第五届全国中尺度气象学论坛

一类致洪暴雨灾害天气预报瓶颈的解析

陆汉城 黄小刚 费建芳

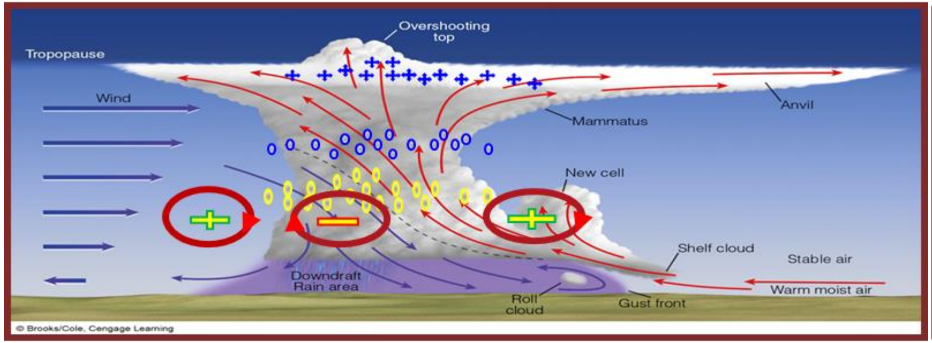
国防科技大学气象海洋学院

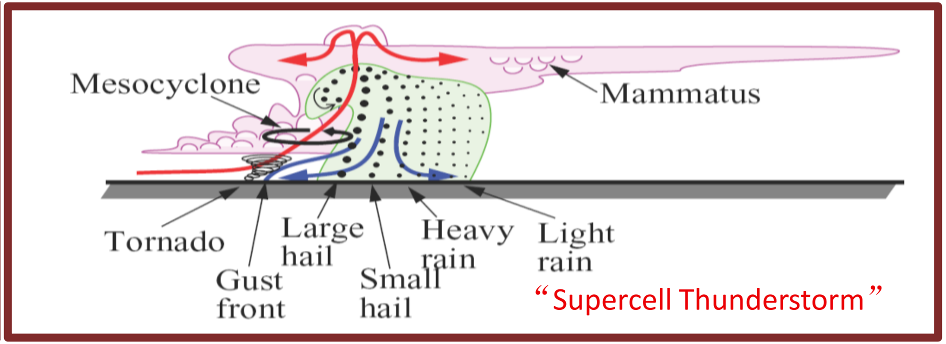
2023年8月10日 银川

致洪暴雨灾害天气的关键科学问题

具有典型意义的强风暴系统的 Concept Model

（Houze； Matejka; Klemp; Doswell; Weisman; Browning; Rotunno et al）





"Supercell Thunderstorm"

深厚湿对流的发生发展是强降水天气过程的基本问题，然而深厚湿对流（或者垂直运动环流）的时间和空间尺度以及强度的差异决定了暴雨洪涝的强度，是暴雨灾害天气的预报瓶颈。

中国气象学家在中尺度气象动力学的重要贡献

涡旋与对流的相互作用（非线性问题）

周晓平先生

李麦村先生

陈受钧先生

巢纪平院士

伍荣生院士

周秀骥院士

曾庆存院士

致洪暴雨灾害天气的类别

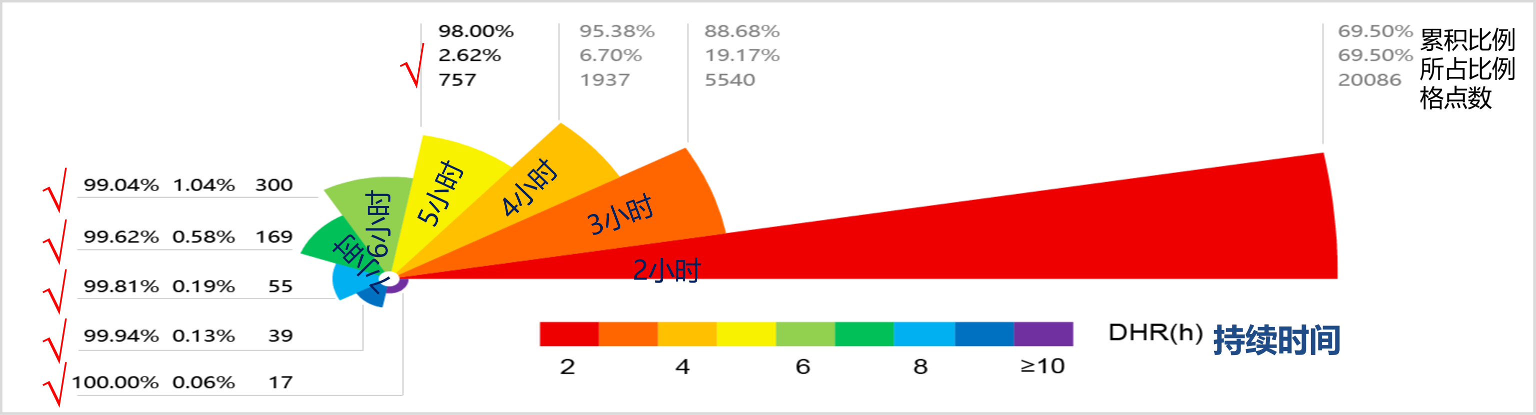
极端降水的定义及分类

类型	定义	极端性特征		缺陷
		降水强度	降水时长	
强降水 **(中央气象台)**	＞20mm/h			
极端小时强降水 *(Li, Yu et al.， 2019)*	小时降水量＞95百分位	✓		忽略降水时长的极端性
持续性极端降水 *(Zhai et al., 2013)*	日降水量＞50mm，且连续3天以上		✓	低估短时强降水或高估长时间弱降水
极端持续性强降水 *(Huang，Fei et al., 2021,2022)*	小时降水量＞20mm，且持续5小时以上	✓	✓	

致洪暴雨灾害天气的类别

极端持续性强降水（EPHR）定义

- 强降水（小时降水率≥20mm/h）持续5小时以上（95%阈值）
- 可同时兼顾降水量和降水时长的极端性

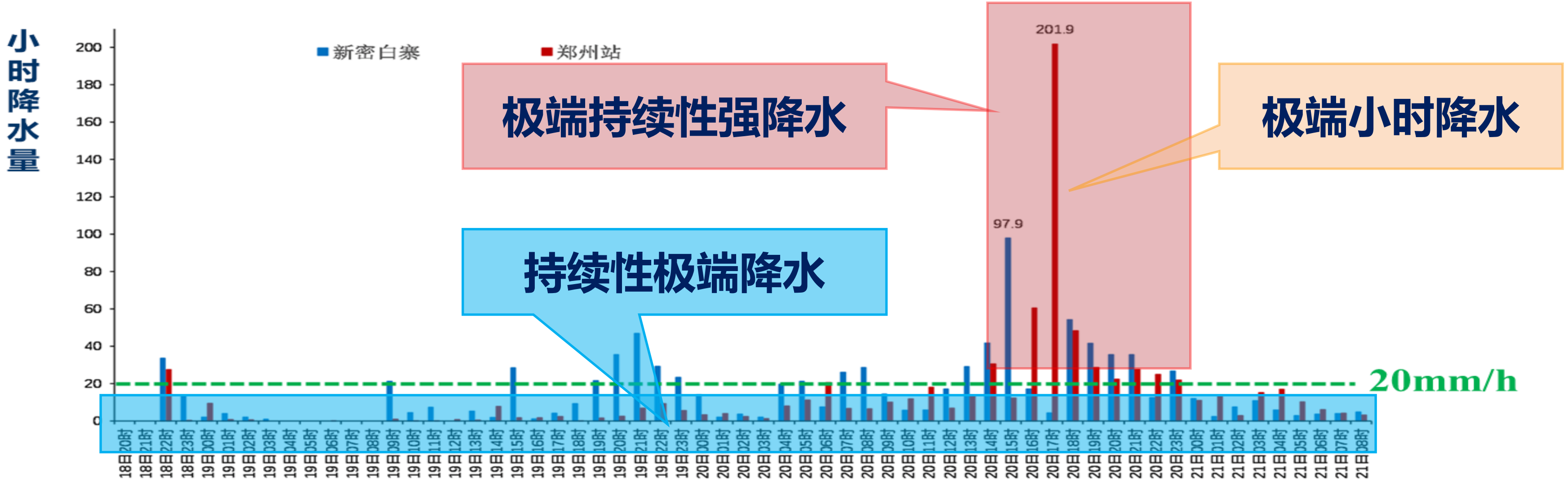


2008-2019年华南区域强降水降水时长极端性判定（ Zhang & Huang，2021）

致洪暴雨灾害天气的类别

“7.20” 郑州极端降水：

- ➢ 极端小时降水：20日17时小时降水量201.9mm
- ➢ 持续性极端降水：18日-21日持续降水
- ➢ 极端持续性强降水：20日14时-23时强降水（超过20mm/h）持续10小时



2021年7月18日20时-21日08时郑州国家站和新密白寨站逐小时降水量时序图（苏爱芳等，2021）

不同类型的极端降水过程具有动力学的差异！

完全的诸力平衡方程

涡度方程：

$$\frac{\partial \zeta_p}{\partial t} = -u\left(\frac{\partial \zeta_p}{\partial x}\right)_p - v\left(\frac{\partial \zeta_p}{\partial y}\right)_p - \omega\frac{\partial \zeta_p}{\partial p} - (\zeta_p + f)\left[\left(\frac{\partial u}{\partial x}\right)_p + \left(\frac{\partial v}{\partial y}\right)_p\right] - v\left(\frac{\partial f}{\partial y}\right)_p + \left[\left(\frac{\partial \omega}{\partial y}\right)_p \frac{\partial u}{\partial p} - \left(\frac{\partial \omega}{\partial x}\right)_p \frac{\partial v}{\partial p}\right]$$

相对涡度平流项

铅直涡度输送项

涡散共存并相互作用

β效应项

扭转项

根据研究物理问题中运动的基本特征，尺度分析取不同的近似。

完全的诸力平衡方程

散度方程：

$$\frac{dD}{dt}+D^2-2J(u,v)+\beta_0 u-f\vec{V}\times\vec{k}=-\alpha\nabla_h p-\nabla_h\omega\cdot\frac{\partial\vec{V}_h}{\partial z}-\nabla_h\alpha\cdot\nabla_h p+\nabla_h\cdot\vec{F}$$

零级近似

$$f\vec{V}_g\times\vec{k}=\alpha\nabla_h p$$

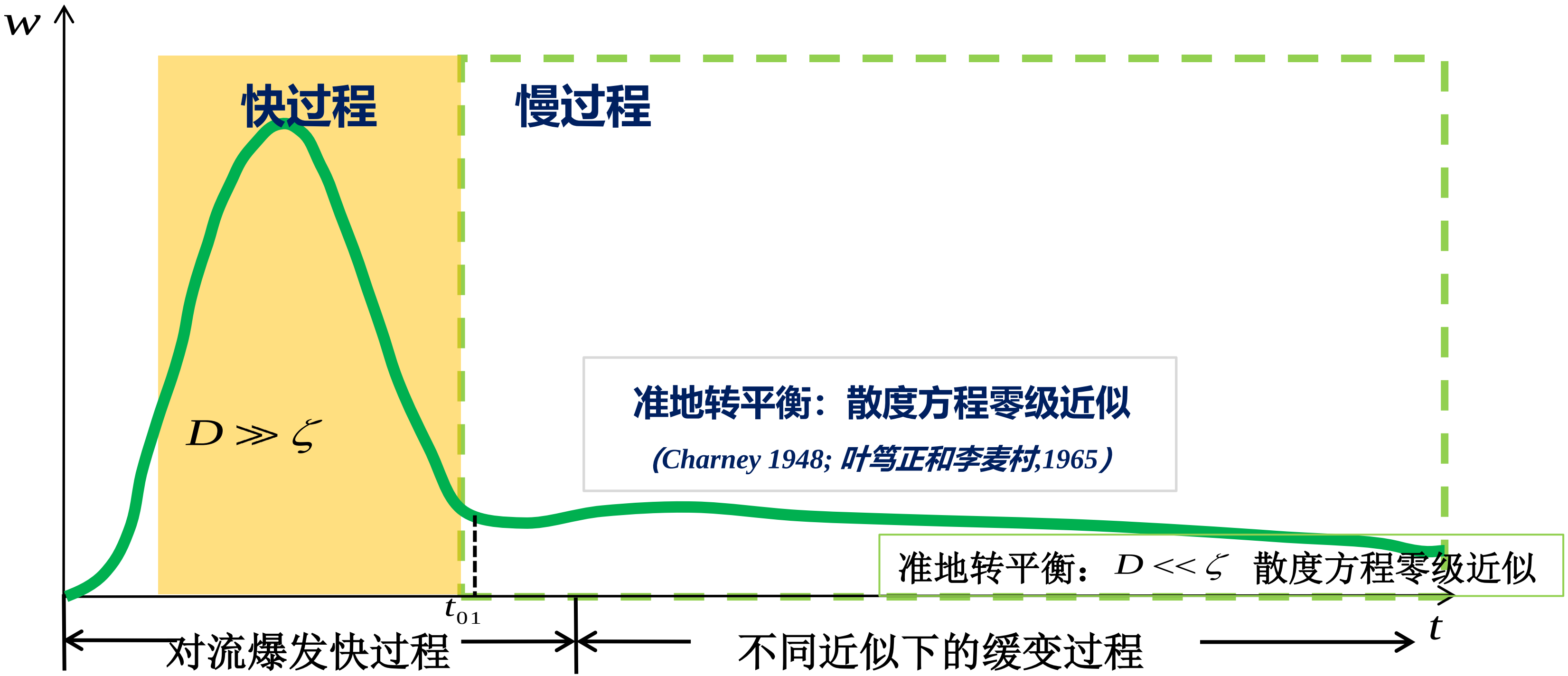
- 非地转
- 准地转平衡
- 地转平衡

一级近似

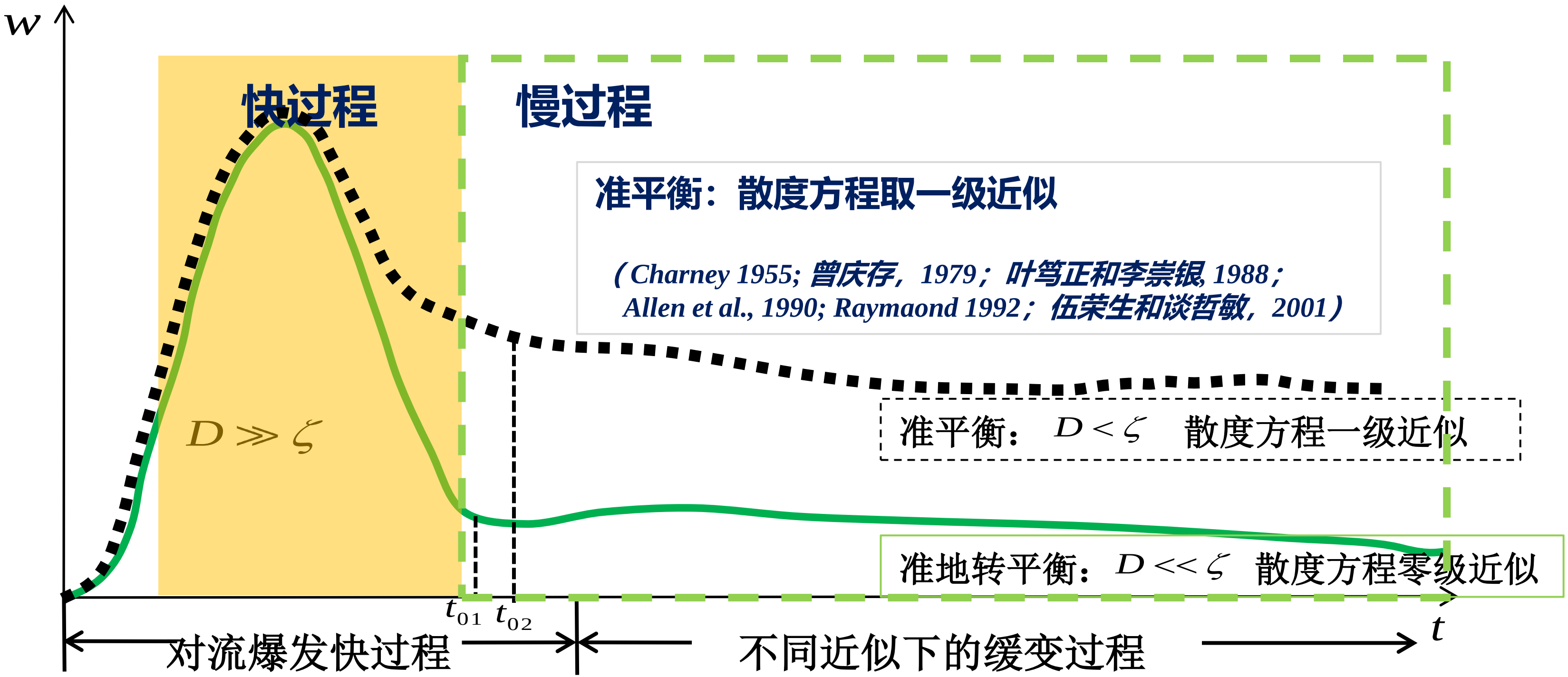
$$\alpha\nabla_h p-2J(u,v)+\beta_0 u-f\vec{V}\times\vec{k}=0$$

- 非平衡
- 准平衡
- 弱平衡

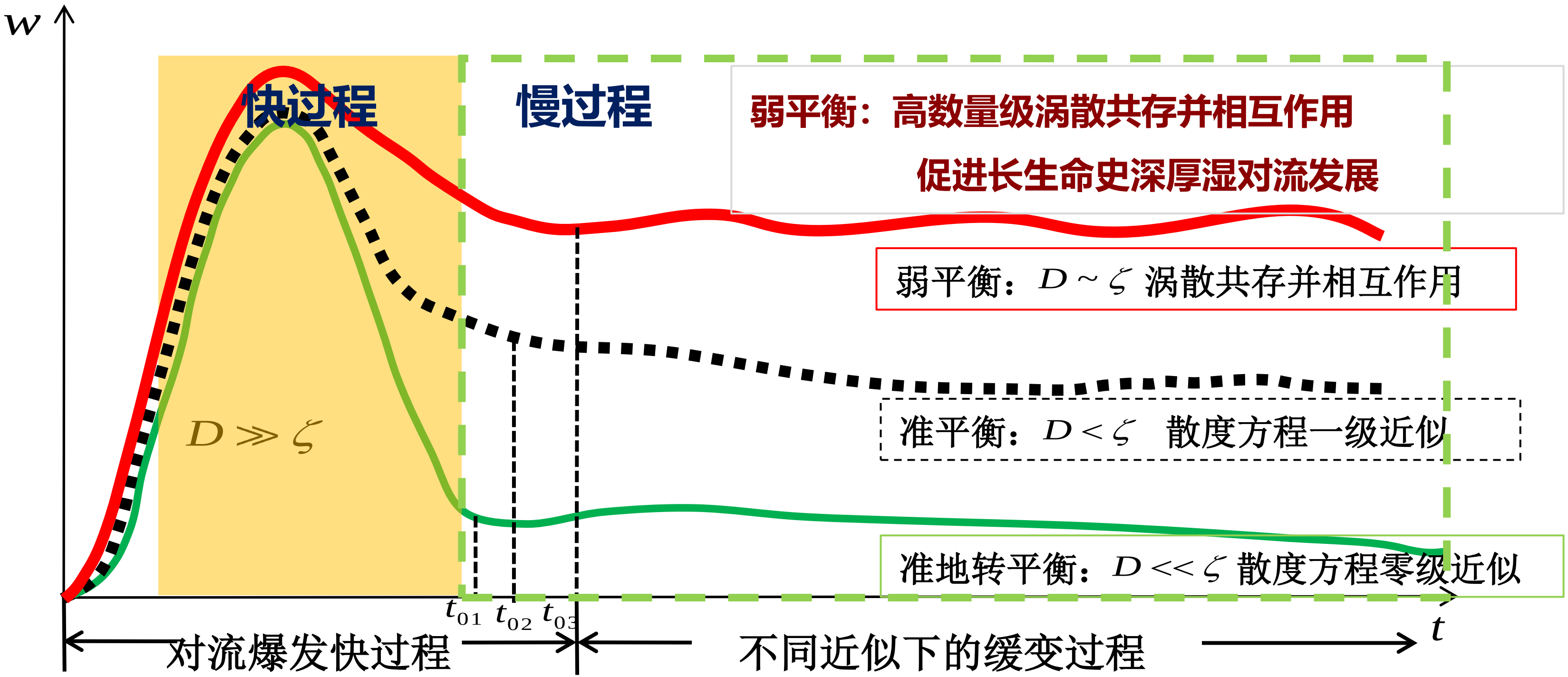
不同类型极端降水过程的对流动力学差异



不同类型极端降水过程的对流动力学差异



不同类型极端降水过程的对流动力学差异



弱平衡模型（Less-Balanced Modes）

A Theory for Mixed Vortex Rossby–Gravity Waves in Tropical Cyclones

WEI ZHONG

Nanjing Institute of Mesoscale Meteorology, and Key Laboratory of Meteorological Disaster of the Ministry of Education, Nanjing University of Information Science and Technology, Nanjing, China

AMS成立百年台风研究综述

Chapter 15

100 Years of Progress in Tropical Cyclone Resea

KERRY EMANUEL

Lorenz Center, Massachusetts Institute of Technology, Cambridge, Massach

ABSTRACT

A century ago, meteorologists regarded tropical cyclones as shallow vortices, extending kilometers into the troposphere, and nothing was known about their physics save th somehow involved. As recently as 1938, a major hurricane struck the densely populated n States with no warning whatsoever, killing hundreds. In the time since the American Met was founded, however, tropical cyclone research blossomed into an endeavor of great encompassing fields ranging from atmospheric and oceanic dynamics to biogeochemistry and scope of forecasts and warnings have achieved a level of success that would have impossible only a few decades ago. This chapter attempts to document the extraordinary cyclone research over the last century and to suggest some avenues for productive researc

1. Introduction

By the time that the American Meteorological Society (AMS) was founded in 1919, mariners, engineers, and scientists had made great strides in characterizing the climatology of tropical cyclones, including their favored formation regions, tracks, seasonal variability, and surface wind field. By the middle of the nineteenth century, these characteristics had been compiled into a number of treatises, most notably by Sir Henry Piddington, whose 1848 work *The Sailor's Horn-Book for the Law of Storms*, which built on earlier research by William Redfield and Lieutenant Colonel William Reid, laid out a strategy by which ships at sea could avoid or more safely ride out tropical cyclones (Piddington 1848). Observations were sparse, although by the late nineteenth century Father Benito Viñes, a Jesuit priest and director of Havana's Belén Observatory, had established a rudimentary network of observations in the Caribbean Sea region and argued for the importance of upper-level winds in steering hurricanes (Viñes 1885).[1]

As valuable as these contri was known about the vertical or the basic physical mechanism that drives them. Indeed, up through the 1930s, it was widely believed, on the basis of the observed rapid diminution of surface winds after landfall, that their circulation extended upward only 3 km or so, while the reigning theory for their power source was that of James Pollard Espy, who had surmised by the middle of the nineteenth century that cyclones in general were powered by latent heat release in a conditionally unstable atmosphere, a belief that persists even today.[2]

The first century of AMS's existence saw much progress in measuring, understanding, and forecasting tropical cyclones. This chapter attempts to document that progress and to set it in the context of important developments in the broad field of meteorology. Indeed, the magnitude and breadth of that progress is so large as to present a challenge to anyone who would attempt to summarize it in single chapter. Here I have attempted to document what, in my view, were the most significant advances, aiming more for readability than for comprehensiveness, and emphasizing historical significance, even in the case of the odd dead-end research path. Of necessity, many important references are omitted.

[1] A summary of Viñes's contribution is provided by Guadalupe (2014).

[2] See Kutzbach (1979) for a detailed account of Espy's work.

Corresponding author: Kerry Emanuel, emanuel@mit.edu

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The instability involves the interaction of a Rossby wave on the boundary of the patch with gravity waves that are well outside the patch, and it is thus filtered from quasibalanced systems. The idea that less-balanced modes might be unstable even if Charney–Stern–Fjørtoft–like sufficient conditions for stability are satisfied is strongly supported by the work of Zhong et al. (2009), who showed using linear shallow water theory that while Rossby-type and inertia–gravity–type oscillations are clearly separable in the eye and outer regions of tropical cyclone vortices, mixed Rossby–gravity waves can occur in and near the eyewall, giving rise to spiral-like structures. A weakness of the theoretical work on relatively low frequency wave disturbances to tropical cyclone– like vortices is that there is no attempt to couple to deep convection.

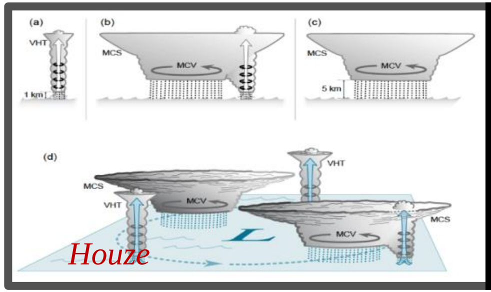
弱平衡模型是解释长生命史强对流维持发展的新理论

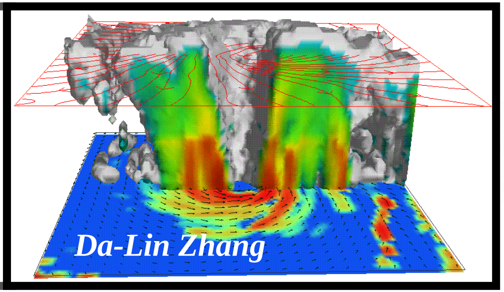
弱平衡模型（Less-Balanced Modes)

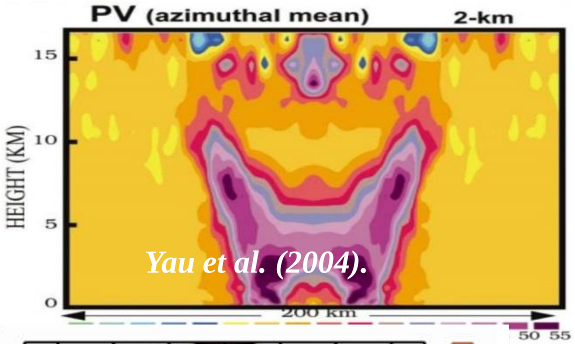
高数量级涡散共存并相互作用， 促进长生命史深厚湿对流发展

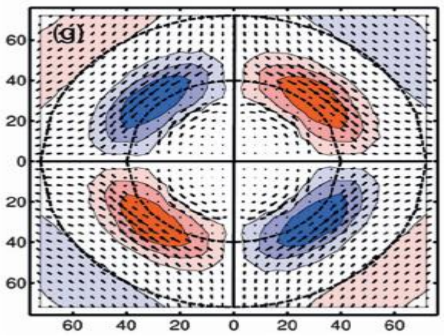
（国防科技大学气象海洋学院中尺度气象团队长期研究提出的动力学新原理）

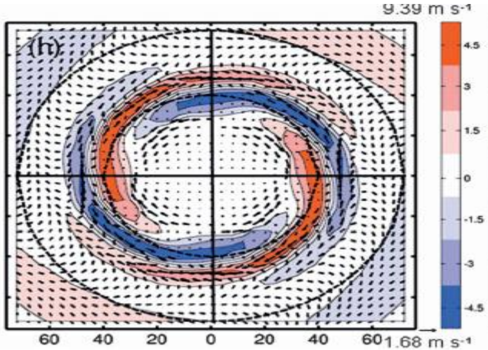
两个基本问题，**其一是**：涡散共存并相互作用时的波动特征（物理性质、频散关系、传播、稳定性）

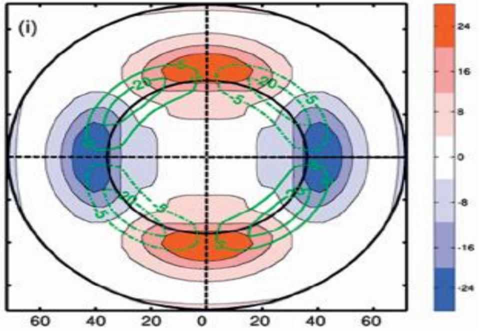












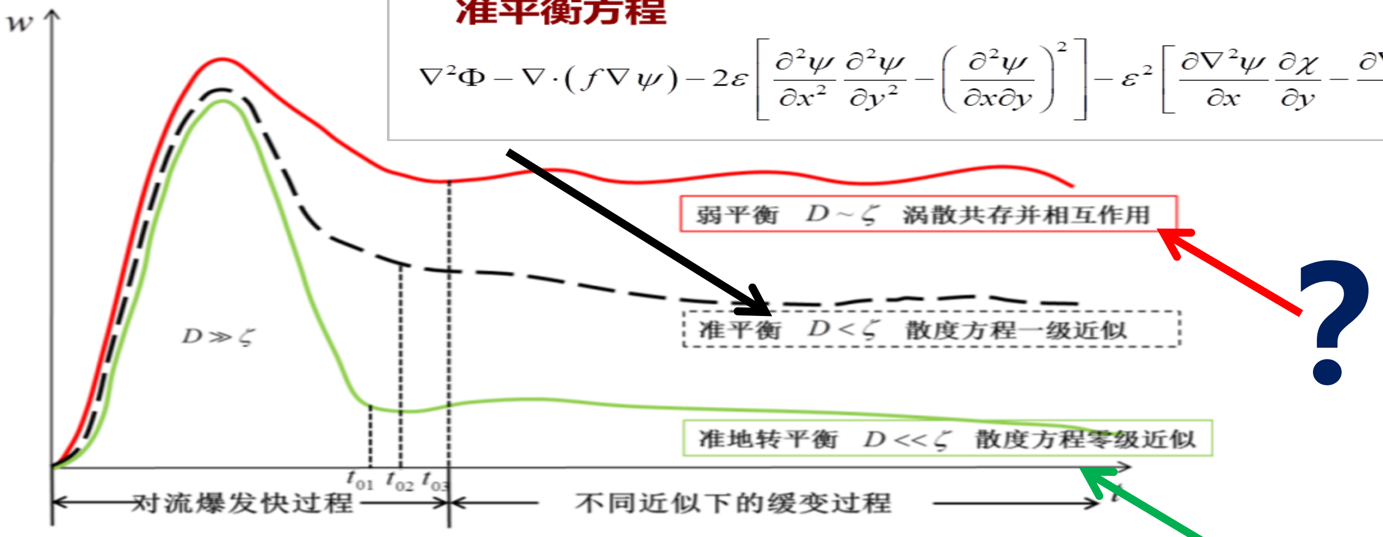
Mixed Vortex Rossby-Gravity waves （Lu, et al 2004,Zhong,Zhang, Lu.2009)

弱平衡模型（Less-Balanced Modes）

高数量级涡散共存并相互作用， 促进长生命史深厚湿对流发展

(国防科技大学气象海洋学院中尺度气象团队长期研究提出的动力学新原理)

两个基本问题，其二是：高数量级涡散共存并相互作用时的垂直运动的诊断分析



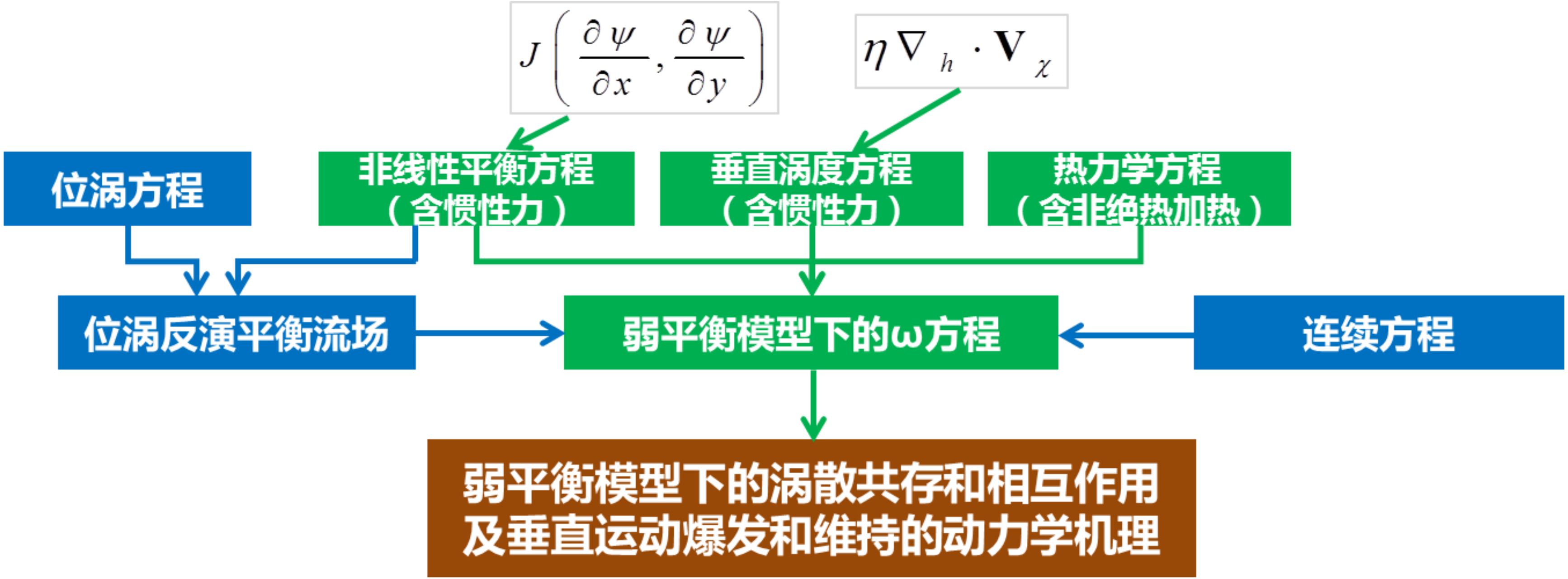
准平衡方程

$$\nabla^2\Phi-\nabla\cdot(f\nabla\psi)-2\varepsilon\left[\frac{\partial^2\psi}{\partial x^2}\frac{\partial^2\psi}{\partial y^2}-\left(\frac{\partial^2\psi}{\partial x\partial y}\right)^2\right]-\varepsilon^2\left[\frac{\partial\nabla^2\psi}{\partial x}\frac{\partial\chi}{\partial y}-\frac{\partial\nabla^2\psi}{\partial y}\frac{\partial\chi}{\partial x}\right]=0$$

准地转ω方程

$$\left(\nabla^2+\frac{f_0^2}{\sigma_s}\frac{\partial^2}{\partial p^2}\right)\omega=\frac{f_0}{\sigma_s}\frac{\partial}{\partial p}\left[\vec{V}_g\cdot\nabla(\zeta_g+f)\right]-\frac{1}{\sigma_s}\nabla^2\left[\vec{V}_g\cdot\nabla\left(\frac{\partial\phi}{\partial p}\right)\right]$$

高数量级涡散共存并相互作用时的垂直运动的诊断分析



高数量级涡散共存并相互作用时的垂直运动的诊断分析

弱平衡模型的ω方程

$$\nabla_h^2\left(\frac{\partial^2\Phi}{\partial z^2}\omega\right)+f\eta\frac{\partial}{\partial z}\left\{(z_a-z)-\mu\frac{\partial}{\partial z}\left[(z_a-z)^\mu\omega\right]\right\}-f\frac{\partial}{\partial z}\left(\frac{\partial\omega}{\partial x}\frac{\partial^2\Psi}{\partial x\partial z}+\frac{\partial\omega}{\partial y}\frac{\partial^2\Psi}{\partial y\partial z}\right.$$

$$-f\frac{\partial}{\partial z}\left(\frac{\partial\omega}{\partial x}\frac{\partial^2\chi}{\partial y\partial z}-\frac{\partial\omega}{\partial y}\frac{\partial^2\chi}{\partial x\partial z}\right)-\left(f\frac{\partial\eta}{\partial z}\frac{\mu}{z_a-z}+f\frac{\partial^2\eta}{\partial z^2}\right)\omega=$$

$$\underbrace{f\frac{\partial}{\partial z}[\mathbf{V}_h\cdot\nabla\eta]}_{\text{① the differential vorticity advection}}-\underbrace{\nabla_h^2\left[\mathbf{V}_h\cdot\nabla_h\frac{\partial\phi}{\partial z}\right]}_{\text{② the Laplacians of thermal advection}}-\underbrace{2\frac{\partial^2}{\partial t\partial z}\left[\frac{\partial^2\Psi}{\partial x^2}\frac{\partial^2\Psi}{\partial y^2}-\left(\frac{\partial^2\Psi}{\partial x\partial y}\right)^2\right]}_{\text{③ the differential deformation}}$$

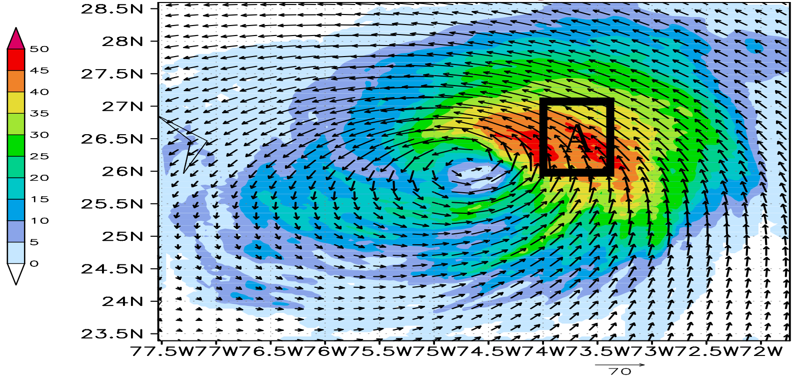
$$\underbrace{-\beta\frac{\partial^3\Psi}{\partial t\partial x\partial y}}_{\text{④ the }\beta\text{ effect}}+\underbrace{\frac{g}{\theta_0}\nabla_h^2\dot{q}_\rho}_{\text{⑤ latent heating}}-\underbrace{f\frac{\partial}{\partial z}\left(\frac{\partial f_y}{\partial x}-\frac{\partial f_x}{\partial y}\right)-\frac{\partial^2}{\partial t\partial z}\left(\frac{\partial f_x}{\partial x}+\frac{\partial f_y}{\partial y}\right)}_{\text{⑥ the effects of friction}}$$

①②③④ **内部动力强迫项**

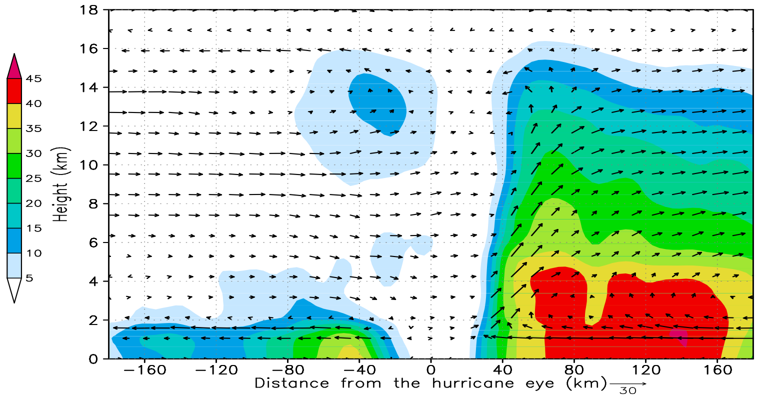
⑤⑥ **外源强迫项**

高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（台风）

The 6-hour averaged radar reflectivity and in-plane flow vectors from 0000 UTC to 0600 UTC 24 August at 850 hPa

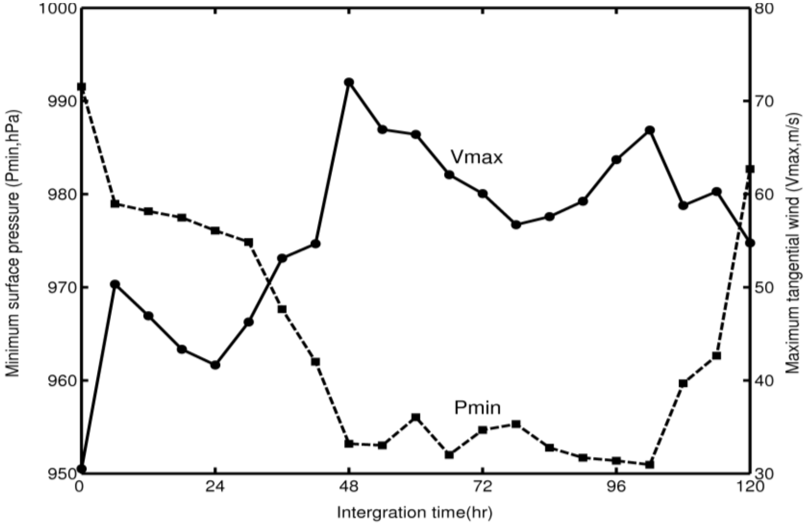


The 6-hour averaged radar reflectivity and in-plane flow vectors along 26°N vertical cross section

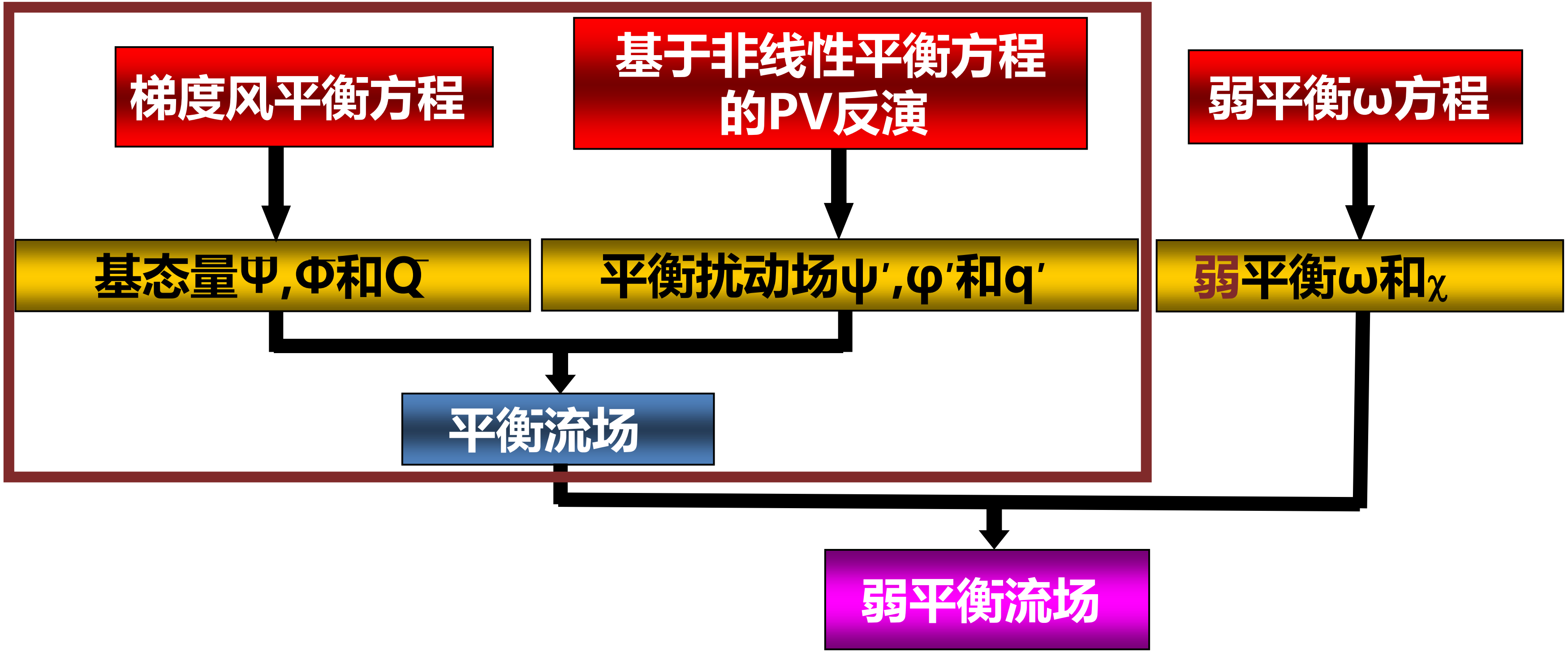


Bonnic(1998)个例分析

Time series (6 h) of the minimum surface pressure and the maximum tangential wind from model simulation



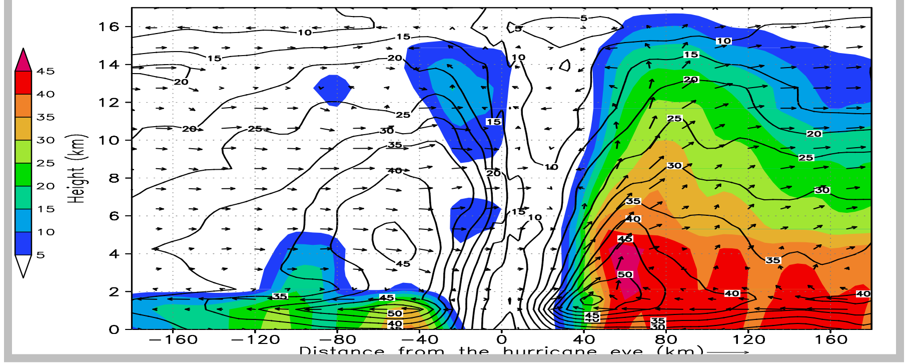
高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（台风）



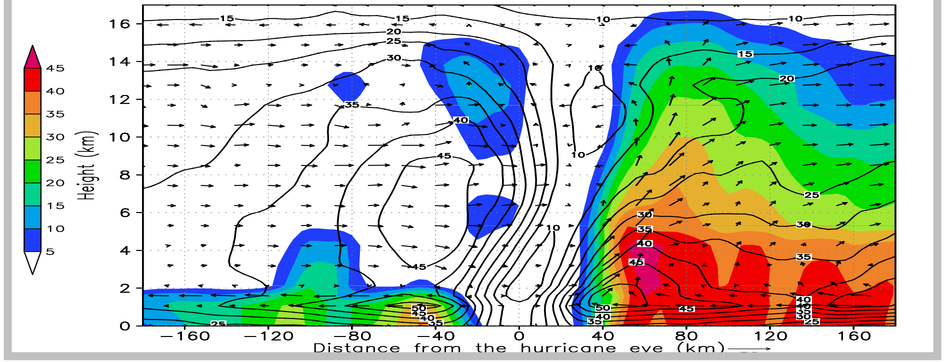
高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（台风）

West-east vertical cross sections of 1-h averaged horizontal wind (contoured, m s^{-1}), superposed with radar reflectivity (shaded, dBz) and model in-plane flow vectors (m s^{-1})from 0200 UTC to 0300 UTC 24 August

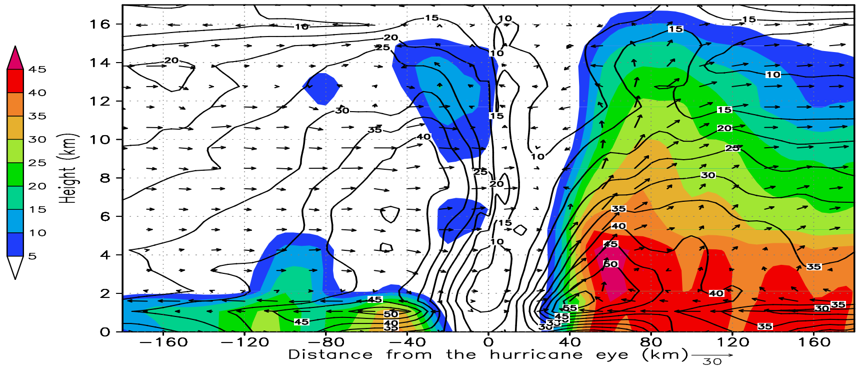
Model results



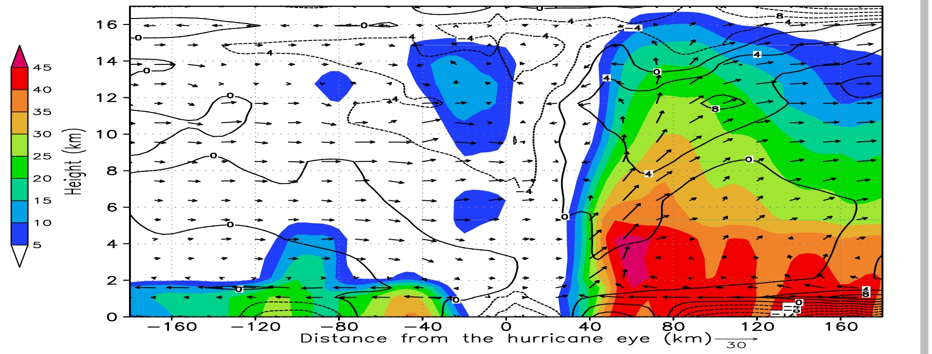
Balanced flows



Less-balanced flows

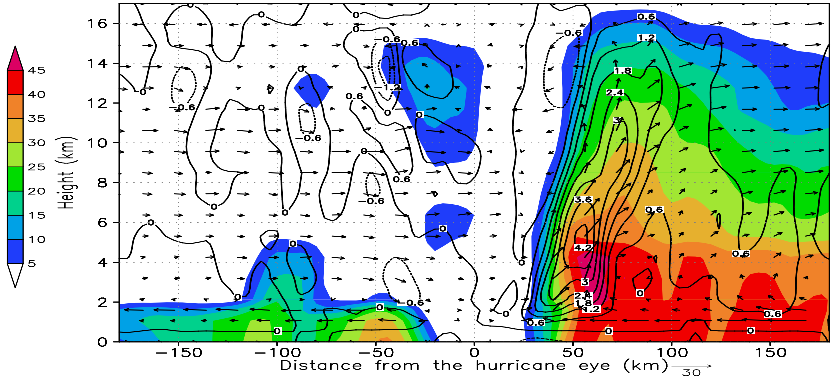


Nonbalanced flows

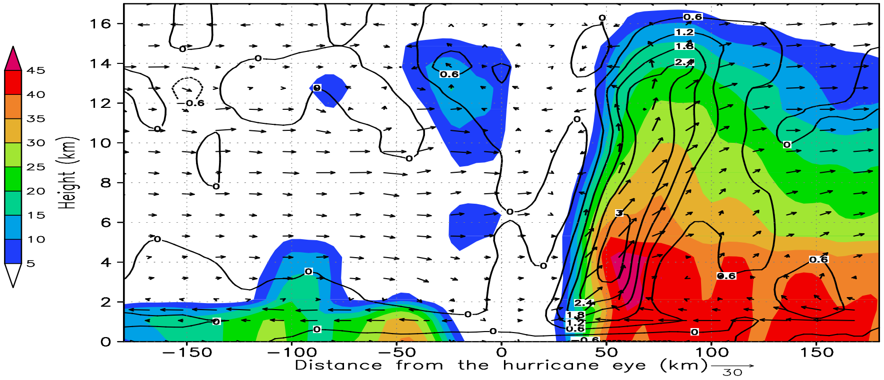


高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（台风）

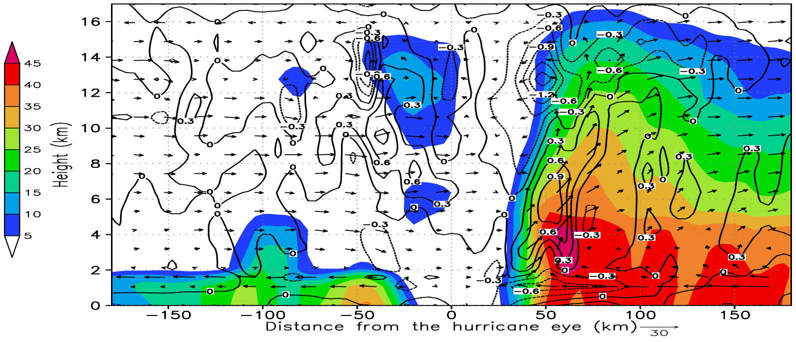
Model results



Less-balanced flows



Nonbalanced flows



高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（台风）

- 对模式大气、平衡流、弱平衡流和非平衡流场中垂直运动的分析发现：

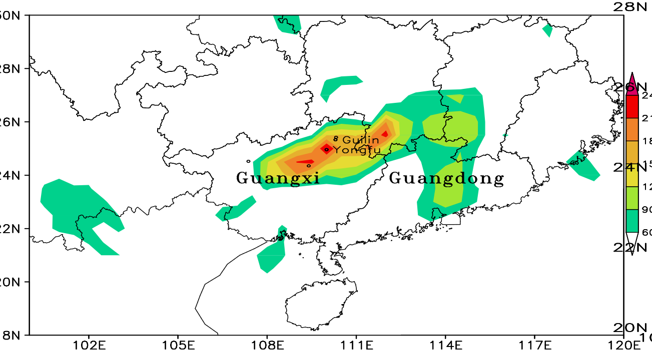
1，平衡流中既保留了平衡模式中略去的与中尺度深对流相联系的辐散风分量，又将与重力波快波频散过程相联系的垂直运动归于非平衡部分。

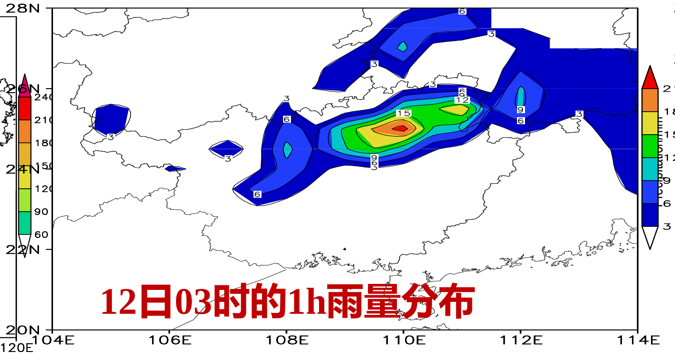
2，平衡流基础上的弱平衡模型的垂直运动诊断表达了涡散共存相互作用

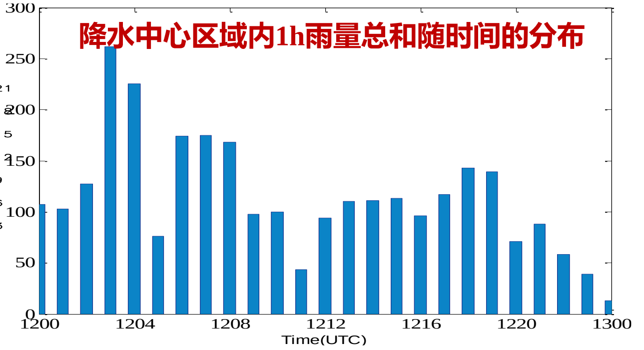
3，强热带气旋系统中与眼壁和螺旋雨带中的雷达反射率的高值区相对应的深厚湿对流系统，不同于重力波能量频散有关的瞬时调整过程，是具有较长生命史组织化过程的深对流系统。反演得到的弱平衡垂直环流具有描述这类深厚湿对流系统的结构分布和演变规律的能力。

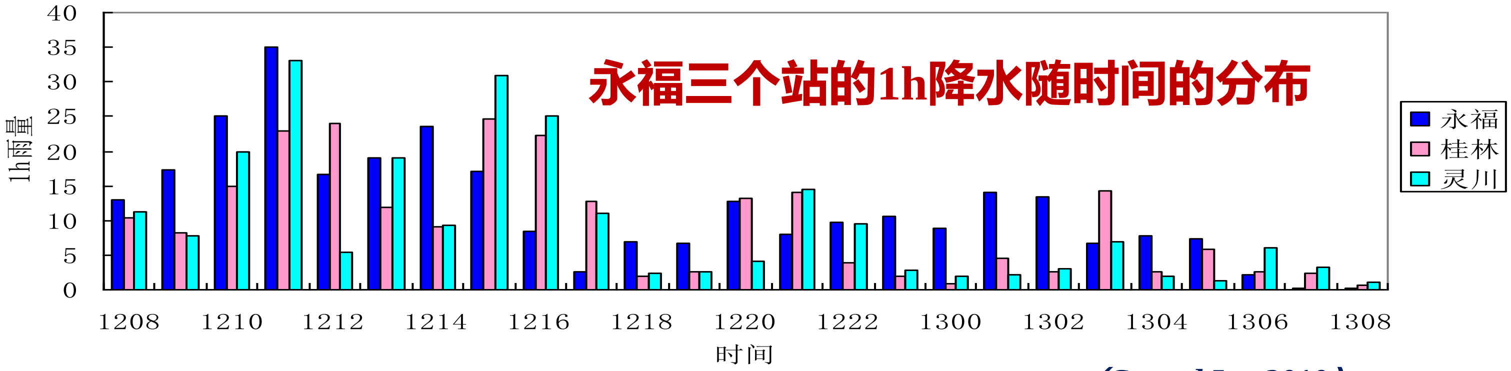
高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（中尺度涡旋）

2008年6月11~13日华南前汛期致洪暴雨：永福站的48h降水量高达413mm，
12日的降水具有极端持续性强降水（EPHR）特征



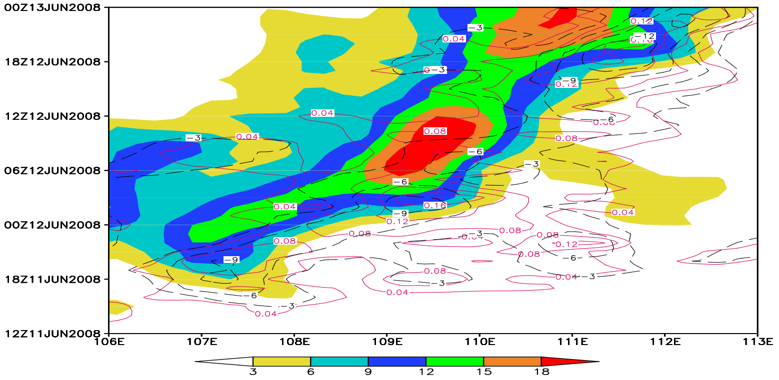




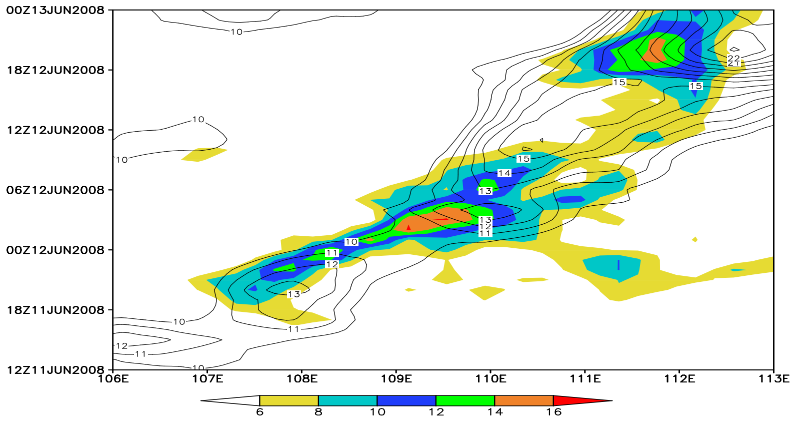


(Ge and Lu, 2010)

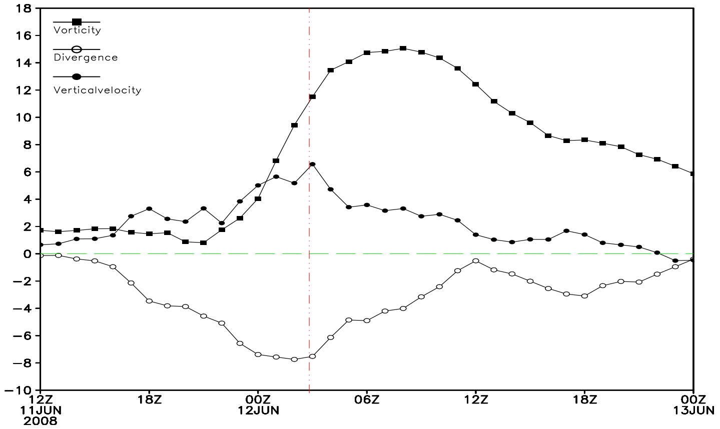
高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（中尺度涡旋）

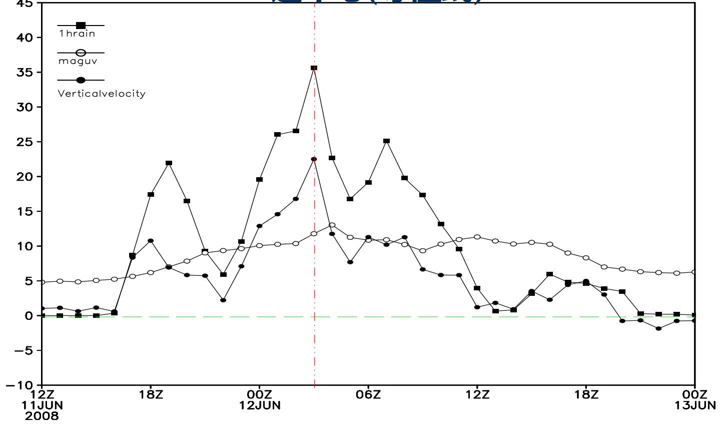


850hPa上24~26ºN纬向平均的涡度(阴影),散度(黑色虚线),垂直速度(红色实线)

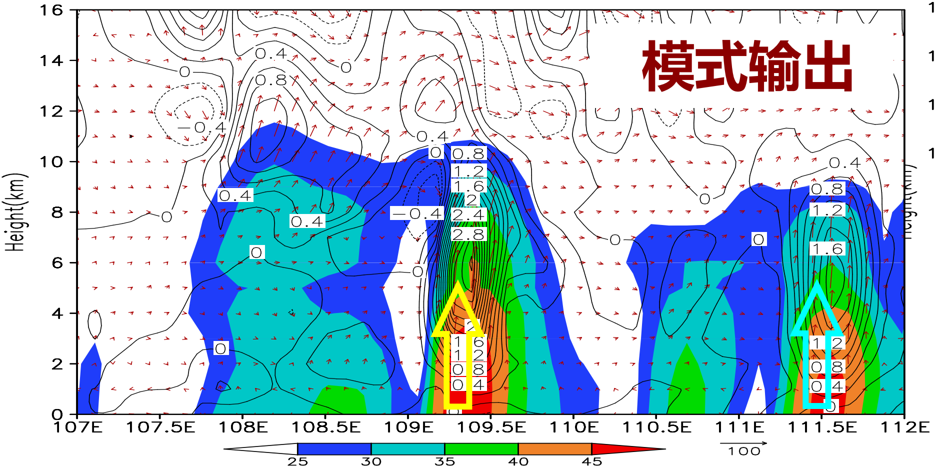


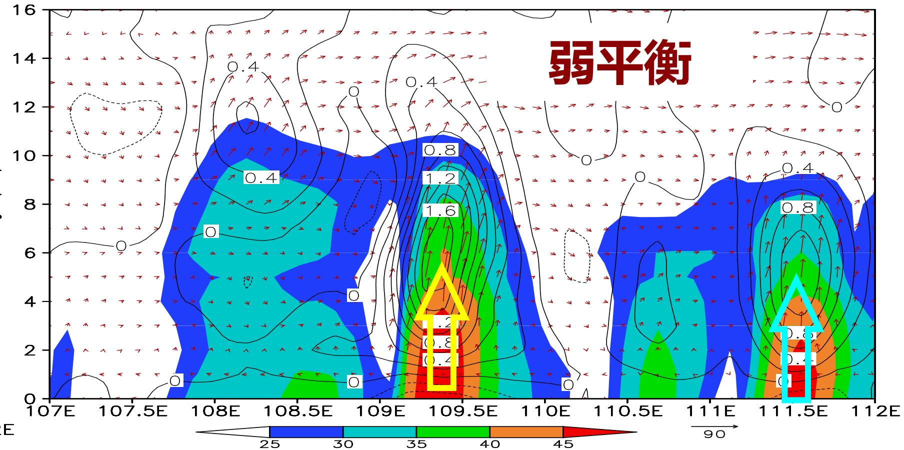
24~26ºN纬向平均的1h降水量(阴影), 850hPa大风速中心(等值线)

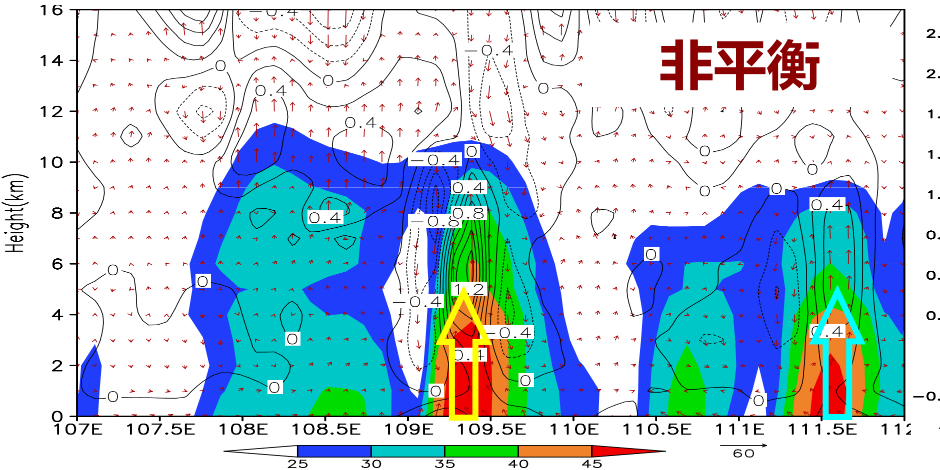


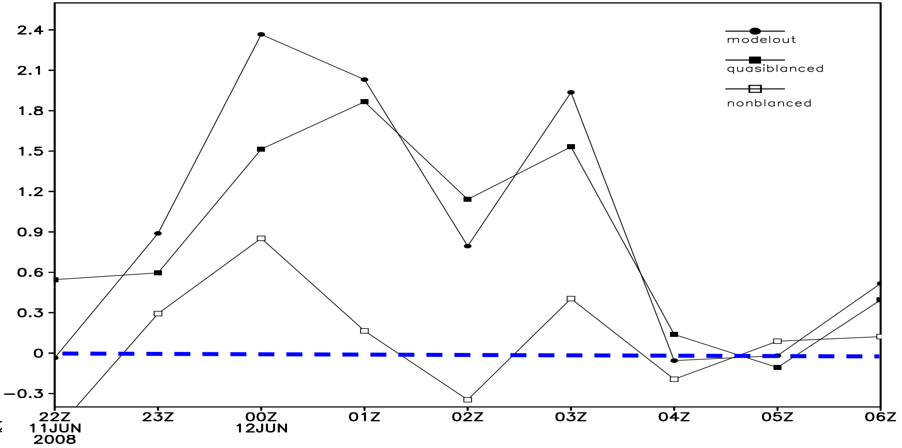


高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（中尺度涡旋）









高数量级涡散共存并相互作用时的垂直运动的个例诊断分析（中尺度涡旋）

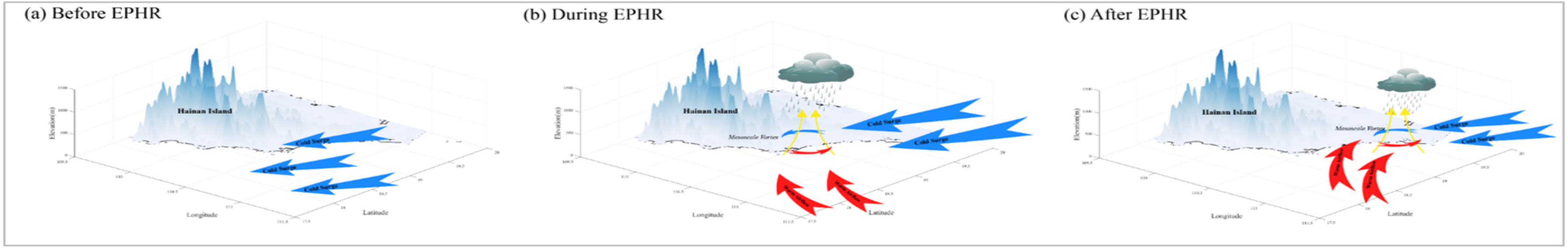
1，中尺度分析表明，广西涡前期长时间在广西区域内准静止发展、后期快速东移，其基本特征是具有深厚的正涡度柱，低层强辐合、水汽高度集中，高层强辐散，涡散运动共存并达同量级，伴随着长时间维持的深厚垂直上升运动。

2，基于弱平衡流分析的PV-ω反演方法，应用于与华南致洪暴雨中尺度低涡相伴随的深厚湿对流的研究，诊断分析大振幅较长生命史具有涡散共存并达同量级特征的中尺度深厚湿对流。

高数量级涡散共存并相互作用时的垂直运动的诊断分析

发现中尺度涡旋在海南极端持续性强降水事件中的关键作用

- **2013年12月14日-15日万宁暴雨**
  - ➤15万人受灾，损失超过15亿元
  - ➤历史罕见的冬季特大暴雨，强降水（≥20mmh^{-1}）持续了15小时



■ 冷空气的侵入 ■ 偏转气流形成的准静止中尺度涡旋 ■ 海南岛独特的地形强迫

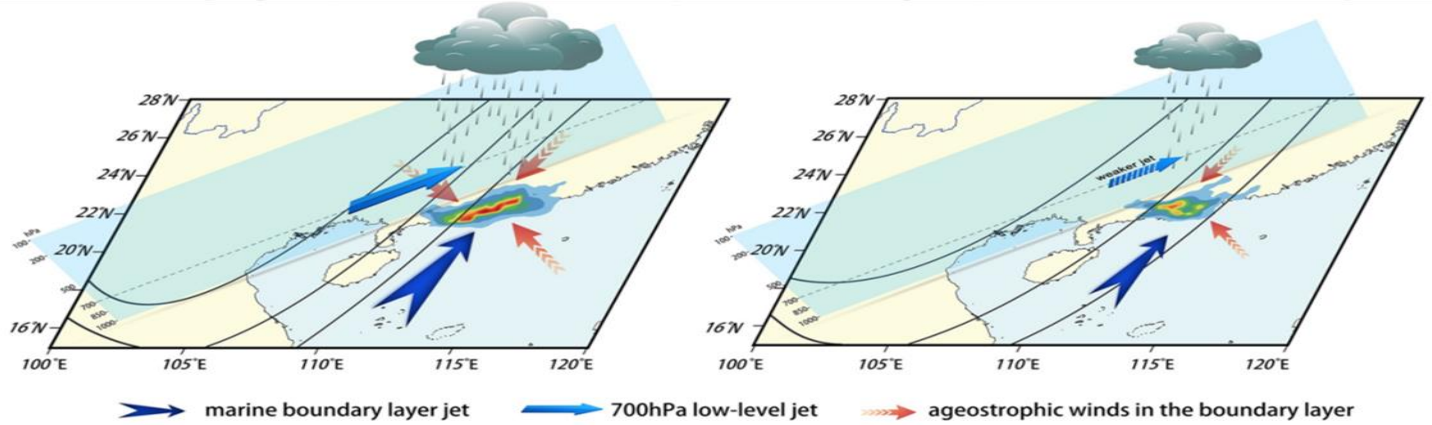
（Liu and Huang, 2023）

高数量级涡散共存并相互作用时的垂直运动的诊断分析

提出边界层非地转风辐合是影响华南前汛期极端持续性强降水的关键因子

$$\vec{V}_a=\frac{1}{f}\vec{k}\times\frac{\partial\vec{V}}{\partial t}+\frac{1}{f}\vec{k}\times\left[\left(\vec{V}\cdot\nabla\right)\vec{V}\right]+\frac{R\omega}{pf^2}\nabla_p T-\frac{1}{f}\vec{k}\times\vec{F}_h+\frac{1}{f}\vec{k}\times\left(\omega\frac{\partial\vec{V}_a}{\partial p}\right)$$

局地变化项　　惯性平流项　　斜压项　　摩擦项　　垂直输送项



华南海岸带状和团状两类极端持续性强降水过程与海洋边界层非地转风的两类不同辐合形势的对应关系（Huang et al., 2022）


谢谢各位专家
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