# 3.4 超级对流单体

**上节课回顾** **定义：包含一个准稳态旋转上升气流，持续时间远长于单体对流，它是危险性对流风暴。**

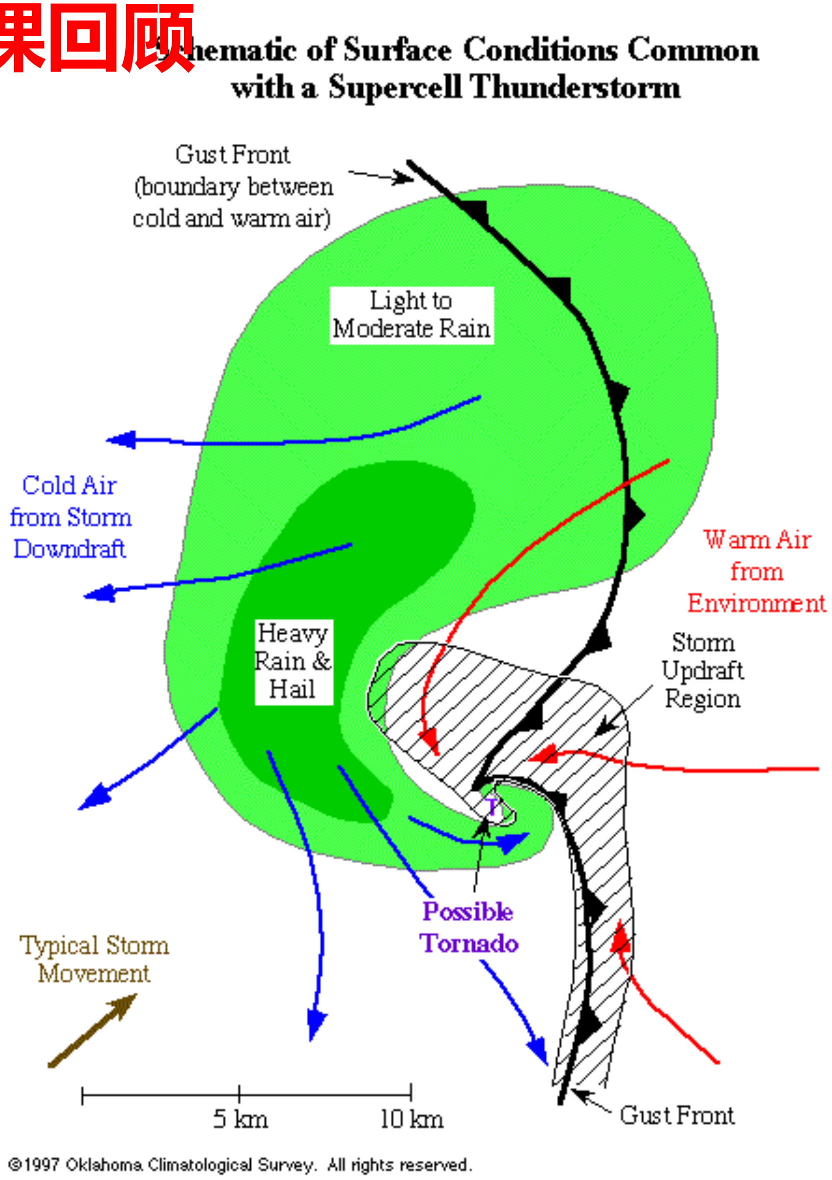
A single dominant updraft and associated mesocyclone

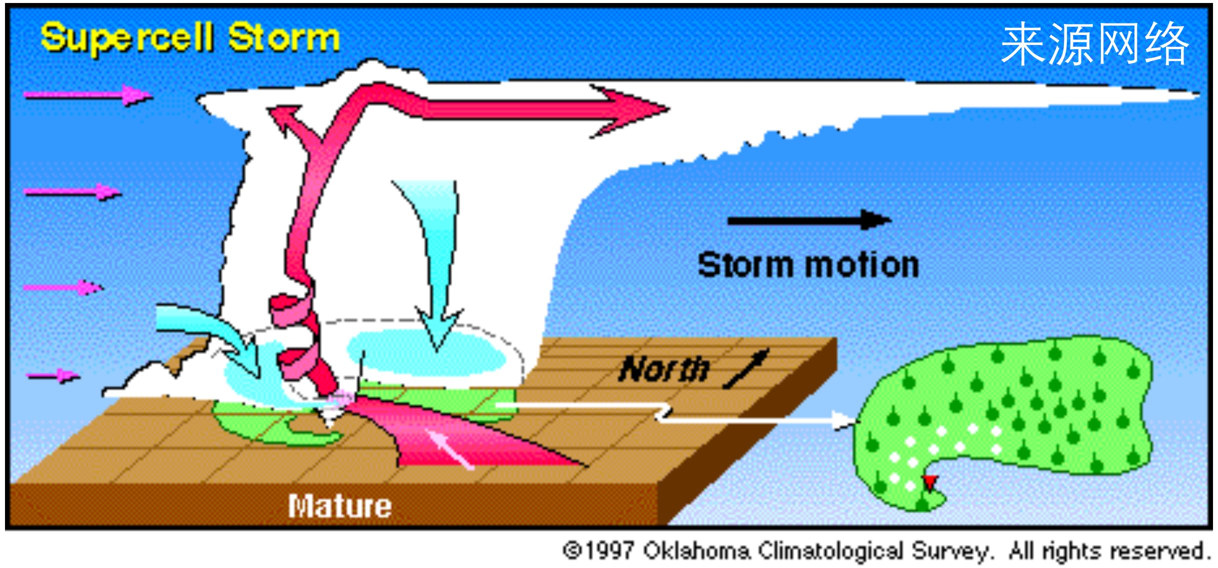
摄影：刘屹靖

2021.8.22，通辽市扎鲁特旗
一团超级单体雷暴迅速形成
旋转结构清晰可见

# A schematic of supercell

**上节课回顾**





来源网络

# （1） 一般特征

## 上节课回顾

1） 最少见，但灾害最重；

Hail (直径可大于5cm), 强龙卷基本上都是超级单体造成。

2） 生命期：1–4h，可达8h。

3） 上升气流中有一个持续性(>20分钟）深厚中气旋，直径3–8 km, 一般达到上升气流的一半高度，涡度为O(0.01) $s^{-1}$.

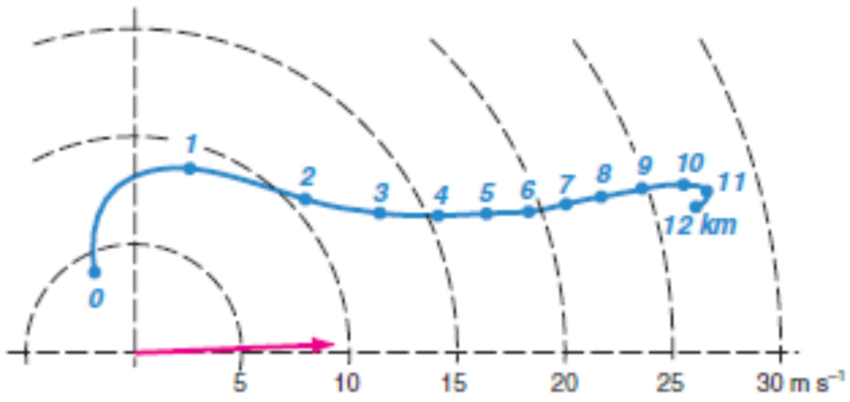
不同于阵风锋前的瞬变浅薄中涡旋。

来源网络

来源网络

## 上节课回顾

4） 生成环境： >20 m/s的0–6 km垂直风（long-curved hodograph），CAPE>1000 J/kg (不必要很大)



5） 上升气流的驱动：扰动气压垂直梯度力

6） 系统移动

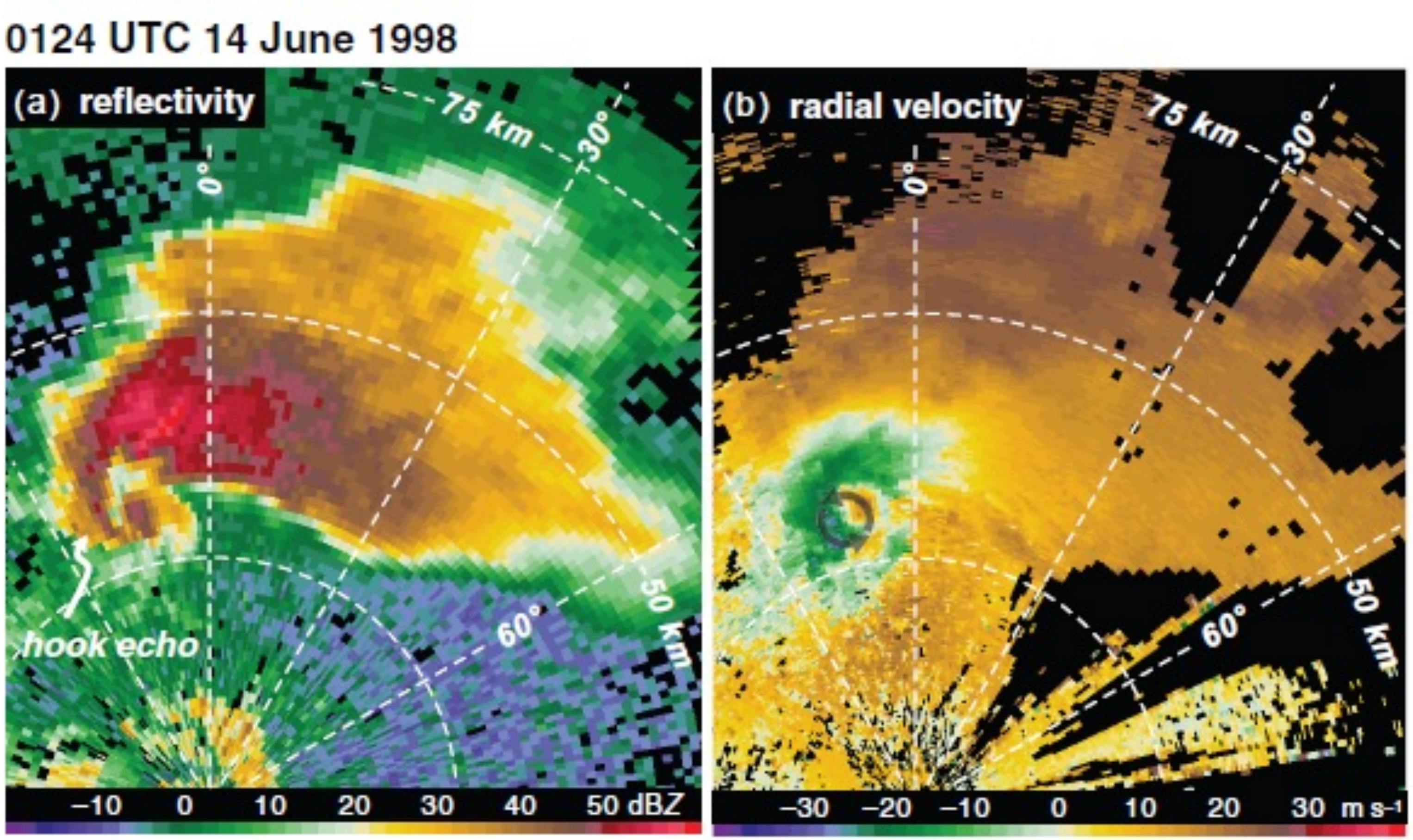
- 明显偏离平均风
- 气旋性超级单体向平均切变矢量的右侧移动
- 反气旋性超级单体向平均切变矢量的左侧移动
- 分裂：两个分裂的单体对称移动，往往其中一个消亡，另一个发展加强。

# (2) 超级单体结构

**上节课回顾**

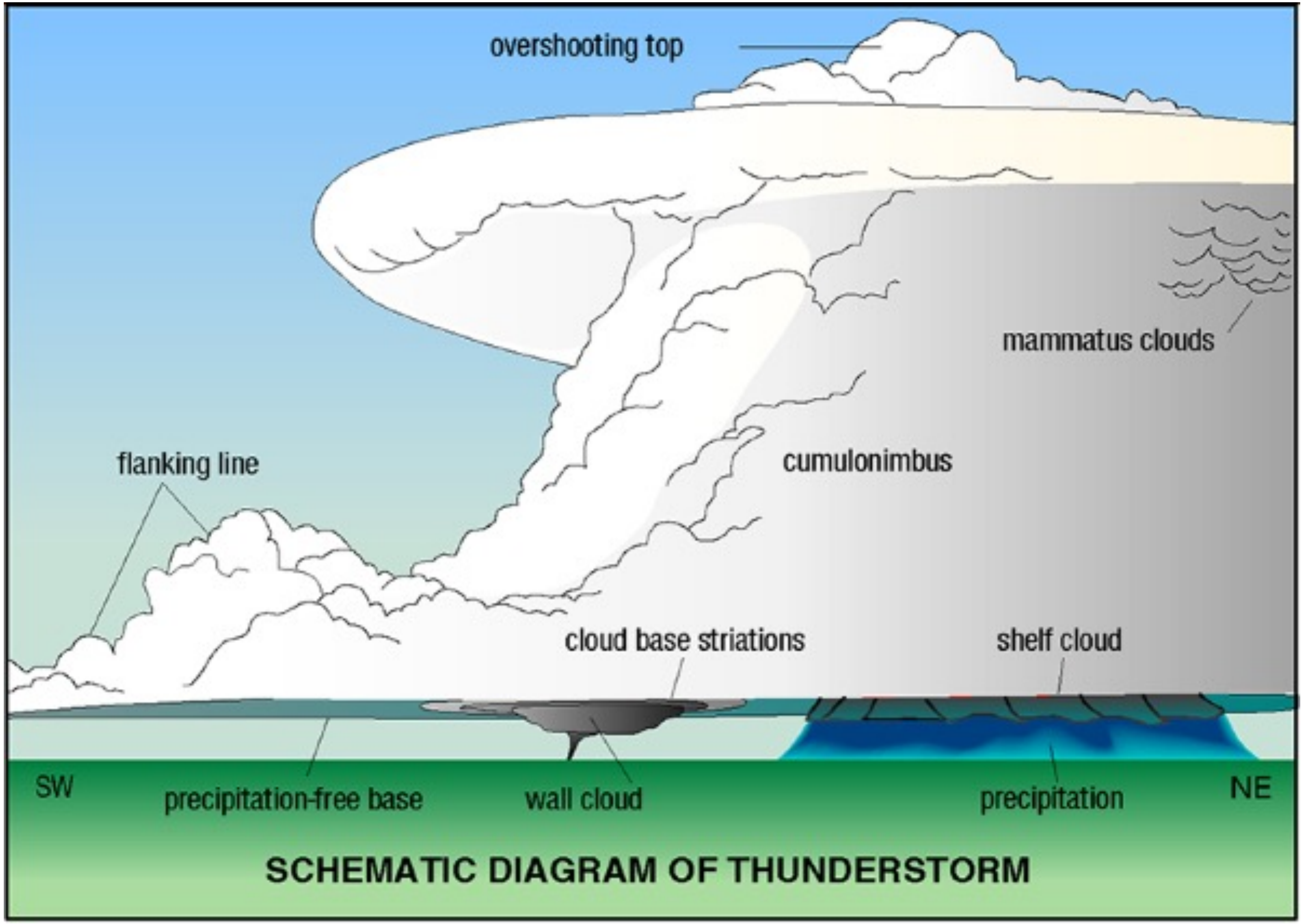
1） **Radar signature**

**Hook echo: lower level reflectivity minimum**



# 2） Cloud features

上节课回顾

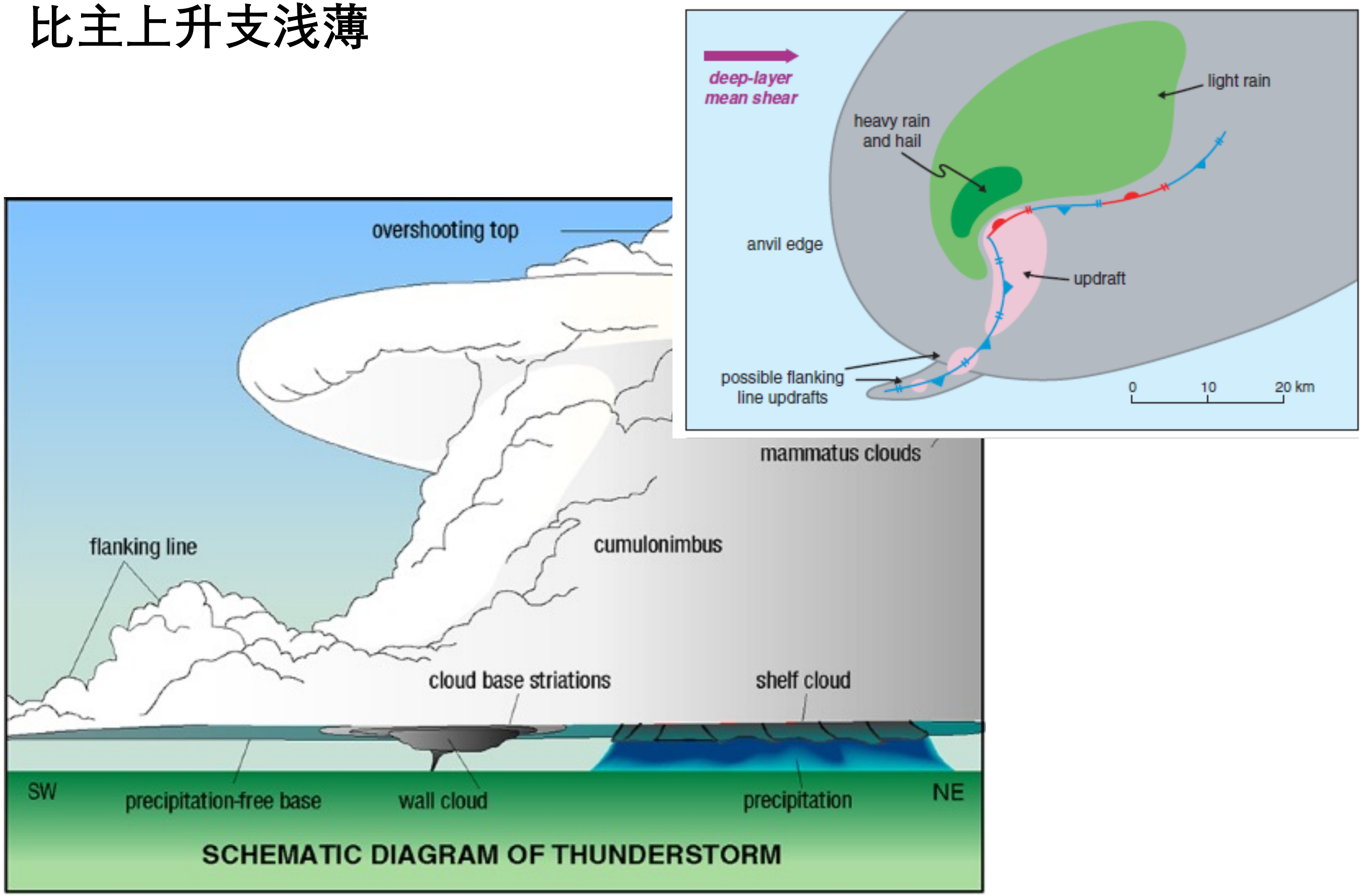


# 3） Flanking line

上节课回顾

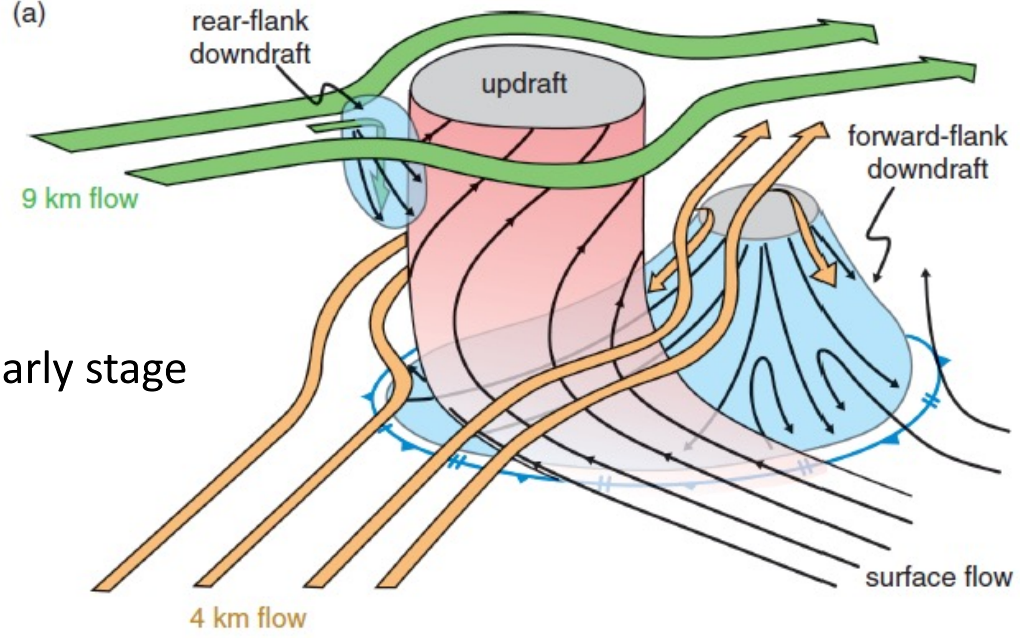
Located at right-rear flank relative to storm motion

比主上升支浅薄

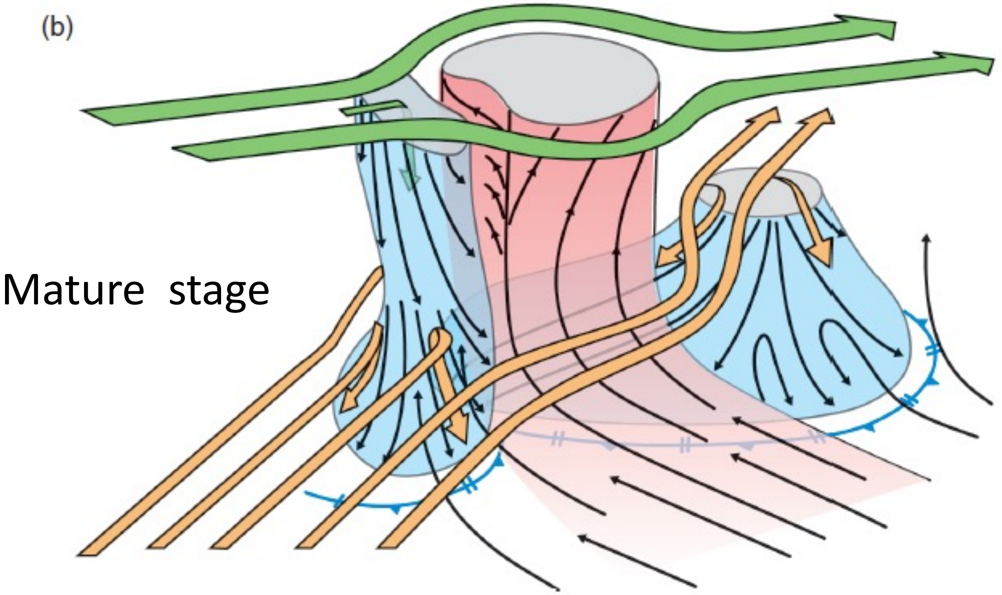


# 4） Downdraft

**上节课回顾**



Early stage



Mature stage

形成机制:

中上层干空气在上升气流后面导致蒸发冷却，产生负浮力（向下加速度）。

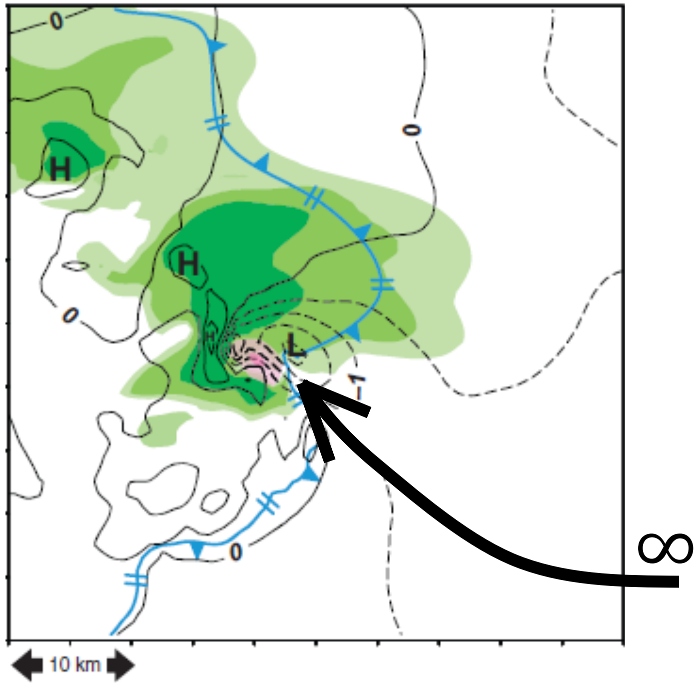
指向下方的垂直扰动气压梯度力。

## 5） Inflow lows

**上节课回顾**

风速可能超过20m/s

最低气压为1–3 hPa



形成机制: 在刚体边界附近，表面气压扰动一般由Bernouli 方程表示

$$\frac{\rho v^2}{2} + p = Const$$

$\rho, v, p$分别为沿流线的空气密度、风速和气压。

风速大的地方气压低

$$\frac{\rho {v_\infty}^2}{2} + p_\infty = \frac{\rho v^2}{2} + p \quad \Rightarrow \quad \Delta p = \frac{\rho (v^2 - {v_\infty}^2)}{2}$$

$\rho$=1 kg/m$^3$　$v$=20 m/s，　$v_\infty$=5 m/s　$\Rightarrow$　$\Delta p = 2\ \text{hPa}$

# 6） 降水分布

**上节课回顾**

**CL： classic supercell**

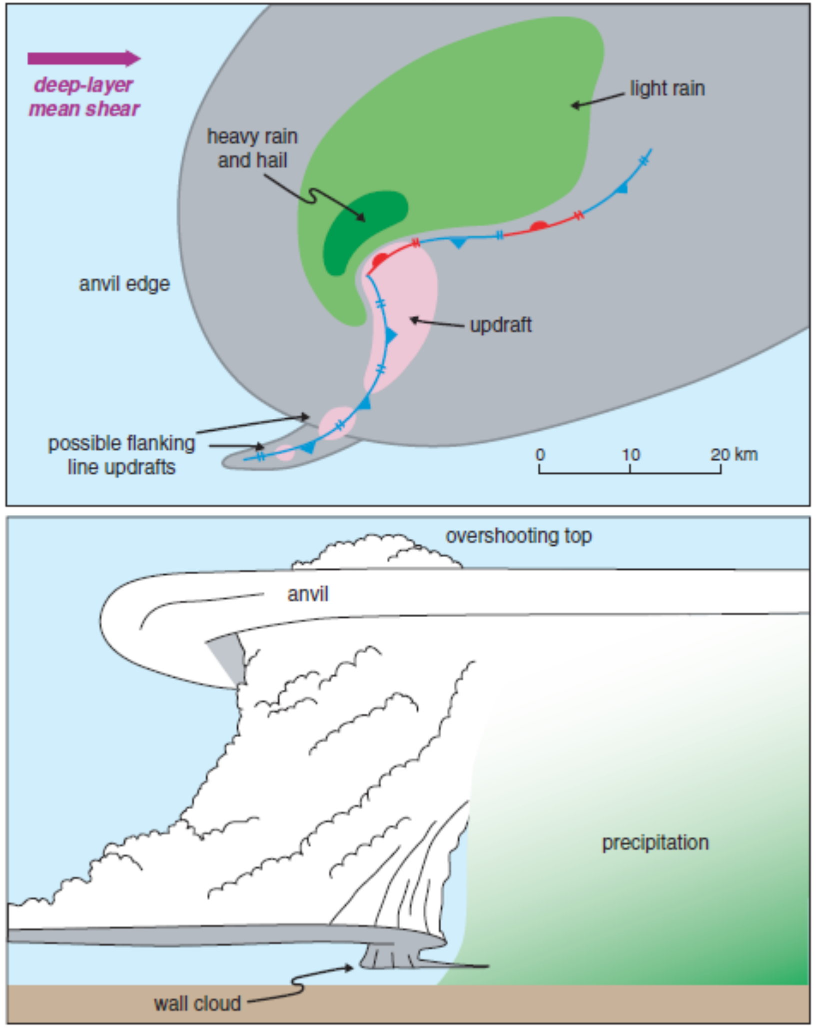
**LP： low-precipitation supercell**

**HP： high-precipitation supercell**

**CL： classic supercell**

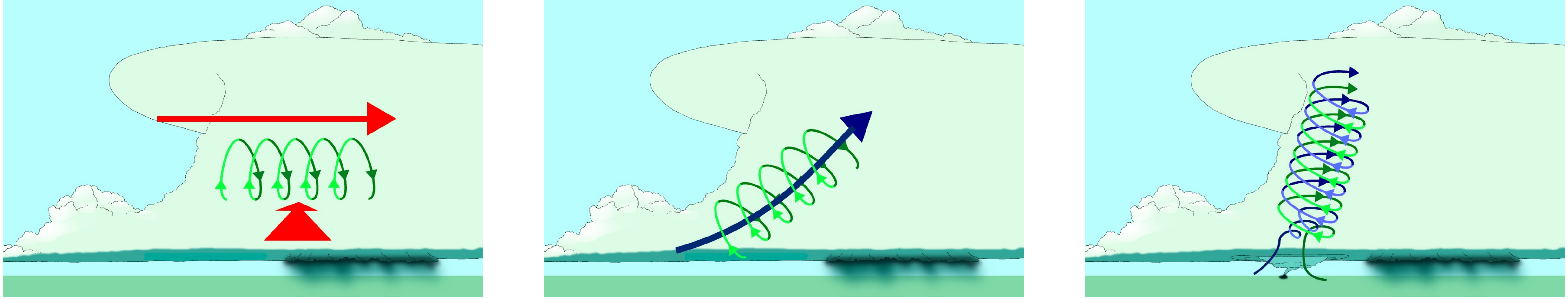
降水主要出现在前部

classic supercell



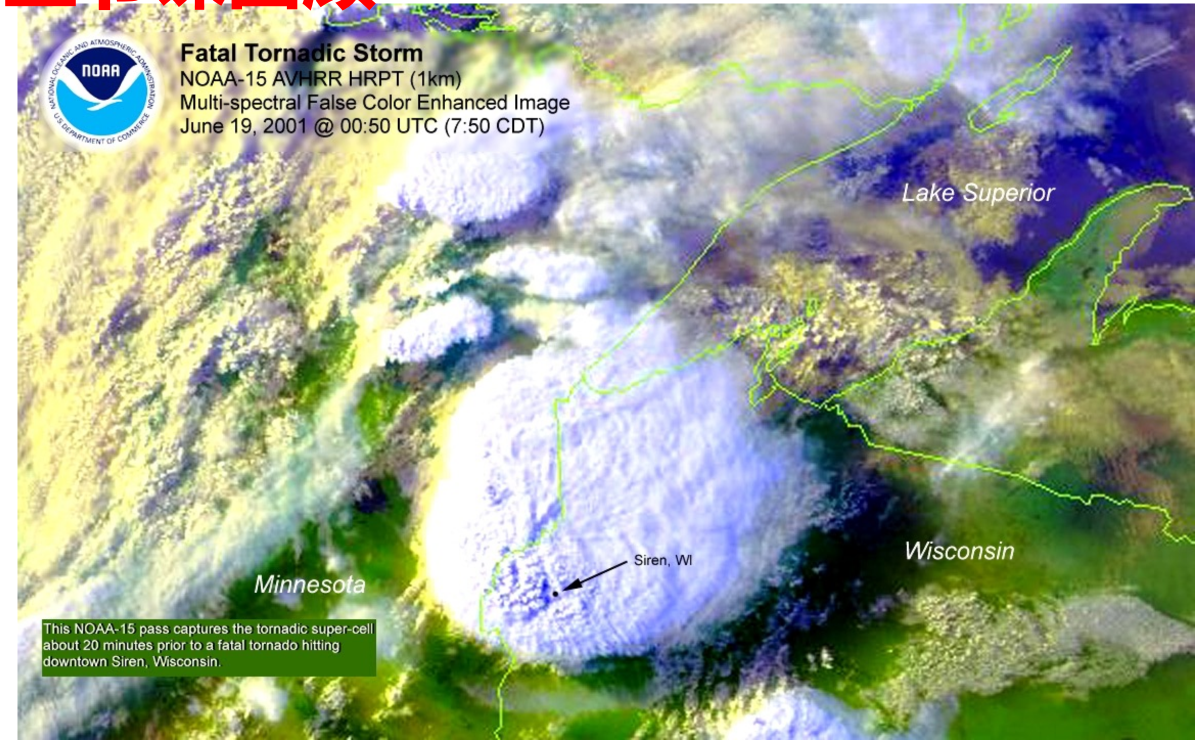
## 7) mesocyclone

# 上节课回顾



8) effects

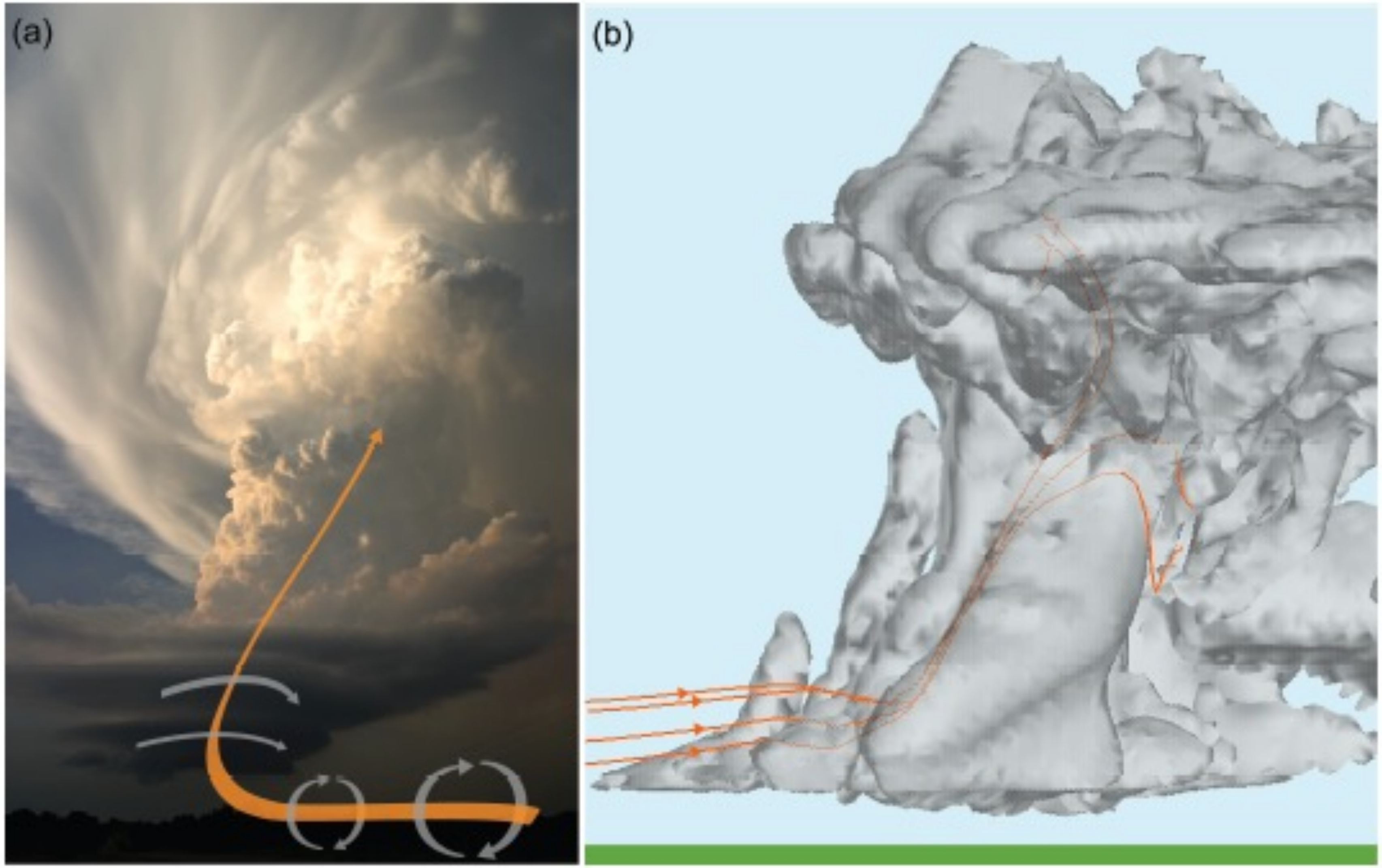
上节课回顾



Supercells can produce hailstones averaging as large as two inches (5.1 cm) in diameter, winds over 70 miles per hour (110 km/h)[*clarification needed*], tornadoes of as strong as EF3 to EF5 intensity (if wind shear and atmospheric instability are able to support the development of stronger tornadoes), flooding, frequent-to-continuous lightning, and very heavy rain. Many tornado outbreaks come from clusters of supercells. Large supercells may spawn multiple long-tracked and deadly tornadoes, with notable examples in the 2011 Super Outbreak.

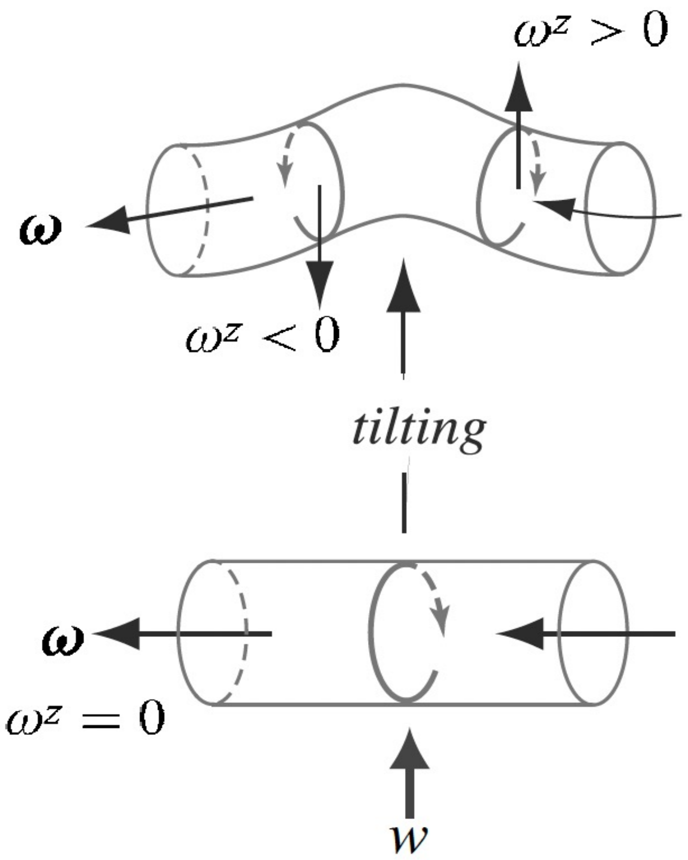
Severe events associated with a supercell almost always occur in the area of the updraft/downdraft interface. In the Northern Hemisphere, this is most often the rear flank (southwest side) of the precipitation area in **LP** and **classic** supercells, but sometimes the leading edge (southeast side) of **HP** supercells.

# （3） 中层旋转的来源



### 4.3.1 The ‘frozen-in’ property of vorticity

Let us first consider some simple topological properties of the vorticity field and its evolution. We define a *vortex line* to be a line drawn through the fluid which is everywhere in the direction of the local vorticity. This definition is analogous to that of a streamline, which is everywhere in the direction of the local velocity. A *vortex tube* is formed by the collection of vortex lines passing through a closed curve (Fig. 4.2. A *material line* is just a line that connects material fluid elements. Suppose we draw a vortex line through the fluid; such a line obviously connects fluid elements and therefore defines a coincident material line. As the fluid moves the material line deforms, and the vortex line also evolves in a manner determined by the equations of motion. A remarkable property of vorticity is that, for an unforced and inviscid barotropic fluid, the flow evolution is such that a vortex line remains coincident with the material line that it was initially associated with. Put another way, a vortex line always contains the same material elements — the vorticity is ‘frozen’ or ‘glued’ to the material fluid.[1]



推导见板书!

$$\frac{\mathrm{D}\delta \boldsymbol{l}}{\mathrm{D}t} = \delta \boldsymbol{v} = \delta \boldsymbol{l} \cdot \nabla \boldsymbol{v}$$

$$\frac{\mathrm{D}\boldsymbol{\omega}}{\mathrm{D}t} = \boldsymbol{\omega} \cdot \nabla \boldsymbol{v}.$$

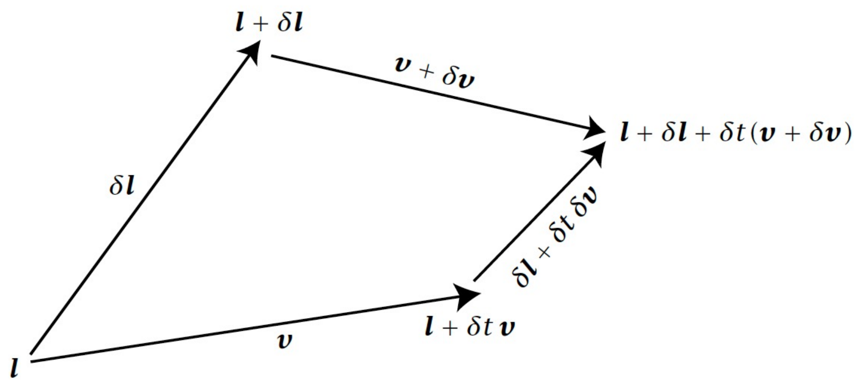


**Fig. 4.3** Evolution of an infinitesimal material line $\delta\boldsymbol{l}$ from time $t$ to time $t + \delta t$. It can be seen from the diagram that $\mathrm{D}\delta\boldsymbol{l}/\mathrm{D}t = \delta\boldsymbol{v}$.

涡度倾向方程

$$\frac{\partial\vec{\boldsymbol{\omega}}}{\partial t}=\nabla\times\left(B\vec{\mathrm{k}}\right)-(\vec{\boldsymbol{v}}\cdot\nabla)\vec{\boldsymbol{\omega}}+(\vec{\boldsymbol{\omega}}\cdot\nabla)\vec{\boldsymbol{v}}$$

$$\frac{\partial\xi}{\partial t}+u\frac{\partial\xi}{\partial x}+v\frac{\partial\xi}{\partial y}+w\frac{\partial\xi}{\partial z}=\frac{\partial B}{\partial y}+\xi\frac{\partial u}{\partial x}+\eta\frac{\partial u}{\partial y}+\zeta\frac{\partial u}{\partial z}$$

$$\begin{cases}\dfrac{d\xi}{dt}=\dfrac{\partial B}{\partial y}+\xi\dfrac{\partial u}{\partial x}+\eta\dfrac{\partial u}{\partial y}+\zeta\dfrac{\partial u}{\partial z}\\[2ex]\dfrac{d\eta}{dt}=-\dfrac{\partial B}{\partial x}+\xi\dfrac{\partial v}{\partial x}+\eta\dfrac{\partial v}{\partial y}+\zeta\dfrac{\partial v}{\partial z}\\[2ex]\dfrac{d\zeta}{dt}=\xi\dfrac{\partial w}{\partial x}+\eta\dfrac{\partial w}{\partial y}+\zeta\dfrac{\partial w}{\partial z}\end{cases}$$

# 垂直涡度倾向方程（Boussinesq近似，忽略摩擦力和科氏力项）

$$\boxed{\frac{d\zeta}{dt} = \xi\frac{\partial w}{\partial x} + \eta\frac{\partial w}{\partial y} + \zeta\frac{\partial w}{\partial z}}$$

$$\frac{\partial\zeta}{\partial t} = -\vec{\boldsymbol{v}}\cdot\nabla\zeta + \vec{\boldsymbol{\omega}}\cdot\nabla w$$

$$= -u\frac{\partial\zeta}{\partial x} - v\frac{\partial\zeta}{\partial y} - w\frac{\partial\zeta}{\partial z} + \xi\frac{\partial w}{\partial x} + \eta\frac{\partial w}{\partial y} + \zeta\frac{\partial w}{\partial z}$$

$$\left.\begin{aligned}
&= -u\frac{\partial\zeta}{\partial x} - v\frac{\partial\zeta}{\partial y} - w\frac{\partial\zeta}{\partial z} && \textbf{平流项（Advection)}\\
&+\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\frac{\partial w}{\partial x} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\frac{\partial w}{\partial y} && \textbf{倾斜项（Tilting）}\\
&+(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y})\frac{\partial w}{\partial z} && \textbf{拉伸项 (Stretching)}
\end{aligned}\right\} \text{①}$$

# 线性化

$$u=\bar{u}(z)+u' \qquad v=\bar{v}(z)+v' \qquad w=w' \qquad \zeta=\zeta'$$

**代入式** ① $\frac{\partial\zeta}{\partial t}=-u\frac{\partial\zeta}{\partial x}-v\frac{\partial\zeta}{\partial y}-w\frac{\partial\zeta}{\partial z}+\left(\frac{\partial w}{\partial y}-\frac{\partial v}{\partial z}\right)\frac{\partial w}{\partial x}+\left(\frac{\partial u}{\partial z}-\frac{\partial w}{\partial x}\right)\frac{\partial w}{\partial y}+\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)\frac{\partial w}{\partial z}$

$$\frac{\partial\zeta'}{\partial t}=-(\bar{u}(z)+\cancel{u'})\frac{\partial\zeta'}{\partial x}-(\bar{v}(z)+\cancel{v'})\frac{\partial\zeta'}{\partial y}-\cancel{w'\frac{\partial\zeta'}{\partial z}}$$
$$+\left(\cancel{\frac{\partial w'}{\partial y}}-\frac{\partial(\bar{v}(z)+\cancel{v'})}{\partial z}\right)\frac{\partial w'}{\partial x}+\left(\frac{\partial(\bar{u}(z)+\cancel{u'})}{\partial z}-\cancel{\frac{\partial w'}{\partial x}}\right)\frac{\partial w'}{\partial y}$$
$$+\left(\frac{\partial(\cancel{\bar{v}}(z)+\cancel{v'})}{\partial x}-\frac{\partial(\cancel{\bar{u}}(z)+\cancel{u'})}{\partial y}\right)\frac{\partial w'}{\partial z}$$

**忽略二阶扰动项，得到：**

$$\frac{\partial\zeta'}{\partial t}=-\bar{u}\frac{\partial\zeta'}{\partial x}-\bar{v}\frac{\partial\zeta'}{\partial y}+\frac{\partial\bar{u}}{\partial z}\frac{\partial w'}{\partial y}-\frac{\partial\bar{v}}{\partial z}\frac{\partial w'}{\partial x}$$

$$\frac{\partial \zeta'}{\partial t} = \underbrace{-\bar{u}\frac{\partial \zeta'}{\partial x} - \bar{v}\frac{\partial \zeta'}{\partial y}}_{\text{平流项}} + \underbrace{\frac{\partial \bar{u}}{\partial z}\frac{\partial w'}{\partial y} - \frac{\partial \bar{v}}{\partial z}\frac{\partial w'}{\partial x}}_{\text{倾斜项}}$$

$$= -\vec{\bar{\boldsymbol{v}}} \cdot \nabla\zeta + \vec{\mathrm{s}} \times \nabla w' \cdot \vec{\mathrm{k}}$$

$\vec{\bar{\boldsymbol{v}}} = \bar{u}\,\vec{\mathrm{i}} + \bar{\mathrm{v}}\,\vec{\mathrm{j}}$ $\quad$ $\vec{\mathrm{s}} = \frac{\partial \vec{\bar{\boldsymbol{v}}}}{\partial \mathrm{z}}$ **垂直风切变矢量**

**在Updraft relative coordinates, 上升气流的移动速度为** $\vec{\mathrm{c}}$

$$\left(\frac{\partial \zeta'}{\partial t}\right)_{\mathrm{sr}} = -(\vec{\bar{\boldsymbol{v}}} - \vec{\mathrm{c}}) \cdot \nabla\zeta' + \vec{\mathrm{s}} \times \nabla w' \cdot \vec{k}$$

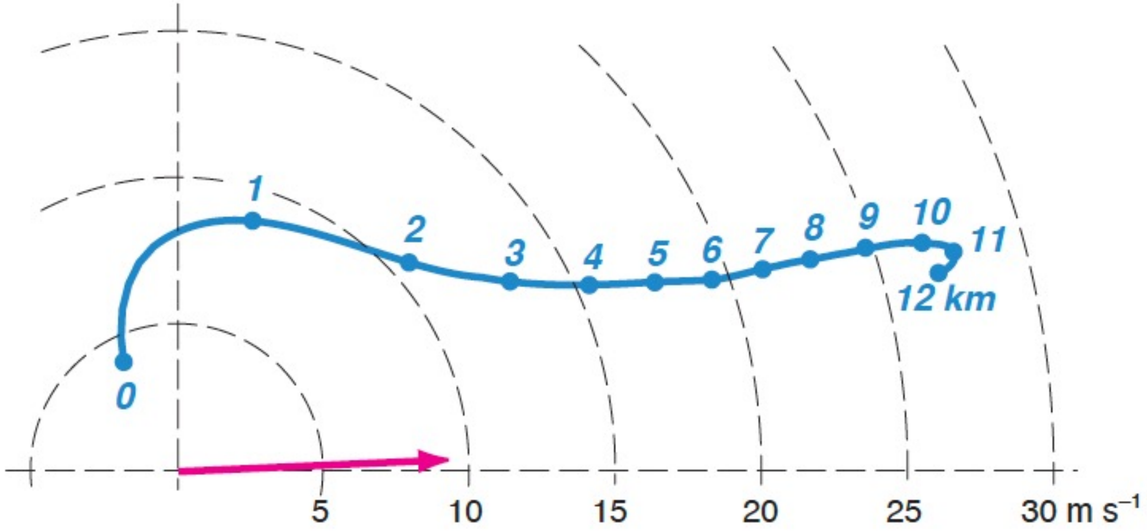


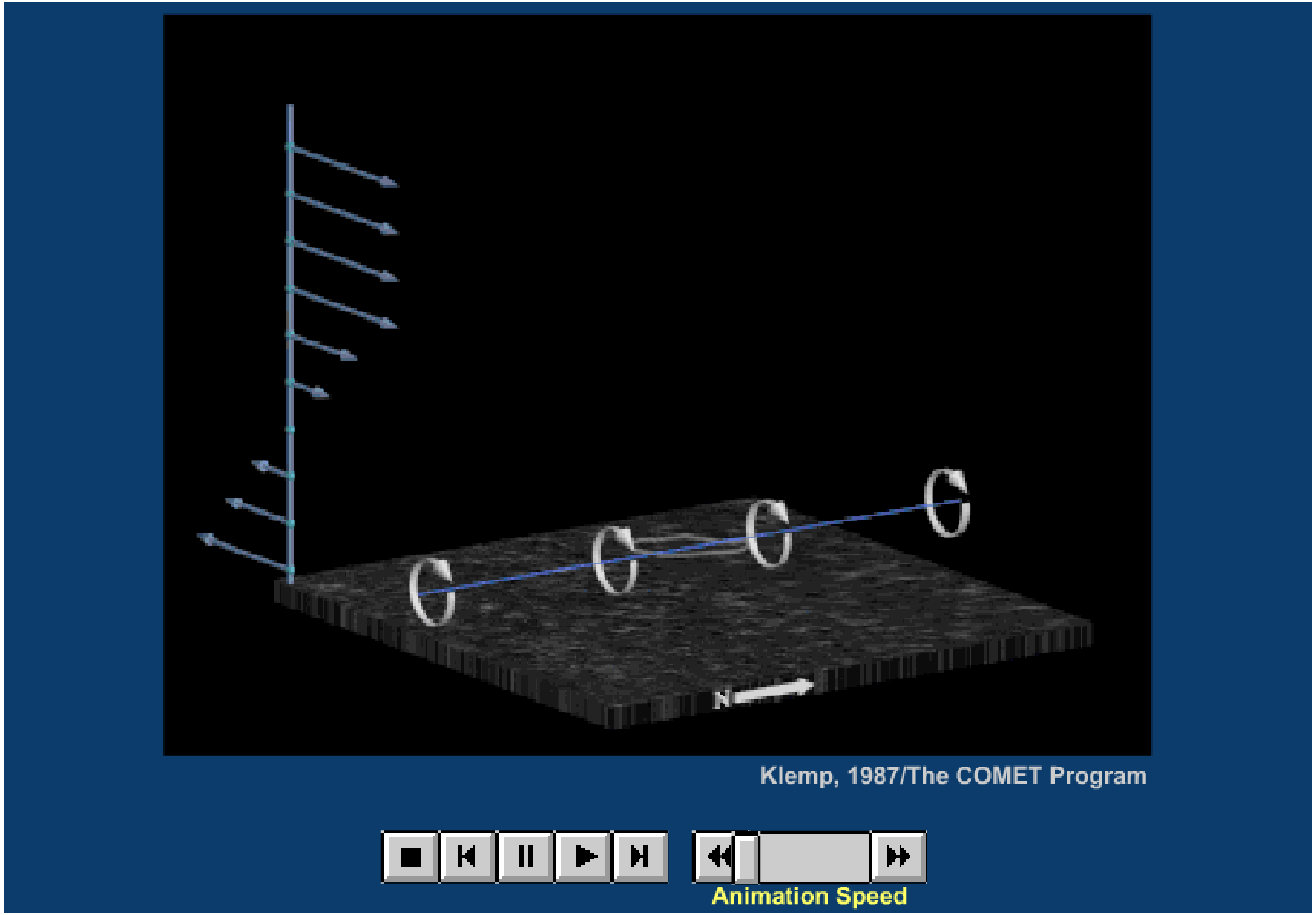
**Figure 8.15** Composite hodograph based on a nationwide sample of over 400 proximity soundings in the environments of cyclonically rotating supercell thunderstorms in the United States. The proximity soundings were obtained from Rapid Update Cycle analyses. The mean storm motion is indicated by the magenta arrow. Notice that it lies not just to the right of the mean wind, but to the right of *all* of the winds that define the hodograph. (Adapted from Markowski *et al*. [2003].)

# Horizontal Vorticity

# 1) Tilting

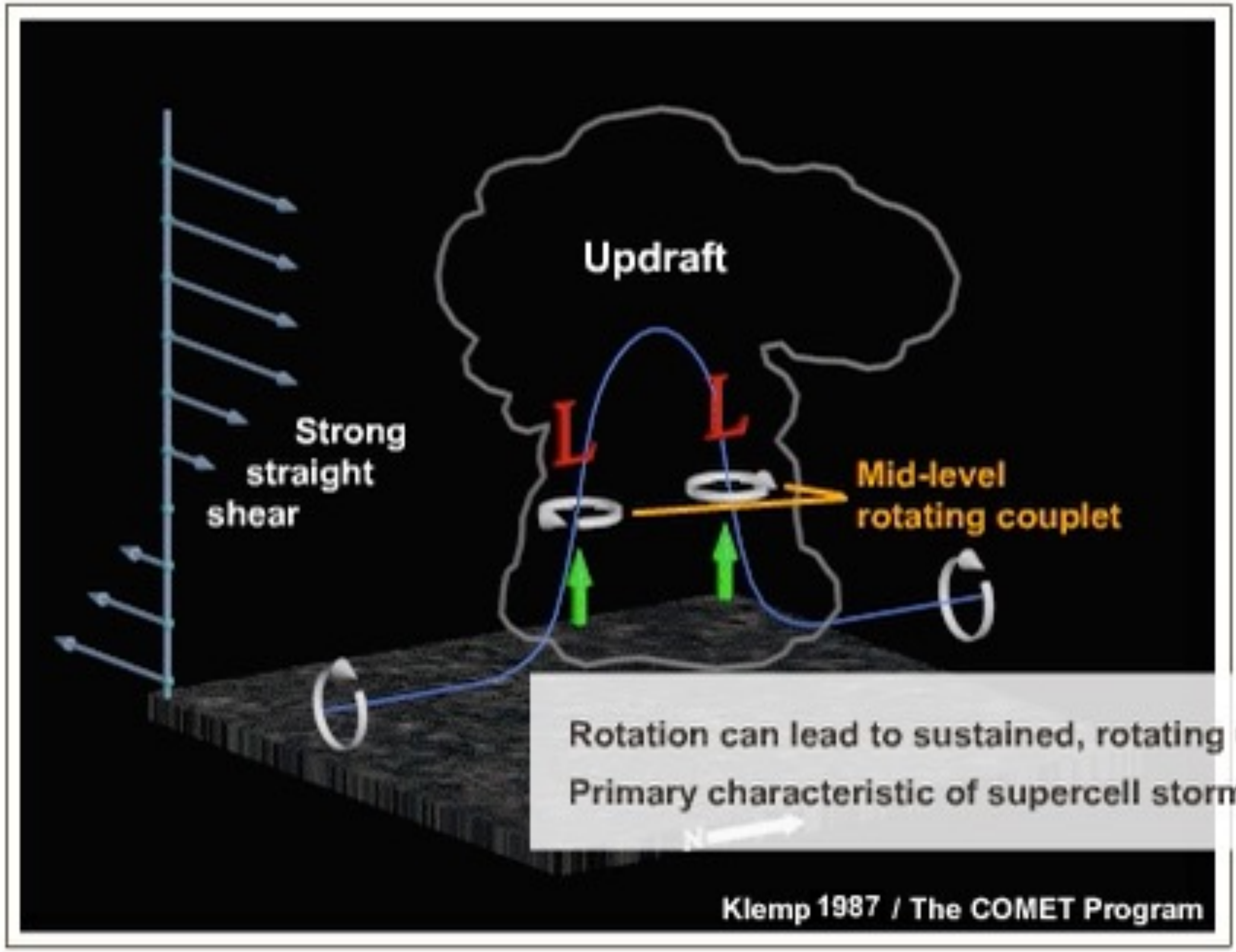
$$\left(\frac{\partial \zeta'}{\partial t}\right)_{\mathrm{sr}} = -(\overline{\vec{\boldsymbol{v}}} - \vec{\mathrm{c}}) \cdot \nabla \zeta' + \vec{\mathrm{s}} \times \nabla w' \cdot \vec{k}$$

# Tilting of horizontal vortex line



Klemp, 1987/The COMET Program

# Supercells



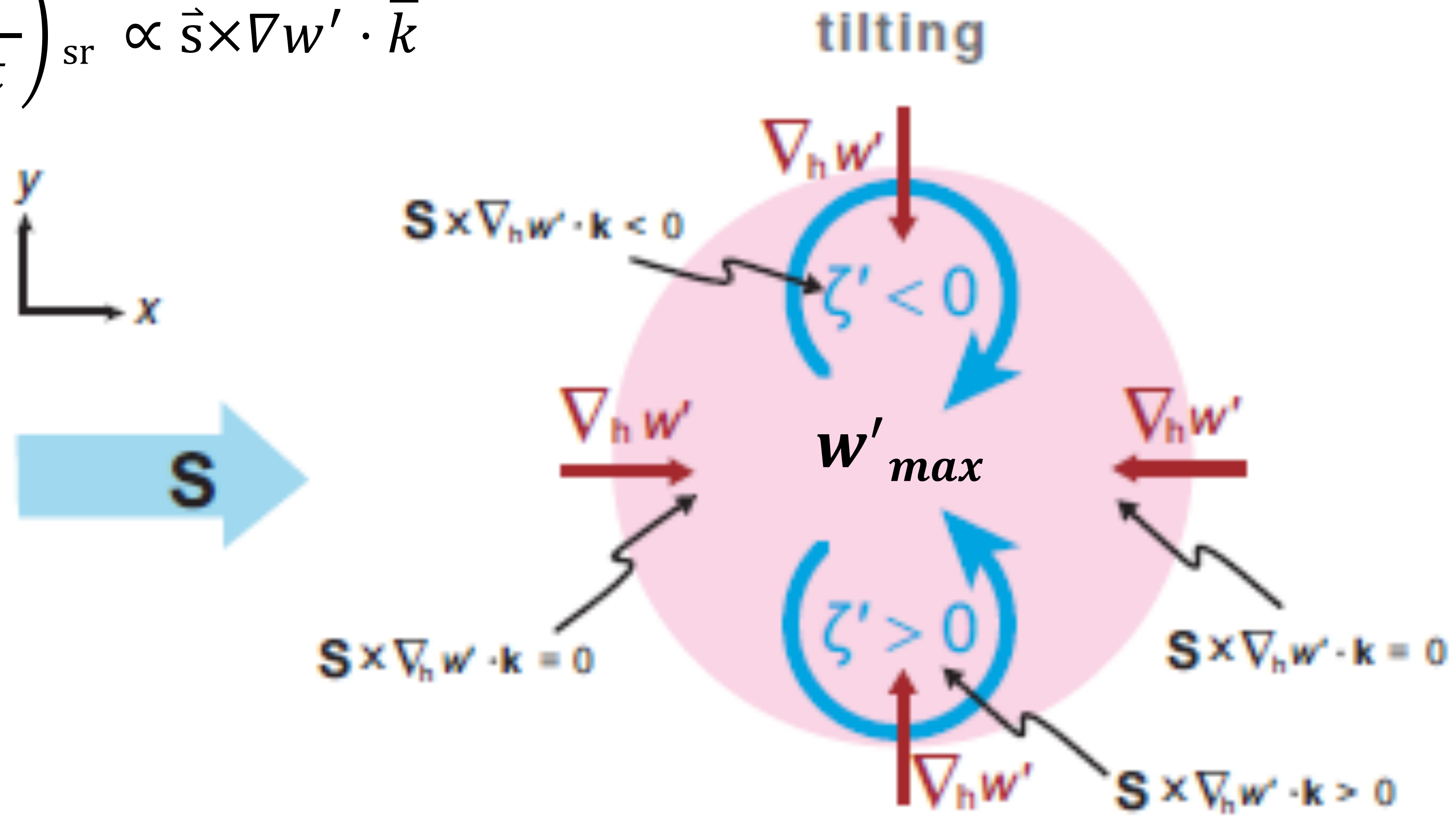
Rotation can lead to sustained, rotating updraft

Primary characteristic of supercell storms

Klemp 1987 / The COMET Program

$$\left(\frac{\partial\zeta'}{\partial t}\right)_{\mathrm{sr}} = -(\vec{\bar{\boldsymbol{v}}} - \vec{\mathrm{c}}) \cdot \nabla\zeta' + \vec{\mathrm{s}}\times\nabla w' \cdot \vec{k}$$

$$\left(\frac{\partial\zeta'}{\partial t}\right)_{\mathrm{sr}} \propto \vec{\mathrm{s}}\times\nabla w' \cdot \vec{k}$$



在垂直于切变矢量的方向上垂直最大抬升的两侧产生两个对称的反向涡旋，切变矢量的左边为负涡度，右边为正涡度

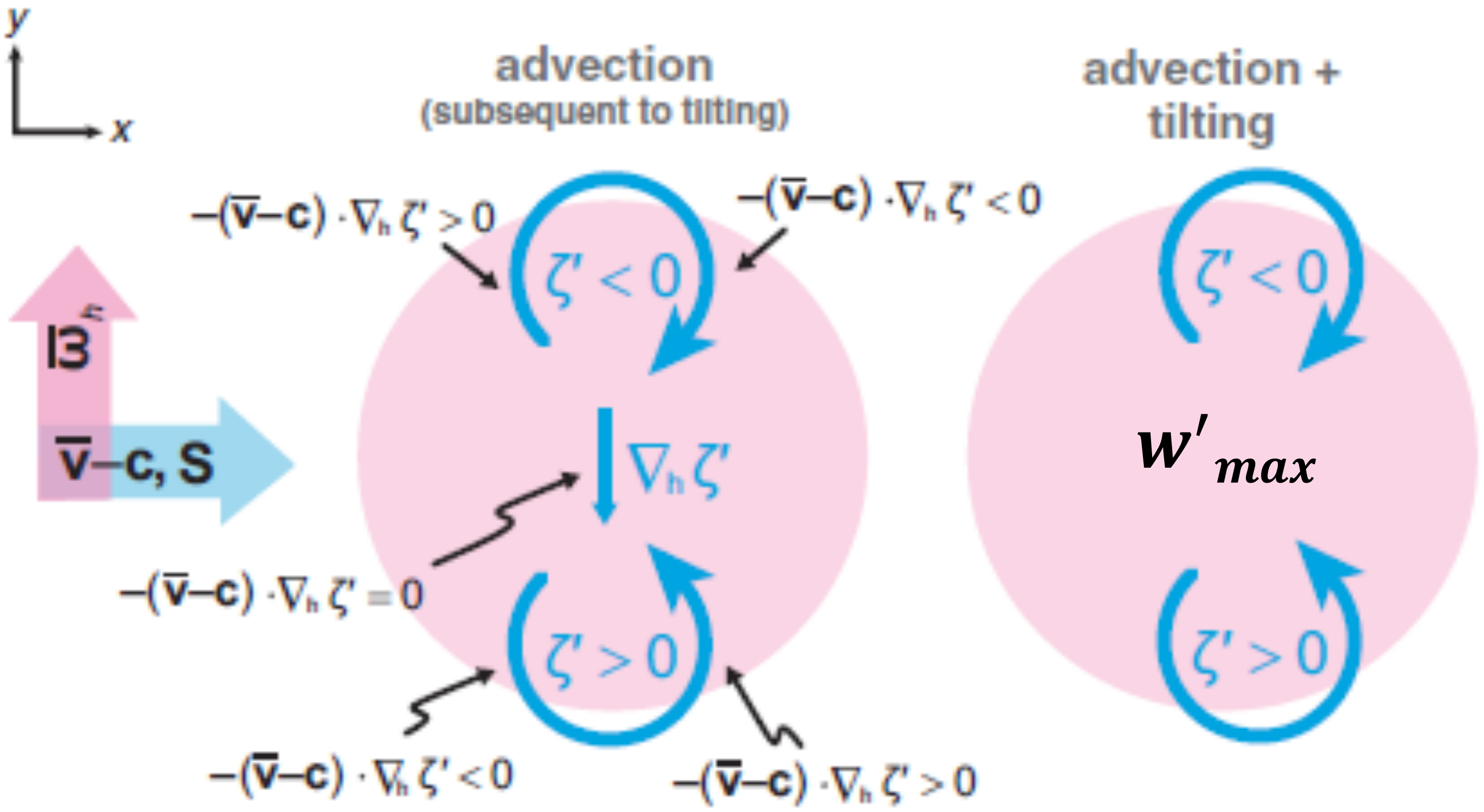
# 2) Advection

$$\left(\frac{\partial \zeta'}{\partial t}\right)_{\mathrm{sr}} = -(\overline{\vec{v}} - \vec{\mathrm{c}}) \cdot \nabla\zeta' + \vec{\mathrm{s}} \times \nabla w' \cdot \vec{k}$$

$$\left(\frac{\partial \zeta'}{\partial t}\right)_{\mathrm{sr}} \propto -(\overline{\vec{v}} - \vec{\mathrm{c}}) \cdot \nabla\zeta'$$

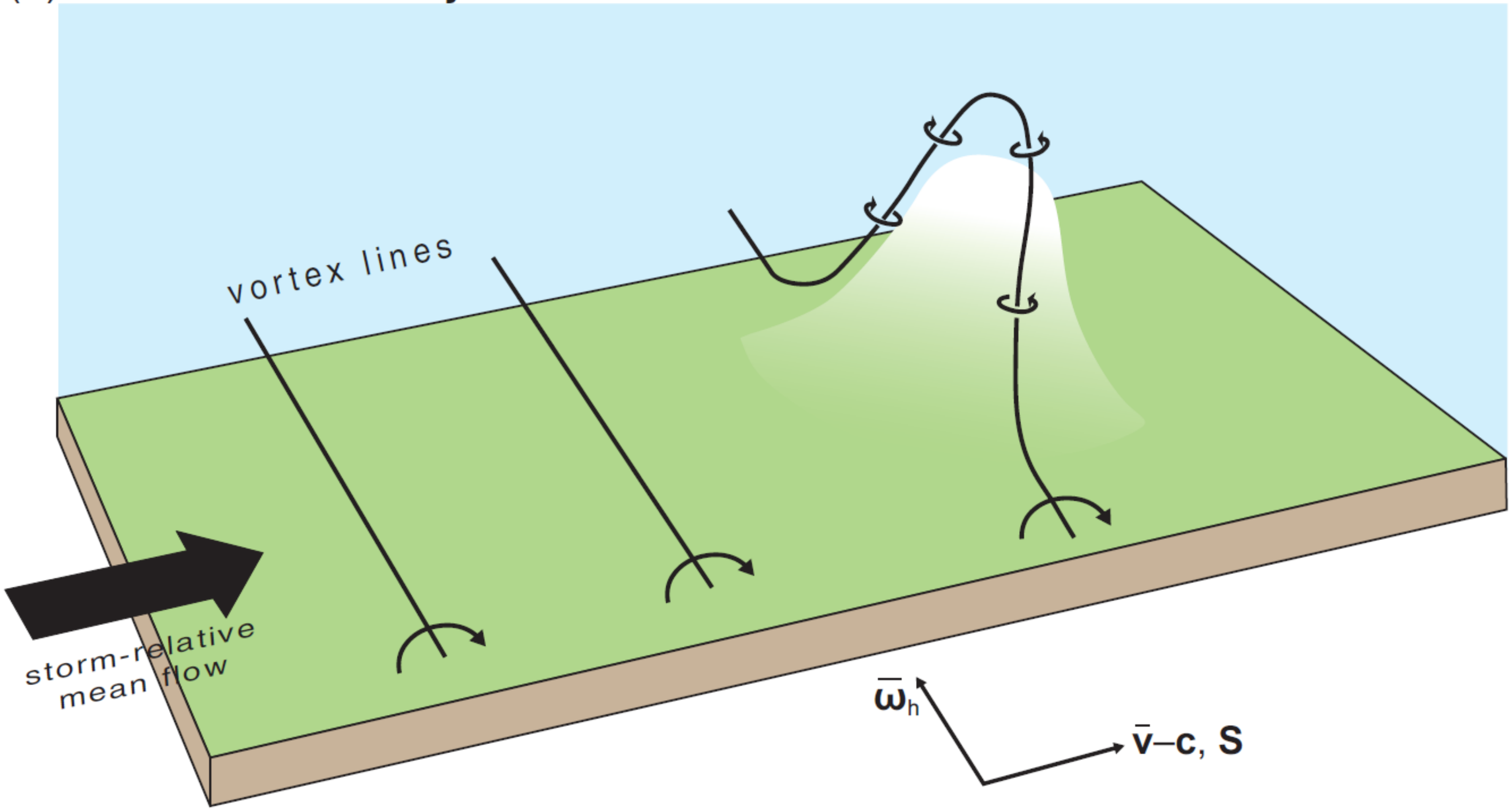
**a. Crosswise vorticity: Storm relative wind与水平涡度垂直**

$$(\overline{\vec{v}} - \vec{\mathrm{c}}) \perp \overrightarrow{\boldsymbol{\omega}_{\mathrm{h}}}$$



涡度对被向下切变方向平流

## (a) crosswise vorticity

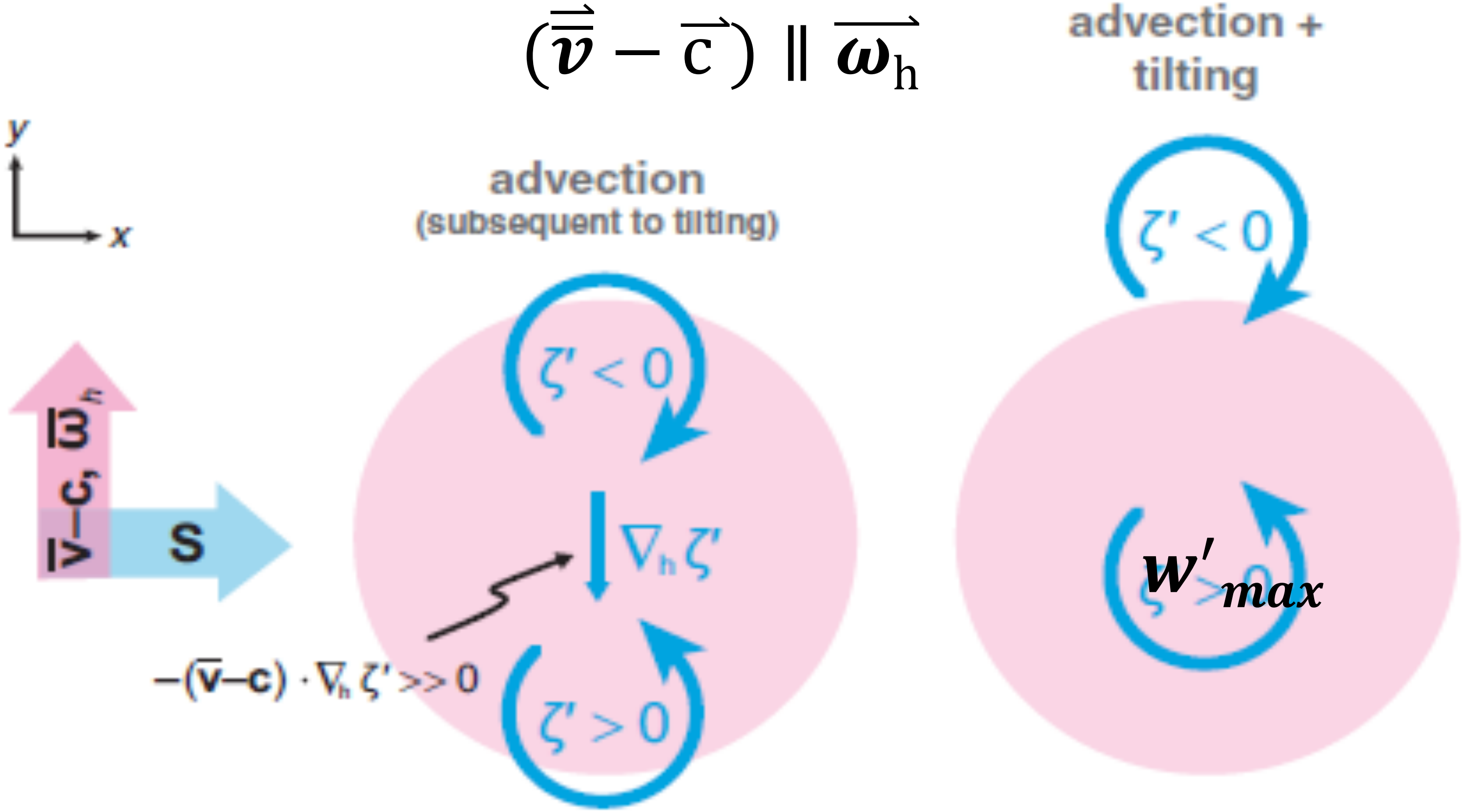


# 2) Advection

$$\left(\frac{\partial \zeta'}{\partial t}\right)_{\mathrm{sr}} \propto -(\vec{\overline{v}} - \vec{\mathrm{c}}) \cdot \nabla \zeta'$$

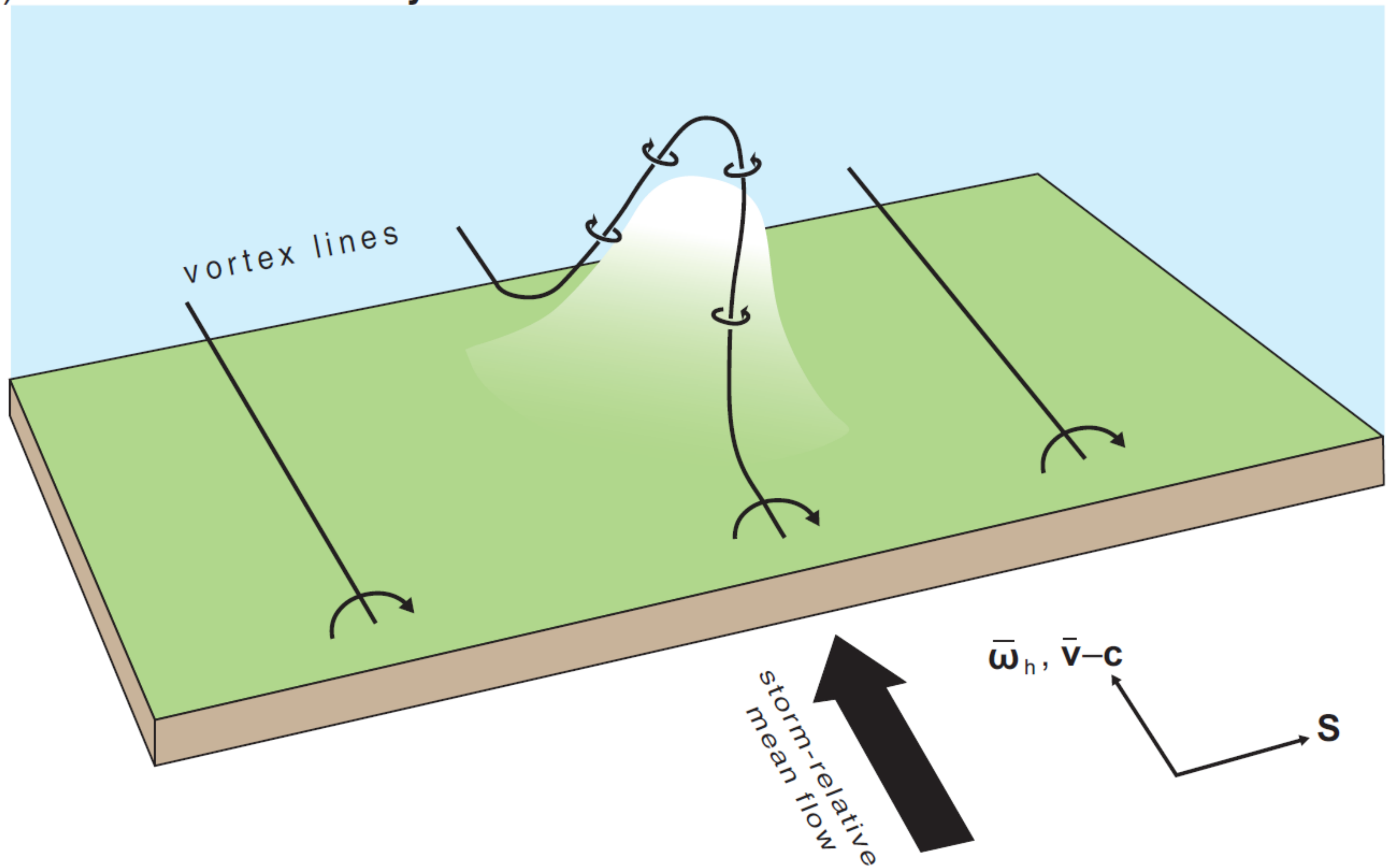
**b. Streamwise vorticity: Storm relative wind与水平涡度平行**

$$(\vec{\overline{v}} - \vec{\mathrm{c}}) \parallel \vec{\boldsymbol{\omega}}_{\mathrm{h}}$$



平流幅度较Crosswise情况大。由于$\nabla\zeta'$较大，再经上升气流拉伸，正涡旋比crosswise的强。Updraft与$\zeta' > 0$的重合程度取决于水平涡度在storm relative wind 方向上的分量大小。

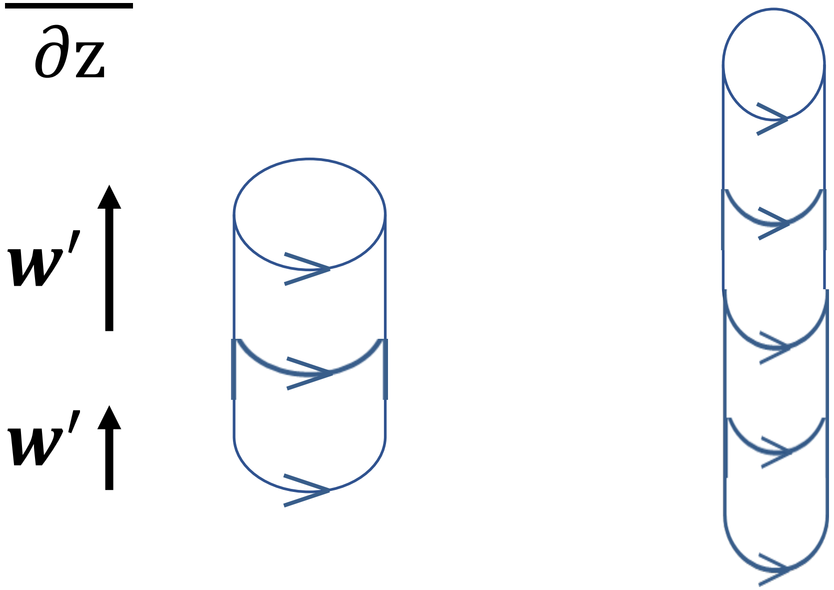
# (b) **streamwise vorticity**



# 3) 拉伸项

$$\frac{\partial\zeta'}{\partial t} = -(\bar{u}(z)+u')\frac{\partial\zeta'}{\partial x} - (\bar{v}(z)+v')\frac{\partial\zeta'}{\partial y} - w'\frac{\partial\zeta'}{\partial z} + \left(-\frac{\partial(\bar{v}(z)+v')}{\partial z}\right)\frac{\partial w'}{\partial x} + \left(\frac{\partial(\bar{u}(z)+u')}{\partial z}\right)\frac{\partial w'}{\partial y} + \boxed{\left(\frac{\partial v'}{\partial x} - \frac{\partial u'}{\partial y}\right)\frac{\partial w'}{\partial z}}$$

$$\left(\frac{\partial\zeta'}{\partial t}\right)_{\mathrm{sr}} \propto \zeta'\frac{\partial \mathrm{w}'}{\partial z}$$

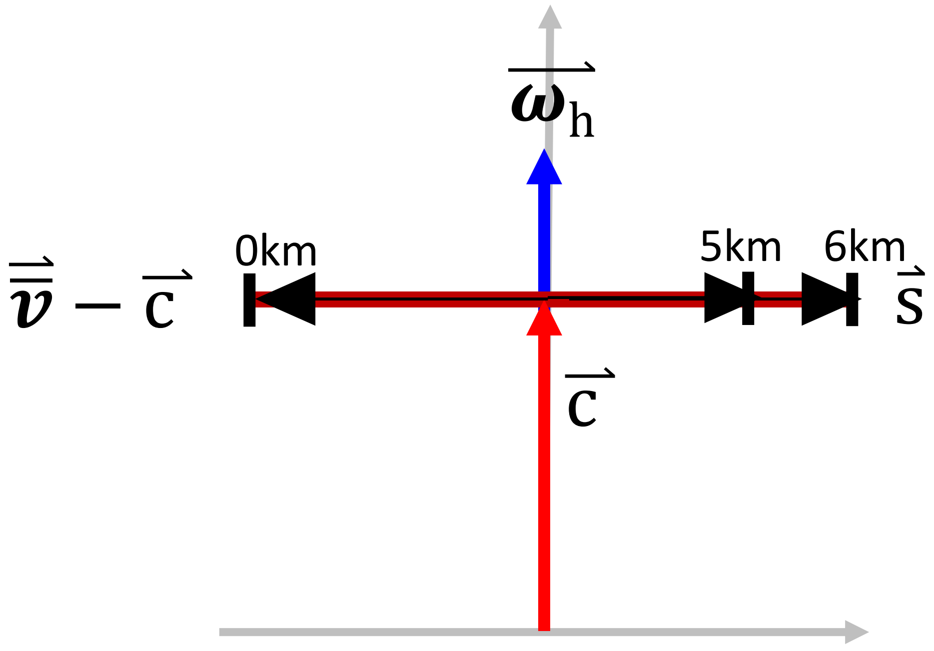


**R变小，由角动量守恒，速度变大，旋转加快，$\zeta'$变大**

# 不同背景风

**Note** $\vec{c}$ $\overrightarrow{\boldsymbol{\omega}_h}$ $\vec{s}$ $\overrightarrow{\overline{v}} - \vec{c}$

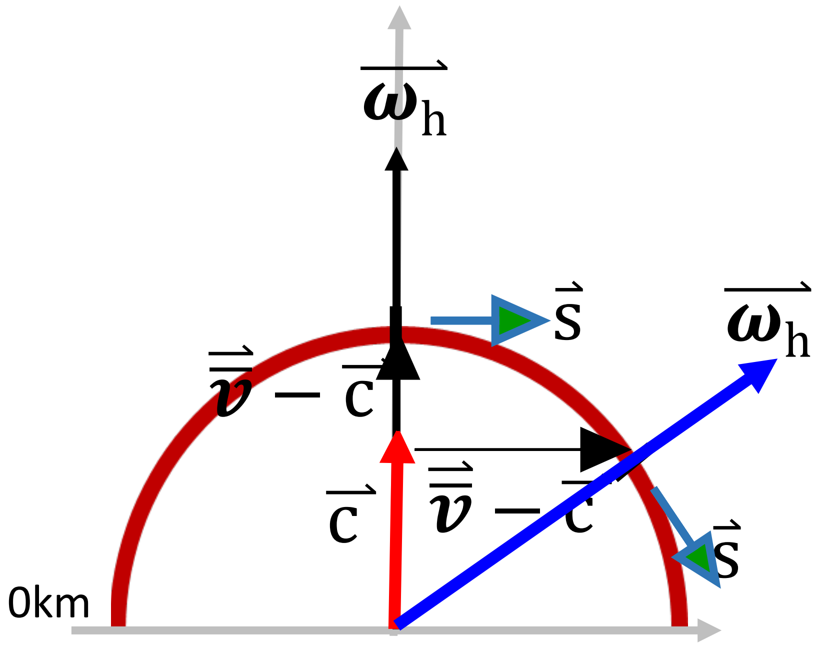
## Straight hodograph



**Pure crosswise vorticity**

$$(\overrightarrow{\overline{v}} - \vec{c}) \perp \overrightarrow{\boldsymbol{\omega}_h}$$

## Curved hodograph



**More streamwise vorticity**

$$(\overrightarrow{\overline{v}} - \vec{c}) \parallel \overrightarrow{\boldsymbol{\omega}_h}$$

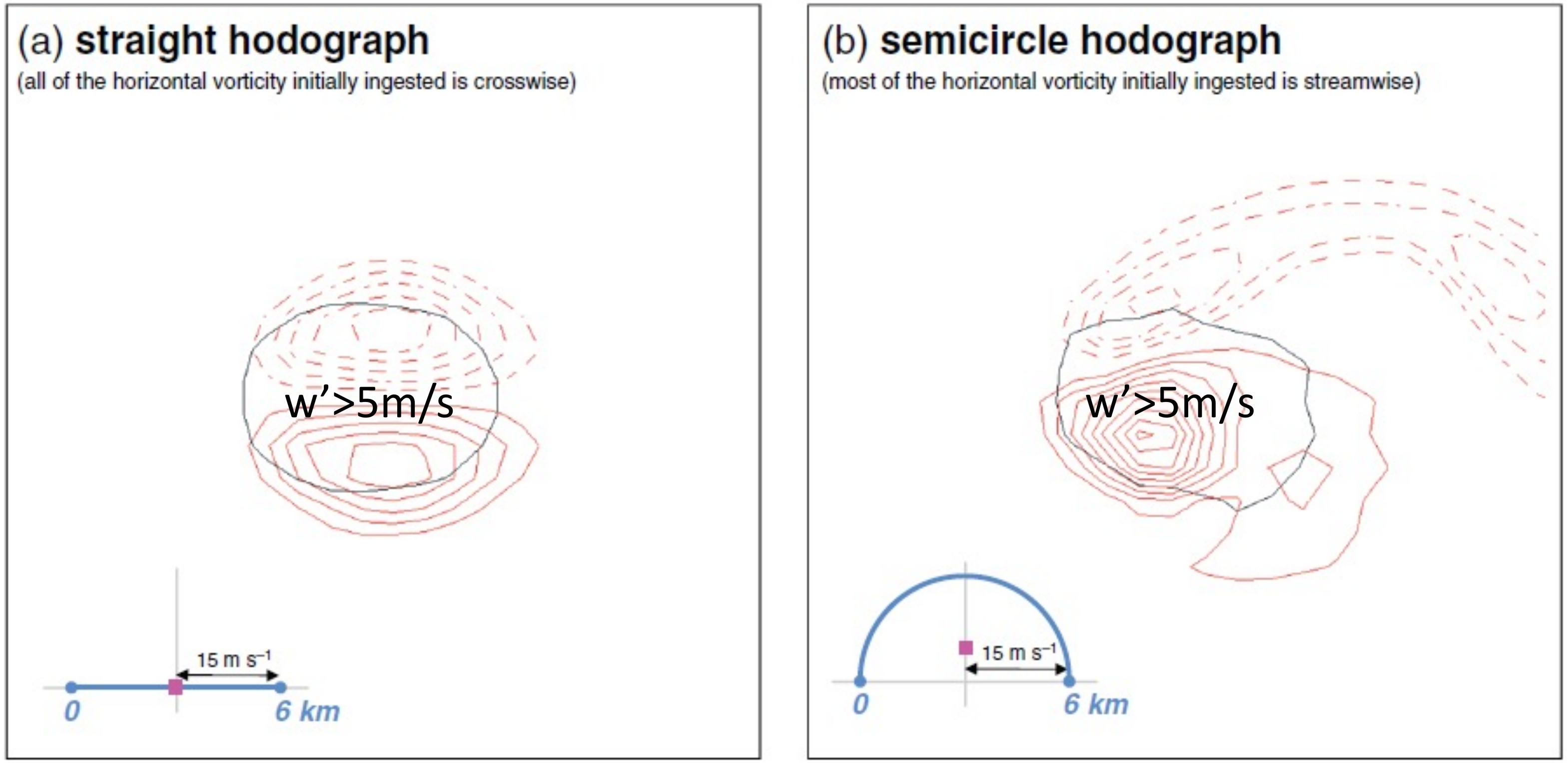


**Figure 8.31** Vertical vorticity fields at $z = 5$ km at $t = 25$ min in numerical simulations in which an isolated storm is initiated using a warm bubble in an environment having (a) a straight hodograph and (b) a semicircular hodograph. Vertical vorticity contours are drawn every $2.5 \times 10^{-3}$ $s^{-1}$. Solid (dashed) contours indicate positive (negative) values, and the zero contour is suppressed. The thin black contour encloses the region where the vertical velocity exceeds 5 m $s^{-1}$. The sounding had approximately 2500 J $kg^{-1}$ of CAPE. The hodographs are shown in each of the two panels; the magenta square indicates the mean updraft motion in the first 25 min of the simulations. In the straight-hodograph environment, the horizontal vorticity ingested in the early stages of storm development is purely crosswise. Note that the updraft is straddled by a couplet of cyclonic and anticyclonic vorticity of equal magnitude. In the semicircular hodograph environment, the updraft acquires net cyclonic rotation and the anticyclonic vorticity is predominantly within a downdraft.

# 螺旋度：Helicity

表征流体运动矢量与其涡度矢量的重合程度

$$\mathrm{H} = \overrightarrow{\boldsymbol{v}} \cdot \overrightarrow{\boldsymbol{\omega}}$$

$$= u\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right) + v\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right) + w\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$$

假定w为0

$$\mathrm{H} = -u\frac{\partial v}{\partial z} + v\frac{\partial u}{\partial z} = \overrightarrow{\boldsymbol{v}} \cdot \overrightarrow{k} \times \frac{\partial \overrightarrow{\boldsymbol{v}}}{\partial z} = -\overrightarrow{k} \cdot \left(\overrightarrow{\boldsymbol{v}} \times \frac{\partial \overrightarrow{\boldsymbol{v}}}{\partial z}\right)$$

$$= -\overrightarrow{k} \cdot (\overrightarrow{\boldsymbol{v}} \times \vec{\mathrm{s}})$$

**一般在对流系统中，我们关注**

$$\mathrm{H} = \int_0^{\mathrm{d}} \vec{\overline{\boldsymbol{v}}} \cdot \overrightarrow{\boldsymbol{\omega}_{\mathrm{h}}}\, dz$$

**d：流入层厚度，~3 km**

**Helical flow may suppress turbulence, which explains the longevity of supercell.**

$$\overrightarrow{\boldsymbol{\omega}_{\mathrm{h}}} = \bar{\xi}\,\vec{\mathrm{i}} + \bar{\eta}\,\vec{\mathrm{j}} \qquad \bar{u} = \bar{u}(z) \qquad \bar{v} = \bar{v}(z) \qquad \bar{w} = 0$$

$$\overrightarrow{\boldsymbol{\omega}_{\mathrm{h}}} = \left(-\frac{\partial \bar{v}}{\partial z}, \ \frac{\partial \bar{u}}{\partial z}\right) = \overrightarrow{k} \times \vec{\mathrm{s}}$$

**假定环境风为15m/s, 风暴以15m/s的速度移动，风暴则感受不到Helicity，因而一般要分析storm relative helicity.**

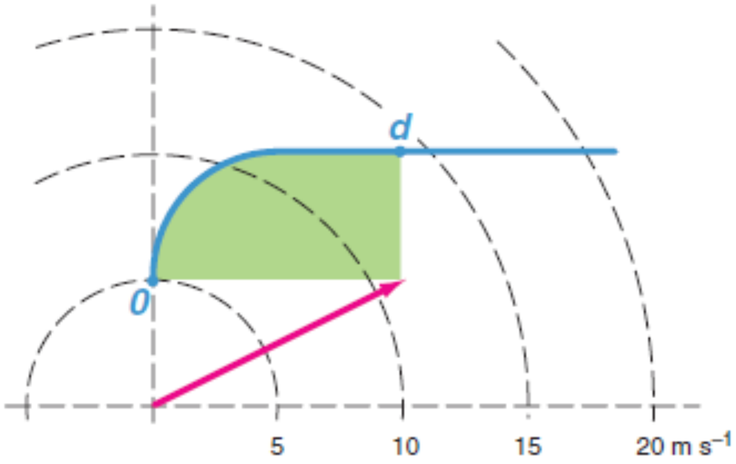
## Storm relative helicity (SRH)

$$\mathrm{SRH} = \int_0^d (\vec{\overline{\boldsymbol{v}}} - \vec{\mathrm{c}}) \cdot \overrightarrow{\boldsymbol{\omega}_\mathrm{h}}\, dz = \int_0^d |\vec{\overline{\boldsymbol{v}}} - \vec{\mathrm{c}}|\boldsymbol{\omega}_\mathrm{s}\, dz$$

$$= \int_0^d (\vec{\overline{\boldsymbol{v}}} - \vec{\mathrm{c}}) \cdot \vec{k} \times \vec{\mathrm{s}}\, dz = -\int_0^d \vec{k} \cdot (\vec{\overline{\boldsymbol{v}}} - \vec{\mathrm{c}}) \times \vec{\mathrm{s}}\, dz$$

## Estimation on a hodograph

$$\mathrm{SRH} = 2\,\mathrm{GreenArea}$$



## 可用于预报Supercell的可能性

0-3 km SRH>150 $\mathrm{m^2 s^{-2}}$ 超级单体

0-3 km SRH>400 $\mathrm{m^2 s^{-2}}$ 龙卷和超级单体爆发

0-1 km SRH 可用于区分tornadic 和nontornadic supercells.

# 06-18 年我国登陆台风龙卷SRH的分布

Bai L, *et al.* *Sci China Earth Sci* 9

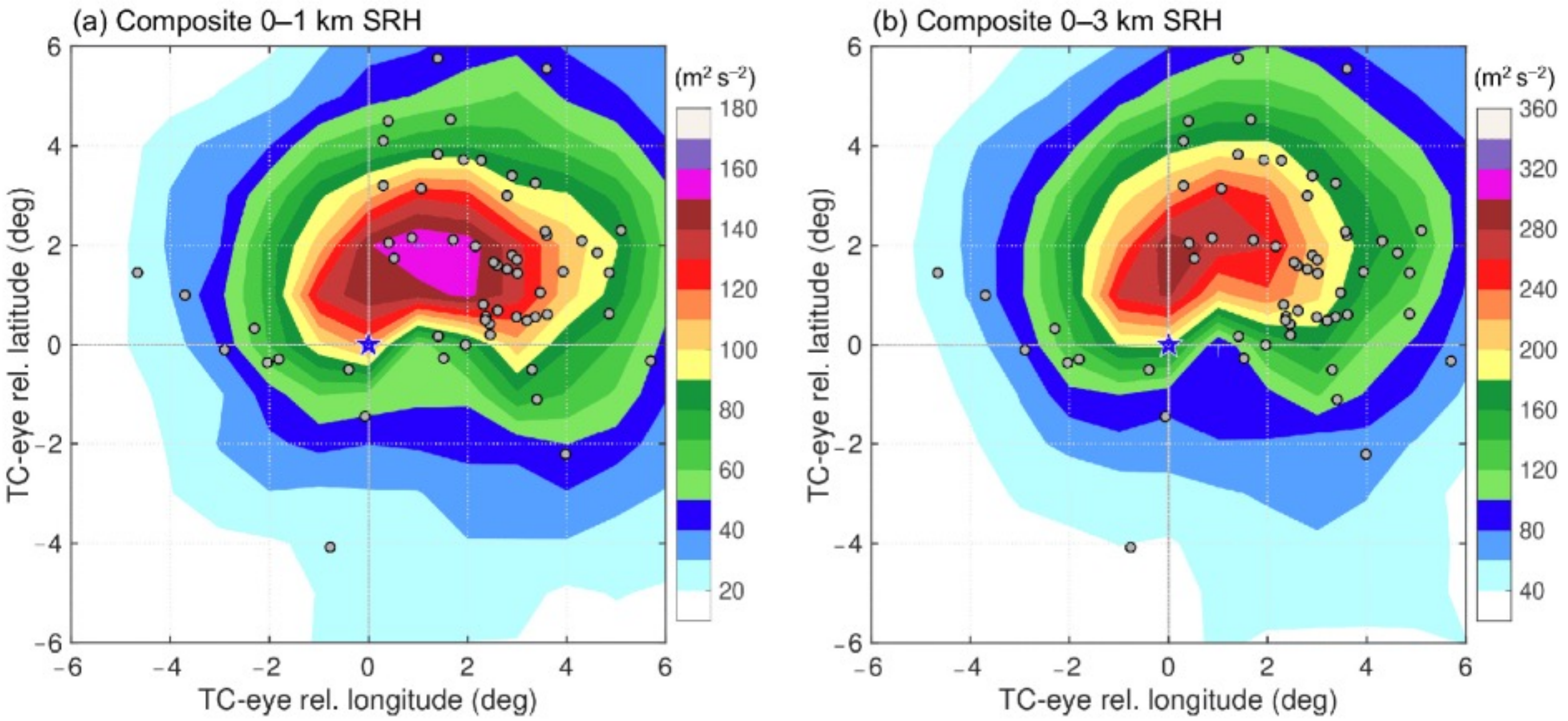


**Figure 8** Composite horizontal distributions of the (a) 0–1 km and (b) 0–3 km SRH around the TC eyes (blue stars). The solid gray circles represent the locations of TC tornadoes in 2006–2018 relative to the eye of their parent TC. The *X* (*Y*) axis is arranged in the TC eye relative longitude (latitude) for convenience.

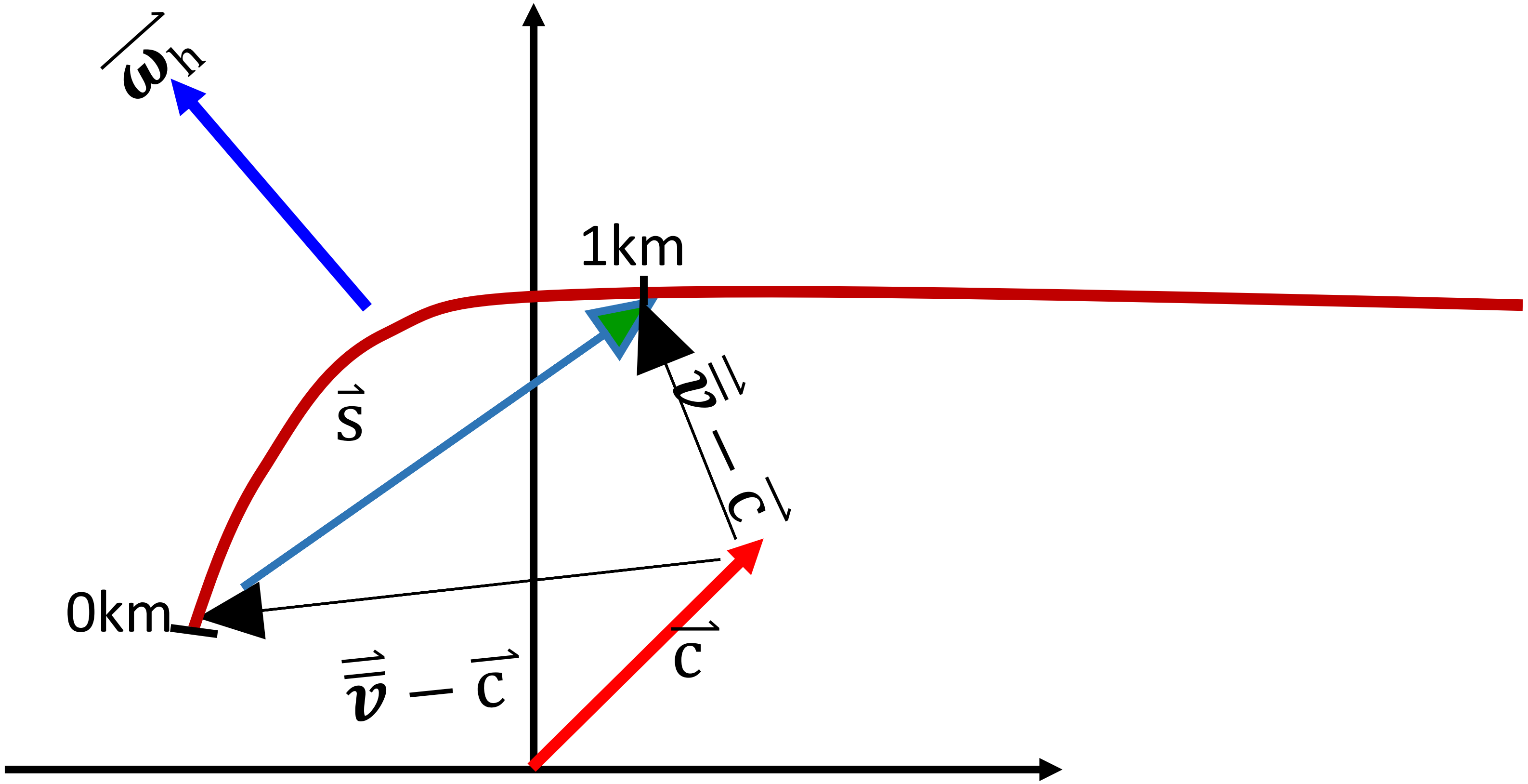
**龙卷高频发区与0-1km的SRH更一致**

(Bai et al. 2019, SCES)

# （4）斜压性产生的水平涡度及其对中气旋的影响

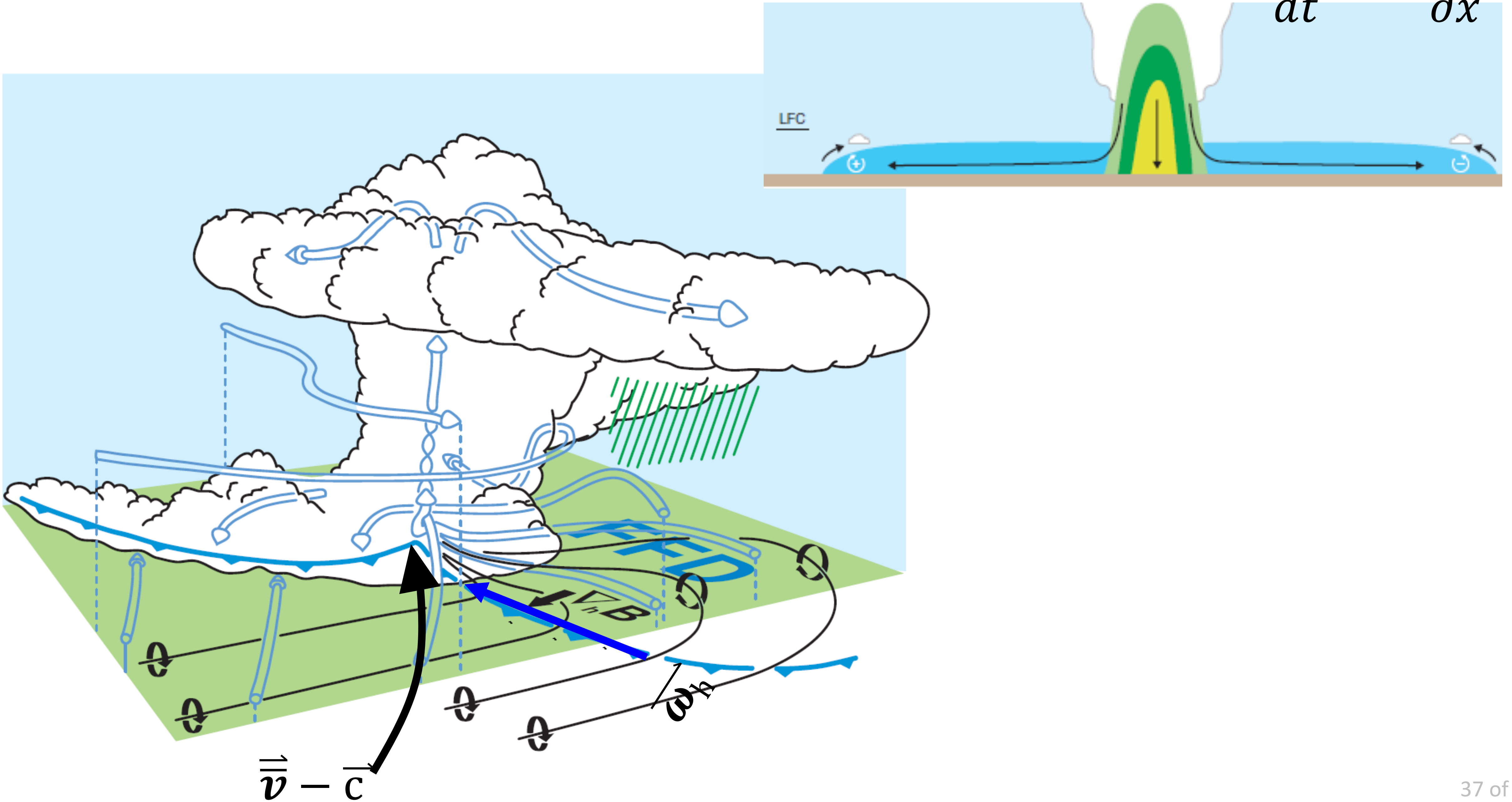
## 1）低层的环境水平涡度

$\vec{c}$ $\vec{\boldsymbol{\omega}}_h$ $\vec{s}$ $\vec{\bar{\boldsymbol{v}}}-\vec{c}$



# 2）FFD斜压性产生的水平涡度有一定的 Streamwise风量

$$\frac{d\eta}{dt} = -\frac{\partial B}{\partial x}$$



## 3）斜压产生的水平涡度与环境水平涡度的关系

- 二者大致在一个方向
- 斜压产生的水平涡度有时会比环境水平涡度更强
- 两个涡度叠加使得涡度加强

## 4）对低层中气旋的影响

- 低层中气旋往往等到大范围的下沉气流出现才生成
- 环境水平涡度的streamwise程度
- 环境水平涡度与斜压水平涡度方向的一致程度