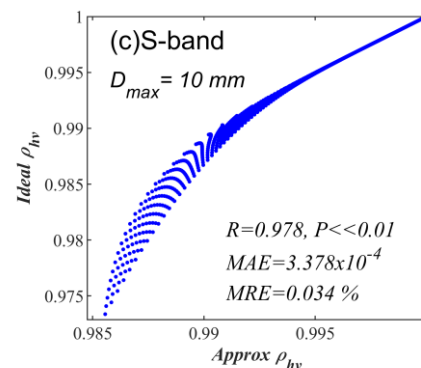
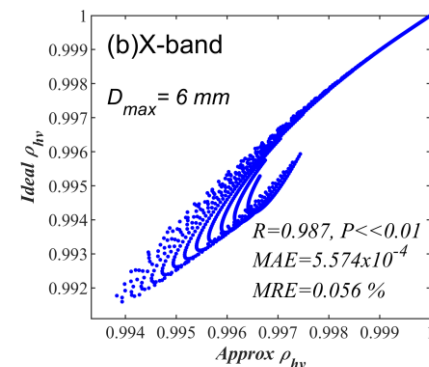
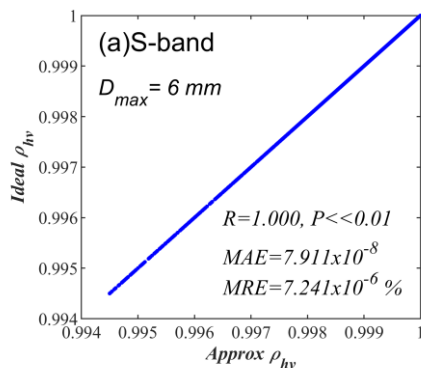
➤ 本研究提出的近似的:

$$\rho_{hv}^{(Approx)} = \frac{\sum (\sqrt{b_h} \cdot \sqrt{b_v})}{\sqrt{\sum b_h \cdot \sum b_v}}$$

$$\sum b_h = Z_h \quad \sum b_v = Z_v$$

分S、X波段讨论

分  $D_{max}=6$  mm (普通降水) 和  $10$  mm (强对流降水) 讨论



Relationships between approximate  $\rho_{hv}$  in this study and ideal  $\rho_{hv}$  in raindrops. (The values of  $D_0$  are from  $0.1$  mm to  $D_{max}$  in  $0.1$  mm intervals. The values of  $\mu$  range from  $-0.8$  to  $16$  in intervals of  $0.2$ .  $R$  is the correlation coefficient between the approximate  $\rho_{hv}$  and ideal  $\rho_{hv}$  enumerated samples, and  $P$  is the significance of  $R$ .  $MAE$  is the mean absolute error, and  $MRE$  is the mean relative error). (a) S-band, (b) X-band, (c) S-band, (d) X-band.

# 新参数的推导

- 提出降水粒子的参数化相态指数 $E$ :

$$E = a_1/m_r + a_0$$

(复折射指数实部 $m$ 的倒数)

- 单个粒子的相态指数 $E$ 、轴比 $r$ 和反射率因子 $b_h$ 、 $b_v$ 的近似关系:

$$\sqrt{b_h} = (E \cdot (r - 1) + r) \cdot \sqrt{b_v}$$

- 粒子群的共极化相关系数 $\rho_{hv}$ 和单个粒子反射率因子 $b_h$ 、 $b_v$ 的近似关系:

$$\rho_{hv}^{(Approx)} = \frac{\sum (\sqrt{b_h} \cdot \sqrt{b_v})}{\sqrt{\sum b_h \cdot \sum b_v}}$$

- 定义 $v$ 路反射率的加权平均轴比:

$$\bar{r} = \frac{\sum (b_v \cdot r)}{\sum b_v} \quad \bar{r}^2 = \frac{\sum (b_v \cdot r^2)}{\sum b_v}$$

- 由 $Z_{dr}$  (线性单位) 可得:

$$\begin{aligned} Z_{dr} &= \frac{\sum b_h}{\sum b_v} \\ &= \frac{\sum [b_v \cdot (E \cdot r - E + r)^2]}{\sum b_v} \\ &\approx (E + 1)^2 \cdot \bar{r}^2 - 2E \cdot (E + 1) \cdot \bar{r} + E^2 \end{aligned}$$

- 由 $Z_{dr}$ 和 $\rho_{hv}$ 可得:

$$\begin{aligned} \rho_{hv} \sqrt{Z_{dr}} &= \frac{\sum [b_v \cdot (E \cdot r - E + r)]}{\sum b_v} \\ &\approx E \cdot \bar{r} - E + \bar{r} \end{aligned}$$

反映粒子轴比相对于1的均匀程度的参数

- 经组合得:

$$\begin{aligned} U_{ar} &= \frac{(\rho_{hv} \sqrt{Z_{dr}} - 1)^2}{Z_{dr} - 2\rho_{hv} \cdot \sqrt{Z_{dr}} + 1} \\ &= \frac{(E + 1)^2 \cdot (\bar{r} - 1)^2}{(E + 1)^2 \cdot (\bar{r} - 1)^2} \\ &= \frac{(\bar{r} - 1)^2}{(\bar{r} - 1)^2} \end{aligned}$$

- 对于 $r$ 全部大于1的粒子群 (譬如雨滴),  $U_{ar}$ 接近1
- 对于 $r$ 在1两侧分布的粒子群 (譬如大部分冰相粒子),  $U_{ar}$ 接近0

Article

## A Uniformity Index for Precipitation Particle Axis Ratios Derived from Radar Polarimetric Parameters for the Identification and Analysis of Raindrop Areas

Yue Sun <sup>1</sup>, Hui Xiao <sup>1,2,\*</sup>, Huiling Yang <sup>1</sup>, Haonan Chen <sup>3</sup>, Liang Feng <sup>1</sup>, Weixi Shu <sup>1,2</sup> and Han Yao <sup>4</sup>

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<sup>2</sup> College of Earth Sciences, University of Chinese Academy of Sciences (UCAS), Beijing 100049, China

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**Abstract:** A uniformity index for the axis ratios ( $U_{ar}$ ) derived from dual polarization weather radar data is proposed for raindrop area identification and analysis. The derivation of this new parameter is based on radar scattering simulations and assumptions.  $U_{ar}$  is between 0 and 1 and can be calculated from the differential reflectivity ( $Z_{DR}$ ) and the copolar correlation coefficient ( $\rho_m$ ), which reflects the uniformity of the axis ratio ( $r$ ) of the particle group. For raindrops,  $U_{ar}$  is close to 1 under ideal conditions, but is clearly different from that of ice particles whose value is close to 0. Studies conducted during two convective weather events observed by X-band and S-band radar are presented to show the  $U_{ar}$  features. In convective areas, high  $U_{ar}$  presents a U-shaped vertical structure. One branch corresponds to the  $Z_{DR}$  column, while the other branch is located at the rear of the convective cloud zone and is lower in altitude, representing the process of ice particles melting into raindrops and then being transported upward by a strong updraft. In stratiform cloud areas, a more than 95% overall identification ratio is obtained when the threshold of  $U_{ar}$  is set to 0.2–0.3 for discriminating rain layers.

**Citation:** Sun, Y.; Xiao, H.; Yang, H.; Chen, H.; Feng, L.; Shu, W.; Yao, H. A Uniformity Index for Precipitation Particle Axis Ratios Derived from

**Keywords:** dual polarization weather radar; axis ratio; rain area identification

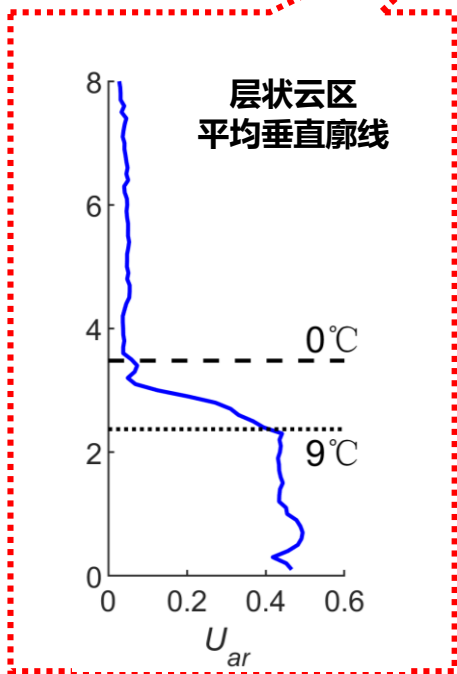
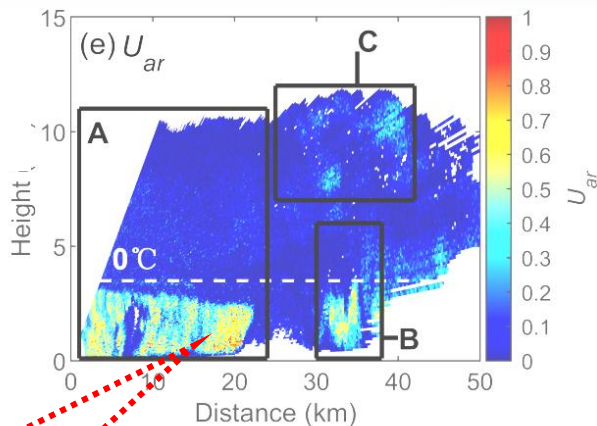
Sun, Y.; Xiao, H.; Yang, H.; Chen, H.; Feng, L.; Shu, W.; Yao, H. A Uniformity Index for Precipitation Particle Axis Ratios Derived from Radar Polarimetric Parameters for the Identification and Analysis of Raindrop Areas. Remote Sens. 2023, 15, 534. <https://doi.org/10.3390/rs15020534>

# 新参数的特征：X波段天气雷达

## 新参数 ( $U_{ar}$ )

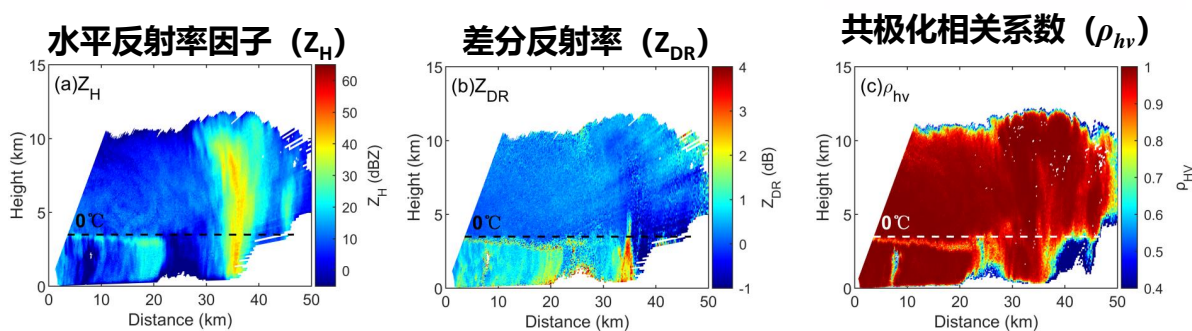
$$U_{ar} = \frac{(\rho_{hv}\sqrt{Z_{dr}} - 1)^2}{Z_{dr} - 2\rho_{hv} \cdot \sqrt{Z_{dr}} + 1}$$

$$= \frac{(\bar{r} - 1)^2}{(r - 1)^2}$$

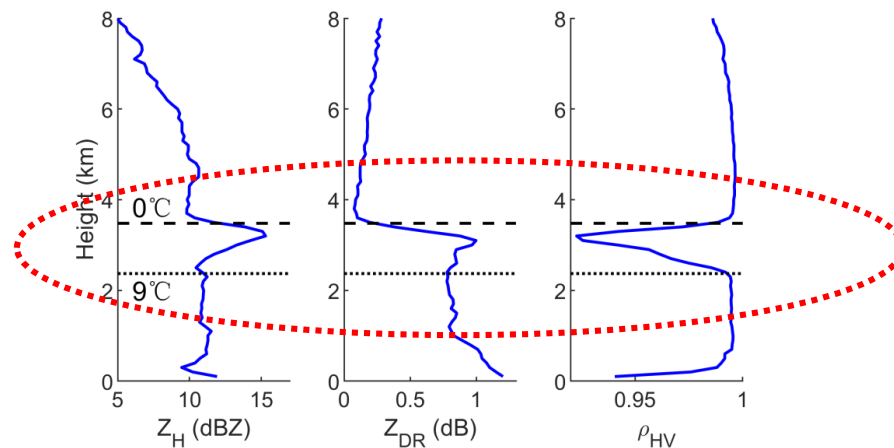


- **层状云区:**  
 $U_{ar}$ 呈阶梯性突变,  
从冷层的接近0突变  
到暖层平均0.4以上

## 原始变量/传统分析



### 层状云区平均垂直廓线

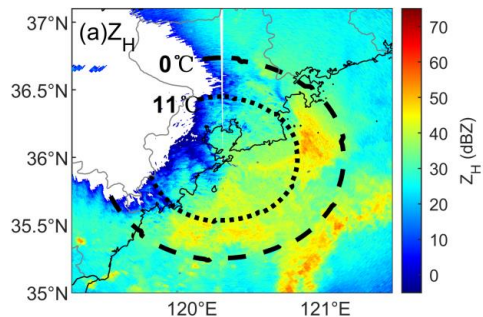


- **传统变量只在融化层内具有大范围水平平均的峰值特征, 不易精细化应用, 无法应用到对流云区**

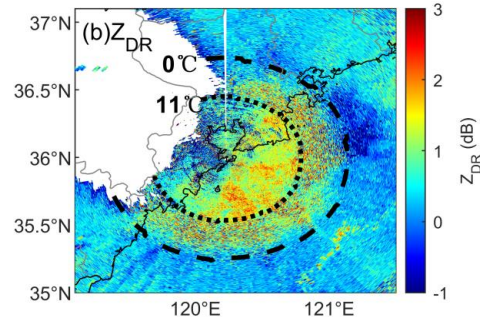


# 新参数的特征：S波段业务天气雷达

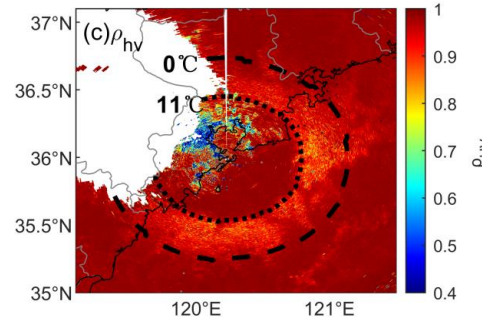
水平反射率因子  
( $Z_H$ )



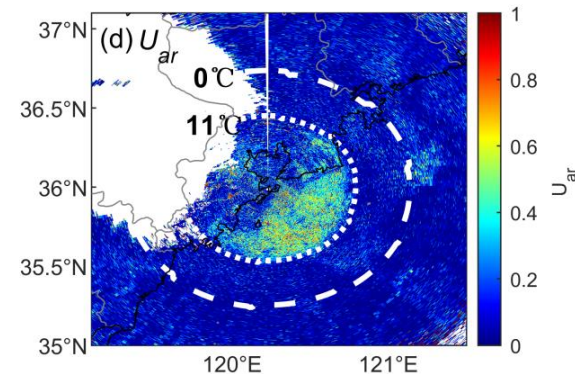
差分反射率  
( $Z_{DR}$ )



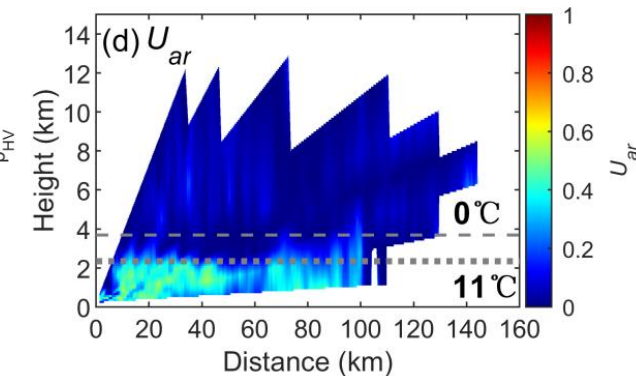
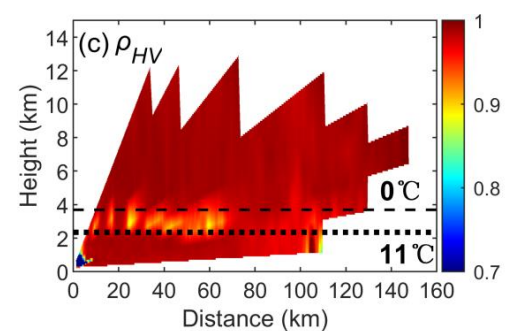
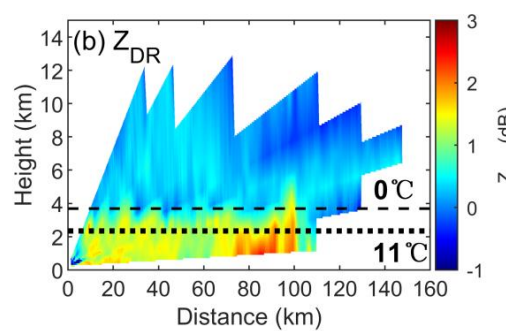
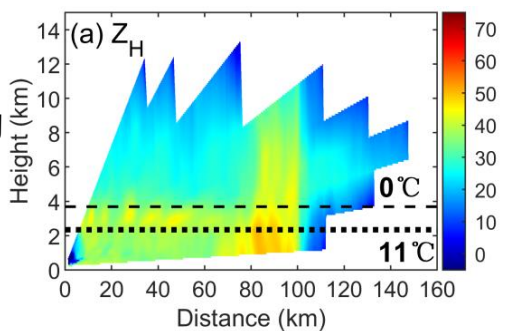
共极化相关系数  
( $\rho_{hv}$ )



新参数 ( $U_{ar}$ )



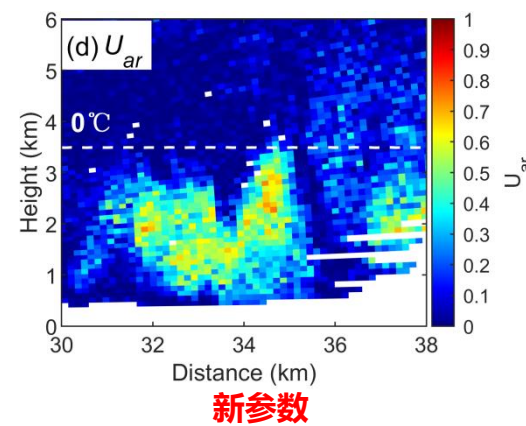
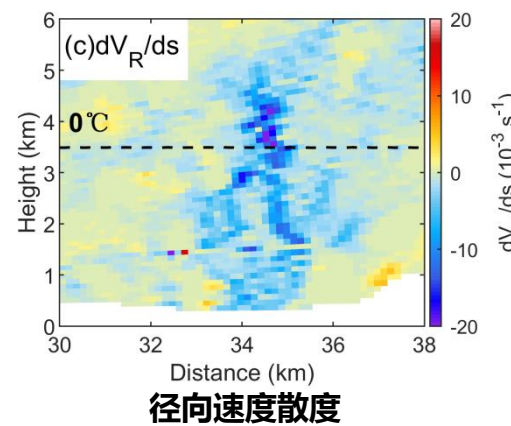
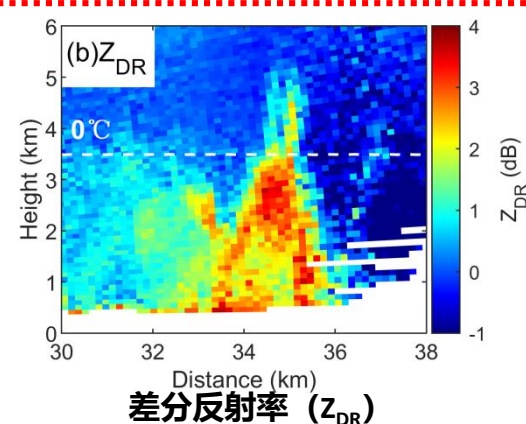
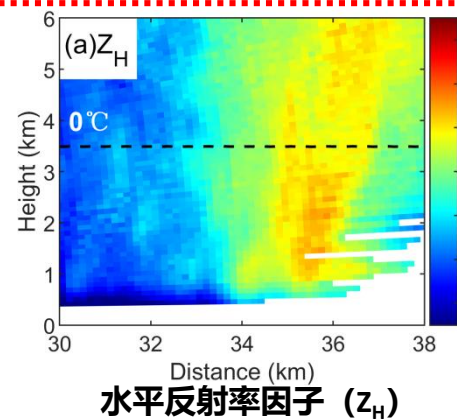
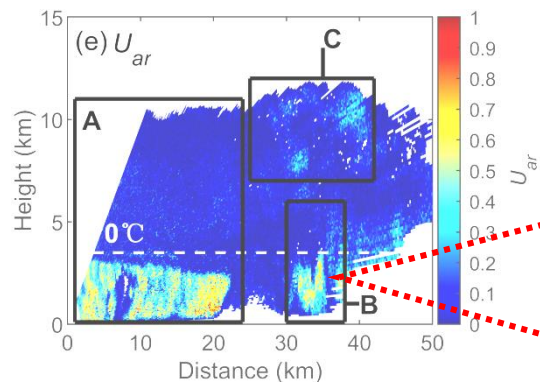
正交于对流线的  
垂直剖面



青岛雷达, 2020年5月17日观测个例

# 新参数应用1: $Z_{DR}$ 柱形成机制研究

## 佐证强对流区 $Z_{DR}$ 柱在动力/微物理耦合条件下的形成机理



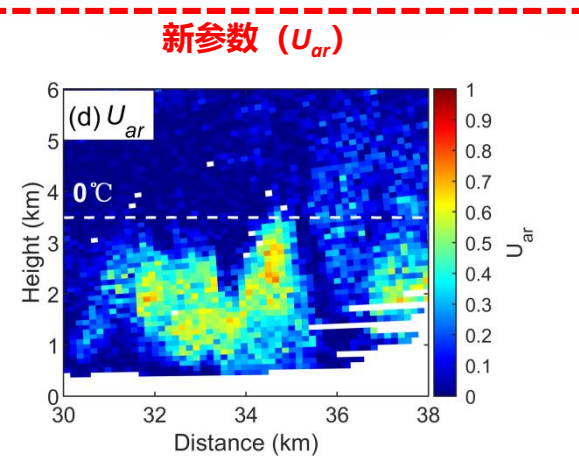
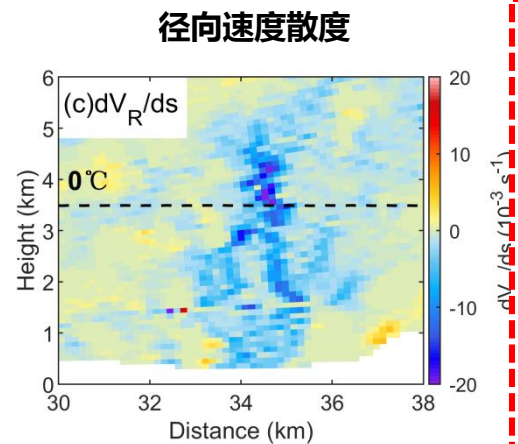
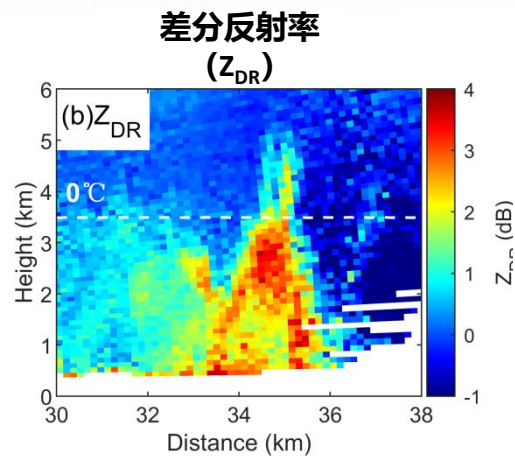
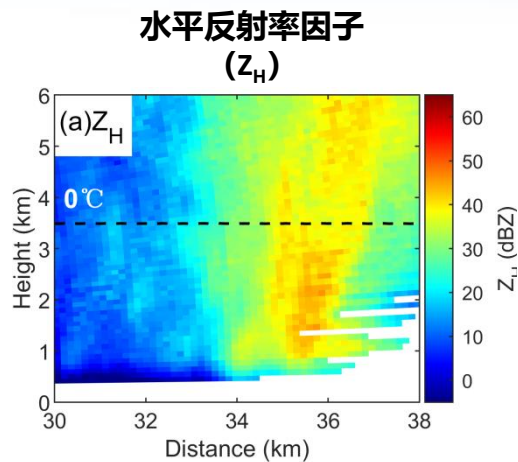
➤ 对流云区:  $U_{ar}$ 呈U型分布, 右支与 $Z_{DR}$ 柱和强辐合带对应



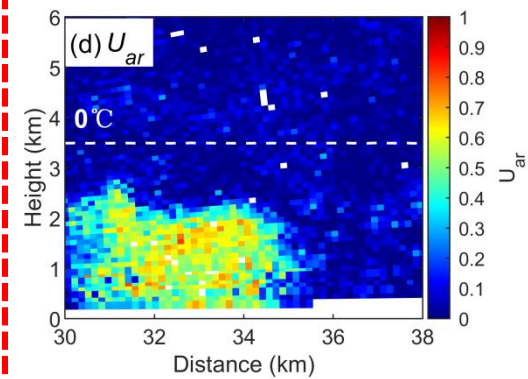
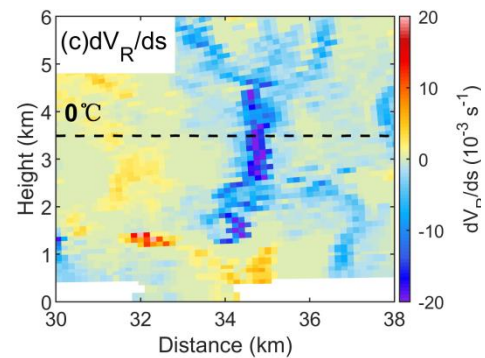
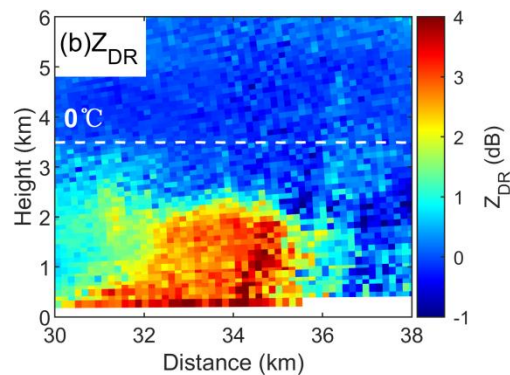
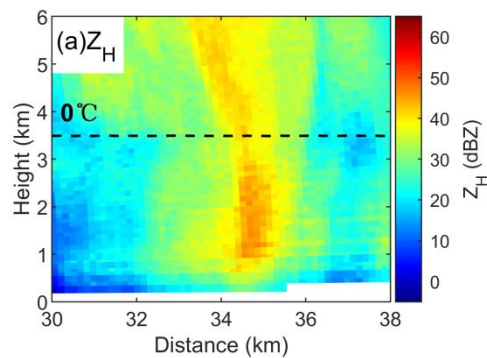


# 新参数应用1: $Z_{DR}$ 柱形成机制研究

有 $Z_{DR}$ 柱时  
(18:46 BJT)



$Z_{DR}$  柱  
消失后  
(18:55 BJT)

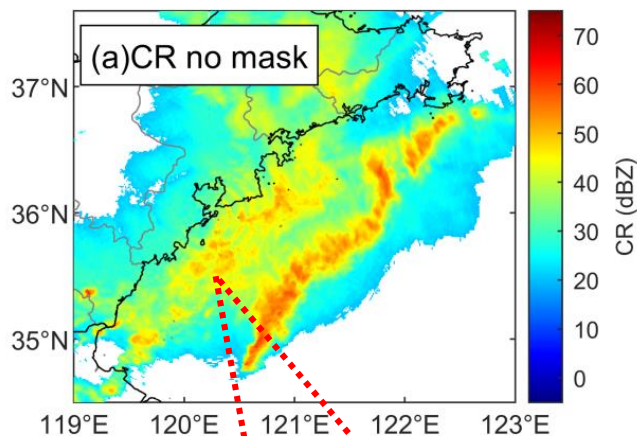




# 新参数应用2：组合反射率屏蔽模板

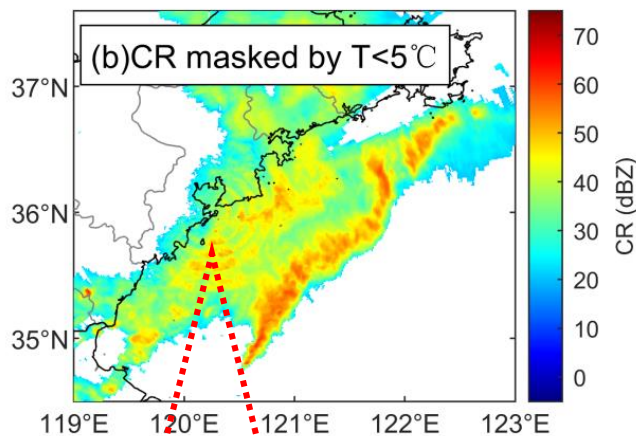
更快速/有效地识别雨区，避免融化层强回波对降水监测的干扰

## 原始数据组合反射率



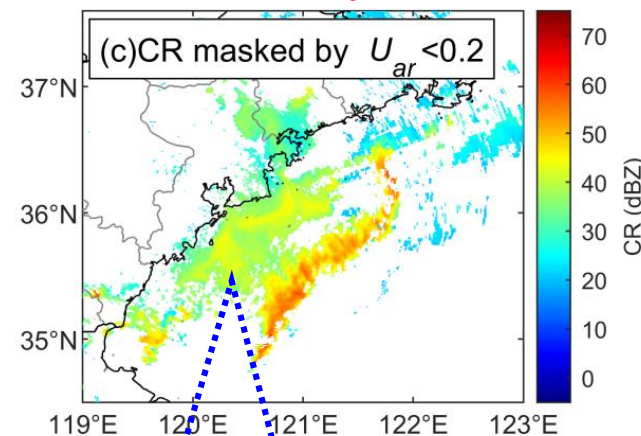
对流线后部的层状云区内，融化层可能有较高的反射率零散点，容易被错误地识别为对流云，造成虚警

## 按经验温度保留雨区



按经验温度保留暖雨层，不容易屏蔽融化层强回波的干扰

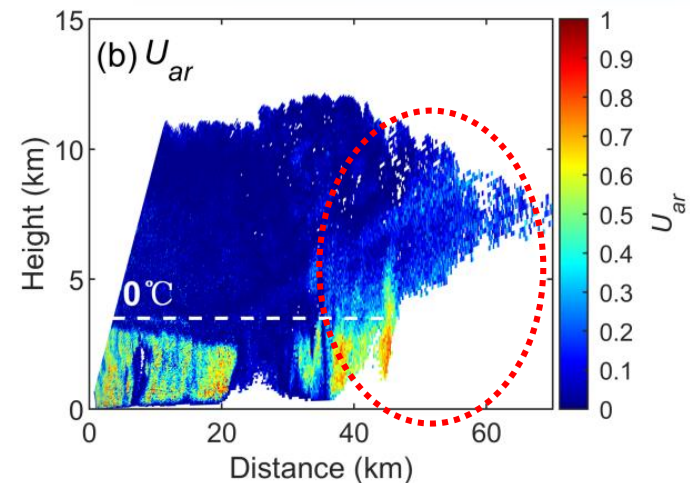
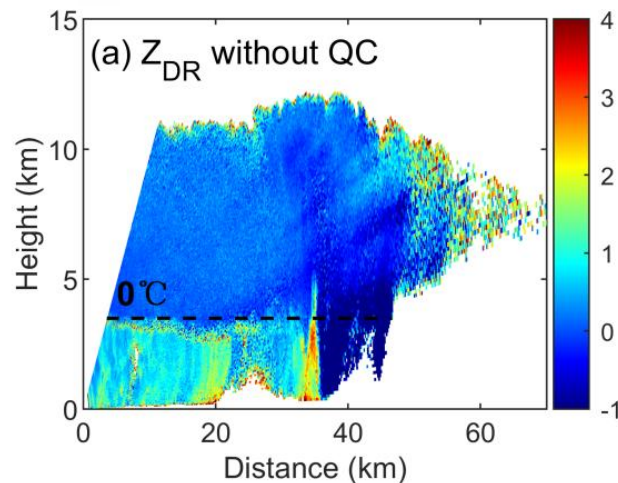
## ✓ 以新参数 $U_{ar}$ 保留雨区



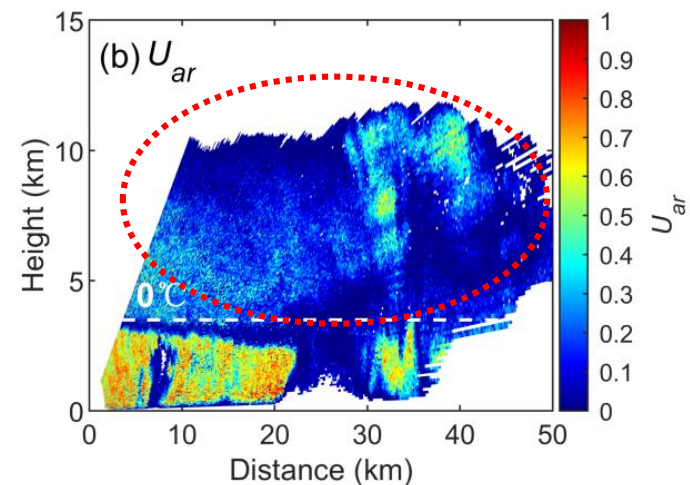
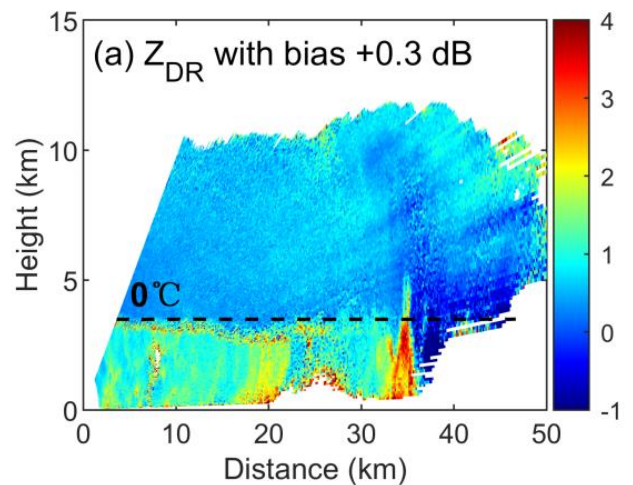
以新参数保留雨区后，可以清晰地区分出对流系统中的对流区和层状云区

# 新参数的局限性

1. 如果不做衰减订正，波束远端衰减区的大片 $Z_{DR}$ 负值会导致 $U_{ar}$ 的高值。

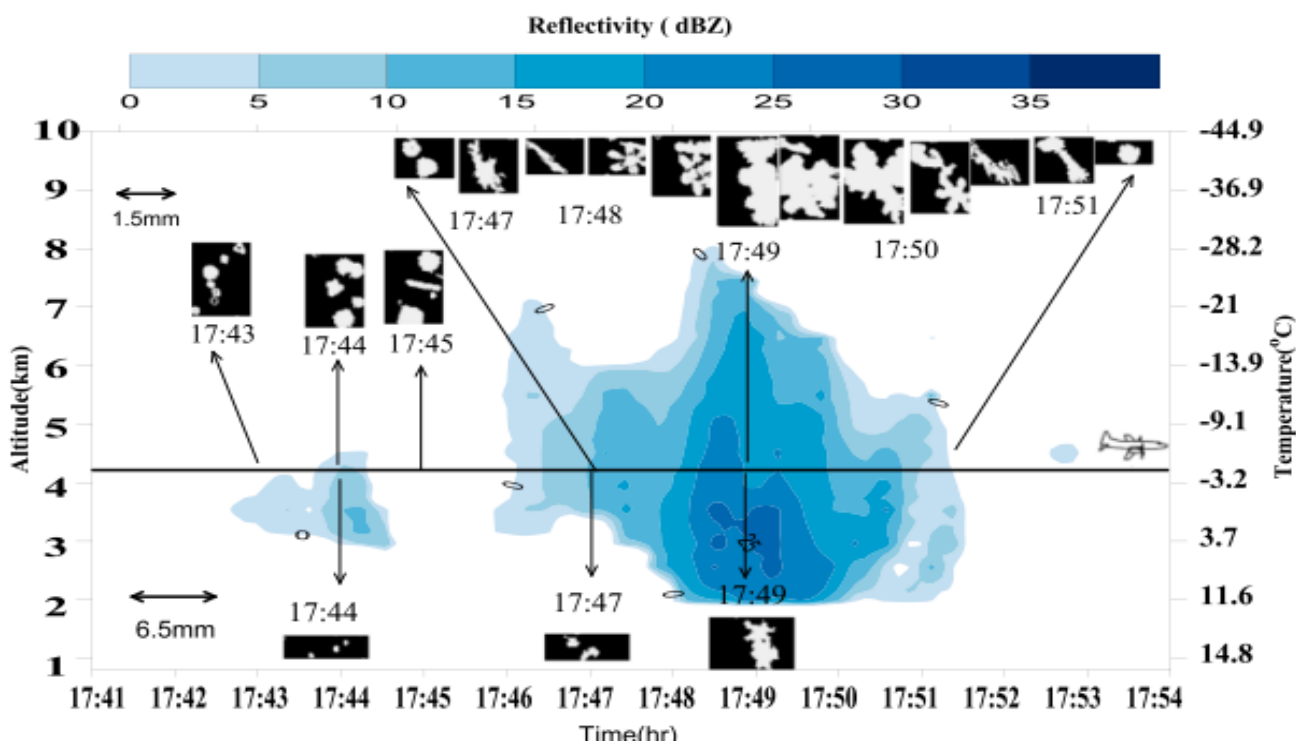


2.  $Z_{DR}$ 系统偏差大于0.3 dB时，过冷层原本接近0的 $U_{ar}$ 会明显偏高。

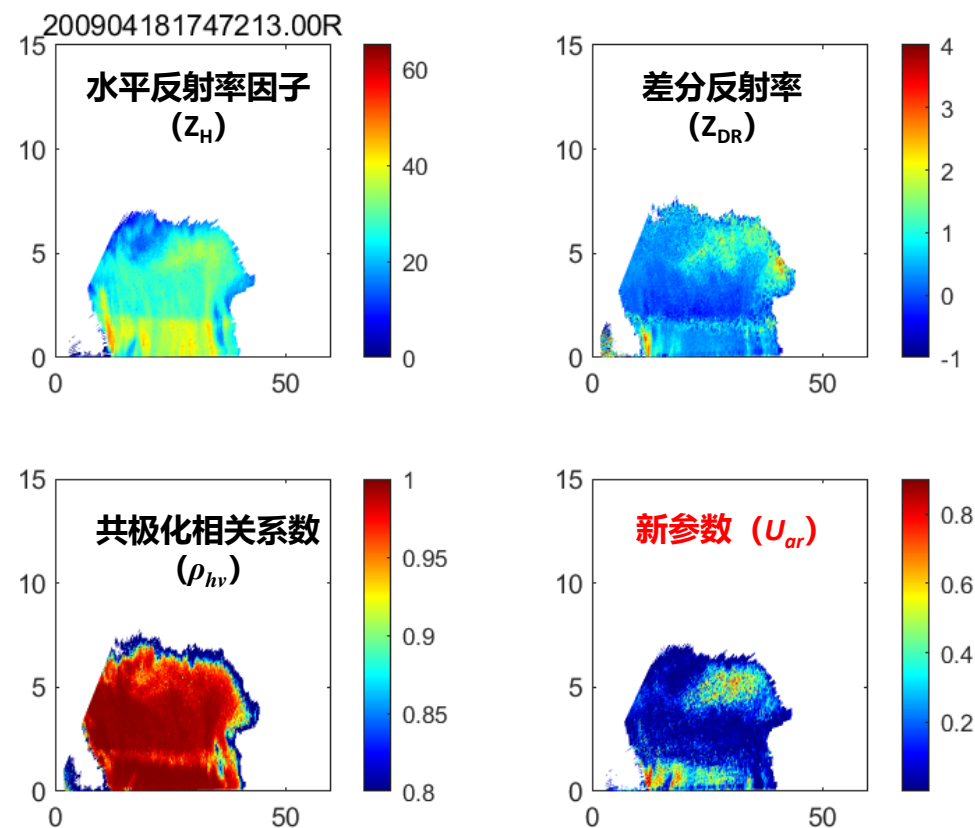


# 新参数的局限性

3. 非降水/弱降水云中某些特定的冰晶/雪—形状/取向分布也会导致 $U_{ar}$ 的高值。



朱士超, 郭学良, 等, 2009年华北三机联合探测



LACS X波段雷达, 2009年4月18日17:47 张北观测

# 正在开展的后续工作

## 衰减订正

- ◆ 通过新参数屏蔽融化层和过冷层可能出现的高差分相移率所导致的过订正

## 相态识别

- ◆ 加入新参数

## 粒子谱反演

**谢谢各位专家**

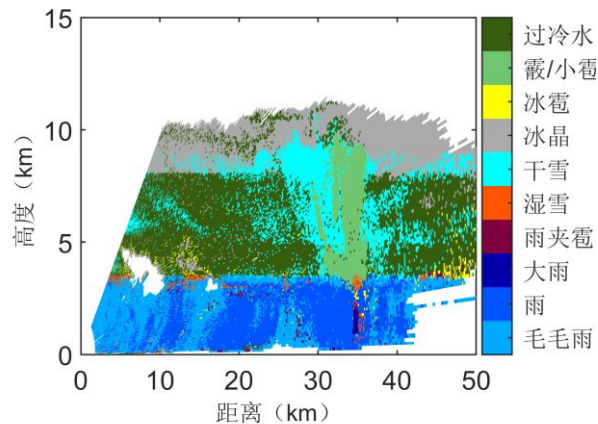
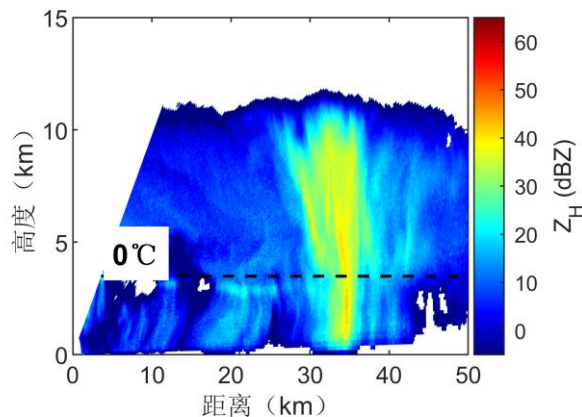
**敬请批评指正**



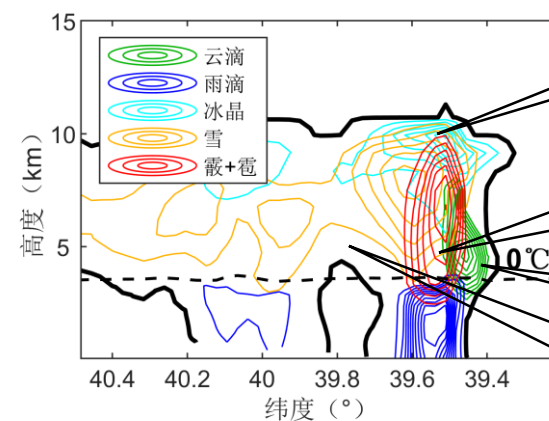
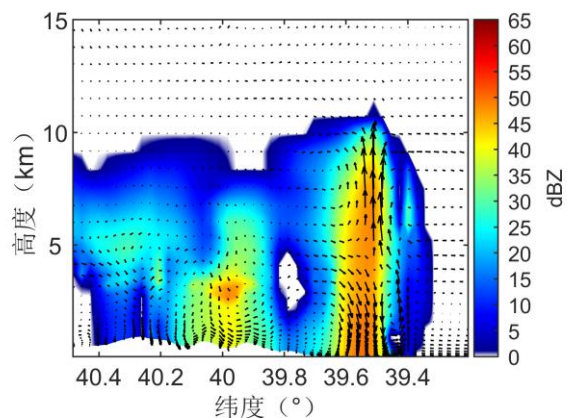
# 天气监测技术：云降水粒子相态识别

## ➤ 数值模拟、理论与研究与雷达反演的相互印证

### $Z_H$ 与相态识别结果



### WRF模拟



最上层是冰晶

对流核心冷层是霰  
暖层融化为雨

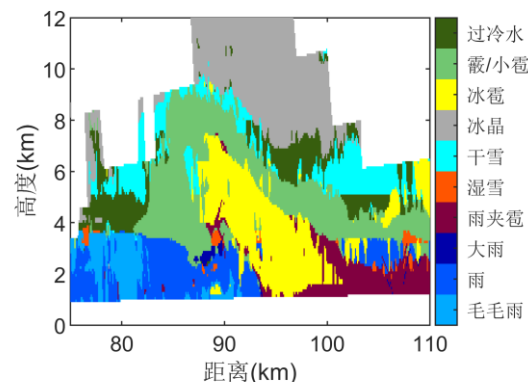
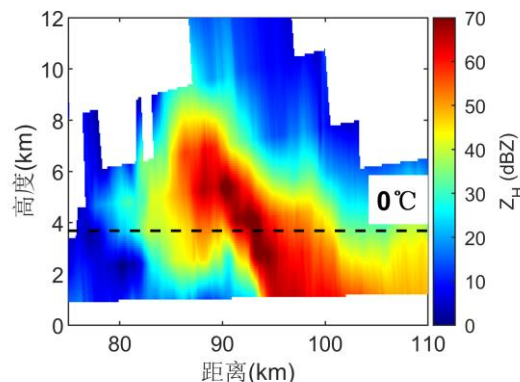
过冷水

对流区外侧和层状  
云区冷层为雪

# 冰雹云早期识别研究

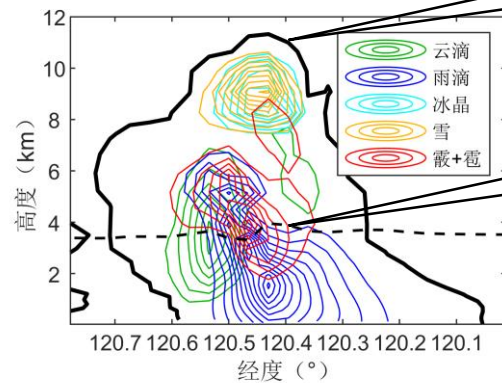
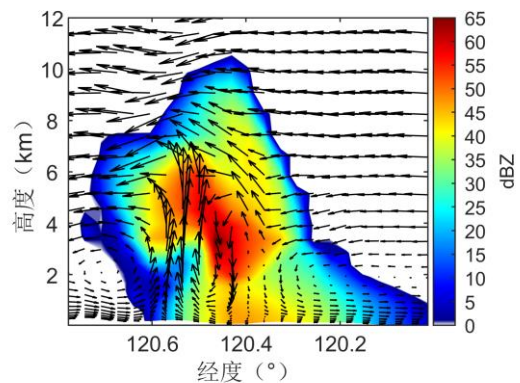
## 雷达反演结果与数值模式相互印证

$Z_H$ 与相态识别结果



高层为冰晶和雪

WRF模拟



对流核心有霰+雹

现有1~10 km级中尺度天气模式虽然模拟不出很强的降雹，但其中的水凝物分类和演化可与雷达反演结果相互印证，是缺乏强对流云内原位观测时的结果合理性评估方法之一