模式结果对初始条件的敏感性

上节课回顾

Source: Dr. David Randall, CSU

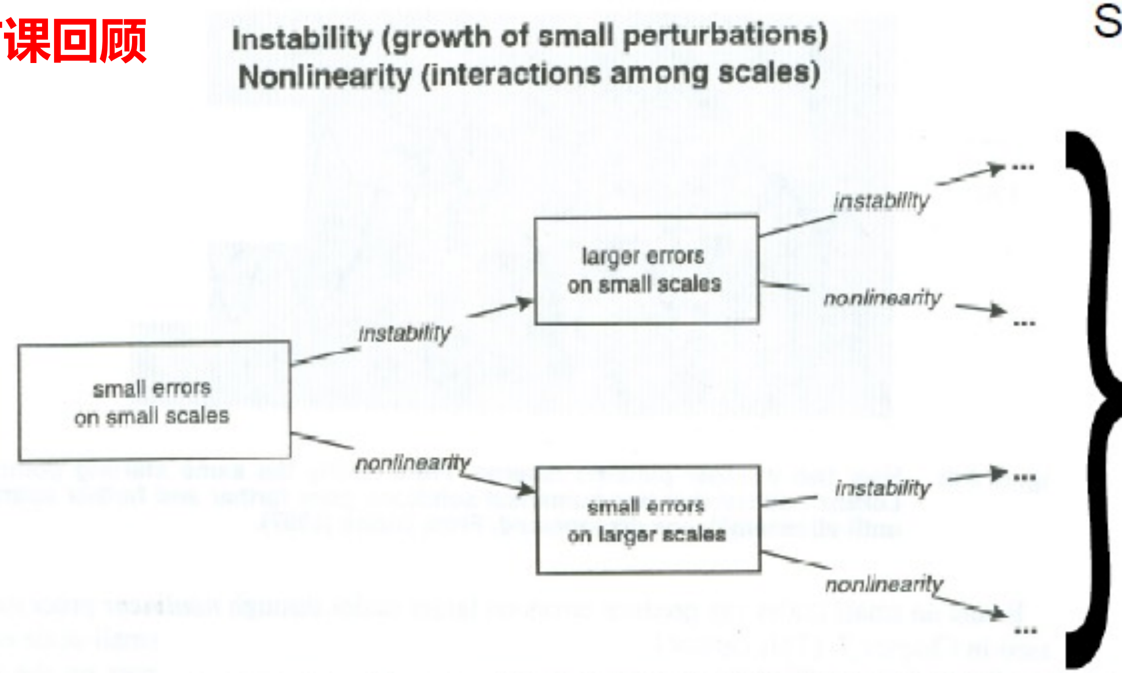


Figure 8.9: Sketch illustrating the role of instability in leading to error growth, and of nonlinearity in leading to the movement of error from small scales to larger scales.

Eventually, after time has passed, it is inevitable that even the very largest scales in a model will be dominated by great uncertainty.

Any forecasting method is subject to this (not just numerical prediction) because the behavior of the system is heavily dependent on the initial conditions!

- there is a sensitive dependence on initial conditions

格距 .vs. 时间步长

上节课回顾

$$\frac{\partial A}{\partial t} = -c\frac{\partial A}{\partial x}$$

Upstream scheme:

$$\frac{A(x,t+1) - A(x,t) =}{\Delta t} - c\,\frac{A(x,t) - A(x-1,t)}{\Delta x}$$

$$A(x,t+1) = A(x,t) - c\frac{\Delta t}{\Delta x}[A(x,t) - A(x-1,t)]$$

Courant Number $c\frac{\Delta t}{\Delta x}$

Criteria of stability $\left|c\frac{\Delta t}{\Delta x}\right| \leq 1$

上节课回顾

Current trends in cloud models:

- Higher and higher resolution
- Studies include more simulations (no longer in the era of “one production run”)
- Ever increasing sophistication of microphysical parameterizations
- Increasing use of ensembles
- Increasing use of dynamical data assimilation techniques
- Operationally useful NWP that resolves smaller scale convective processes

强对流天气的可预报性

大气可预报性

- 指可以提前多长时间做出准确预报

$$\alpha(t) = \alpha(0) + t \times F$$

- 未来时刻 t 的大气
- 初始大气
- 影响大气变化的过程

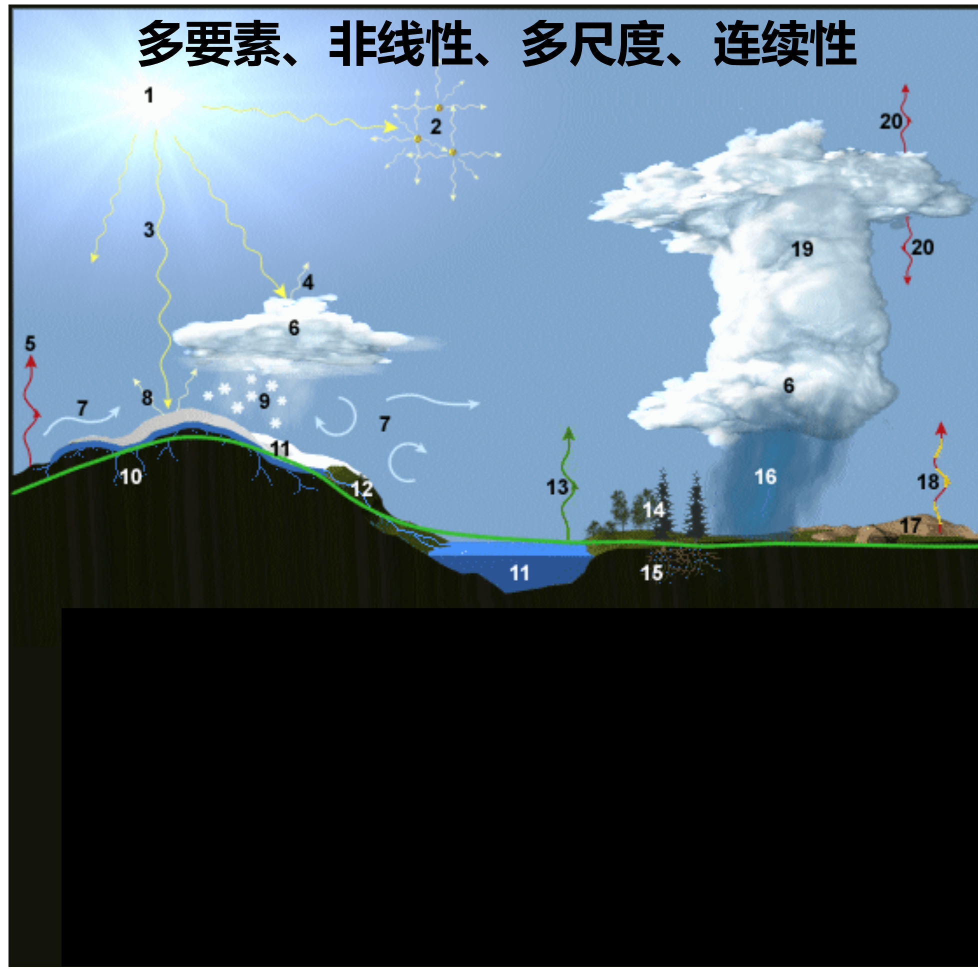
$$\frac{d\bar{u}}{dt} - f\bar{v} + \frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial x} + \frac{\partial}{\partial z}\left(\overline{w'u'}\right) = 0$$

$$\frac{d\bar{v}}{dt} + f\bar{u} + \frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial y} + \frac{\partial}{\partial z}\left(\overline{w'v'}\right) = 0$$

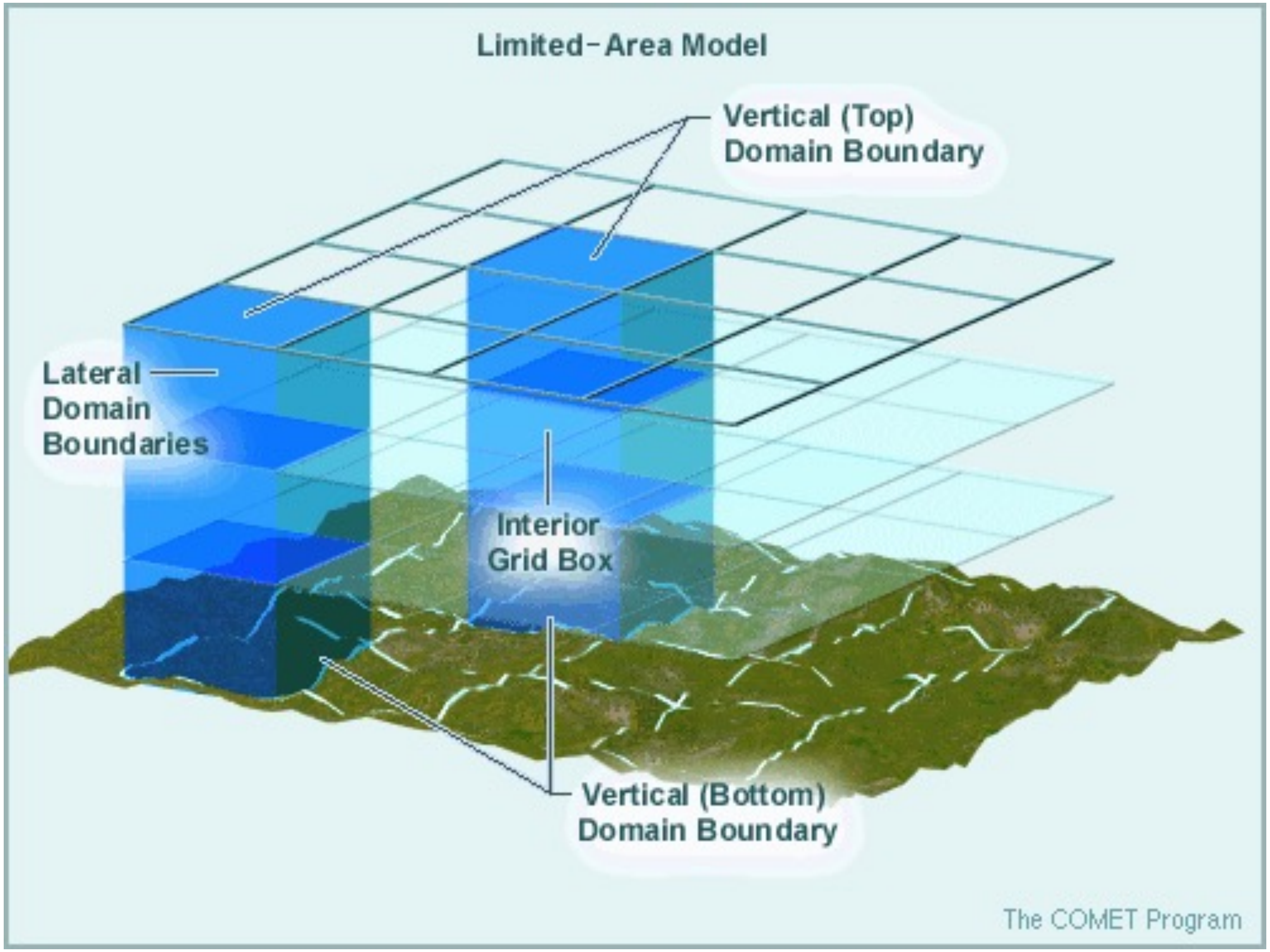
$$\frac{d\bar{\theta}}{dt} + \bar{w}\frac{d\theta_0}{dz} + \frac{\partial}{\partial z}\left(\overline{w'\theta'}\right) = 0$$

$$\frac{\partial \bar{p}}{\partial z} + g\rho_0 = 0$$

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{w}}{\partial z} = 0$$



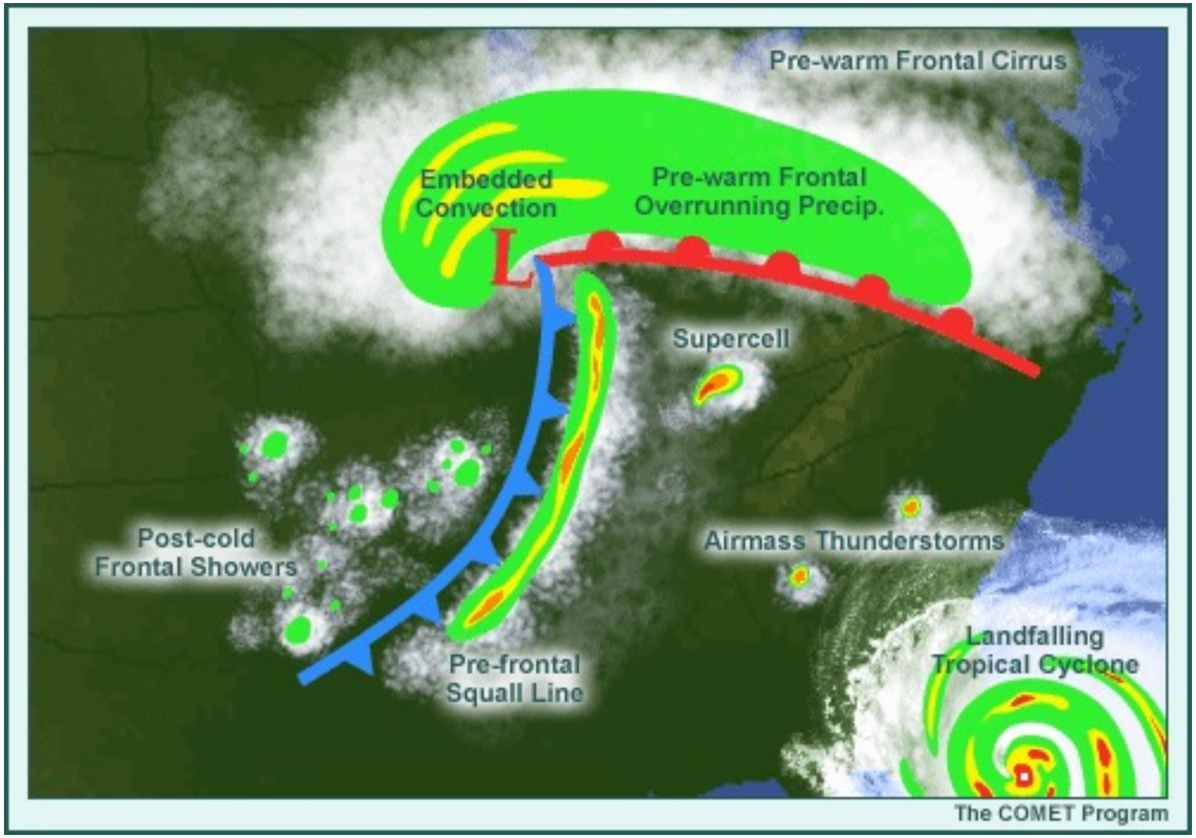
误差来源：离散化

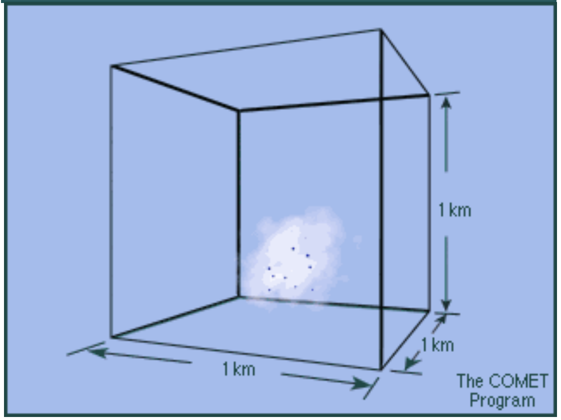


Limited-Area Model
Vertical (Top)
Domain Boundary
Lateral
Domain
Boundaries
Interior
Grid Box
Vertical (Bottom)
Domain Boundary
The COMET Program

误差来源：初始和模式误差

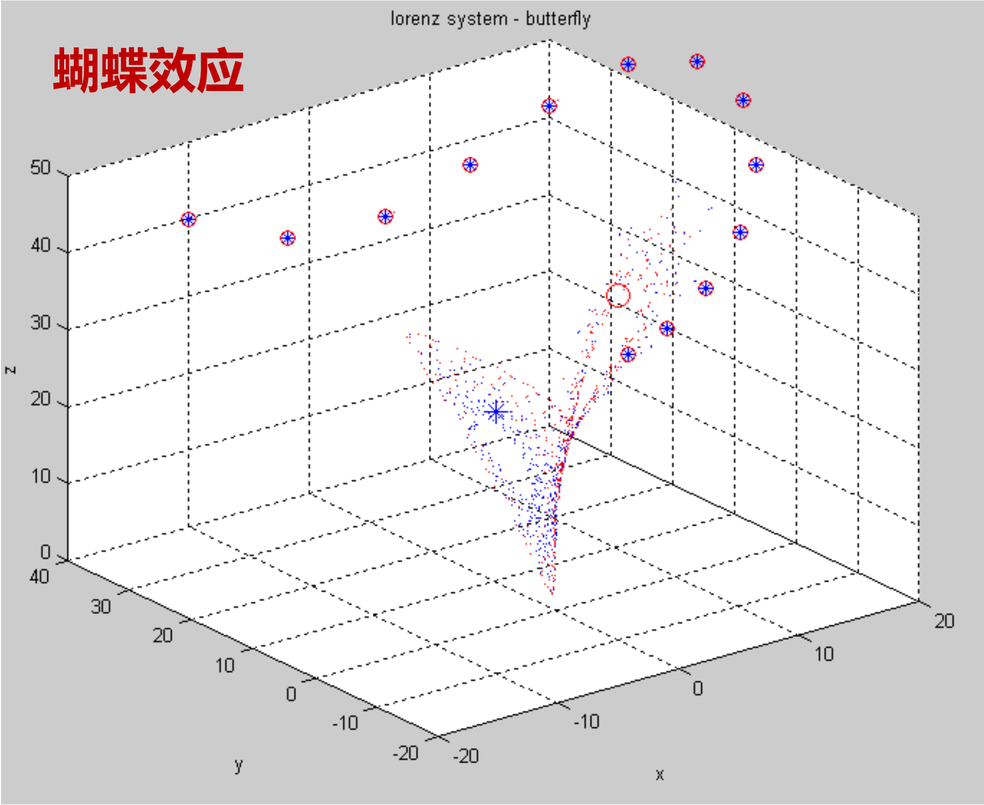
- 观测时空密度和类别、资料同化算法
- 模式的物理过程描述



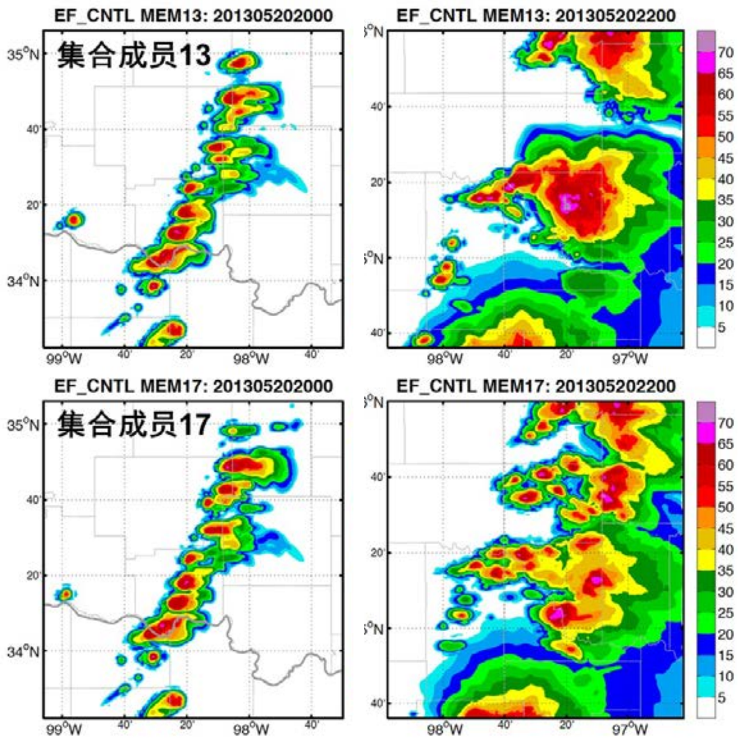


天气预报对误差的敏感性

- 初始很小的误差会造成一段时间后较大的误差
- 导致天气预报存在预报时效上限



2小时前后的雷暴预报差异



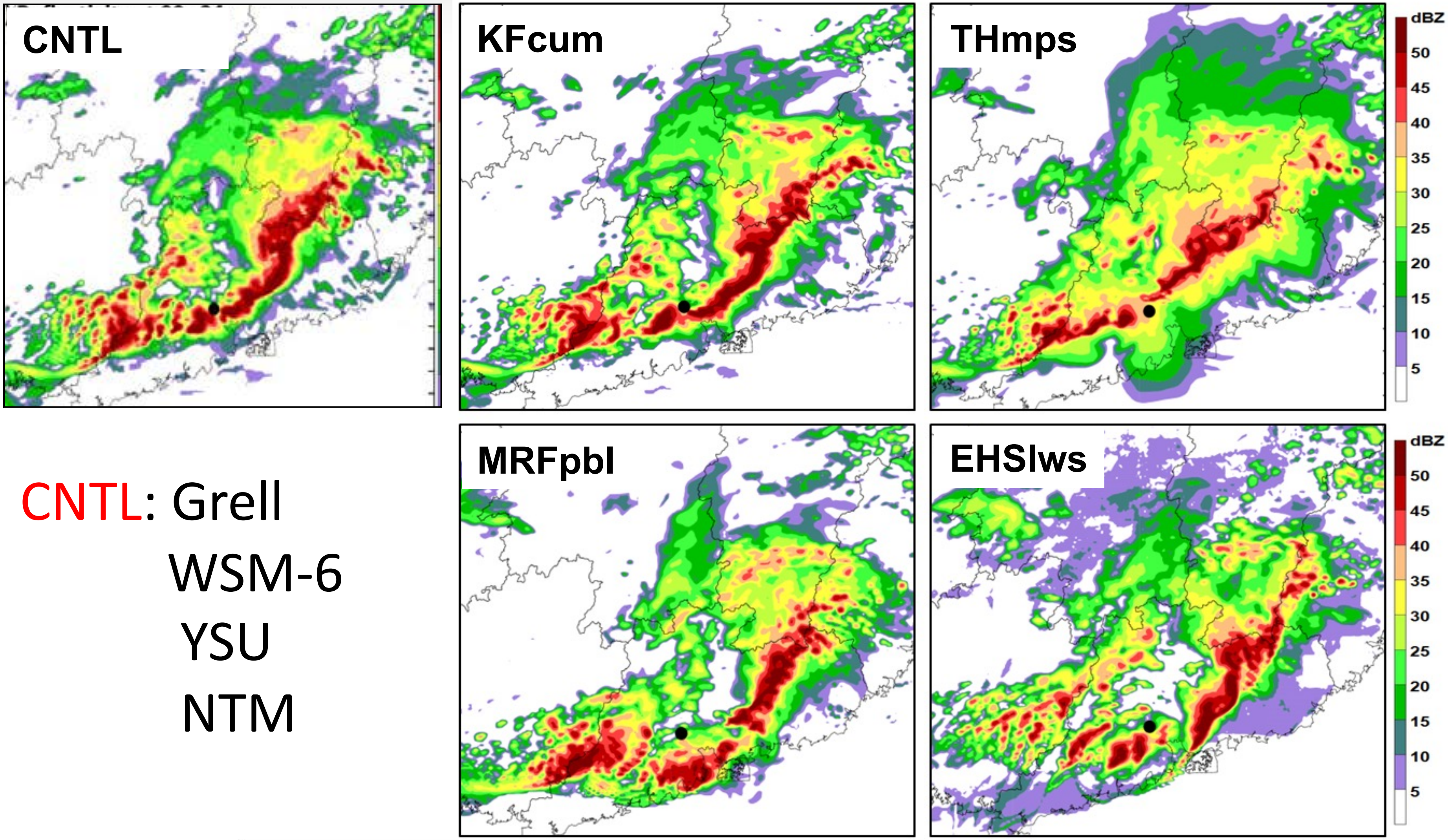
个例1：飑线

The predictability of the squall line

(Wu, Meng, Yan , AAS, 2012)

- Sensitivity to the model error
  - Physical parameterization
  - Grid size
- Sensitivity to the initial error
- Possible way to improve the forecast skill

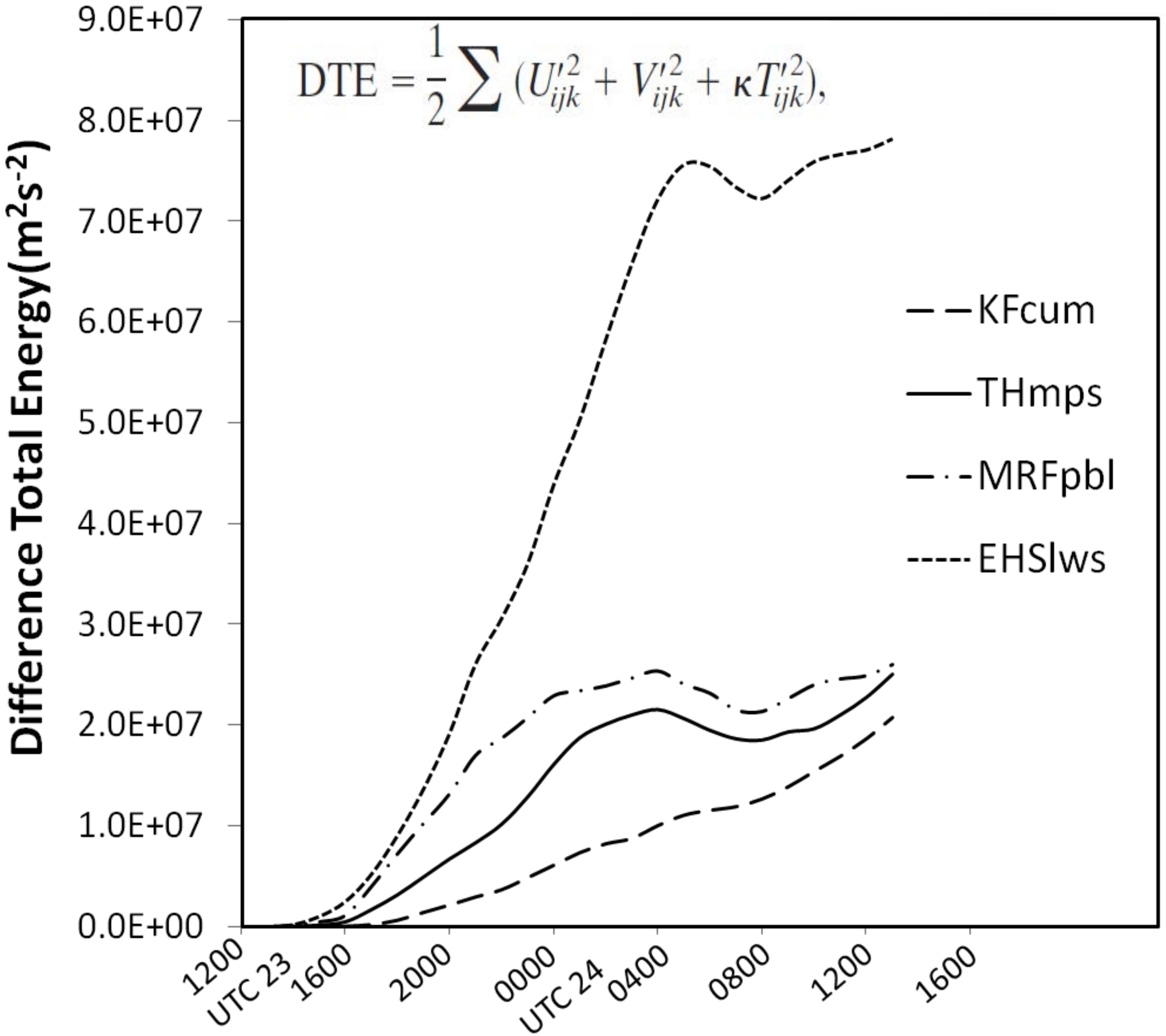
Sensitivity to physical parameterization



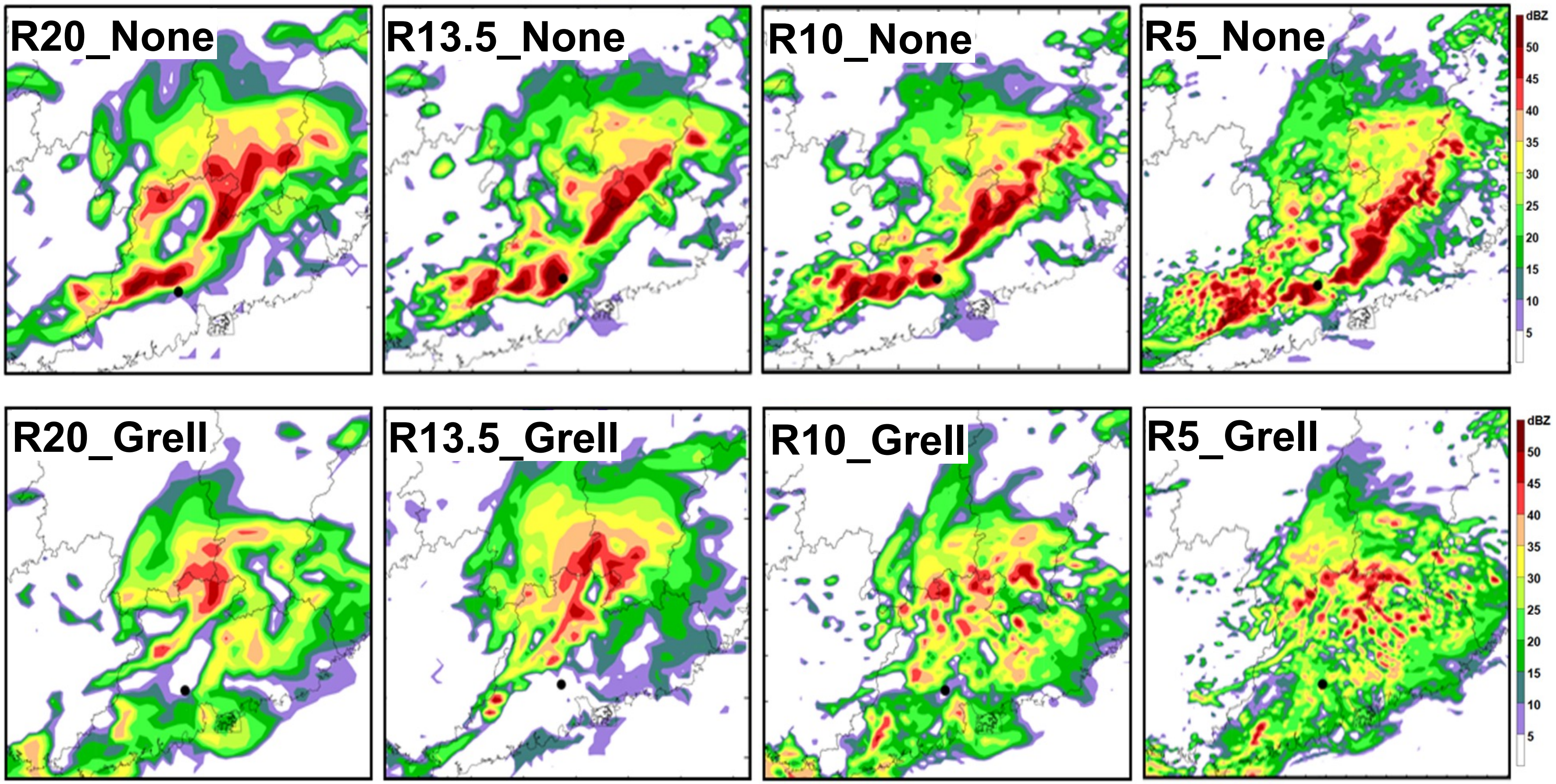
CNTL: Grell
WSM-6
YSU
NTM

Expt.	Grid Size (km)	Cumulus schemes For D1 and D2	Microphysics schemes	PBL schemes	Longwave radiation schemes
C4.5	4.5	Grell-Devenyi for D1 & D2	WSM6	YSU	rrtm
KFcum	*4.5*	***Kain-Fritsch*** for D1 & D2	WSM6	YSU	rrtm
THmps	4.5	Grell-Devenyi for D1 & D2	***Thompson***	YSU	rrtm
MRFpbl	4.5	Grell-Devenyi for D1 & D2	WSM6	***MRF***	rrtm
EHSlws	4.5	Grell-Devenyi for D1 & D2	WSM6	YSU	***EHS forcing***

Impact of physical parameterization



Sensitivity to grid size

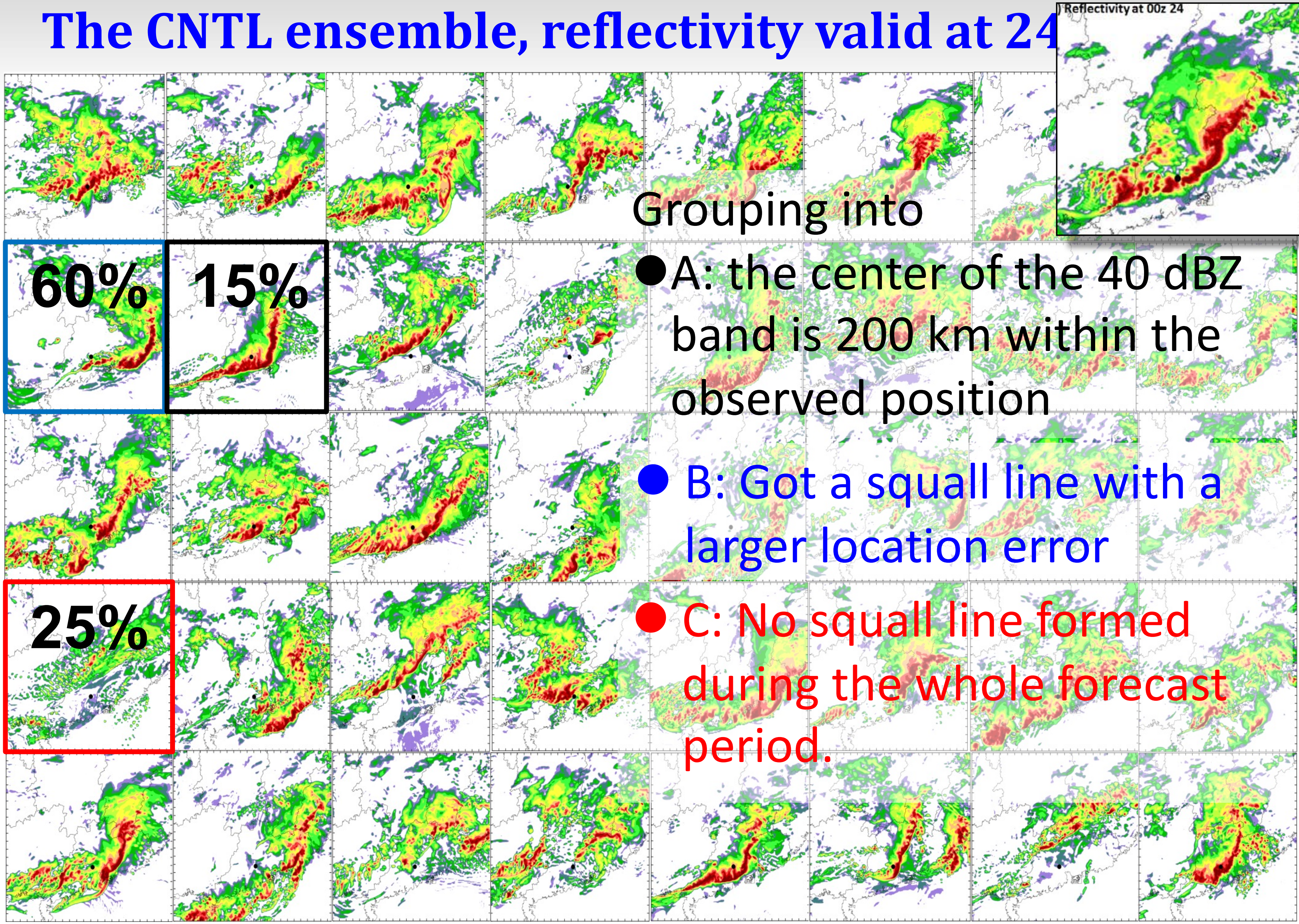


Sensitivity to initial error

Setup of ensemble forecast

- **Initial ensemble： WRF-3DVar**
- **Ensemble size： 40**
- **STD: 1K for T, 2m/s for u and v, 0.5g/kg for qv**

The CNTL ensemble, reflectivity valid at 24



Grouping into

- A: the center of the 40 dBZ band is 200 km within the observed position
- B: Got a squall line with a larger location error
- C: No squall line formed during the whole forecast period.

Splitting experiments

$$\Delta=\{\text{initial}_{good} - \text{initial}_{bad}\}/10$$

$$\text{All\_1}= \text{initial}_{bad} + \Delta * 1$$

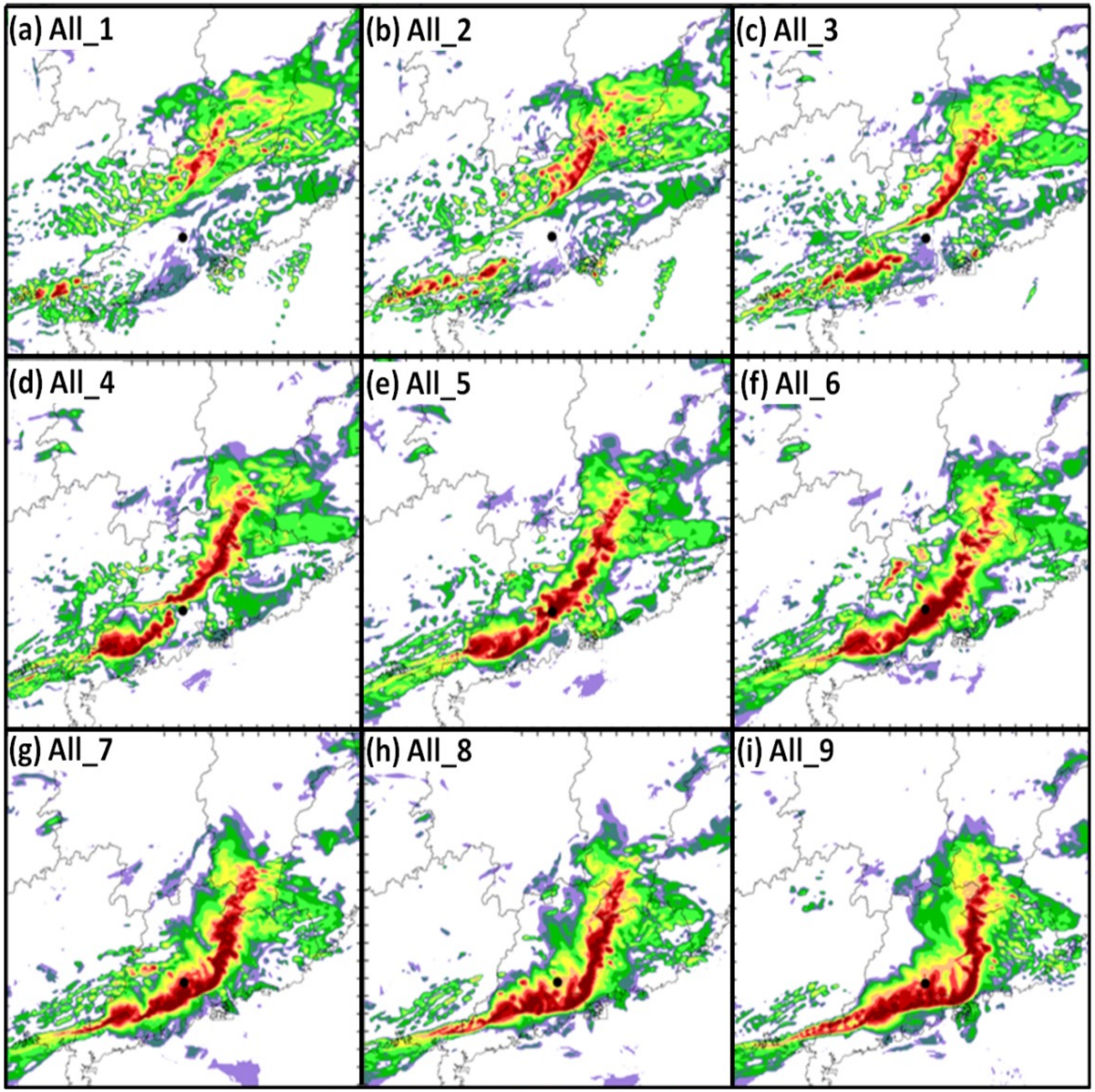
$$\text{All\_2}= \text{initial}_{bad} + \Delta * 2$$

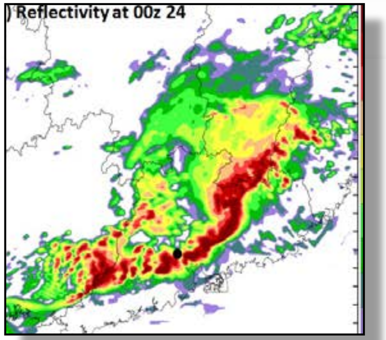
$$\vdots \qquad \vdots \qquad \vdots$$

$$\text{All\_9}= \text{initial}_{bad} + \Delta * 9$$

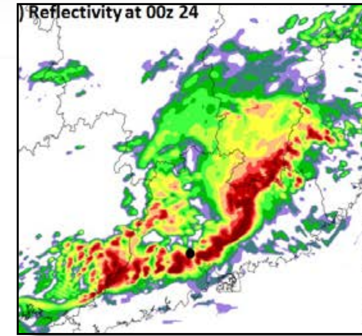
(Melhauser & Zhang 2012)

Sensitivity to the initial error: all variables





Sensitivity to the initial error: different variables

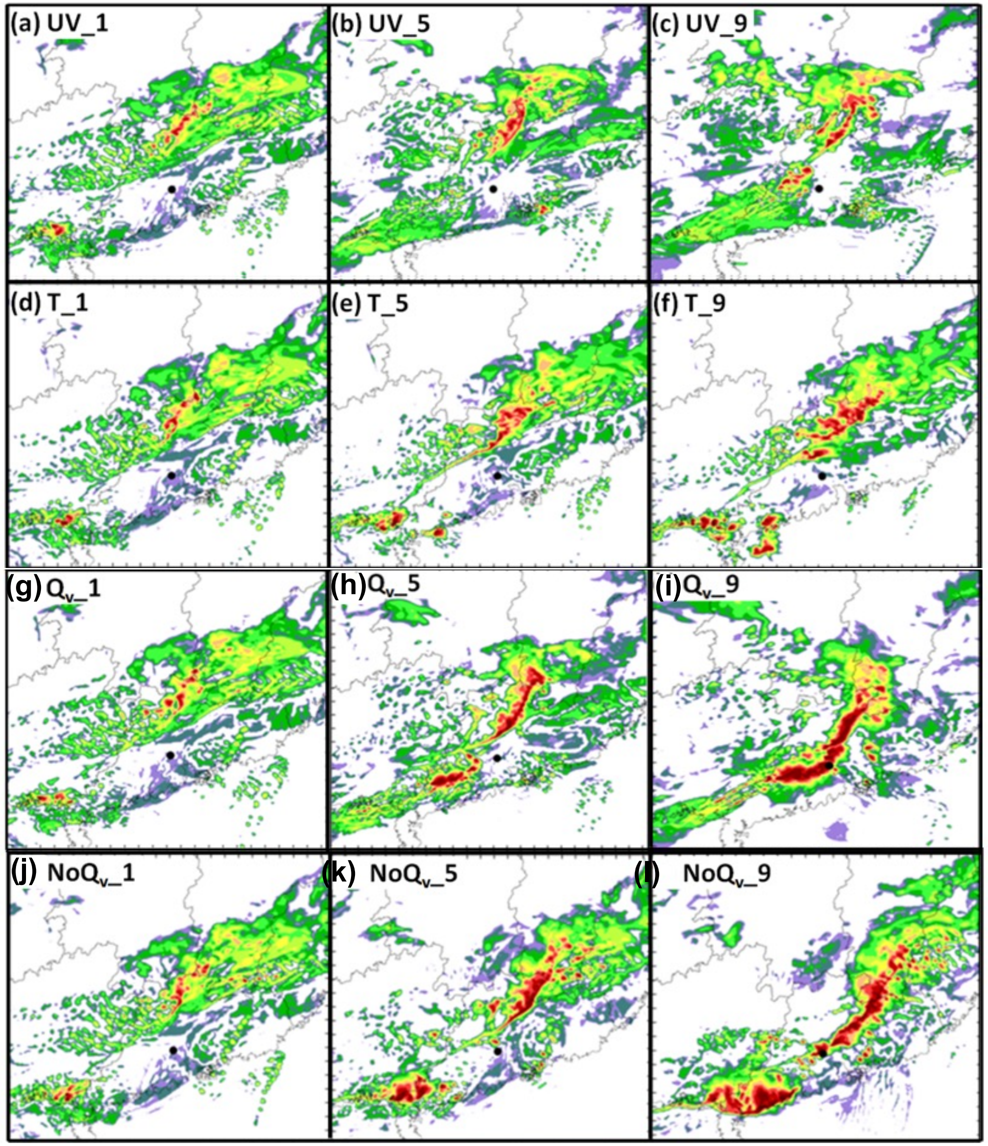


Only UV

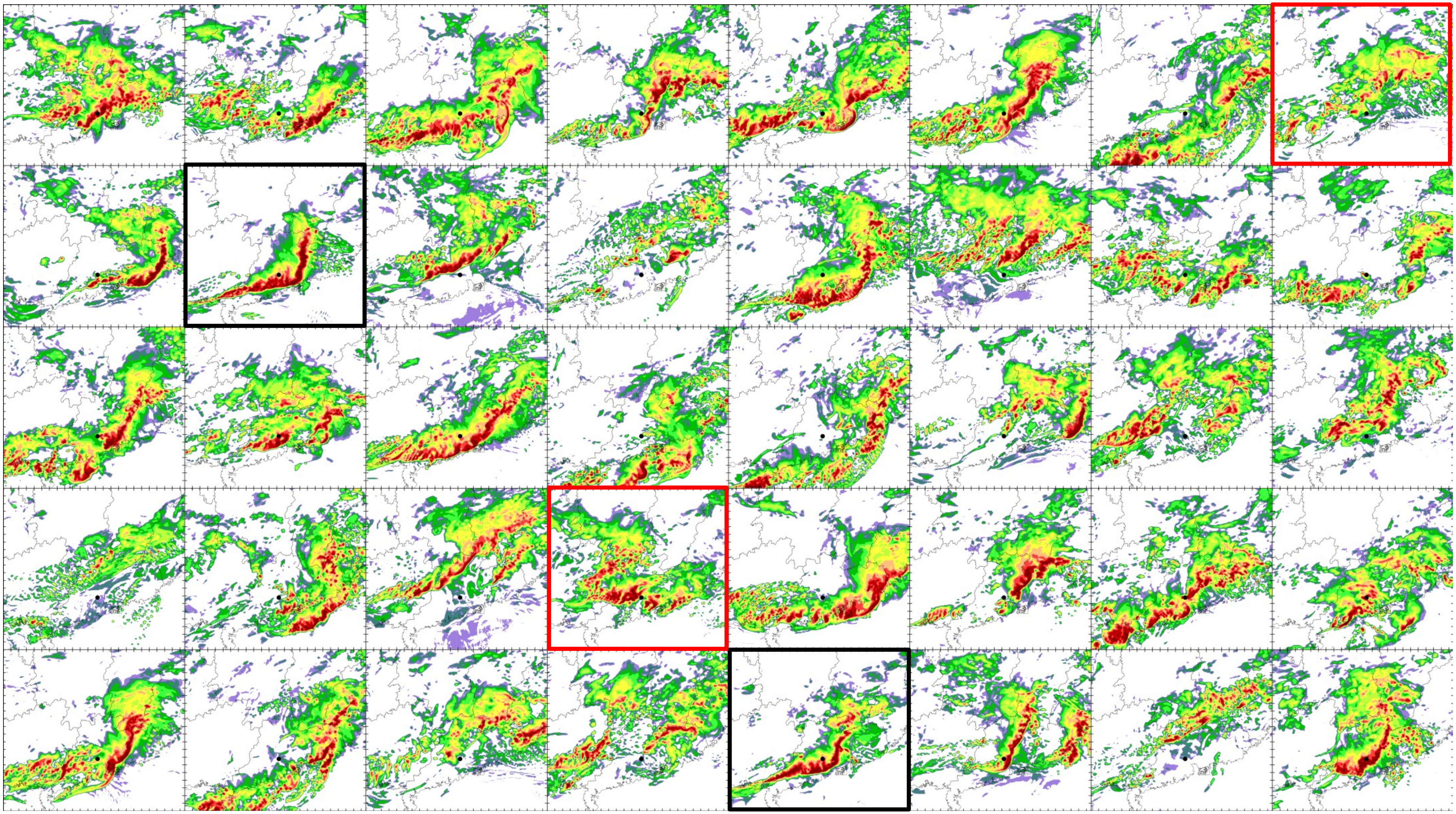
Only T

Only Qv

All but Qv



Sensitivity to the initial error: different pairs

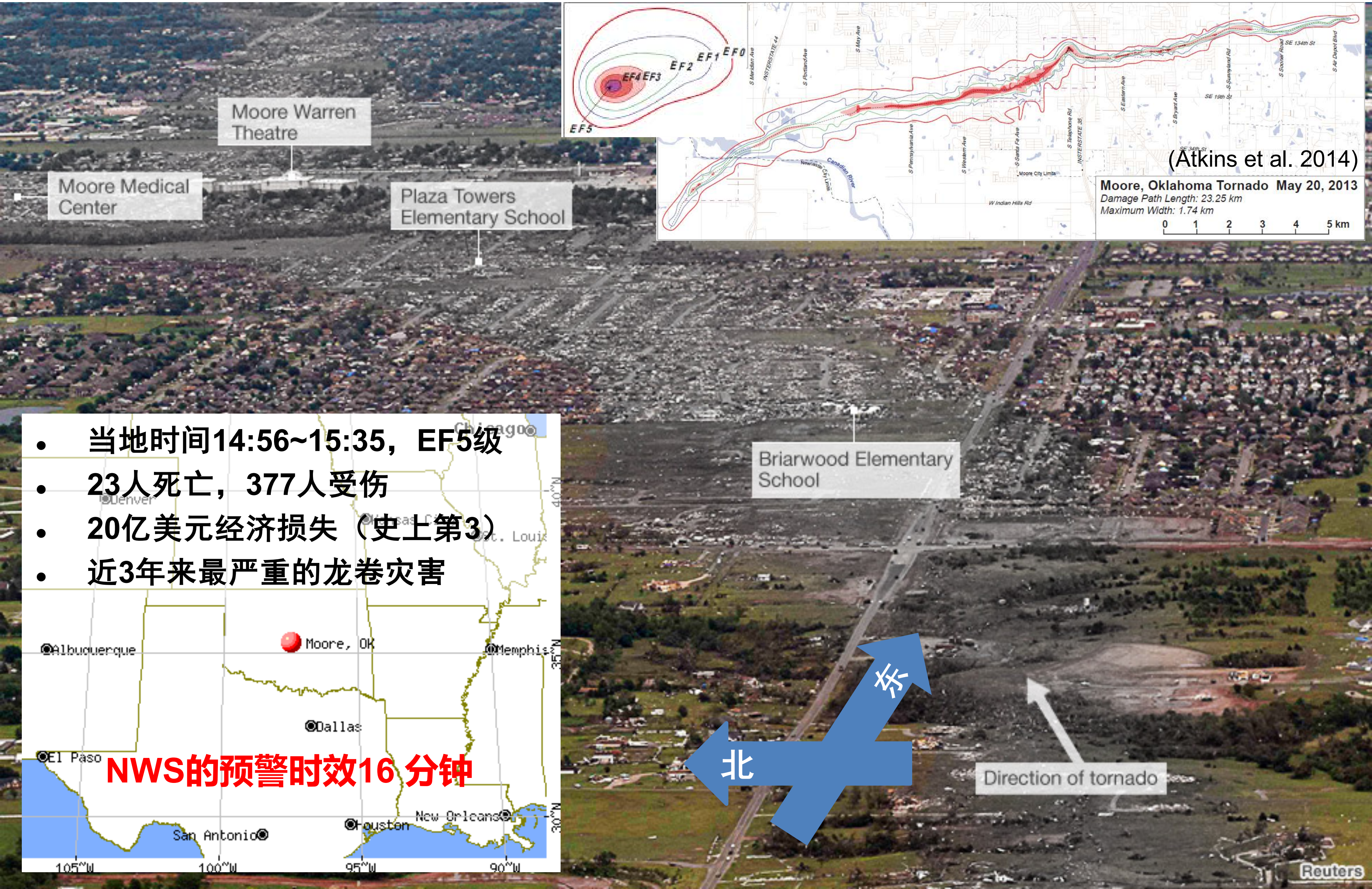


Summary

- **Model error apparently affect the predictability of the squall line**
  - Physical parameterization
  - Grid size
  - Cumulus parameterization
- **Initial error apparently affect the predictability of the squall line**
  - Linear impact
  - The moisture condition and moist processes played an important role

个例2：强对流雷暴过程

2013年5月20日穆尔（Moore）强龙卷



(Atkins et al. 2014)

- 当地时间14:56~15:35，EF5级
- 23人死亡，377人受伤
- 20亿美元经济损失（史上第3）
- 近3年来最严重的龙卷灾害

NWS的预警时效16 分钟

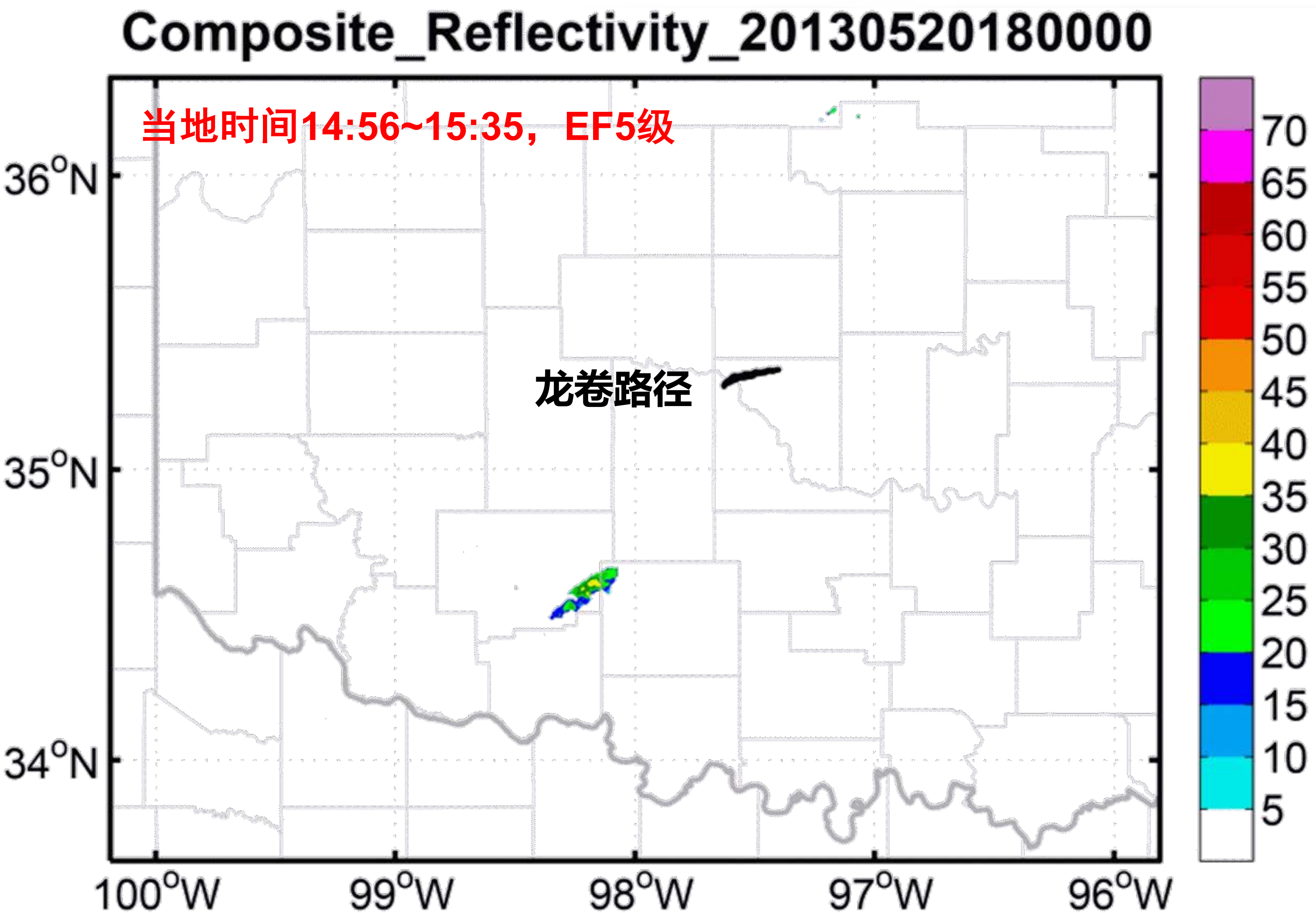
造成龙卷的雷暴天气的可预报性

以2013年5月20日美国俄克拉荷马州造成穆尔强龙卷的雷暴天气过程为基础考察

- 两种常见实际误差来源如何影响其实际可预报性
  - 初始场中天气背景条件的提前或滞后
  - 对流触发的误差
- 微小的初始误差如何影响其本性可预报性
  - 减小初始误差是否能够提高预报技巧
  - 不同尺度中的误差增长特征
  - 导致误差增长的物理过程

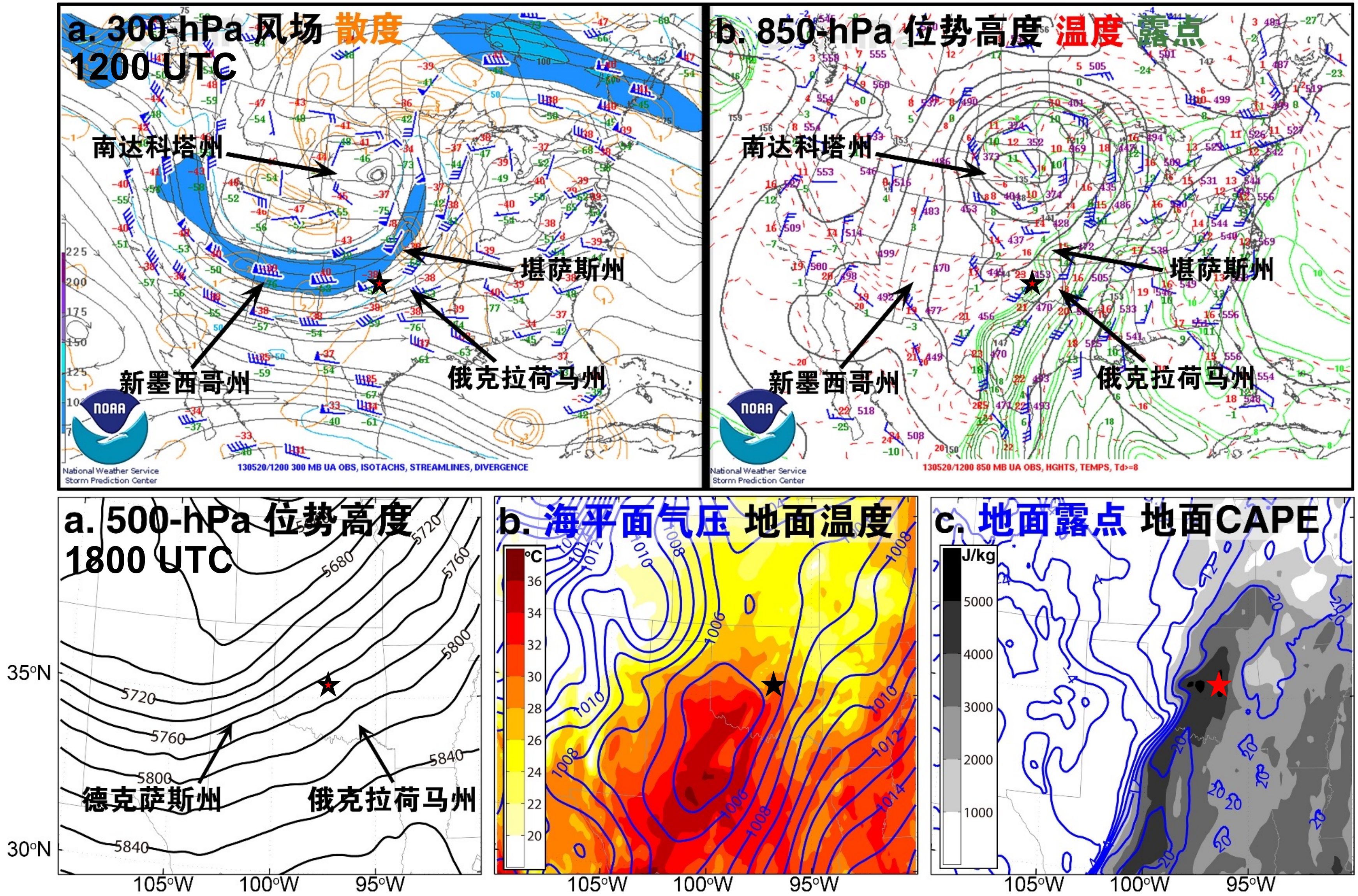
Zhang Y., F. Zhang, D. Stensrud, and Z. Meng*, 2015: Predictability of the Tornadic Thunderstorm Event in Oklahoma on 20 May 2013: Sensitivity of Convection Initiation and Organization to Small Changes in Synoptic Timing and Topographical Forcing, Monthly Weather Review, 143, 2973-2997

生成龙卷的强对流雷暴过程



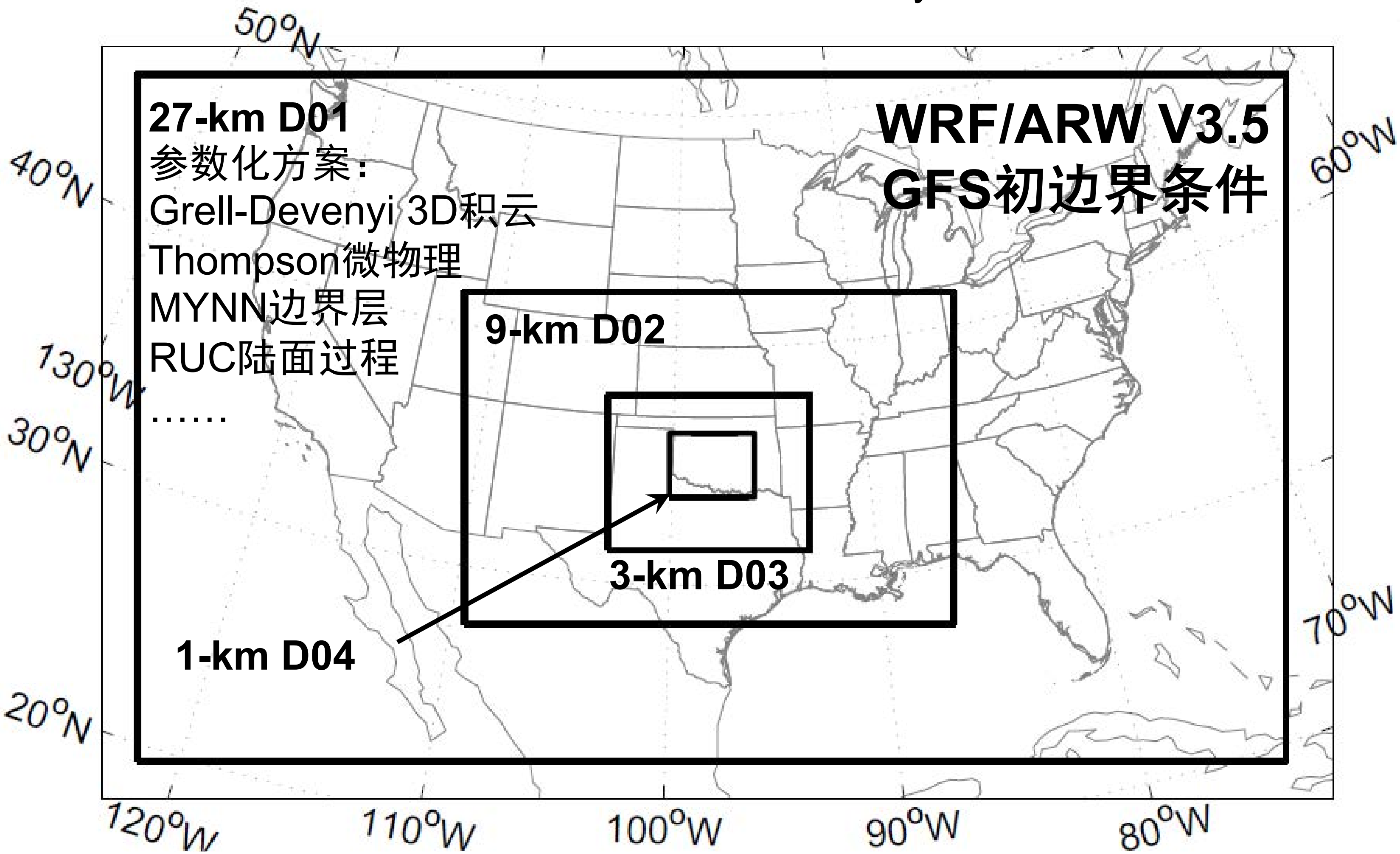
天气背景

CDT=UTC−0500



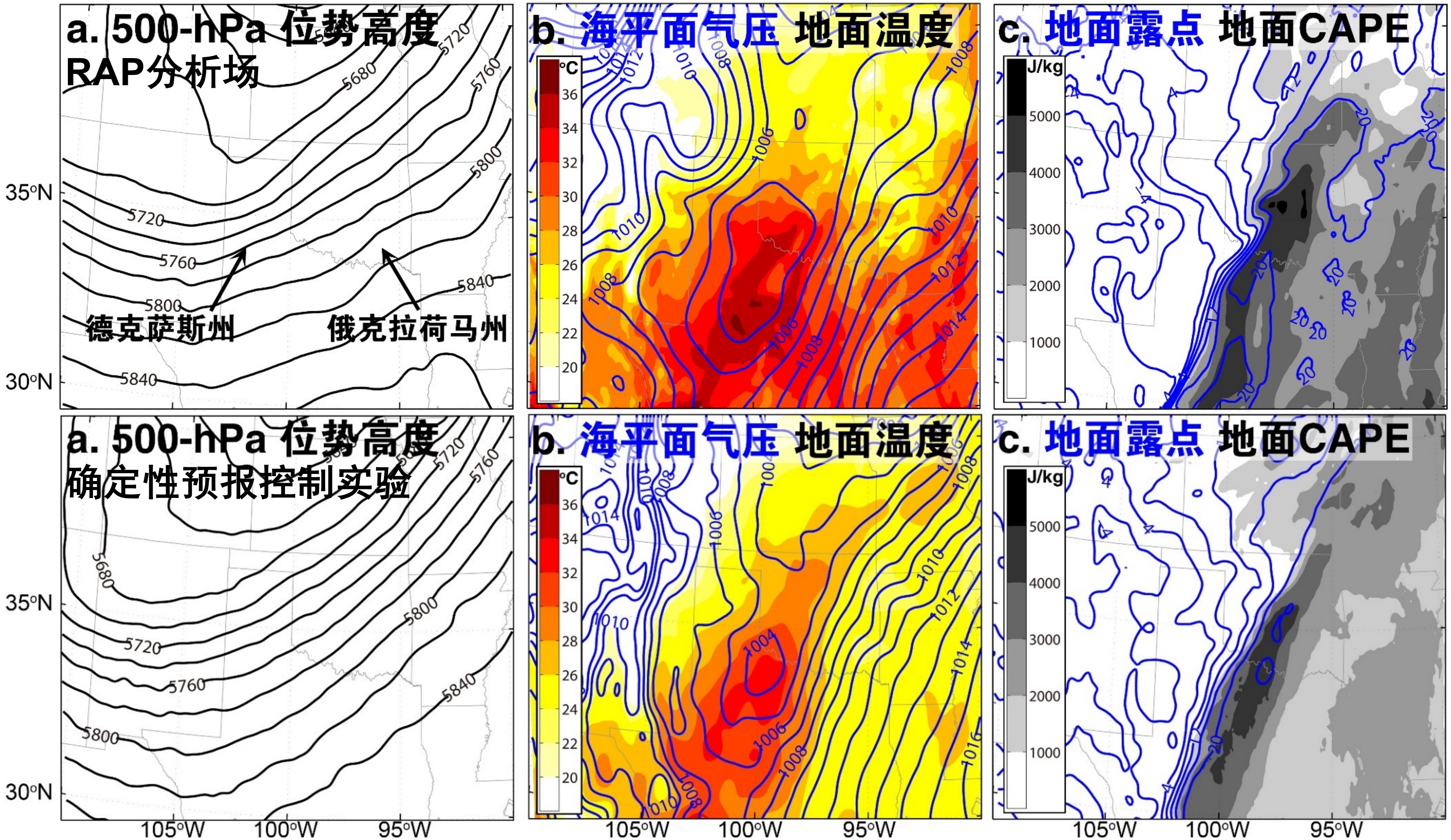
数值模式设置

“one-way nested”

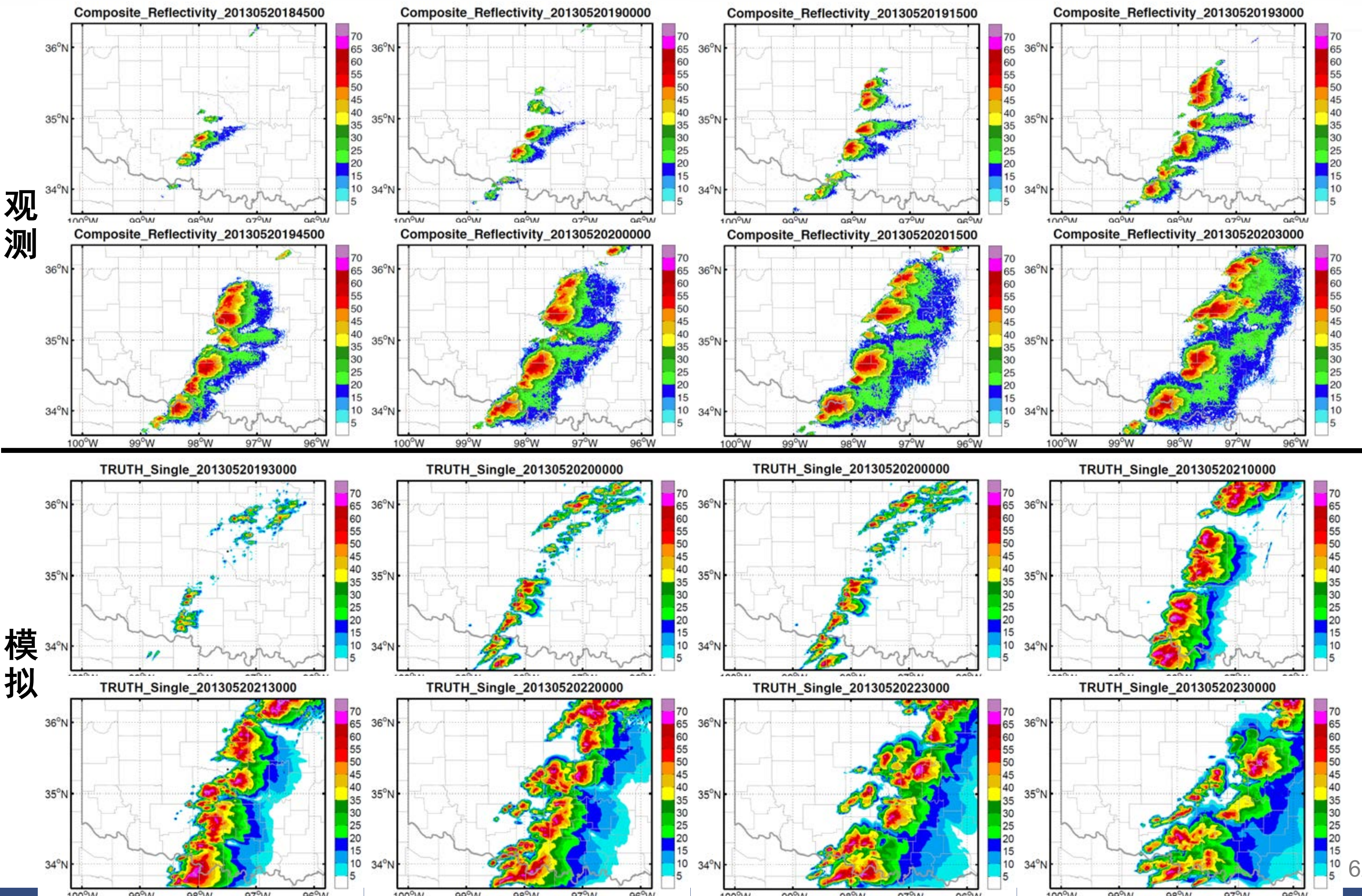


D01	D02 & D03	D04	1956~2035	
5月19日 1200 UTC	5月20日 1200 UTC	5月20日 1500 UTC	龙卷	5月21日 0000 UTC

数值模式对天气背景条件的模拟



确定性预报控制实验模拟的雷暴



可预报性

Predictability is the degree to which a correct prediction or forecast of a system's state can be made, either qualitatively or quantitatively.

强对流雷暴预警方法的变化

- 现有预警方法：Warn-on-Detection
  - 对流环境的分析、雷达观测（中气旋、勾状回波）
  - 预警时间很难进一步提高
- 探索使用高分辨率集合预报提供灾害天气预警（Warn-on-Forecast）
- 需要了解中小尺度强对流天气的可预报性

中尺度可预报性的研究进展和局限

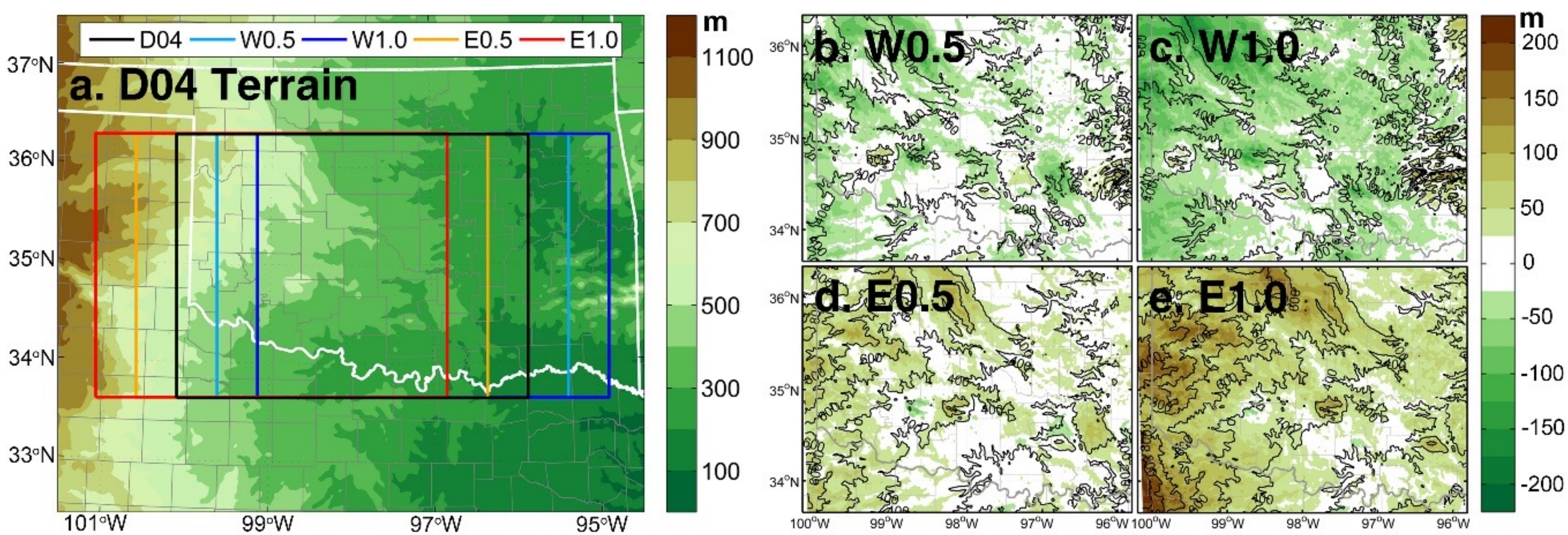
- **实际可预报性**：当前水平下对天气过程能够准确预报的最长时限
  - 多集中于中α和中β尺度
    - TC: Sippel et al. (2008), Zhang et al. (2014), etc.
    - MCS: Melhauser and Zhang (2012), Wu et al. (2013), etc.
  - 中γ尺度（雷暴尺度）多使用理想模式，较少探讨初始场中天气条件的误差如何影响雷暴预报

- **本性可预报性**：近乎完美的数值模式和初始场对天气过程能够准确预报的最长时限
  - 湿对流系统误差饱和及升尺度增长（Zhang et al. 2007）
  - 有大量的对于TC和MCS的个例研究
  - 鲜有针对强雷暴的工作

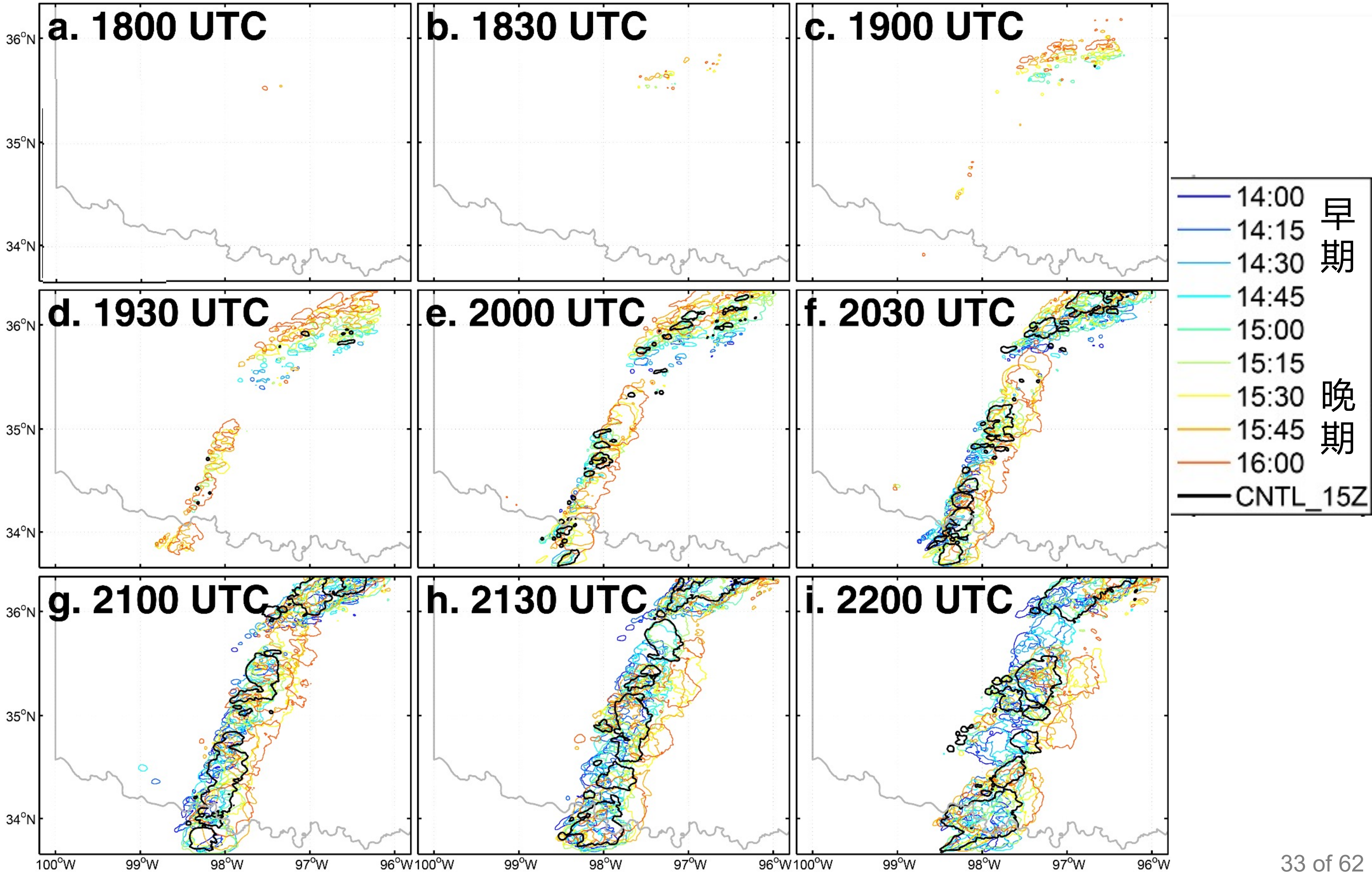
实际可预报性

- 时间错位（TIME_SHIFT）：使用1400至1600 UTC每15分钟的模式输出作为1500 UTC时的初始场，积分至0000 UTC

- 位置错位（TOPO_SHIFT）：将1500 UTC时初始场的下垫面地形向西或向东移动0.5°或1.0°，积分至0000 UTC

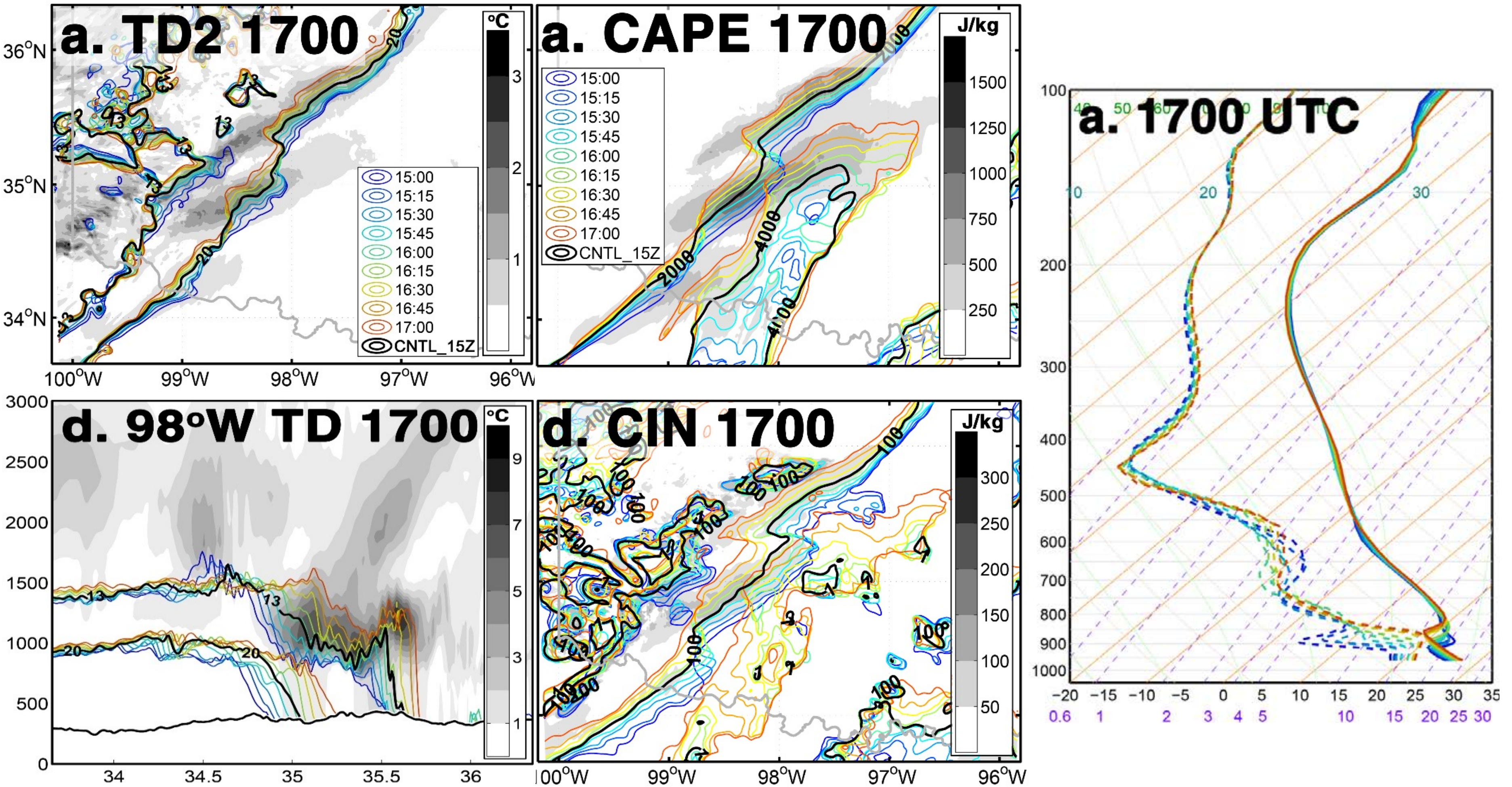


TIME_SHIFT的模拟结果



对流条件

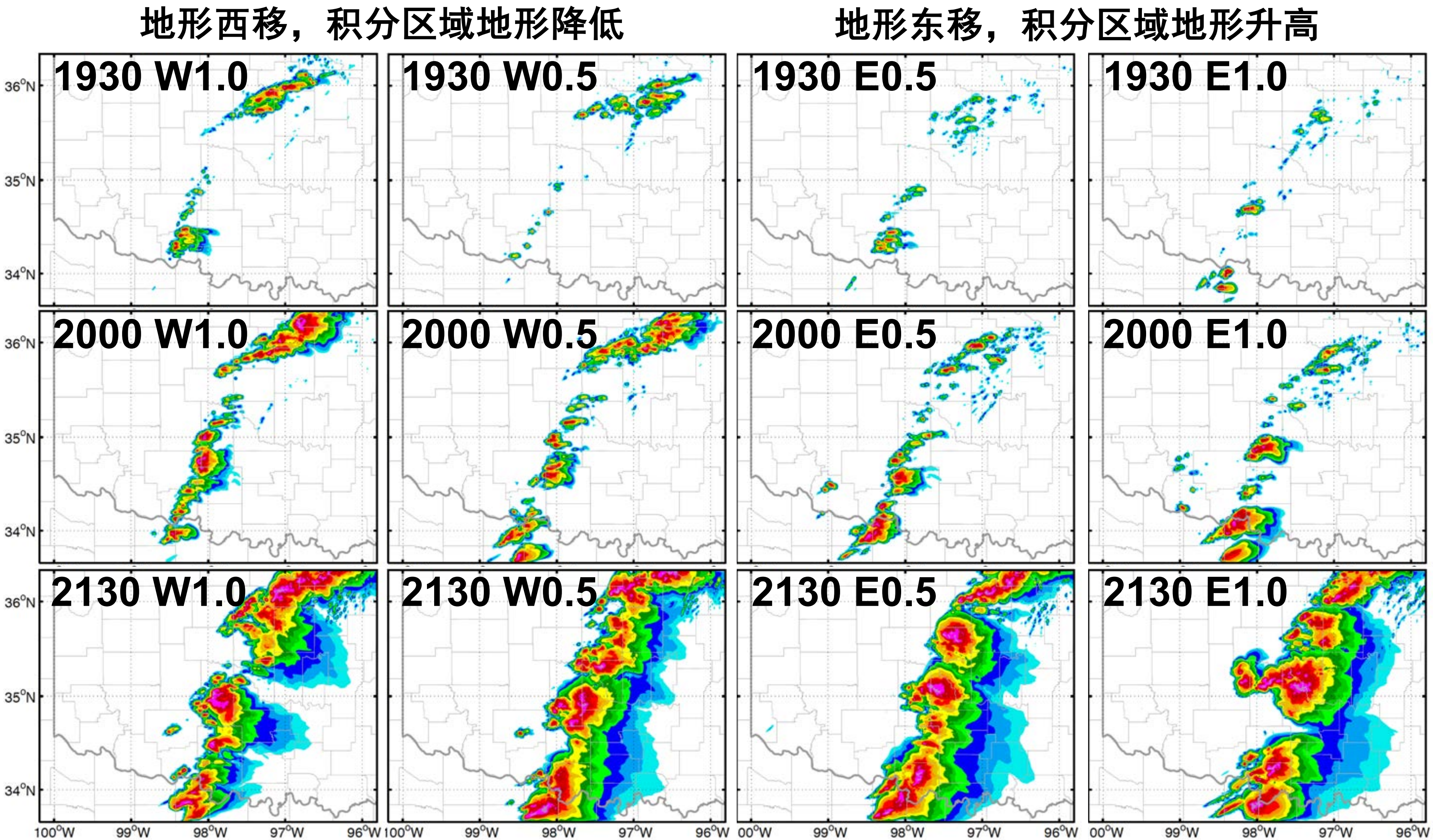
天气背景时间对边界层的**调制作用**改变不同模拟的对流条件



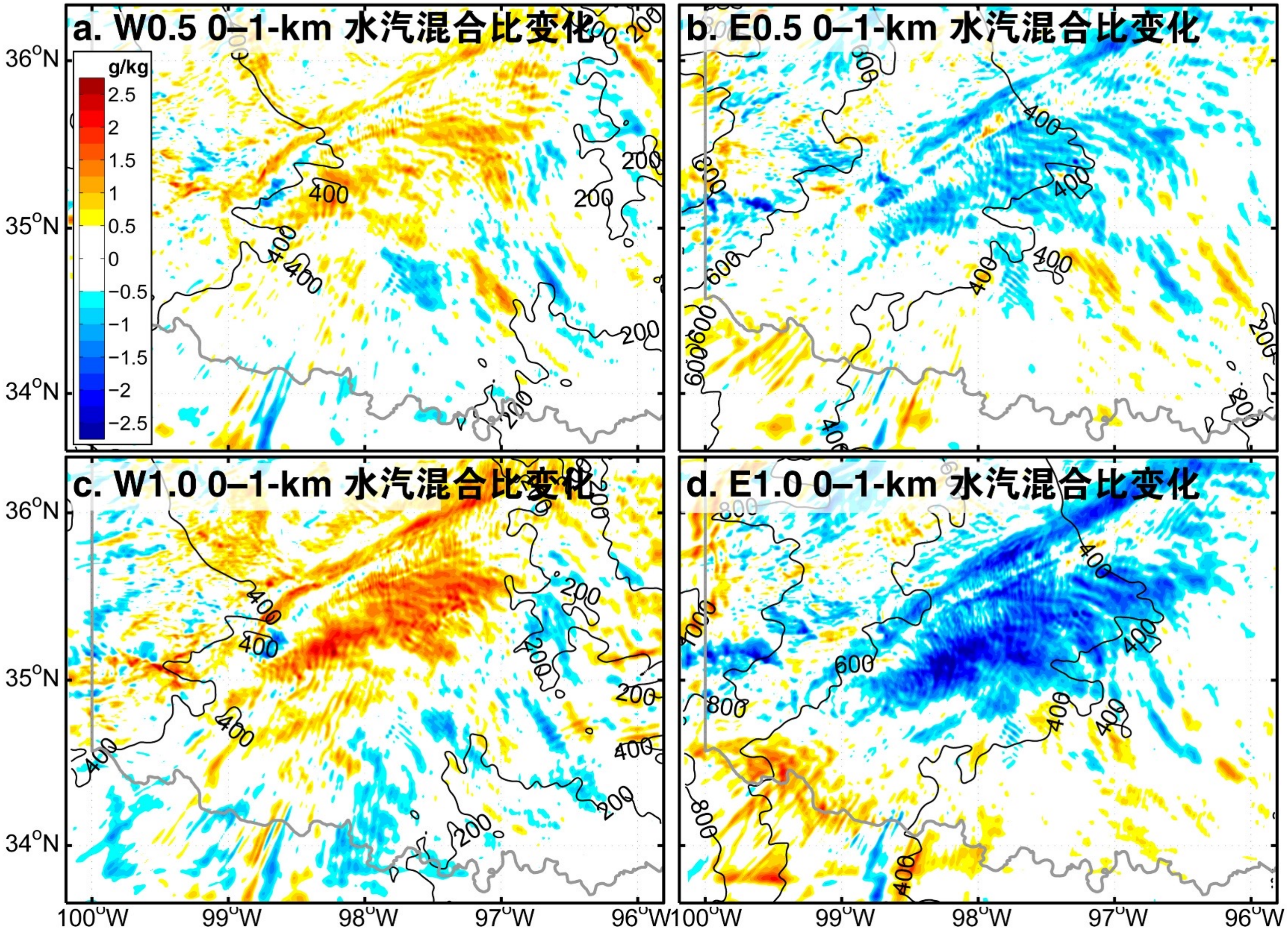
13 & 20 ℃露点温度（等值线）
及露点温度集合发散度（阴影）

2000 & 4000J/kg CAPE和1 &
100J/kg CIN及集合发散度

TOPO_SHIFT的模拟结果

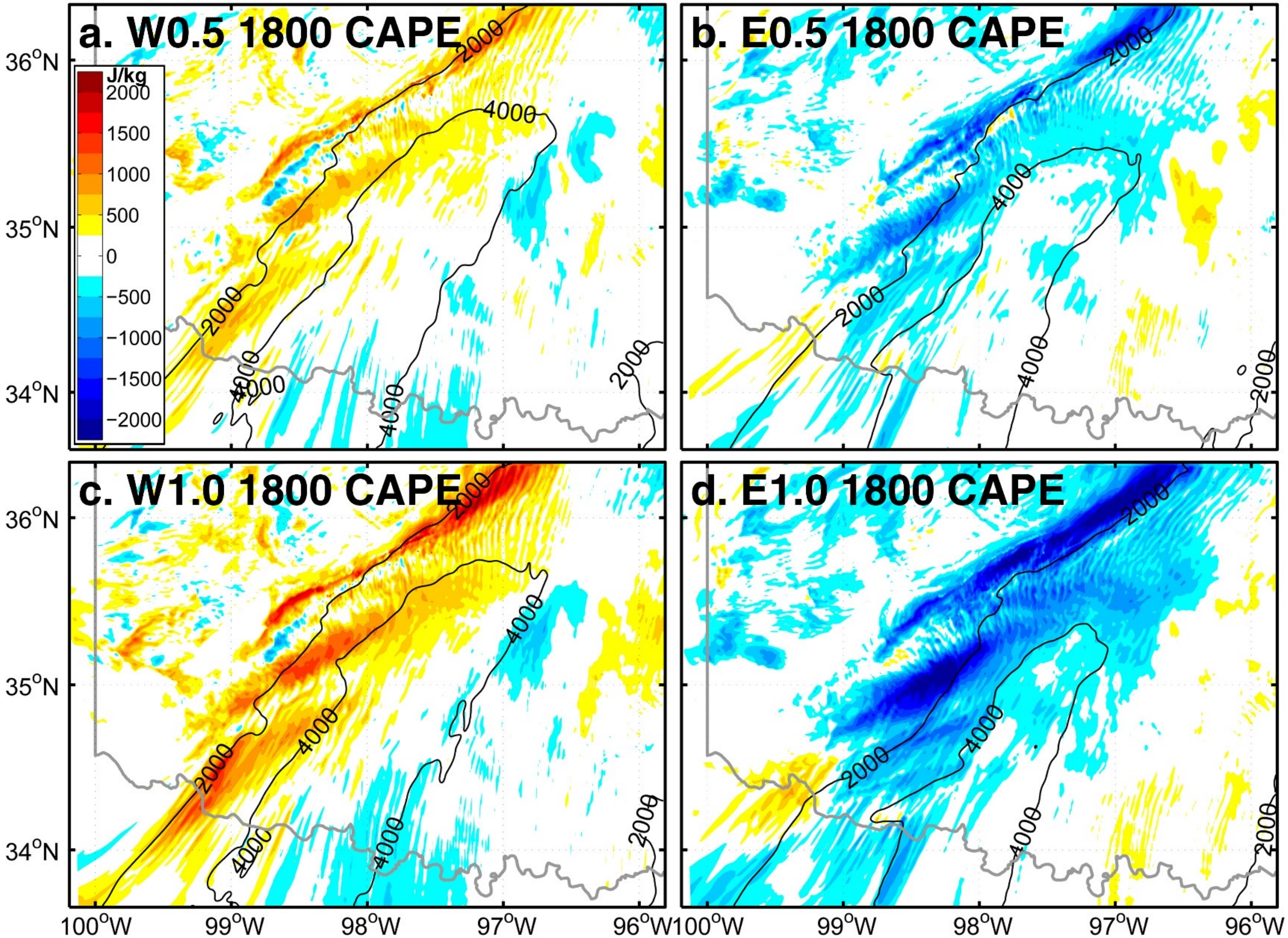


对流条件：水汽



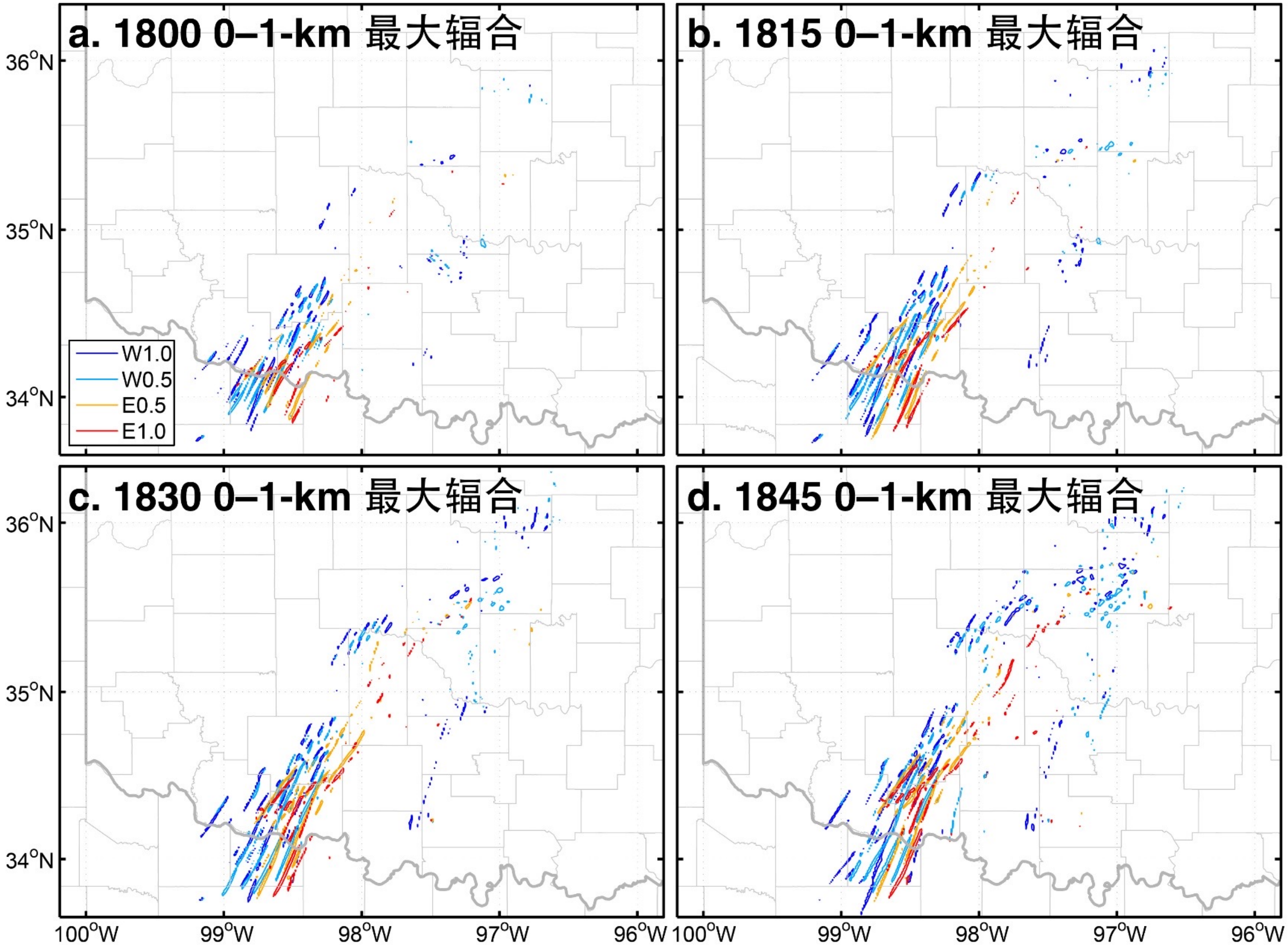
1500–1800 UTC 0–1-km平均水汽变化TOPO_SHIFT与CNTL之差

对流条件：不稳定性



CAPE TOPO_SHIFT与CNTL之差

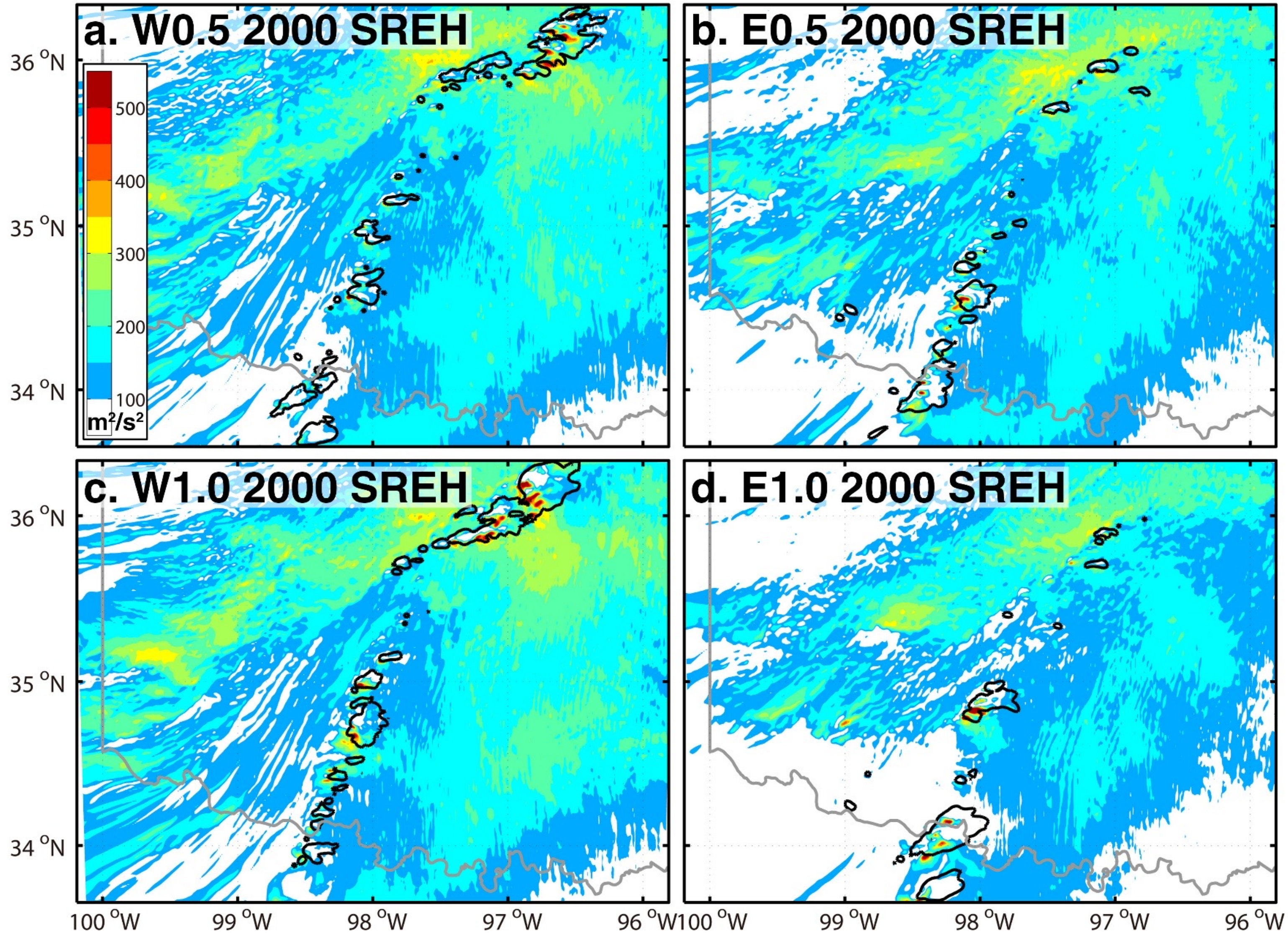
动力条件：低层辐合



TOPO_SHIFT 0–1-km最大辐合0.0015 s^{-1}等值线

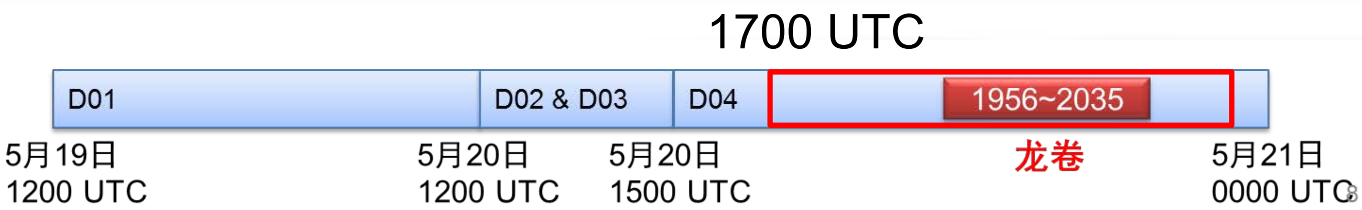
动力条件：环境螺旋度

composite reflectivity (contours)



TOPO_SHIFT雷暴相对环境螺旋度（SREH）

本性可预报性

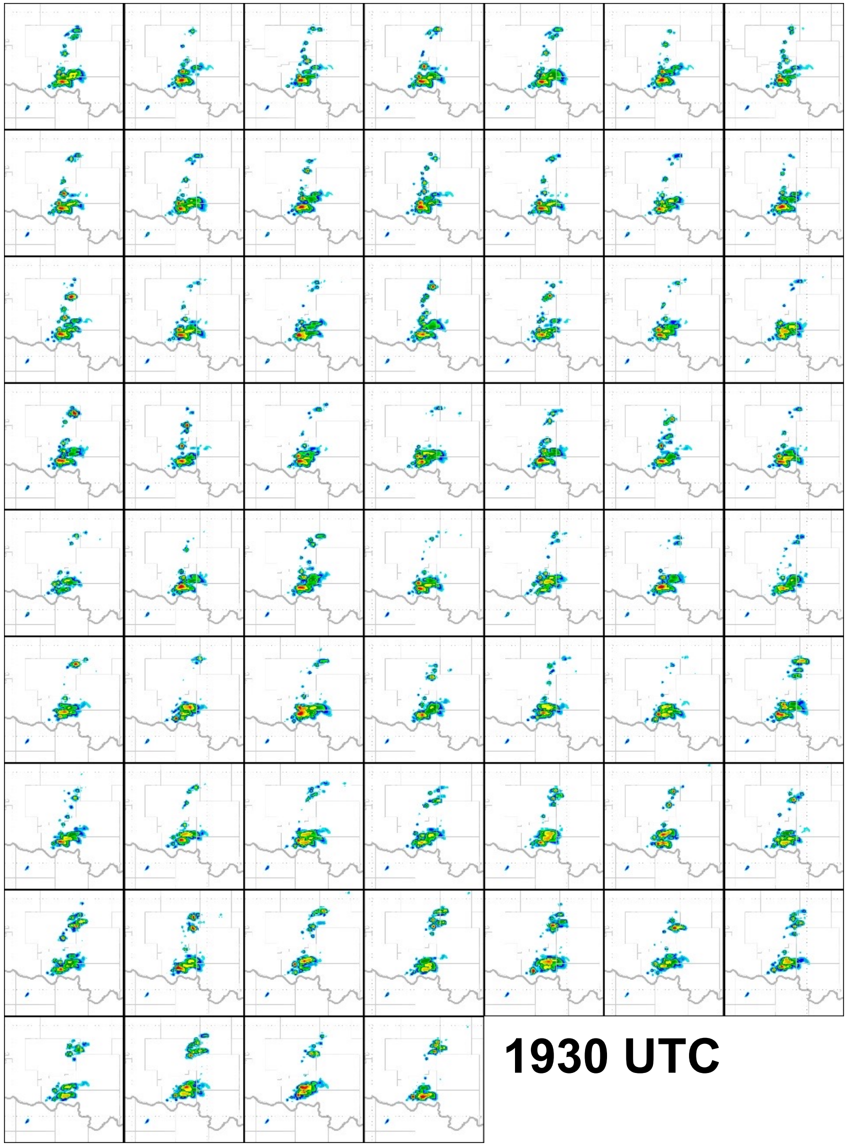


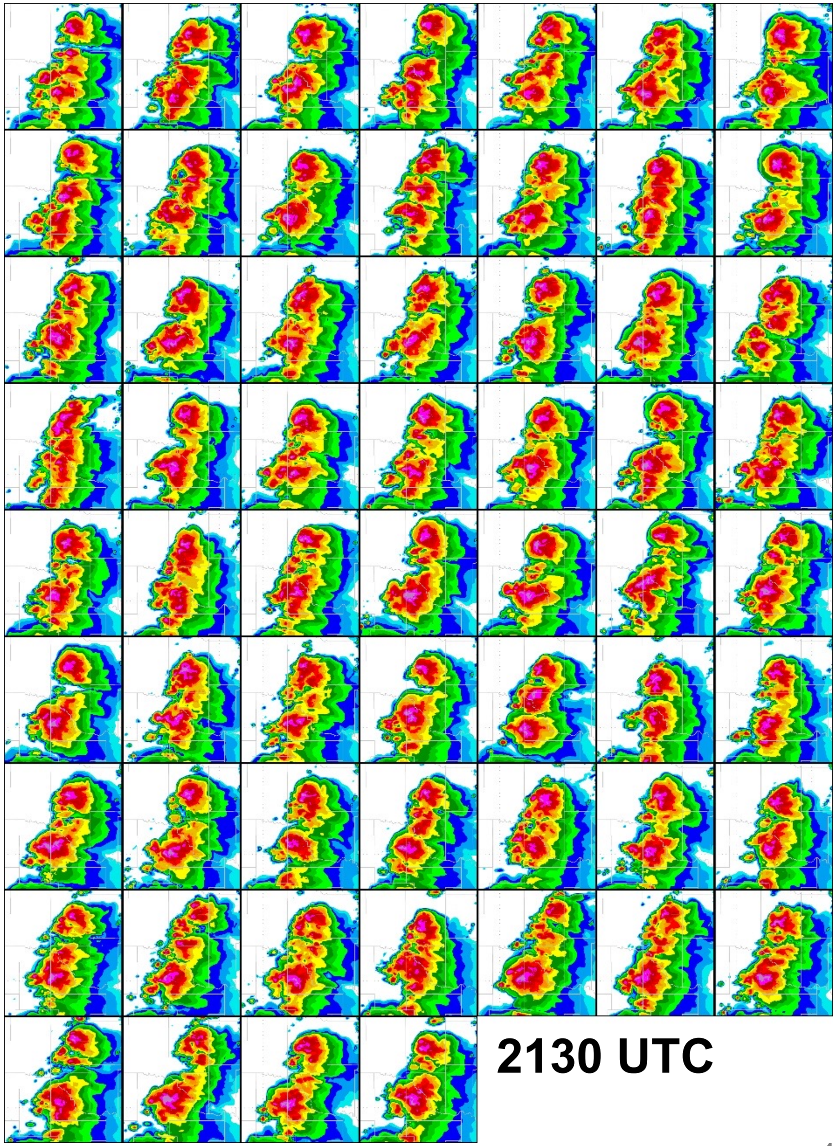
- EF_PERT：在1700 UTC时扰动生成60个集合成员的初始场，进行6小时集合预报至2300 UTC
- EF_TINY：将初始扰动缩小至10%，其余不变
- 1715 UTC时集合发散度统计特征：

		T (K)	Qv (g/kg)	U (m/s)	V (m/s)
EF_PERT 100%初始扰动	标准偏差	0.066	0.11	0.19	0.20
EF_TINY 10%初始扰动	标准偏差	0.0082	0.014	0.024	0.025

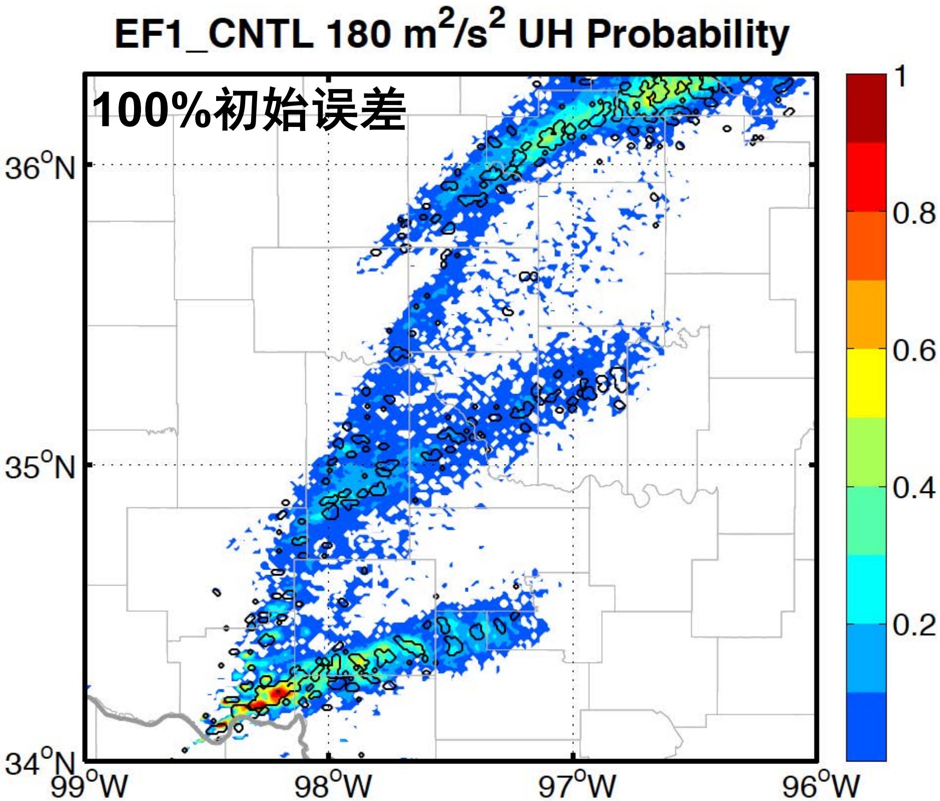
Zhang, Y., Zhang, F., Stensrud, D.J. and Meng, Z., 2016. Intrinsic predictability of the 20 May 2013 tornadic thunderstorm event in Oklahoma at storm scales. *Monthly Weather Review*, *144*(4), pp.1273-1298.

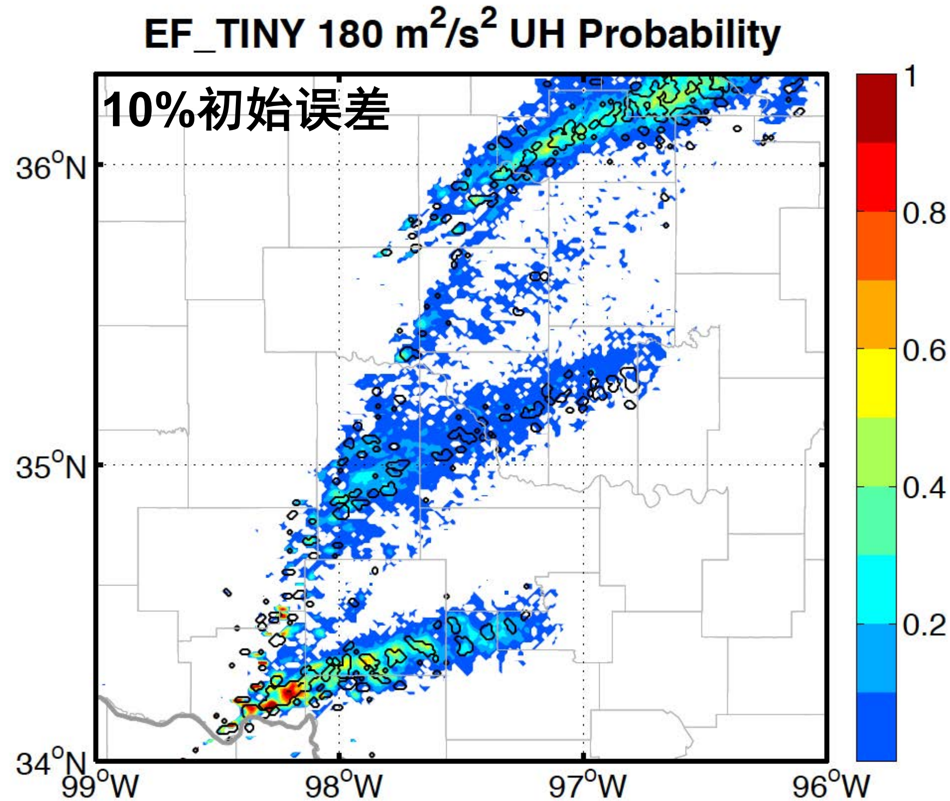
微小初始扰动带来的预报误差





对中气旋位置的概率预报

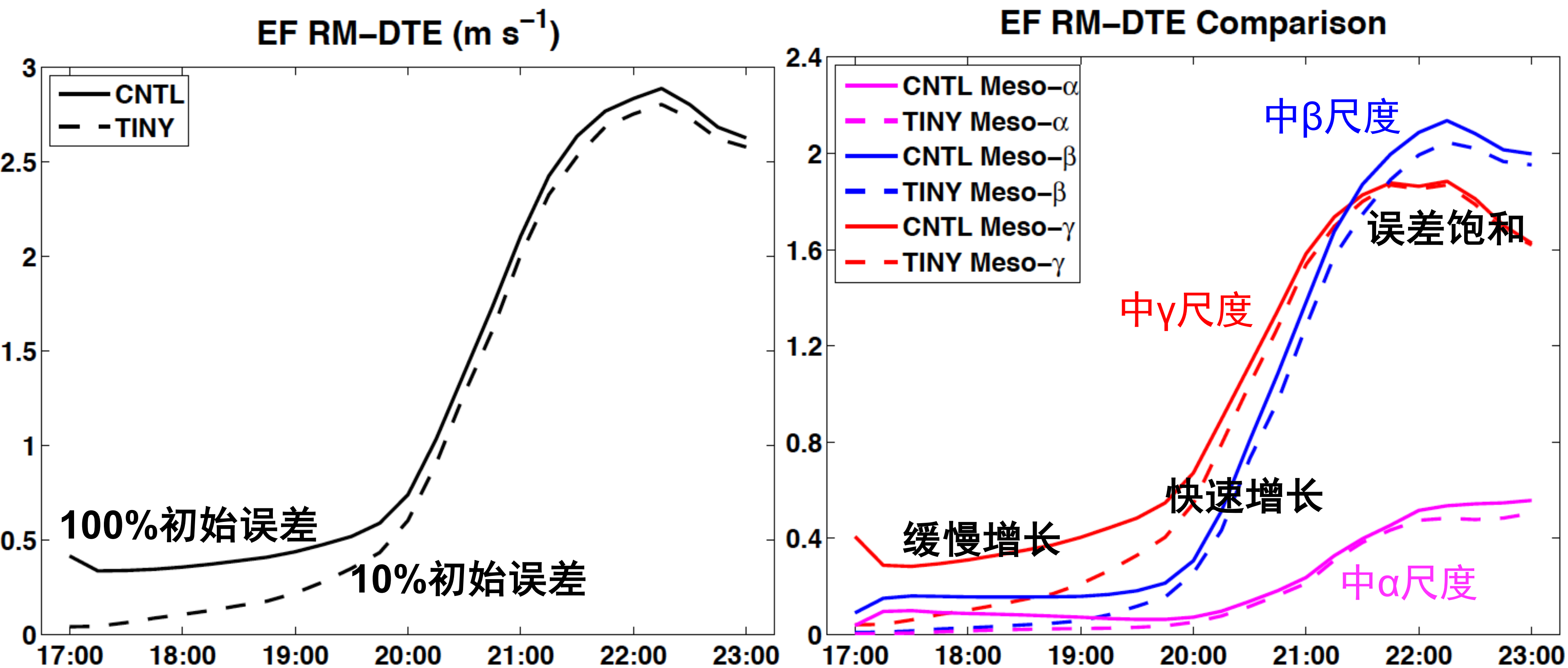




UH（updraft helicity），$\mathrm{UH} = \int_{z=2km}^{z=5km} w\zeta dz$

即使集合初始扰动减小为10%，中气旋可能的路径分布依然没有明显的变化，预报技巧并未明显提高

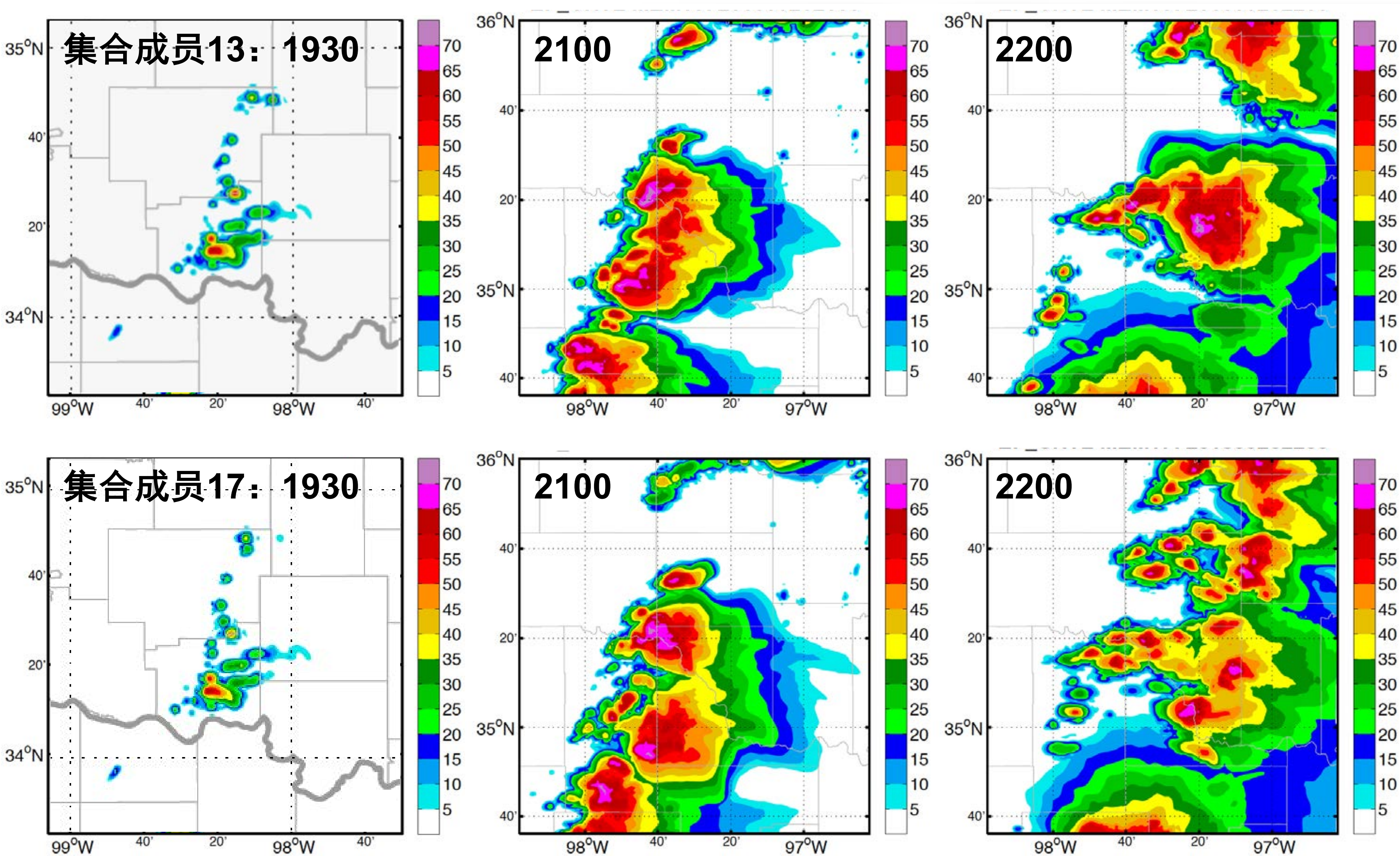
不同尺度的误差增长过程



$$DTE = \frac{1}{2}\left(u'^2 + v'^2 + \frac{c_p}{T_r}T'^2\right)$$

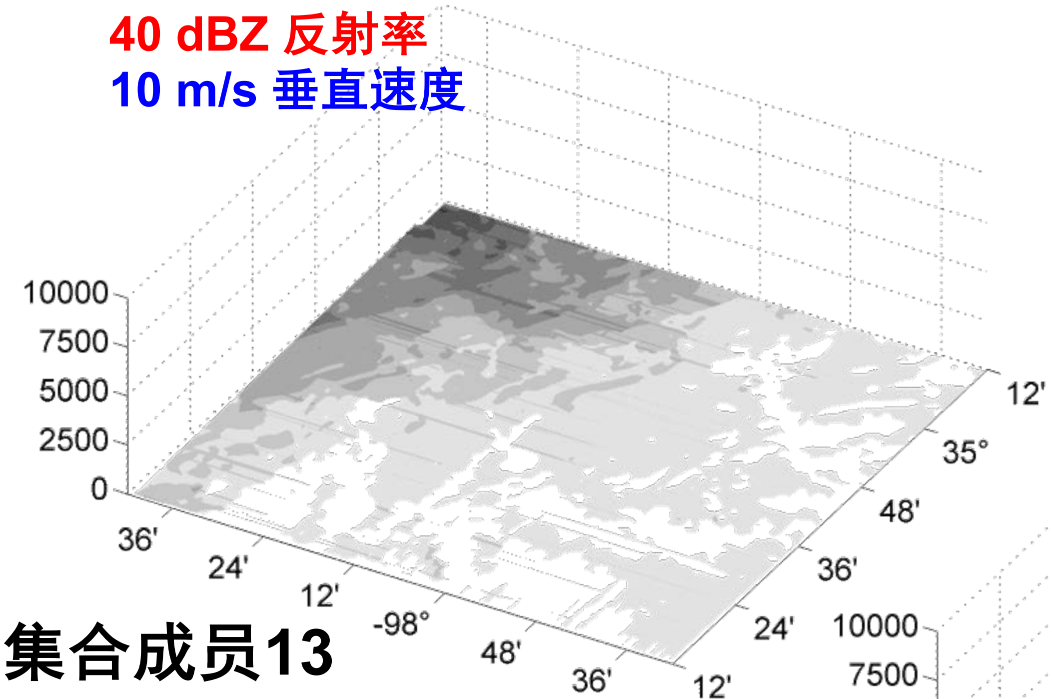
- 存在误差升尺度增长
- 深湿对流并非误差升尺度增长的必要条件
- 深湿对流会加速和放大这个过程

对两个集合成员的详细分析



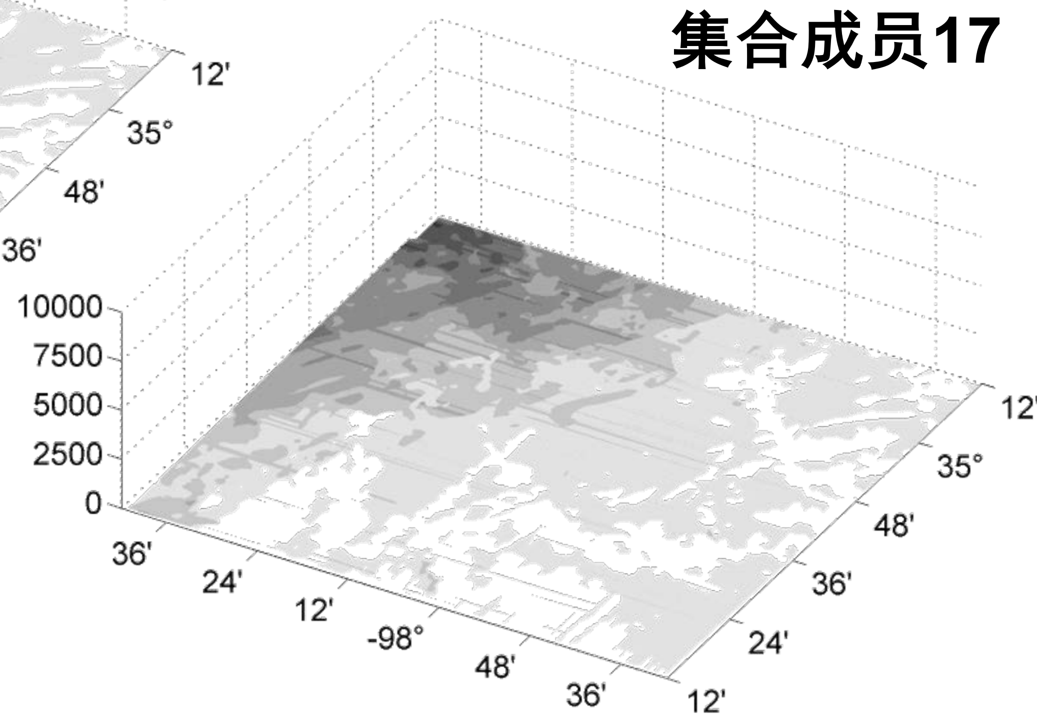
对流触发阶段

40 dBZ 反射率
10 m/s 垂直速度

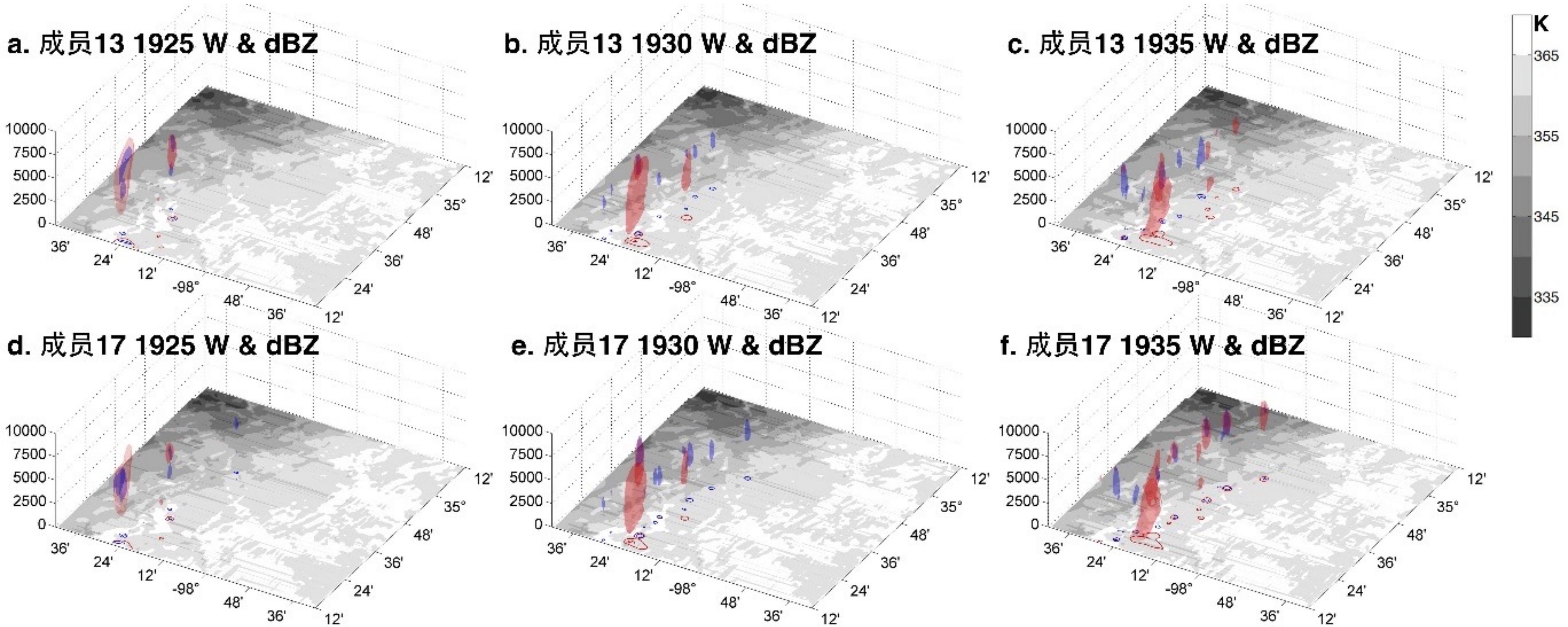


集合成员13

集合成员17

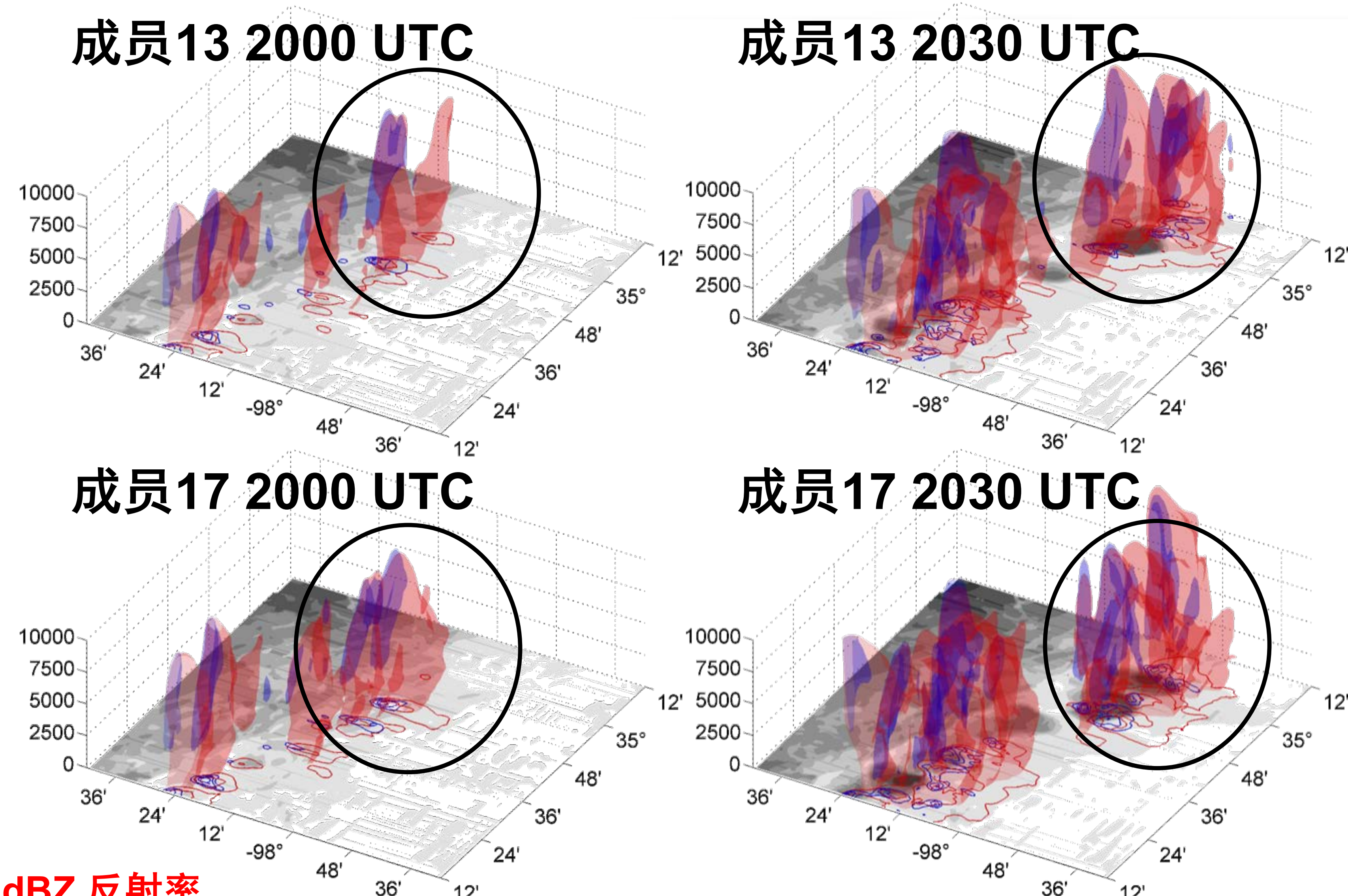


对流触发阶段



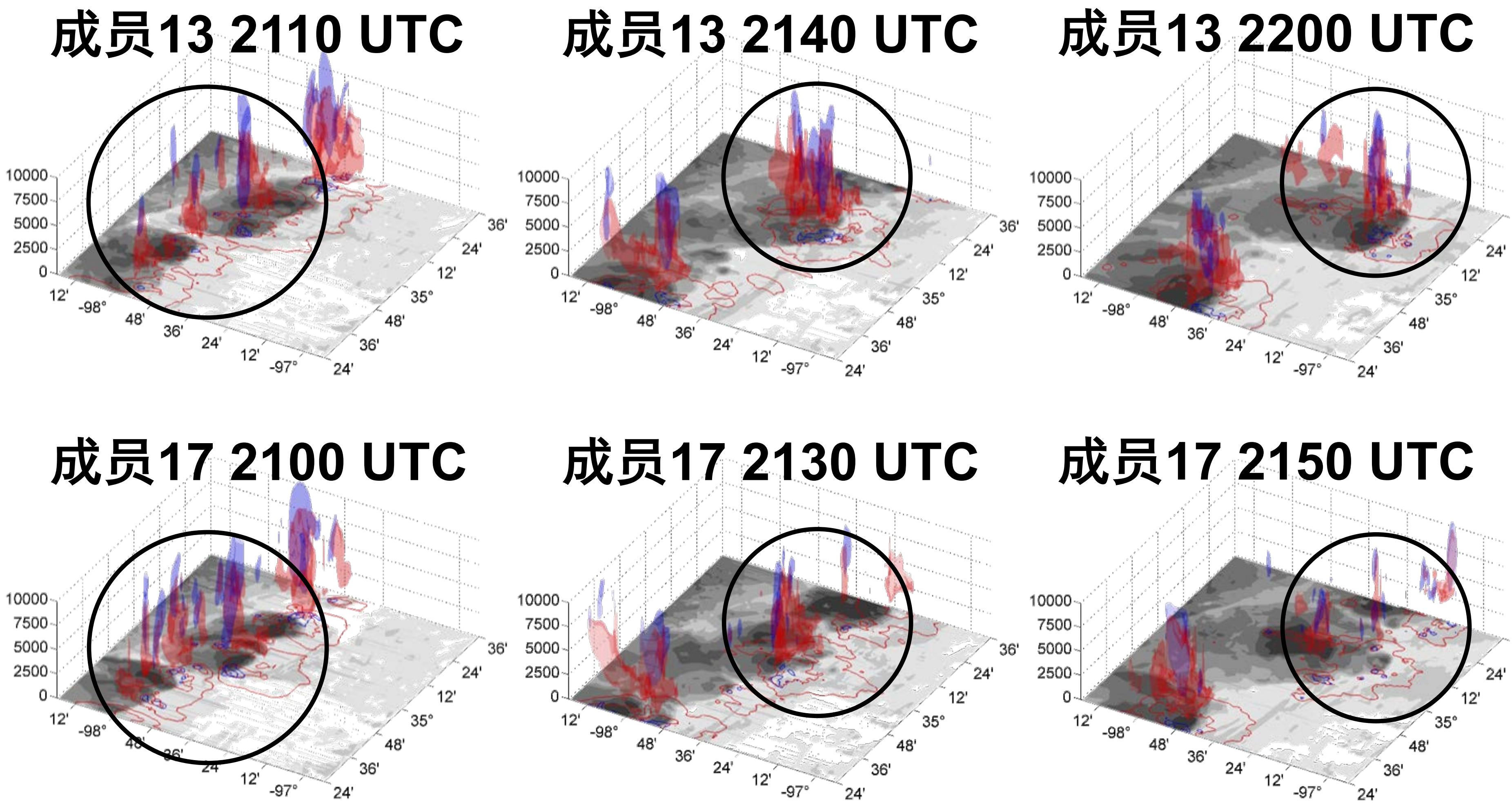
由于小尺度的湍流，对流触发的准确位置无法提前预报

对流的发展



40 dBZ 反射率
10 m/s 垂直速度

雷暴的组织和合并



60 dBZ 反射率
20 m/s 垂直速度

两个雷暴再合并前的相互位置会影响合并之后新雷暴的发展和维持

总结

- 2013年5月20日发生在美国俄克拉荷马州的强对流雷暴天气过程的可预报性与尺度有关
  - 准线性对流系统的时间范围的可预报性较强，而单体雷暴的位置、强度和结构的可预报性有限（3~6小时）
  - 初始条件中天气条件和下垫面地形的误差导致水汽、不稳定性、垂直层结等对流条件和平均风场、风切变、低层辐合等动力条件的变化，影响对流的触发和组织
  - 湿对流过程和冷池与环境的相互作用会将微小的初始误差迅速放大并升尺度增长，使得预报技巧在初始误差减小90%的情况下依旧没有显著提高

- 对于数值预报实践的意义
  - 如果对于天气背景的预报发生了时间的误差，以此为基础的模拟对流触发预报要相应地调整触发时间
  - 当模拟对流触发出现位置误差时，简单地将模式模拟的雷暴过程进行平移并不能弥补预报误差
  - 虽然强对流雷暴的本性可预报性极为有限，但是可以使用集合预报的方法，弥补初始场的不确定性
  - 提供了强对流雷暴预报可能的误差量级

集合预报

本性可预报性

- 最理想条件下的可能预报时效
- 有近乎完美的数值模式和初始条件

实际可预报性

- 当前技术条件下的最长预报水平
- 受限于数值模式和初始条件中的误差

各种误差难以避免，决定了单一模式预报的局限，需要做考虑各种不确定性的集合预报。

集合预报：飑线

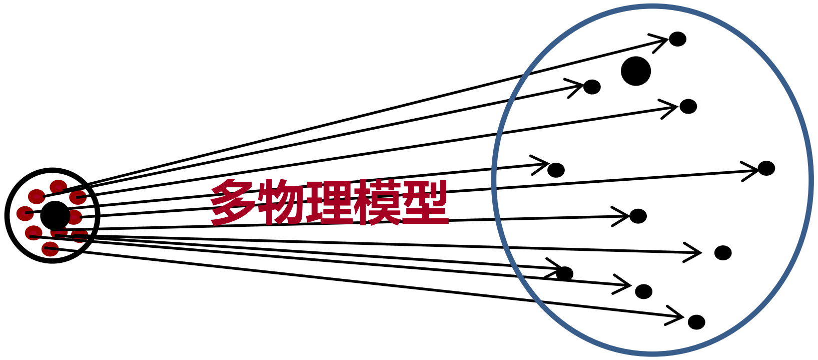
问题：如何提高飑线的预报技巧？

前人的工作：

大多仅考虑了初始场的不确定性，物理过程采用单一模型

我们的工作：

考虑物理过程的不确定性



(Wu，Meng，Yan, AAS, 2013)

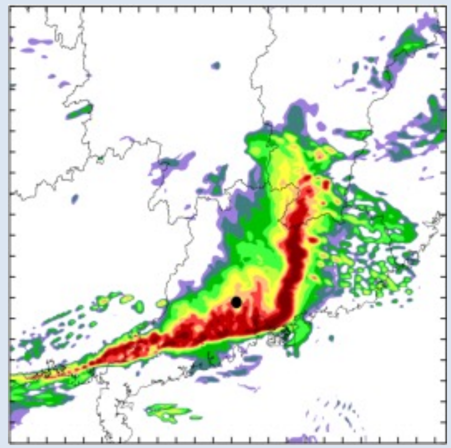
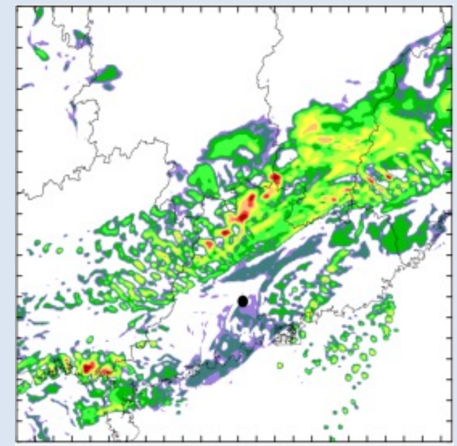
Impact of using a multi-scheme on the predictability

Model configuration of Multi-scheme

No. of members using a cumulus scheme and the scheme used	No. of members using a microphysics scheme and the scheme used	No. of members using the PBL scheme and the scheme used	No. of members using the longwave scheme and the scheme used
13, Kain-Fritsch	4, Lin et al.	1,YSU;2,ETA;1,MRF	3,rrtm;1,cam
	4, Thompson et al.	1,YSU;2,ETA;1,MRF	3,rrtm;1,cam
	5, WSM six-class graupel	2,YSU;2,ETA;1,MRF	3,rrtm;2,cam
13, Betts-Miller	4, Lin et al.	1,YSU;2,ETA;1,MRF	3,rrtm;1,cam
	4, Thompson et al.	1,YSU;2,ETA;1,MRF	3,rrtm;1,cam
	5, WSM six-class graupel	2,YSU;2,ETA;1,MRF	3,rrtm;2,cam
14, Grell-Devenyi	4, Lin et al.	1,YSU;2,ETA;1,MRF	3,rrtm;1,cam
	5, Thompson et al.	2,YSU;2,ETA;1,MRF	3,rrtm;2,cam
	5, WSM six-class graupel	2,YSU;2,ETA;1,MRF	3,rrtm;2,cam

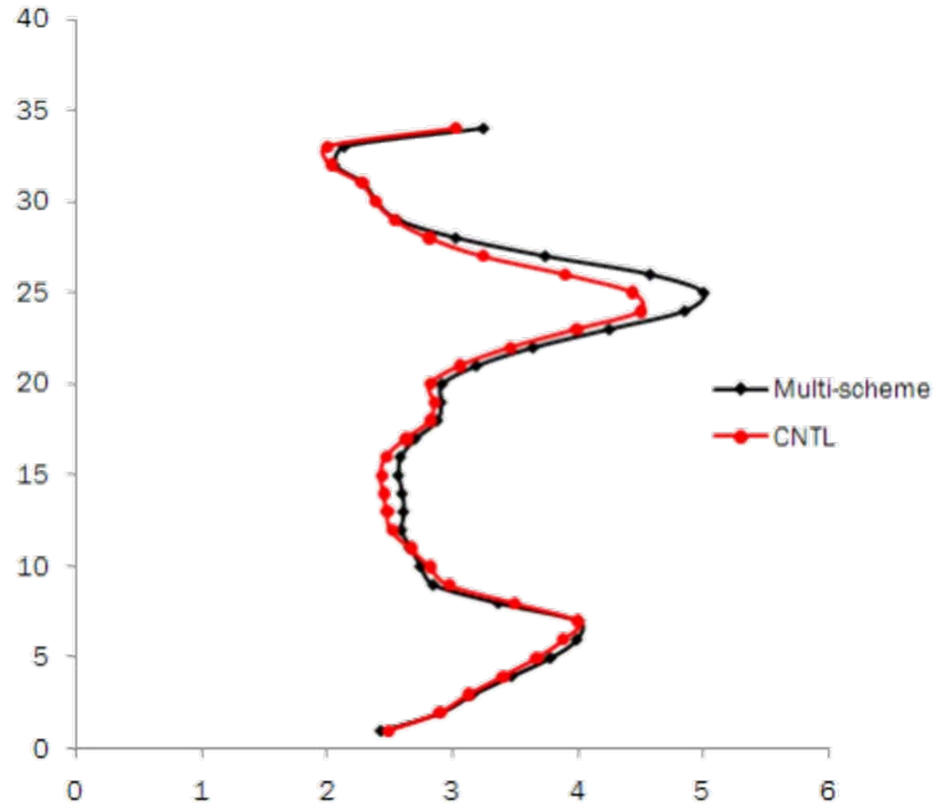
(Wu, Meng, Yan , AAS, 2012)

飑线的可预报性

	预报出飑线 	没报出飑线 
单物理模型	75%	25%
多物理模型	85%	15%

(Wu，Meng，Yan, AAS, 2013)

Ensemble spread of Multi vs. Single



U(m/s), 24/00z

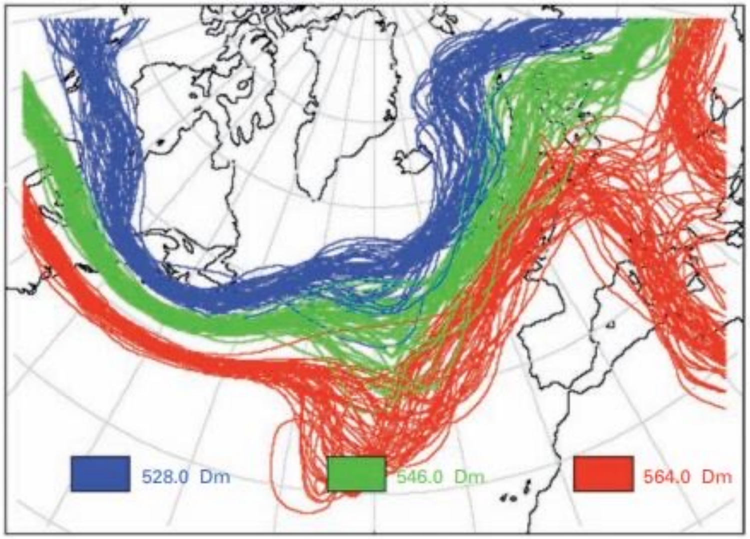
Summary

- **Model error apparently affect the predictability of the squall line**
  - Physical parameterization
  - Grid size
  - Cumulus parameterization
- **Initial error apparently affect the predictability of the squall line**
  - Linear impact
  - The moisture condition and moist processes played an important role
- **Adding physical perturbation helped to improve the forecast skill**

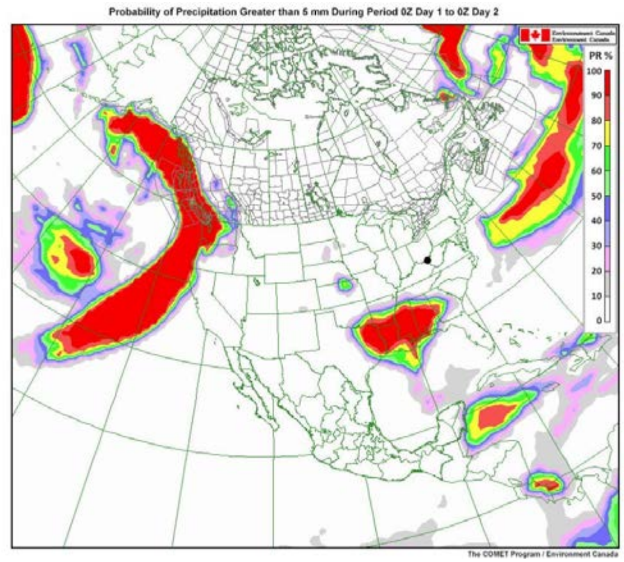
集合预报：台风

集合预报：平均场+可信度+发生概率

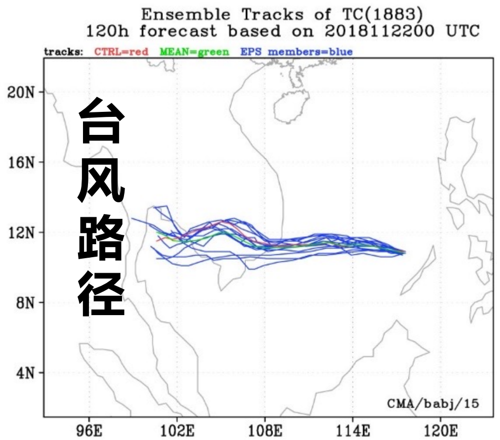
面条图



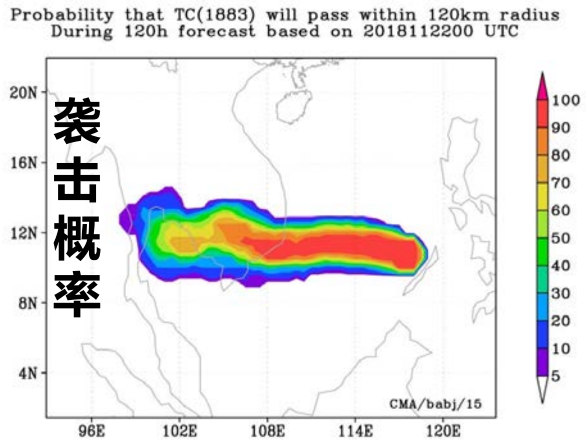
降水概率

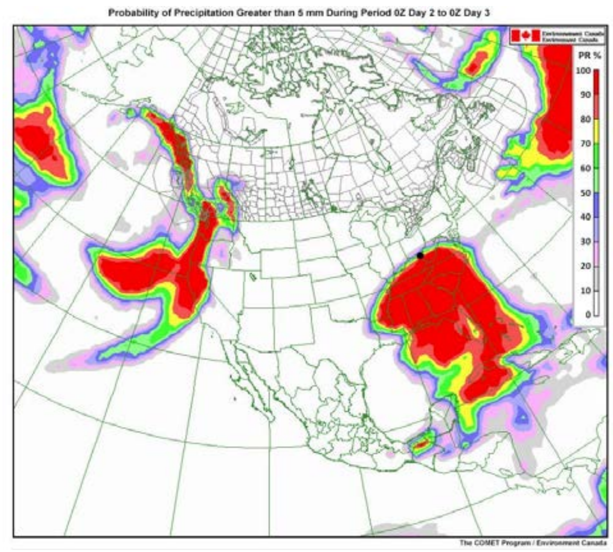


台风路径

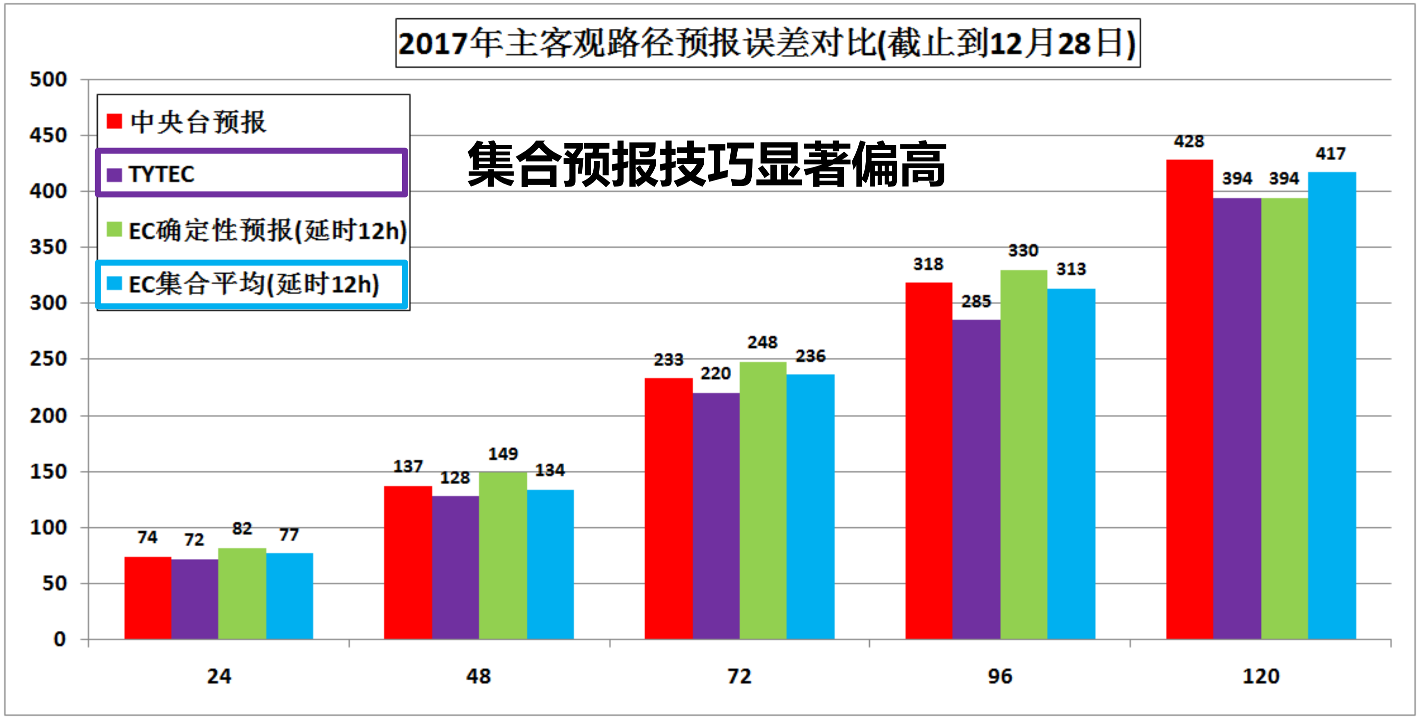


袭击概率

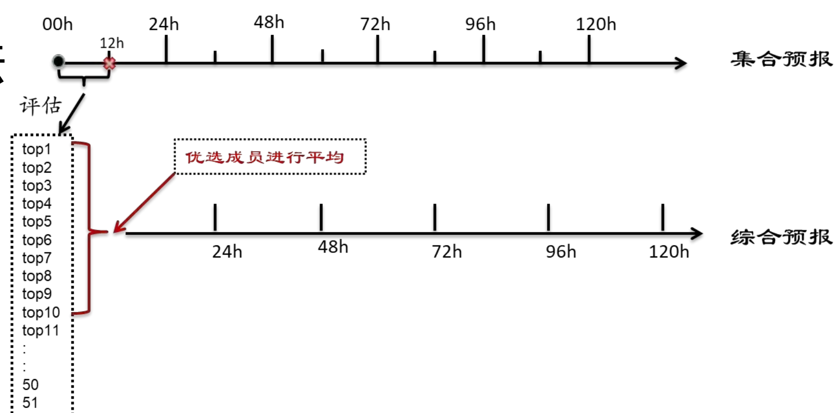


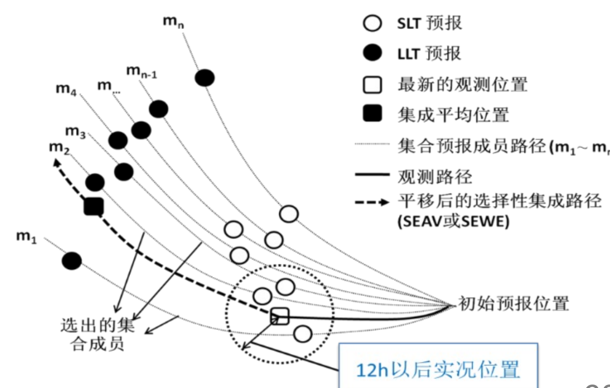


2017年台风路径预报技巧评估

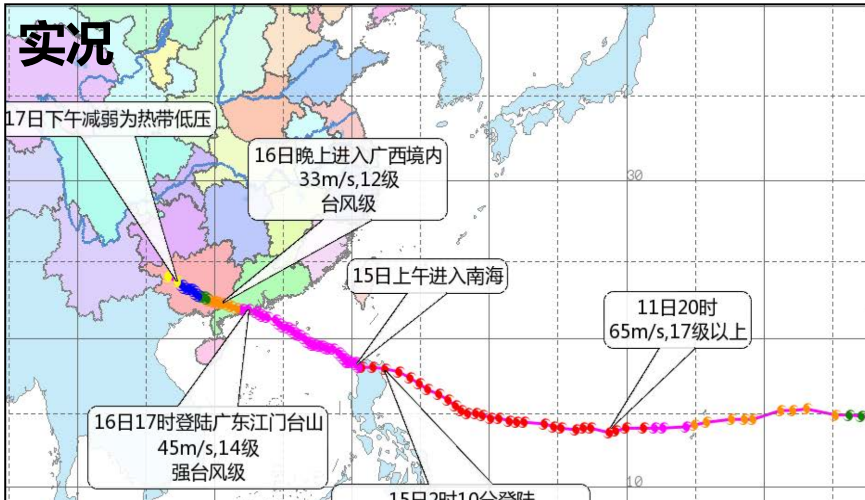


TYTEC方法

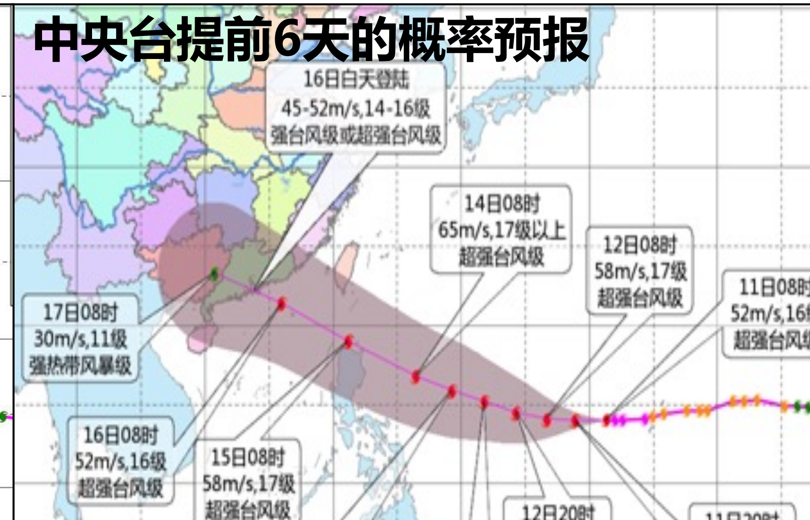




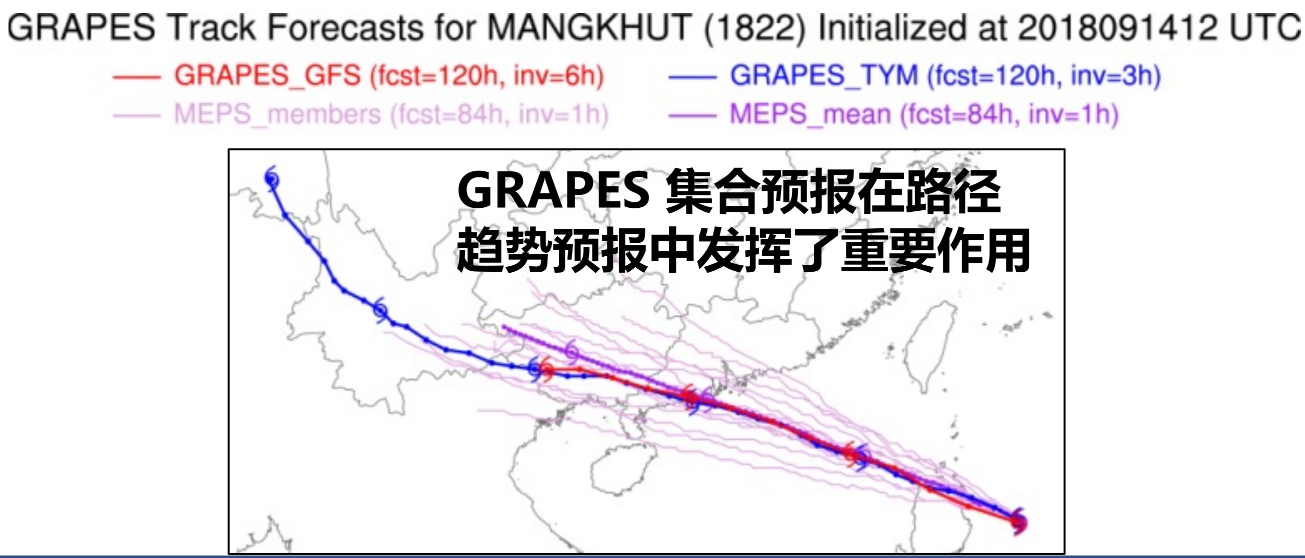
台风“山竹”的GRAPES 集合预报



16日17时“山竹”登陆广东江门台山，14级（45m/s）



16日白天登陆广东中部一带沿海（45-52米/秒，14-16级，



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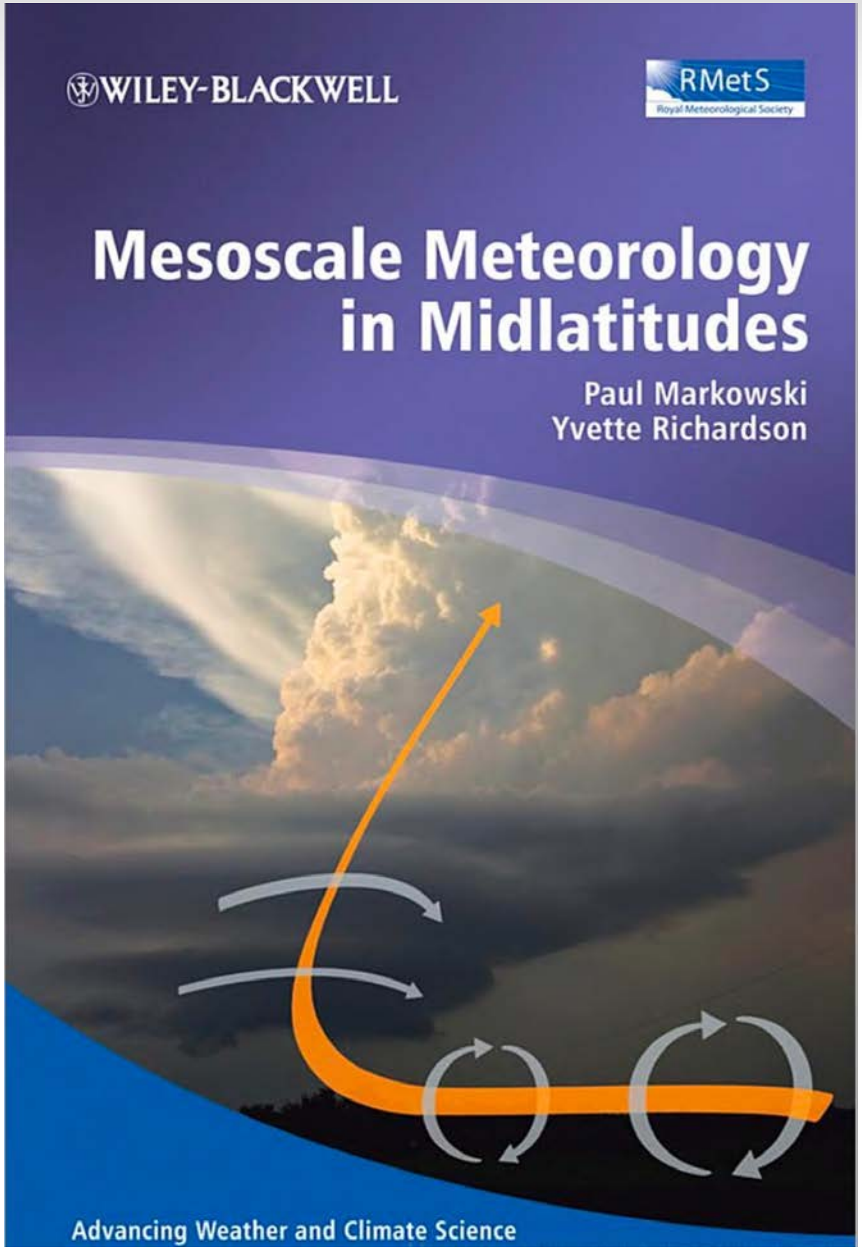
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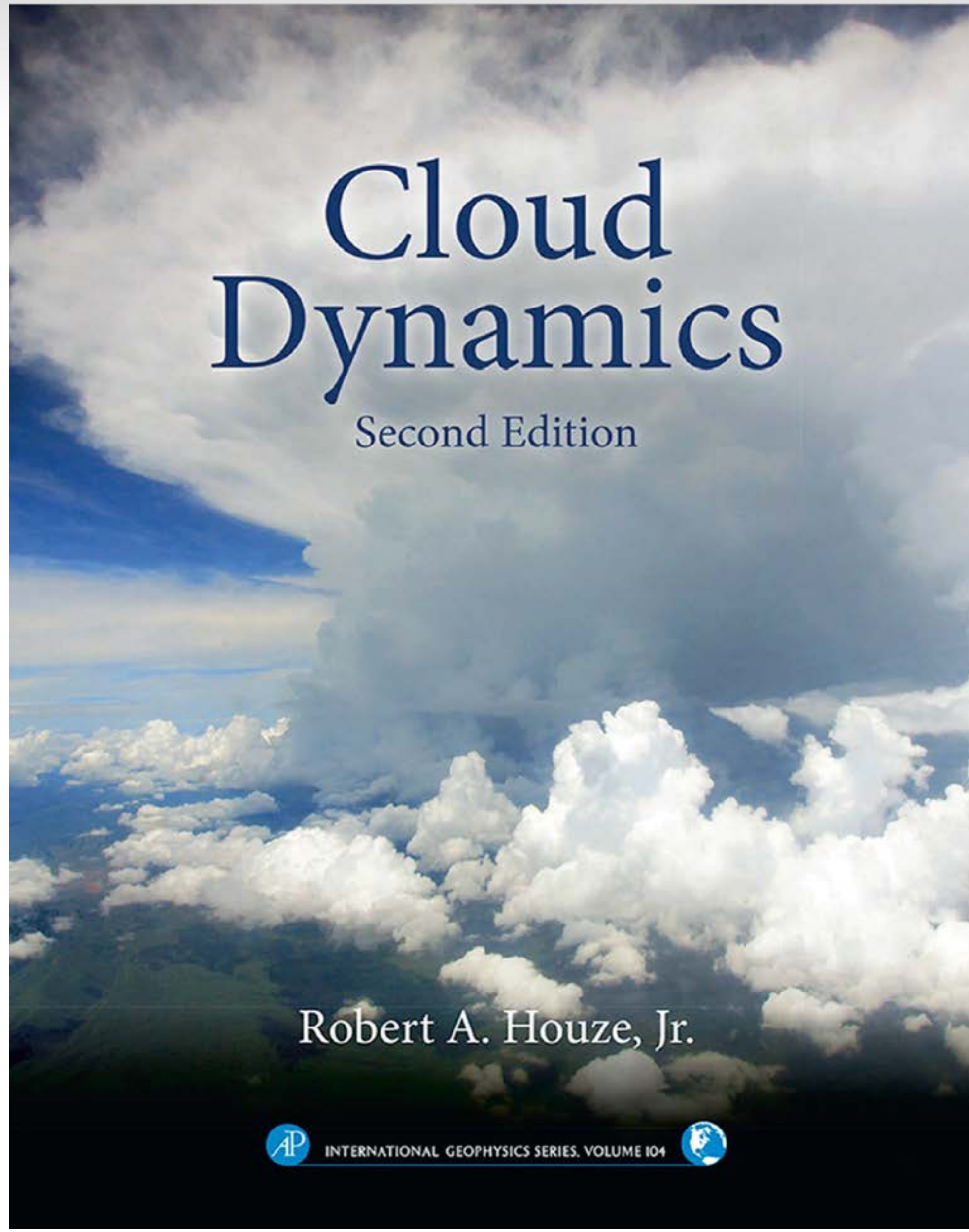
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Robert A. Houze, Jr.
INTERNATIONAL GEOPHYSICS SERIES, VOLUME 104

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Contents

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