



第五届全国中尺度气象学论坛

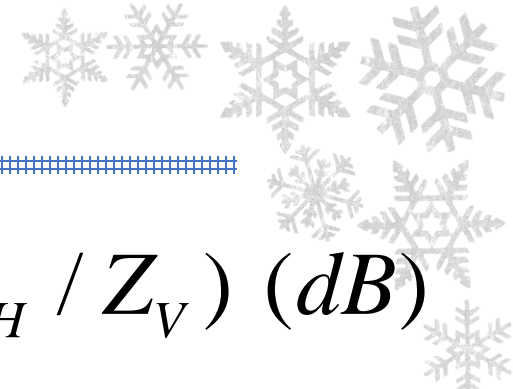
近地面冰相和液相粒子 形状特征研究

郑鹤鹏 张云 张立凤 李浩然 吴祖航

2023.08 银川



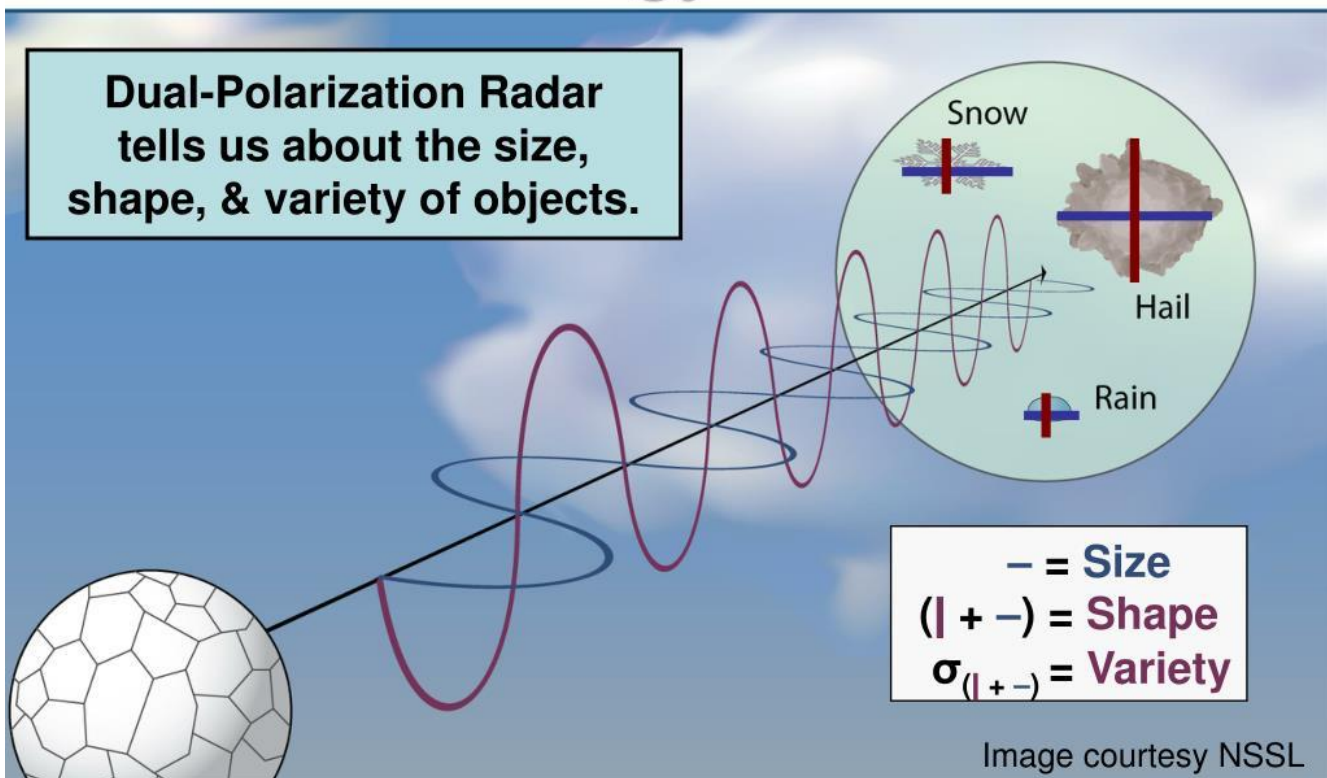
为什么要研究粒子形状？



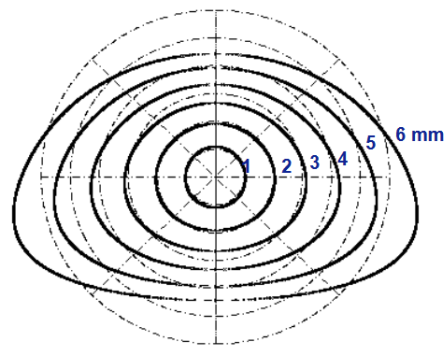
How Is Dual-Polarization Radar Technology Useful?

$$Z_{DR} \sim 10 \log(Z_H / Z_V) \text{ (dB)}$$

Dual-Polarization Radar tells us about the size, shape, & variety of objects.



- 粒子形状直接影响双偏振量的探测
- 粒子形状，尤其是冰相粒子的形状变化较大且规律性差
- 观测比较匮乏

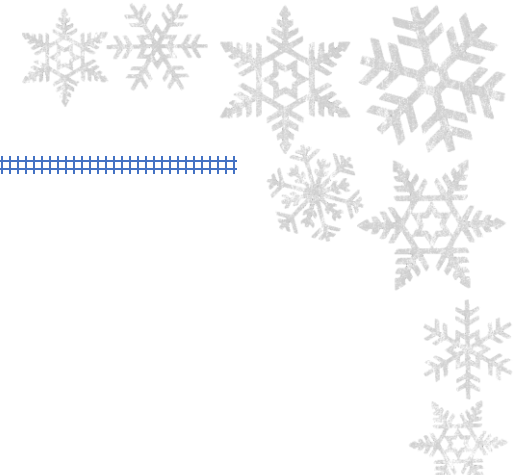


Simple Prisms	Solid Columns	Sheaths	Scrolls on Plates	Triangular Forms
Hexagonal Plates	Hollow Columns	Cups	Columns on Plates	12-branched Stars
Stellar Plates	Bullet Rosettes	Capped Columns	Split Plates & Stars	Radiating Plates
Sectored Plates	Isolated Bullets	Multiply Capped Columns	Skeletal Forms	Radiating Dendrites
Simple Stars	Simple Needles	Capped Bullets	Twin Columns	Irregulars
Stellar Dendrites	Needle Clusters	Double Plates	Arrowhead Twins	Rimmed
Ferrolike Stellar Dendrites	Crossed Needles	Hollow Plates	Crossed Plates	Graupel

From: Daniel C. Miller



为什么要研究粒子形状？



□ 粒子散射模拟

- 双偏振雷达变量模拟 --- 观测和模式的桥梁

T-Matrix的输入参数

- 粒子轴比和方向参数
- 等效体积直径
- 入射和散射波的方向
- 雷达波长
- 复折射率
- • •

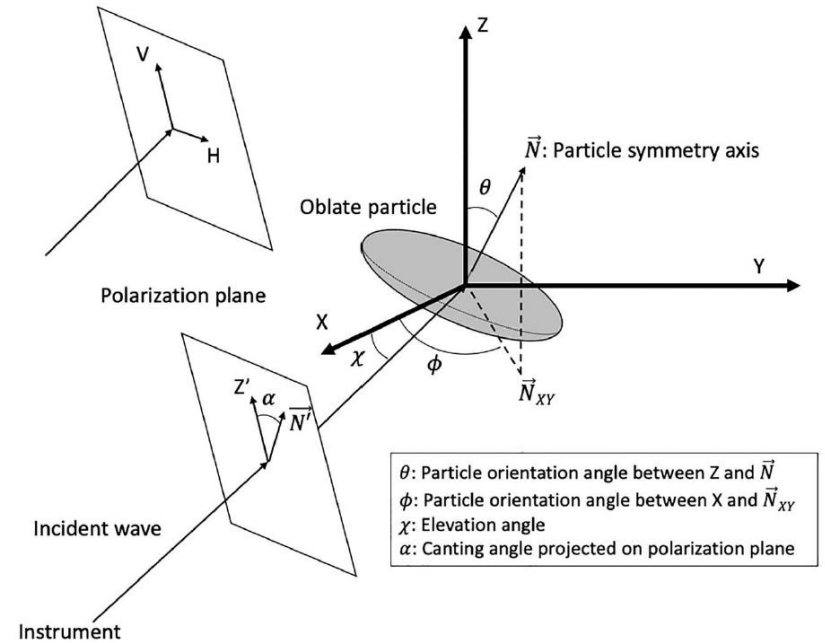
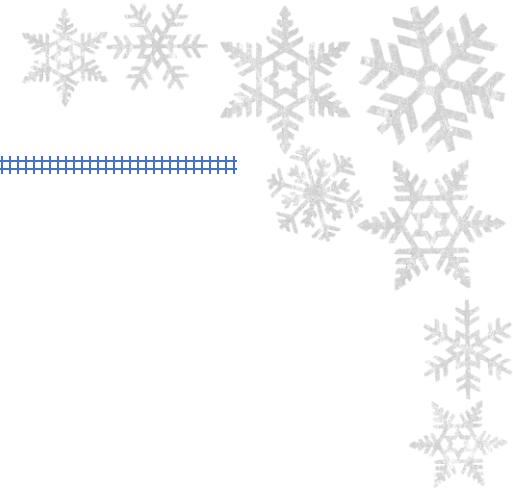


Figure 1. Scattering geometry of an oblate particle with a specific orientation direction (\vec{N}) within a Cartesian coordinate (X, Y, and Z). \vec{N}_{XY} is the projection of \vec{N} on the X-Y plane. \vec{N}' and Z' are the projections of \vec{N} and the Z axis on the polarization plane. V and H are the linear polarization base vectors. Adapted from Vivekanandan et al. (1991).



01

观测仪器

02

冰相粒子形状

03

雨滴的形状

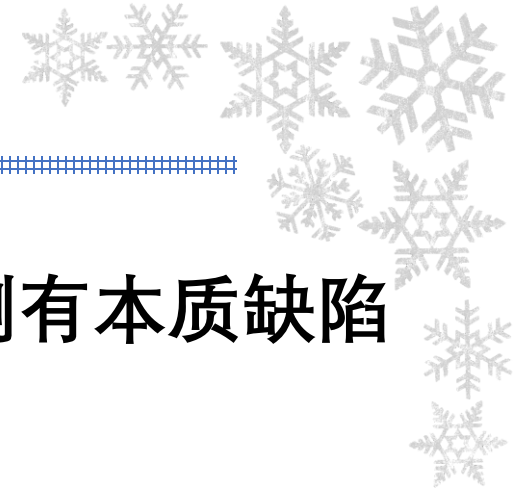
04

总结



一、观测仪器

□ 激光粒子谱仪---最常见的观测



探测原理：对固态降水的探测有本质缺陷

OTT Parsivel²

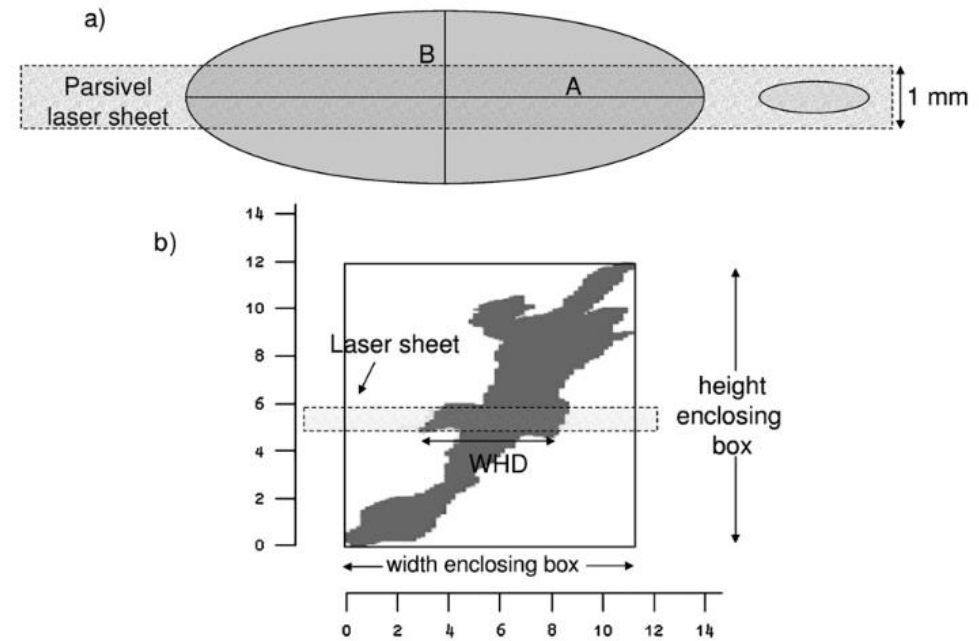


FIG. 4. (a) Schematic diagram of a small and a large spheroidal particle shadowing the 1-mm-thick PARSIVEL beam. (b) Schematic measuring example for a snowflake.

Battaglia et al. 2010

强风下雨滴的探测订正：Lin & Bao et al. 2021

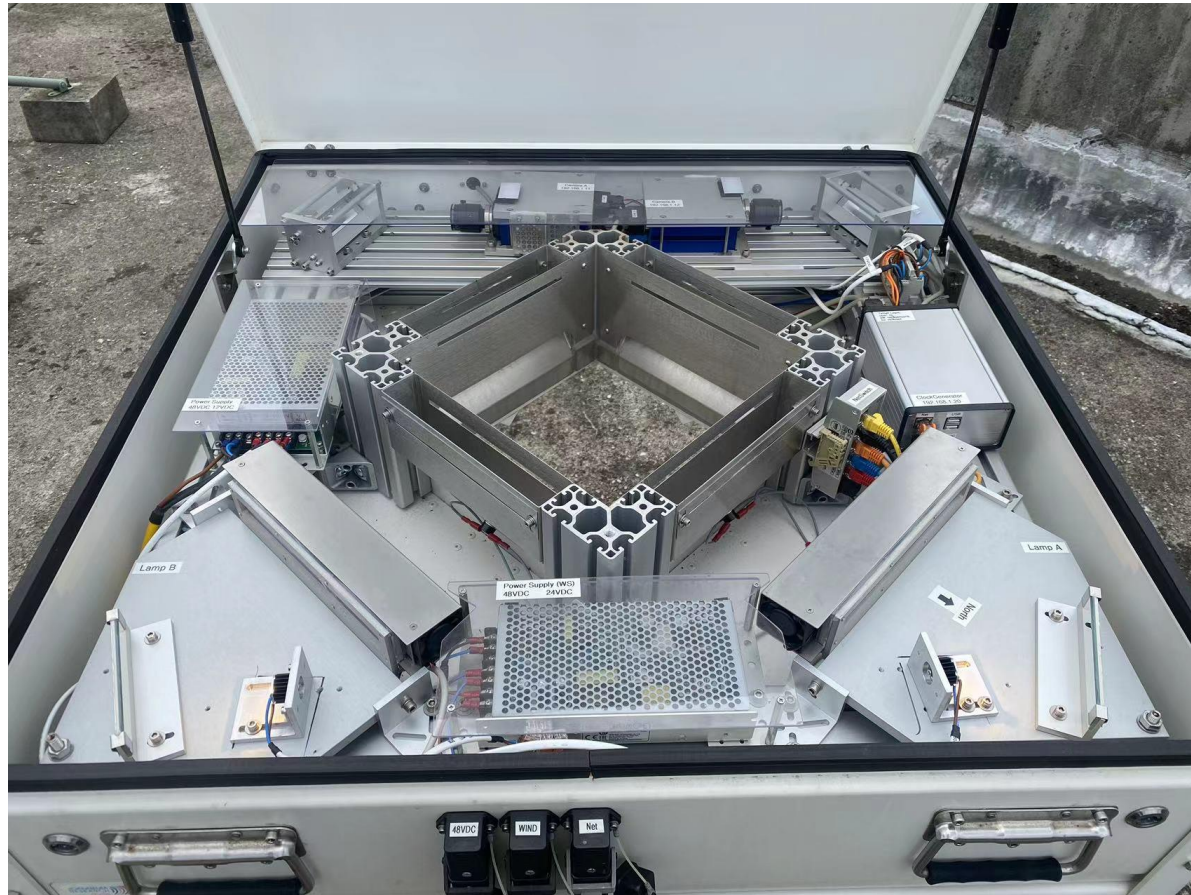


一、观测仪器

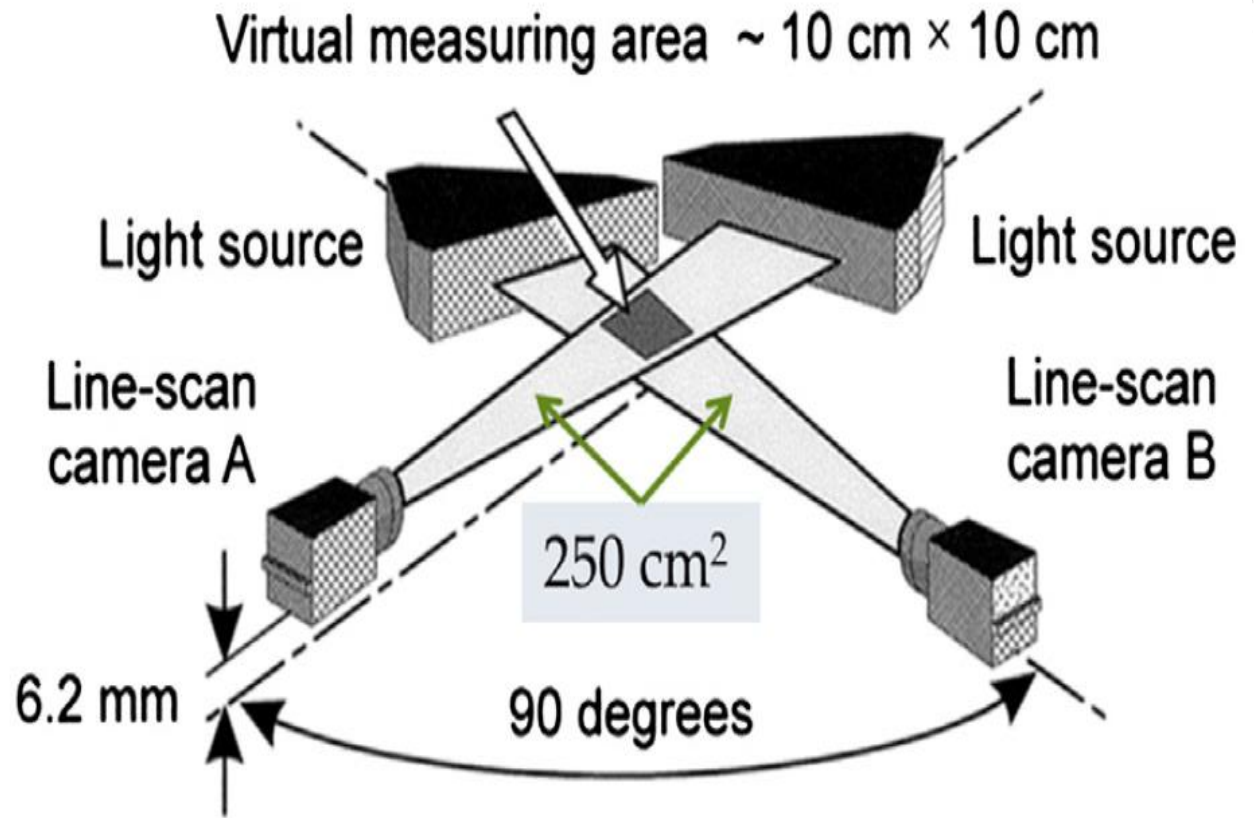
□ 二维视频粒子谱仪---本研究采用



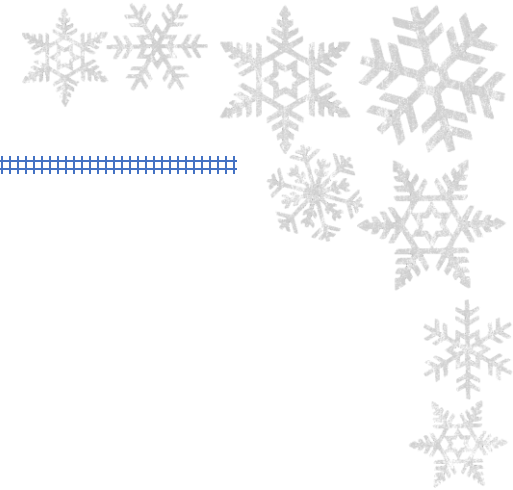
2DVD-2D Video Disdrometer



探测示意图



Kruger and Krajewski, 2002
Schönhuber et al., 2008



01

观测仪器

02

冰相粒子形状

03

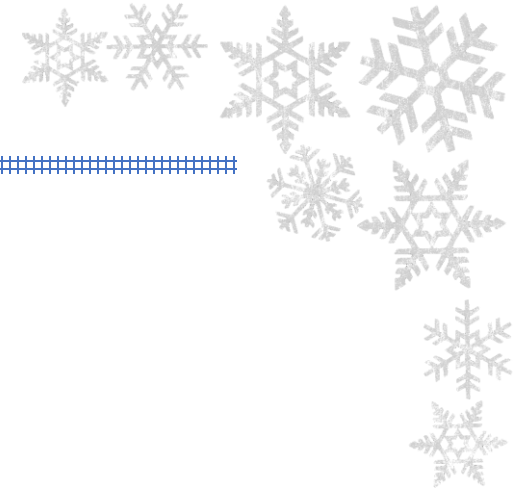
雨滴的形状

04

总结



讨论的问题



- 1 淞附对华东降雪的贡献如何？
- 2 淞附对冰相粒子形状变化有什么影响？



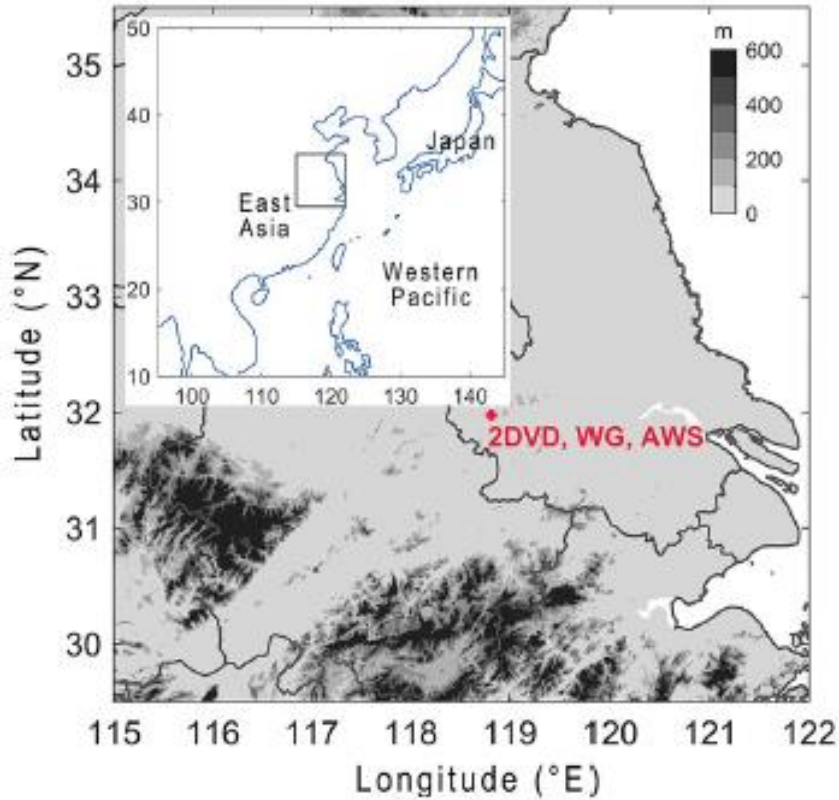
二、冰相粒子形状

采用的数据



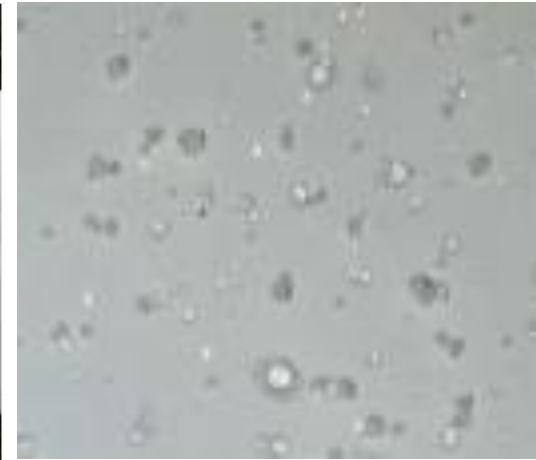
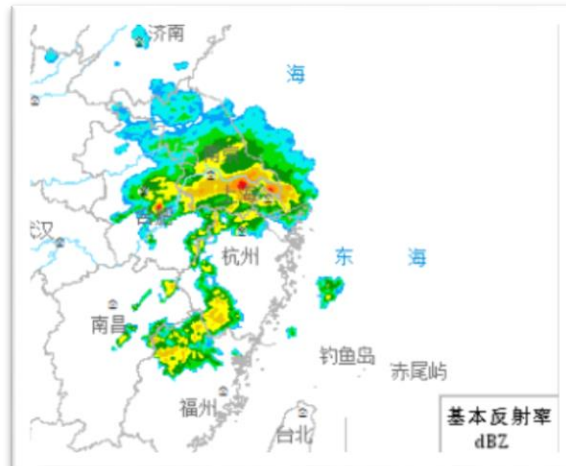
研究地点

时间段



个例	时间段	累积降雪量
1	2018.1.25 00:00-20:00	16.9mm
2	2018.1.27 08:00-12:00	7.4mm
3	2018.1.27 16:00-20:00	3.1mm
4	2019.2.8 00:00-04:00	13.5mm

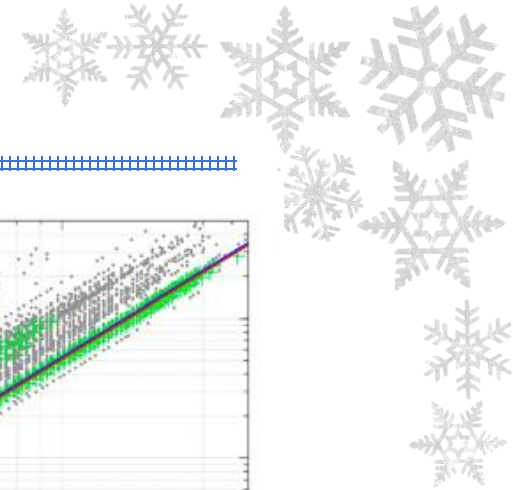
个例4为对流性降雪事件



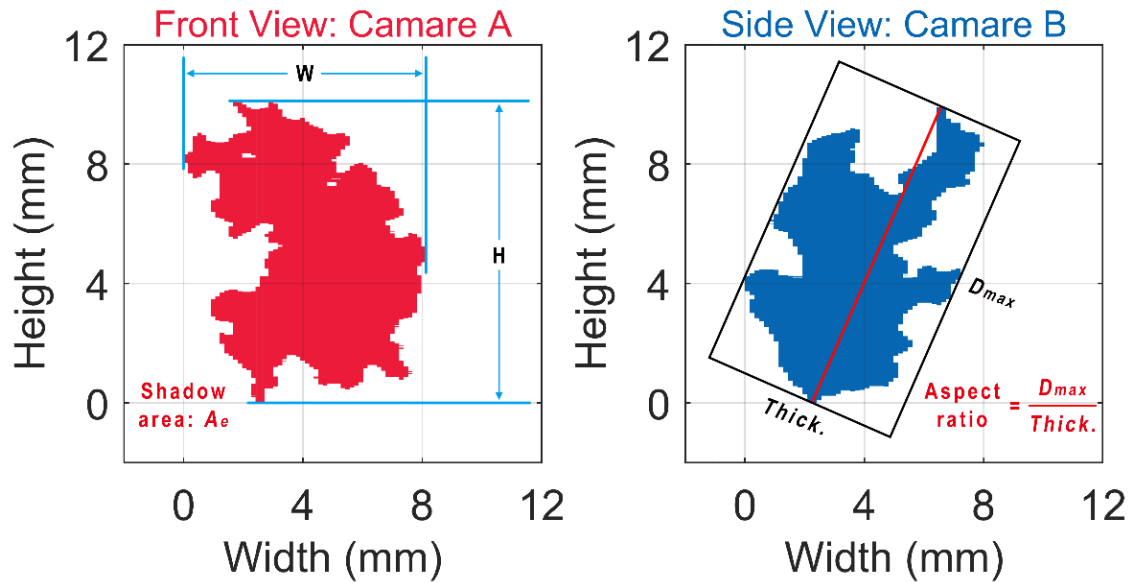


二、冰相粒子形状

采用的方法

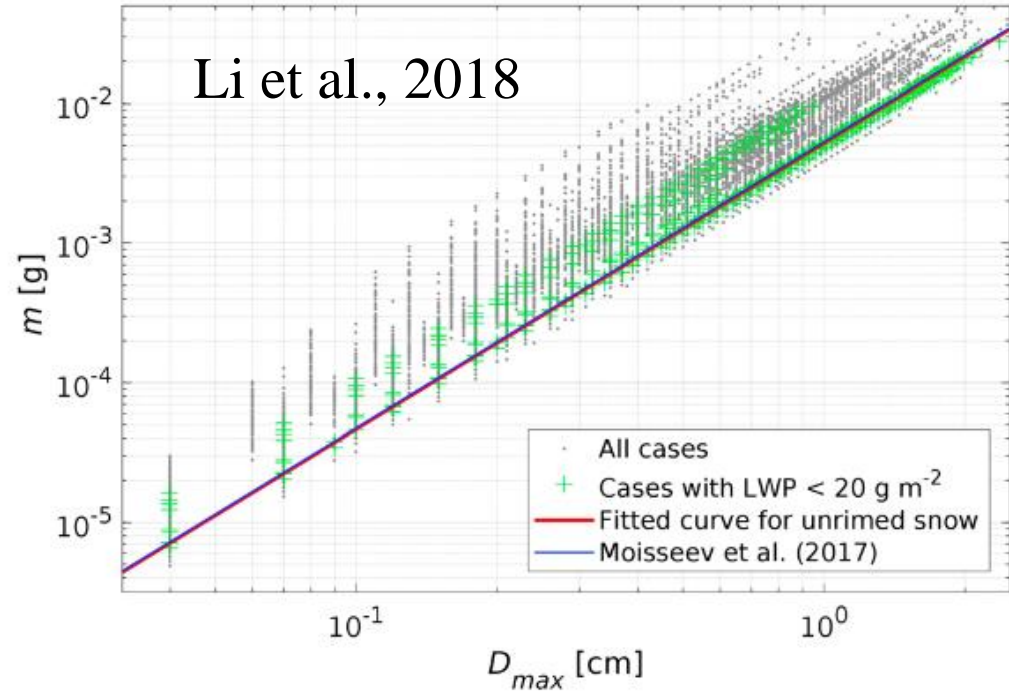


两个相机分别得到的粒子轮廓



粒子几何形状 + 下落速度

$$m \sim D_{\max}$$



$$FR = 1 - \frac{m_{us}(D_{\max})}{m_{ob}(D_{\max})}$$

衡量淞附程度的因子: FR 淞附率

(Lin & Colle 2011 **SBU-YLIN**;
Morrison & Milbrandt, 2014 **P3**;
Moisseev et al. 2017; Li et al. 2018)

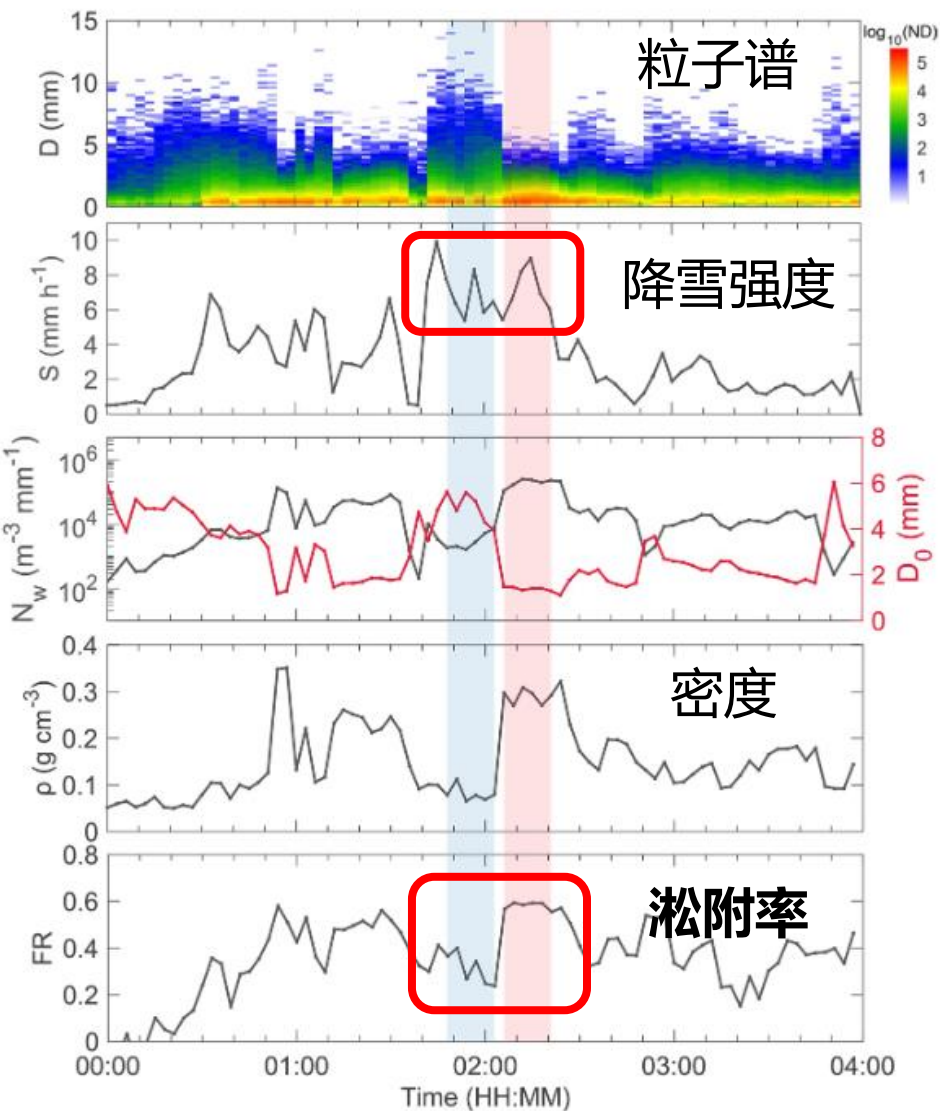


二、冰相粒子形状

□ 时间演变



个例4-强降雪



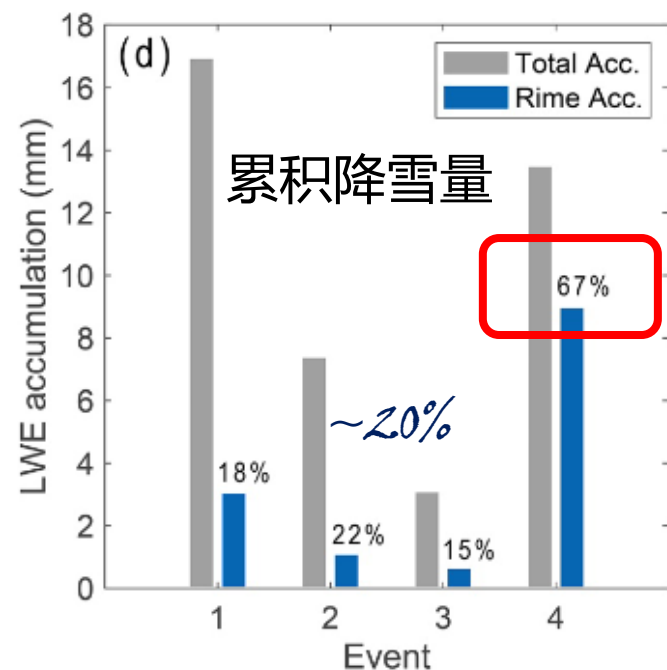
蓝色阴影区： 淞附程度弱， 粒子平均密度低， 直径大， 浓度低

红色阴影区： 淞附程度高， 粒子平均密度高， 直径小， 浓度高

降雪强度相当， 但微物理特征有明显转换， 这可能给雷达定量降雪预计和估计带来不确定性

(Tao & Zhao et al. 2020; Huang & Tao et al. 2023)

强对流降雪中淞附对降雪量的贡献达 ~70%

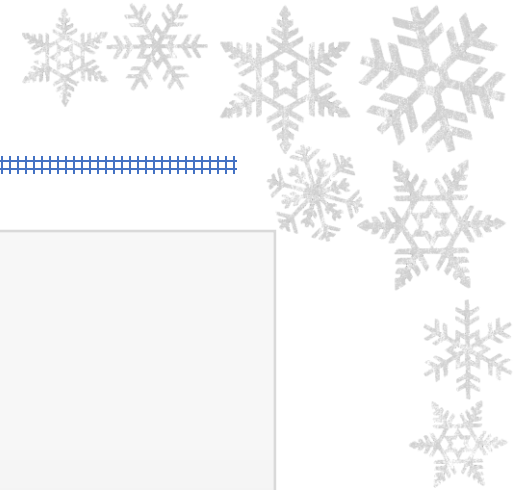


5%–40%： 芬兰南部 (Moisseev et al. 2017)
30%–40%： 美国加利福尼亚 (Mitchell et al. 1990)



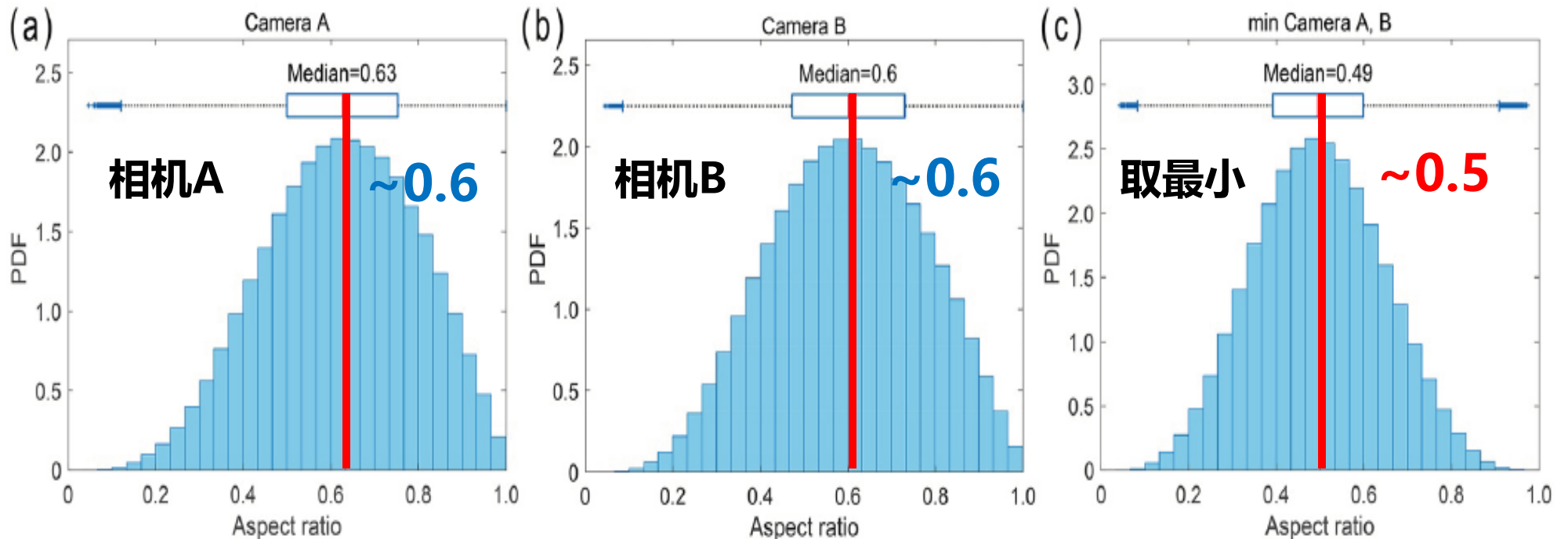
二、冰相粒子形状

□ 粒子轴比统计

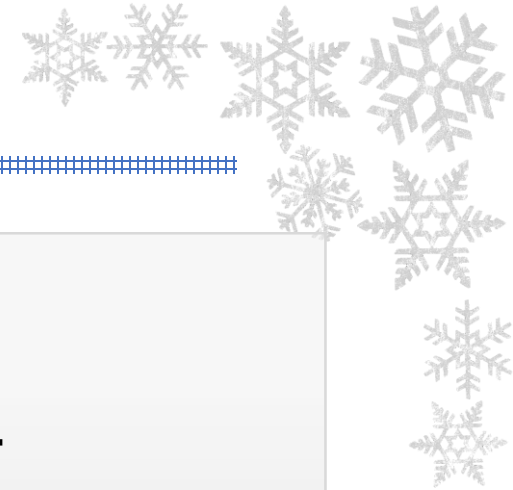


- 雪花统计轴比在0.6左右 --- 单平面观测结果
(Matrosov et al. 2005; Hogan et al. 2012; Garrett et al. 2015)
- 双相机取最小轴比，更接近粒子真实轴比：中值在0.5左右
- 传统飞机PIP观测的轴比可能偏高

轴比分布

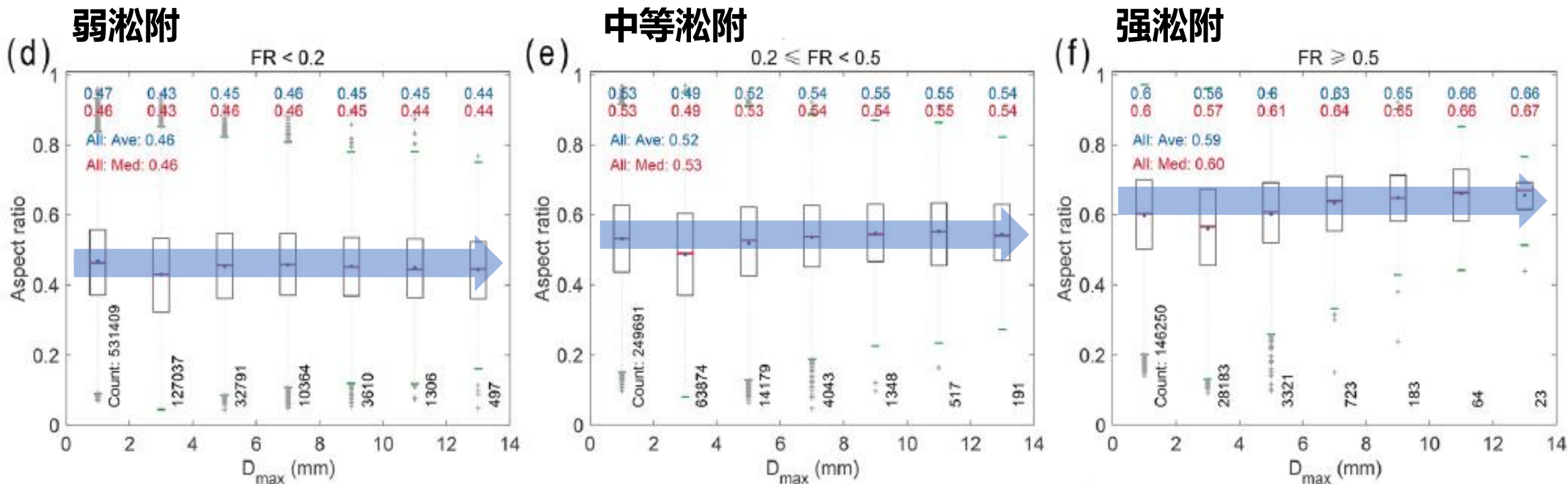


二、冰相粒子形状 □ 淞附对粒子轴比的影响



- 相同淞附率范围下，粒子轴比随直径变化较小
- 相比最大尺寸，冰相粒子的轴比对淞附程度的依赖性更高

轴比

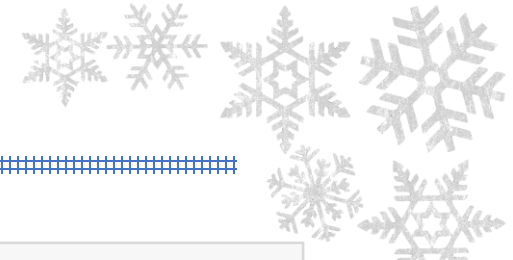


粒子最大维度 --- D_{max}



二、冰相粒子形状

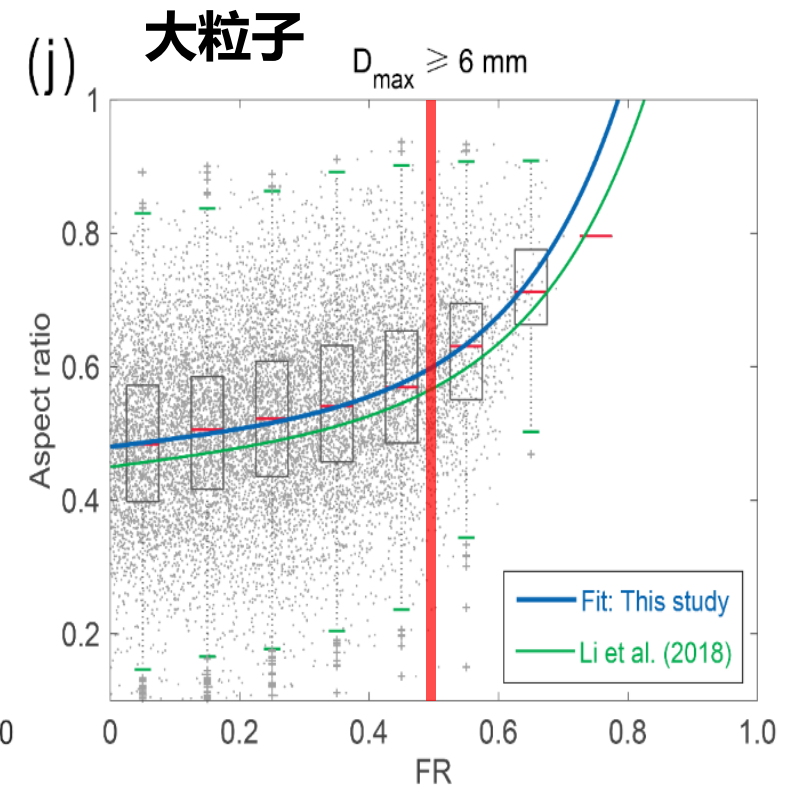
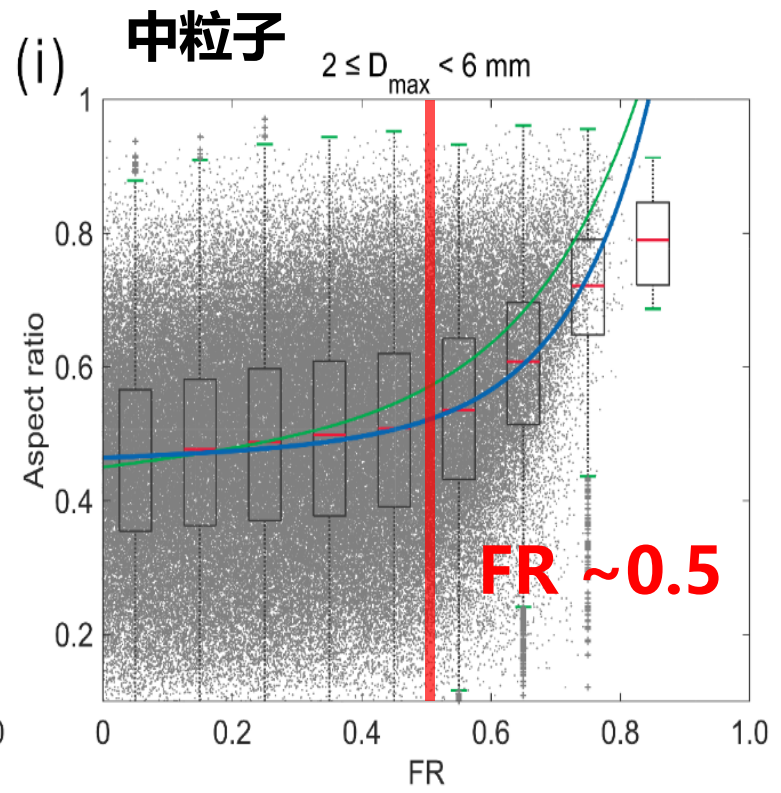
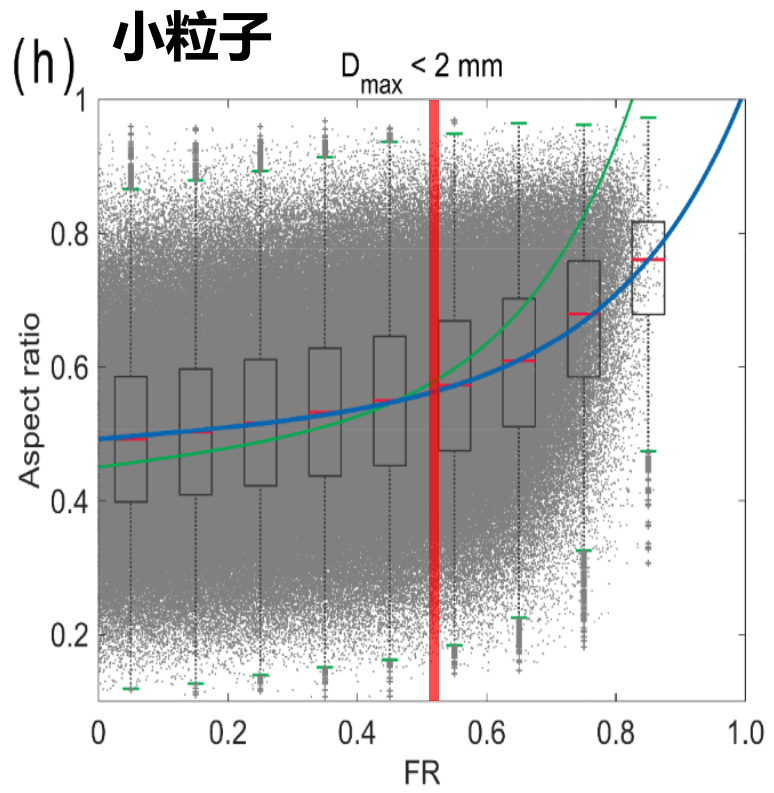
□ 淞附对粒子轴比的影响



- 利用**实况观测**建立了**粒子轴比**和**淞附率**之间的定量关系式

$$AR = c_0 + c_1 FRe^{c_2 FR^2}$$

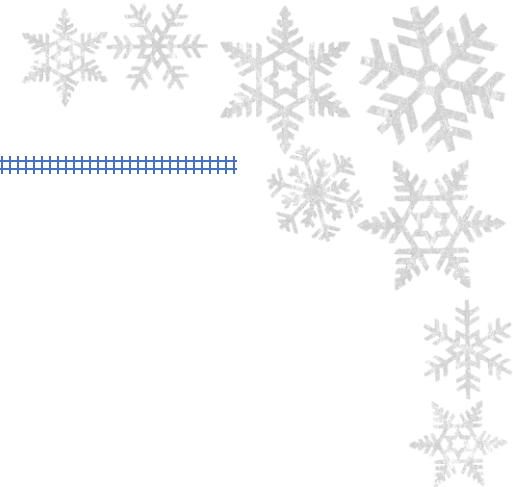
轴比



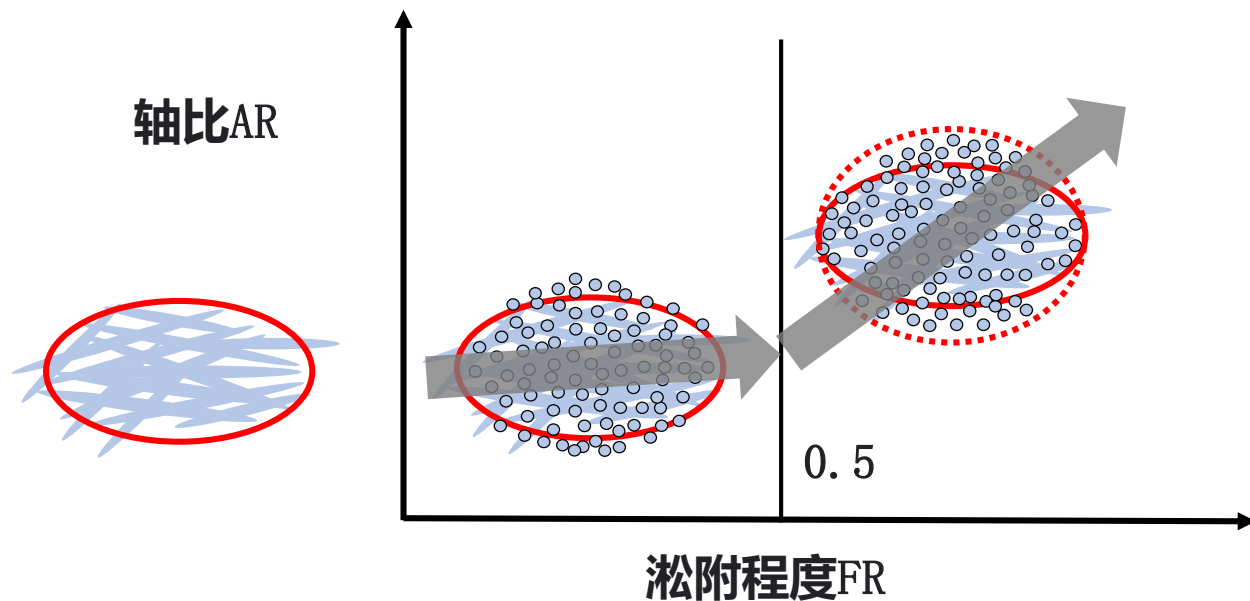
淞附程度 --- FR

二、冰相粒子形状

□ 淞附对粒子轴比的影响



淞附对粒子形态影响的概念图 – 华东地区降雪



- 冰相粒子观测算子的构建中，是否可以采用变化的轴比关系？
- 将FR引入粒子散射计算

雪晶的轴比 (AR) 对淞附质量比 (FR) 的响应

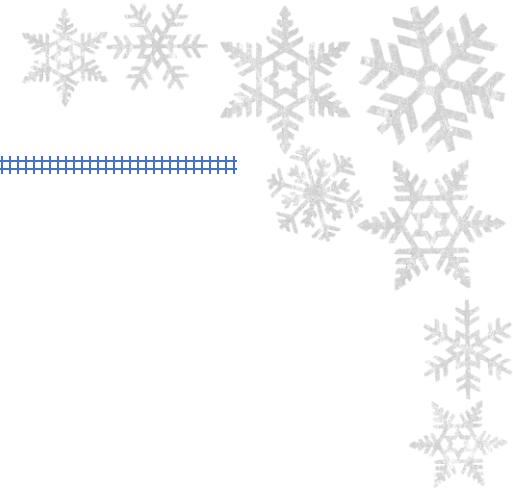
Heymsfield et al. 1982

Moisseev et al. 2017

Li et al. 2018

随着淞附程度的增强，粒子轴比经历两个明显不同的阶段：

先基本不变后迅速增大 (FR > 0.5)



01

观测仪器

02

冰相粒子形状

03

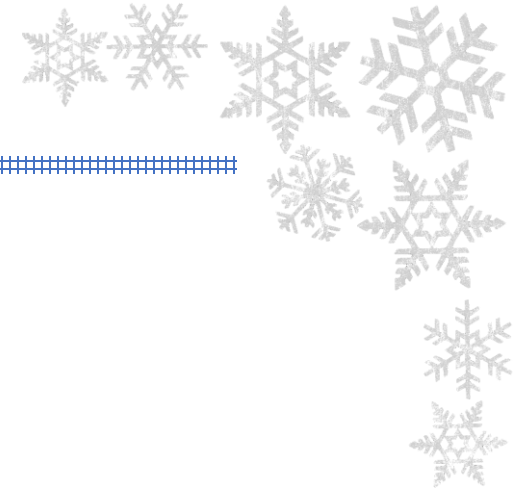
雨滴的形状

04

总结



讨论的问题



- 1 单平面观测能否表征雨滴的真实形状？
- 2 从三维椭球重构视角重新审视雨滴轴比
- 3 雨滴形状/轴比对双偏振量及其应用的影响？



三、雨滴形状研究

□ 进展简介 - 风洞试验

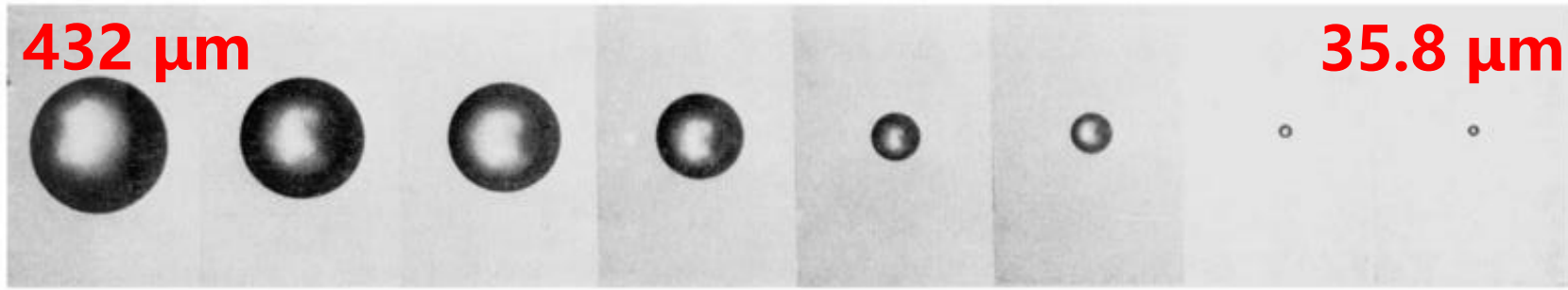


Figure 3. Typical shape of small water drops falling at terminal velocity (from left to right a_0 : 432, 393, 354, 282, 155.5, 130.9, 44.5, 35.8 μm corresponding to the following values for V_x : 351, 319, 289, 229, 119, 98, 21, 14 cm s^{-1}).

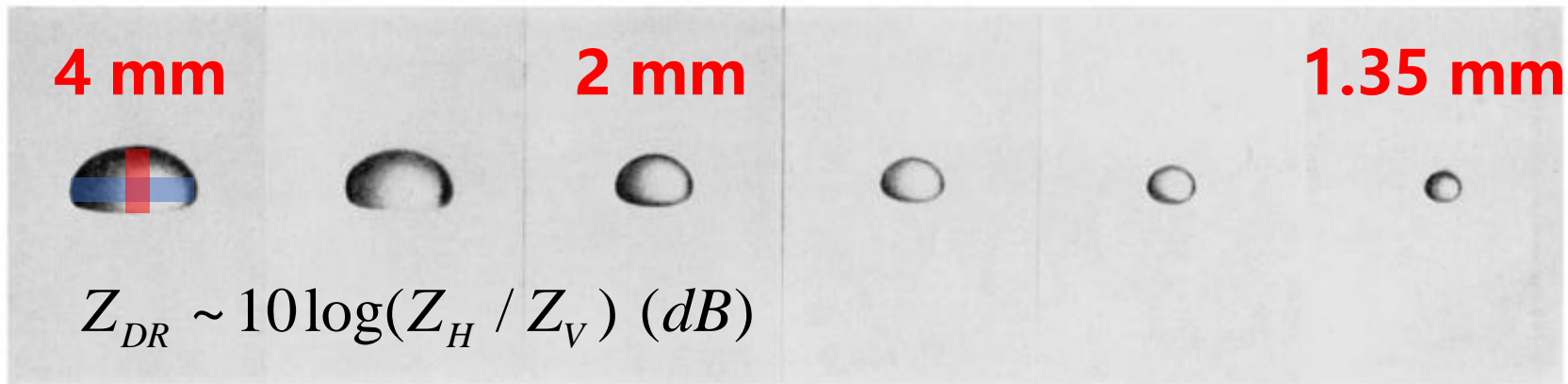


Figure 5. Typical shape of large drops falling at terminal velocity (from left to right a_0 : 4.00, 3.675, 2.90, 2.65, 1.725, 1.35 mm corresponding to the following values for V_x : 920, 920, 917, 913, 846, 770 cm s^{-1}).

Vol. 96. Plate III.

To face page 252

Pruppacher & Beard 1970



三、雨滴形状研究

□ 进展简介 - 理论模型和观测



平衡条件下雨滴形状理论模型

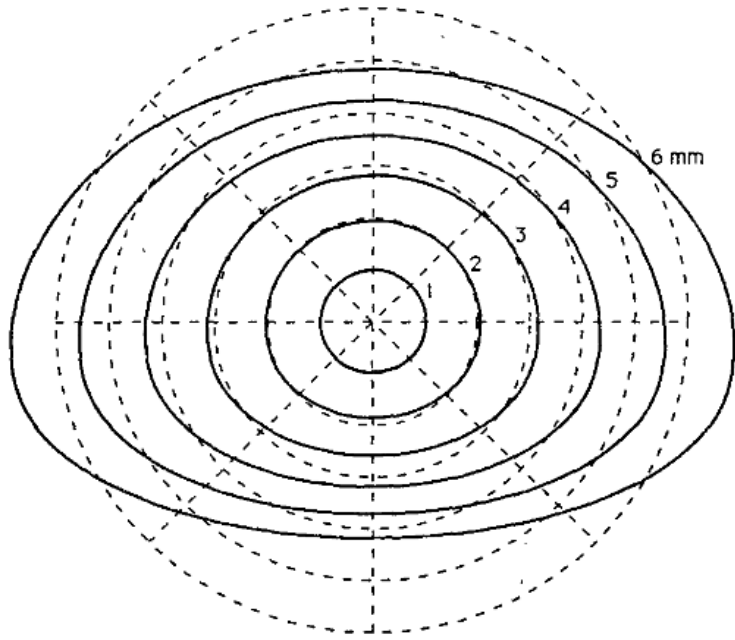


FIG. 7. Computed shapes for $d = 1, 2, 3, 4, 5$ and 6 mm with origin at center of mass. Shown for comparison are dashed circles of diameter d divided into 45 degree sectors.

Beard & Chuang 1987
雨滴平衡形状模型

静风条件下雨滴2DVD观测

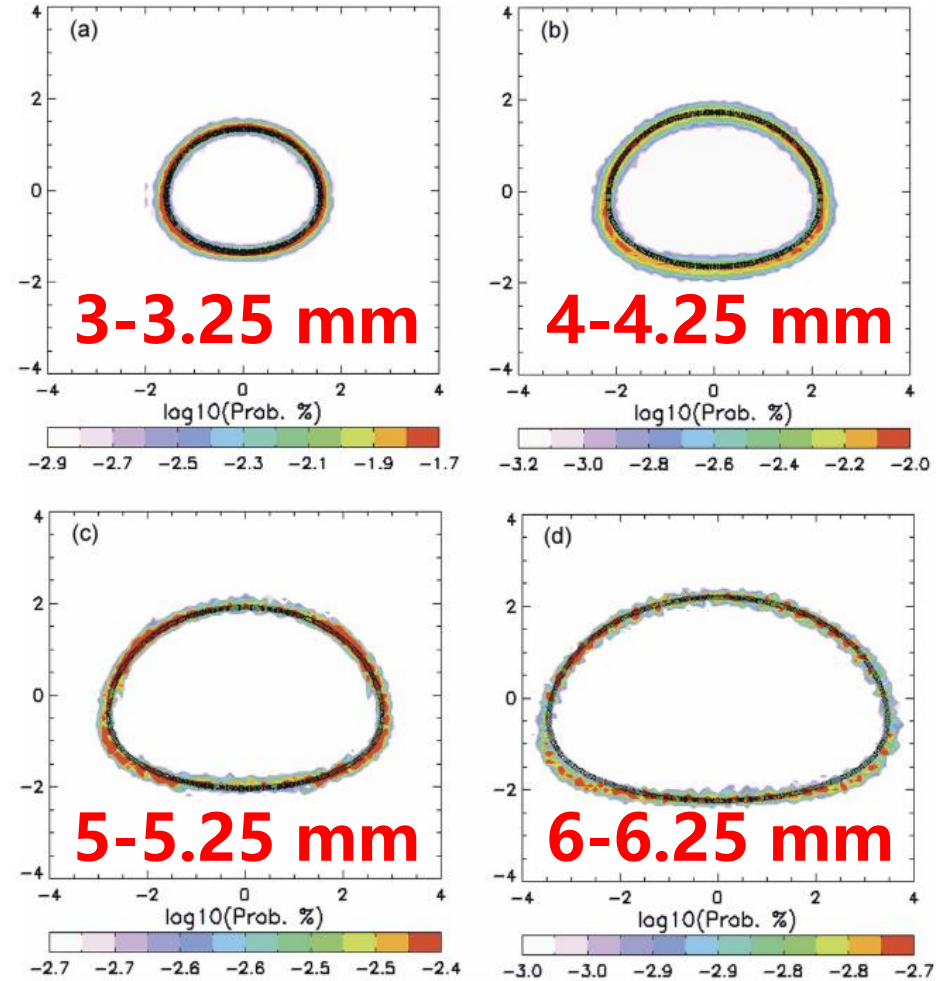


FIG. 2. The same probability contours as in Fig. 1, but compared with the Beard and Chuang (1987) shapes (shown in black) derived using Table 4 of their paper.

Thurai & Huang & Bringi et al. 2007



利用ZDVD恢复雨滴形状，逐粒子进行散射计算

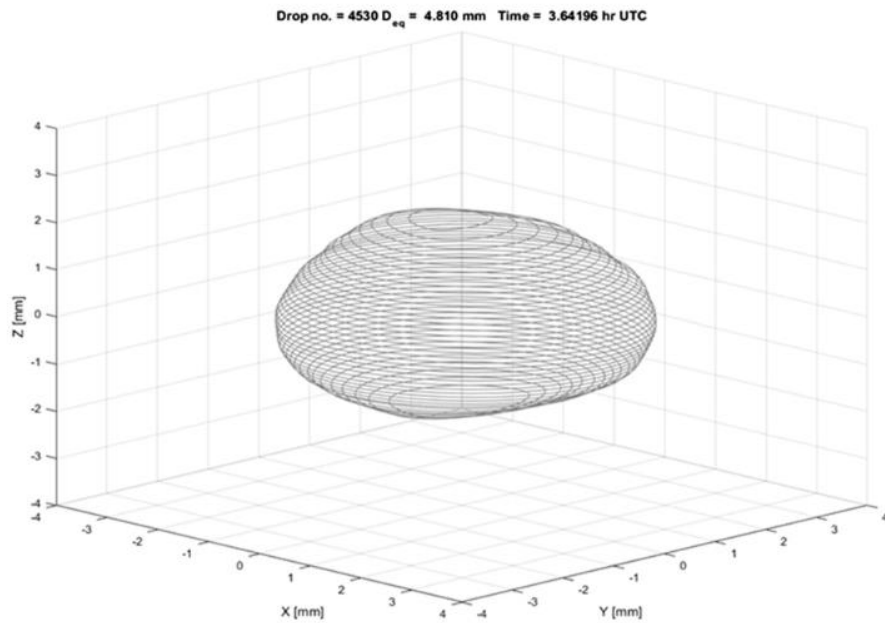


FIG. 4. Final full 3D reconstruction of the drop based on the procedure in Figs. 1-3.

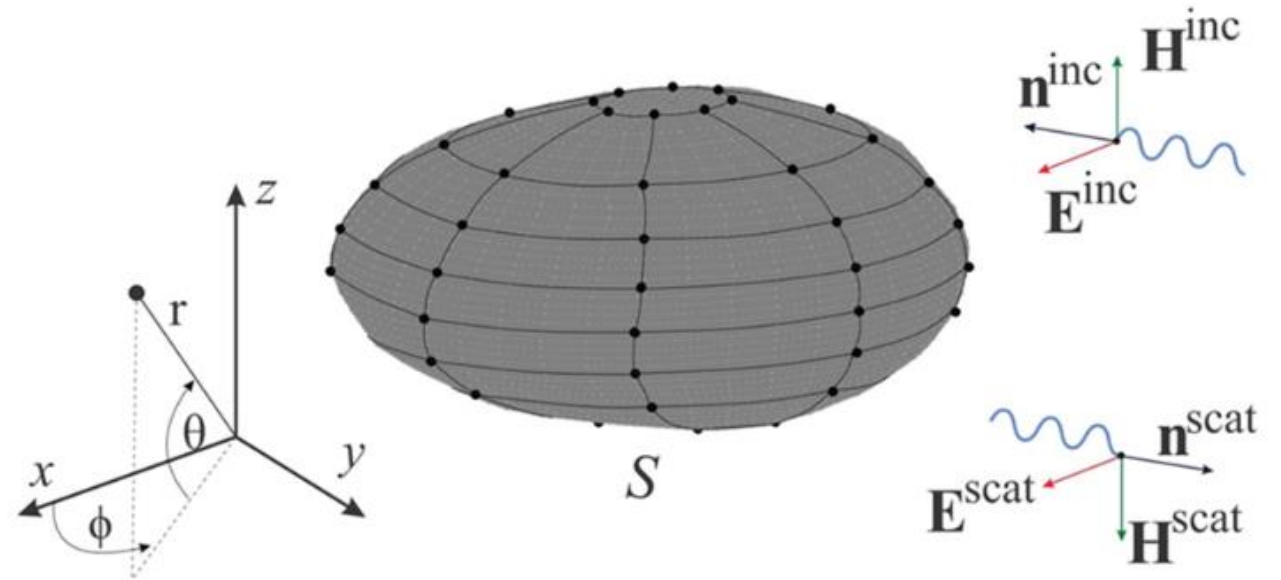


FIG. 5. Surface integral equation (SIE)-based electromagnetic scattering analysis of asymmetric raindrops modeled by method of moments (MoM) patches.



三、雨滴形状研究

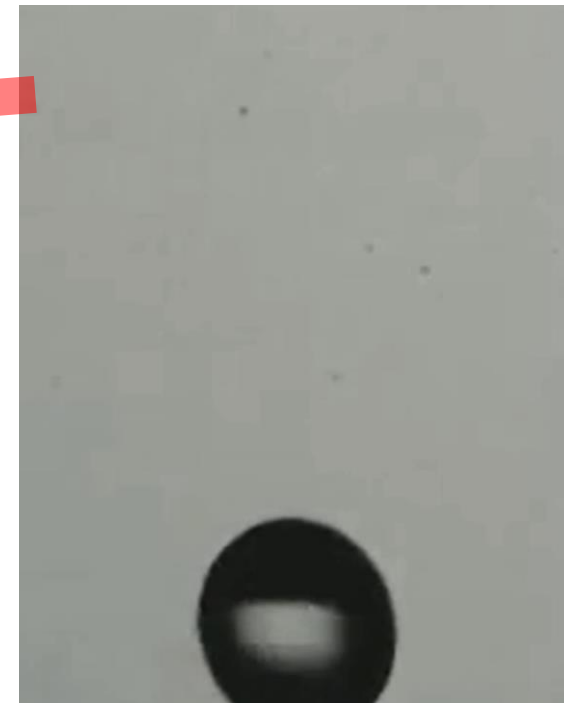
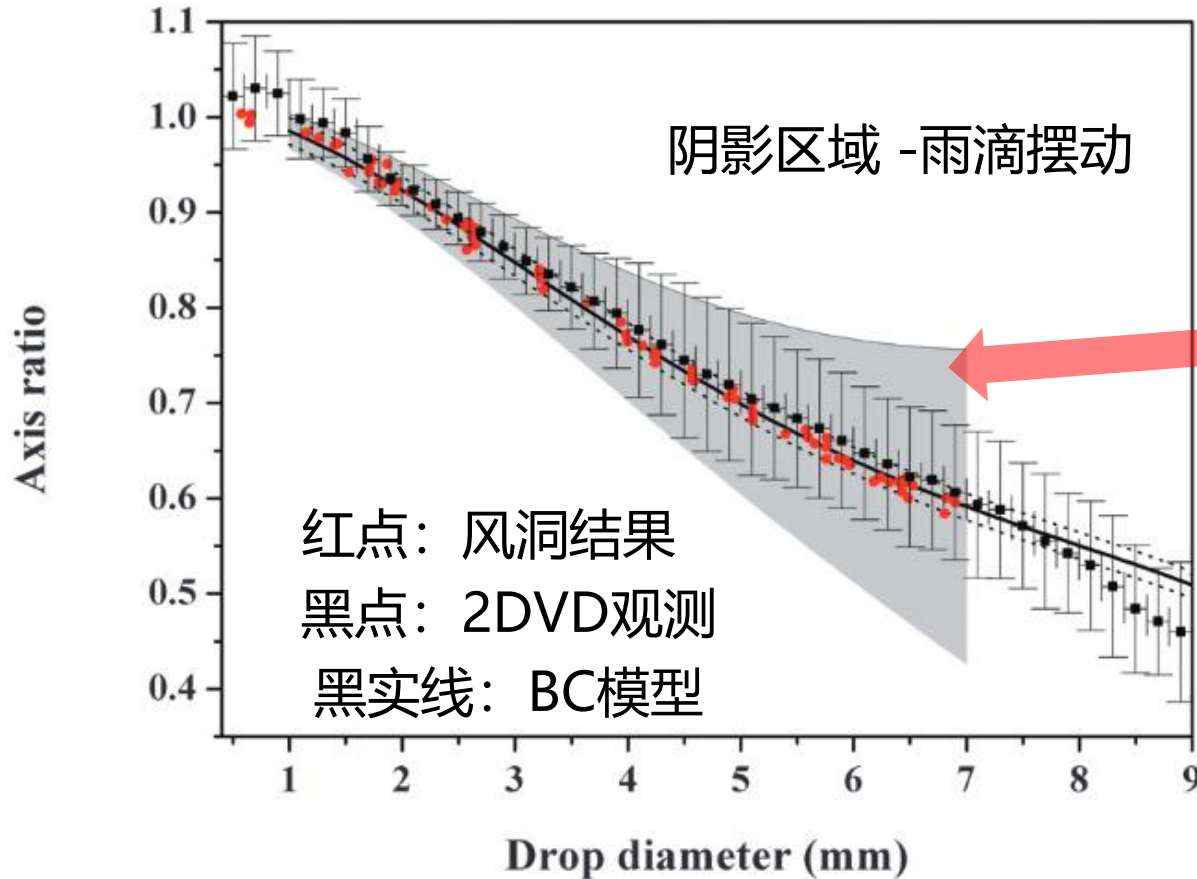
□ 常用的轴比关系



风洞试验、雨滴平衡理论模型
和2DVD观测的对比

存在的科学问题？

- 非稳定状态下，仅仅从单个角度观测雨滴形状存在多大误差？



Thurai & Bringi & Szakáll & Beard et al. 2009

Agrawal et al. 2020



三、雨滴形状研究

雨滴三维椭球恢复

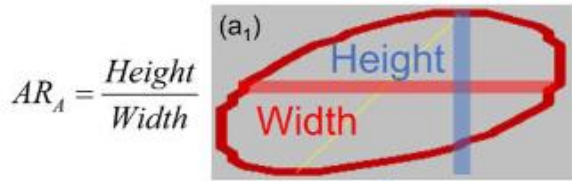


相机A

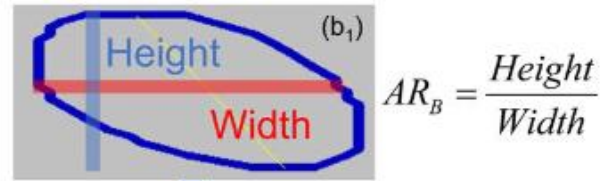
相机B

Camera A (Front view)

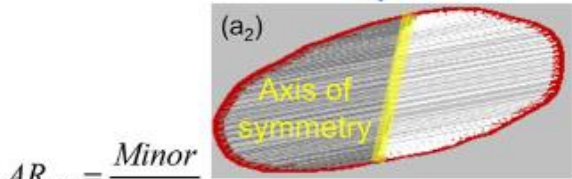
Camera B (Side view)



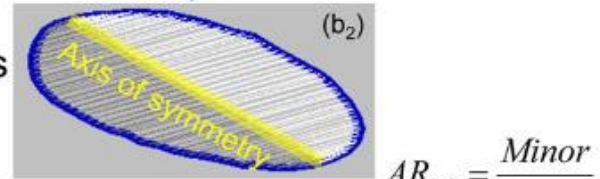
2DVD Raw Product
 $AR_P = \sqrt{AR_A \cdot AR_B}$



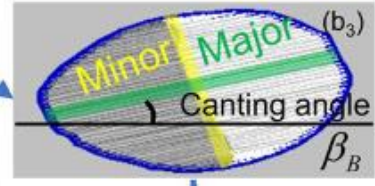
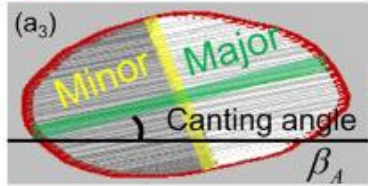
2DVD原始输出轴比



Find the symmetry axis

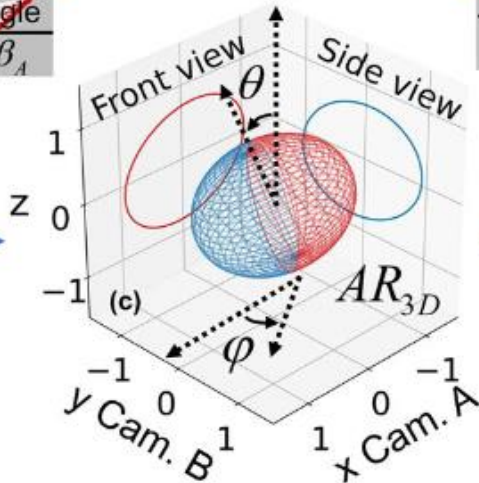


形状订正 -> 轴比+倾角



$AR_{AC} + \beta_A$

$AR_{BC} + \beta_B$



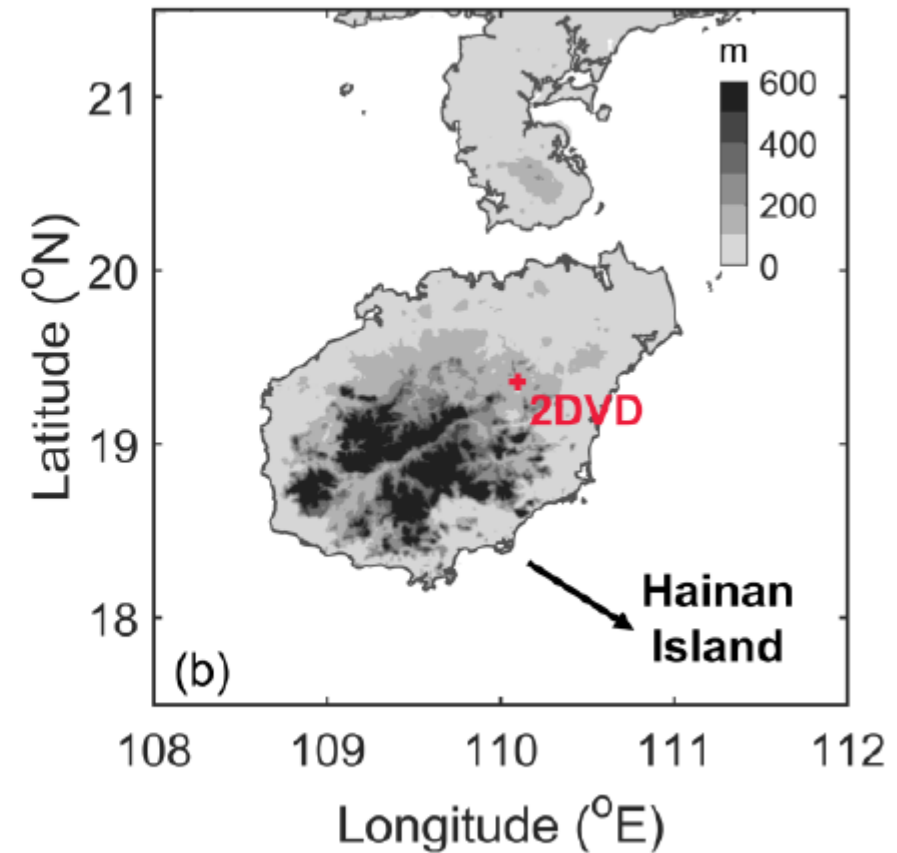
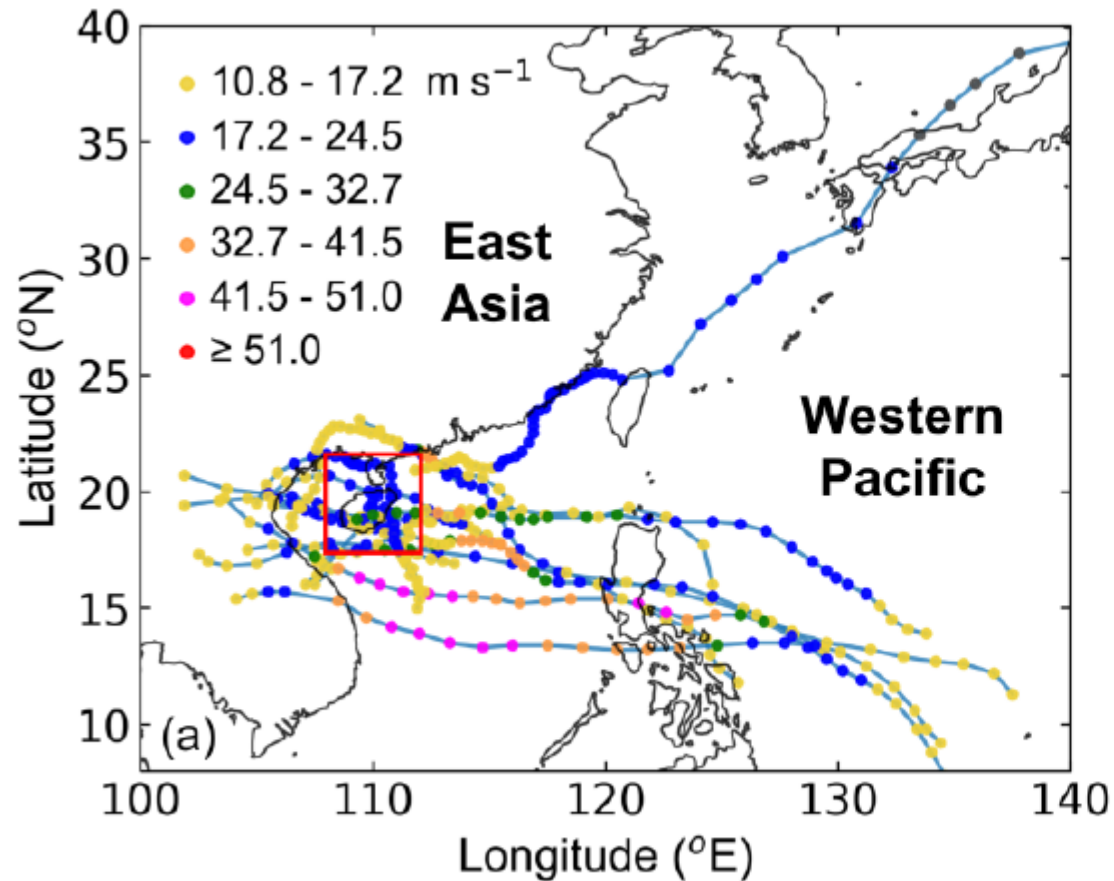
三维椭球反演



三、雨滴形状研究 ▣ 采用的数据



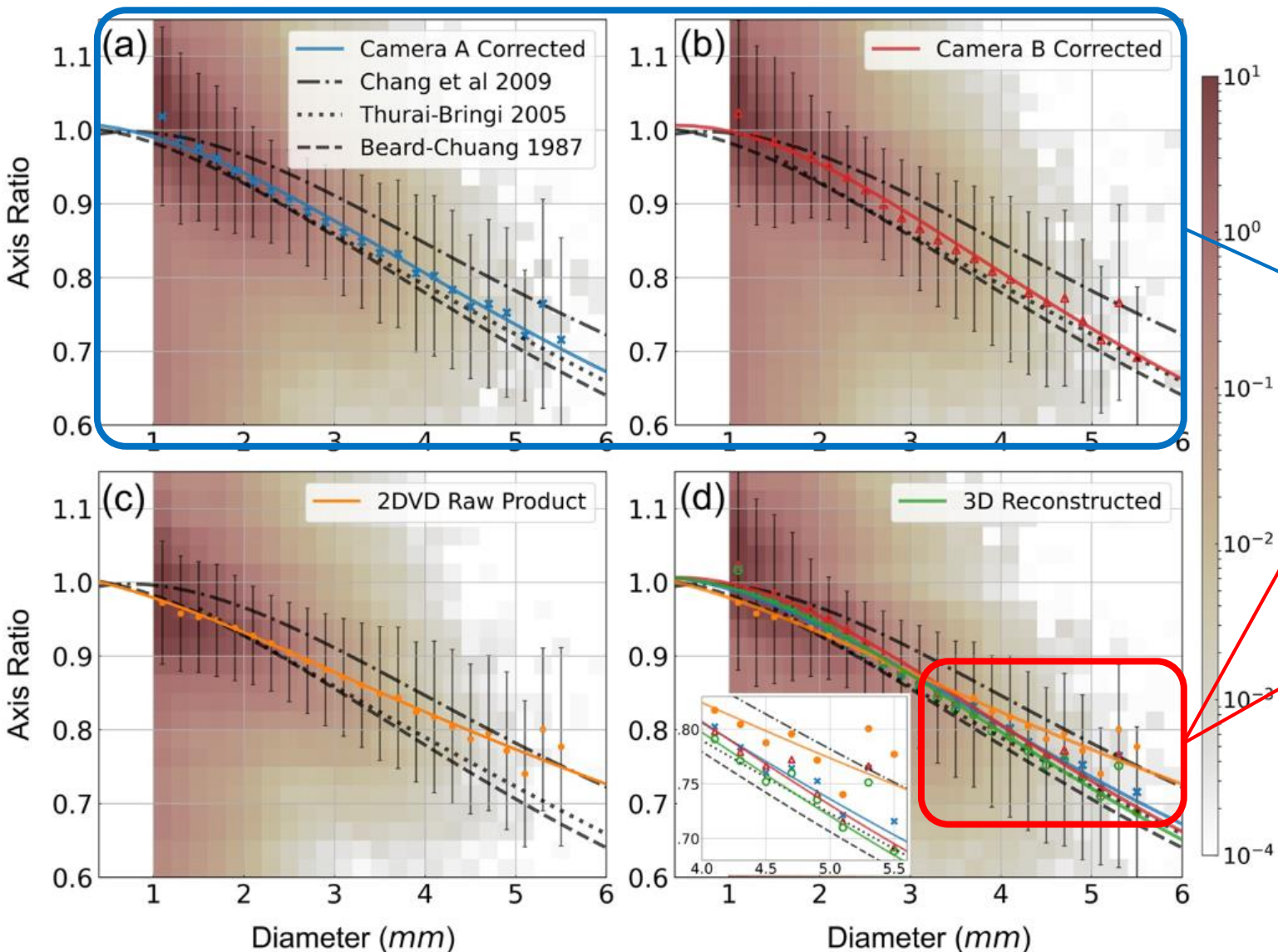
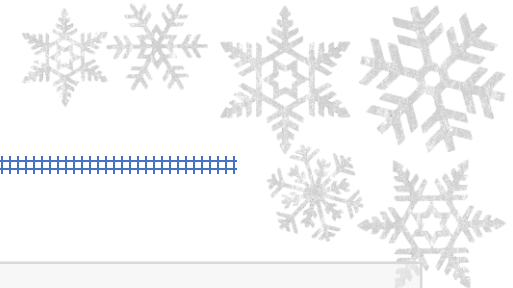
课题组在海南岛部署的2DVD多年观测2019-2021



三、雨滴形状研究

□ 结果分析

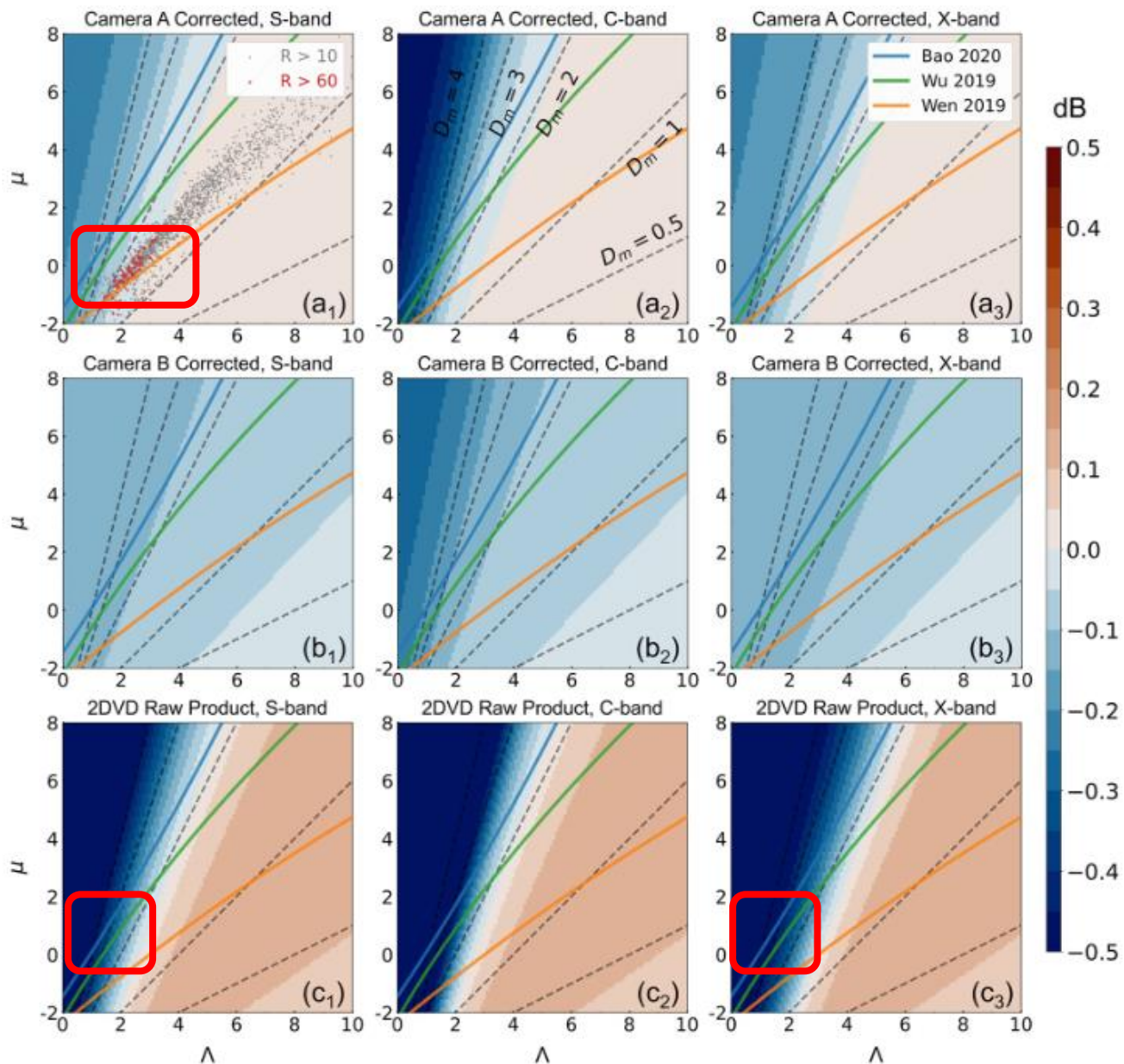
轴比关系的2DVD观测结果



- Chang 2009 台湾TCs
 - Thurai-Brinigi 2005 静风
 - BC1987 雨滴平衡理论模型
-
- 订正后的雨滴轴比曲线略高于TB2005和BC1987
 - 2DVD的原始输出轴比，在大粒子端明显偏高
-
- 在大雨滴 ($D > 3mm$) 三维反演轴比均低于单相机订正结果
 - 更接近TB2005和BC1987

三、雨滴形状研究

对双偏振量 Z_{DR} 模拟的影响

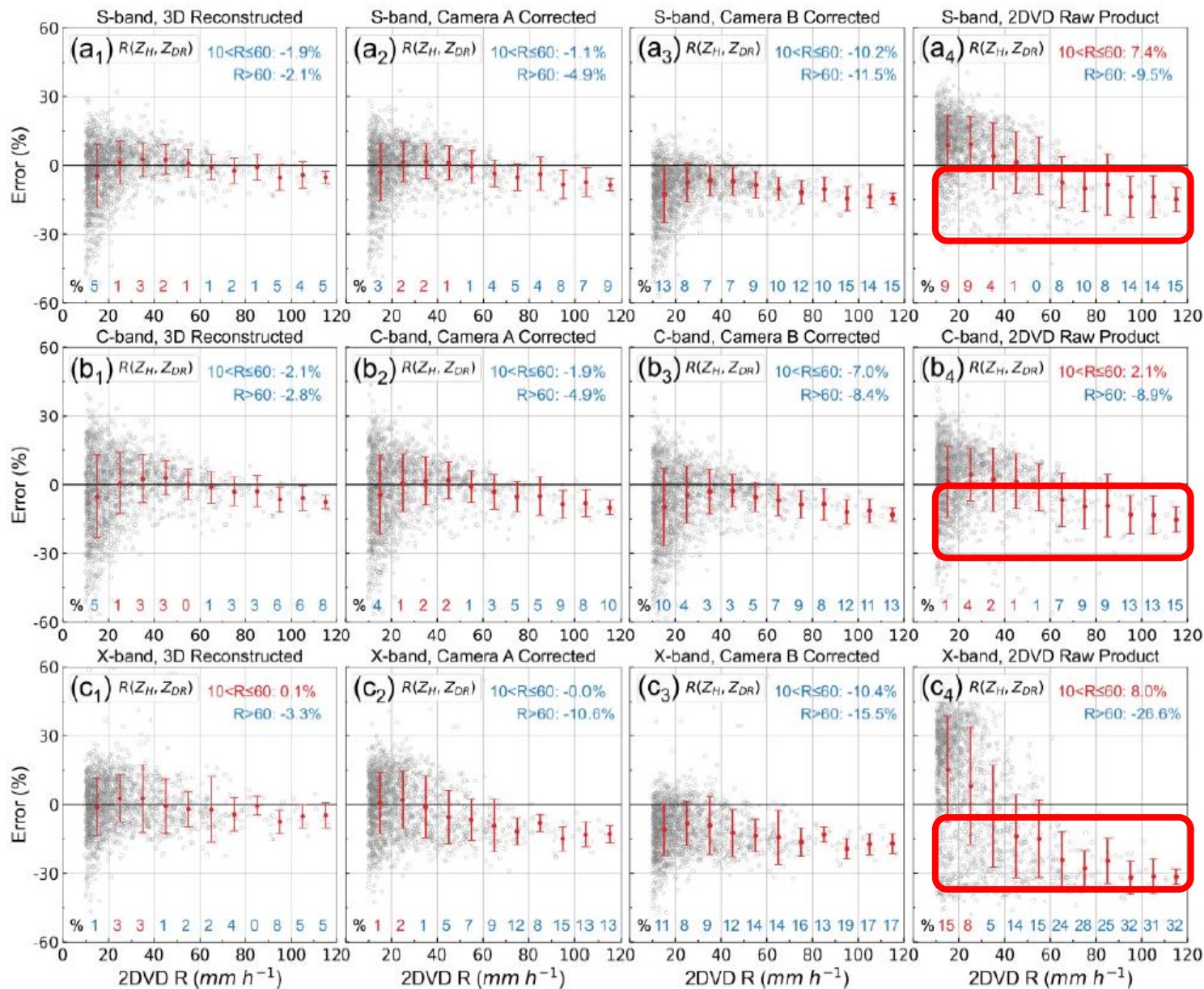


- 设定 μ - λ , 变化雨滴谱, 以三维轴比-直径关系为参考, 计算不同轴比-直径关系下的 Z_{DR} 偏差值

- 当 D_m 较大时, Z_{DR} 偏差明显增大, 在TC眼墙 (Bao-2020)、极端降水条件下 (陈刚2022; 张哲2022等), D_m 可达3mm
- 此时 Z_{DR} 低估在X波段可超过0.4dB, 在S波段也达 ~ -0.2 dB

三、雨滴形状研究

对定量降水估计的影响



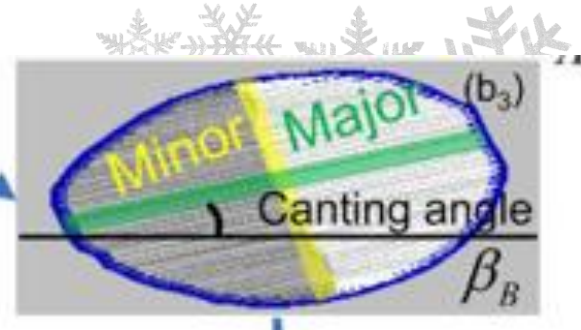
• 利用2DVD实测雨滴谱，变化雨滴轴比-直径关系，分别拟合 $R(Z_H, Z_{DR})$ 关系式

• 利用 $R(Z_H, Z_{DR})$ 关系估计的降水强度，在强降水 ($R > 50 \text{ mm h}^{-1}$) 时明显偏低

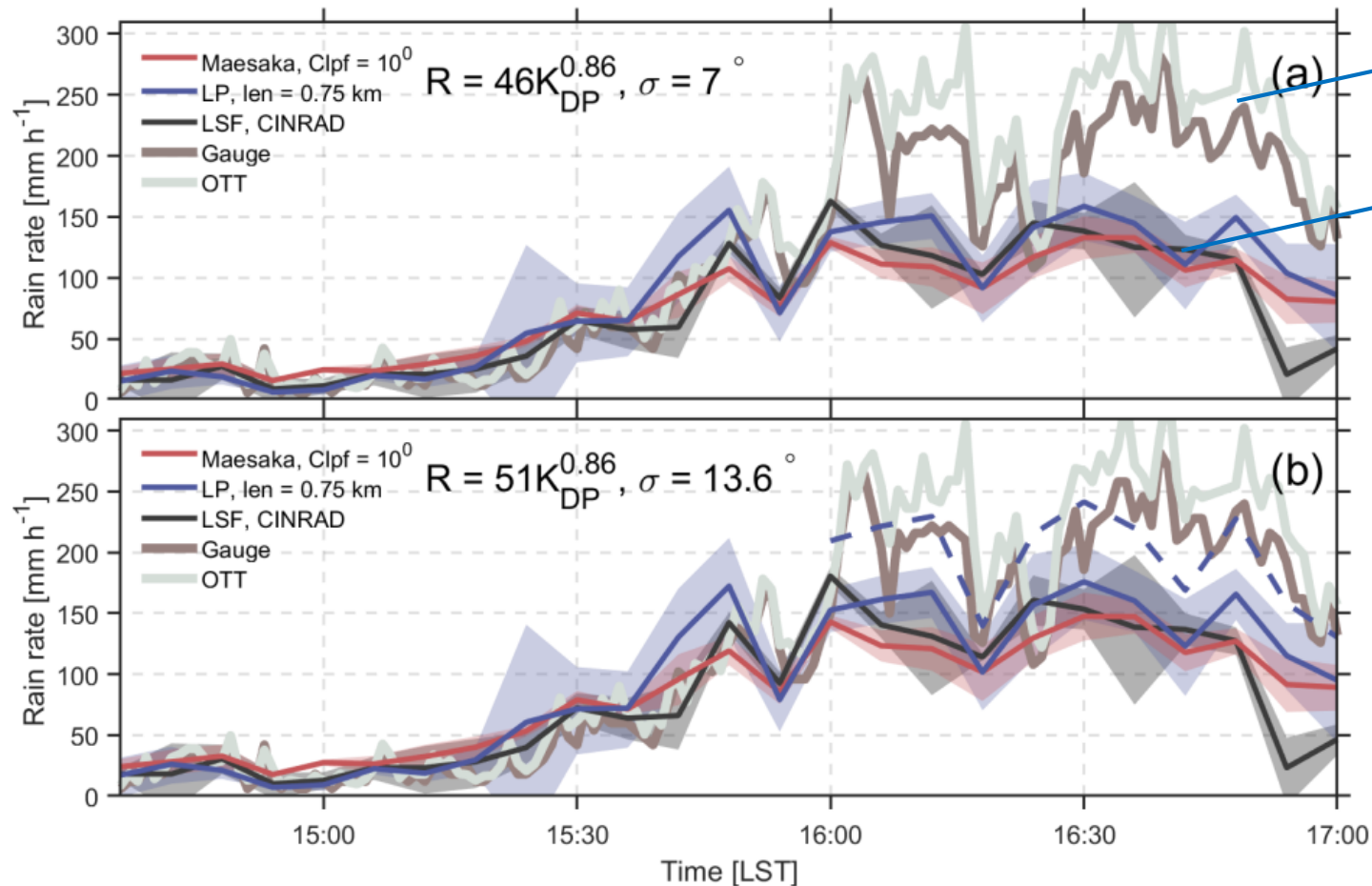
• 偏差在S和C波段可达-15%，在X波段可超过-20%

三、雨滴形状研究

对定量降水估计的影响



郑州720极端小时雨强的定量降水估计



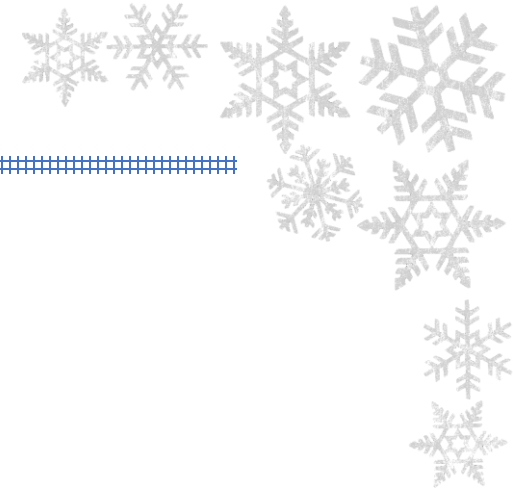
OTT和雨量计的观测降水强度

$R(K_{DP})$ 估计的降水强度

• 利用常规 $R(K_{DP})$ 关系估计的降水强度明显偏低！与观测相差甚远

- 误差来源？极端降水雨滴更圆？
 - 雨滴倾角标准差 σ ？
 - 雨滴轴比-直径关系？

Li et al. 2022 利用 Thurai-2007 的轴比-直径关系



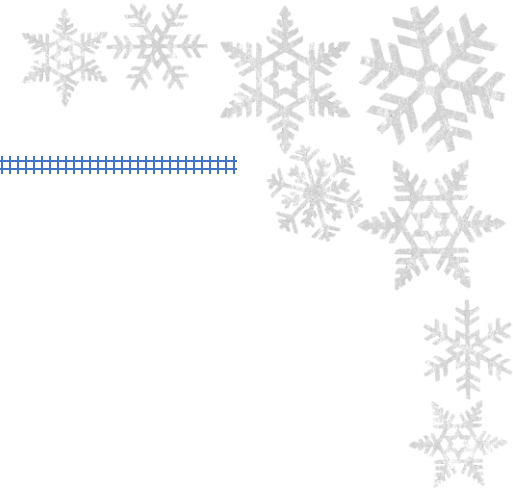
- 01** 观测仪器
- 02** 冰相粒子形状
- 03** 雨滴的形状
- 04** 总结

总结

- 基于 $zDVD$ 实况观测给出了冰相粒子轴比对淞附率变化的定量关系式
 - 发现随着淞附程度的增强，粒子轴比经历两个明显不同的阶段：先基本不变后迅速增大 ($FR > 0.5$)
-
- 开发了 $zDVD$ 正交观测反演雨滴三维椭球形状的反演算法
 - 发现基于单平面观测和 $zDVD$ 原始输出轴比对雨滴真实轴比存在高估现象，这将给基于雨滴轴比关系的应用带来严重误差

相关文献：

- Zhang, Y., Zheng, H., Zhang, L., Huang, Y., Liu, X., & Wu, Z. (2021). Assessing the Effect of Riming on Snow Microphysics: The First Observational Study in East China. *Journal of Geophysical Research: Atmospheres*, 126(7). <https://doi.org/10.1029/2020JD033763>
- Zheng, H., Zhang, Y., Li, H., Wu, Z., & Zhou, Z. (2023). Revisiting Raindrop Axis Ratios Based on 3D Oblate Spheroidal Reconstruction: 2D Video Disdrometer Observations During Tropical Cyclone Passages. *Geophysical Research Letters*, 50(9), e2023GL103281. <https://doi.org/10.1029/2023GL103281>



敬请各位批评指正
谢谢！

