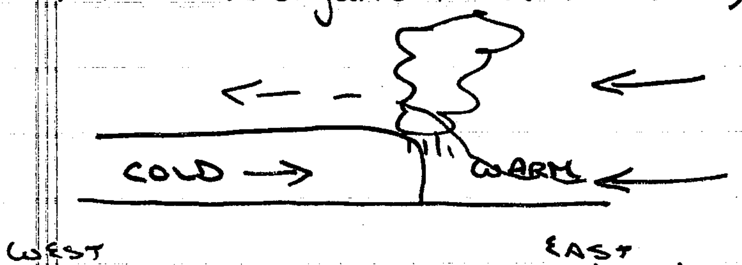
Gust Front Processes

Low level wind shear interactions with outflows play a critical role in the organization of convection, especially the formation of new convection



So, first we need to know how horizontal vorticity is generated... ugh.

$\frac{d\omega_2}{dt}$ is what we're after in the above case (see pg C5)

$$\omega_2 = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}$$

So $\epsilon_{2li} \frac{\partial}{\partial x_l}$ C5.4 leads to

$$\frac{d\omega_2}{dt} + \epsilon_{2li} \frac{\partial u_j}{\partial x_l}\frac{\partial u_i}{\partial x_j} = \epsilon_{2li}\delta_{i3}\frac{\partial b}{\partial x_l}$$

$$\frac{d\omega_2}{dt} + \overset{-1}{\epsilon_{213}} \frac{\partial u_j}{\partial x_1}\frac{\partial u_3}{\partial x_j} + \overset{1}{\epsilon_{231}} \frac{\partial u_j}{\partial x_3}\frac{\partial u_1}{\partial x_j} = \overset{-1}{\epsilon_{213}}\frac{\partial b}{\partial x}$$

$$\frac{d\omega_2}{dt} = \frac{\partial u}{\partial x}\frac{\partial w}{\partial x} + \frac{\partial v}{\partial x}\frac{\partial w}{\partial y} + \frac{\partial w}{\partial x}\frac{\partial w}{\partial z} - \frac{\partial u}{\partial z}\frac{\partial u}{\partial x} - \frac{\partial v}{\partial z}\frac{\partial u}{\partial y} - \frac{\partial w}{\partial z}\frac{\partial u}{\partial z} - \frac{\partial b}{\partial x}$$

$$= \frac{\partial u}{\partial z}\left[-\frac{\partial u}{\partial x} - \frac{\partial w}{\partial z}\right] + \frac{\partial w}{\partial x}\left[\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z}\right] + \frac{\partial v}{\partial x}\frac{\partial w}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial z} - \frac{\partial b}{\partial x}$$

$$= -\omega_2\left[\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z}\right] + \frac{\partial v}{\partial x}\frac{\partial w}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial z} - \frac{\partial b}{\partial x}$$

From continuity, ignoring vertical density variations, $\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = -\frac{\partial v}{\partial y}$

So

$$\frac{d\omega_2}{dt} = \omega_2\frac{\partial v}{\partial y} + \frac{\partial v}{\partial x}\frac{\partial w}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial z} - \frac{\partial b}{\partial x} \qquad \text{C12.1}$$

(stretching term; tilting terms; buoyancy term)

Horizontal vorticity is generated most easily by the buoyancy term

For completeness

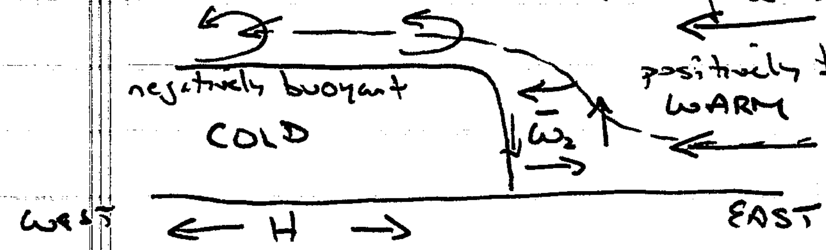
$$\frac{d\omega_1}{dt} = \omega_1\frac{\partial u}{\partial x} + \frac{\partial u}{\partial z}\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\frac{\partial w}{\partial x} + \frac{\partial b}{\partial y} \qquad \text{C12.2}$$

$$\omega_1 = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}$$

Consider the following situations.

Case 1. Outflow with no environmental vertical wind shear

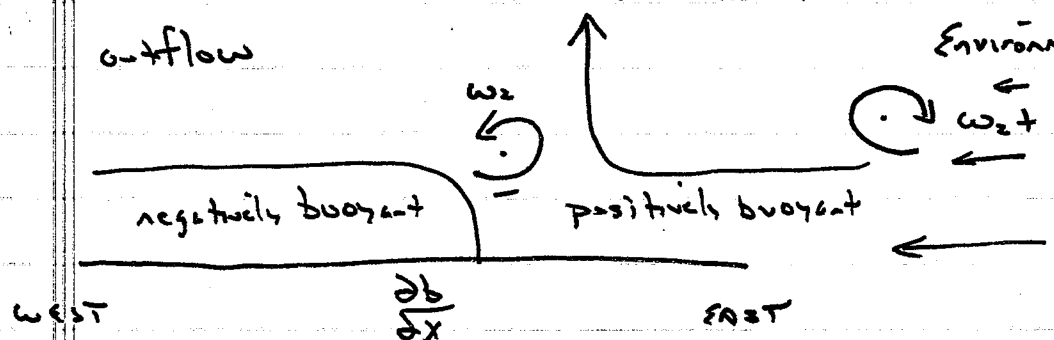
Assume reference frame moving with speed of outflow



$$\frac{\partial b}{\partial x} + \Rightarrow \frac{d\omega_z}{dt} -$$

Gradient in buoyancy generates cclockwise ($-\omega_z$) vorticity at leading edge. Result: air flows over gust front with cc ω_z vorticity generated

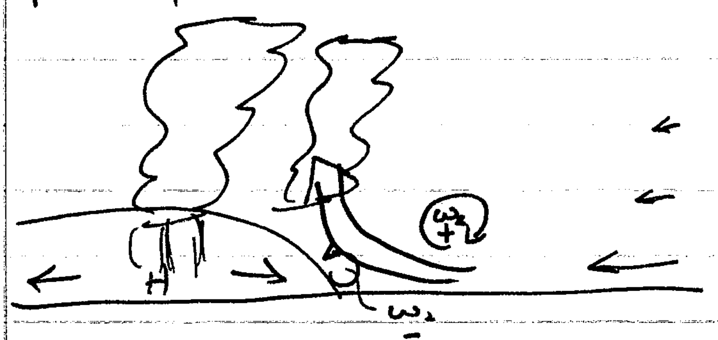
Case 2: Outflow with low level shear in reference frame moving with outflow



1) environmental shear generating $+\omega_z$
2) cold outflow generating $-\omega_z$
 ~ balance, which means more lift

Vortex generated by environment & outflow tend to cancel

So, triggering of convection cells is favored where cold pool spreading into low level flow



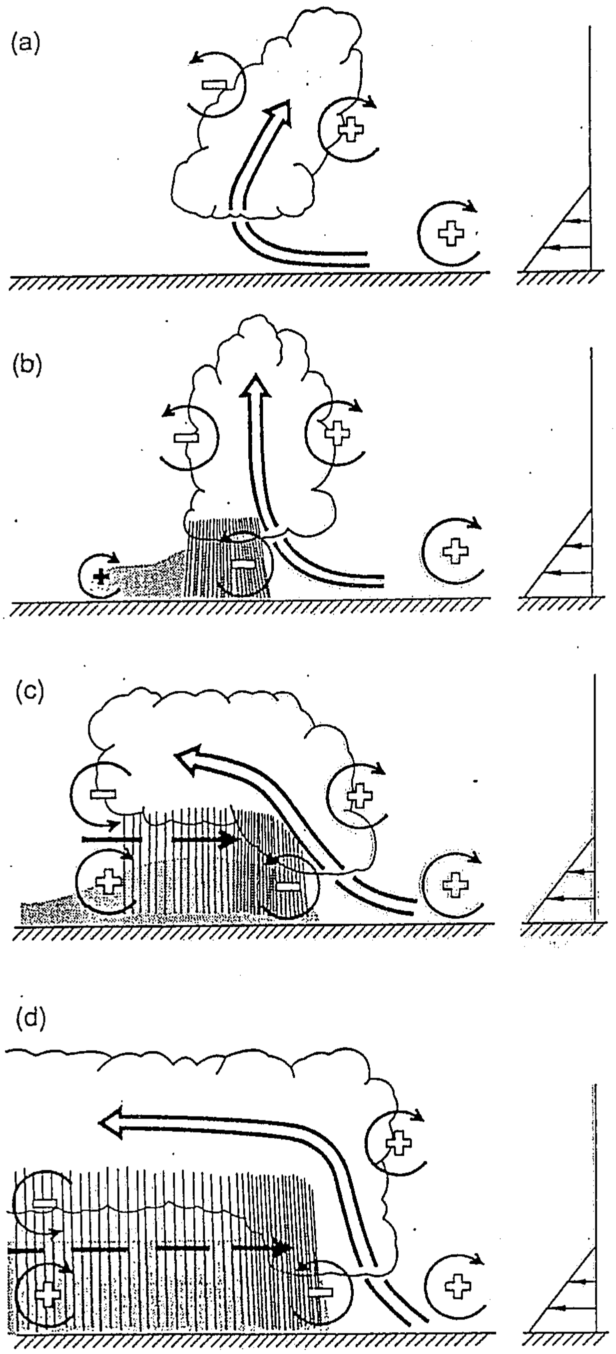


FIG. 14. Four stages in the evolution of an idealized bow echo. (a) An initial updraft leans downshear in response to the ambient vertical wind shear, which is shown on the right. (b) The circulation generated by the storm-induced cold pool balances the ambient shear, and the system becomes upright. (c) The cold pool circulation overwhelms the ambient shear, and the system tilts upshear, producing a rear-inflow jet. (d) A new steady state is achieved whereby the circulation of the cold pool is balanced by both the ambient vertical wind shear and the elevated rear-inflow jet. The updraft current is denoted by the thick double-lined flow vector, with the rear-inflow current in (c) and (d) denoted by the thick dashed vector. The shading denotes the surface cold pool. The thin, circular arrows depict the most significant sources of horizontal vorticity, which are either associated with the ambient shear or are generated within the convective system, as described in the text. Regions of lighter or heavier rainfall are indicated by the more sparsely or densely packed vertical lines, respectively. The scalloped line denotes the outline of the cloud (adapted from Weisman 1992).

inent feature of the midlevel flow through the remainder of the simulation.

As the system expands, however, a stronger vertical circulation develops in a broad zone between the bookend vortices, associated with the development of a quasi-two-dimensional updraft and elevated rear-inflow jet. As is demonstrated in the pressure analysis, the horizontal pressure gradient accelerating this rear inflow is primarily associated with a quasi-two-dimensional buoyancy-produced mesolow that extends above and behind the spreading cold pool. It is the development of this elevated rear inflow, which reaches intensities of greater than 20 m s^{-1} along the symmetry axis, that appears to be the dominant factor promoting the new steady-state structure by 180 min.

In light of this, we will proceed first with an analysis of the two-dimensional processes important to the development of this elevated rear-inflow jet and will explain how it contributes to producing an intense, steady uplift along the leading edge of the system. We will then discuss in more detail the processes promoting the development of the bookend vortices and will attempt to clarify their role in initiating and strengthening this rear-inflow circulation.

4. The development and role of the rear-inflow jet

A detailed analysis of the physical mechanisms responsible for the development of the rear-inflow jet within this simulation has recently been presented in a companion study by Weisman (1992). In this study, which extends the recent work of RKW and Lafore and Moncrieff (1989), the generation of the rear inflow is analyzed via the two-dimensional horizontal vorticity equation for inviscid Boussinesq flow; for example,

$$\frac{d\eta}{dt} = -\frac{\partial B}{\partial x}, \quad (8)$$

where $\eta = \partial u/\partial z - \partial w/\partial x$ and where B represents the buoyancy, defined by (2). Within this framework, the only source of horizontal vorticity is horizontal gradients of buoyancy. Thus, the analysis of the development of circulation is simplified to understanding the evolution of the buoyancy field.

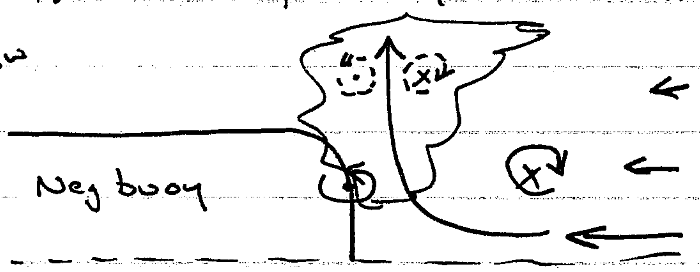
This perspective allows for a simple interpretation of the evolution of quasi-two-dimensional convective systems, based on the interactions between the buoyant updraft, the storm-induced cold pool, and the ambient vertical wind shear. This evolution is presented schematically in Fig. 14 for an isolated cell evolving in a vertically sheared environmental flow. Initially, the convective cell leans downshear in response to the am-

Role of the Rear-Inflow Jet

As the cold pool develops & spreads, the flow in the cold pool is not stagnant (relative to the storm motion) as previously assumed.

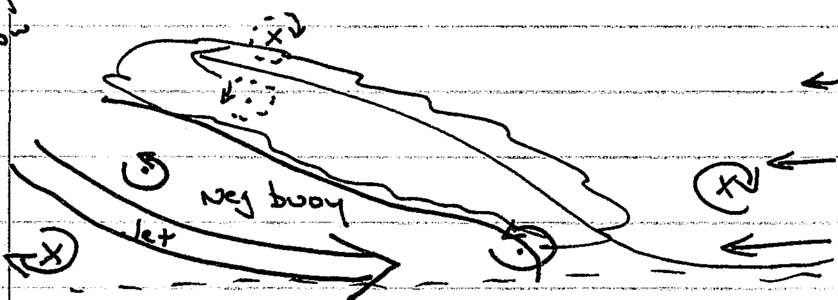
Consider first the case of a rear-inflow jet that descends to the surface presumably as a result of mixing downward of high momentum air.

(1) No rear-inflow jet



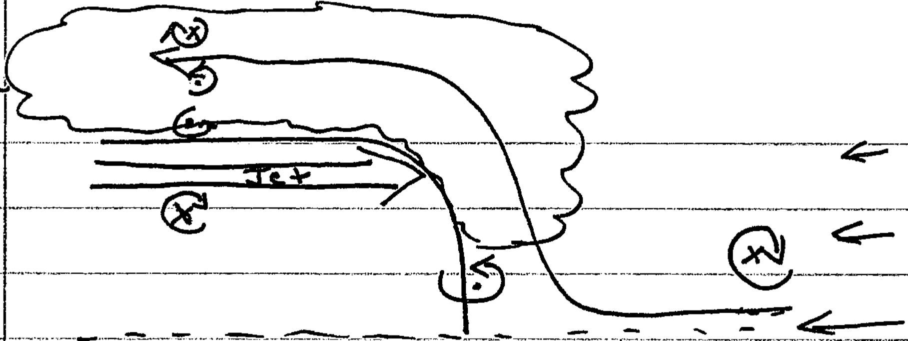
If no rear-inflow jet, then horizontal vorticity of environment is balanced by vorticity generated by the cold pool's buoyancy gradient.

(2) Descending rear-inflow jet



The Sinking Jet is a source for greater generation of horizontal vorticity in the same sense as that generated by the buoyancy gradients. So, the environmental shear is overwhelmed AND the rising plume tilts over the cold pool. This weakens the lift & makes it shallower.

(3) Elevated inflow jet

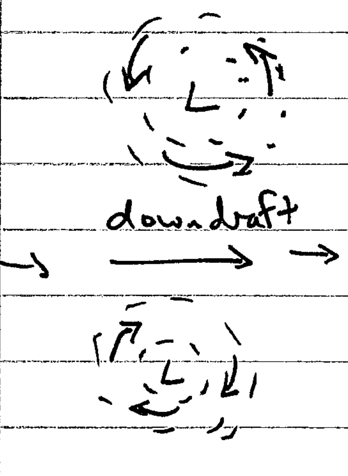


An elevated jet leads to horizontal vorticity that opposes the buoyancy-generated vorticity & helps to sustain lift at the leading edge

Typically, convective lines evolve through the cycle described in Fig. 14, which helps to sustain the line.

Origin of Bookend Vortices

As described in Holton & in the earlier notes, vortices rotating about a vertical axis are generated by the tilting of environmental shear & the development of downdrafts that lead to distinct rotating vortices. Once vertical vorticity is generated, the vortices may be stretched (or compressed) by the stretching term. As shown in Holton (Fig 9.12) & notes (C7), a pair of vortices form about the downdraft as follows



A critical feature is the rear inflow jet induced between the two vortices

Summary

Modeling studies suggest that bow echos are more likely in high CAPE high LOW level shear while splitting supercells are favored in high CAPE high deep level shear.

Review the different cases in the MCS matrix to see the rich diversity in storm evolution as a function of buoyancy & shear. Note especially from the right column the impact of considering the rotation of the earth. Previously, we have ignored "large-scale" dynamics. Basically, for a long N-S oriented line, the cyclonic rotation induced on the north end of the line will be favored over the anticyclonic rotation on the south end as a result of the earth's rotation.