The Fluid Dynamics of Tornadoes

Richard Rotunno

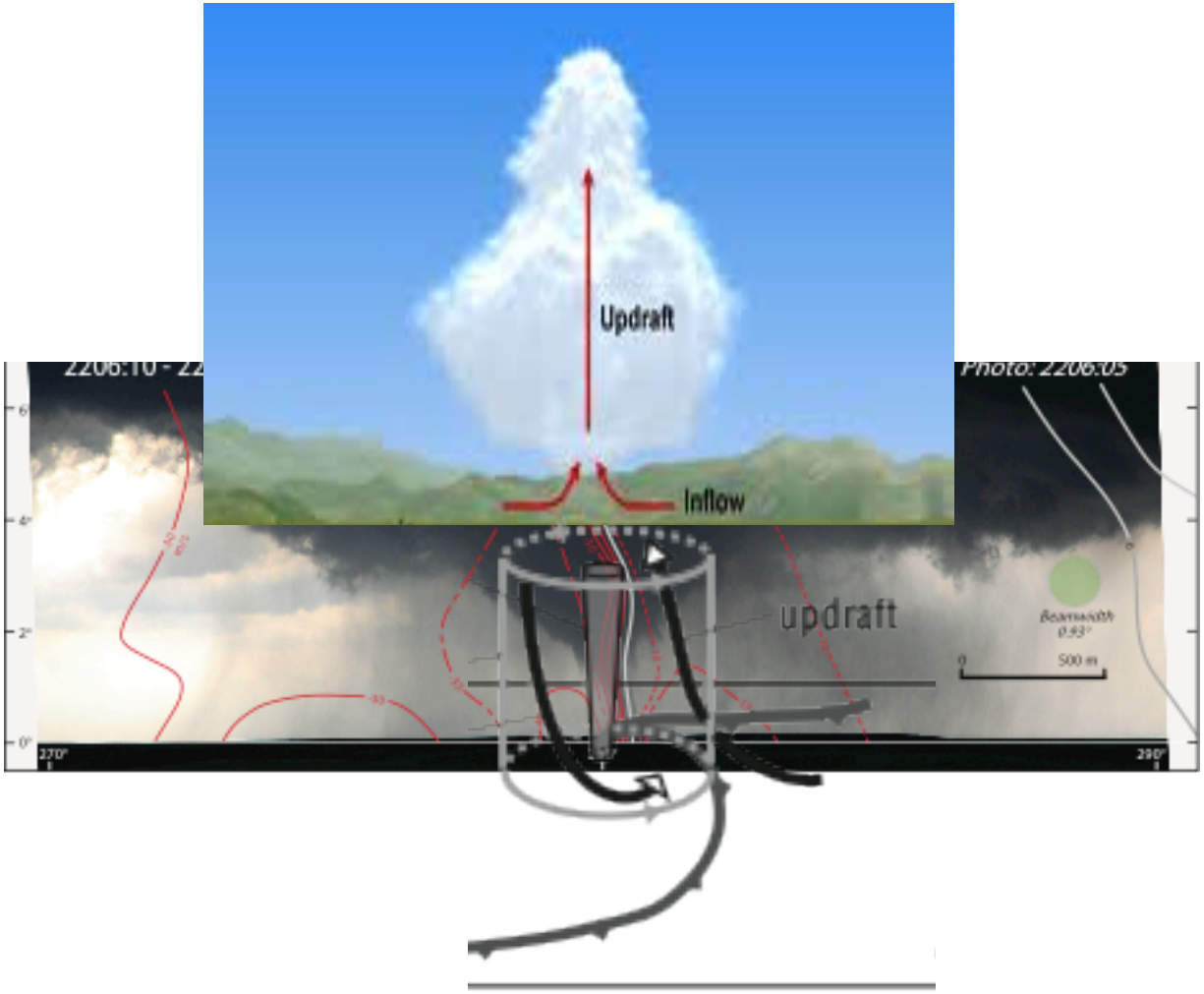
NCAR

Lecture 2: Neil Ward's Laboratory Model

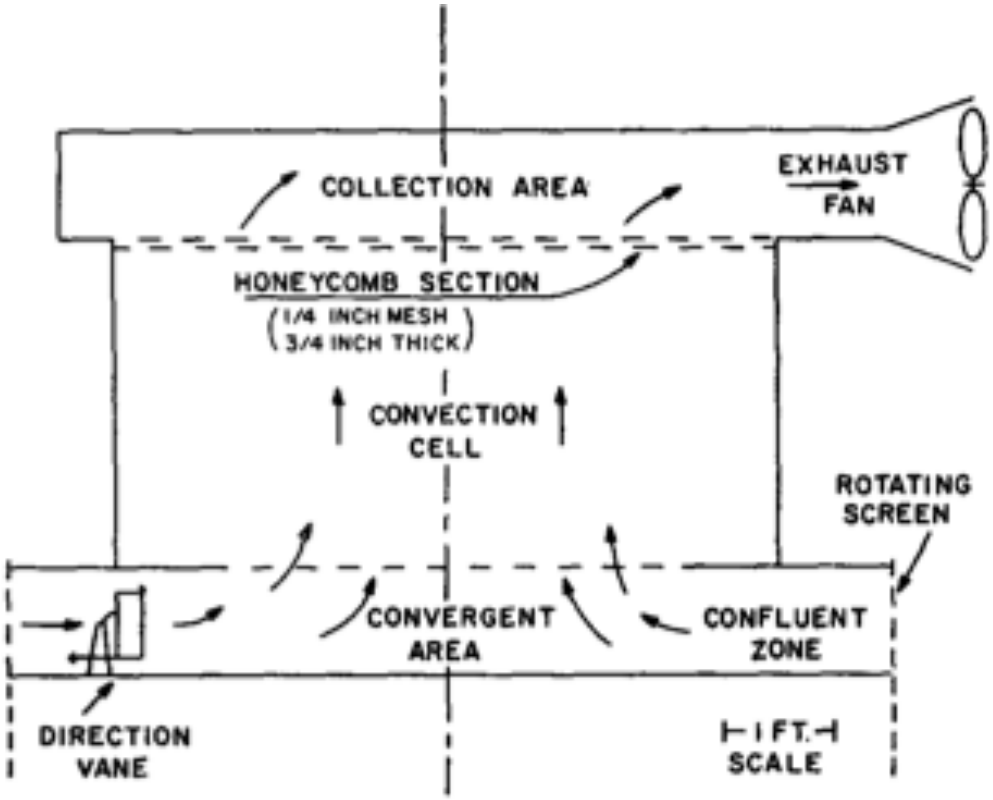
NCAR

NCAR is funded by the National Science Foundation

Idealization for Tornado Study

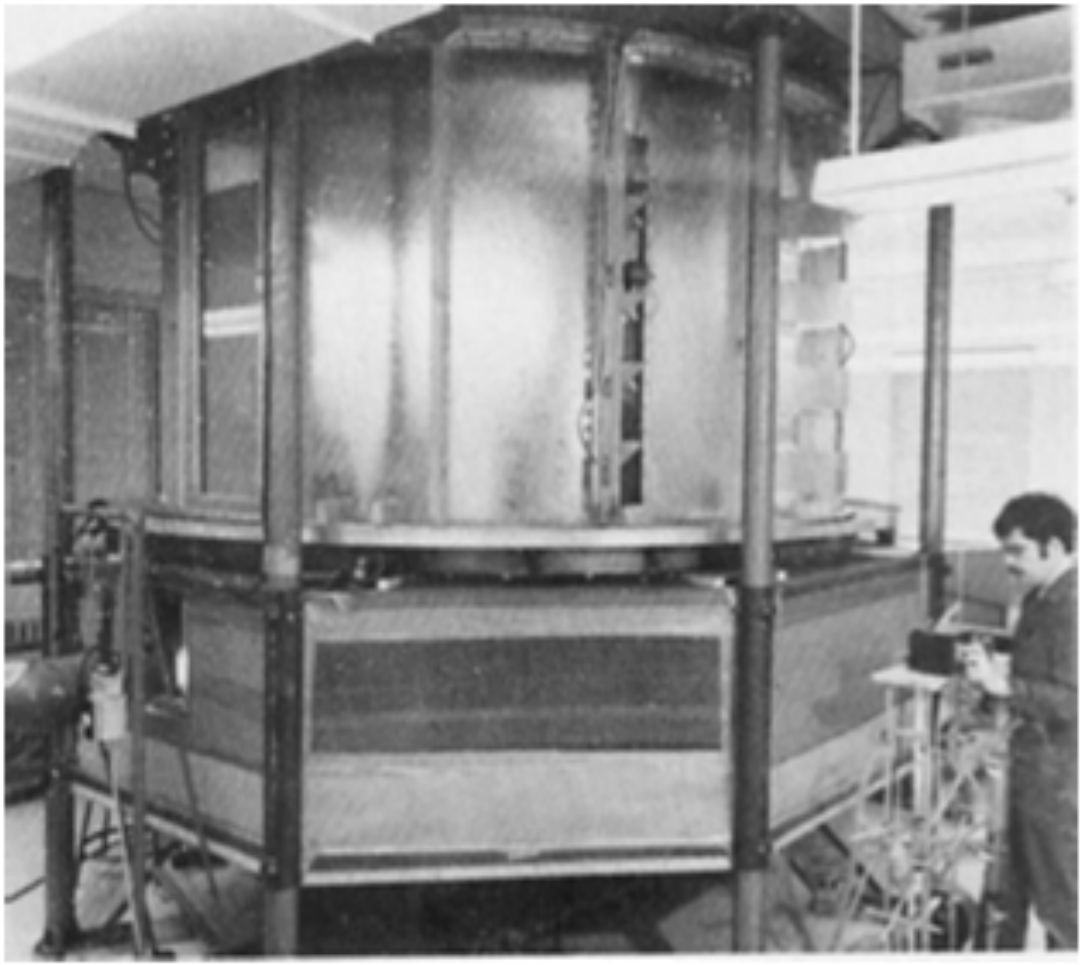


Ward Vortex Chamber



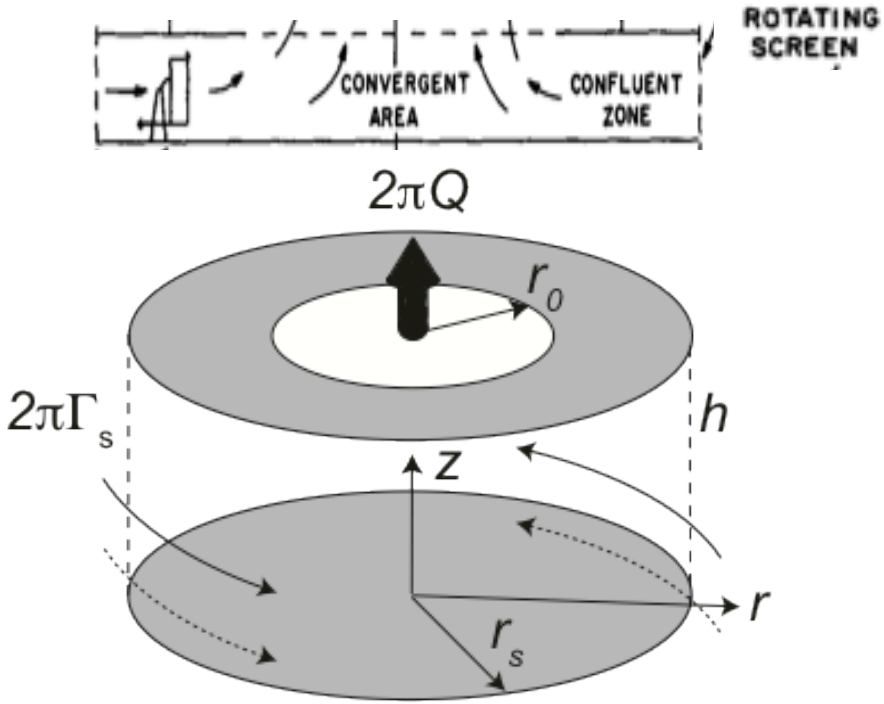
Ward (1972, *JAS*)

Purdue Vortex Chamber



Church et al. (1977, *BAMS*)

Ward Vortex Chamber



$$S = \frac{r_o \Gamma_s}{2Q}$$

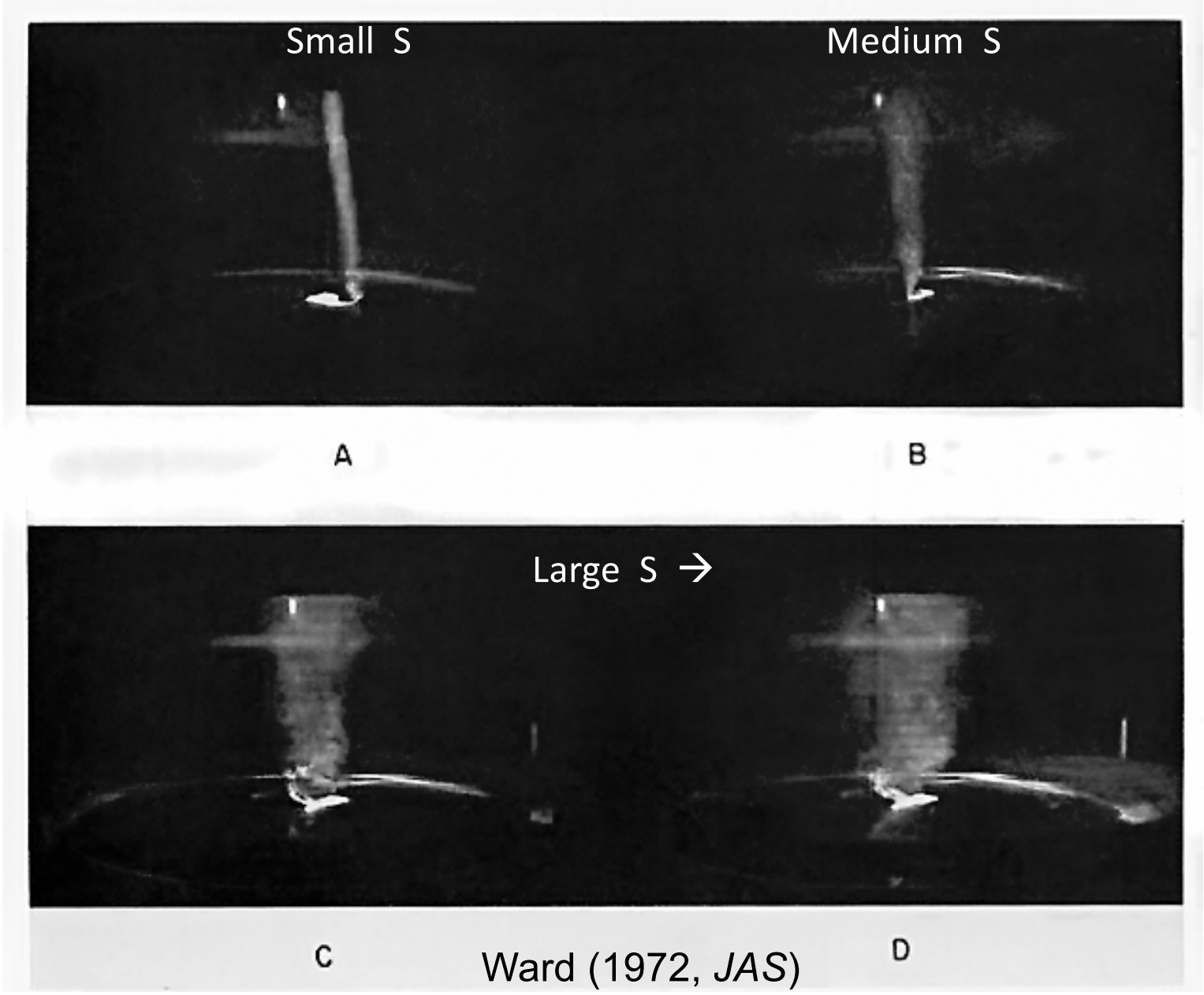
Swirl Ratio

$$Re = \frac{Q}{\nu h}$$

Reynolds Number

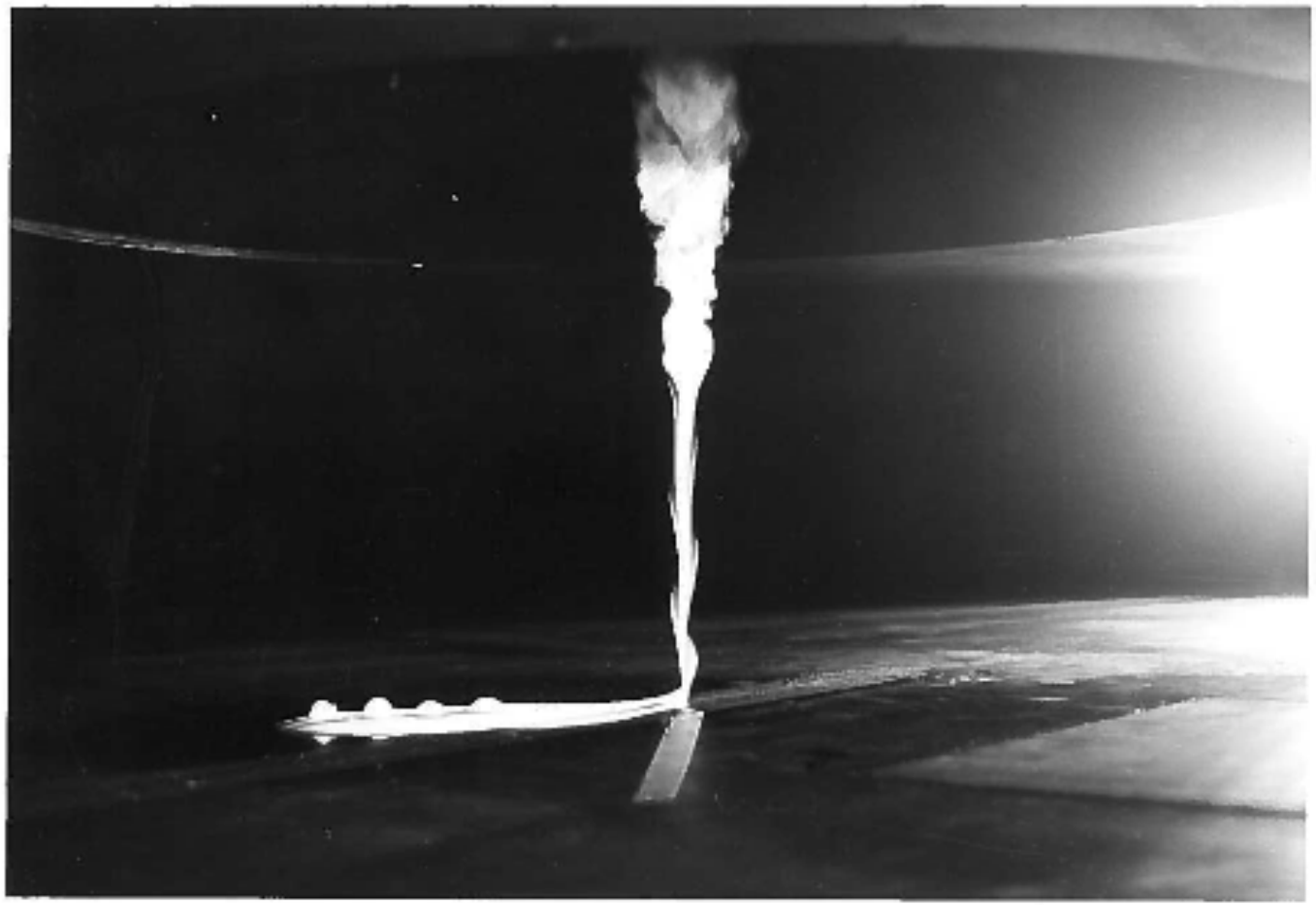
Davies-Jones (1973, *JAS*)

Core Size vs. *S*



Ward (1972, *JAS*)

$S = 0.1$



Purdue Tornado Vortex Simulator
Church et al (1979, *JAS*)

$S = 0.4$

Purdue Tornado Vortex Simulator
Church et al (1979, *JAS*)

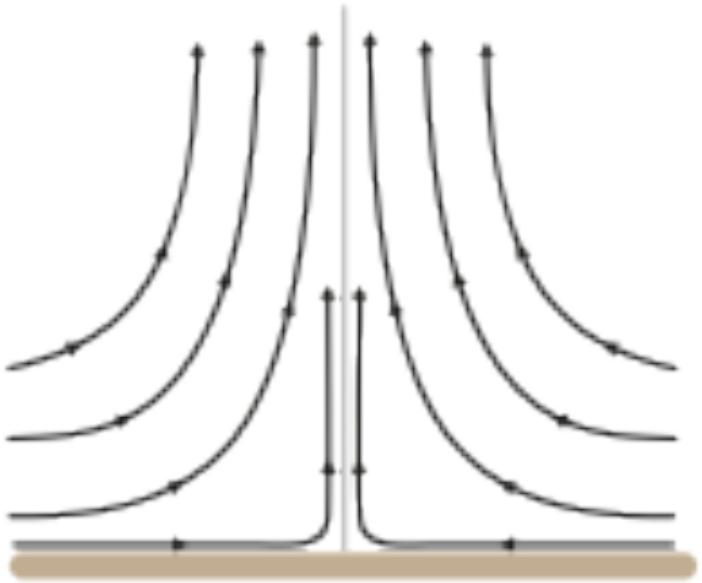
S = 0.5

S=1.0

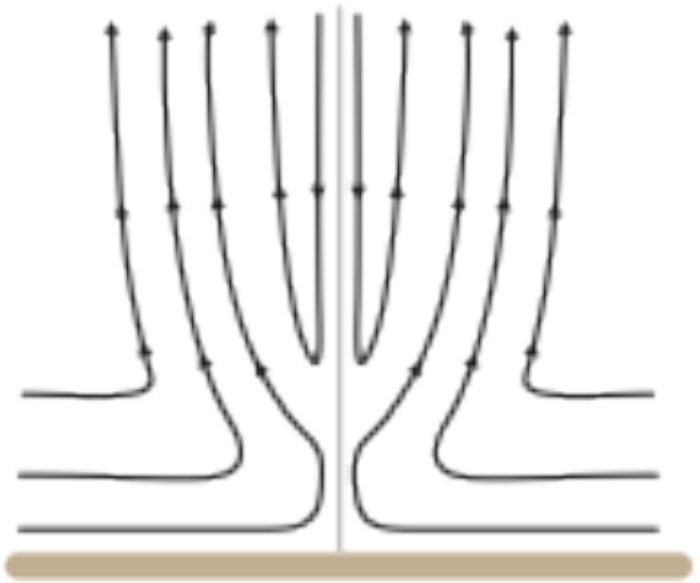
Purdue Tornado Vortex Simulator
Church et al (1979, *JAS*)

Focus on Explanation of Transitions of Vortex Type with *S*

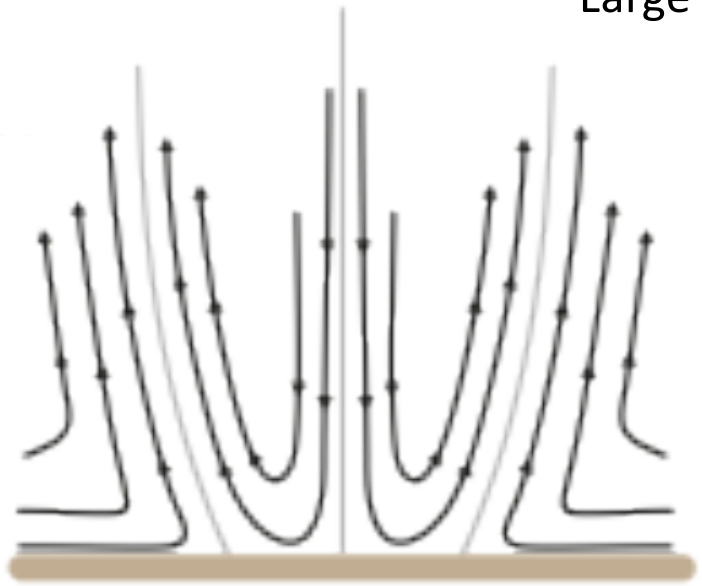
Small S



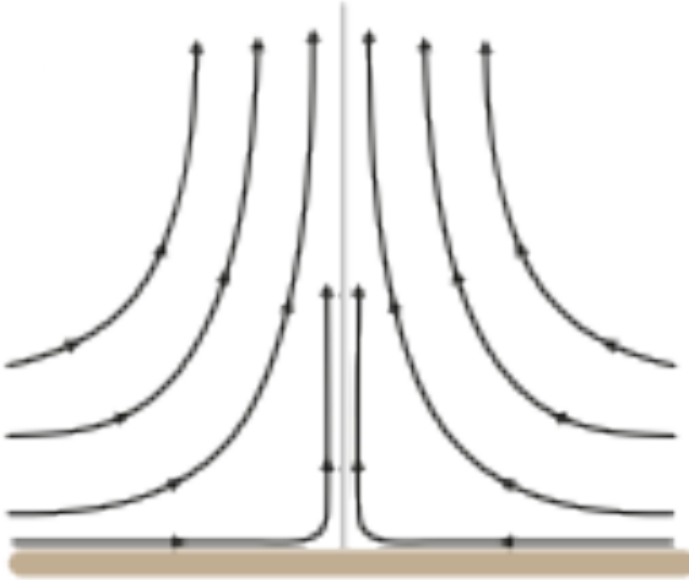
Medium S



Large S →



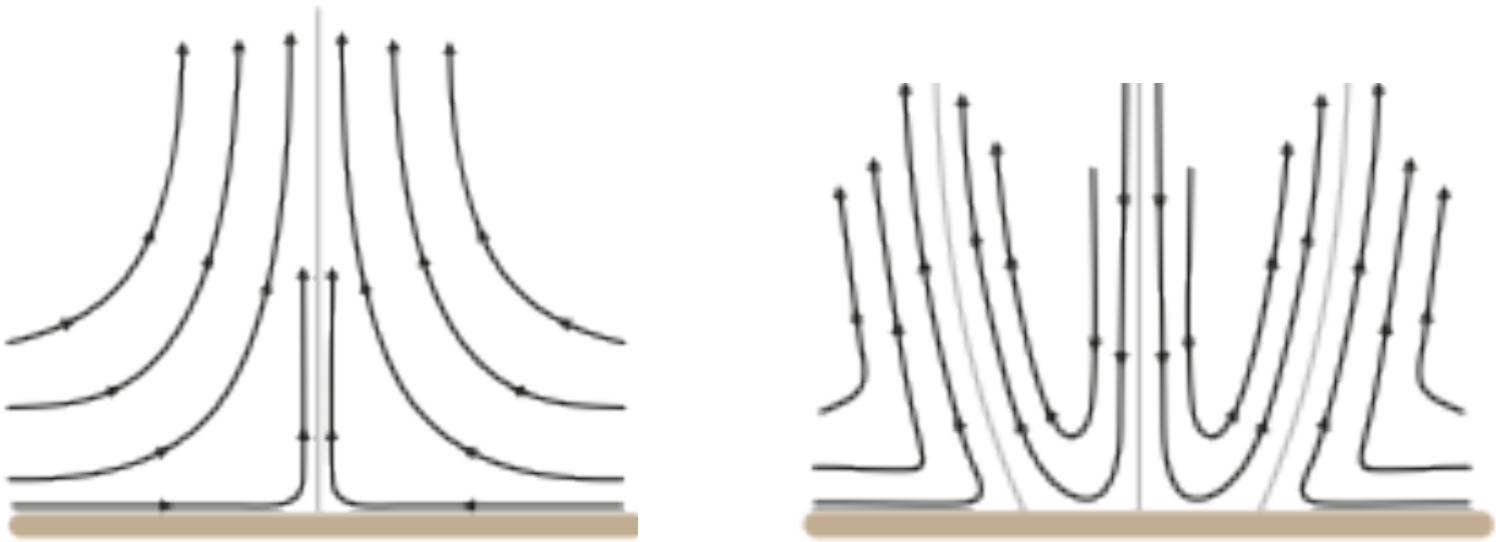
Small S



Conservation of angular momentum,

Small S

Large S



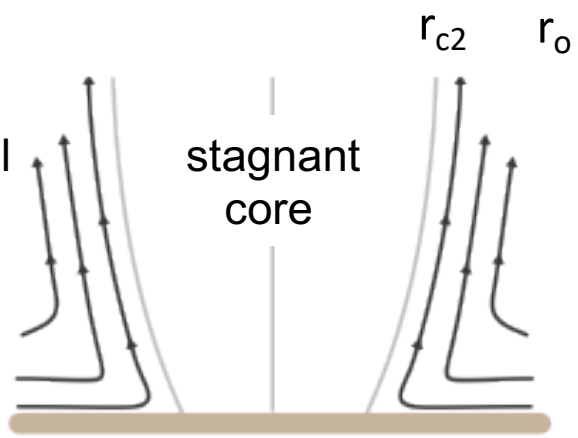
r_{c1}

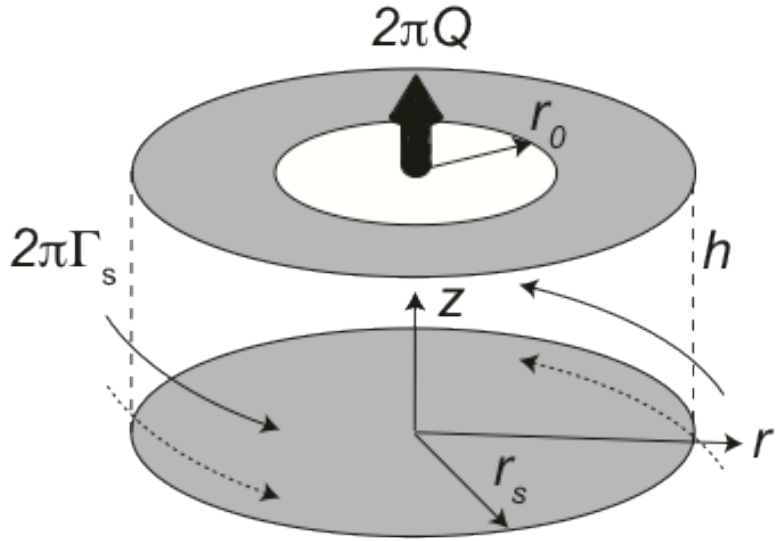
$$\Gamma_s = rv = \text{constant}$$

$$\int_{r_{c1}}^{r_s} F dr = \Delta p = \int_{r_{c1}}^{r_s} \frac{v^2}{r} dr \approx \frac{\Gamma_s^2}{2r_{c1}^2} \quad @\, z = 0$$

- Large amount of work (per unit mass) required to bring angular-momentum-conserving parcel to small radius
- Vortex adjusts by flow separation at finite radius

Simple Model for Two-Celled Core Radius vs. *S*

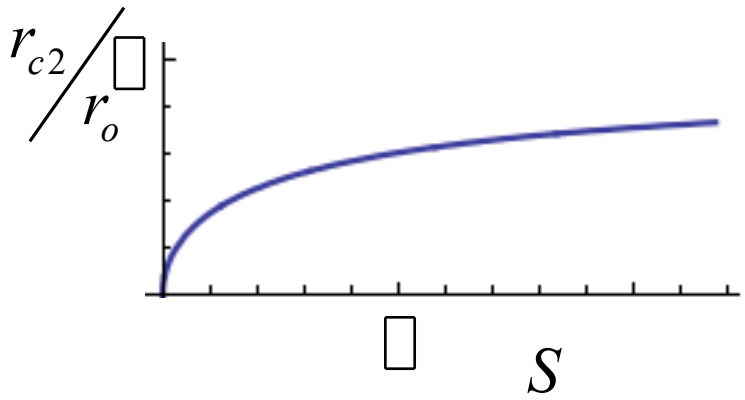




Bernoulli on dividing streamline

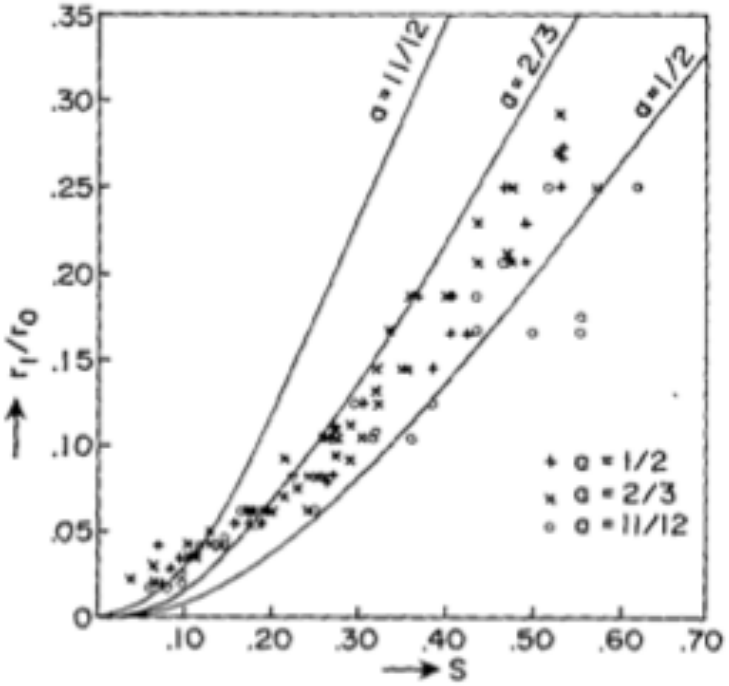
$$\frac{\Gamma_s^2}{2r_{c2}^2} + \frac{2Q^2}{\left(r_o^2 - r_{c2}^2\right)^2} = \Delta p$$

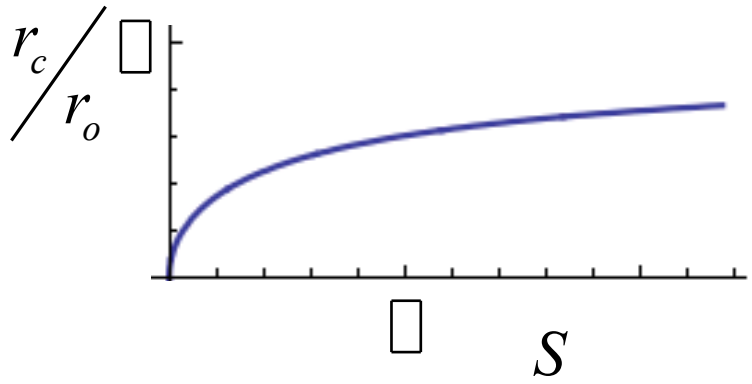
$$\frac{\partial \Delta p}{\partial r_c} = 0 \rightarrow S = \frac{\sqrt{2} r_o r_{c2}^2}{\left(r_o^2 - r_{c2}^2\right)^{3/2}}$$



Davies-Jones (1973, *JAS*)

Ward Lab Data

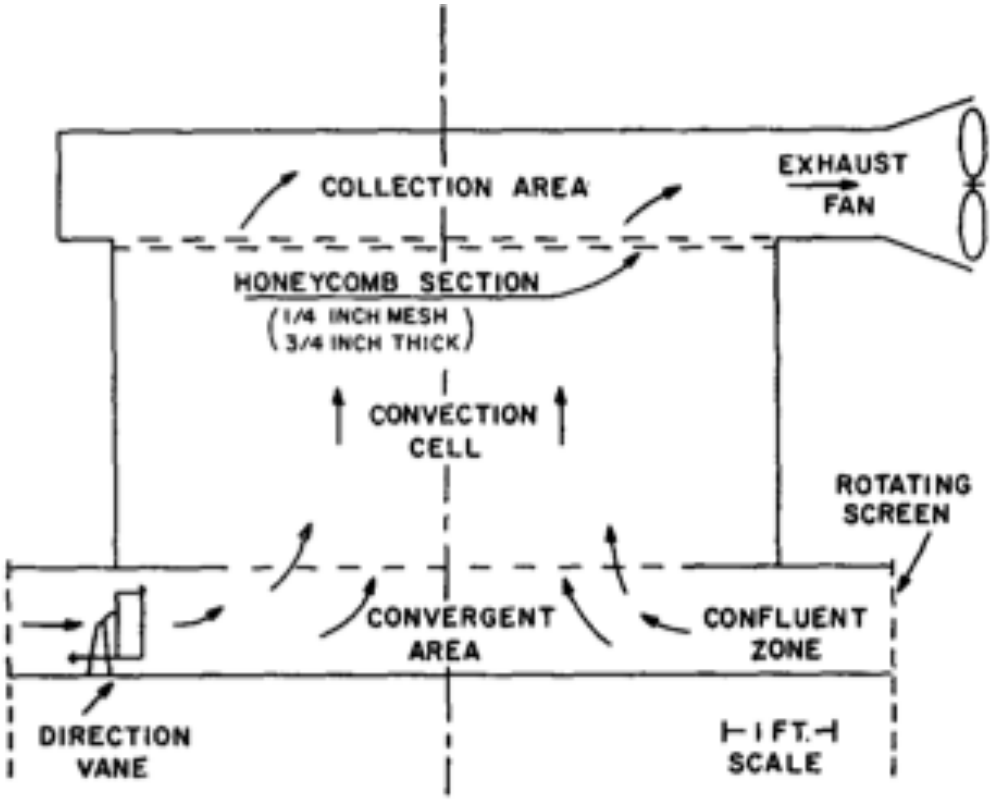




Davies-Jones (1973, *JAS*)

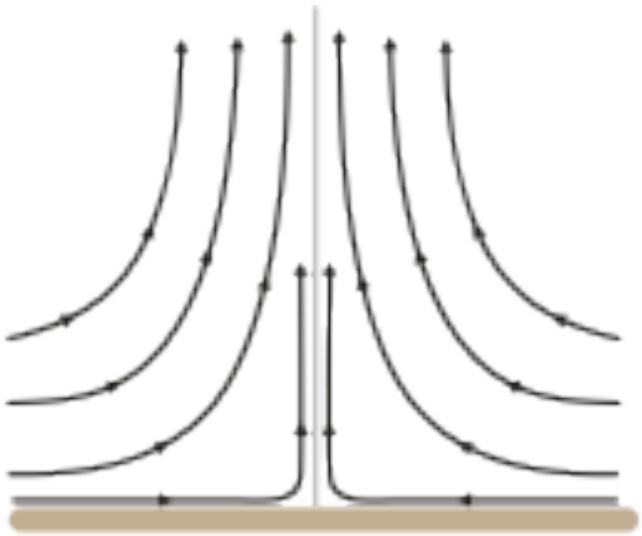
Model weaknesses: potential flow, optimization of pressure deficit not from first principles, core not stagnant, *inadequate top boundary condition*…

…inadequate top boundary condition…

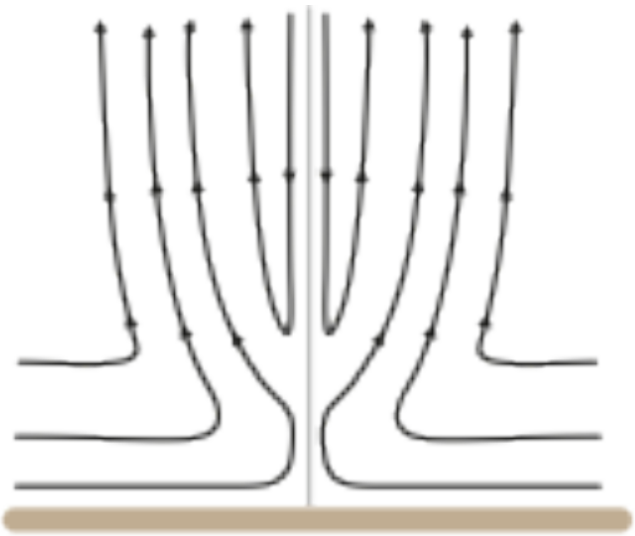


Ward (1972, *JAS*)

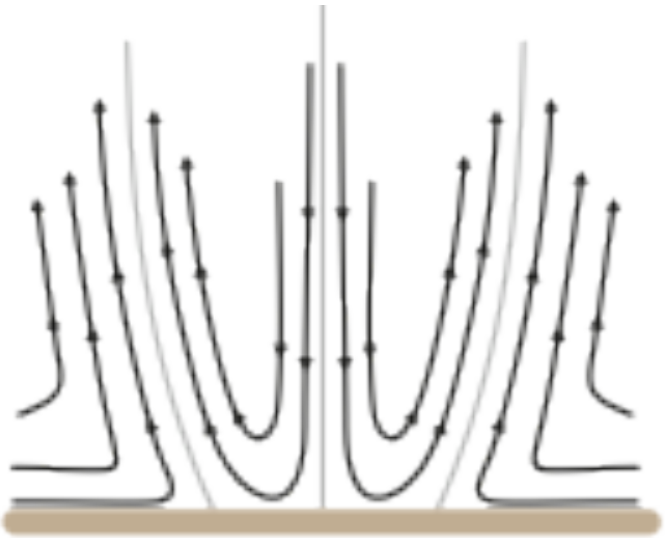
Small S



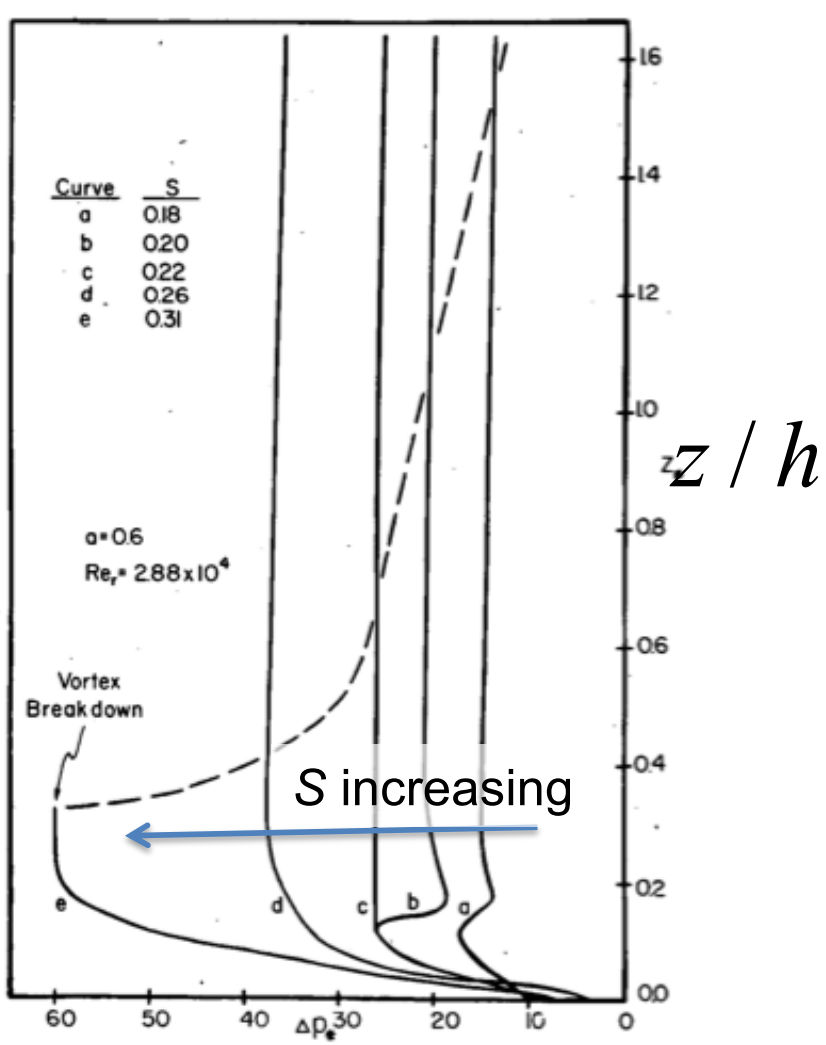
Medium S

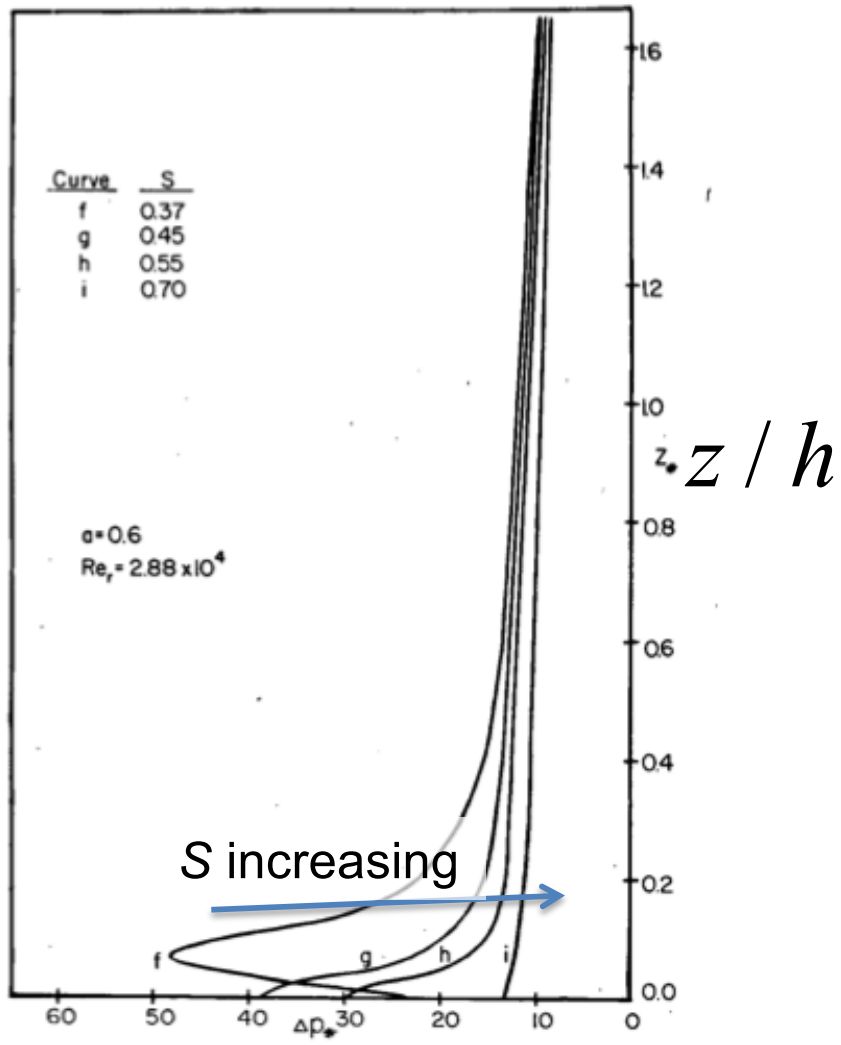


Large S

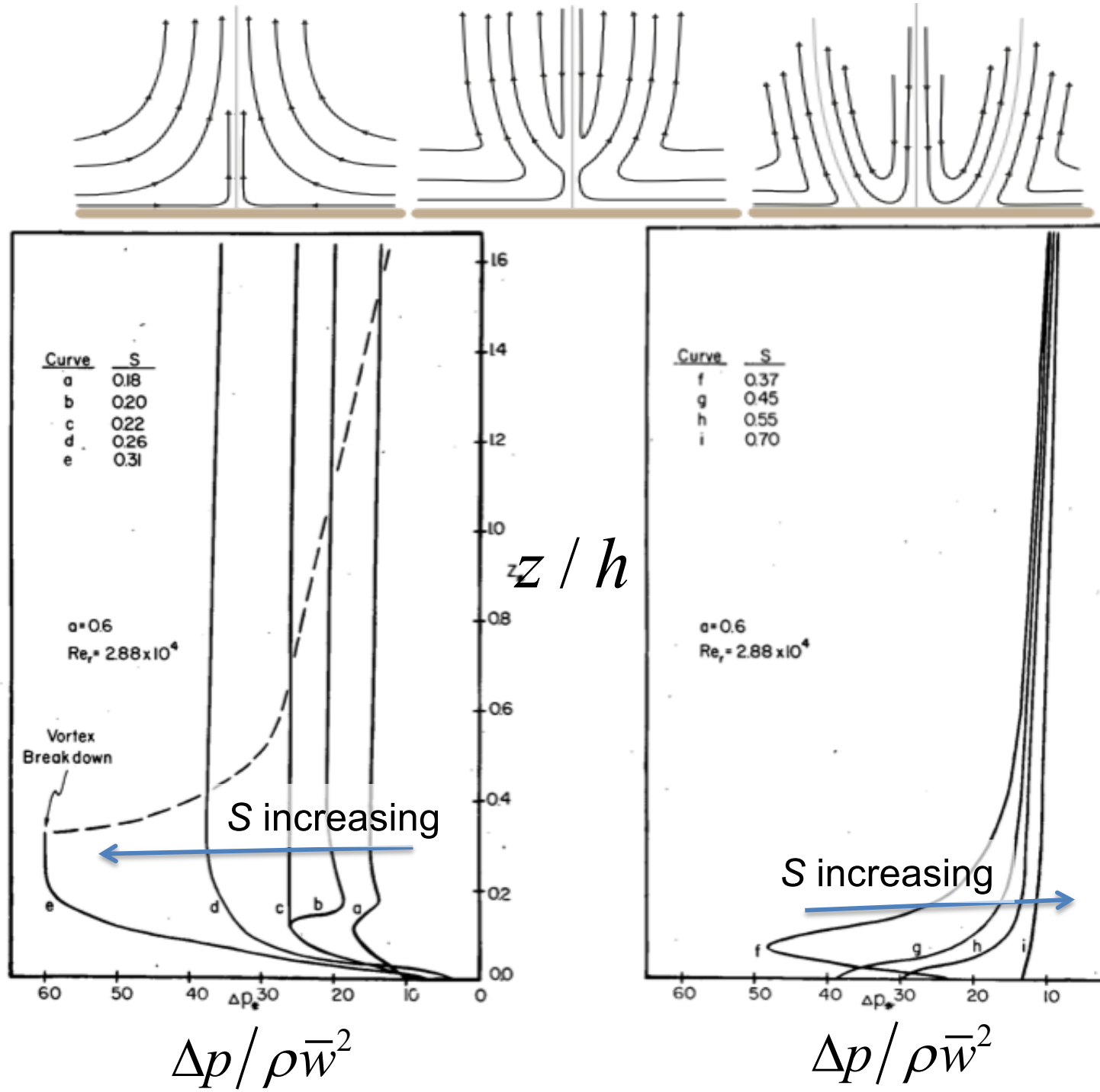


Core Pressure Deficit vs *S*





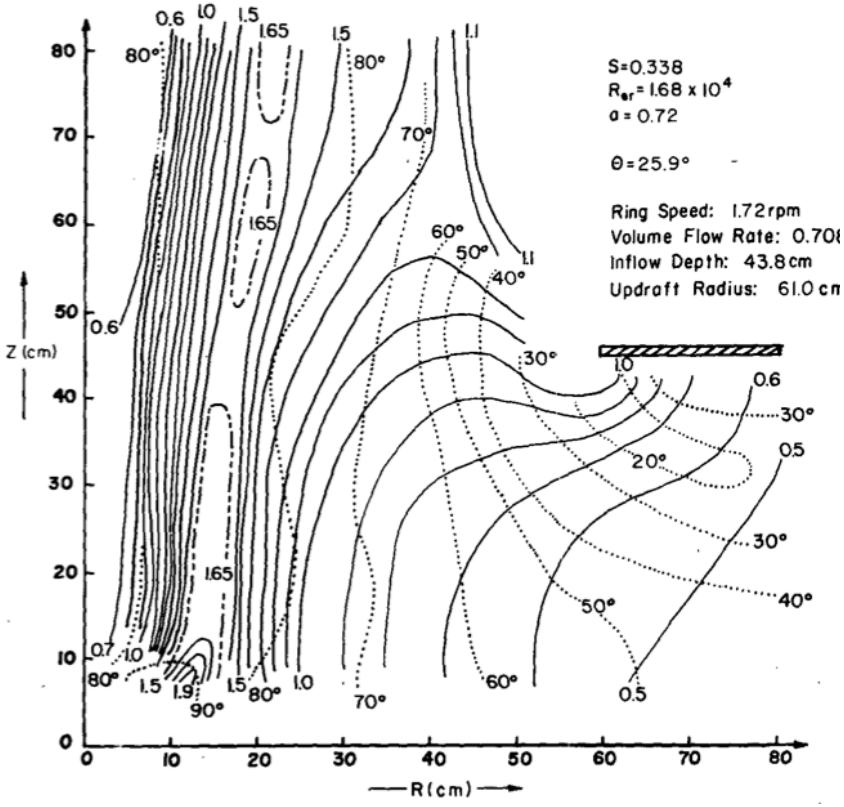
Church & Snow (1985, *JAS*)



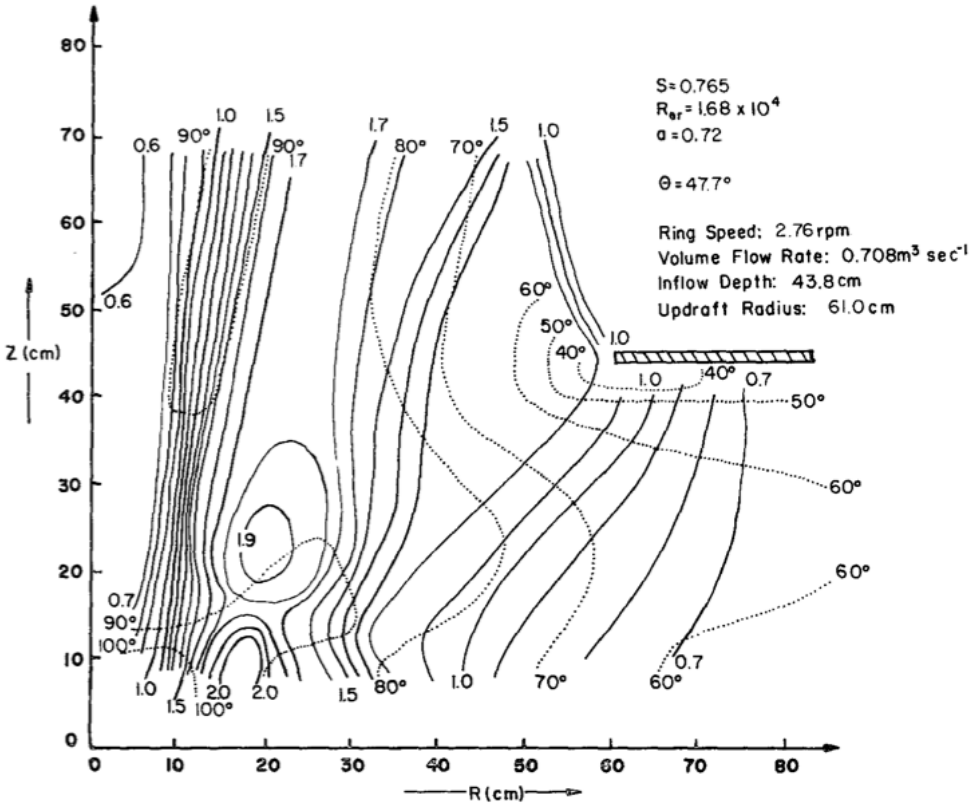
Church & Snow (1985, *JAS*)

Velocity Measurements

S = 0.4

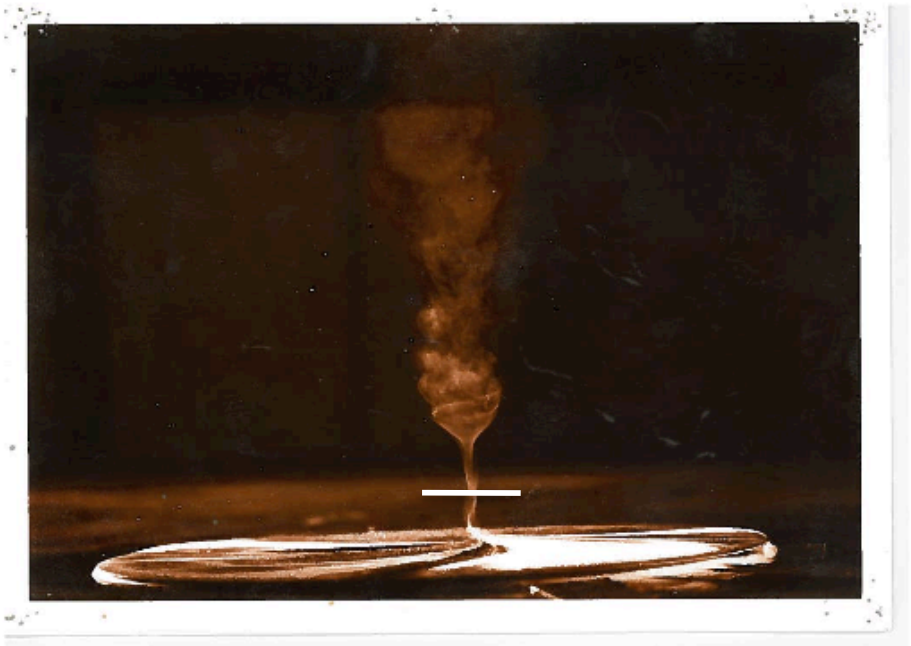


S = 0.8

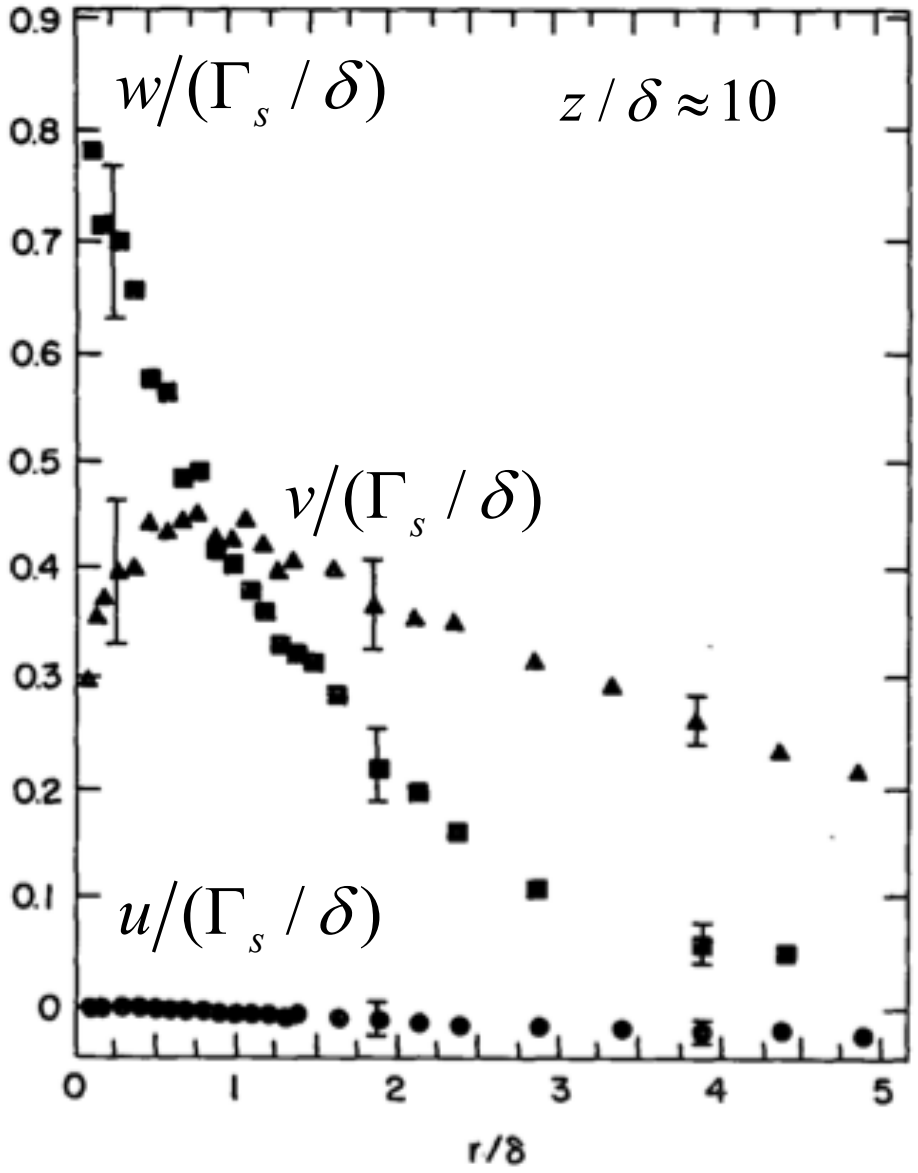


Purdue Tornado Vortex Simulator
Church et al (1979, *JAS*)

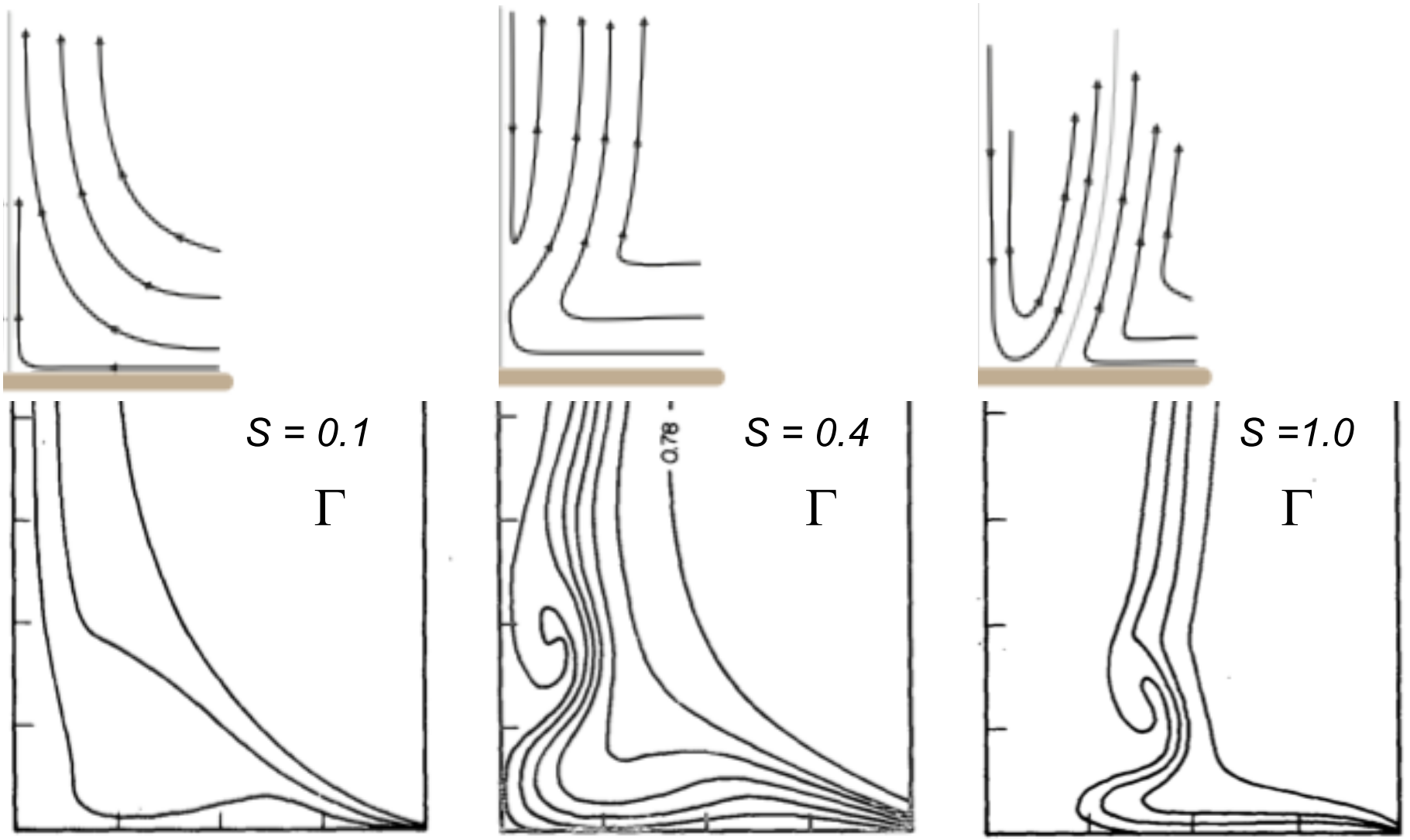
Laser-Doppler Velocimeter



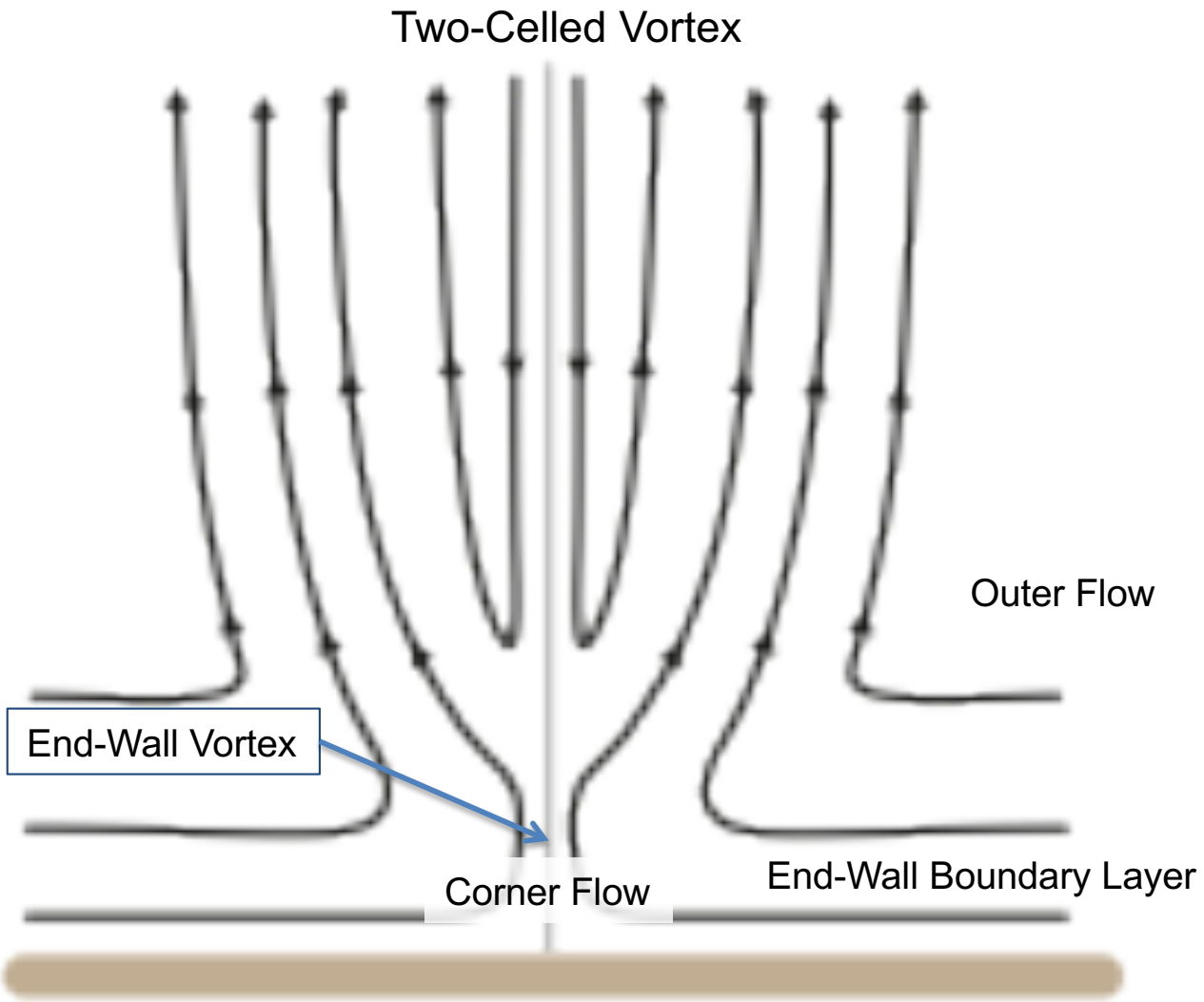
Baker (1981, *Ph. D. Thesis, Purdue*)



Numerical Simulations of Ward Chamber

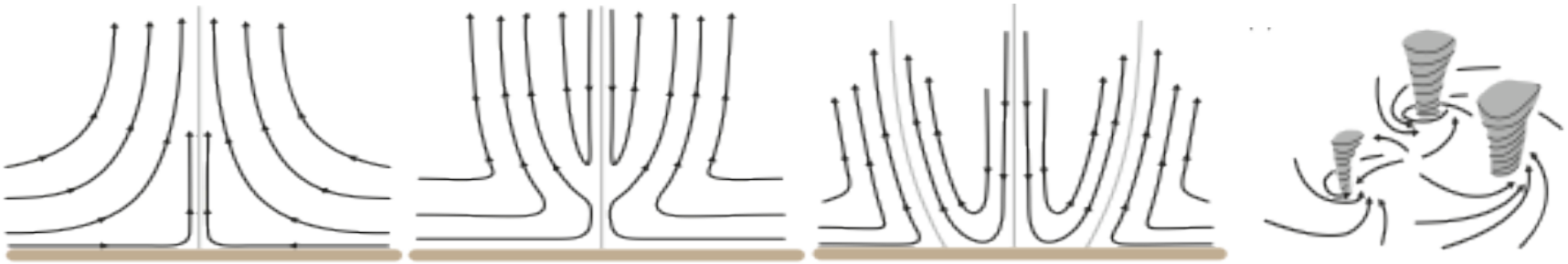


Rotunno (1979, *JAS*)


Two-Celled Vortex
Outer Flow
End-Wall Vortex
Corner Flow
End-Wall Boundary Layer

Ward Lab Model Summary

1. Realistic Range of Vortex Structures



2. Measurements Suggest Important Role for Vortex Corner Flow & Boundary Layer