A Theory for Strong, Long-Lived Squall Lines

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OUTLINE

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INTRODUCTION

Introduction

FEATURES OF SQUALL LINE

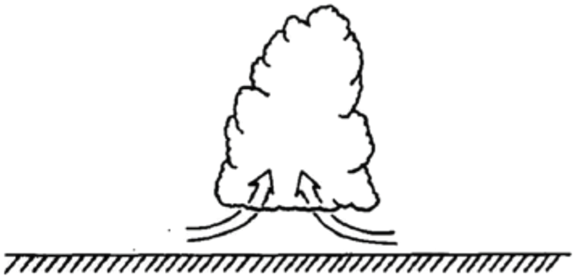
- line or narrow band of active thunderstorms (Glossary of Meteorology)
- lasting several hours

TWO DISTINCT PREMISES

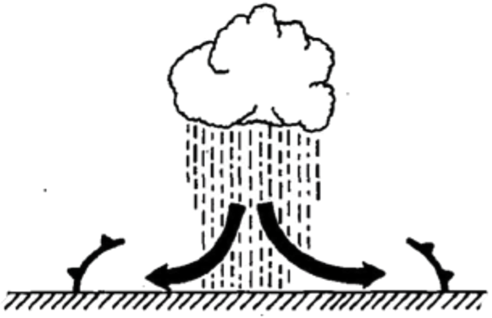
- prone to having a steady structure
- occurring in concert along a line (Moncrieff, 1978)

Introduction

(a)



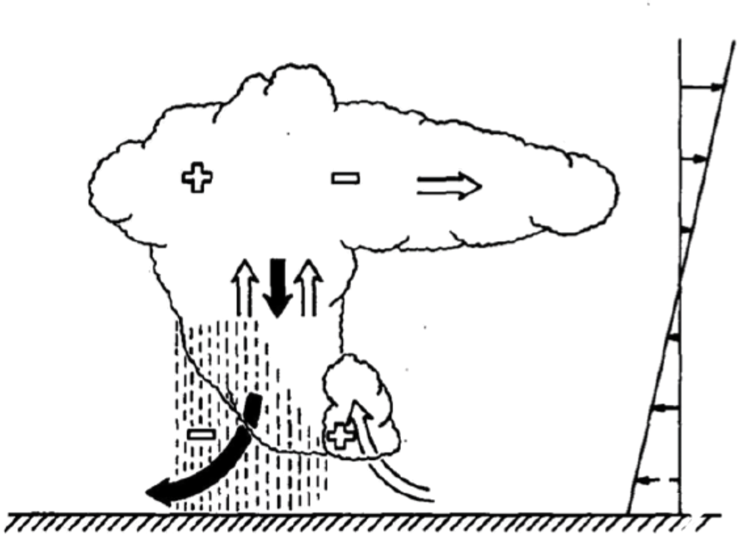
(b)



Byers and Braham(1949)

- A thunderstorm cell has a life cycle over which the cell updraft will yield to a downdraft induced by the accumulation of rain within the updraft and, for this reason, a thunderstorm cell is naturally short-lived (roughly 30-60 min) .

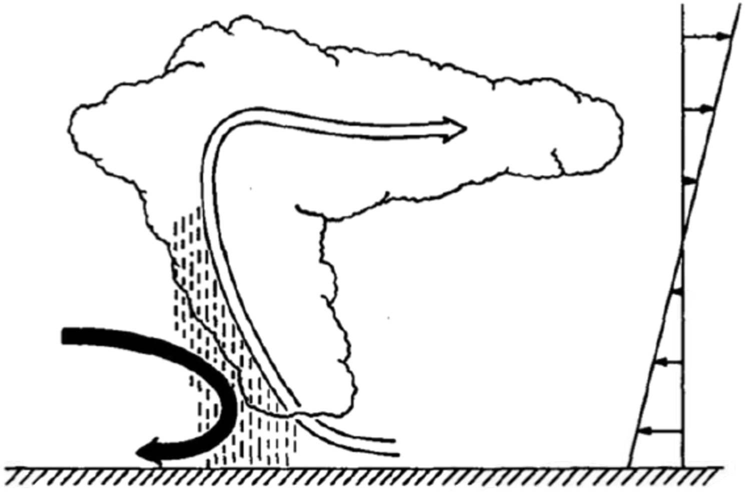
Introduction



Newton(1950)

- squall-line, a **system** of updrafts and downdrafts aligned **perpendicularly** to the shear
- reducing the shear within the system
- setting up the convergence and divergence:
  - produces new cells on the downshear side
  - suppress old cells on the upshear side

Introduction



Ludlam-Newton Model

- strong updraft canting against the wind shear:
  - allowing the updraft to unload its rain upshear
  - permitting the circulations to continue indefinitely
- squall line, a collection of such long-lived cells

Introduction

- Modelers failed to replicate the Ludlam-Newton observational model in two-dimensional simulations.

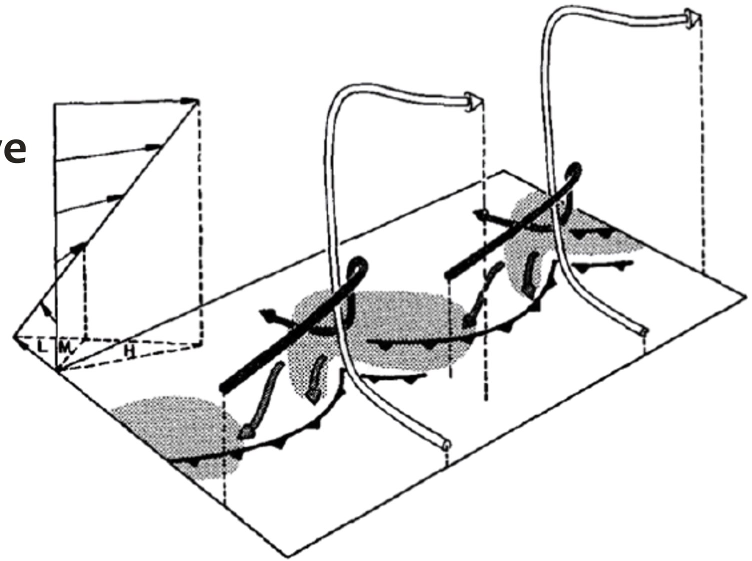
  due to the inherent three-dimensionality of cumulonimbus clouds (Lilly,1979)

- the revised version of the Ludlam-Newton model:

  squall line, a collection of supercells?

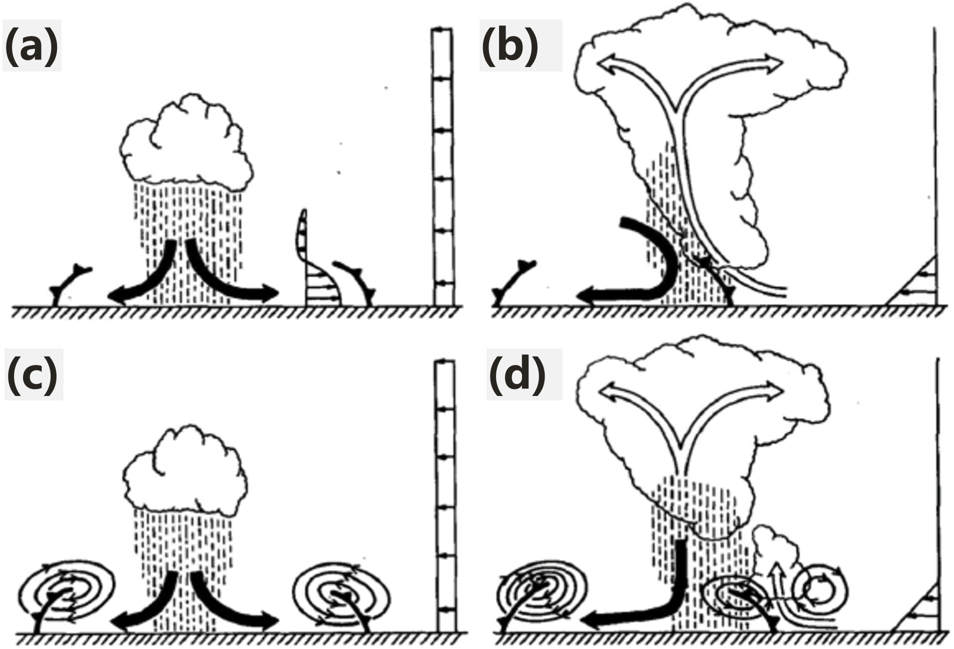
Introduction

- A steady squall line if they aligned at an angle to the shear so that their respective circulations did not interfere. (Lilly,1979)
- Contained supercell-like circulations allowed their system to be long lived. (Moncrieff and Miller ,1976)



- However, most squall lines are not composed of supercell thunderstorms. (Bluestein and Jain, 1985)

Introduction



- The long life of the strictly two-dimensional solution is a consequence of the **low-level shear** in the ambient wind profile. (Thorpe et al., 1982; hereafter TMM)

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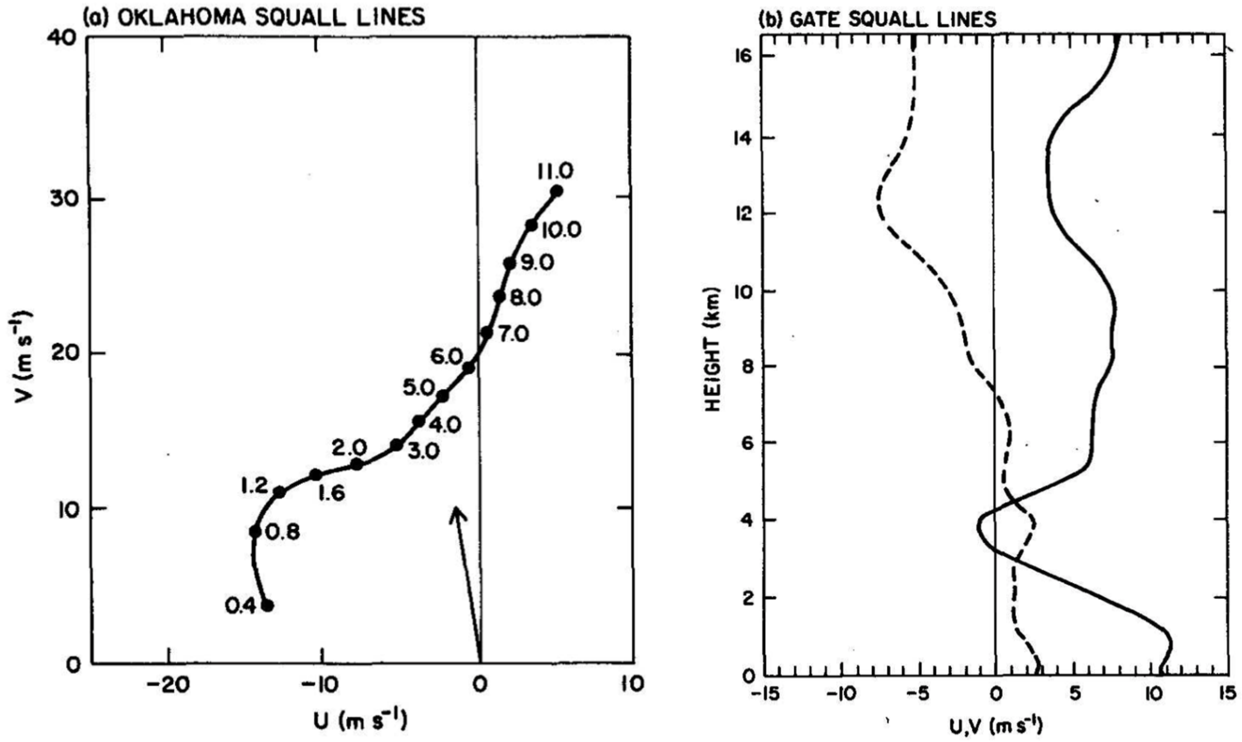
OBSERVATIONS

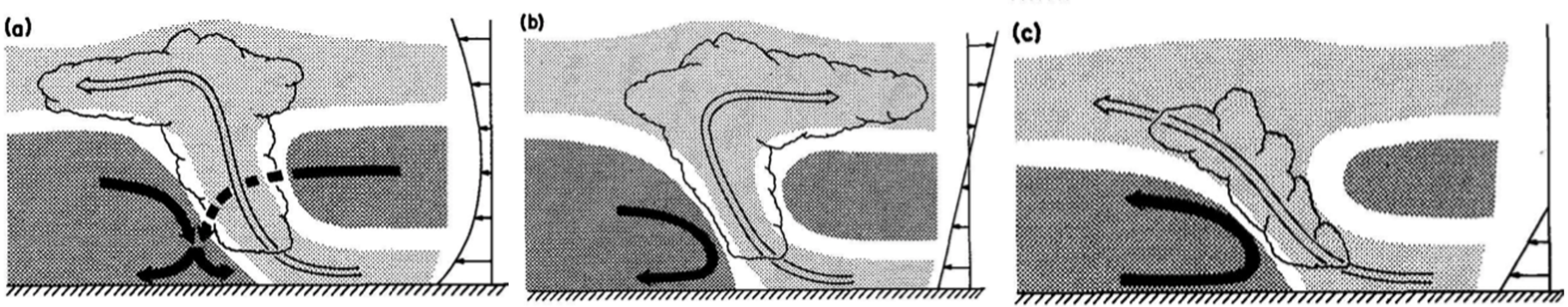
Observations

a. Squall-line Environment



Observations

b. Squall-line Circulation



Zipser's analysis

- flow from ahead of to behind the line in the mature phase
- low-level outflow directed towards the front

Newton's analysis

- all the air approaching the line ascend
- not consider the possibility of substantial three-dimensional motion

Carbone's analysis

- a "gravity current"
- a wintertime squall line

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SQUALL-LINE SIMULATIONS

Squall-line Simulation

a. Shallow shear normal to the line: two-dimensional simulation

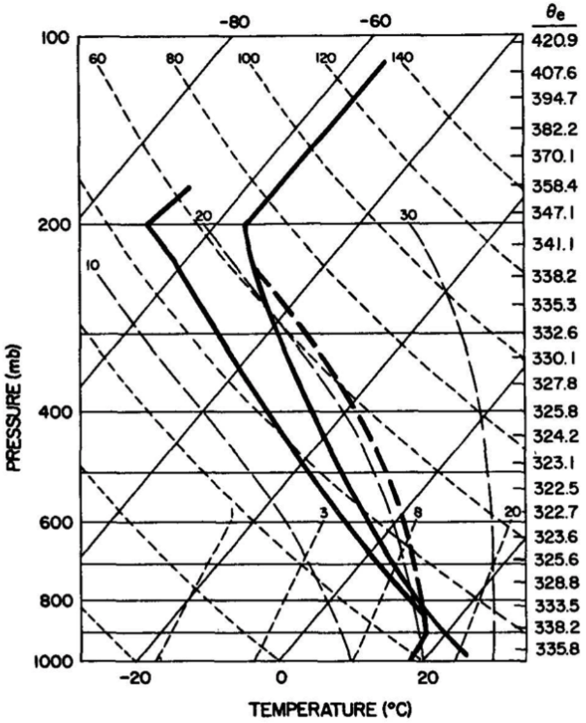
Klemp-Wilhelmson cloud model (hereinafter KW cloud model)

Model setting:

- 180km in x direction; grid interval Δx= 2km
- 17.5km in z direction; grid interval Δz= 700m
- x: open boundary condition
- z: zero-flux-type at low surface
- no ice processes included

Squall-line Simulation

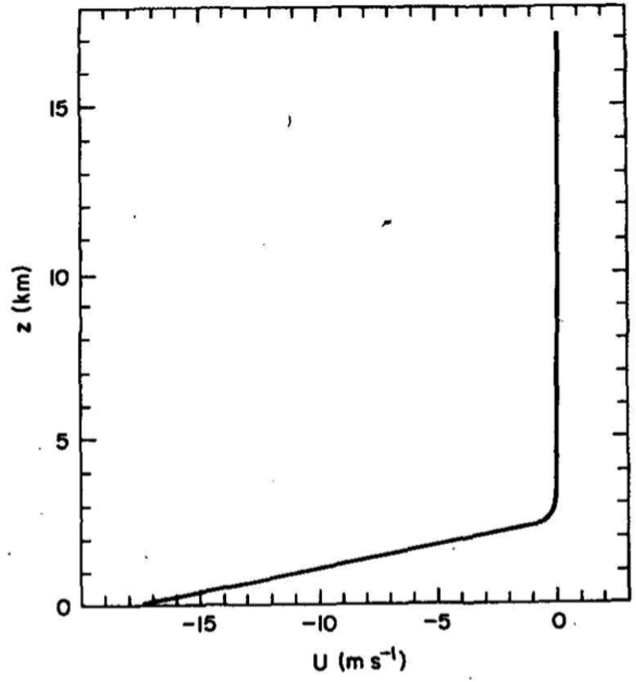
a. Shallow shear normal to the line: two-dimensional simulation



- broadly typical of the environment of midlatitude squall lines
- motion initiated with a warm(2K exceed) line centered at x=90, z=1.4km
- decay to 0 for |x-90|>10; |z-1.4|>1.4

Squall-line Simulation

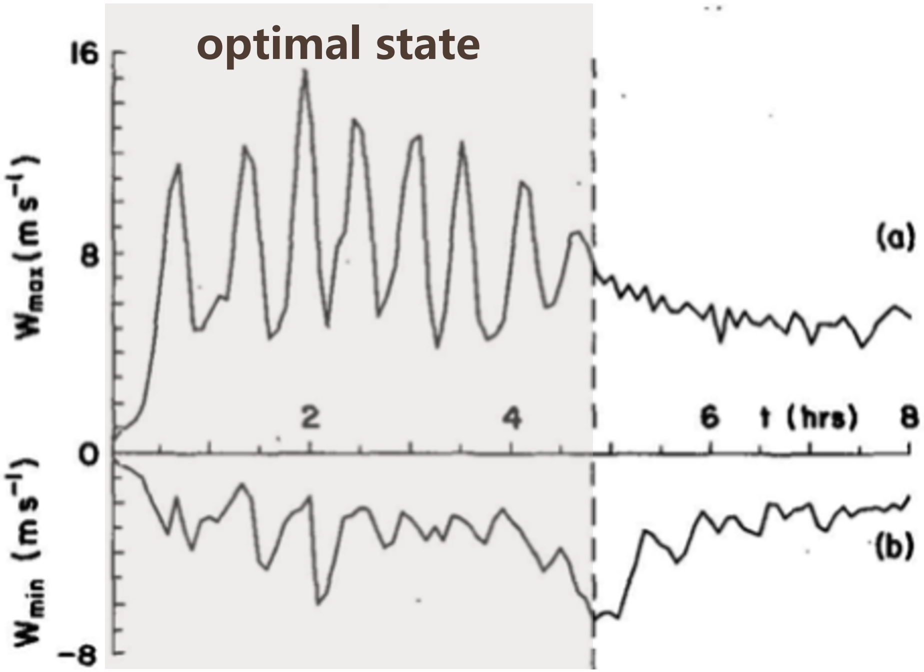
a. Shallow shear normal to the line: two-dimensional simulation



- A shear of **17.5 m/s in the lowest 2.5 km** allows for the longest sequence of the strongest cell updrafts.

Squall-line Simulation

a. Shallow shear normal to the line: two-dimensional simulation



Squall-line Simulation

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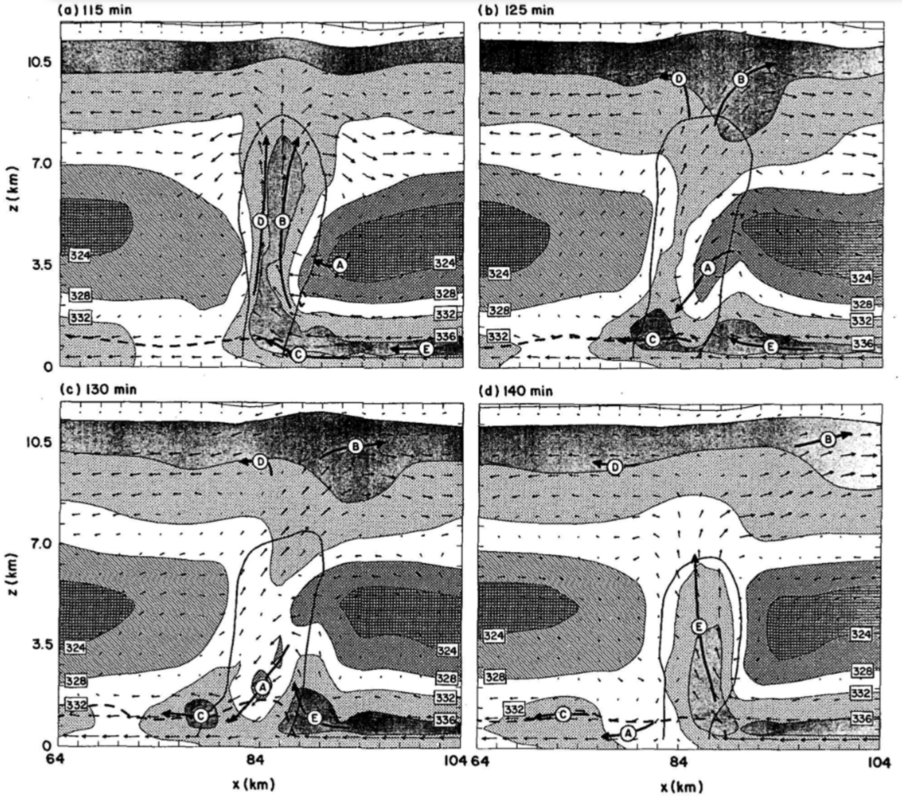


- **optimal state**

- **thick dashed line：-1K perturbation**

  θ_e contour

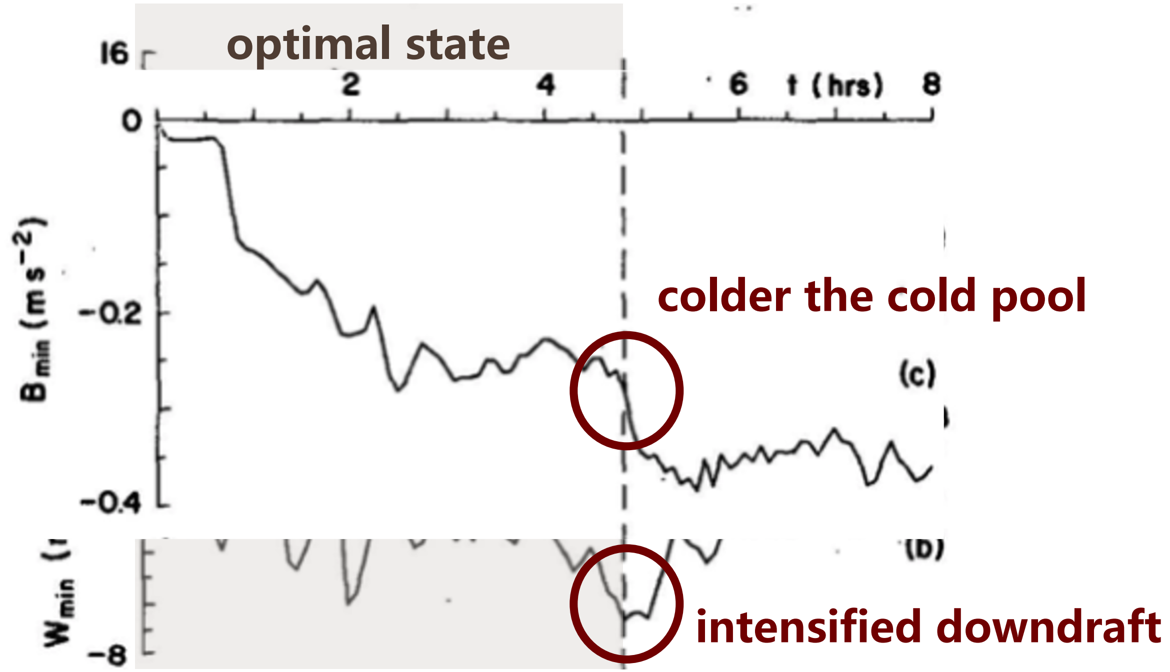
- **solid line: 2 g/kg rainwater contour**

- **shaded: θ_e field**

- **grid interval: 16m/s**

Squall-line Simulation

a. Shallow shear normal to the line: two-dimensional simulation



Squall-line Simulation

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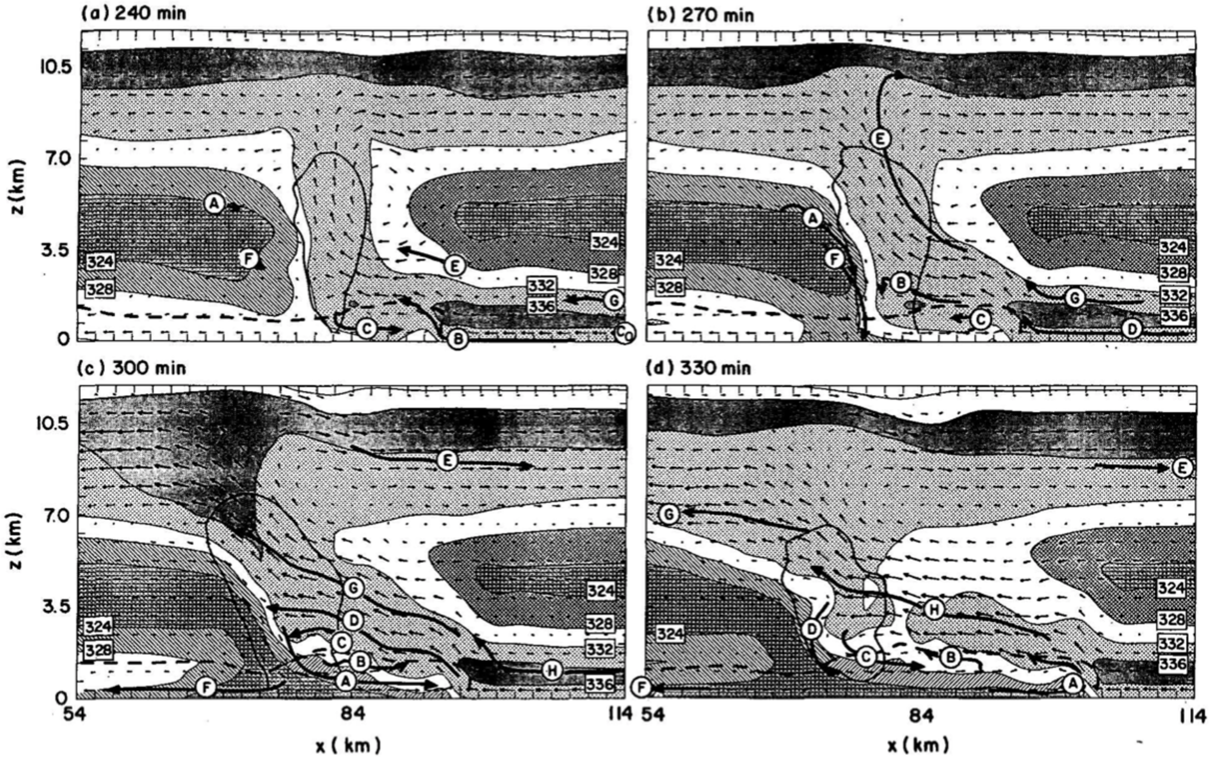
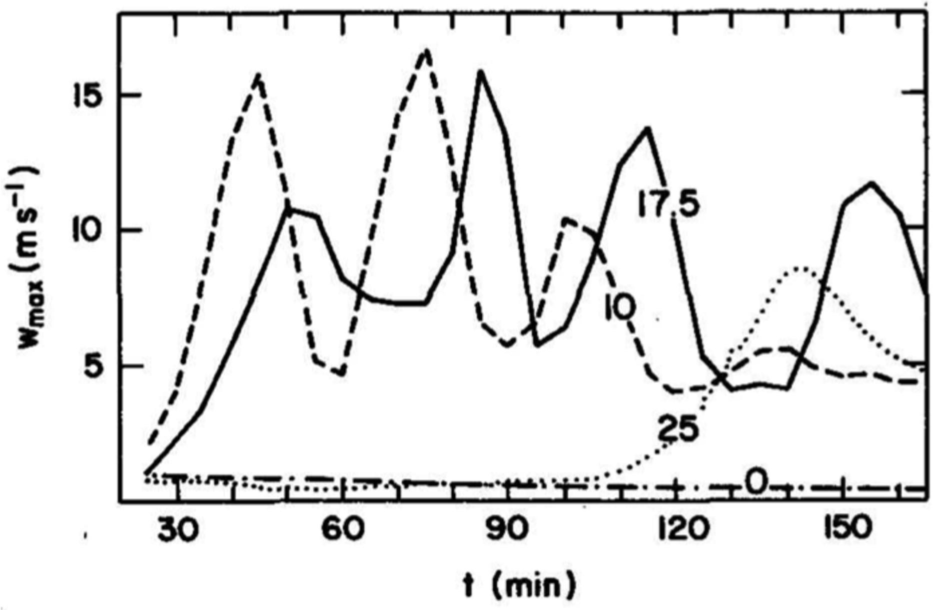


- weaker

  mode

Squall-line Simulation

a. Shallow shear normal to the line: two-dimensional simulation



- cold-pool initialization

Squall-line Simulation

b. Shallow shear normal to the line: three-dimensional simulation

KW cloud model

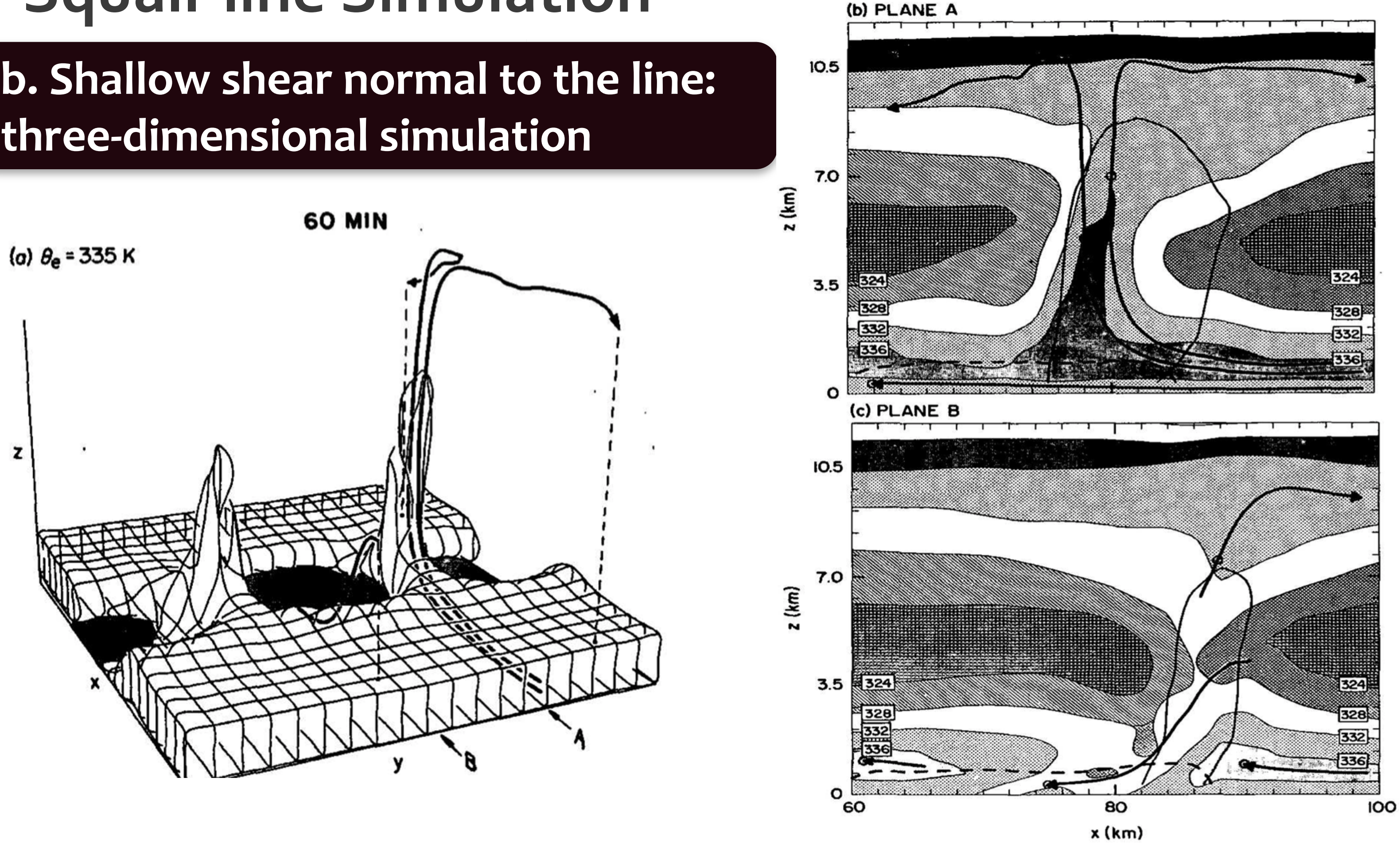
Model setting:

- **120km in y direction; grid interval Δy= 2km**
- **y: periodic boundary condition**
- **small (<0.1 K) random temperature perturbations on the initiating line thermal**

Other conditions are the same as in the two-dimensional simulation.

Squall-line Simulation

b. Shallow shear normal to the line: three-dimensional simulation



Squall-line Simulation

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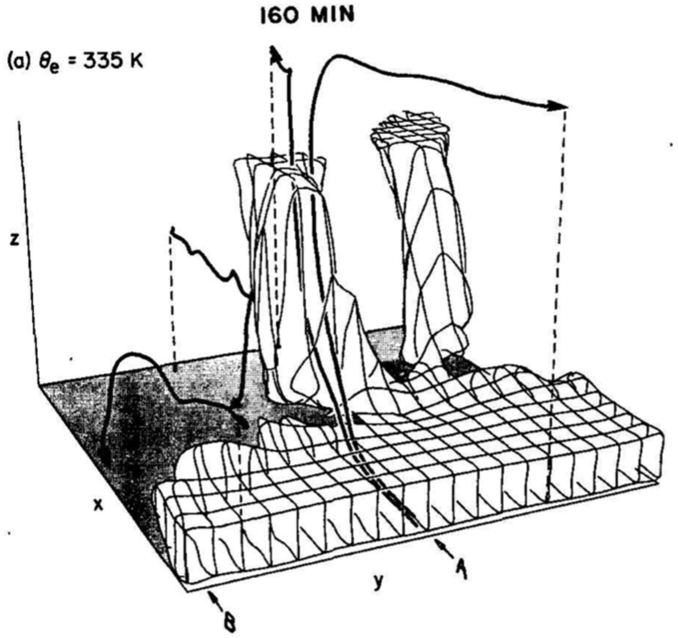
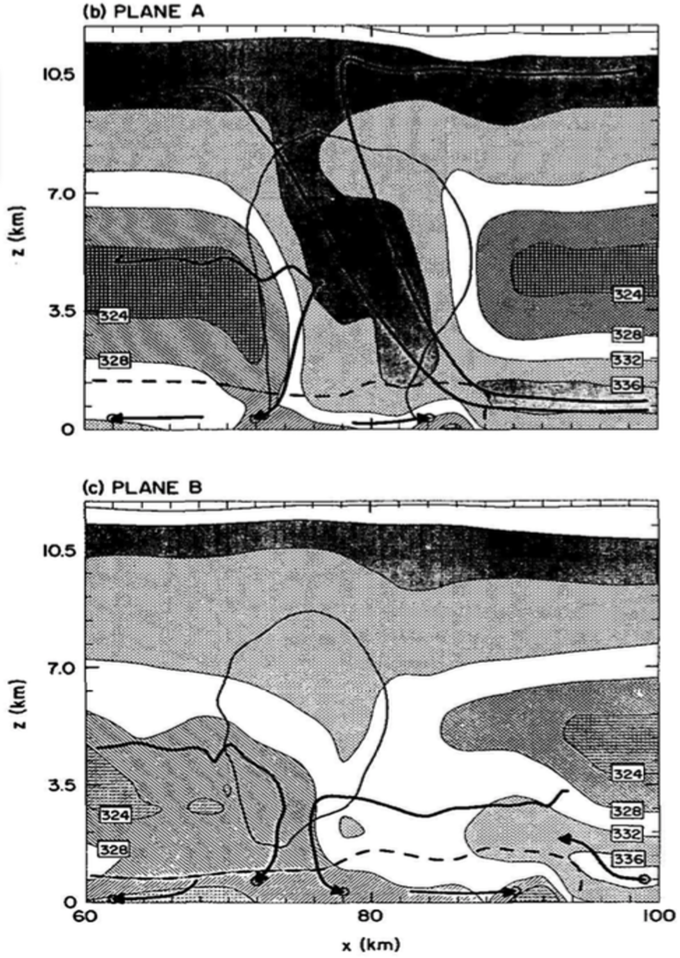
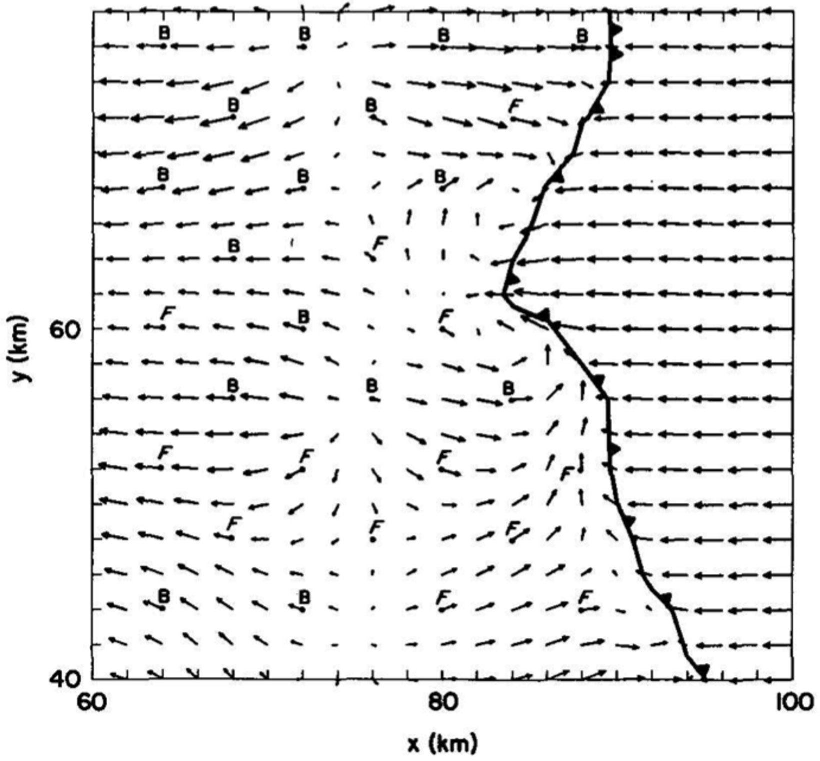




Squall-line Simulation

b. Shallow shear normal to the line: three-dimensional simulation



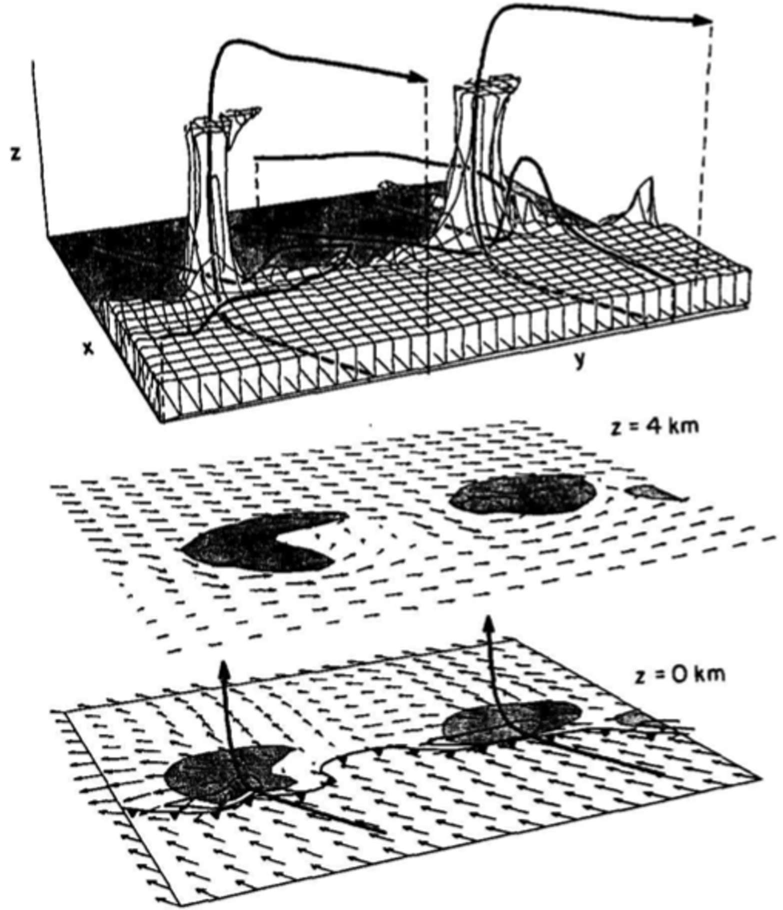
- z = 350 km
- grid interval: 16m/s
- Barbed line: -1K perturbation

  θ_e contour

Squall-line Simulation

c. Deep shear at 45° to the line

- The time-dependence found in the three-dimensional, nonsupercellular squall-line simulations **is not an inevitable feature** of the present numerical simulation.



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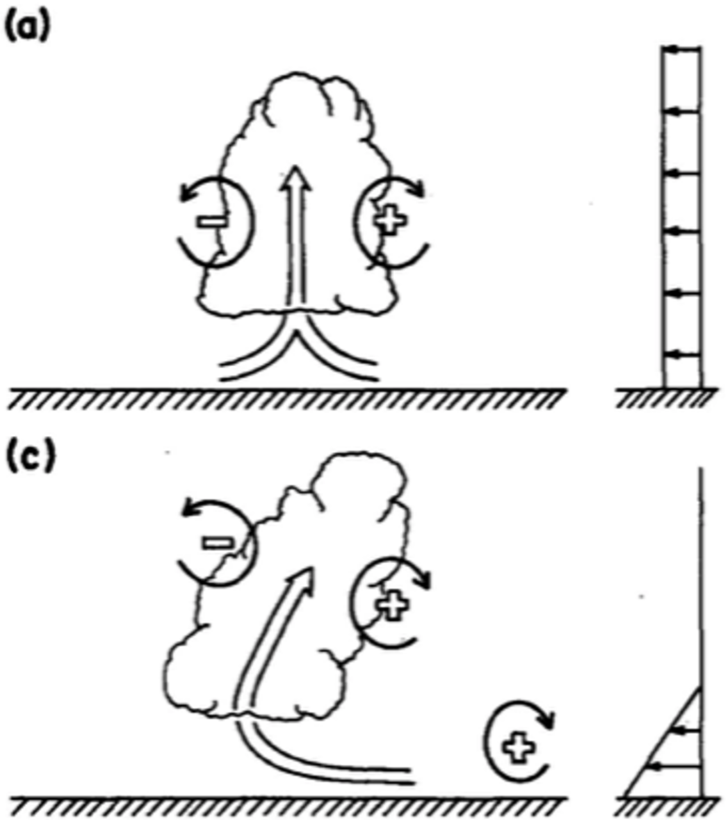
INTERPRETATION

Interpretation

a. The role of wind shear

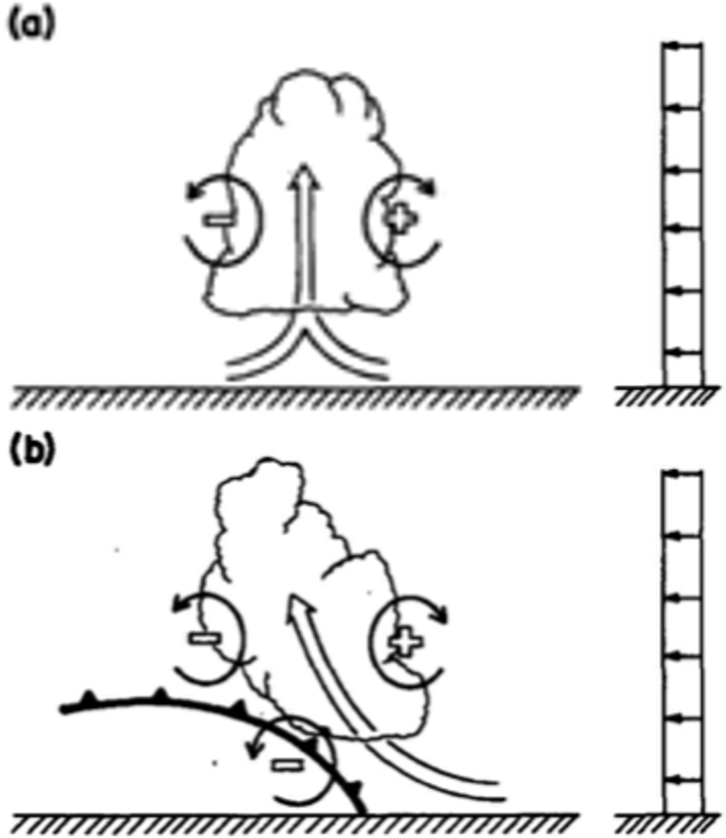
$$\frac{d\eta}{dt} = -\frac{\partial B}{\partial x}, \quad \eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}$$



Interpretation

b. The role of the cold pool

$$\frac{d\eta}{dt} = -\frac{\partial B}{\partial x}\ , \ \eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}$$



Interpretation

c. The cold pool with and without low-level shear

$$\frac{d\eta}{dt} = -\frac{\partial B}{\partial x}\ , \ \eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}$$

, with $\eta\frac{\partial u}{\partial x} + \eta\frac{\partial w}{\partial z} = 0$

$$\frac{\partial \eta}{\partial t} = -\frac{\partial(u\eta)}{\partial x} - \frac{\partial(w\eta)}{\partial z} - \frac{\partial B}{\partial x}$$

$$\frac{\partial}{\partial t}\int_0^d\int_L^R \eta \,dx\,dz = \int_0^d (u\eta)_L\,dz - \int_0^d (u\eta)_R\,dz - \int_L^R (w\eta)_d\,dx + \int_0^d B_L\,dz$$

Let $\eta \approx \frac{\partial u}{\partial z}$,

$$0 = \int_0^d u_L\,du_L - \int_0^d u_R\,du_R - \int_L^R (w\eta)_d\,dx + \int_0^H B_L\,dz$$

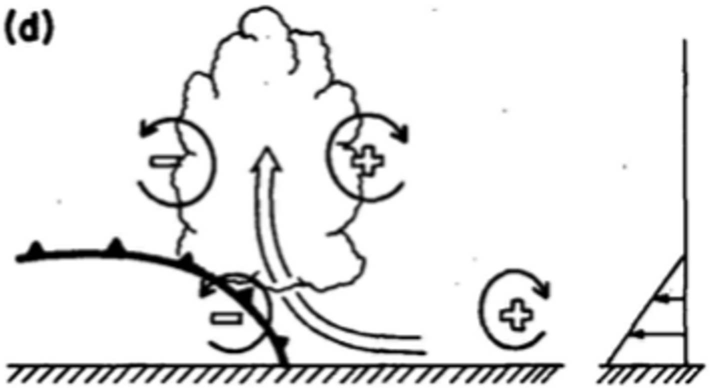
$$= \left(\frac{u_{L,d}^2}{2} - \underbrace{\frac{u_{L,0}^2}{2}}_{=0}\right) - \left(\underbrace{\frac{u_{R,d}^2}{2} - \frac{u_{R,0}^2}{2}}_{=0}\right) - \int_L^R (w\eta)_d\,dx + \int_0^H B_L\,dz,$$

x = R no vertical shear

$$\boxed{u_{L,d}^2 = -2\int_0^H B_L\,dz \equiv c^2}$$

Interpretation

c. The cold pool with and without low-level shear



$$u_{\mathrm{L},d}^2 = -2\int_0^H B_\mathrm{L}\,\mathrm{d}z \equiv c^2$$

$$0 = \int_0^d u_\mathrm{L}\,du_\mathrm{L} - \int_0^d u_\mathrm{R}\,du_\mathrm{R} - \int_\mathrm{L}^\mathrm{R} (w\eta)_d\,\mathrm{d}x + \int_0^H B_\mathrm{L}\,\mathrm{d}z$$

$$= \left(\frac{u_{\mathrm{L},d}^2}{2} - \underbrace{\frac{u_{\mathrm{L},0}^2}{2}}_{=0}\right) - \left(\frac{u_{\mathrm{R},d}^2}{2} - \frac{u_{\mathrm{R},0}^2}{2}\right) - \int_\mathrm{L}^\mathrm{R} (w\eta)_d\,\mathrm{d}x + \int_0^H B_\mathrm{L}\,\mathrm{d}z,$$

$\boxed{\text{set } u_{L,d},\ u_{R,d} \text{ and } \int_L^R (w\eta)_d dx = 0}$

$\boxed{\Delta u = c, \quad \text{where} \quad \Delta u \equiv u_{R,d} - u_{R,0} = -u_{R,0}}$

Interpretation

c. The cold pool with and without low-level shear

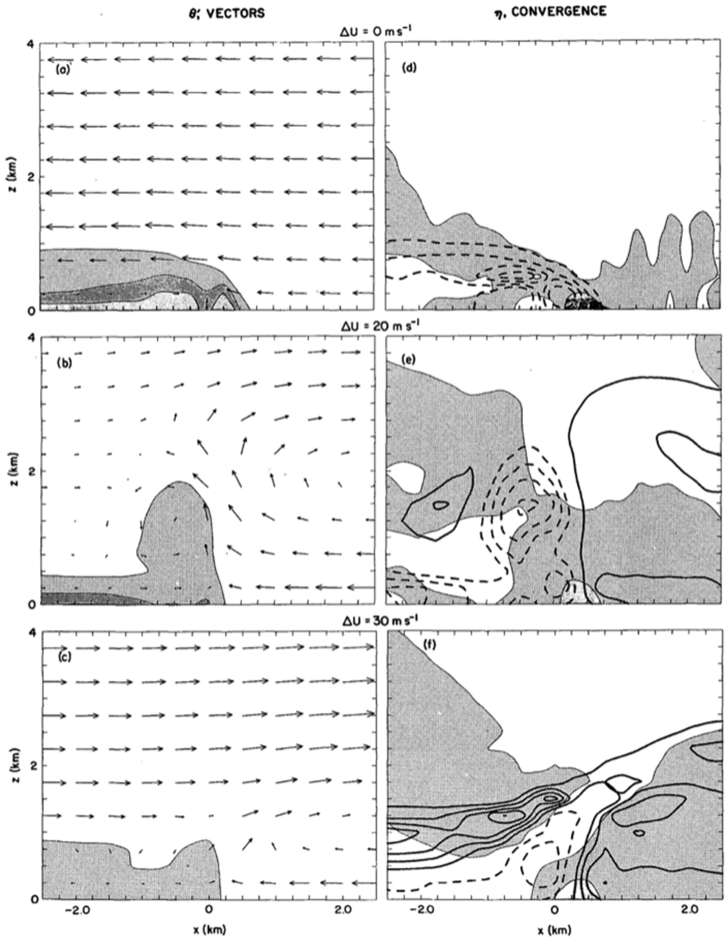
$$\Delta u = c, \quad \text{where} \quad \Delta u \equiv u_{R,d} - u_{R,0} = -u_{R,0}$$

(a)-(c)

- **shaded regions: negative θ perturbation** (2K intervals)

(d)-(f)

- shaded regions: convergence
- contour: η



Interpretation

d. Speed of the cold pool

$$0 = \int_0^d u_L \, du_L - \int_0^d u_R \, du_R - \int_L^R (w\eta)_d \, dx + \int_0^H B_L \, dz$$

$$= \left(\frac{u_{L,d}^2}{2} - \frac{u_{L,0}^2}{2}\right) - \left(\frac{u_{R,d}^2}{2} - \frac{u_{R,0}^2}{2}\right) - \int_L^R (w\eta)_d \, dx$$

$$+ \int_0^H B_L \, dz,$$

$$\boxed{u_{L,d} = \epsilon u_{R,d}}$$

$$\epsilon^2 u_{R,d} = \Delta u - [(1-\epsilon^2)\Delta u^2 + \epsilon^2(c^2 + u_{L,0}^2)]^{1/2}$$

$$\boxed{U_c = \begin{cases} U_{R,0} + c\left[1 - \frac{\beta}{2}\left(\frac{\Delta u}{c} - 1\right)^2\right], & \Delta u < c \\ U_{R,0} + c, & \Delta u \approx c \\ U_{R,0} + \Delta u, & \Delta u > c \end{cases}}$$

$$\beta = \epsilon^2 - 1$$

$$\Delta u \leqslant U_c - U_{R,0} \leqslant \max(c, \Delta u)$$

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SUMMARY

Summary

- two basic types of simulated long-lived squall lines:

  ˙lines of more-or-less ordinary cells that continually grow and decay

  ˙lines of nearly steady supercells
- lines composed of supercell-like circulations occurring far less frequently
- sustaining a long-lived line of time-dependent cells:

  ˙an optimal value of wind-shear magnitude in comparison to the depth and coldness of the outflow
- the system ultimately changing to the weaker state
- a *ipso facto* steady squall line composed of supercells
- evaluating whether atmospheric condition favor the long-lived squall lines by equations

Thanks for listening!