基金委重大研究计划：青藏高原地-气耦合系统变化及其全球气候效应

集成项目：青藏高原云降水物理及其对能量收支和水分循环的影响

喜马拉雅山脉南坡云降水特征研究

傅云飞

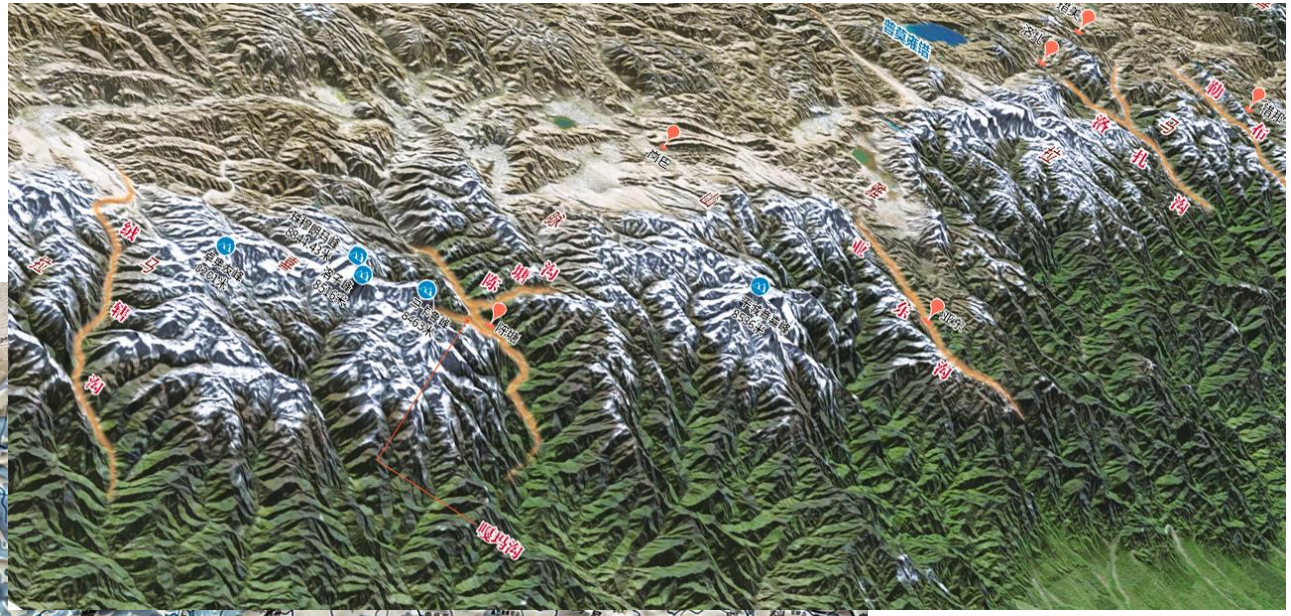
中国科学技术大学 地学院

fyf@ustc.edu.cn

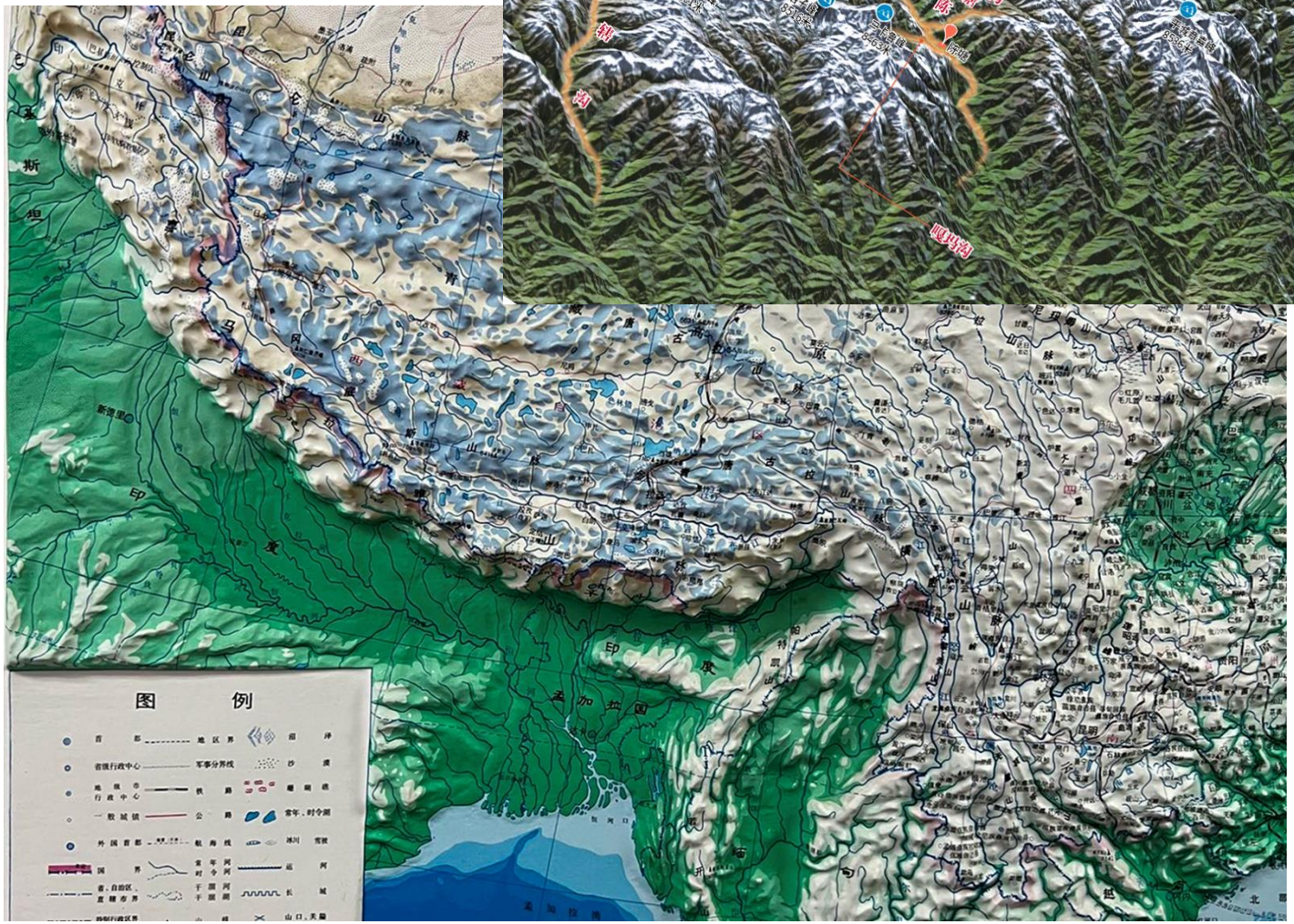
南京大学，2022-5-24

青藏高原地形

（3000~5000m，平均4000m）



喜马拉雅山脉地形



地形—降水

北纬26~39°N、东经73~104°E，总面积约250万平方千米









Background

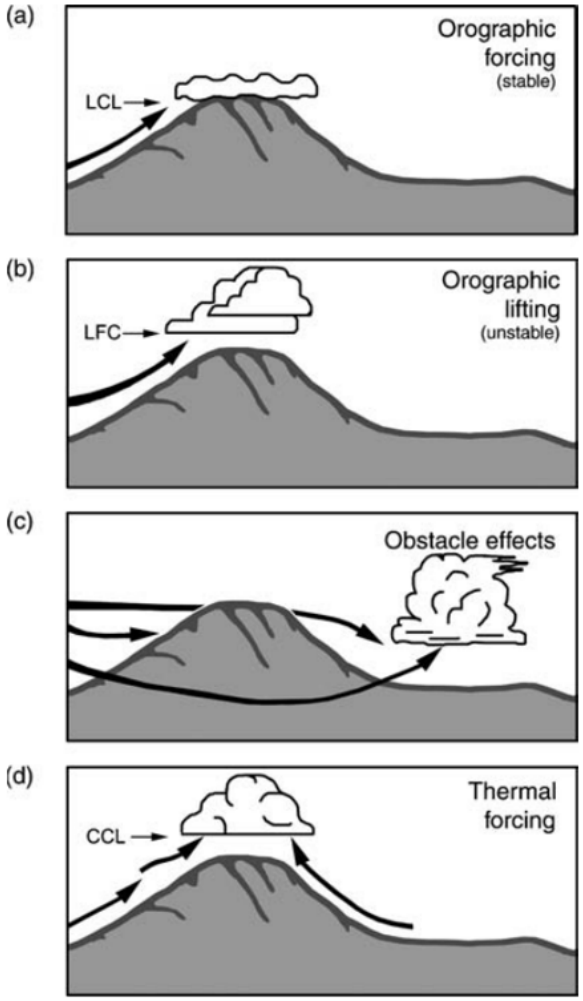
Precipitation occurs in the appropriate atmospheric environment

- favorable atmospheric temperature, humidity and air upward movement
- atmospheric disturbance trigger mechanism, such as mountain barrier

✓ **喜马拉雅山脉（长、陡峭）**

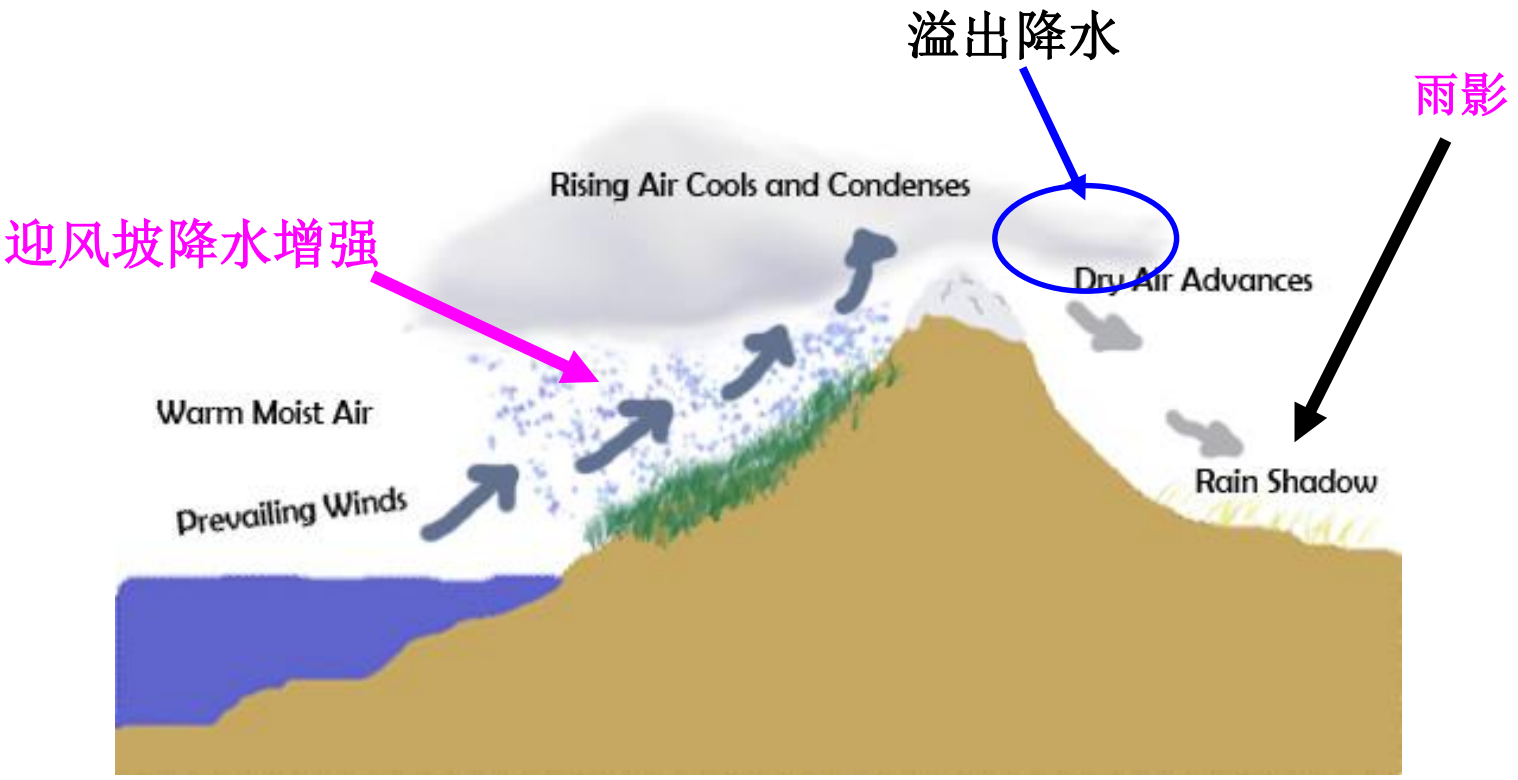
✓ **地形强迫+季风环境**

云降水？

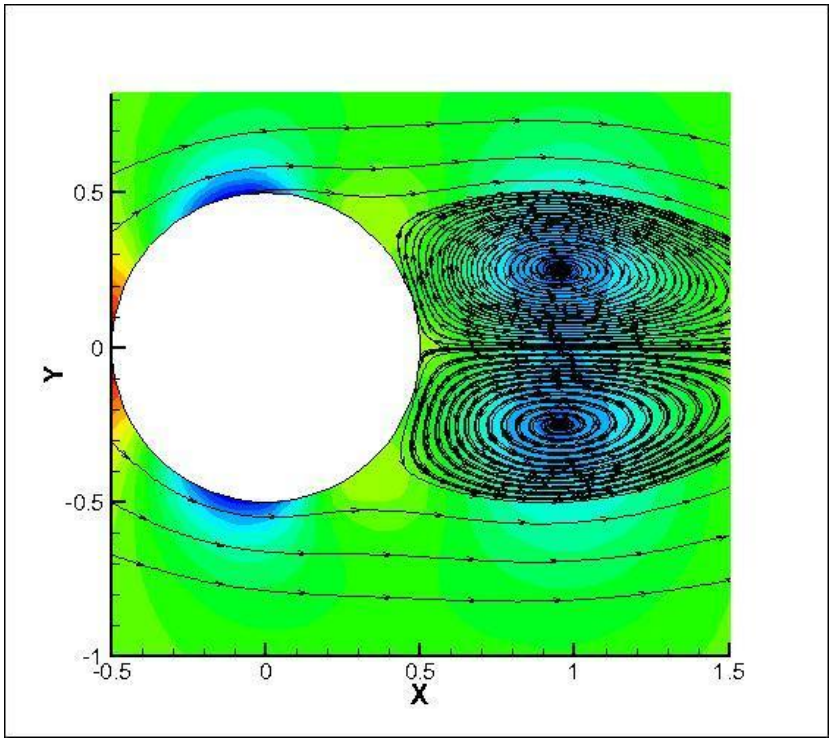


Schematic illustration of the effects of a mountain barrier on cloud formation (modified after Banta, 1990)

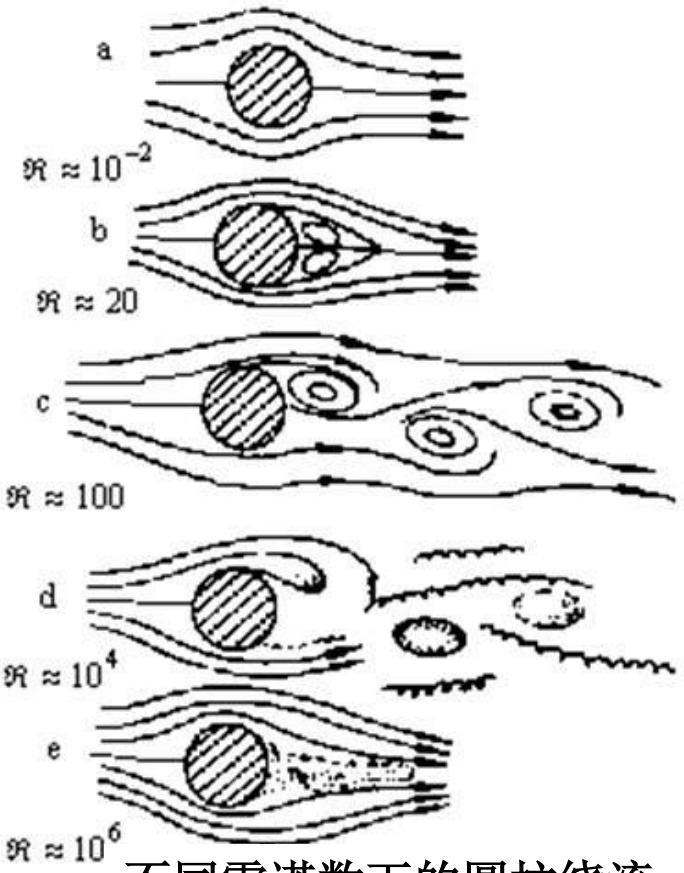
地形降水——大地形阻挡的爬坡流降水



地形降水——孤立高山绕流降水



流体力学原理，粘性—切变—涡旋



不同雷诺数下的圆柱绕流

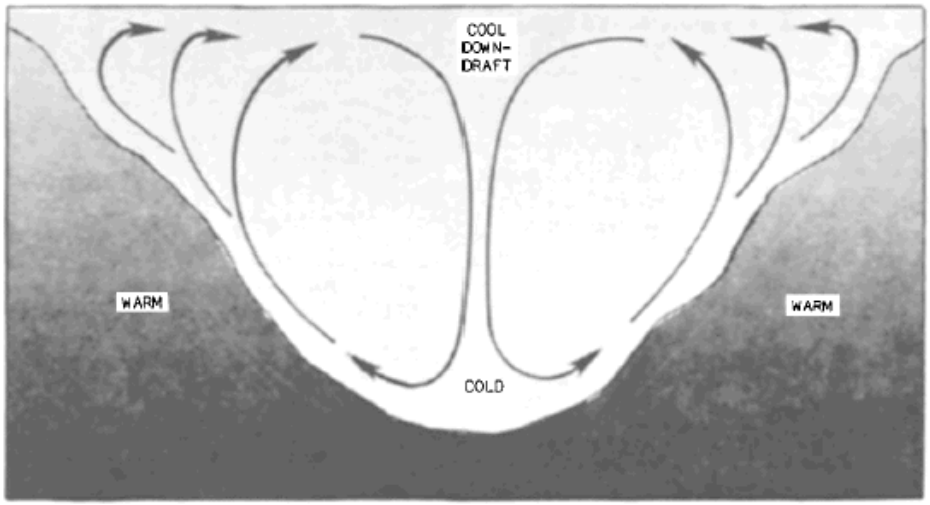
地形降水——热辐射环流降水

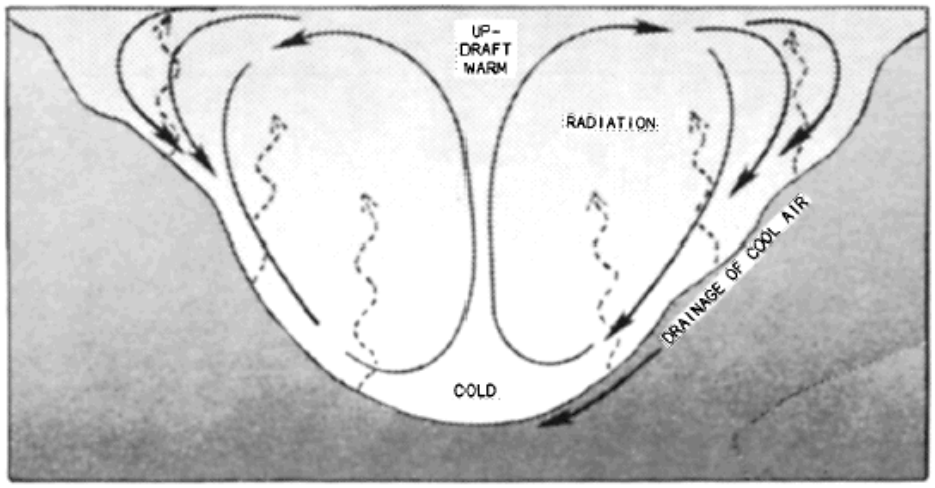
-- 上坡风（Anabatic wind）

白天太阳辐射引起山地温差变化，导致暖空气沿山坡爬升

-- 下坡风（Katabatic wind）

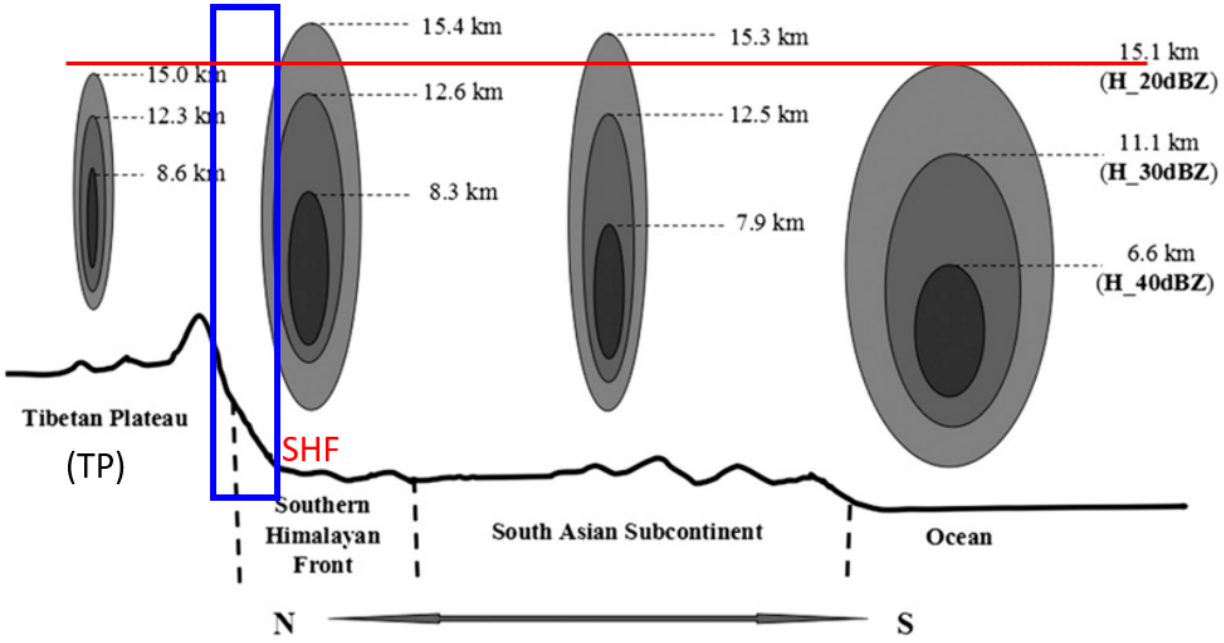
夜间地表辐射冷却引起山地温差变化，导致冷空气沿山坡下沉





整体上看降水回波：青藏高原—喜马拉雅山脉—印度次大陆—印度洋

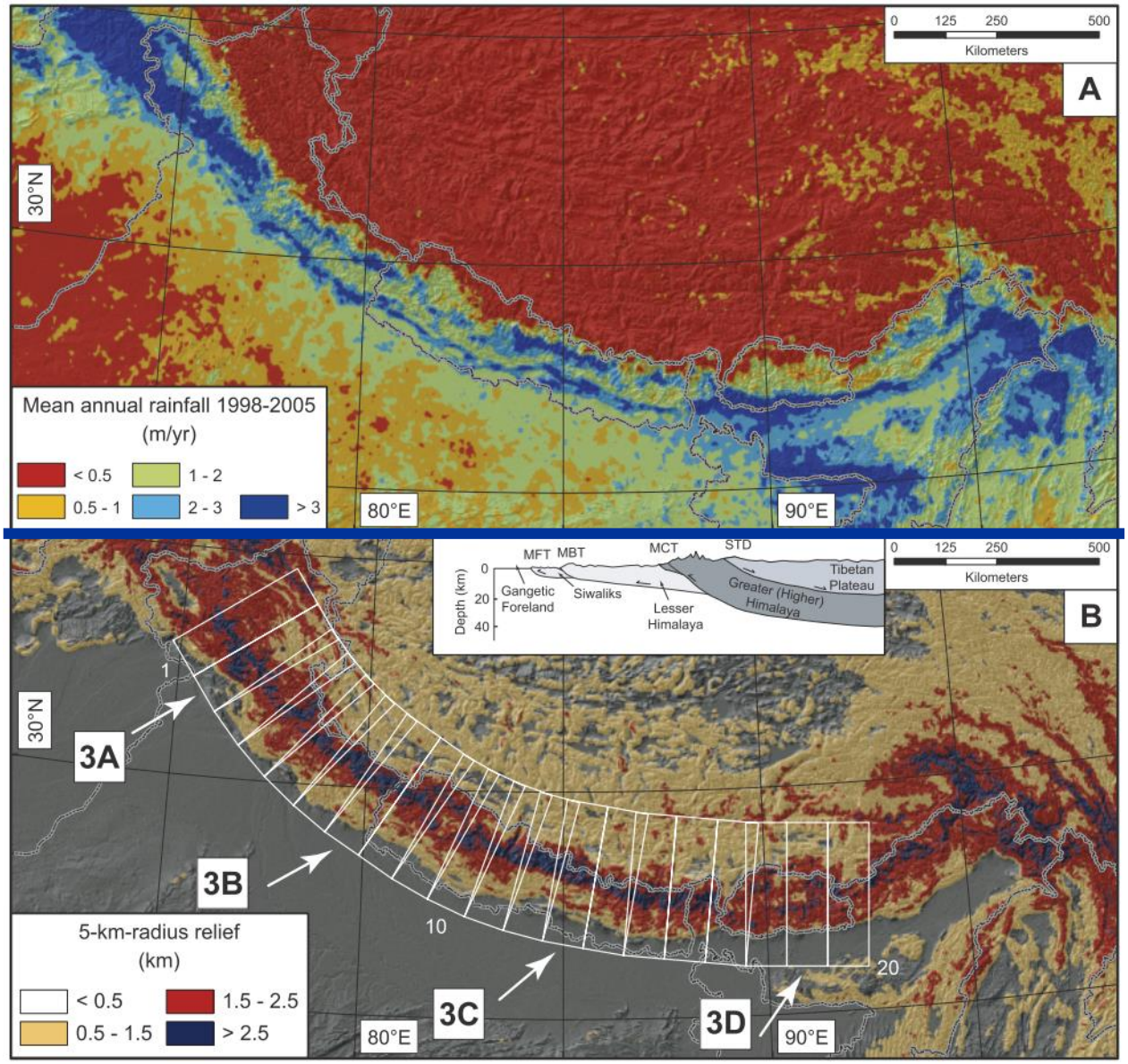
Climatological structural features of DCS over four different subregions



- The size of the ellipses reflects schematically the mean 20-, 30-, and 40-dBZ echo top height and size of the DCS.
- The size is deduced from the radar pixel count for reflectivity exceeding 20, 30, and 40 dBZ, respectively. (Qie et al. 2011, JC)

- **Different height of echo top**
- **A little higher in SHF**
- **Relative lower in ocean**
- **Weak convective system in TP**
- **Missed in the blue box (Steep slope of southern Himalayas)**

地形起伏度—降水

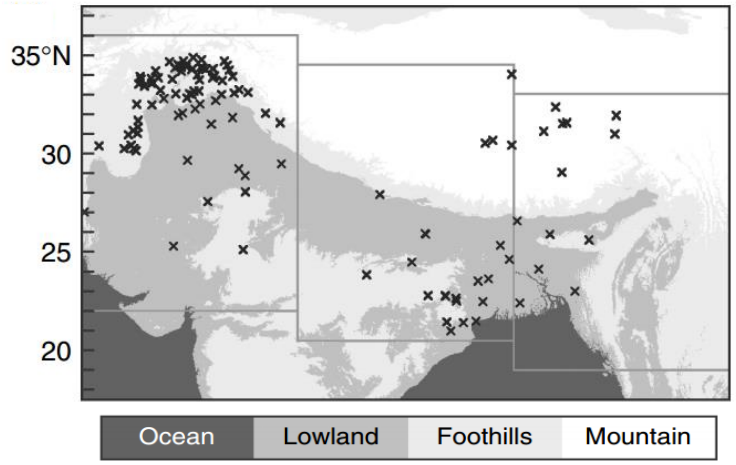


A: Calibrated TRMM-based monsoon rainfall amounts averaged from January 1998 to December 2005

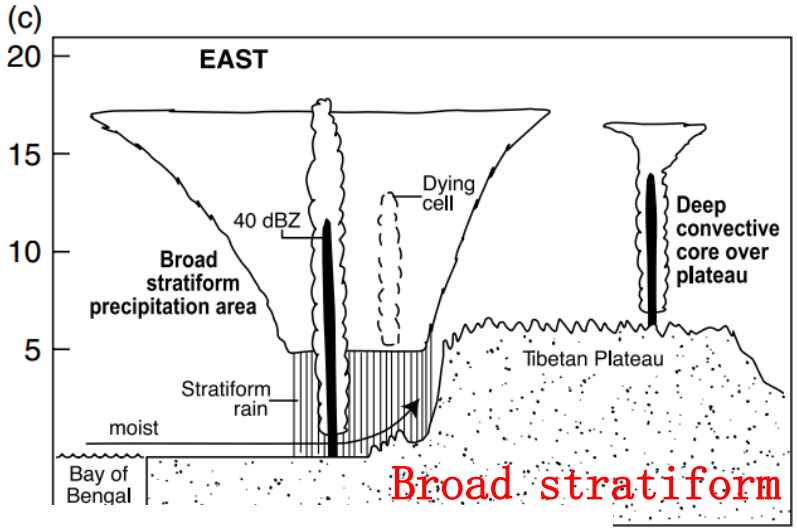
B: 5-km-radius relief calculated from topographic data

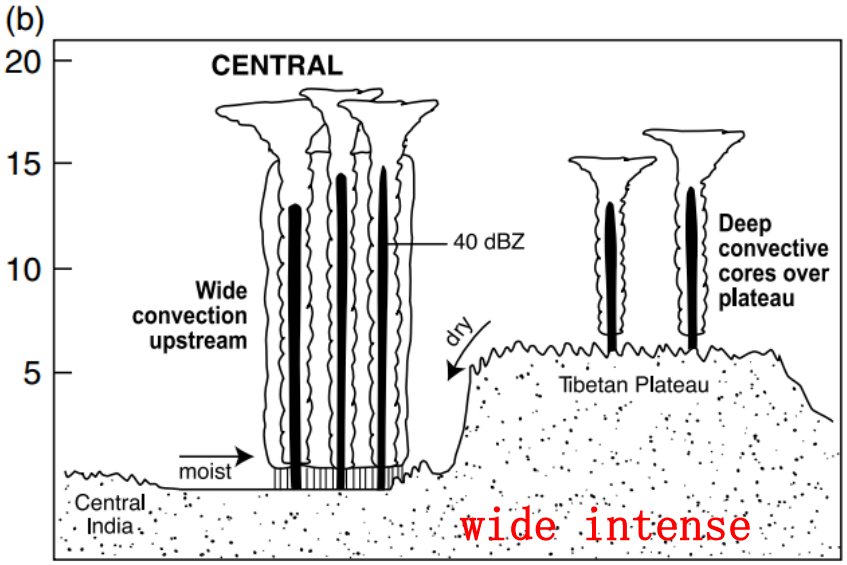
Bookhagen and Burbank,2006: Topography, relief, and TRMM-derived rainfall variations along the Himalaya. G.R.L. 33, L08405

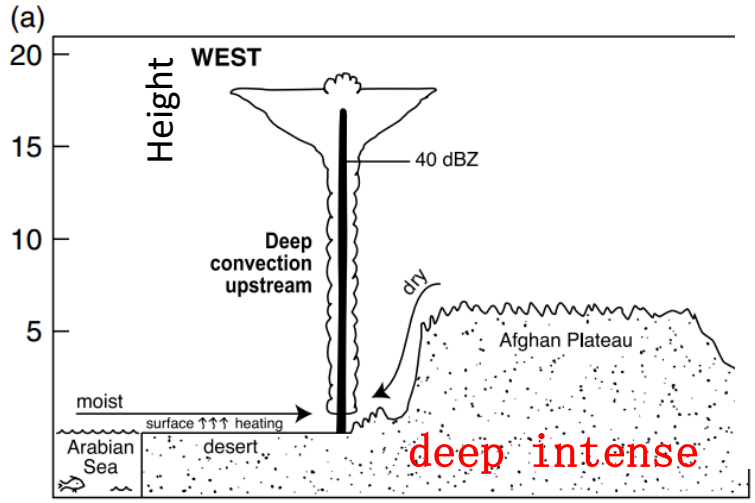
地域差异—降水结构差异



Schematic illustrations of typical extreme precipitation events in each subregion (Houze et al. 2007)



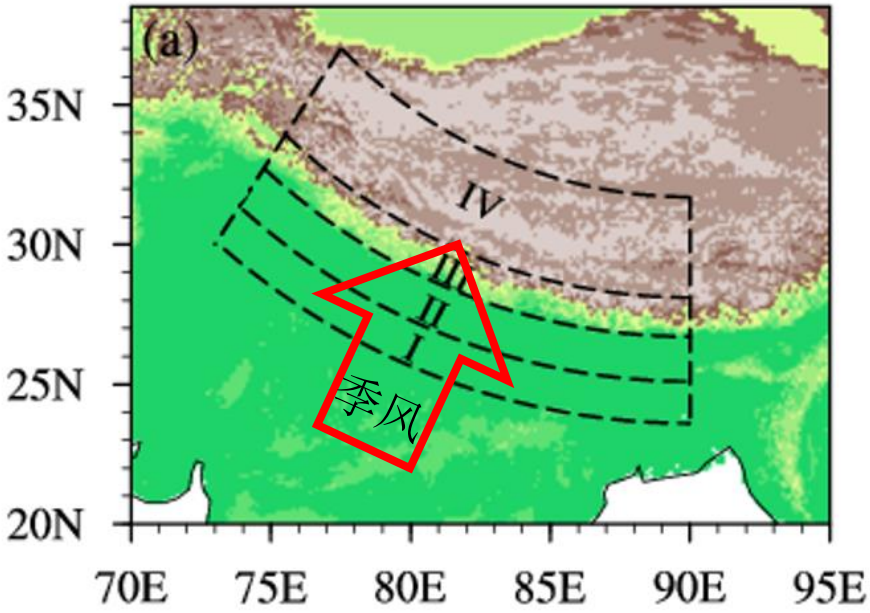




Houze et al, 2007: Monsoon convection in the Himalayan region as seen by the TRMM Precipitation Radar. Q. J. R. Meteorol. Soc. 133: 1389–1411

研 究 目 的

- 降水分布
- 降水垂直结构
- 云顶相态
- 地形起伏度与降水强度
- 大气环流特征



Precipitation characteristics along the path from the northern plains of India via foothill to southern Himalayas and the south part of Tibetan Plateau

地形特点划分：地形自印度北部恒河平原（**FGP**）、喜马拉雅山脚（低于**1km**，**the foothills of Himalayas, FHH**）、山脉陡坡（**2~3.5km, SSSH** ）、高原台地（高于**3.5km**，**HTPT**）

系列研究

INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **37**: 4043–4052 (2017)
Published online 28 February 2017 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4992

RMetS
Royal Meteorological Society

Characteristics of cloud cluster over the steep southern slopes of the Himalayas observed by CloudSat

Yilun Chen, Yunfei Fu,* Tao Xian and Xiao Pan

School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China

Clim Dyn (2018) 51:1971–1989
DOI 10.1007/s00382-017-3992-3

CrossMark

Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS

Yunfei Fu[1] · Xiao Pan[2] · Tao Xian[1] · Guosheng Liu[3] · Lei Zhong[1] · Qi Liu[1] · Rui Li[1] · Yu Wang[1] · Ming Ma[1]

Atmospheric Research 202 (2018) 10–22

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Impact of the surface wind flow on precipitation characteristics over the southern Himalayas: GPM observations

Aoqi Zhang[a], Yunfei Fu[a,*], Yilun Chen[a], Guosheng Liu[b], Xiangdong Zhang[c]

[a] School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China
[b] Department of Earth Ocean & Atmospheric Science, Florida State University, Tallahassee, Florida 32306, USA
[c] International Arctic Research Center and Department of Atmospheric Sciences, University of Alaska Fairbanks, 930 Koyukuk Dr., Fairbanks, AK 99775, USA

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2018JD029297

A Simplified Algorithm to Estimate Latent Heating Rate Using Vertical Rainfall Profiles Over the Tibetan Plateau

Rui Li[1], Wencheng Shao[1], Jingchao Guo[2], Yunfei Fu[1], Yu Wang[1], Guosheng Liu[1], Renjun Zhou[1], and Wenzhuo Li[3]

Key Points:
- A new latent heating retrieval algorithm is developed
- Validation and consistency check of the new algorithm are conducted
- The new algorithm has its advantage

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2019JD031803

Trumpet-Shaped Topography Modulation of the Frequency, Vertical Structures, and Water Path of Cloud Systems in the Summertime Over the Southeastern Tibetan Plateau: A Perspective of Daytime–Nighttime Differences

Lu Yu[1], YunFei Fu[1], Yuanjian Yang[2,3], Xiao Pan[4], and Ruiting Tan[1]

Key Points:
- Clouds tend to be a slight increase and at greater heights at nighttime than in the daytime over the TST region of the SETP
- Single-layered clouds, Cu, and Sc occur more during the daytime, while multilayered clouds, DC, and

ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 38, APRIL 2021, 677–689

• Original Paper •

Morphological Characteristics of Precipitation Areas over the Tibetan Plateau Measured by TRMM PR

Yilun CHEN[1,2,3], Aoqi ZHANG[1,3], Yunfei FU[*2], Shumin CHEN[1,3], and Weibiao LI[1,3]

[1]*Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies,*

atmosphere

MDPI

Article

The Phenomenon of Diurnal Variations for Summer Deep Convective Precipitation over the Qinghai-Tibet Plateau and Its Southern Regions as Viewed by TRMM PR

Jing Luo, Jianqiu Zheng, Lei Zhong, Chun Zhao and Yunfei Fu *

ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 38, APRIL 2021, 641–660

• Original Paper •

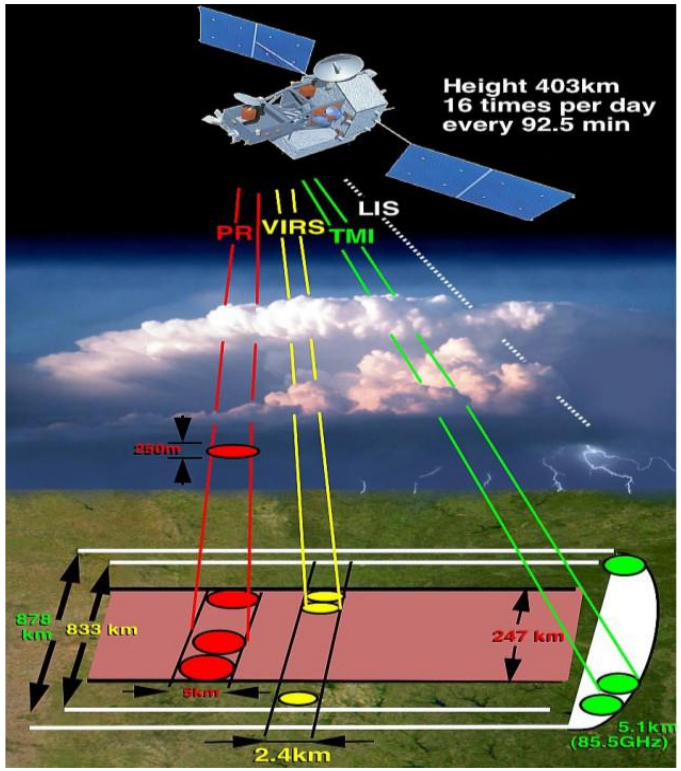
Diurnal Variations of Precipitation over the Steep Slopes of the Himalayas Observed by TRMM PR and VIRS

Xiao PAN[1,2], Yunfei FU[*2], Sen YANG[1], Ying GONG[1], and Deqin LI[1]

[1]*Institute of Atmospheric Environment, China Meteorological Administration, Opening Key Laboratory for*

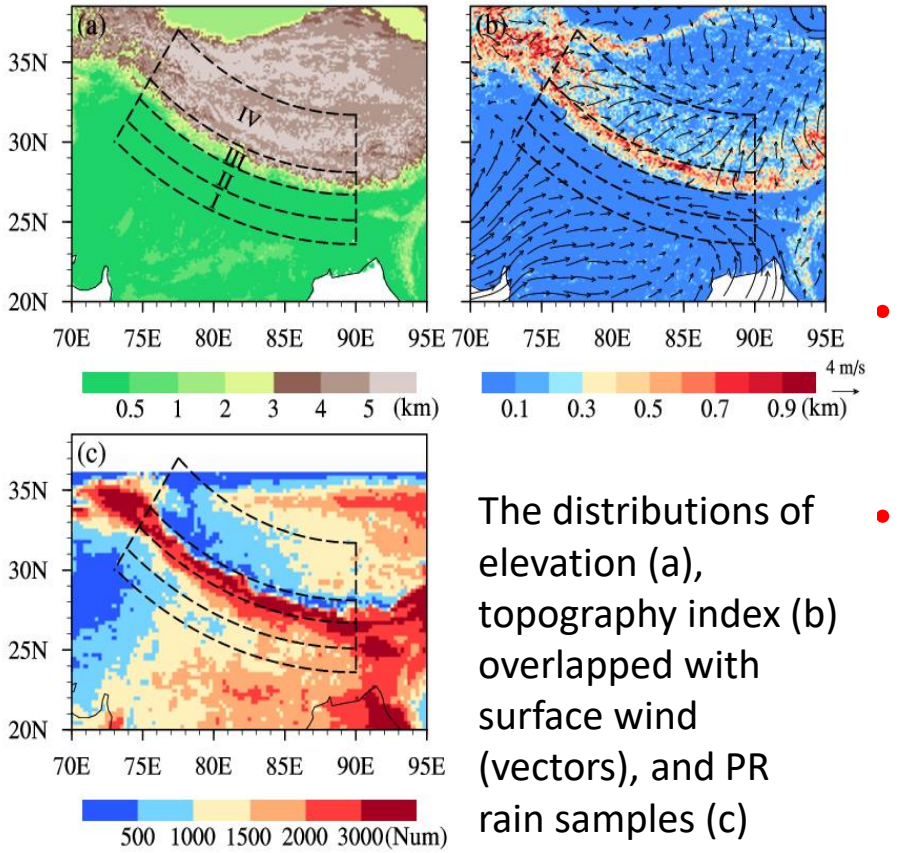
使用数据和采用方法

- Standard data sets of 1B01 and 2A25 at version 7, rainy season in south Asian summer monsoon (May-August) from 1998 to 2012
- 2A25, precipitation profile and types, vertical and horizontal resolutions of 250 m and 5 km, respectively.
- 1B01, radiances at five wavelengths (0.63, 1.6, 3.7, 10.8 and 12.0 μm) with 2.1 km horizontal resolutions at nadir.
- Topography data (3 km horizontal resolution) from NGDC/NOAA (http://www.ngdc.noaa.gov/)
- Collocated 1B01, terrain elevation and 2A25 at PR rain pixels by a weighted-averaging method (PR and VIRS simultaneous measurements)



Schematic view of the scan geometries of the three TRMM primary rainfall sensors: TMI, PR, and VIRS (From JAXA web site)

在测雨雷达探测像元上融合可见光/红外信号，表征降水类型、垂直结构和云顶相态。



The distributions of elevation (a), topography index (b) overlapped with surface wind (vectors), and PR rain samples (c)

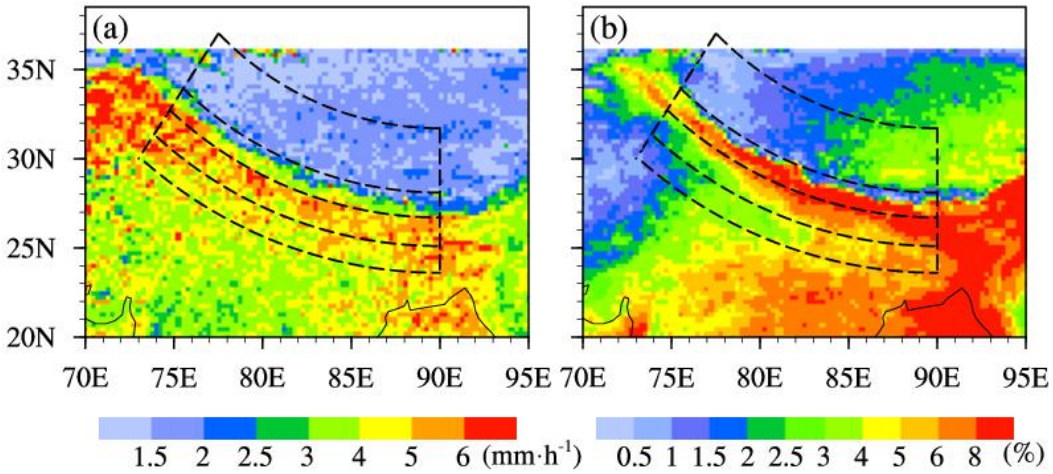
The sectors I, II, III and IV represent the flat Gangetic Plains (FGP), the foothills of Himalayas (FHH), the steep slope of south Himalayas (SSSH), and the Himalayas-Tibetan Plateau tableland (HTPT), respectively（**0.25度格点统计**）

定义地形陡峭度参数：TI

（ 6 km × 6 km square ）

- **地形指数：**突出了山脉陡坡（山腰的部分——III区，这里TI大于0.4）
- **地表风场：**近地面风场受到了明显的地形强迫（季风在接近山脚时，水平气流速度减小，在山脉陡坡水平速度更小，而到达山顶后增大）
- **PR降水样本：**山脉陡坡降水次数多（3000次），高原上数量小，山脉陡坡—山脚—恒河平原的降水次数依次减少。

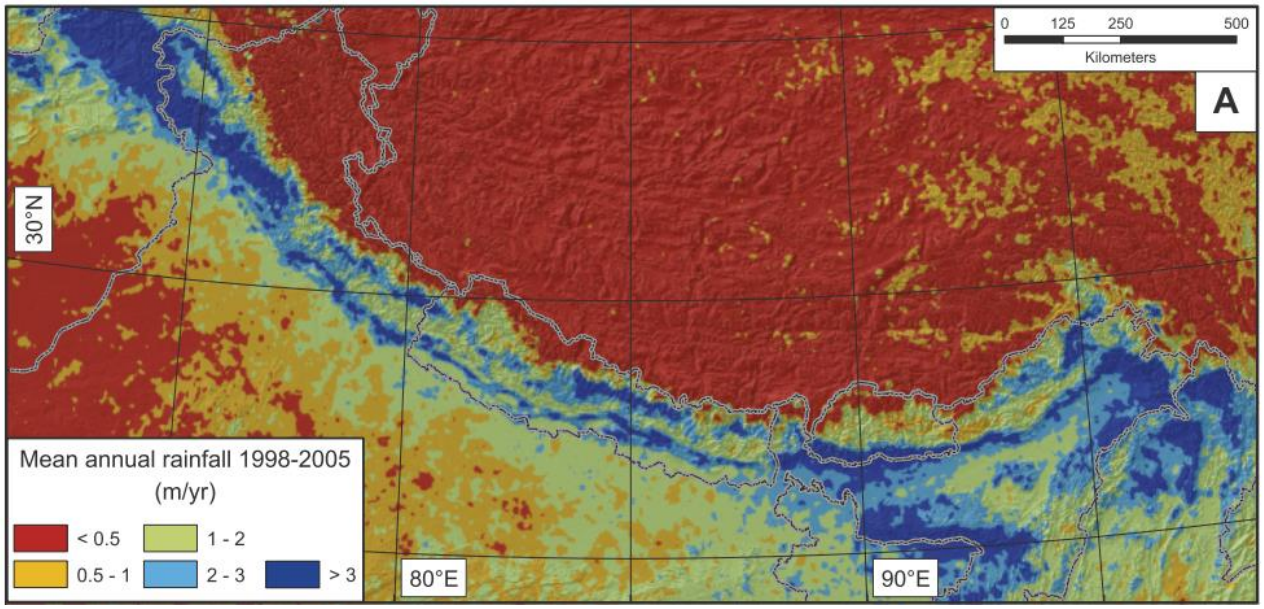
降水强度　　降水频次

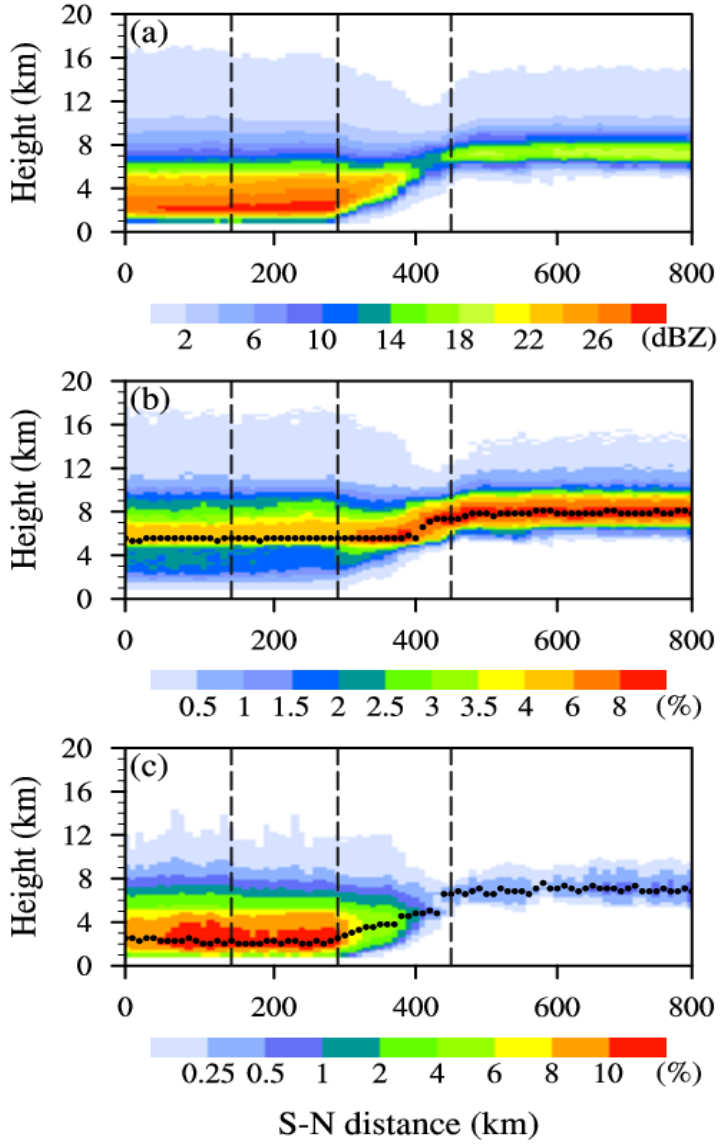


The distributions of rain rate (RR, a), rain frequency (RF, b)

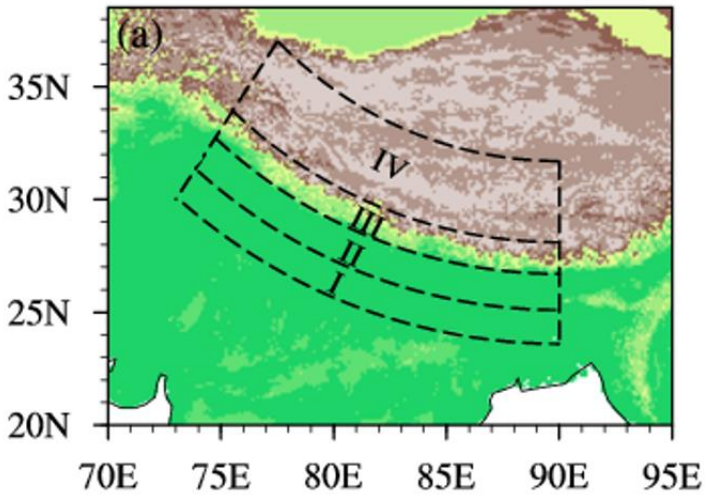
格点统计计算总探测数、降水数

- 山脚区降水强度大
- 山脉陡坡区降水频次高、降水强度不大
- 高原降水强度最小、频次最低





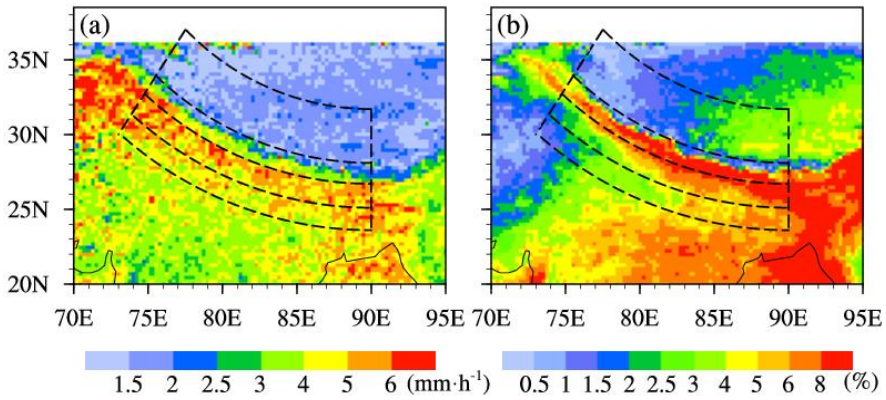
(a): mean radar reflectivity, (b): frequency of storm top altitude (STA), and (c): frequency of echoes greater than 40 dBZ.



扇面内统计计算，强回波统计

- 最强回波在平原；
- 平原降水回波顶高度高，降水云非常深厚；
- 到达高原台地前，降水云回波顶高度下降。

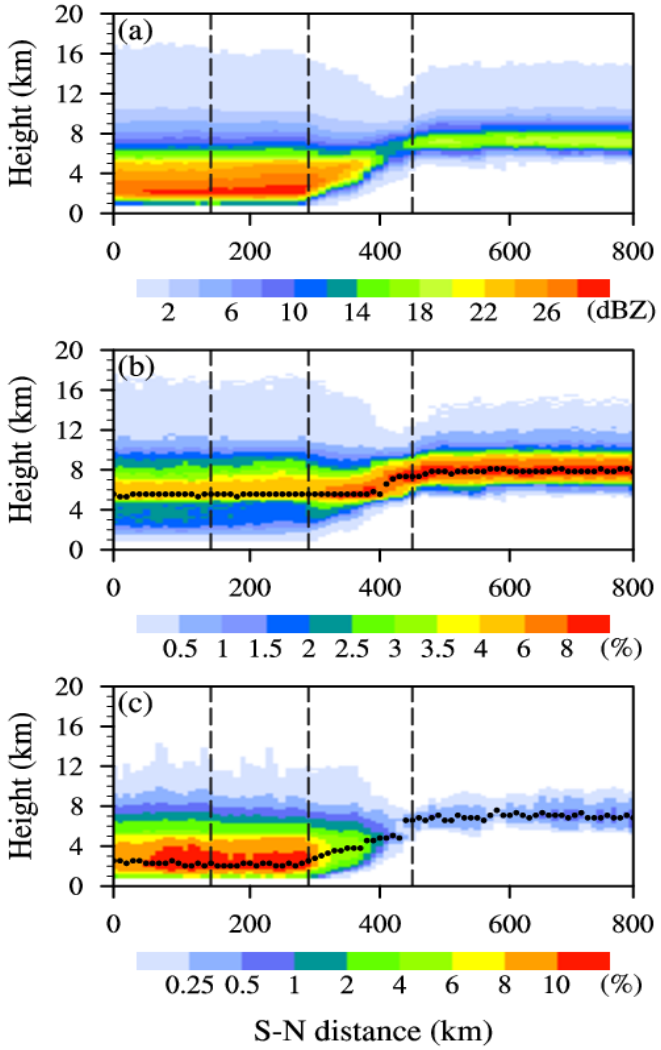
降水强度　　降水频次



The distributions of rain rate (RR, a), rain frequency (RF, b)

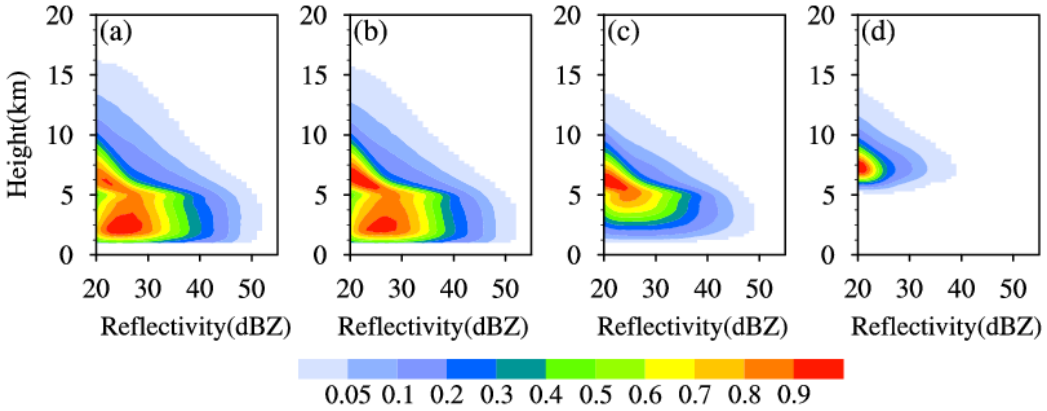
平面与垂直对比方法

- 山脚降水强度大、降水云深厚；
- 山脉陡坡降水频次高、降水强度小、降水云深厚度减小；
- 高原降水强度最小、频次最低、降水云深厚度最小。

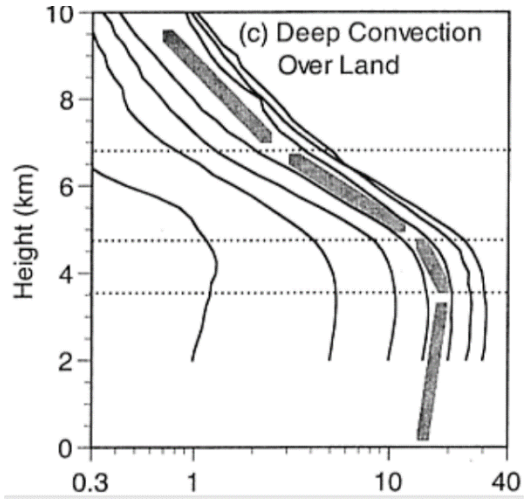


(a): mean radar reflectivity, (b): frequency of storm top altitude (STA), and (c): frequency of echoes greater than 40 dBZ.

与以往结果对比

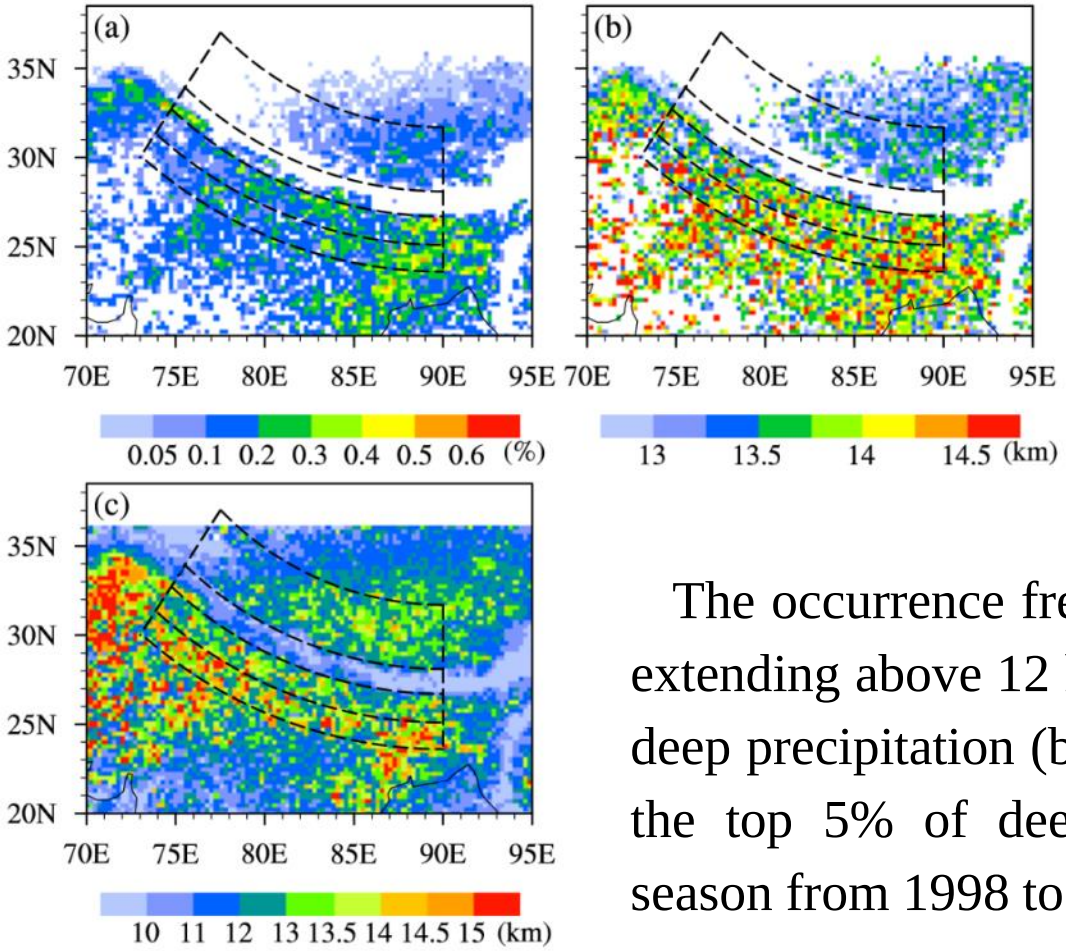


The normalized CFAD of TRMM PR reflectivity data for May-August 1998-2012 for (a) FGP, (b) FHH, (c) SSSH, and (d) HTPT.



(Liu and Fu, 2001)

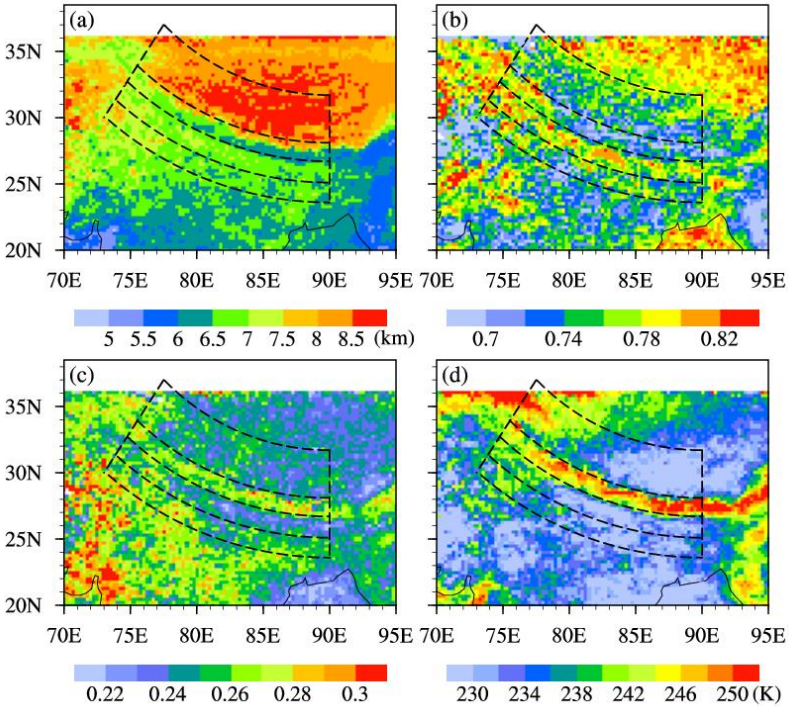
- Layer differences: four over FGP and FHH (evaporation of rain droplet, coalescence of particles (size and phases), mixture of different phases, and crystallization of particles), three over SSSH, two over HTPT
- Ratio difference above 5km（mixing layer) —— intensity of ascending



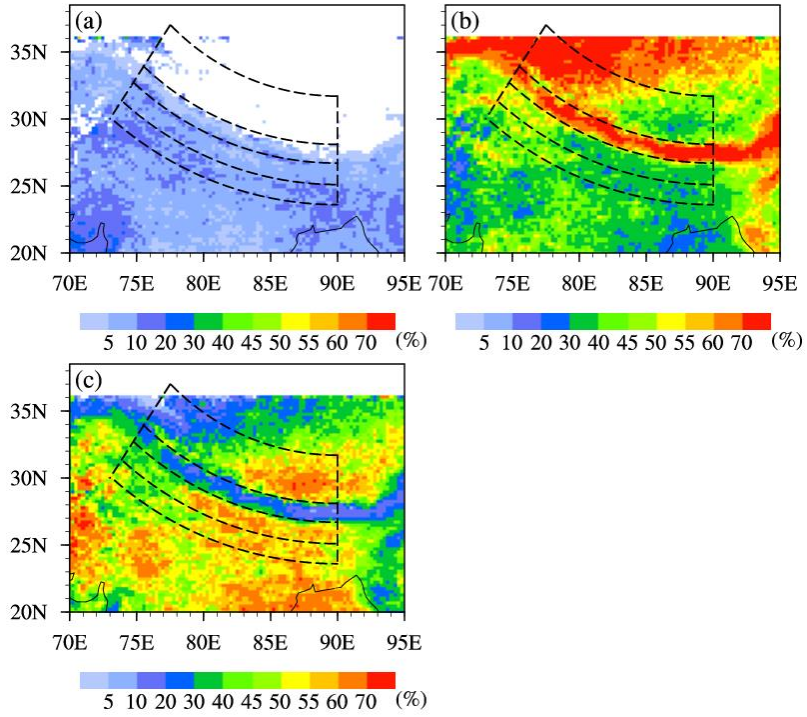
格点统计计算总探测数、降水数、排序取百分比计算方法

The occurrence frequency of deep precipitation extending above 12 km (a), the averaged STAs of deep precipitation (b), and the averaged STAs for the top 5% of deep precipitation (c) in rainy season from 1998 to 2012.

- 山脚区、平原区，多深厚降水；平均顶高多高于**13.5km**
- 山腰区低于**10km**



The distributions of mean STA (a), RF1 (b), RF2 (c) in daytime (from 0800 to 1600 local time), and $TB_{10.8}$ (d) in a whole day



The distribution of precipitation fraction for liquid-phase (a), mixed-phase (b), and ice-phase (c) near cloud top statistical calculated in a whole day

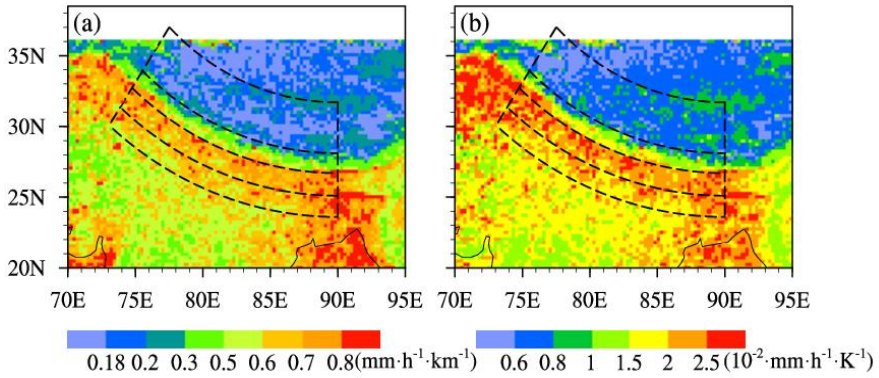
近红外通道的相态识别技术

- 山腰区降水云顶部：冰水混合相态
- 山脚区、平原区：云顶冰相

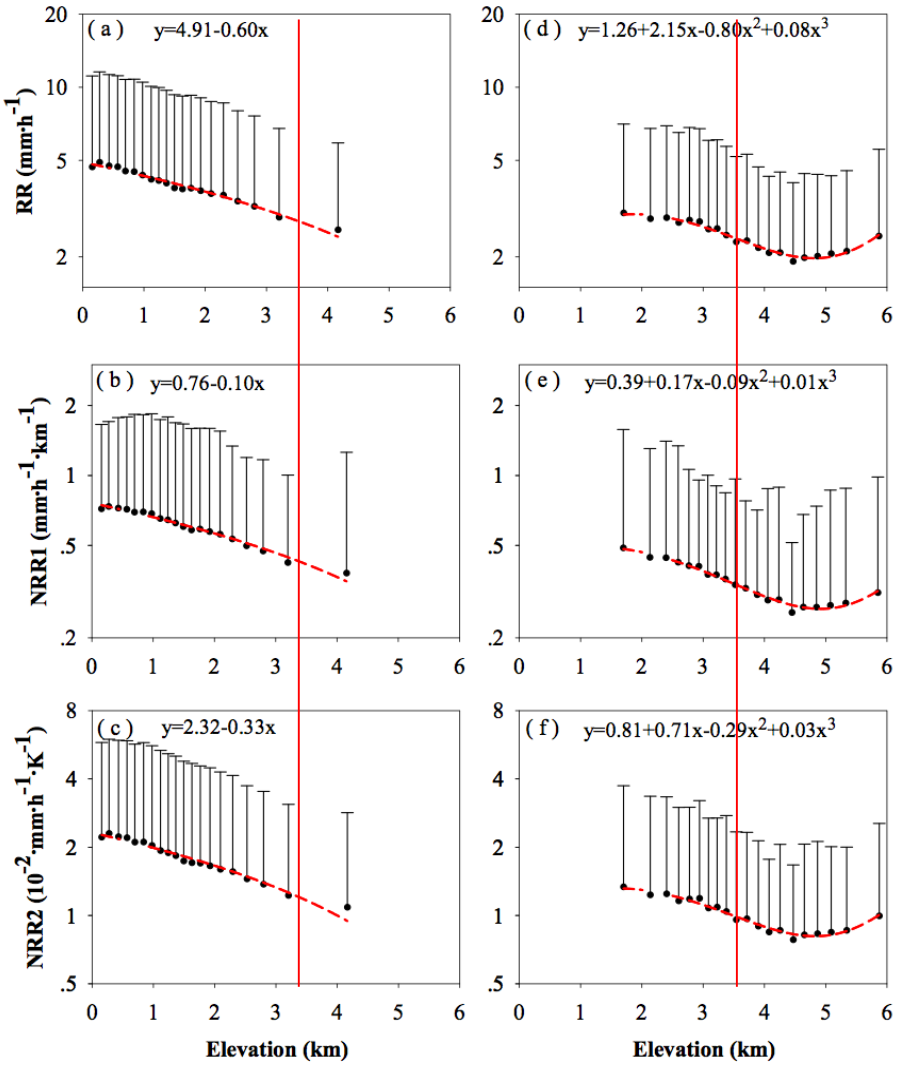
Fu et al., 2018: Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS. Clim Dyn, 51:1971–1989

地面降水强度与海拔高度的关系

扇面内统计



The distributions of normalized rain rate (a) by STA (NRR1) and (b) by $TB_{10.8}$ (NRR2) in a whole day



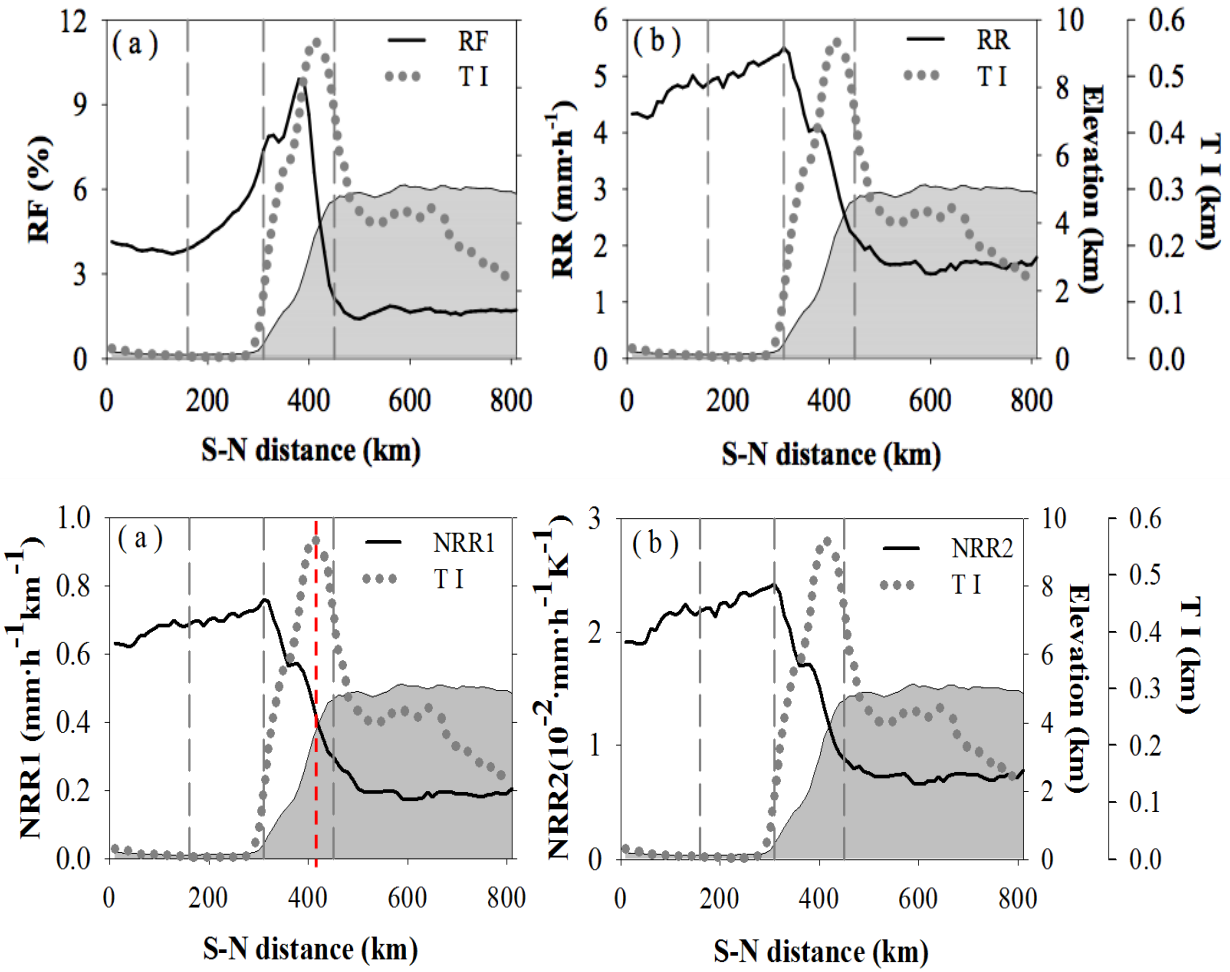
分析技术：

用降水云深厚度来标准化地面降水强度

数据融合技术：

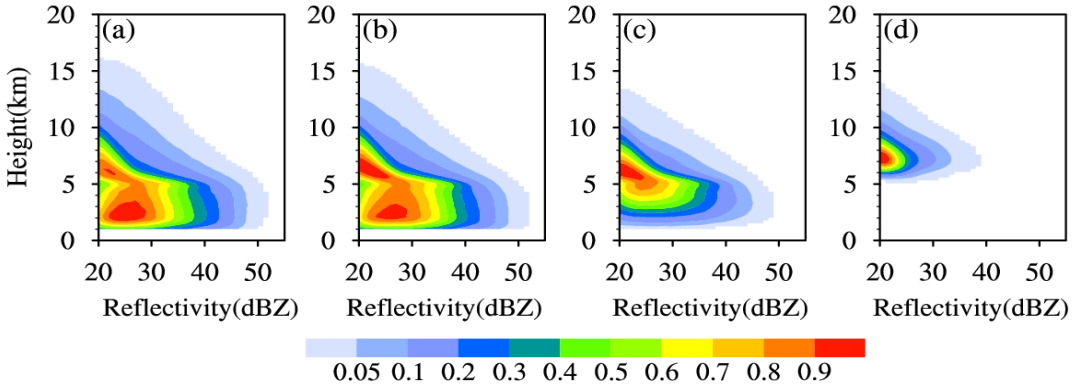
雷达探测数据与可见光/红外遥感数据的融合

山脚区、平原区的降水效率高！



4km以下，降水频次随着高度增加而增加，而降水强度则减小！

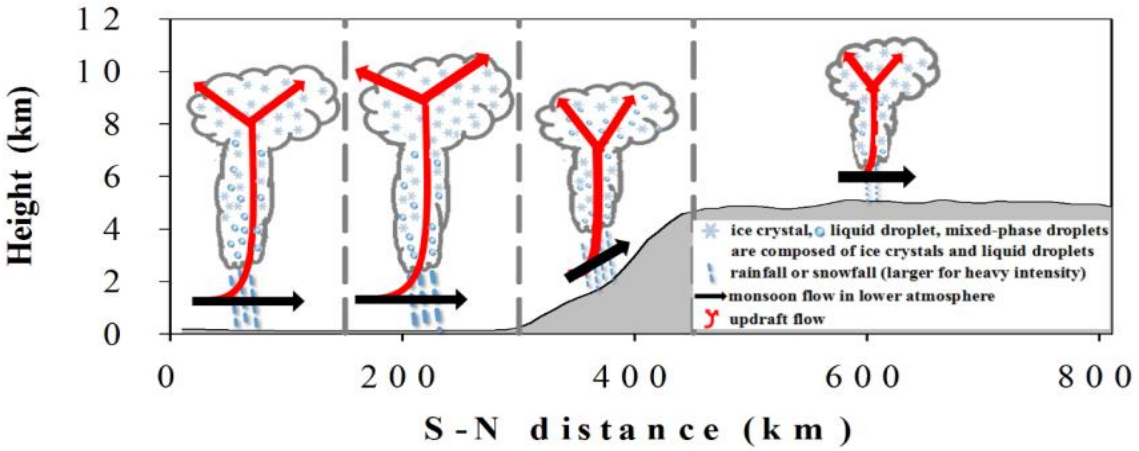
Fu et al., 2018: Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS. Clim Dyn, 51:1971–1989



The normalized CFAD of TRMM PR reflectivity data in rainy season from 1998 to 2012 for the FGP (a), the FHH (b), the SSSH (c), and the HTPT (d)

山脉腰区：

降水云的深厚度的减小！

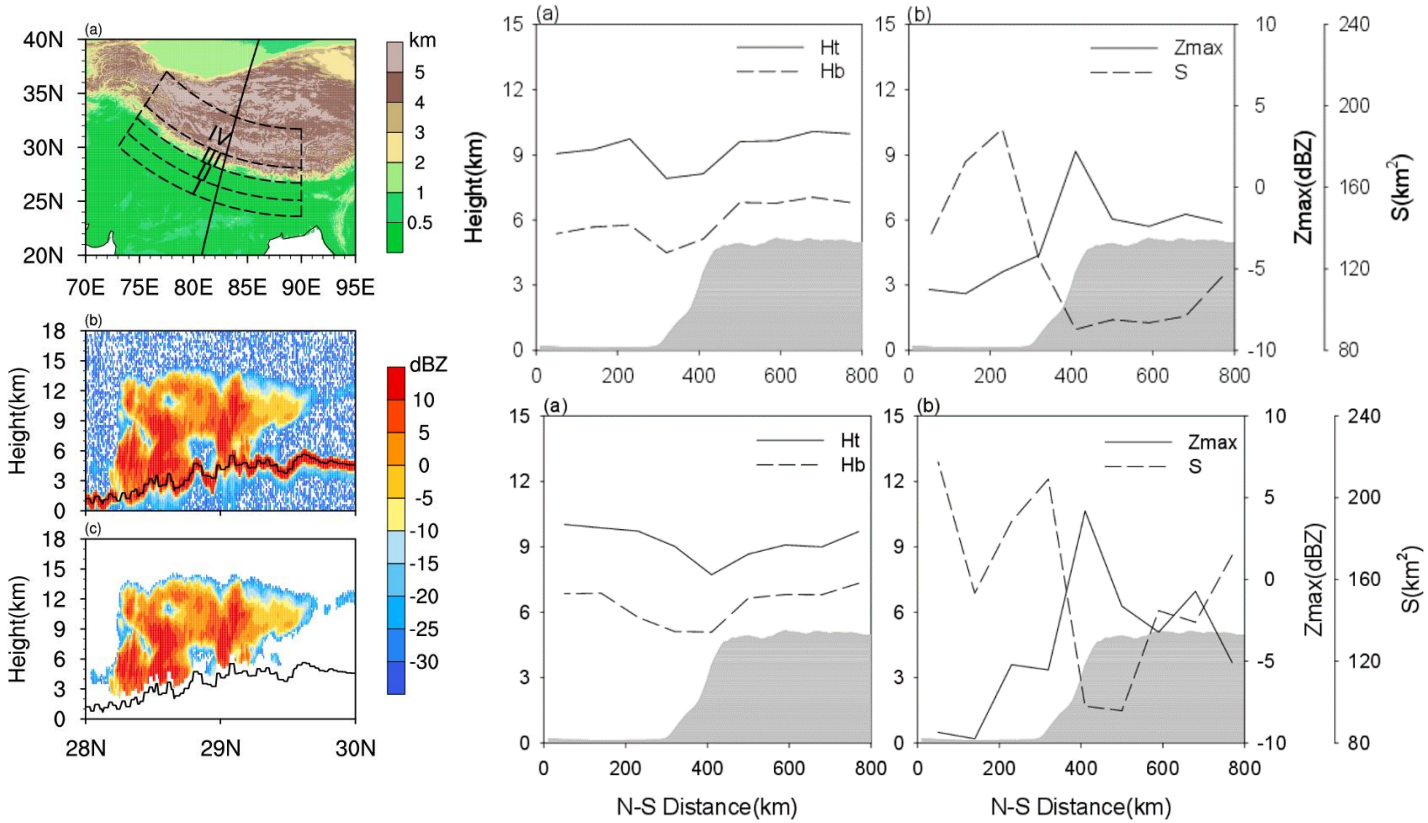


Schematic diagram of the distribution for precipitating clouds submerged in South Asian Monsoon flows from the FGP via the FHH and the SSSH to the HTPT

- 强降水出现在山脚区，消耗水汽；
- 南坡陡峭地形强迫抬升作用，增加了坡面区降水频率；
- 深厚降水多出现在山脚区、平原区；
- 山腰区降水云顶塌陷，估计潜热激发作用小。

Fu et al., 2018: Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS. Clim Dyn, 51:1971–1989

高原南坡陡峭地形的云和降水——CPR云廓线的云团垂直结构

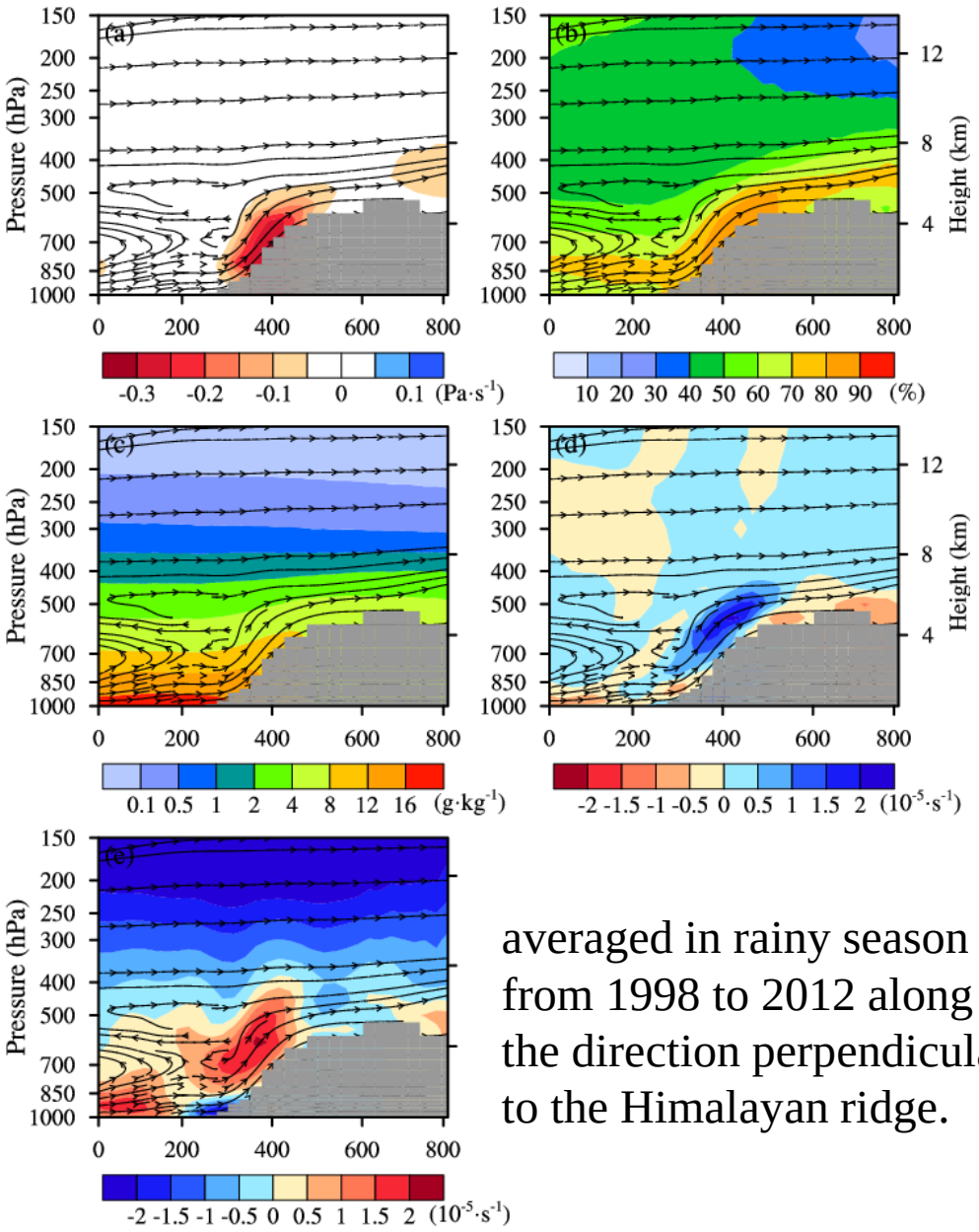


通过分析CloudSat CPR 2006年至2010年的探测结果，建立了一个云团数据集。

云团：CPR探测剖面上连续的云像元。定义和计算了雨团的特征参数。

- 云顶高度分布逐渐从山脚的双峰（3km和15km），变为了高原台地的单峰（7-9km）
- 从山脚到高原内部，云顶平均高度和云底平均高度先减后增（与PR探测的回波顶高度变化一致）
- 云团面积在山脚区达到最大（与PR探测的强降水去一致）；
- 云团的特征参数均呈现半日变化，由季风日变化和山谷风环流共同作用的结果。

Chen et al., 2017: Characteristics of cloud cluster over the steep southern slopes of the Himalayas observed by CloudSat. Int. J. Climatol. 37: 4043–4052



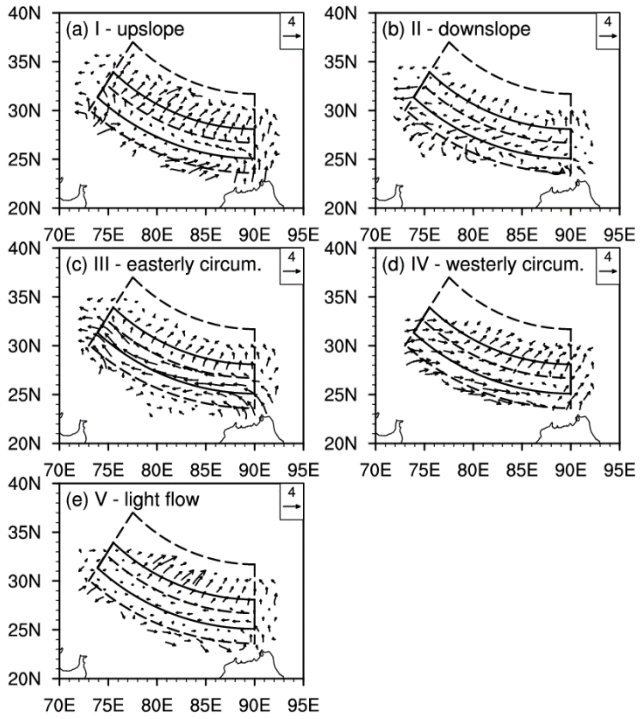
averaged in rainy season from 1998 to 2012 along the direction perpendicular to the Himalayan ridge.

The cross section view with pressure (Y-axis) and distance (X-axis) for
(a) Vertical velocity,
(b) relative humidity,
(c) specific humidity,
(d) Divergence
(e) vorticity overlapped by streamlines (ω×1000)

机理分析

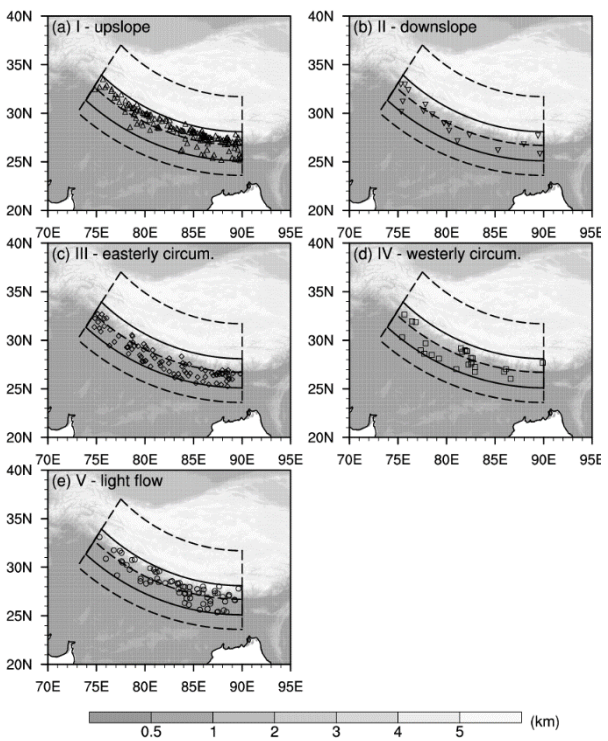
- 自印度北上的大气低层季风暖湿气流遇到山脚地形阻挡而产生辐合，故强降水出现在喜马拉雅山脉的山脚地区；
- 残存水汽沿山腰地形爬升，故降水强度小，但降水频次高！

高原南坡陡峭地形的云和降水——南坡风向与雨团

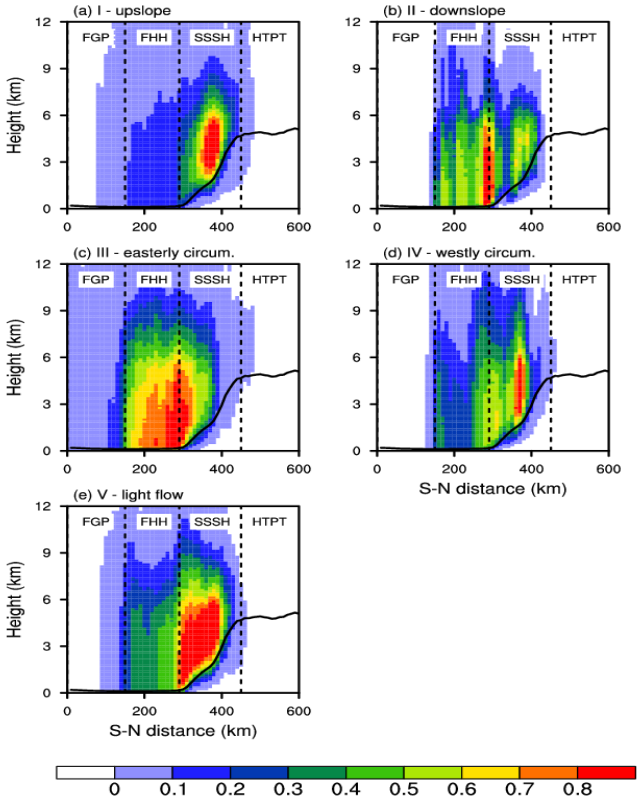


Horizontal distribution of the composited surface wind for precipitating systems

降水系统的不同特征可能由特定地形的地表风作用所致!

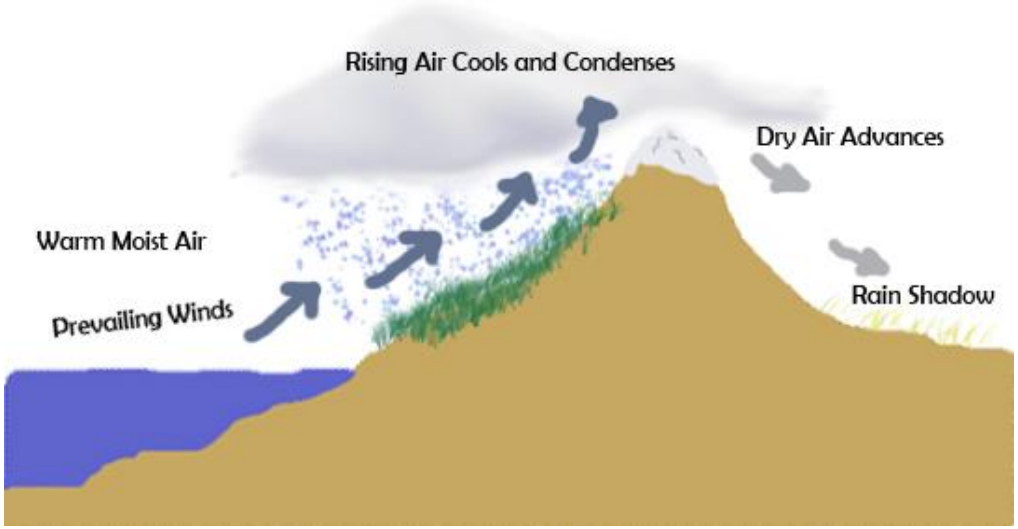


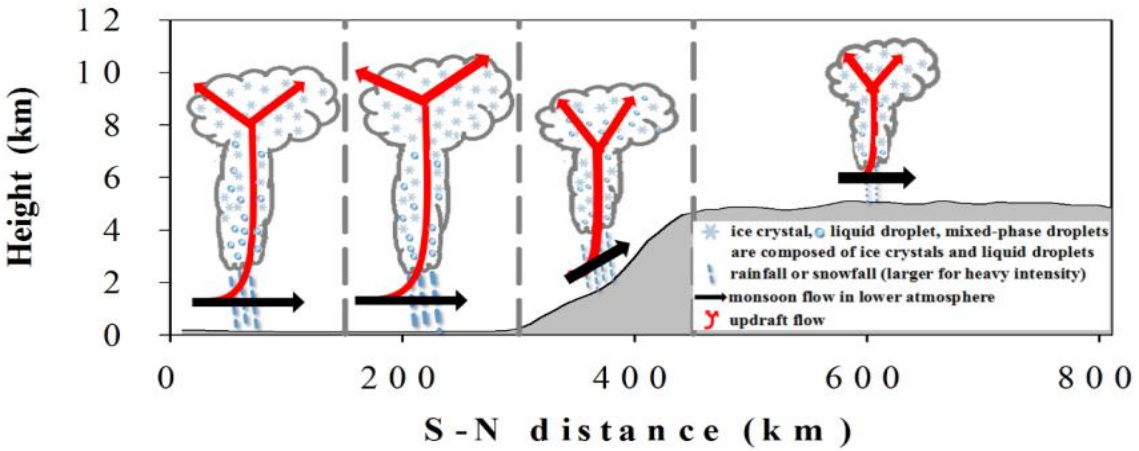
Regional distribution of the large precipitating systems (> 600 km2 in area) of (a) upslope (I); (b) downslope (II); (c) easterly circumfluent (III); (d) westerly circumfluent (IV); and (e) light flow (V) classes



Distributions of normalized precipitating frequency in each grid (0.125 km in height and 10 km along the horizontal) for the precipitating systems

Zhang et al., 2018: Impact of the surface wind flow on precipitation characteristics over the southern Himalayas: GPM observations, Atmospheric Research 202: 10–22





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Fu et al., 2018: Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS. Clim Dyn, 51:1971–1989

小　结

- 建立新的数据融合方法（众数法），将主被动仪器探测结果，在PR像元上实现融合；
- 建立新的分析技术（降水厚度的标准化降水强度），分析降水云的降水效率；
- 揭示喜马拉雅南坡陡峭地形的降水强度随高度变化的分布特征（有别于传统山脉强迫降水落区的认识）
- 认知了陡峭地形的降水厚度、相态特征
- 潜热结构、潜热对环流贡献、辐射与降水、云演变，等等？

Fu et al., 2018: Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS. Clim Dyn, 51:1971–1989

感谢聆听！

敬请批评指正！