How many types of severe hailstorm environments are there globally?

Qinghong Zhang

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Co-Authors: Ziwei Zhou, John T. Allen, Xiang Ni and Chan-Pang Ng

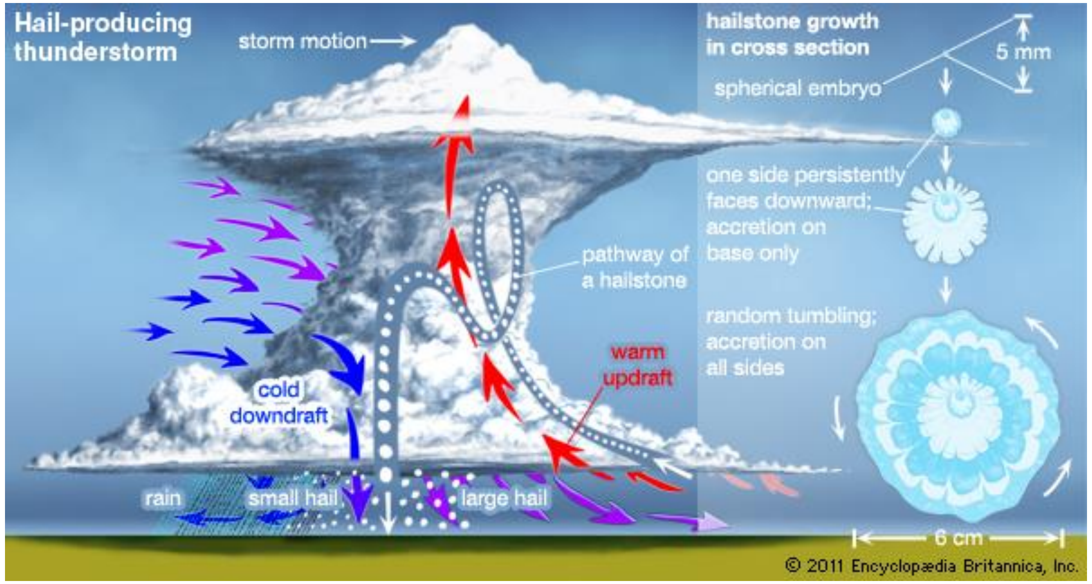
Zhou, Z., **Zhang, Q.,*** Allen, J. T., Ni, X., & Ng, C.-P. 2021. How many types of severe hailstorm environments are there globally? **Geophysical Research Letters**, 48, e2021GL095485.

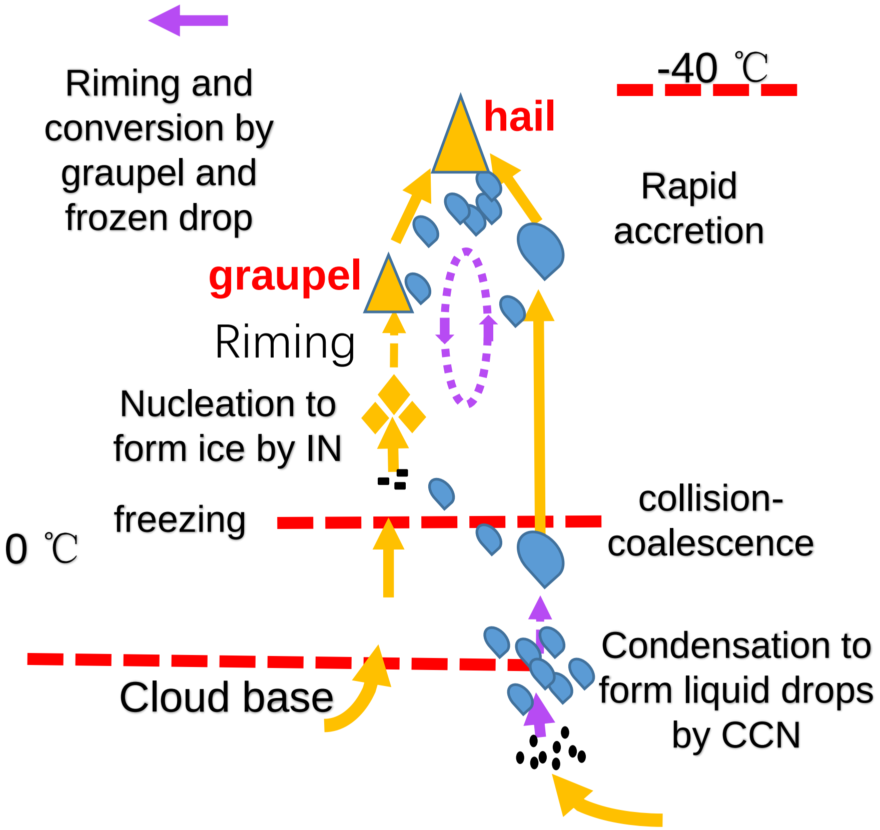
Raupach T-H., O. Martius, J T. Allen, M. Kunz, S. L. Trapp, S. Mohr, K. L Rasmussen, R. J. Trapp and **Q. Zhang,** 2021: The effects of climate change on hailstorms. *Nature Reviews*.

Ni, Xiang, C. Liu*, D. J. Cecil, **Q. Zhang**.2017: On the hail detection using satellite passive microwave radiometers and precipitation radar**. *Journal of Applied Meteorology & Climatology*.**

Ni, X., Liu, C., Q. **Zhang*,** & Cecil, D. J. 2016: Properties of hail storms over china and the united states from the tropical rainfall measuring mission. *Journal of Geophysical Research, Atmos.,*121(20). 121.

Hailstorm & Hailstone Formation

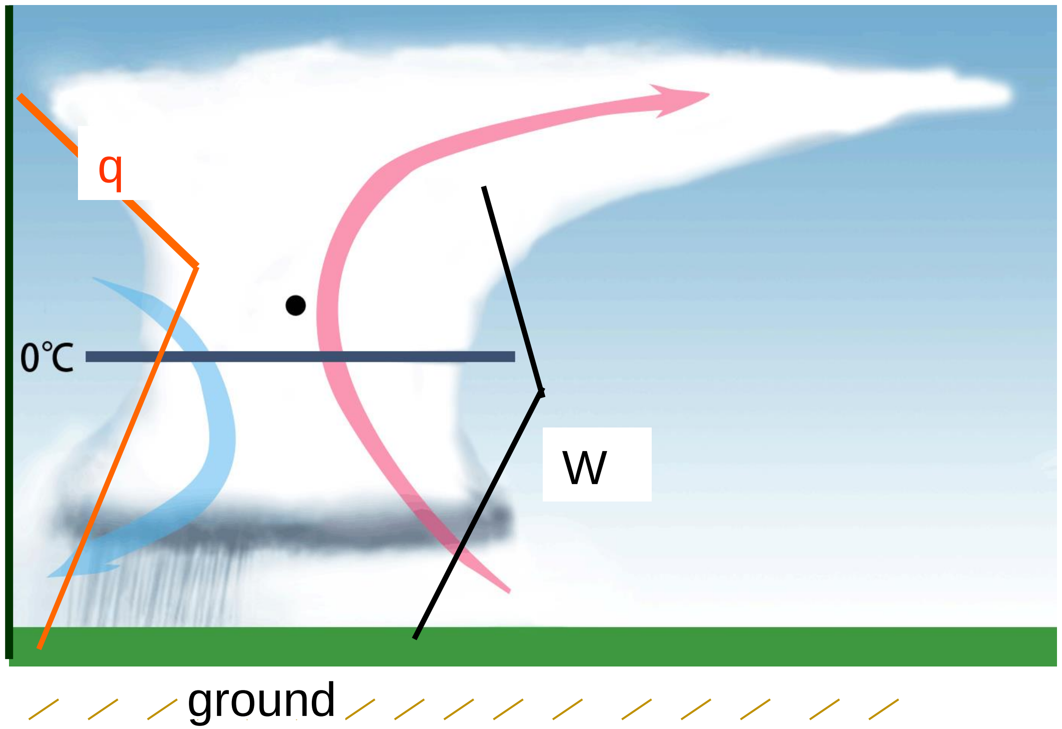




Lamb and Verlinde, 2011

冰雹指直径大于5mm的球状或不规则形状的冰粒降水（WMO）

Hailstorm environment & hailstone formation ?



CAPE
PW
FLH
C-base H — 热力

VWS — 动力

Aerosol — 气溶胶

辐射

IN
CCN

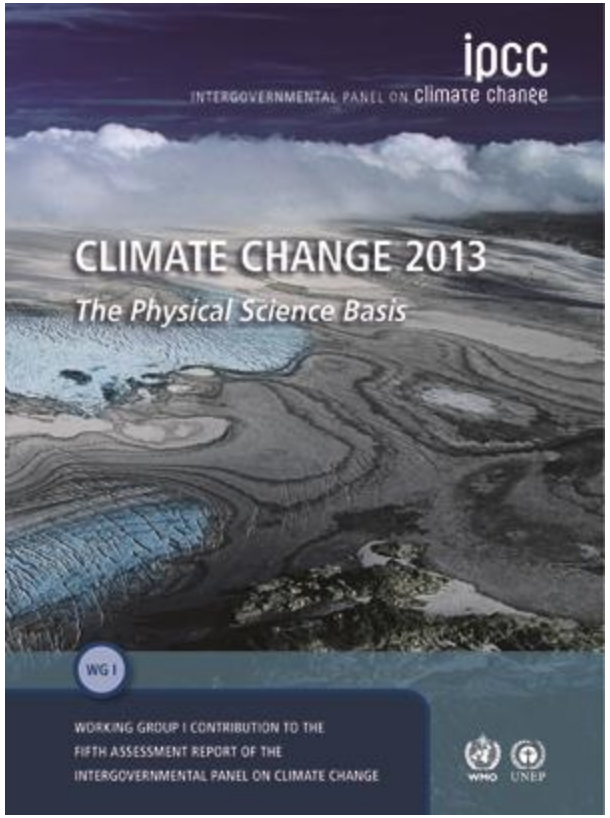
大尺度环境

微物理过程

特征	描述	单位
MUCAPE	Most-unstable convective available potential energy	J/ kg
MUCIN	Most-unstable convective inhibition	J/ kg
PW	Precipitable water	mm
SHR06	0-6km bulk shear	m/ s
Hlift	Height of lifting parcel with MUCAPE	m AGL
HGZ	Height interval between -30℃ and -10℃	m above ground level （AGL）
Hmelt	Height interval between FLH and terrain height	m AGL
Hterrain	Terrain height	m
TLCL	Temperature of Lifting Condensation Level （LCL）	℃
TLFC	Temperature of Level of Free Convection （LFC）	℃
TEL	Temperature of Equilibration Level	℃
T500	500hPa temperature	℃
HLCL	Height of LCL	m AGL
HLFC	Height of LFC	m AGL
HEL	Height of Equilibration Level	m AGL
L700500	700hPa-500hPa lapse rate	℃/ km
Normalized MUCAPE	MUCAPE divided by the depth of the layer where CAPE is present	m/ s²
CAPE_FLH	H_lift-FLH MUCAPE	J/ kg
CAPE_3km	H_lift-3km MUCAPE	J/ kg
CAPE_6km	H_lift-6km MUCAPE	J/ kg
SBCAPE	Surface-based convective available potential energy	J/kg
SBCIN	Surface-based convective inhibition	J/kg
PRECIP RATE	Precipitation Rate	mm/h
EBWD	Effective bulk wind difference	m/s
Tlift	Temperature of lifting parcel with MUCAPE	℃
Plift	Pressure of lifting parcel with MUCAPE	hPa
Year	-	-
Month	-	-
Day	-	-
Hour	-	-
Lon	Longitude	°
Lat	Latitude	°

"The long-term trend of hail is in low-confidence."

IPCC-5&6



- **Observation:**
- Insufficient studies and data quality issues
- Inhomogeneity of observation methods

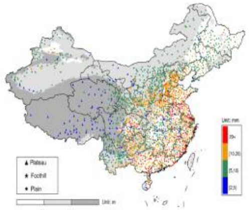
- **Physics:**
- Linkage between global scale to small scale
- Complex hail formation process
  microphysics & dynamics

Hailstorms Observation & modeling

Cocorahs.org

测雹板

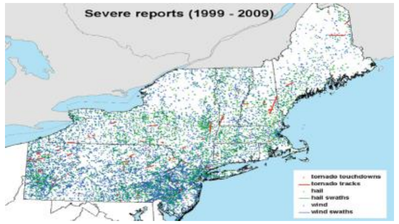
稀少、需人工



Ni, 2017

气象站

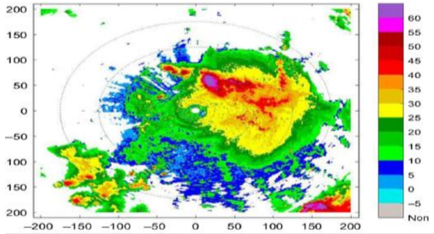
覆盖不均、观测指南、需人工



Hurlbut, 2012

公共报告

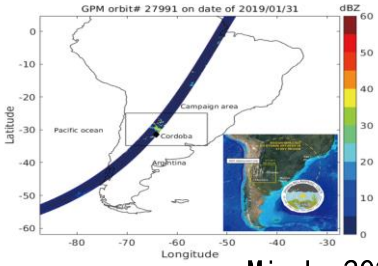
分布广泛、受人口密度影响大



Chen, 2022

地基雷达

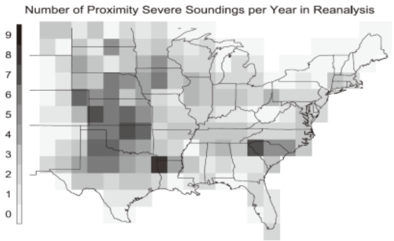
全天候观测、建筑遮挡



Minda, 2020

卫星

时空限制少、数据源均一、非全天覆盖

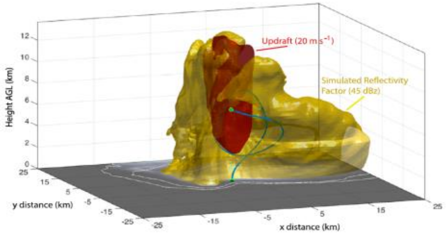


Brooks, 2003

复合参数

判别式区域差异

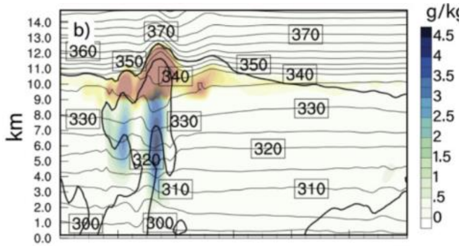
冰雹研究尺寸不一致



Dennis, 2017

云模式

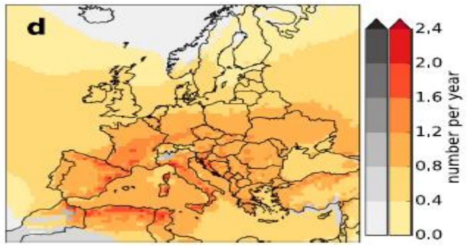
理想化、半理想化



Toker, 2021

中尺度模式

分辨率高、参数化方案敏感



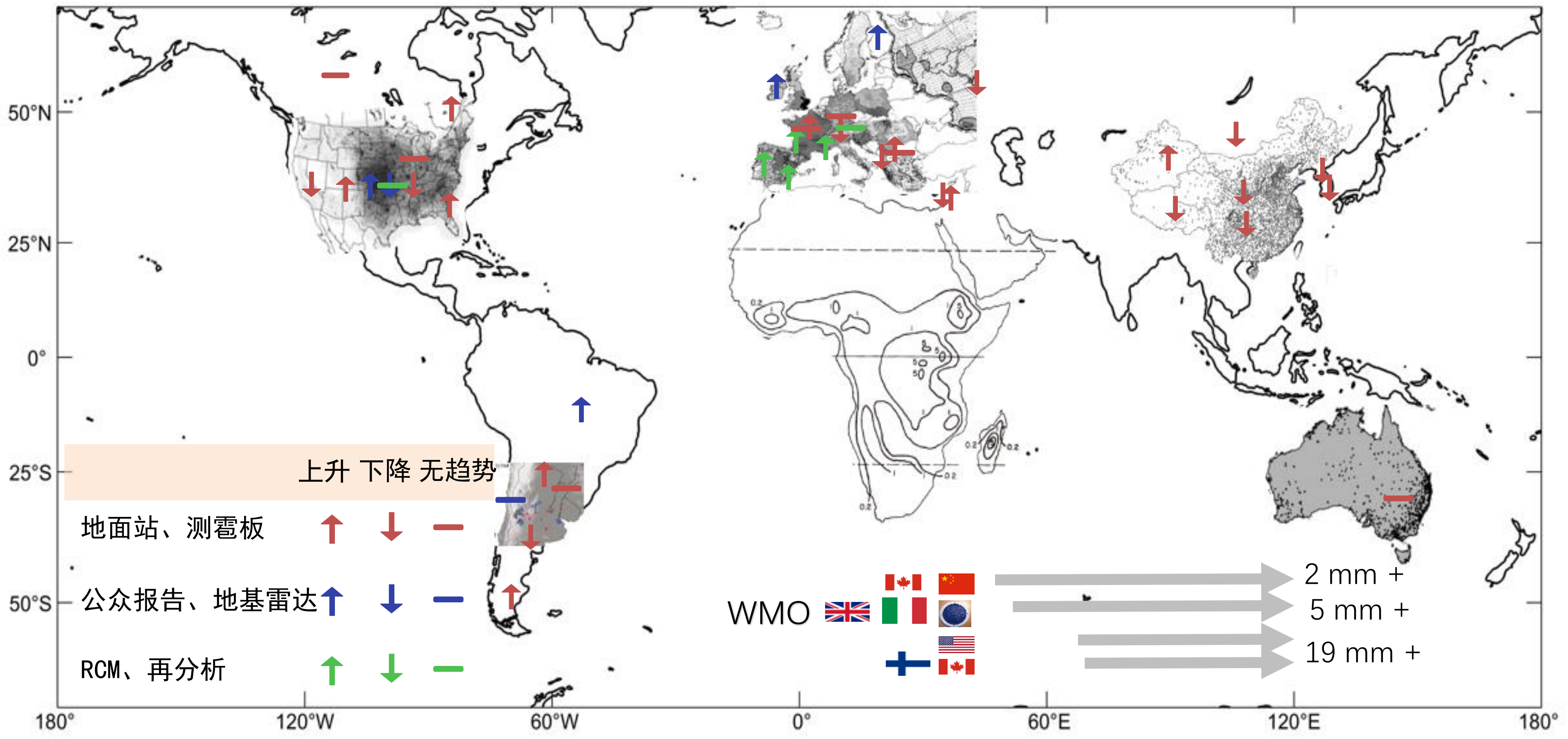
Radler, 2019

GCM/RCM

粗分辨率、模式可解析对流

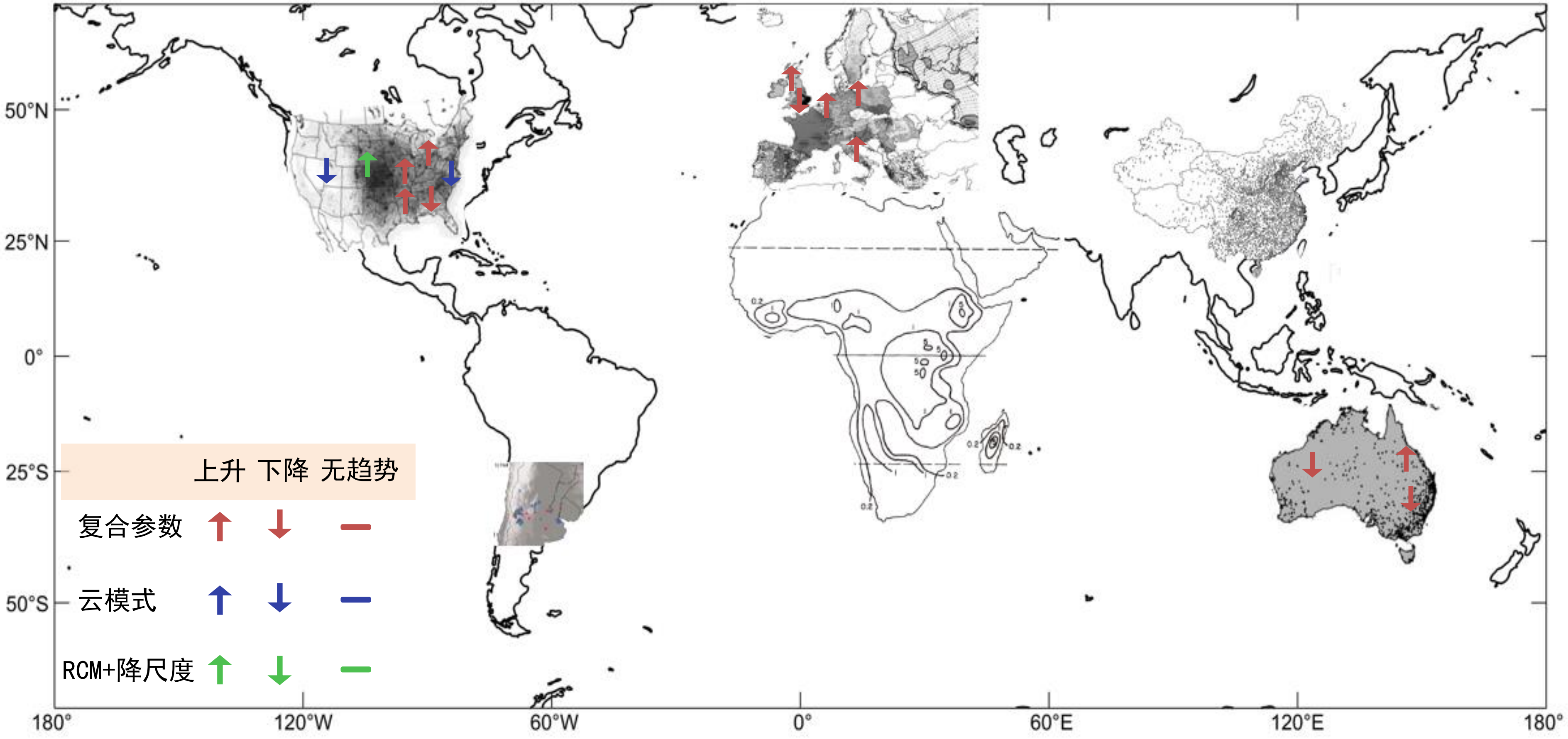
依赖于复合参数/云模式/中尺度模式

全球各地区过去冰雹频率趋势统计



（Allen and Tippett 2015、Rasmussen et al. 2014、Webb et al. 2009、Ćurić and Janc 2016、Vinet 2001、Kunz et al. 2009、Frisby and Sansom 1967、Li et al. 2018b、Allen et al. 2011、Mohr et al. 2015、Sanchez et al. 2017、Madonna et al. 2018、Schlie et al. 2019、Tuovinen et al. 2009、Barrett and Henley 2014、Martins et al. 2017、Prieto et al. 1999）

全球各地区未来冰雹频率趋势预测

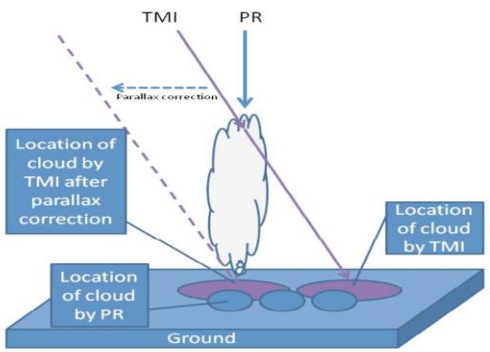


（Kapsch et al. 2012、Rädler et al. 2019、Sanderson et al. 2015 、Trapp et al. 2019、Gensini et al. 2014、Trapp et al. 2007、Brimelow et al. 2017、Allen et al. 2014）

Objective

2 mm +

19 mm
+



全球强冰雹风暴一致性数据集

定义：冰雹直径>19 mm

ERA5

AI聚类分析

气候态分析

分类强冰雹环境场

一维冰雹增长模式

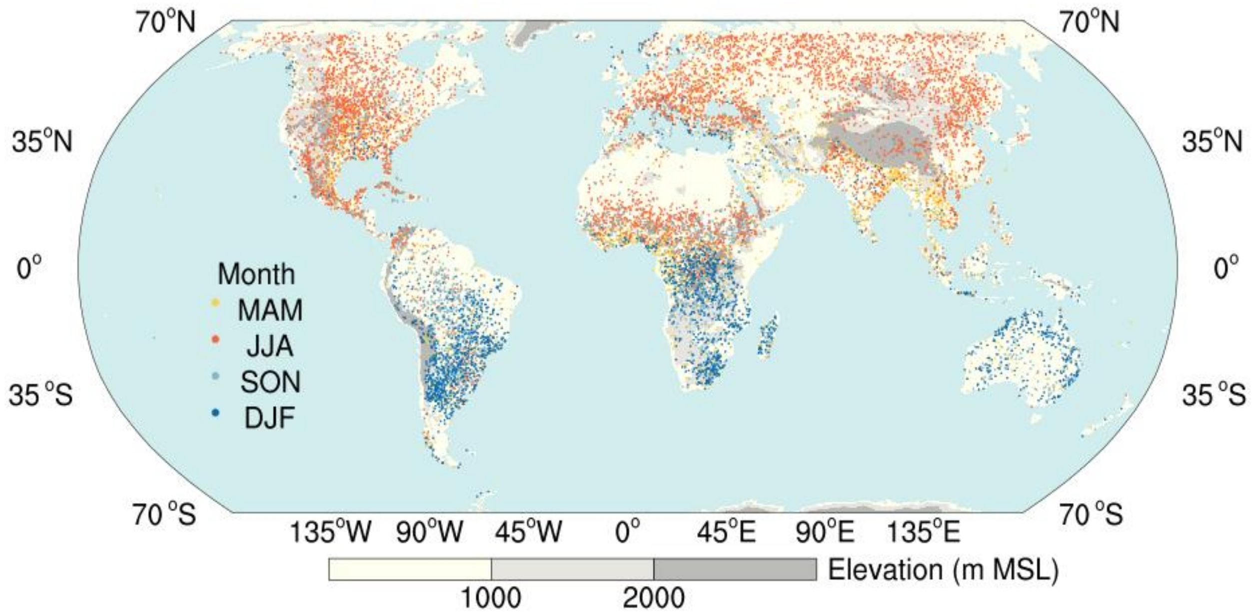
Critiariu

识别标准(Ni et al. 2017):

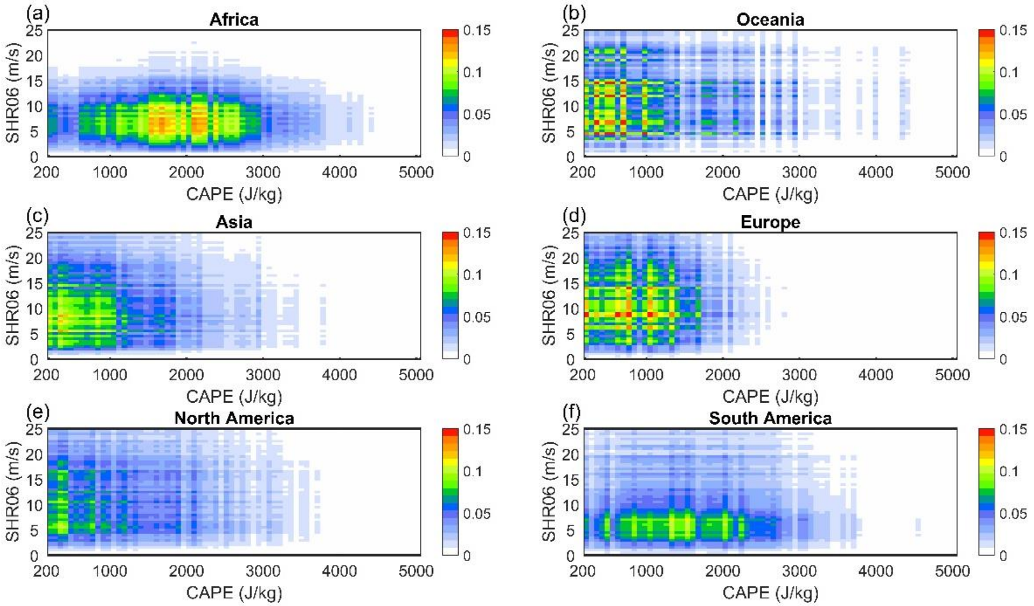
- **44 dBZ 雷达回波等值面顶温度<-22ºC**
- **地面温度>10ºC**

2014-2021 GPM	14,297	MUCAPE ⩾200 J/kg	12,412 (66ºS-66ºN)
1998-2013 TRMM	10,512		9,000 (36.5ºS-36.5ºN)

全球强冰雹事件空间分布&环境特征分析



2014-2021年 GPM卫星 12,412个强冰雹风暴



可能存在多种环境场类型能够有利于强冰雹风暴的发生

全球强冰雹风暴环境特征聚类

- 聚类方法及聚类数选择

特征	描述	单位
MUCAPE	Most-unstable convective available potential energy	J/ kg
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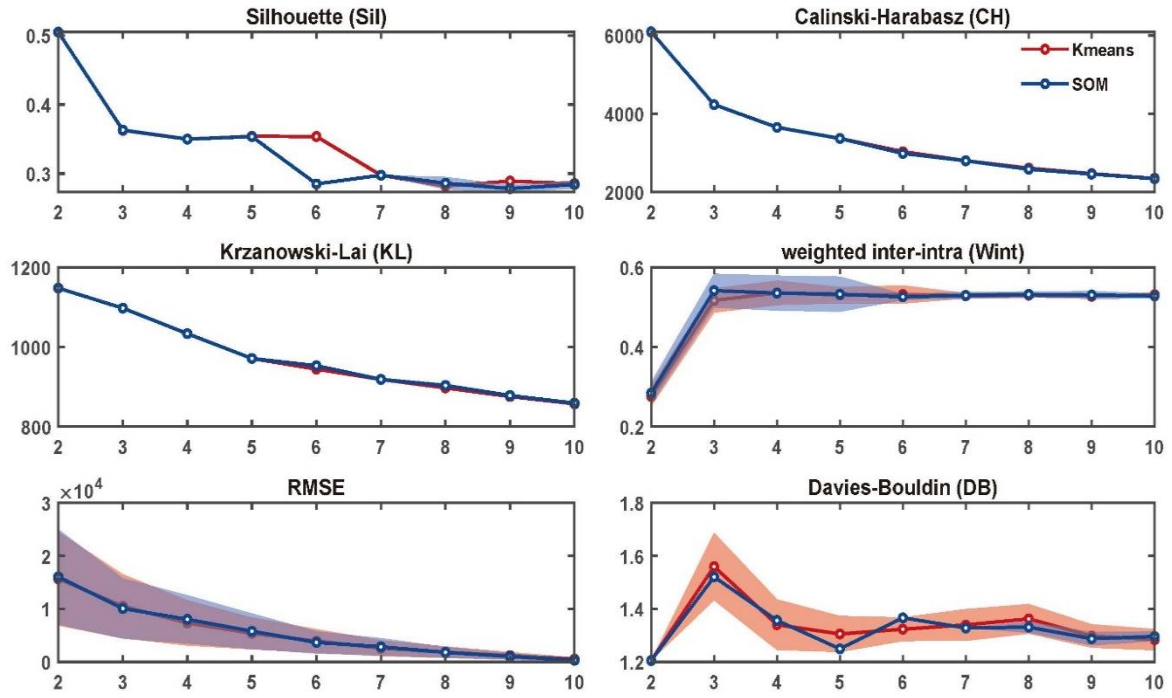
Hterrain	Terrain height	m



数　　据：ERA5再分析

聚类方法候选：SOMs和Kmeans ++

聚　类　数：2类到10类进行聚类遍历

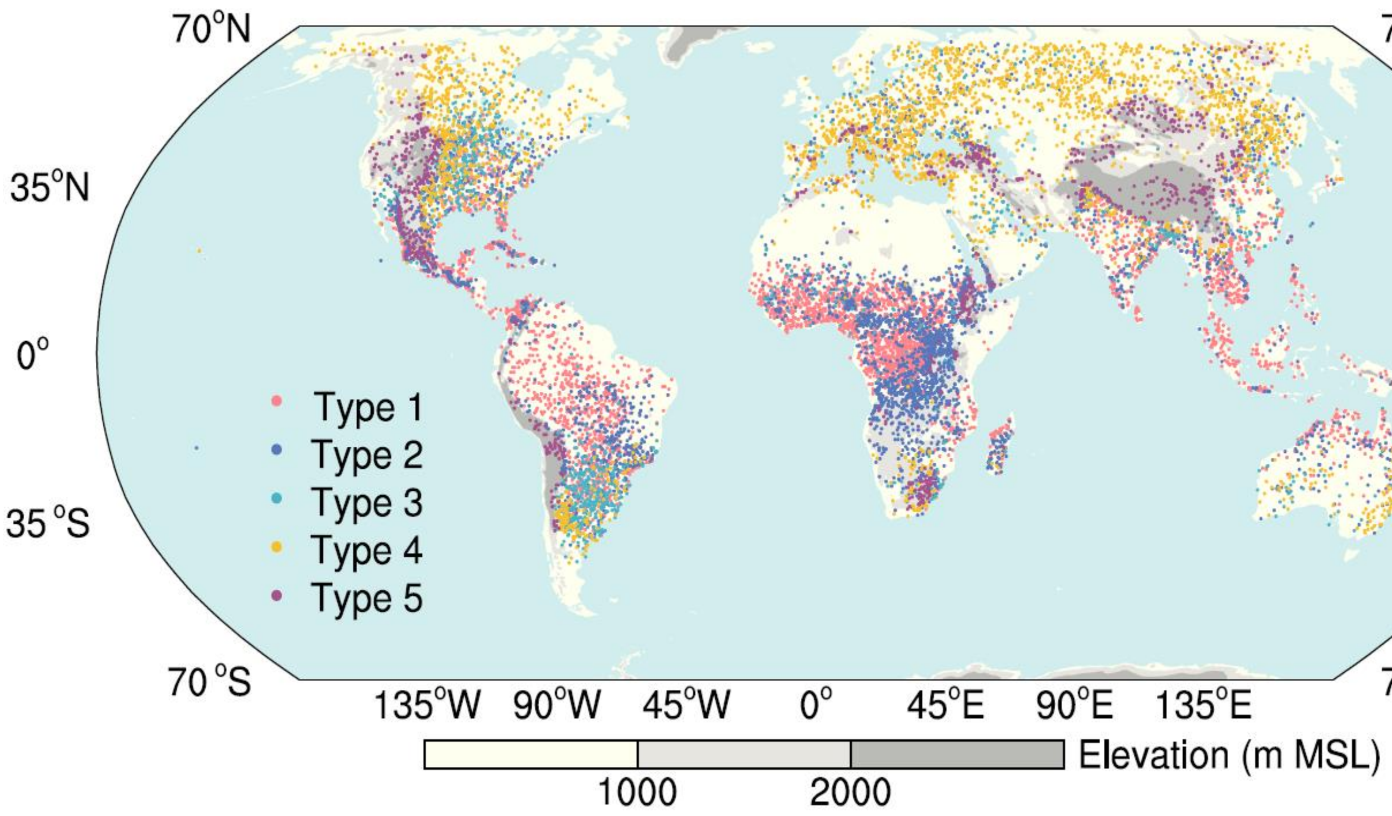
将聚类实验重复500次

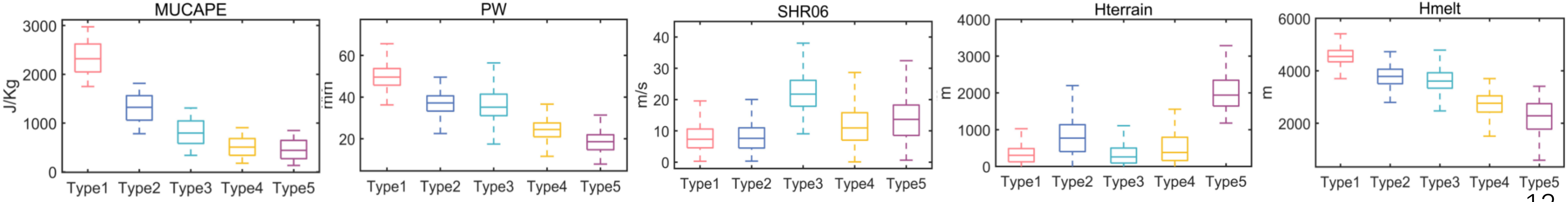
衡 量 指 标： 6种内部性能度量指标

→ 分五类聚类效果最好，实现类内距离与类间距离的平衡

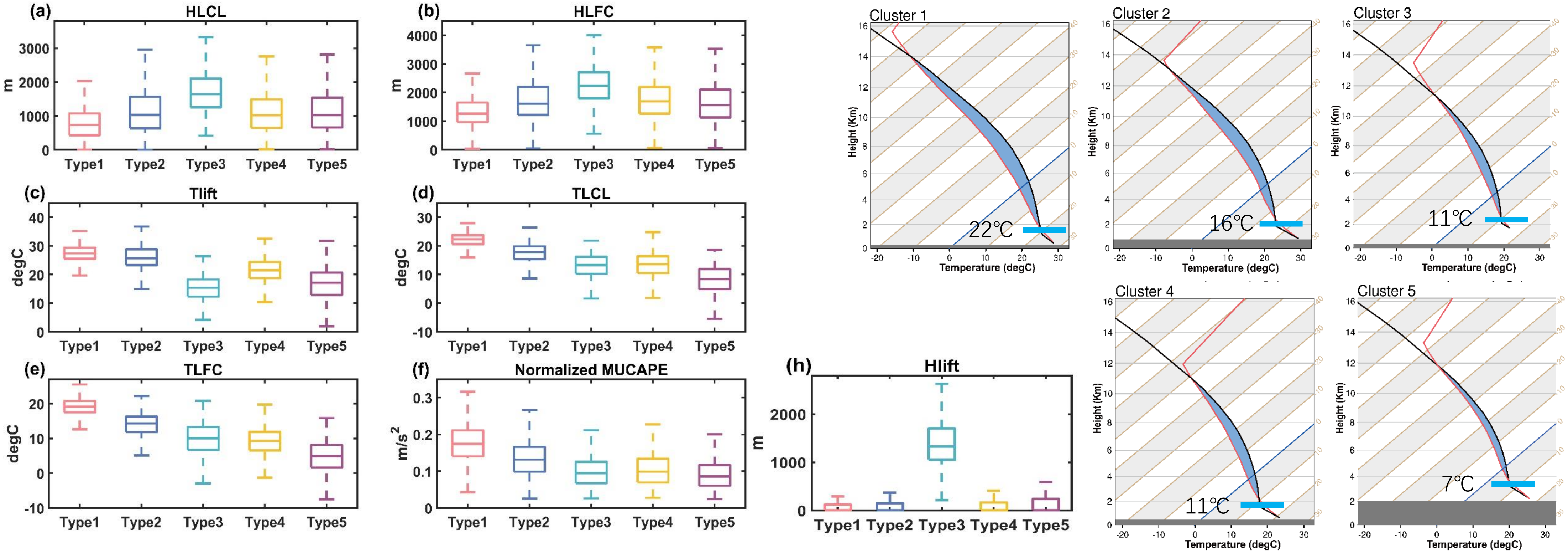
SOMs相比Kmeans++的聚类结果更加稳定

五类强冰雹环境场全球分布及环参特征





五类强冰雹环境场探空特征

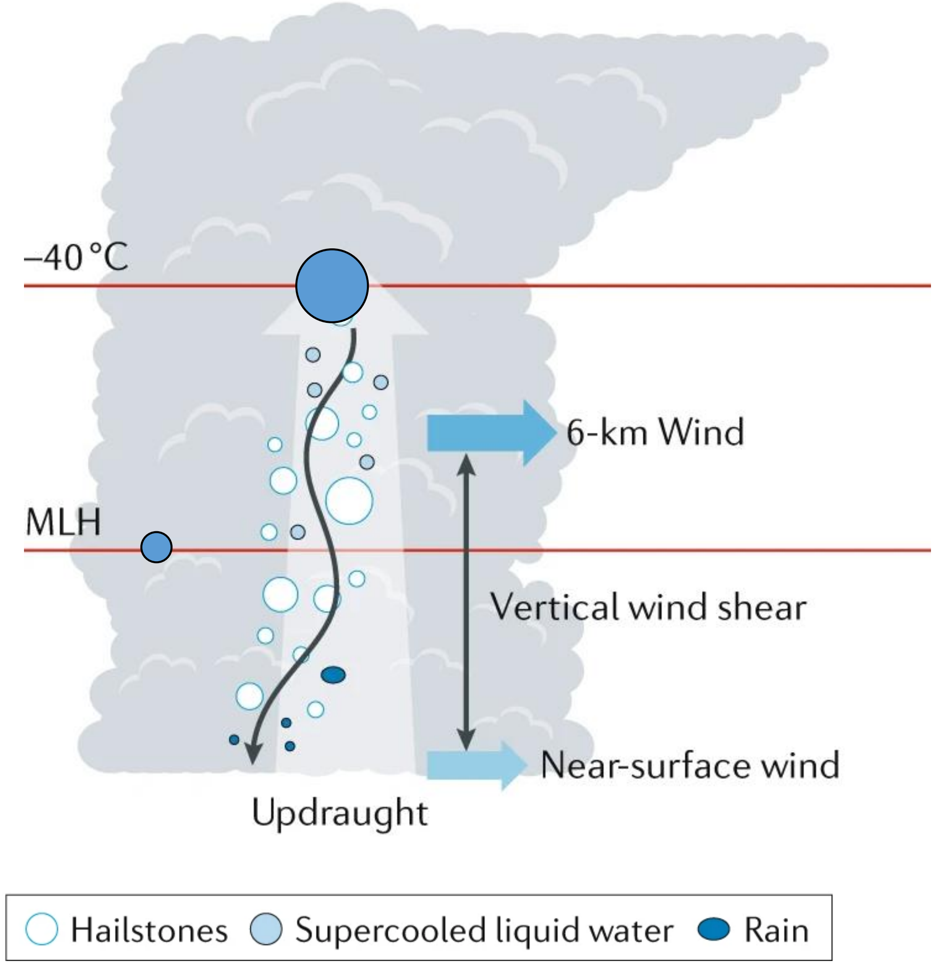


垂直加速度： type 1 and 2雹云中上升气流发展潜势要大于其他 Normalized MUCAPE= $\frac{\text{MUCAPE}}{\text{HEL}-\text{HLFC}}$

对流起始高度： type 1, 2, 4 and 5为120m AGL ; type 3为1400m AGL 更可能是高架对流

雹胚类型： type 1, 2, 3, and 4雹胚更有可能是冻滴型; type 5雹胚更可能是霰粒型

Hailstone growing model



From Raupach et al., 2021

Hailstone Moving Equation

$$\frac{dx}{dt} = u(x,y,t) \qquad \frac{dy}{dt} = v(x,y,z)$$

$$\frac{dh}{dt} = W_{wind}(x,y,h) - W_{hail}(r)$$

$$W_{hail} = \frac{\mathrm{Re}\ \nu}{D_h} \quad \mathrm{Re} = \begin{cases} 0.106X^{0.693} & X < 6.77\times10^4 \\ 0.55X^{0.545} & X > 6.77\times10^4 \end{cases}$$

Hailstone Growing Equation

$$\frac{dr}{dt} = \frac{|\Delta W| q_w (E_{cc}(1-P_{ci}) + E_{ci}P_{ci})}{4\rho_h}$$

$$P_{ci} = 0.008(1.274)^{T'}$$

$$E_{ci} = 0.8 \cdot (T(h) - T_0)/(T_1 - T_0)$$

$$\Delta W = \sqrt{(u^2 + v^2 + (w_h - w_c)^2)}$$

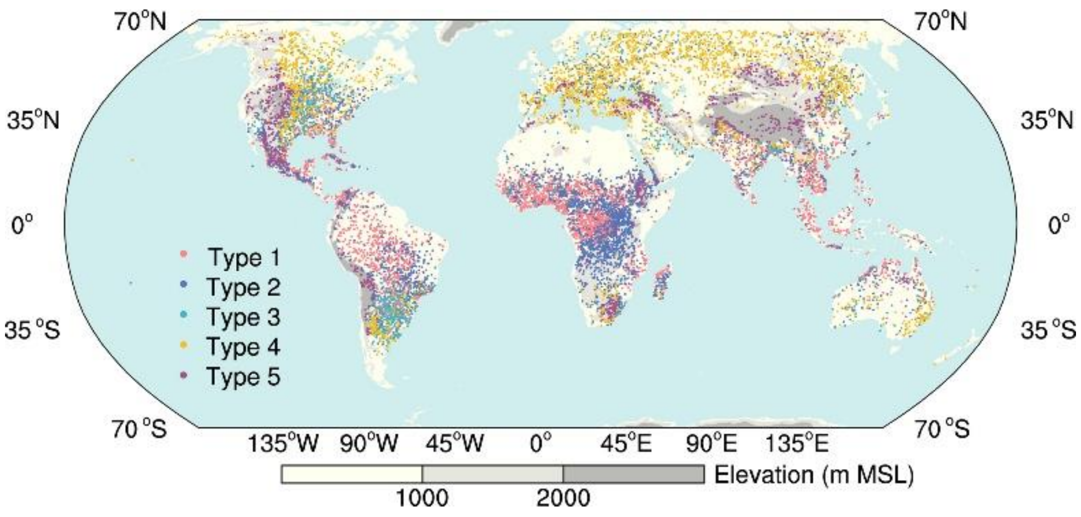
Relative velocity

Hailstone Melting Equation

$$\frac{dR}{dt} = \frac{-1}{\rho_h L_f R}[f_h k_a (T(h) - T_r) + f_v L_v D_v \Delta\rho_w] - \frac{c_w (T(h) - T_r)}{L_f}\frac{dr}{dt}$$

$$\frac{dR}{dt} = \frac{-R_0}{\rho_h L_f R^2}[f_h k_a (T(h) - T_r) + f_v L_v D_v \Delta\rho_w]$$

Five Types of severe hailstorm environments



Environmental parameters

MUCAPE ⟷ Thermodynamic condition

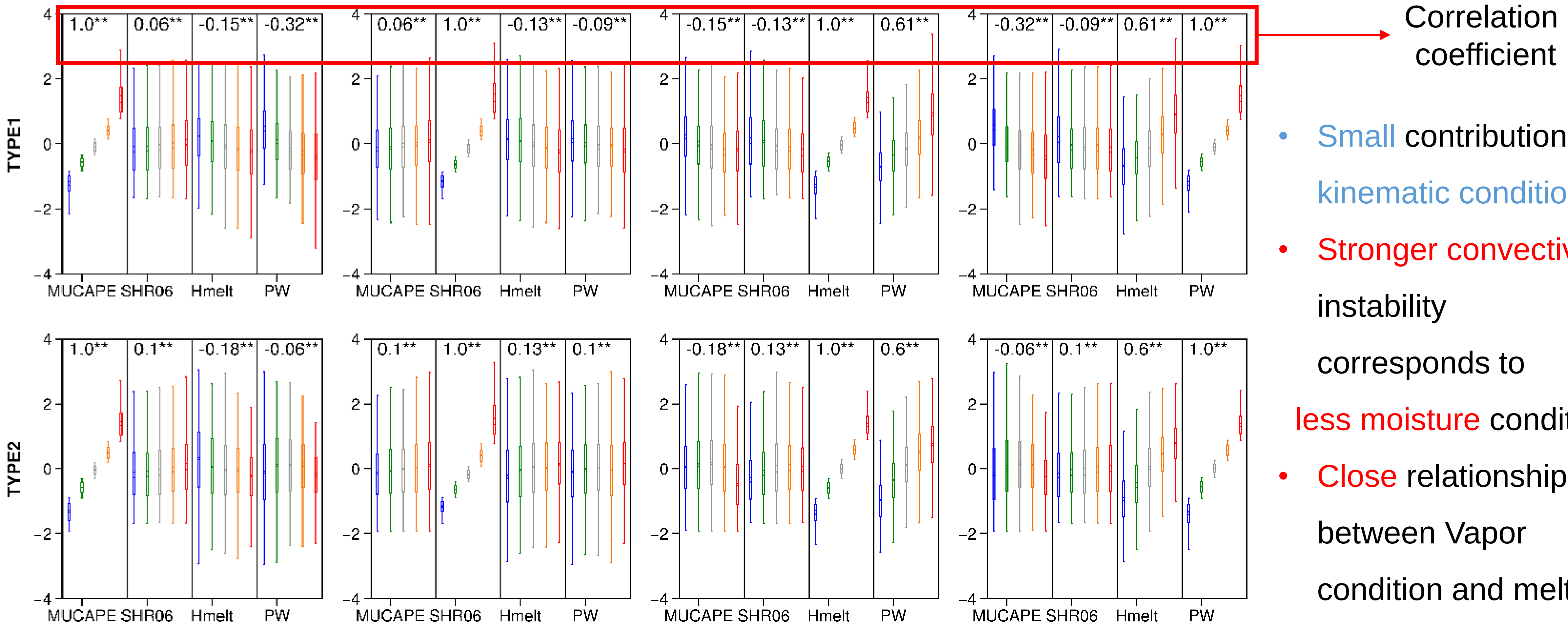
SHR06 ⟷ Kinematic condition

MLH ⟷ Melting condition

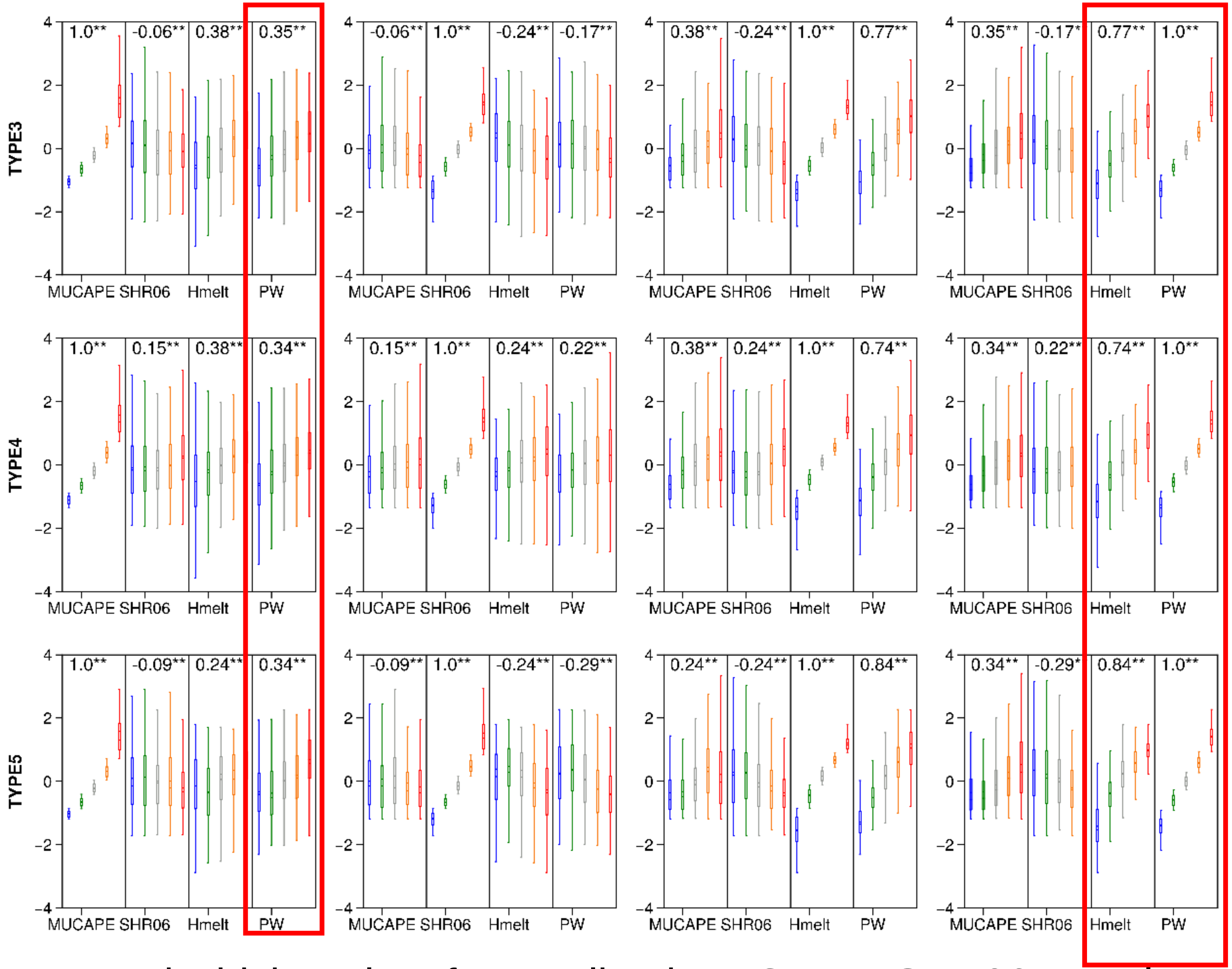
PW ⟷ Moisture condition

MUCAPE: Most Unstable Convective available potential energy
SHR06: 0-6km wind shear
MLH: Melting Level Height (above surface)
PW: Precipitation Water

Box and whisker plot of normalized MUCAPE, SHR06, Hmelt and PW



- Small contribution of kinematic condition
- Stronger convective instability corresponds to less moisture condition
- Close relationship between Vapor condition and melting condition



Box and whisker plot of normalized MUCAPE, SHR06, Hmelt and PW for the third, forth and fifth type hailstorm environments

- Huge contribution of kinematic condition
- Stronger convective instability corresponding to more moisture condition
- Increasingly strengthening relationship between Vapor condition and melting condition from type 1 to type 5

Simulated trajectories of hailstones in different type hailstorm environment

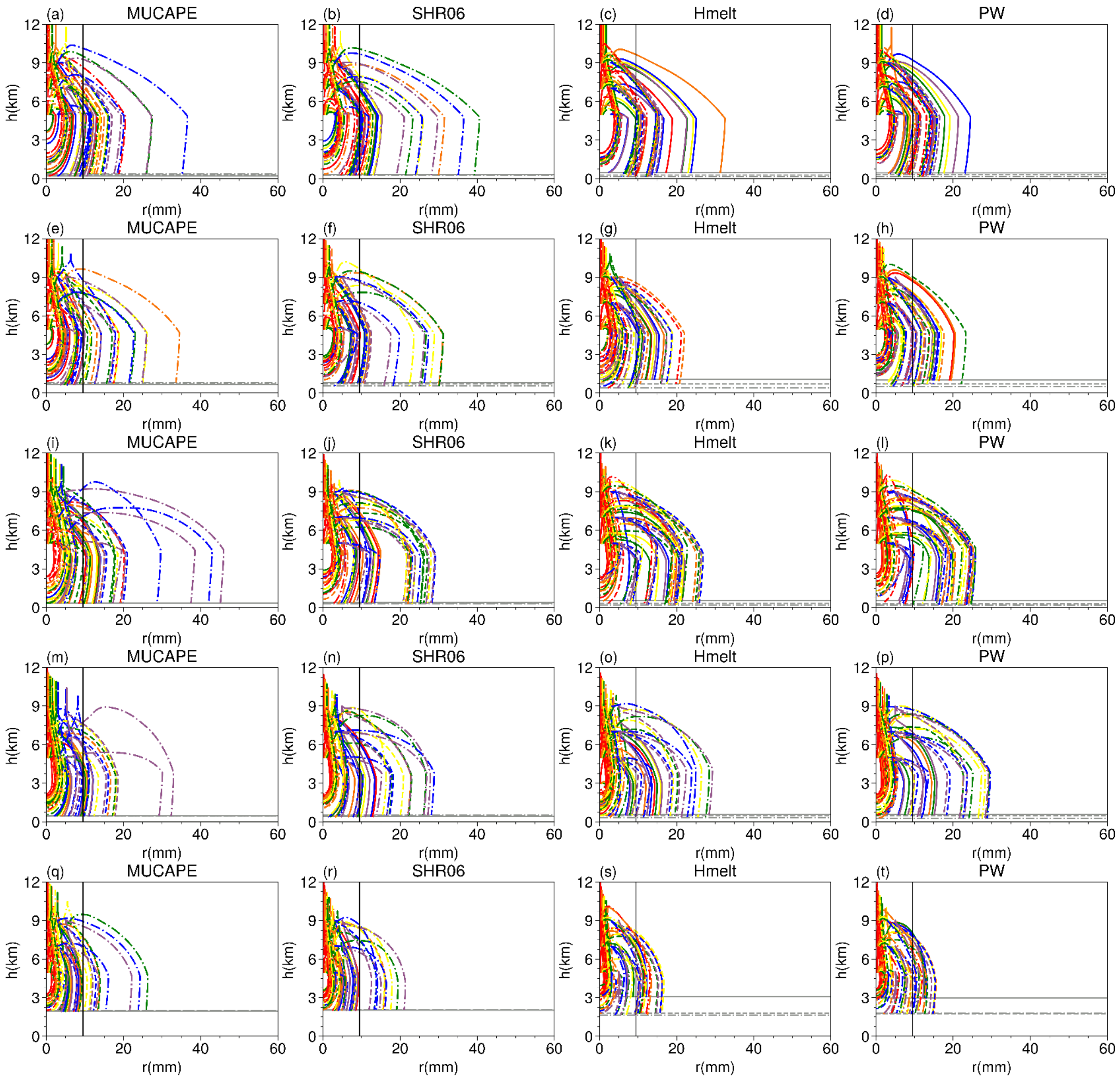
Type1

Type2

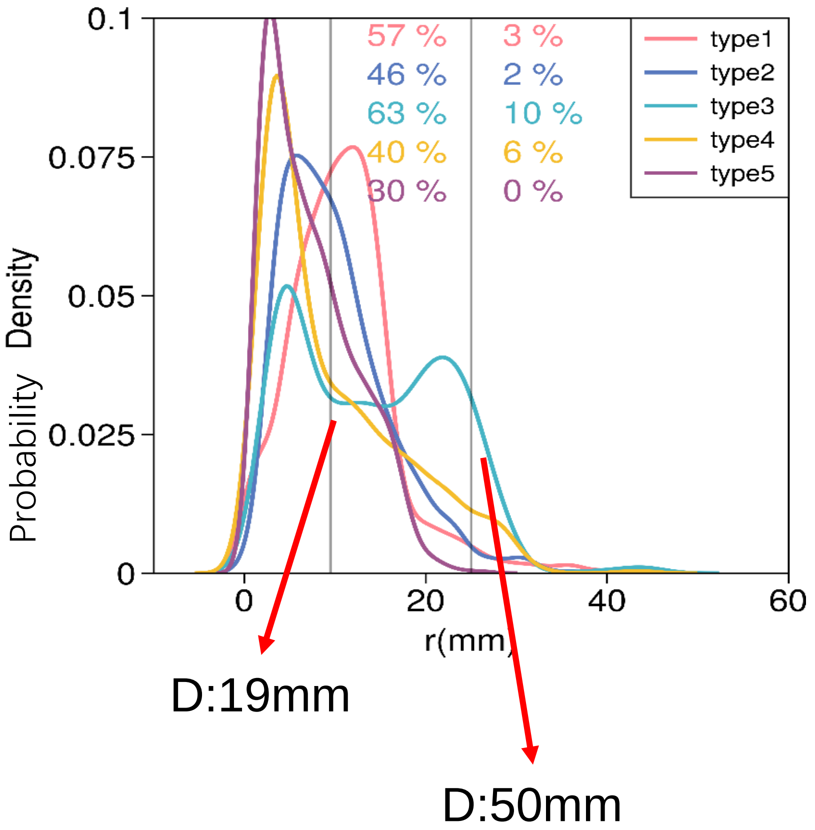
Type3

Type4

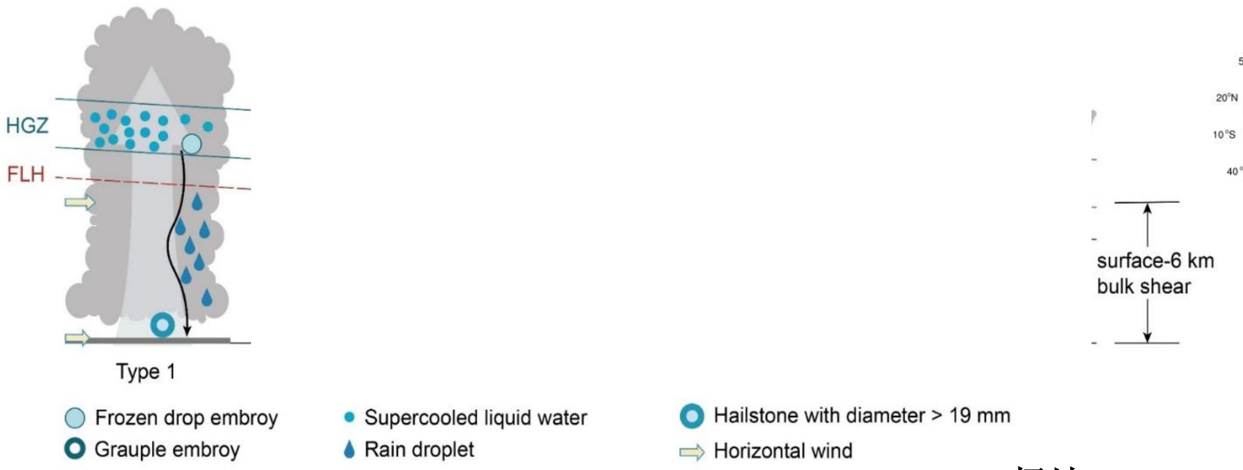
Type5



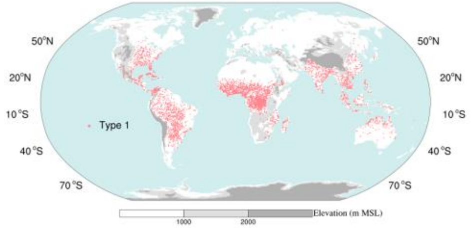
Spectral distribution of simulated hailstone size



Summary



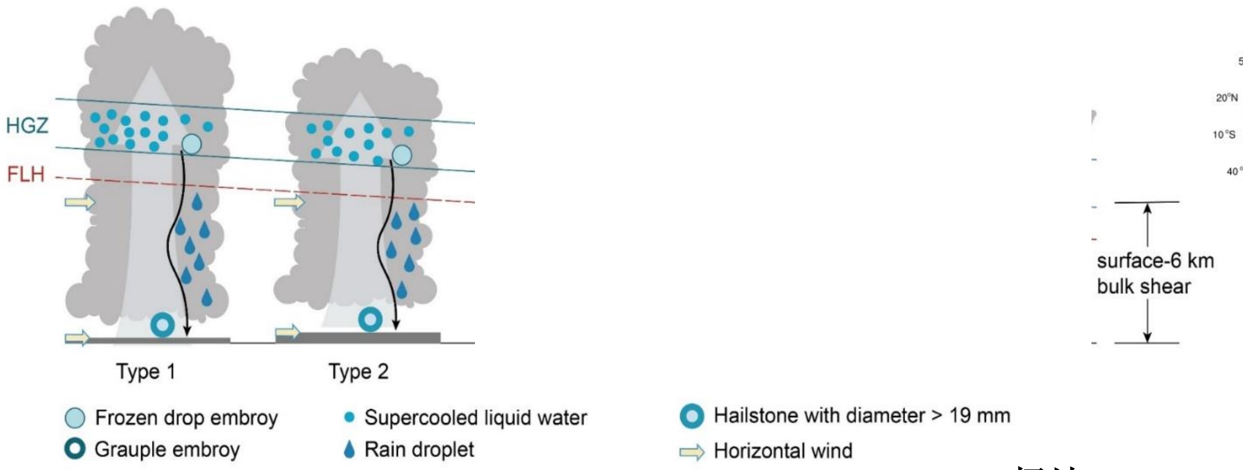
Type 1



赤道 极地

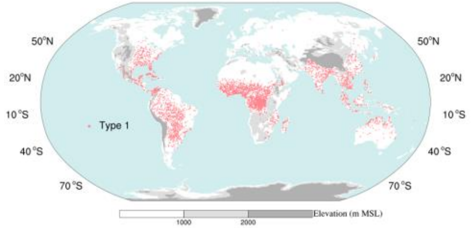
类别	高发区	MUCAPE	PW	SHR06	Hmelt	对流组织形式	雹胚
Type 1	热带平原	高	高	低	高	单体	冻滴

Summary

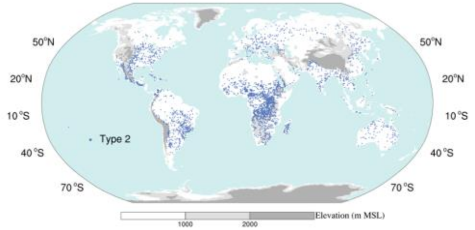


赤道 极地

Type 1

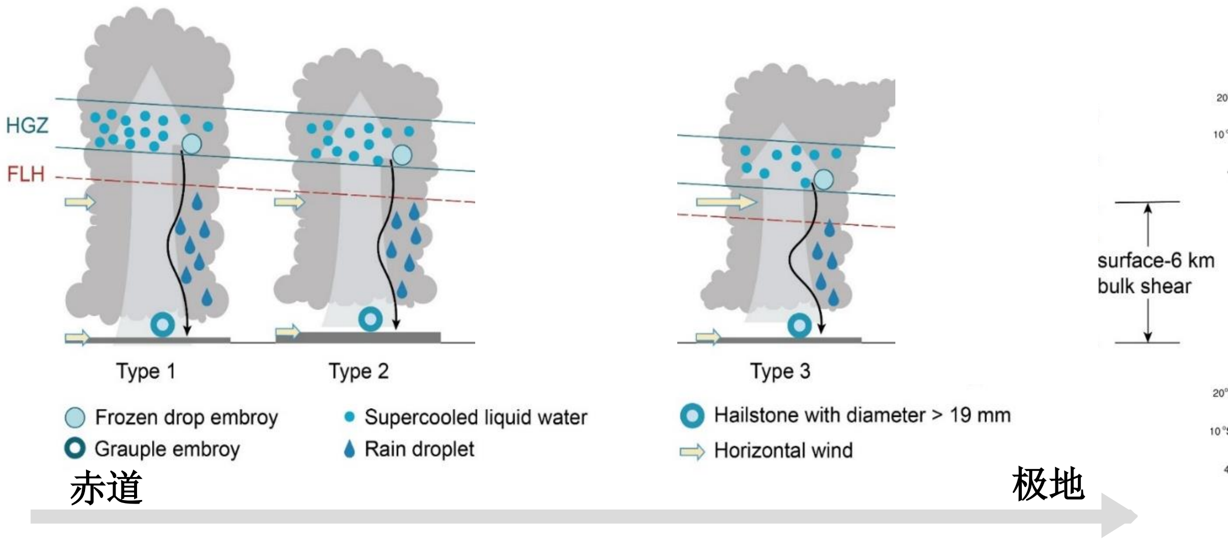


Type 2

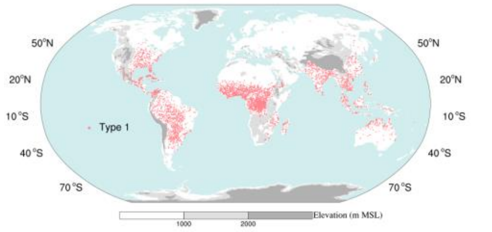


类别	高发区	MUCAPE	PW	SHR06	Hmelt	对流组织形式	雹胚
Type 1	热带平原	高	高	低	高	单体	冻滴
Type 2	热带丘陵	高	中	低	中	单体	冻滴

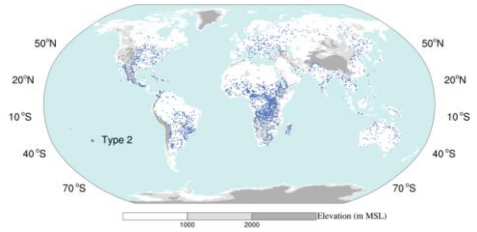
Summary



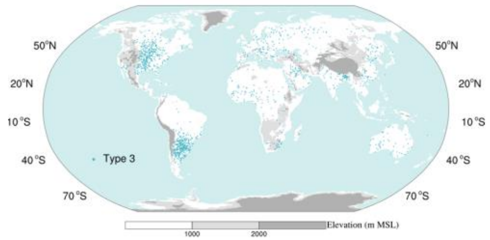
Type 1



Type 2

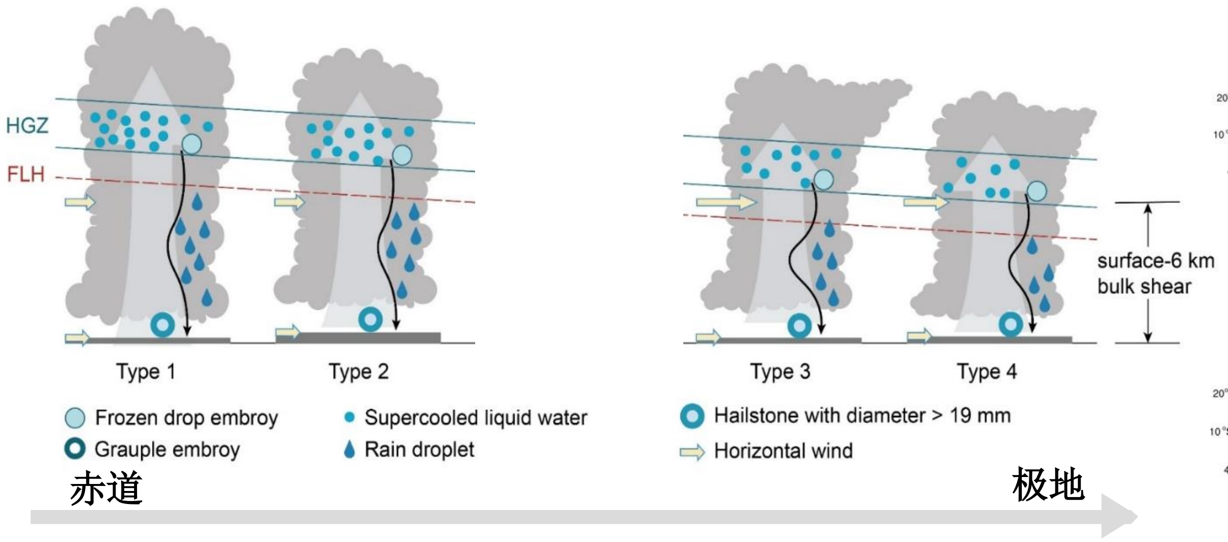


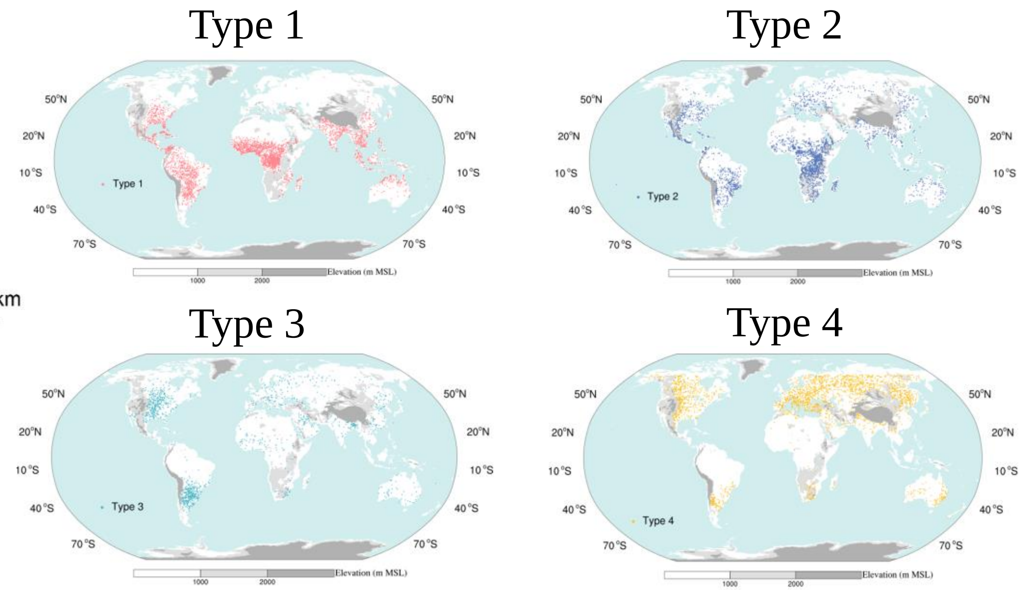
Type 3



类别	高发区	MUCAPE	PW	SHR06	Hmelt	对流组织形式	雹胚
Type 1	热带平原	高	高	低	高	单体	冻滴
Type 2	热带丘陵	高	中	低	中	单体	冻滴
Type 3	中纬度平原	中	中	高	中	超级单体	冻滴

Summary





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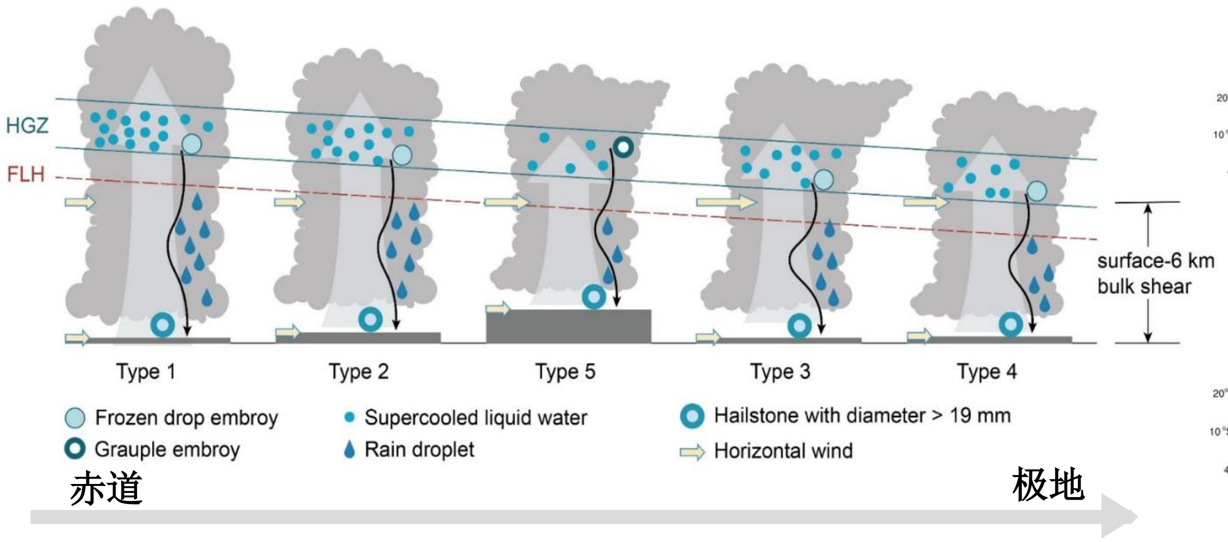
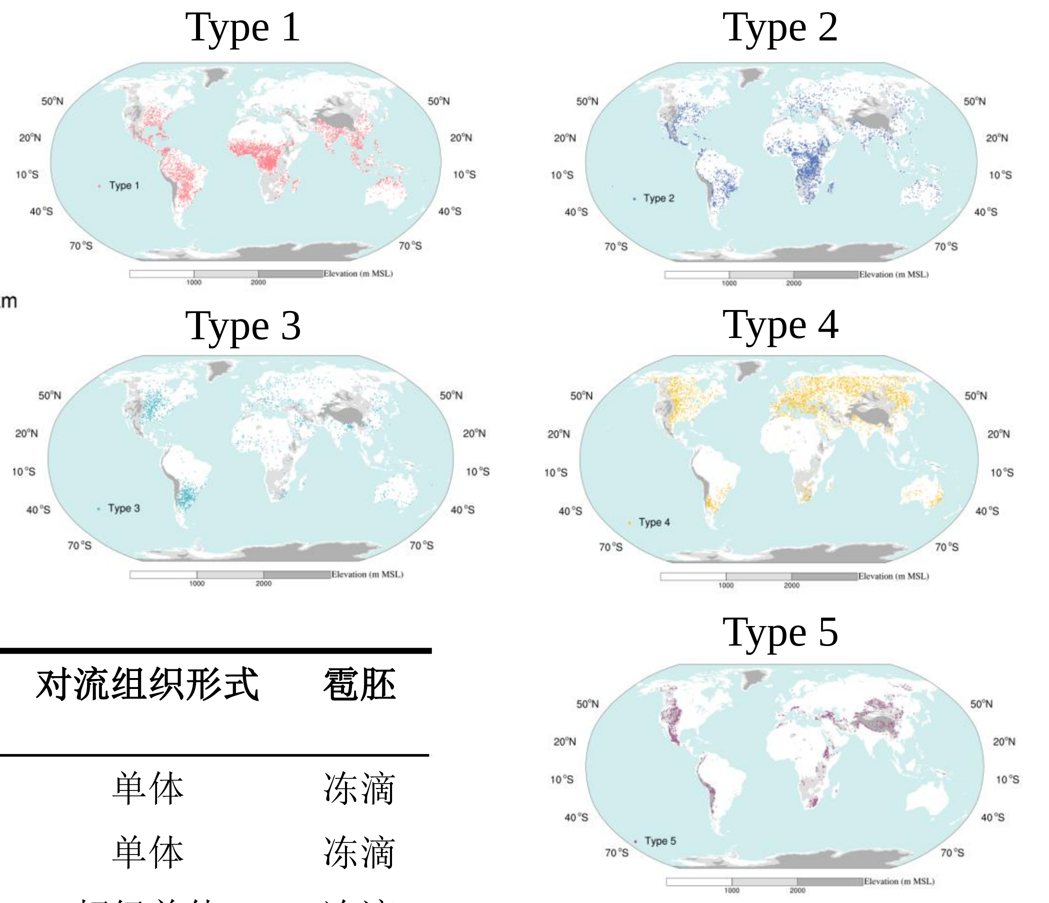
Type 1	热带平原	高	高	低	高	单体	冻滴
Type 2	热带丘陵	高	中	低	中	单体	冻滴
Type 3	中纬度平原	中	中	高	中	超级单体	冻滴
Type 4	高纬度平原	低	低	中	低	多单体	冻滴

Summary





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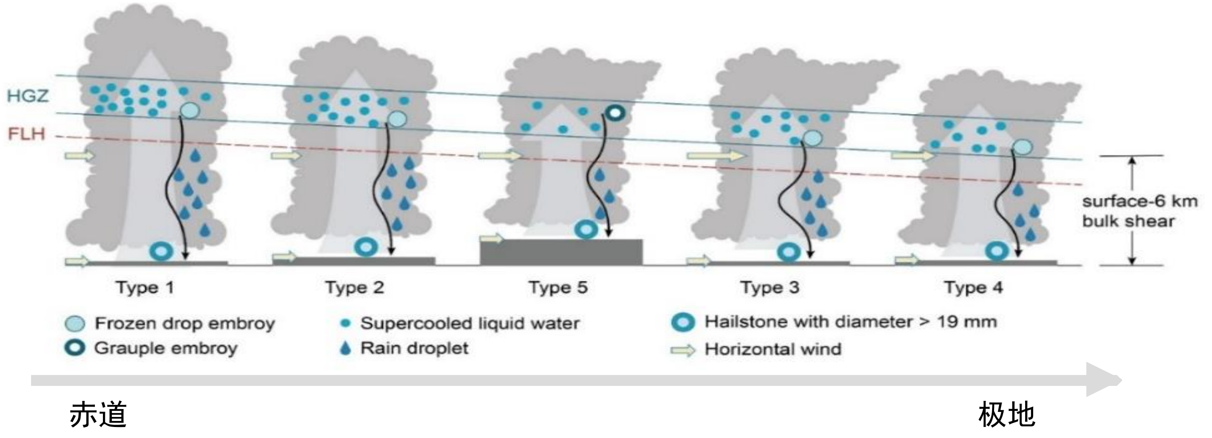
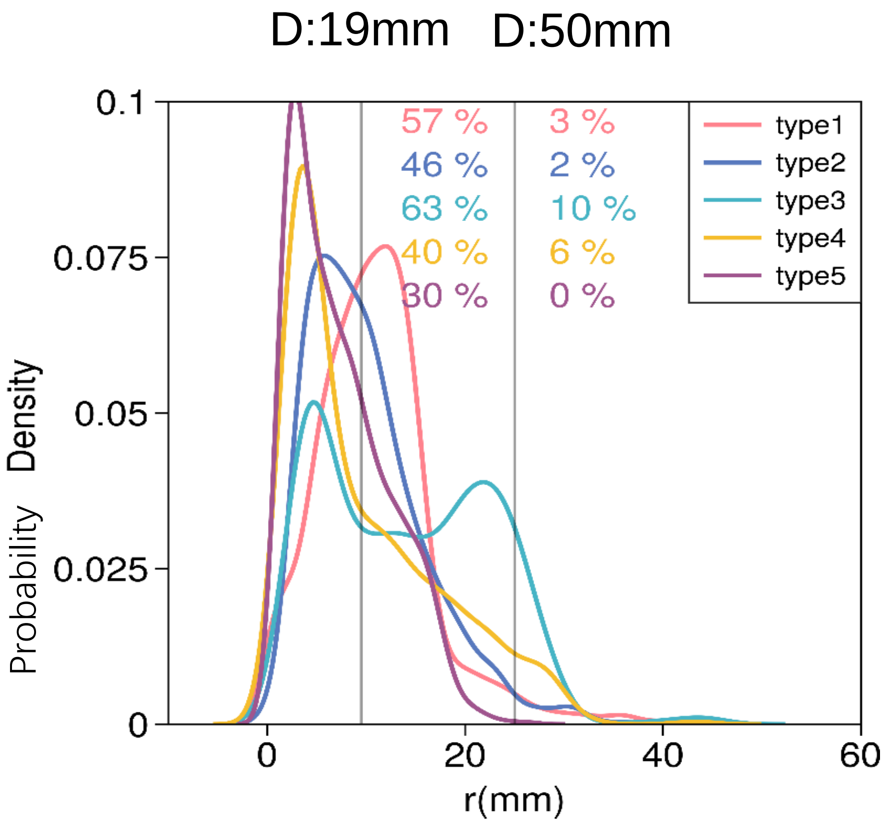
Type 2	热带丘陵	高	中	低	中	单体	冻滴
Type 3	中纬度平原	中	中	高	中	超级单体	冻滴
Type 4	高纬度平原	低	低	中	低	多单体	冻滴
Type 5	山脉、高原	低	低	中	低	多单体	霰粒

Summary





地球上存在五种强冰雹风暴环境场，在动力、热力以及融化条件之间形成平衡，具有不同的高发区、对流组织形式、雹胚种类与探空特征。

Thanks for your Attention

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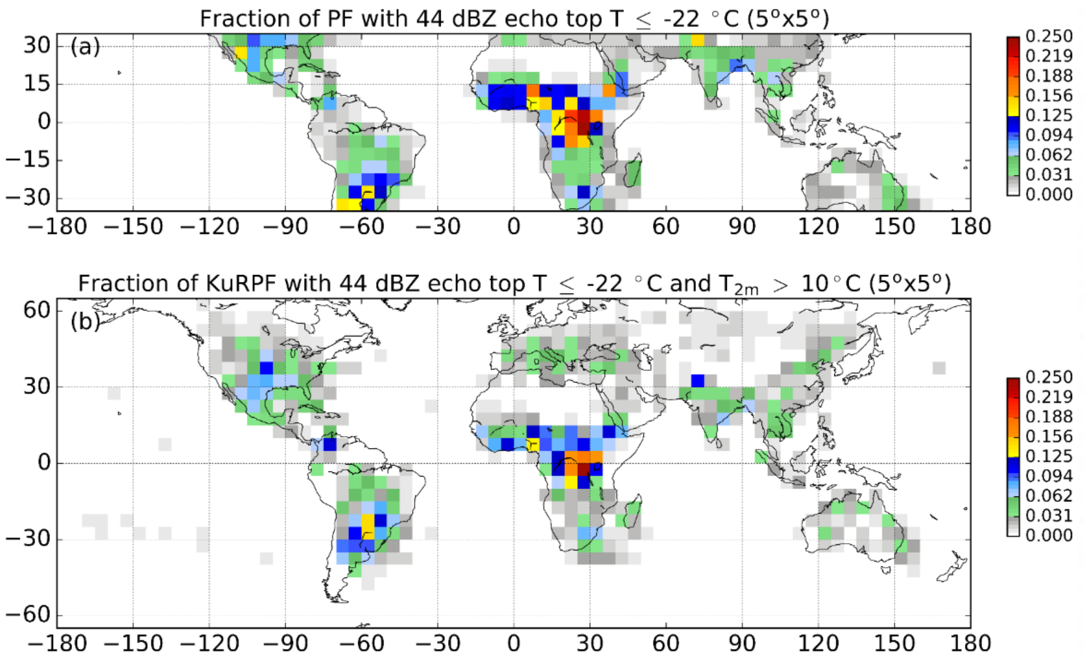


Ni et al. (2017, JAMC)

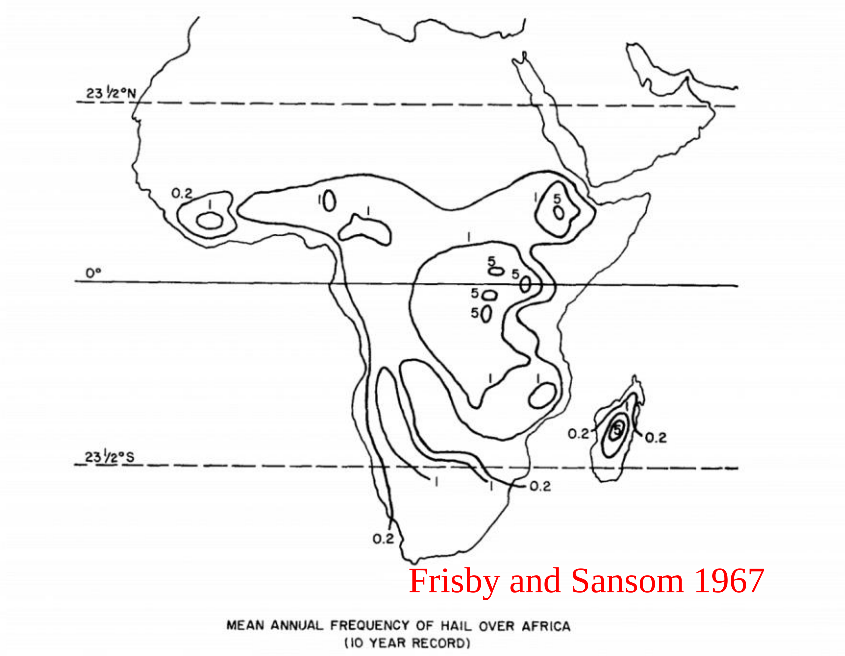
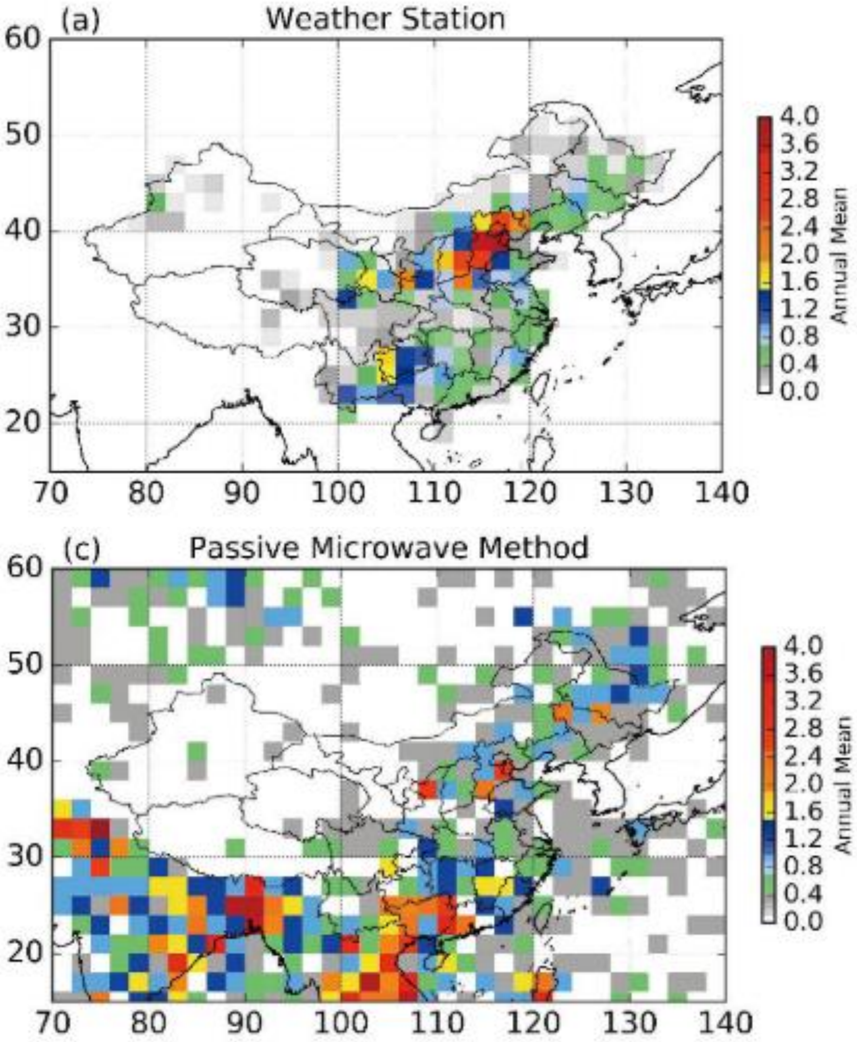
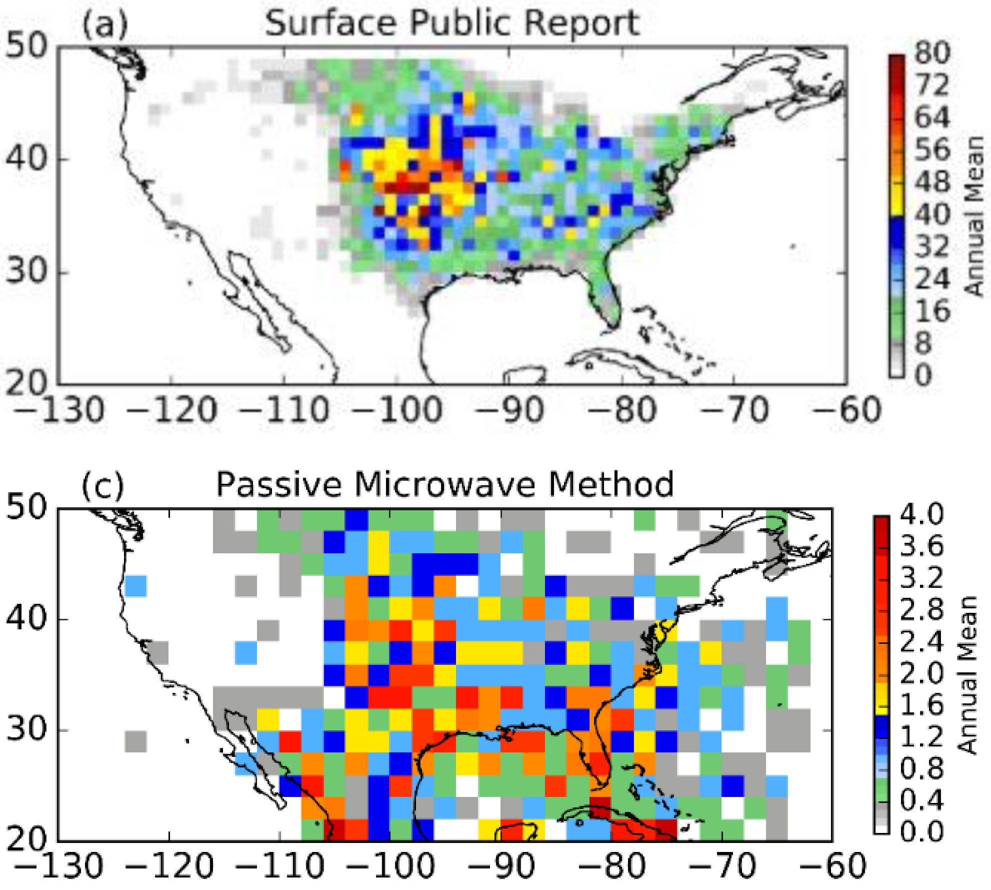
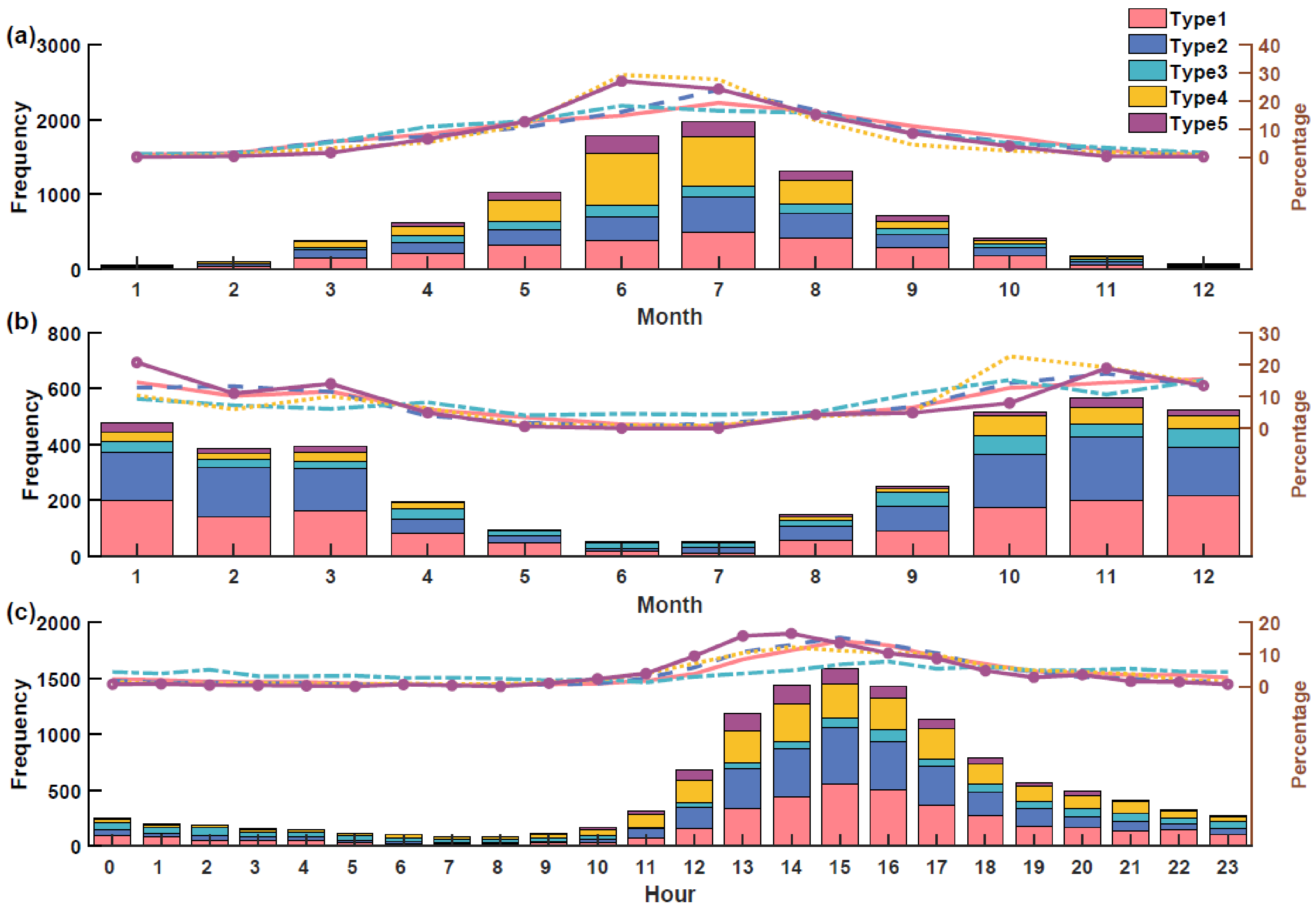


Fig. 2a. Hailstorm distribution for Africa.

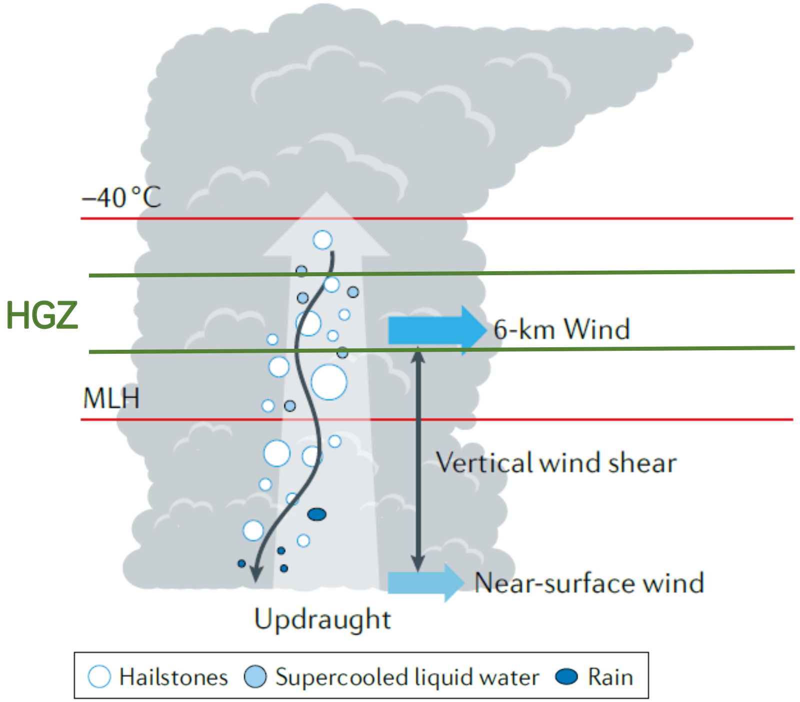

(a) Weather Station
(c) Passive Microwave Method
Annual Mean
4.0 3.6 3.2 2.8 2.4 2.0 1.6 1.2 0.8 0.4 0.0
60 50 40 30 20
70 80 90 100 110 120 130 140


(a) Surface Public Report
Annual Mean
80 72 64 56 48 40 32 24 16 8 0
(c) Passive Microwave Method
4.0 3.6 3.2 2.8 2.4 2.0 1.6 1.2 0.8 0.4 0.0
50 40 30 20
−130 −120 −110 −100 −90 −80 −70 −60


(a)
(b)
(c)
Frequency
Percentage
Month
Hour
Type1
Type2
Type3
Type4
Type5

1. 研究背景

- 影响冰雹风暴的环境因素



✓ CAPE：对流发展潜势、最大上升速度

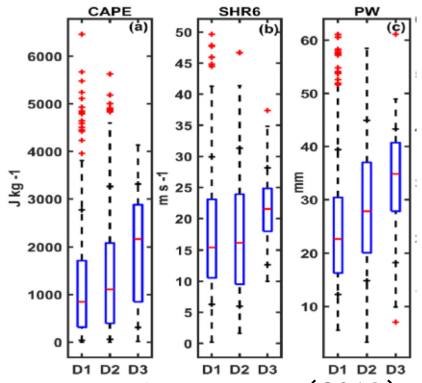
✓ 水汽：直径越大的冰雹出现时PW越高

✓ SHR：　影响对流组织形式和生命周期

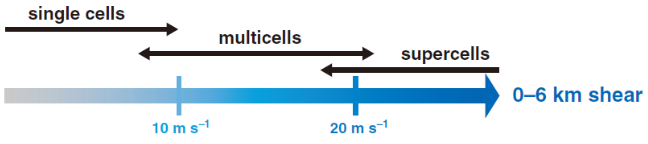
　　　　改变上升气流的宽度

✓ 云底温度：冻滴型与霰粒型雹胚

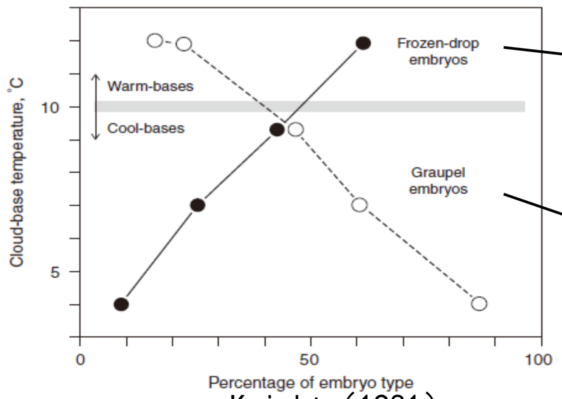
✓ 融化过程：受多个子因素的影响，包括融化层厚度、平均温度与湿度、冰雹的直径

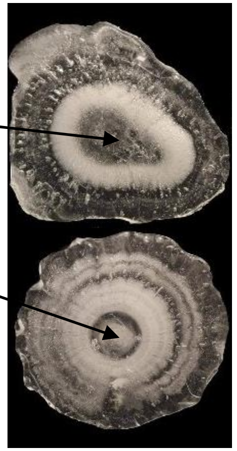


Li et al. (2018)



Markowski and Richardson (2010)





Knight (1981)

2. 资料方法

■ ERA5

0.25º×0.25º

36个环境参数

热动力、动力、融化、基本属性

特征	描述	单位
MUCAPE	Most-unstable convective available potential energy	J/ kg
MUCIN	Most-unstable convective inhibition	J/ kg
PW	Precipitable water	mm
SHR06	0-6km bulk shear	m/ s
Hlift	Height of lifting parcel with MUCAPE	m AGL
HGZ	Height interval between -30℃ and -10℃	m above ground level （AGL）
Hmelt	Height interval between FLH and terrain height	m AGL
Hterrain	Terrain height	m
TLCL	Temperature of Lifting Condensation Level （LCL）	℃
TLFC	Temperature of Level of Free Convection （LFC）	℃
TEL	Temperature of Equilibration Level	℃
T500	500hPa temperature	℃
HLCL	Height of LCL	m AGL
HLFC	Height of LFC	m AGL
HEL	Height of Equilibration Level	m AGL
L700500	700hPa-500hPa lapse rate	℃/ km
Normalized MUCAPE	MUCAPE divided by the depth of the layer where CAPE is present	m/ s²
CAPE_FLH	H_lift-FLH MUCAPE	J/ kg
CAPE_3km	H_lift-3km MUCAPE	J/ kg
CAPE_6km	H_lift-6km MUCAPE	J/ kg
SBCAPE	Surface-based convective available potential energy	J/kg
SBCIN	Surface-based convective inhibition	J/kg
PRECIP RATE	Precipitation Rate	mm/h
EBWD	Effective bulk wind difference	m/s
Tlift	Temperature of lifting parcel with MUCAPE	℃
Plift	Pressure of lifting parcel with MUCAPE	hPa
Year	-	-
Month	-	-
Day	-	-
Hour	-	-
Lon	Longitude	-
Lat	Latitude	-

■ 聚类与分类算法

SOMs

Kmeans ++

随机森林模型

■ 地面观测数据集

1998-2013 CMA地面站冰雹观测资料

2019 NOAA 冰雹公众报告

■ 分类模型度量指标

$$R^2 = \frac{\sum_i (\hat{y}_i - \bar{y})^2}{\sum_i (y_i - \bar{y})^2} = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}$$

$$MAE = \frac{1}{m}\sum_{i=1}^{m} |y_i - \hat{y}_i|$$

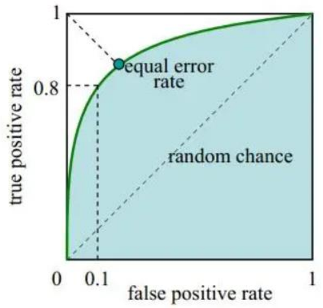
$$ACC = \frac{TP + TN}{TP + TN + FP + FN}$$

$$POD = \frac{TP}{TP + FN}$$

$$FAR = \frac{FP}{FP + TN}$$

		实际情况	
		P	N
预测情况	T	TP	TN
	F	FN	FP

AUC



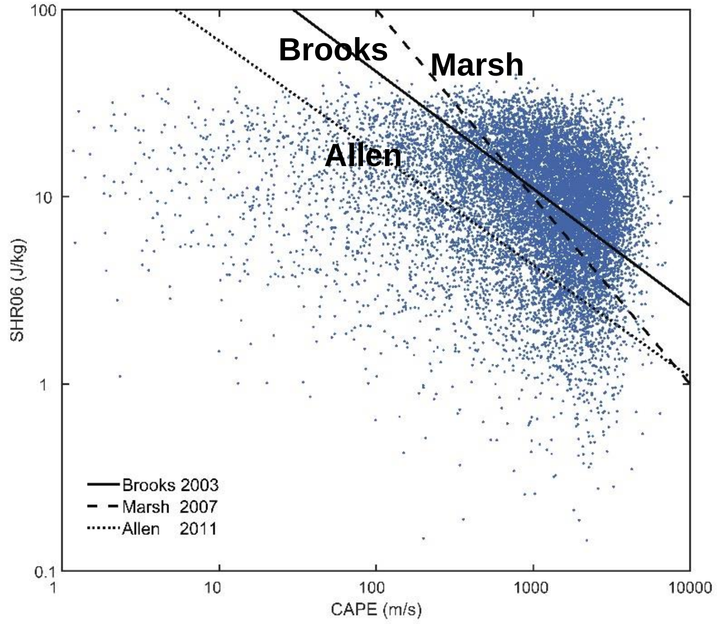
3. 全球强冰雹事件环境特征分析

• 复合参数：特别强对流风暴判别式

环境条件判别式预报特别强对流风暴

定义：直径为50mm以上的冰雹、阵风风速达120km/h或F2级及以上的龙卷风

判别式	POD	FAR	来源
$CAPE \times SHR06^{1.6} \geq 46800$	0.430	0.059	Brooks et al. 2003
$CAPE \times SHR06 \geq 10000$	0.503	0.080	Marsh et al. 2007
$CAPE \times SHR06^{1.67} \geq 11500$	0.768	0.184	Allen et al. 2011



✓ CAPE和SHR06不能完整描述强冰雹风暴环境场的动力与热力特征

✓ 将考虑更多环境参数，对强冰雹风暴的环境场特征进行针对性分析