The Tropical Atmospheric Boundary Layer

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Dept. of Atmospheric Science

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1. Historical Background for Boundary Layer Flows
   - ★ Lessons learned from the Arctic!
   - ★ The Ekman Layer

2. The Boundary Layer Under Tropical Cyclones
   - ★ Motivation from Hurricane Hugo
   - ★ Lessons learned from a slab BL model

3. The Boundary Layer Under the ITCZ
   - ★ Motivation from satellite images and the MJO
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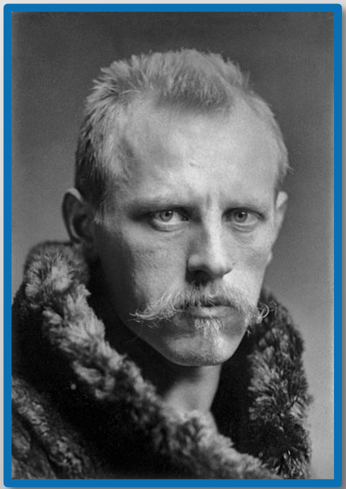
Discovery of Boundary Layer Flows

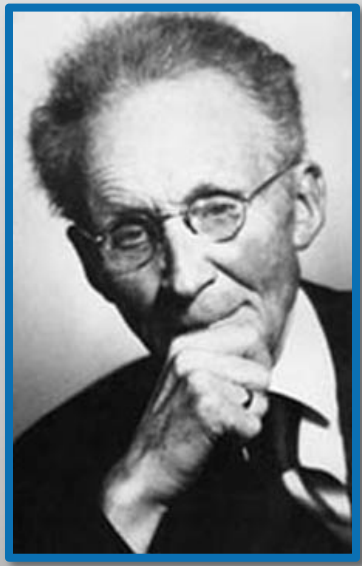
- F. Nansen organized the *Fram* expedition in 1893-96 to try to reach the North Pole
  - Observed that ice drifted 20-40° to the right of the surface wind direction
  - Explained this fact as a consequence of the Earth's rotation
  - Made the qualitative prediction that the current vector would spiral clockwise with increasing depth



Fridtjof Nansen
(1861 – 1930)

Discovery of Boundary Layer Flows

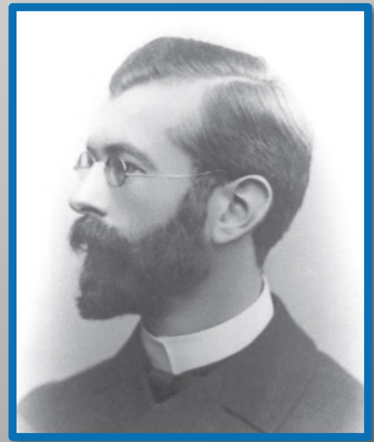
- ★ F. Nansen organized the *Fram* expedition in 1893-96 to try to reach the North Pole
- ★ Nansen suggested to V. Bjerknes (father of J. Bjerknes) that this ice drift phenomenon should be examined more formally



Vilhelm Bjerknes
(1862 – 1951)

Discovery of Boundary Layer Flows

- ★ F. Nansen organized the *Fram* expedition in 1893-96 to try to reach the North Pole
- ★ Nansen suggested to V. Bjerknes (father of J. Bjerknes) that this ice drift phenomenon should be examined more formally
- ★ Bjerknes assigned the problem to a young mathematical physicist, V. W. Ekman
- ★ Ekman solved the problem and presented his results in 1902 as his doctoral thesis
- ★ This phenomenon became known as the Ekman spiral



V. Walfrid Ekman
(1874 – 1954)

Nansen's Amazing Polar Expedition

The Planned Route:

- Based on the ill-fated voyage of the USS Jeannette during 1879 – 1881

The Actual Route: 1893 – 1896

(from http://www.fram.nl/)

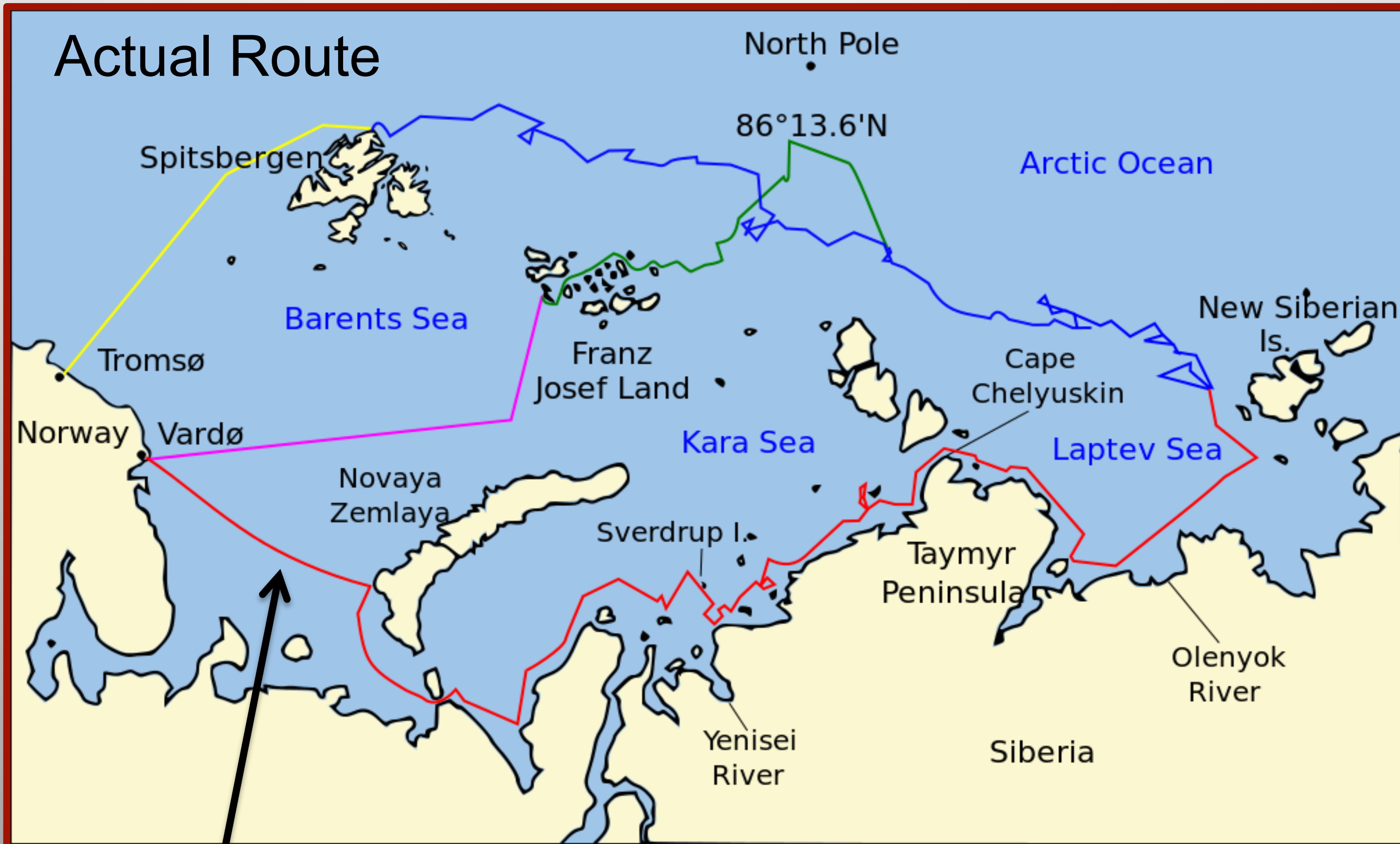
Nansen's Amazing Polar Expedition

A Special Ship

The *Fram* ("Forward"):

- 3-masted schooner that was unusually wide and shallow
- Rounded, thick, well-insulated wood hull
- Designed to be pushed upward, not crushed, by the ice
- 12 hand-selected crew members and provisions for 5 years
- Windmill to generate electricity for lighting and a good library!
- Preserved and on display in the Fram Museum in Oslo, Norway

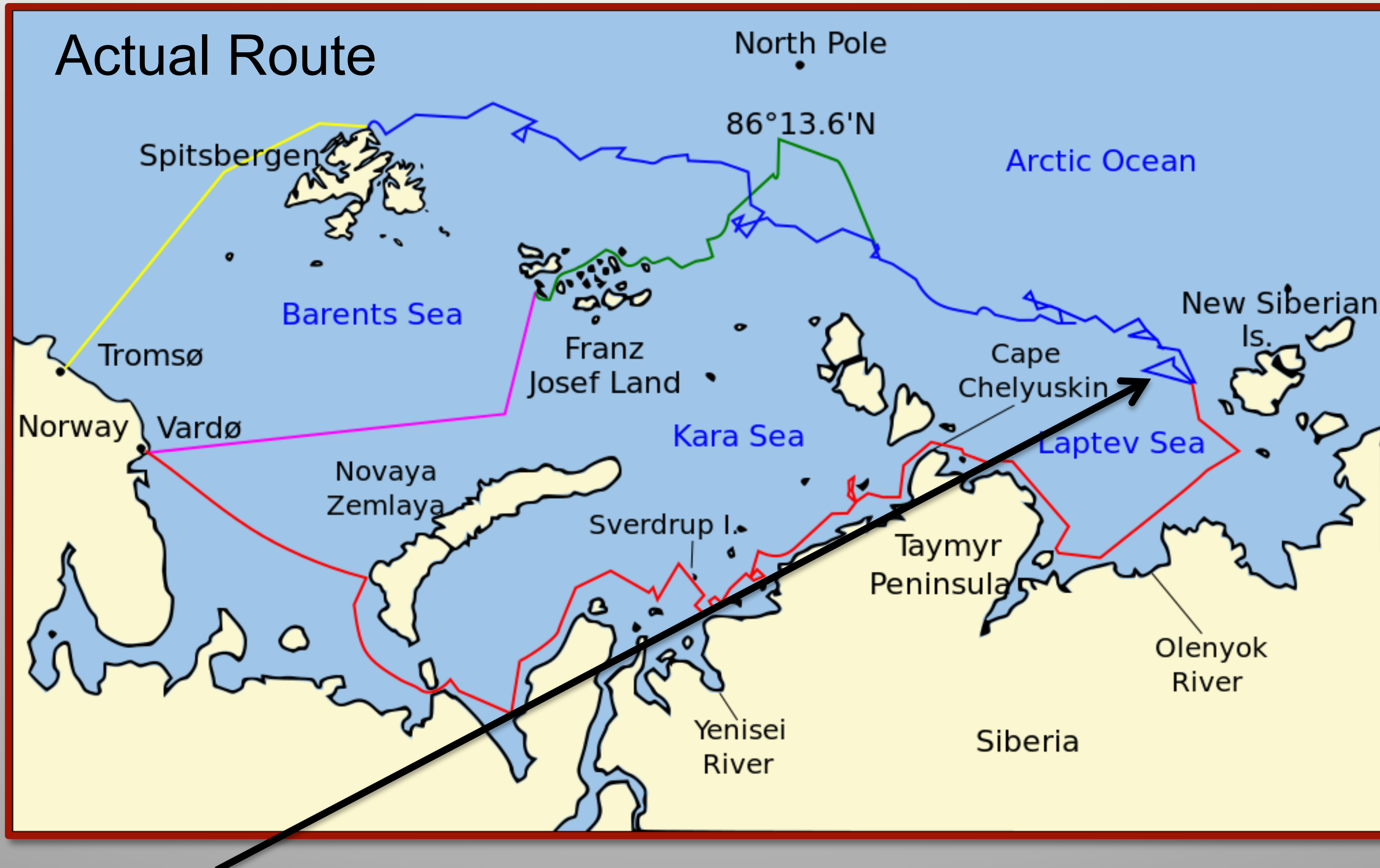
Nansen's Amazing Polar Expedition



July – Sept. 1893

The *Fram* sails eastward from Norway along the Siberian coast

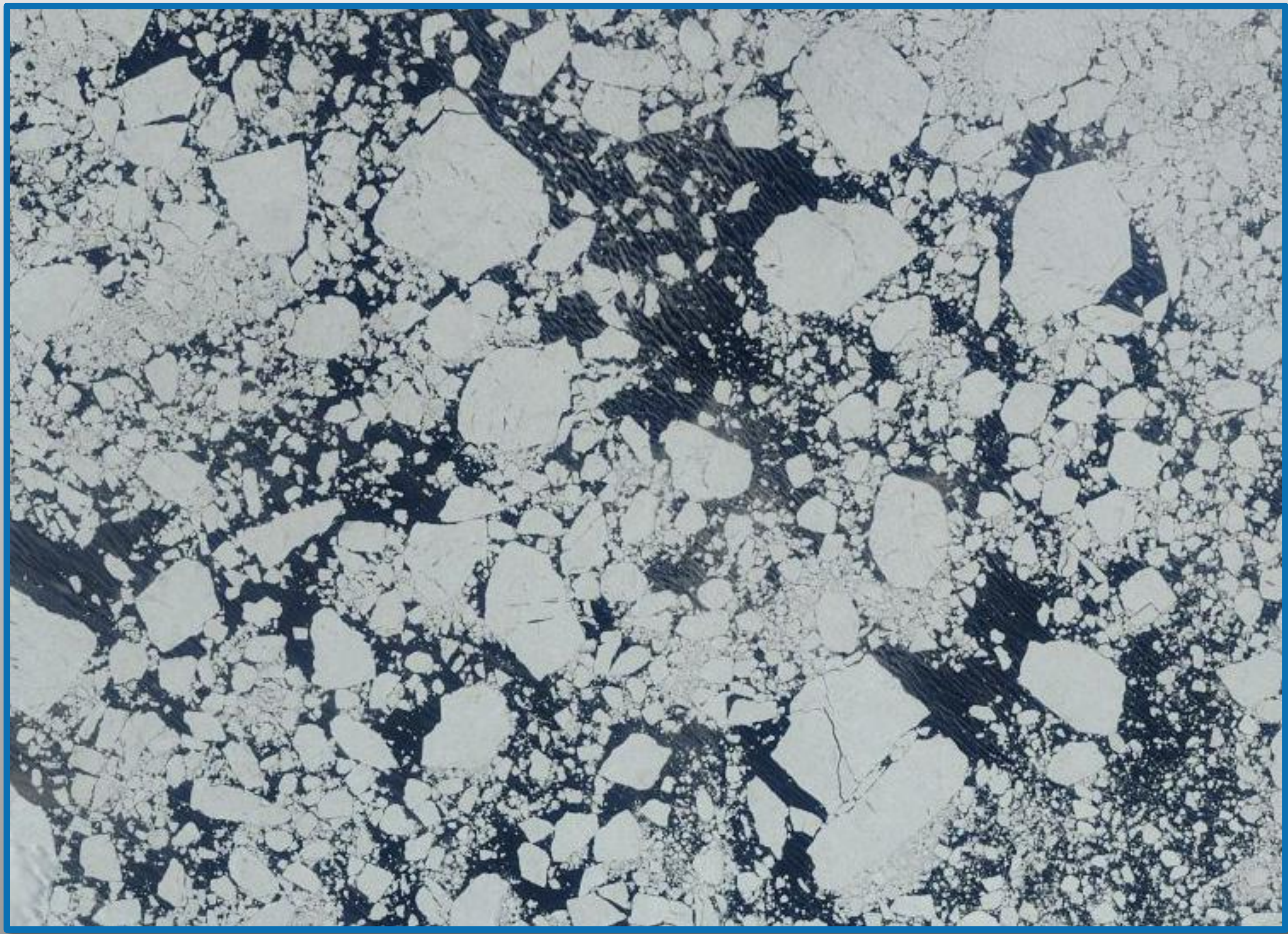
Nansen's Amazing Polar Expedition



Sept. 1893 – Aug. 1896

The *Fram* enters the ice pack and drifts with the ice

The Ice Pack as a Fluid

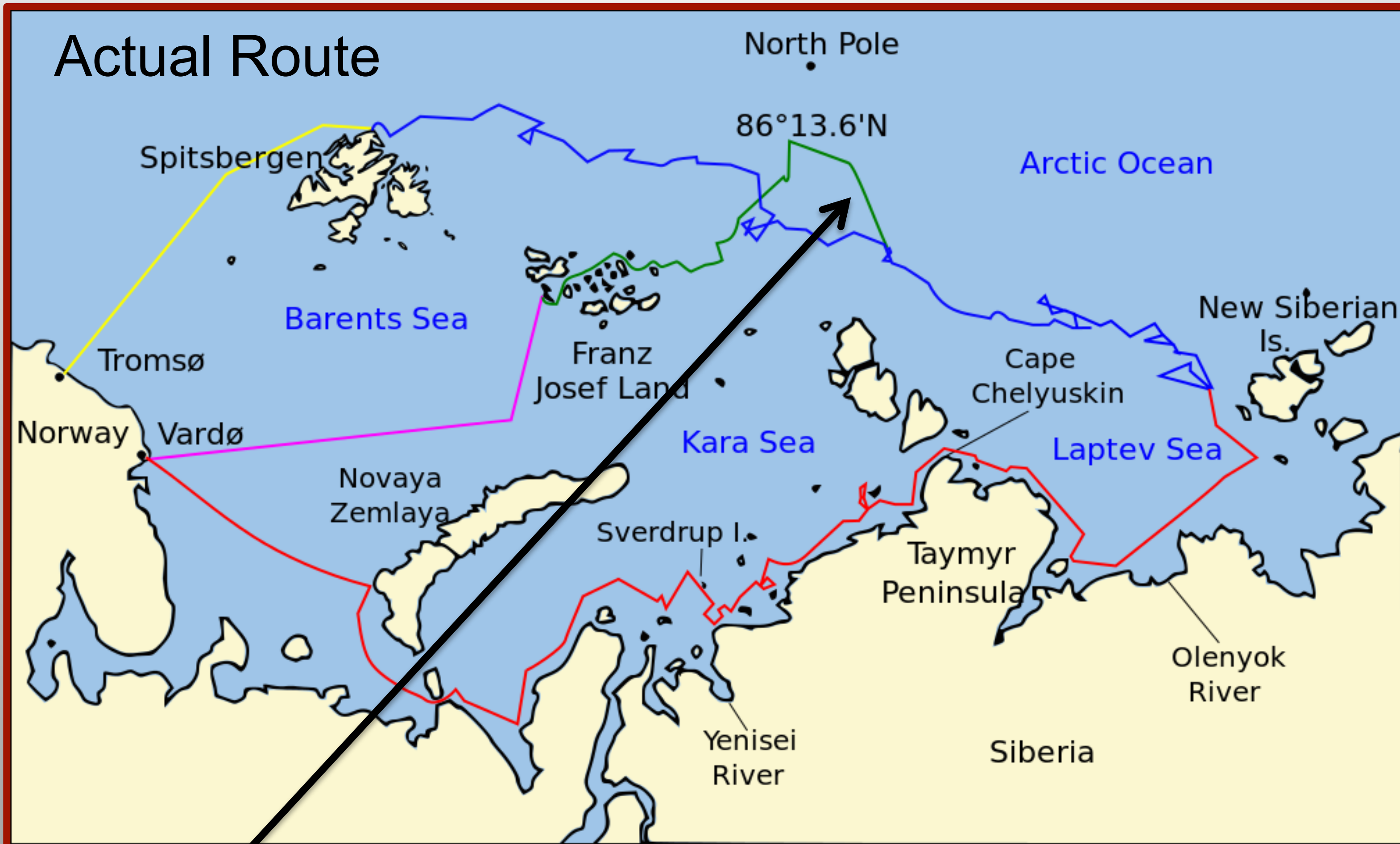


(MODIS image from http://robertscribbler.com/tag/alaska/)

Nansen's Amazing Polar Expedition

The *Fram* in Ice

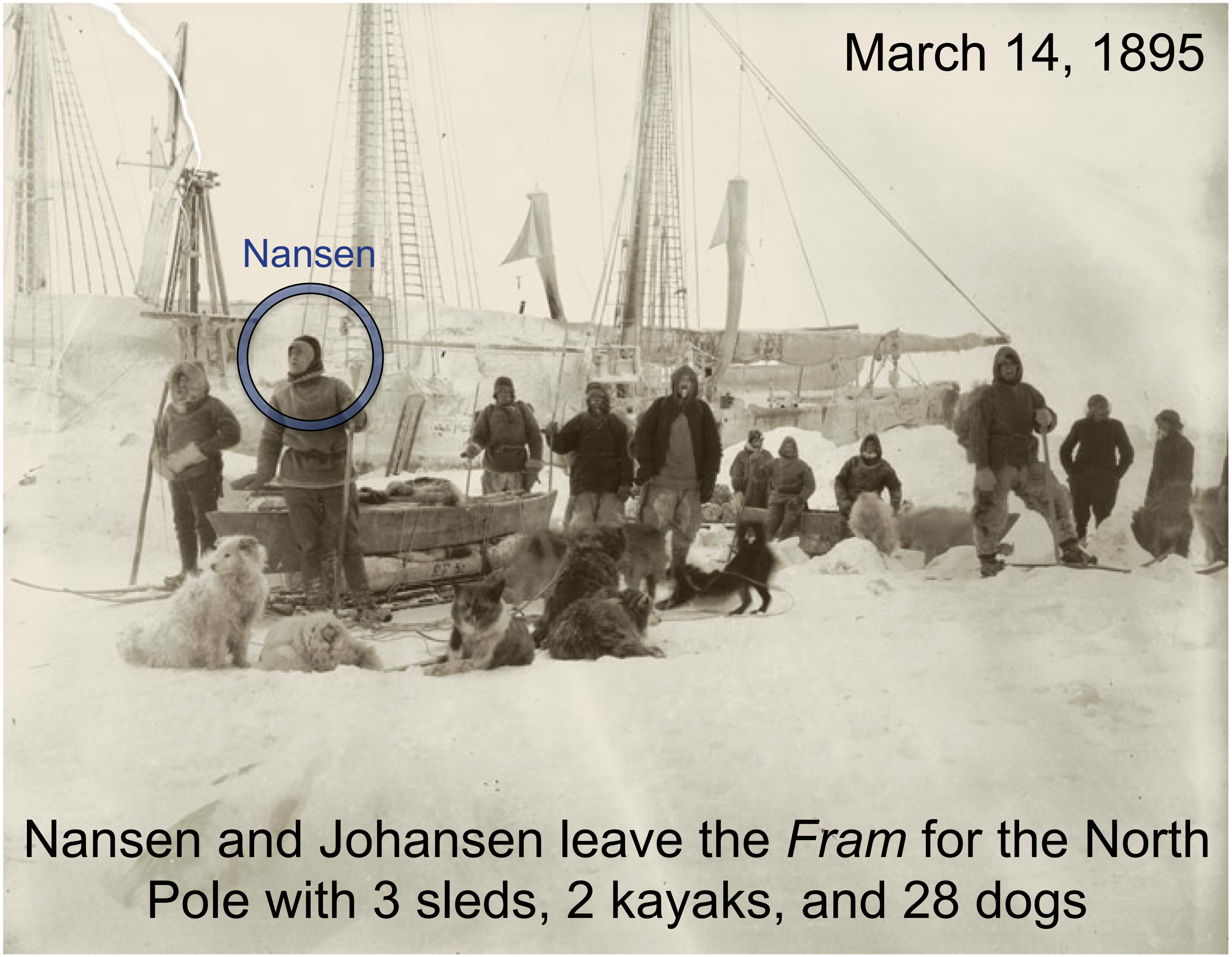
Nansen's Amazing Polar Expedition



Mar. 1895 – Jun. 1896

Nansen and H. Johansen leave the *Fram* and try to reach the North Pole on foot, eventually retreating to Franz Josef Land

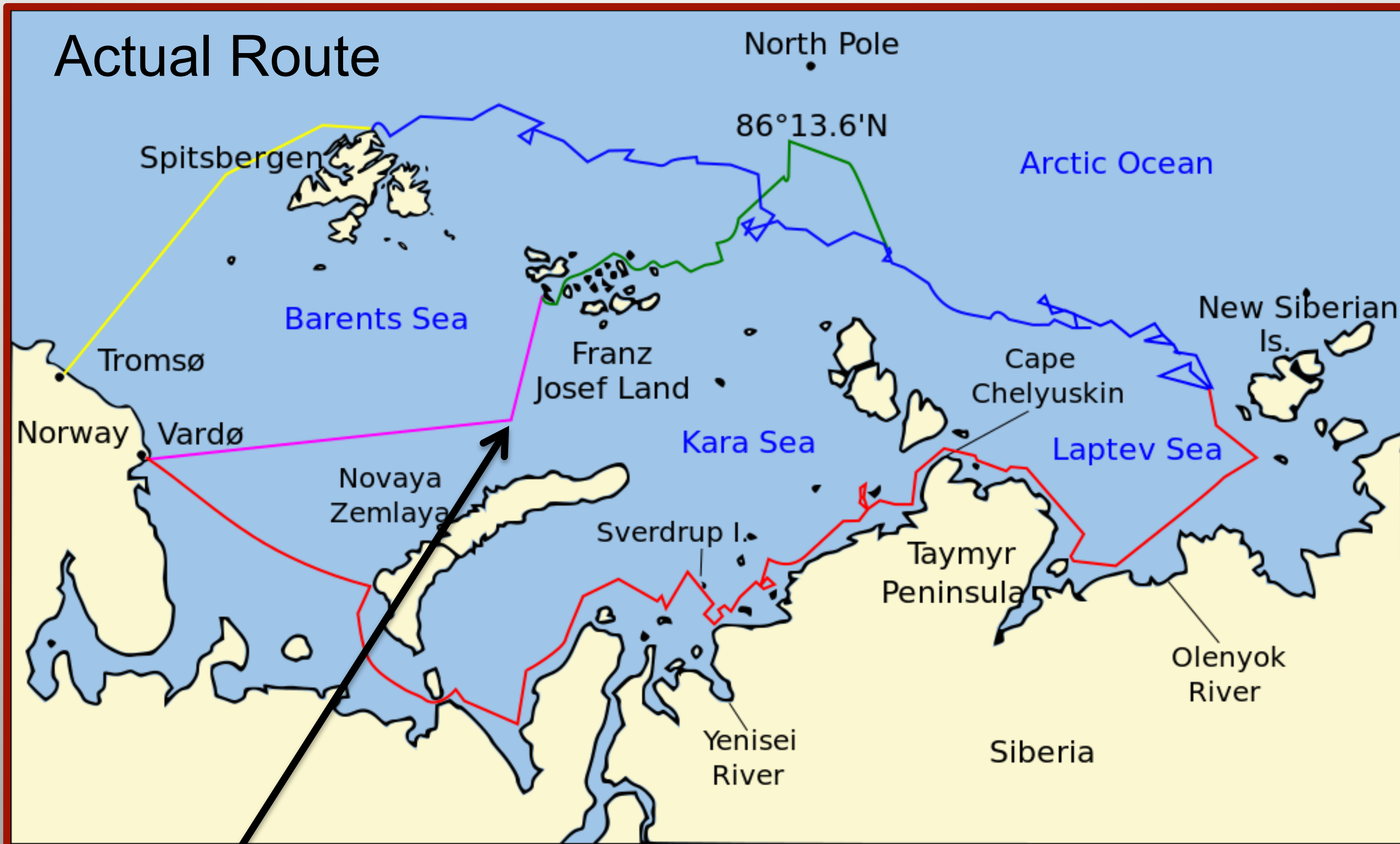
Nansen’s Amazing Polar Expedition



Nansen and Johansen leave the *Fram* for the North Pole with 3 sleds, 2 kayaks, and 28 dogs

Photograph by Fridtjof Nansen, National Library of Norway Picture Collection

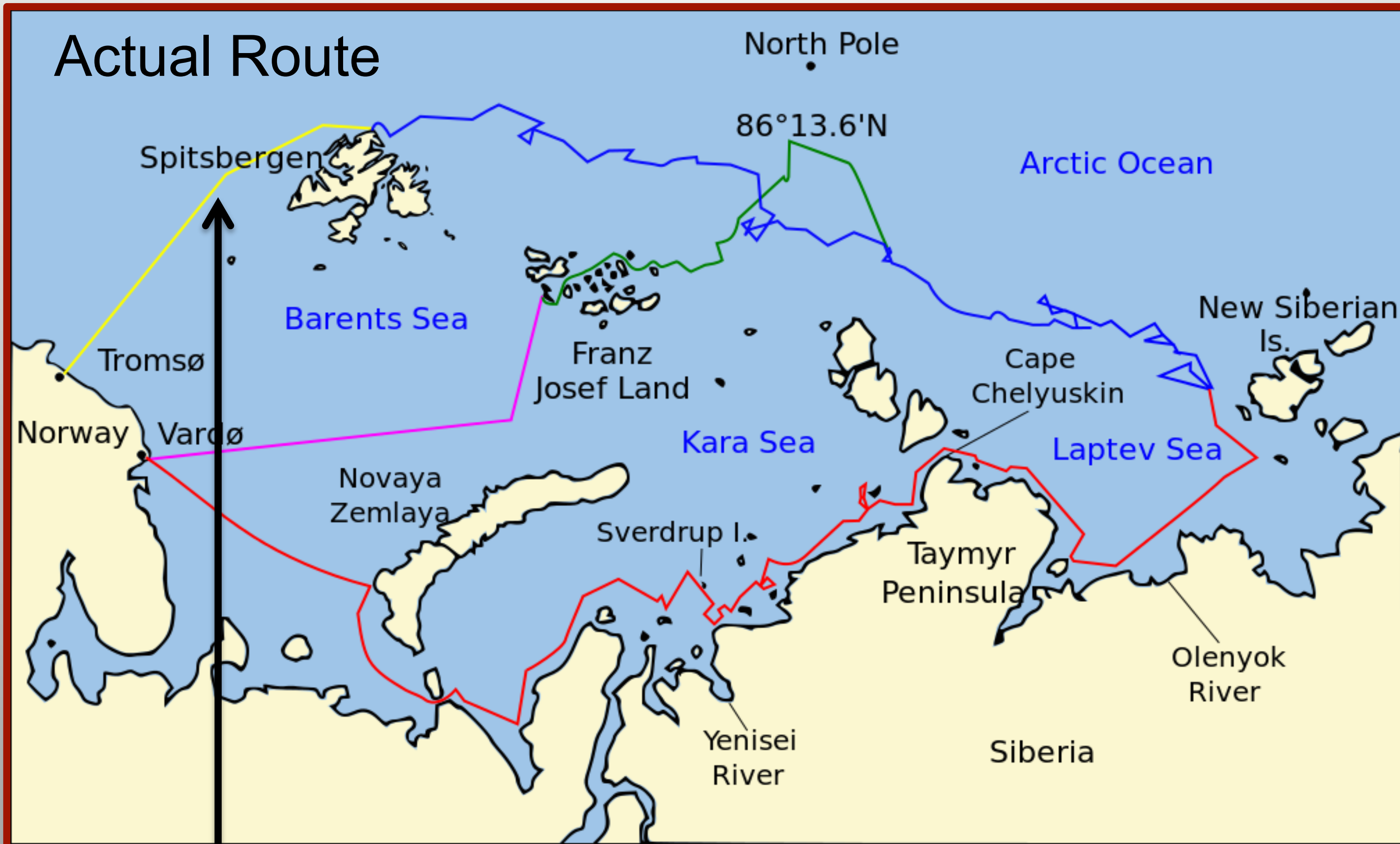
Nansen's Amazing Polar Expedition



Jun. – Aug. 1896

Nansen and Johansen stumble upon a British explorer and sail back to Norway with him

Nansen's Amazing Polar Expedition



Aug. 1896

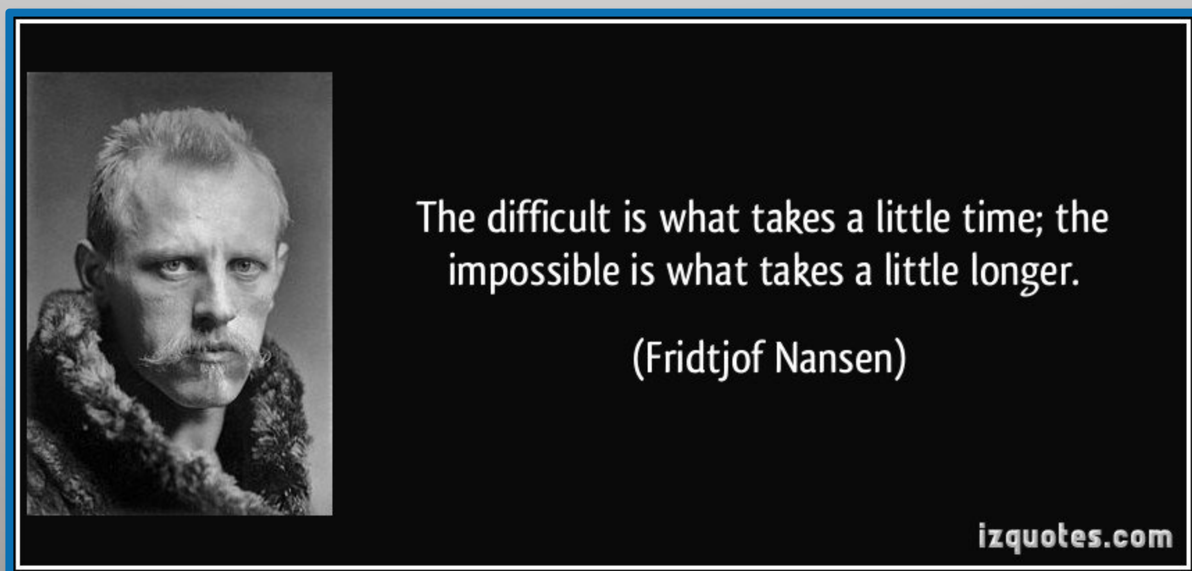
On the same day Nansen & Johansen reached Norway, the *Fram* breaks free from the ice and sails back to Norway

The Impressive Life of Fridtjof Nansen (1861 – 1930)

- Norwegian scientist
  - Zoologist by training
  - Helped establish modern theories of neurology
  - Developed a deep interest in ice and oceanography

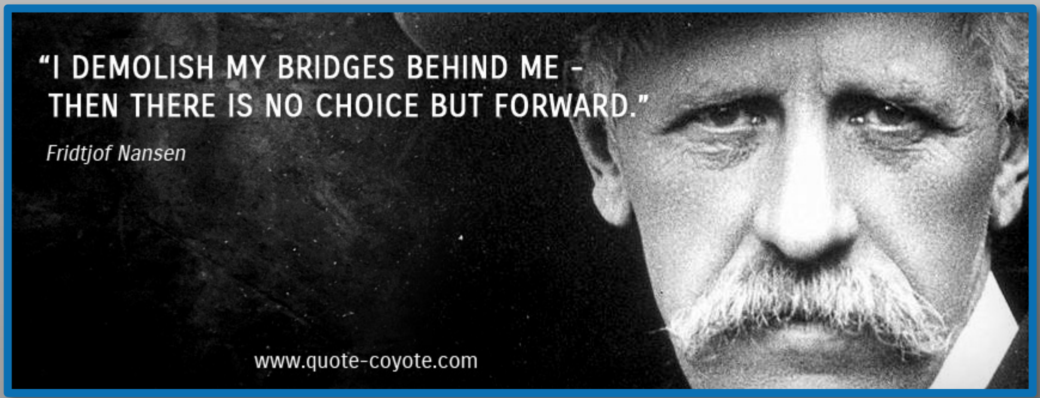
The Impressive Life of Fridtjof Nansen (1861 – 1930)

- ★ Norwegian scientist
- ★ Polar adventurer and explorer
  - Led first team to cross the interior of Greenland (1888)
  - Organized the first *Fram* expedition to the Arctic (1893 – 1896)



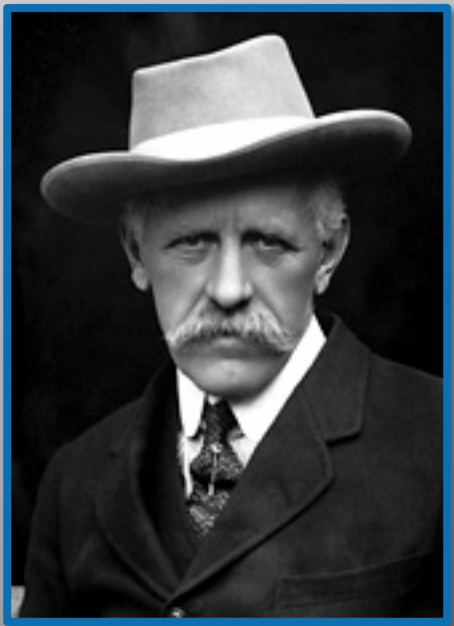
The Impressive Life of Fridtjof Nansen (1861 – 1930)

- ★ Norwegian scientist
- ★ Polar adventurer and explorer
- ★ Statesman, diplomat, and humanitarian
  - A delegate to the League of Nations from Norway
  - Appointed the League's High Commissioner for Refugees in 1921
  - Developed the "Nansen Passport" to provide stateless refugees with an ID document so they could enter other countries

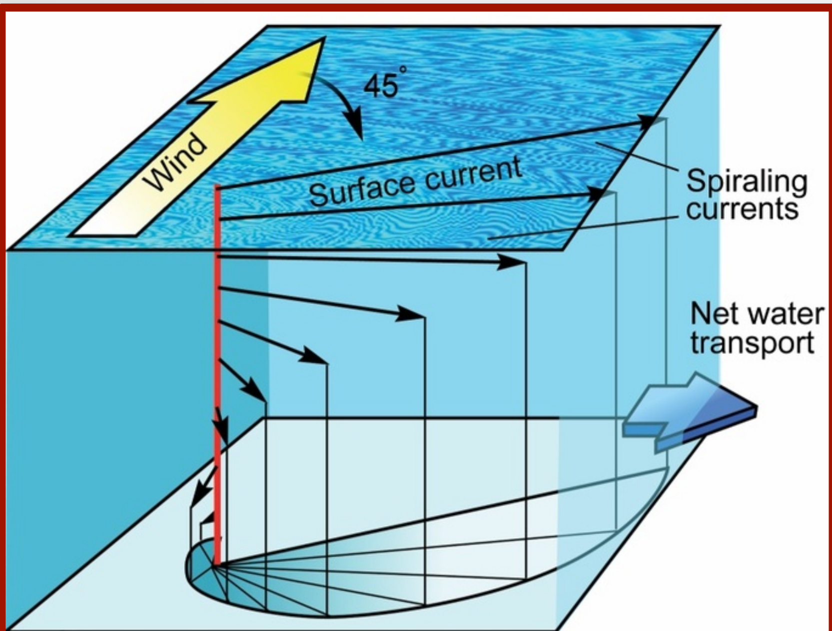


The Impressive Life of Fridtjof Nansen (1861 – 1930)

- Norwegian scientist
- Polar adventurer and explorer
- Statesman, diplomat, and humanitarian
- Awarded the Nobel Peace Prize in 1922
  - For his great humanitarian efforts to assist the many victims and refugees of World War I and related conflicts

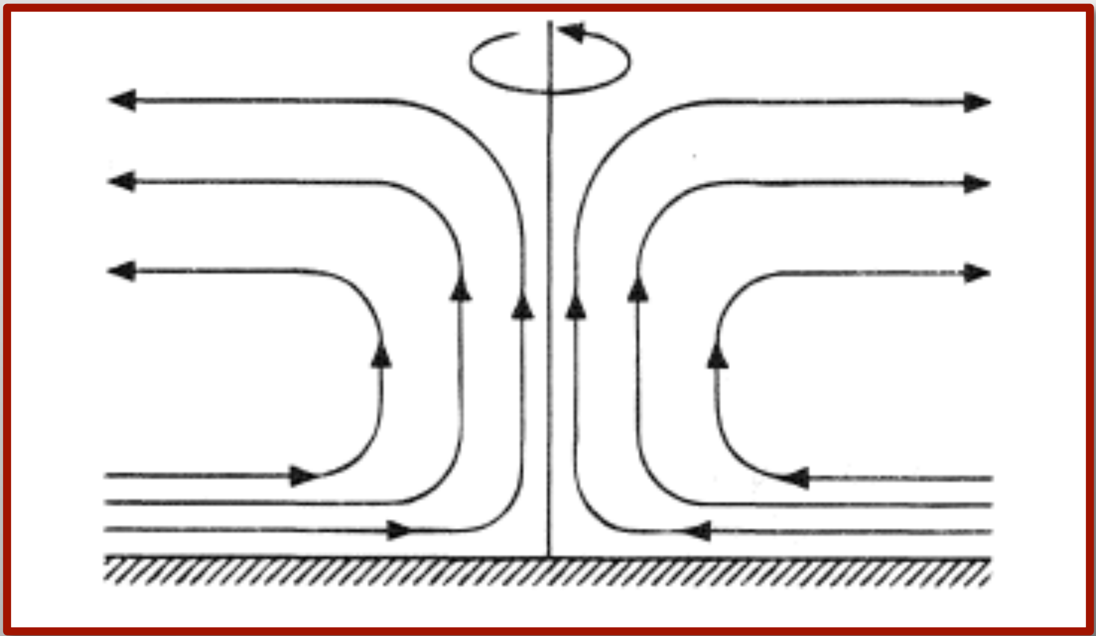


Ekman Layer and Ekman Spiral



- ★ Nansen found that the ice and the ship drifted 20° to 40° to the right of the surface wind
- ★ The Ekman layer = surface layer of ocean affected by the movement of wind-driven surface waters
- ★ Frictional effect: surface wind drags along surface water layer, and each water layer below that is dragged along by the water layer above it (but more slowly) until this effect diminishes to nothing
- ★ Coriolis effect: surface water layer is deflected to the right of the surface wind, and each water layer below that is deflected to the right of the water layer above it (deflection is to the left in the S.H.)

Ekman Pumping and Suction



Ekman pumping under cyclonic flow

- ★ Atmospheric vorticies over the ocean drive a vertical circulation called Ekman Pumping (for cyclones) and Ekman Suction (for anticyclones)

- ★ These Ekman layer processes also apply to other frictional boundary layers, such as the atmospheric boundary layer

Ekman Pumping and Shock-Like Structures in the Tropical Boundary Layer

★ Ekman pumping can create shock-like structures in the tropical atmospheric boundary layer under certain tropical events, such as

- Tropical cyclones
- The ITCZ

★ Our research group has utilized slab boundary layer models (SBLMs) to investigate such structures

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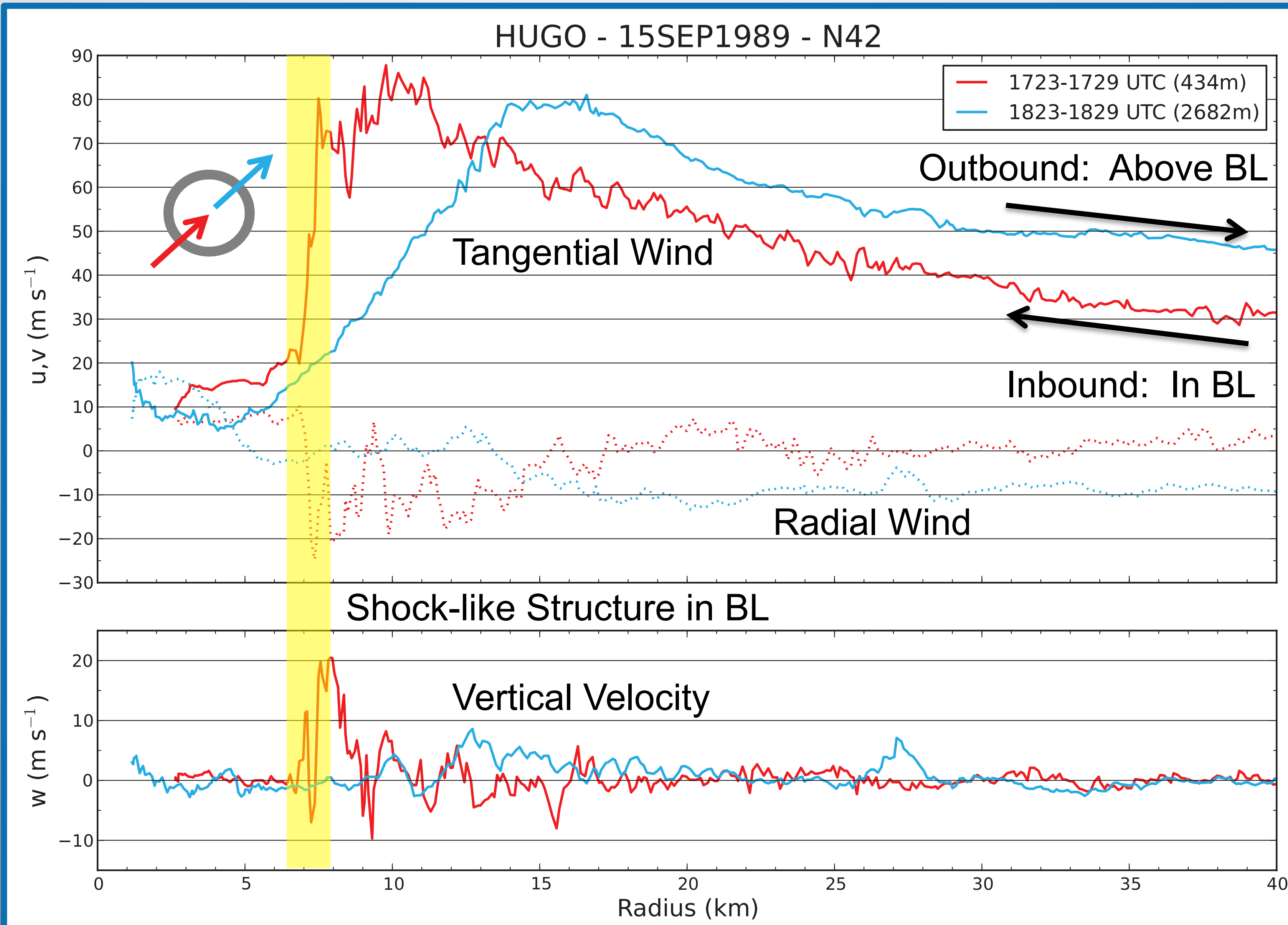
Flight Data for Hurricane Hugo



(see Marks et al. 2008 for more details)

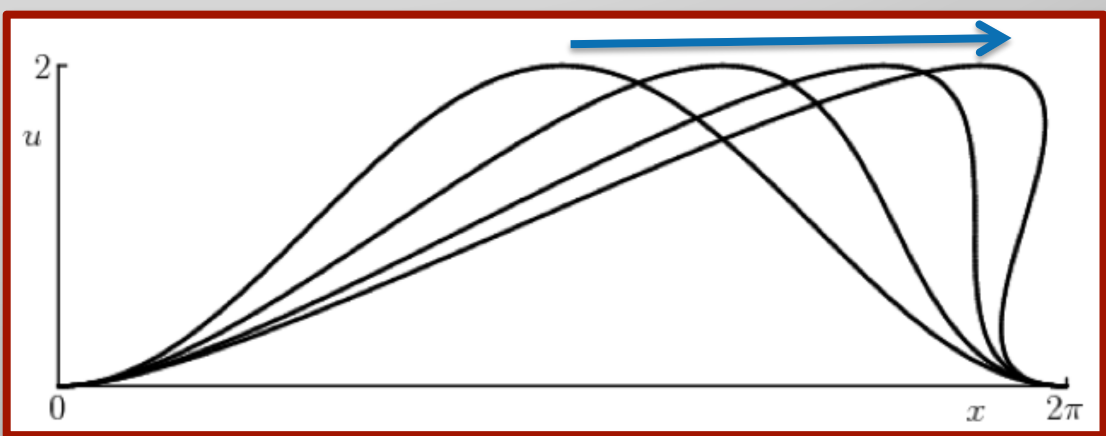
Inviscid Burgers' Equation

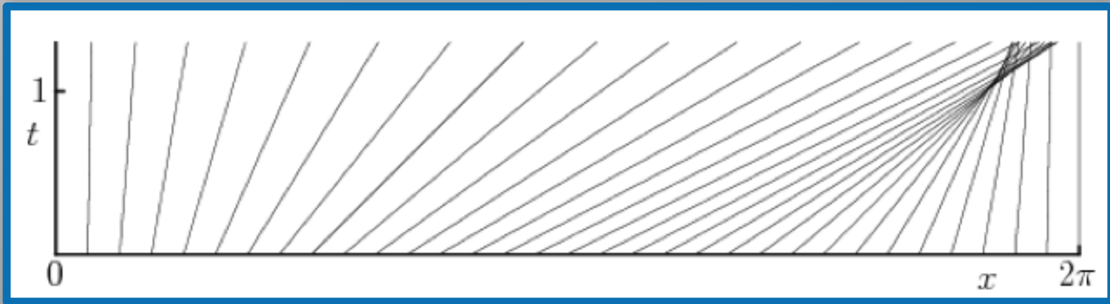
★ Model for nonlinear wave propagation: $$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = 0$$

★ Example initial condition: $$u(x,0) = 1 - \cos(x)$$

★ Results:

- Solution steepens and then becomes multi-valued
- Characteristics intersect and cross
- Not physically meaningful





(from http://www.eng.fsu.edu/~dommelen/pdes/style_a/burgers.html)

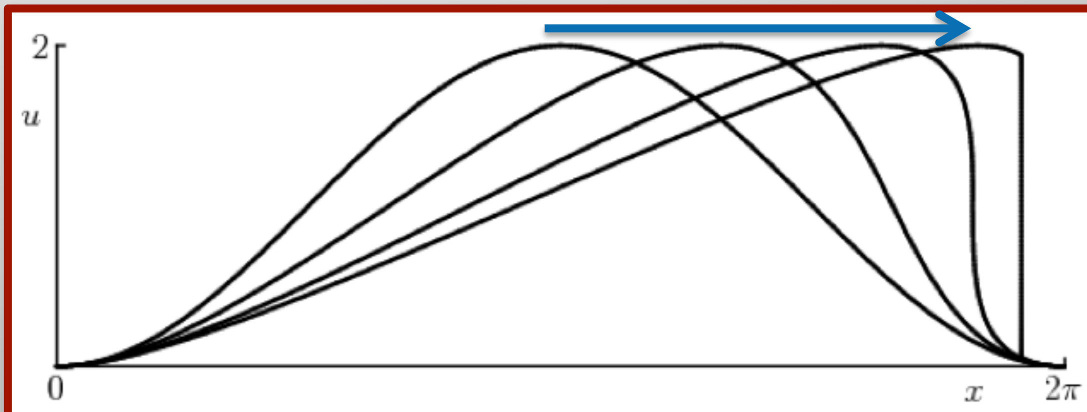
Viscous Burgers' Equation

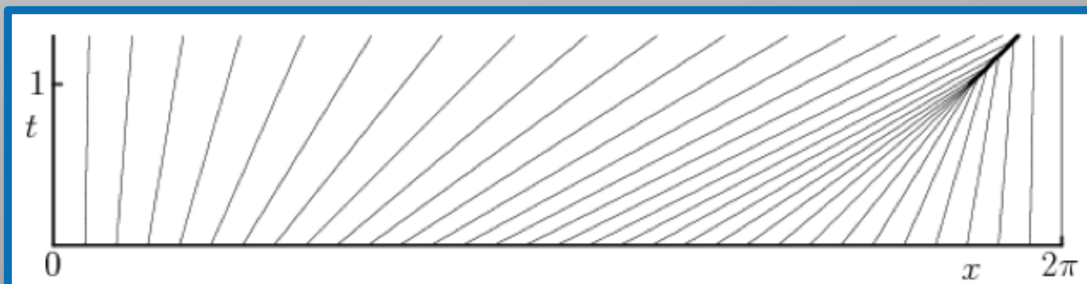
★ Now include a viscosity term:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \varepsilon\frac{\partial^2 u}{\partial x^2}$$

★ Get more physically meaningful results:

- Solution steepens, but does not go multi-valued
- In the limit $\varepsilon \to 0$ solution develops a jump-discontinuity or "shock"
- Characteristics run into this shock and disappear





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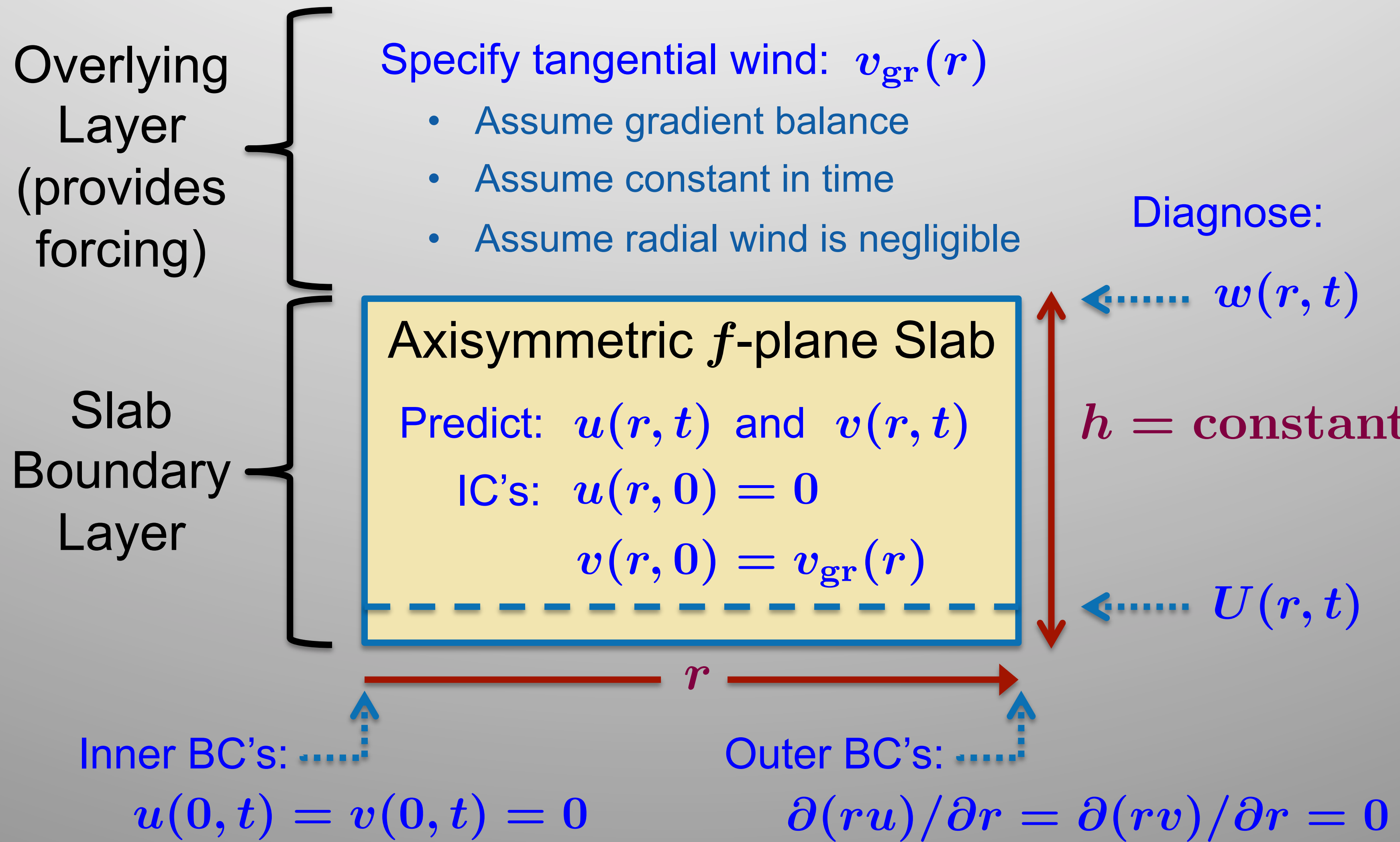
Slab Boundary Layer Model for Tropical Cyclones (SBLM-TC)



SBLM-TC Governing Equations

- ★ 2 predictive equations for the horizontal winds in the slab:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + w\,(1-\alpha)\,\frac{u}{h} = \left(f + \frac{v + v_{\text{gr}}}{r}\right)(v - v_{\text{gr}}) - c_{\text{D}} U \frac{u}{h} + K\frac{\partial}{\partial r}\left(\frac{\partial (ru)}{r\partial r}\right)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} - w\,(1-\alpha)\left(\frac{v - v_{\text{gr}}}{h}\right) = -\left(f + \frac{v}{r}\right)u - c_{\text{D}} U \frac{v}{h} + K\frac{\partial}{\partial r}\left(\frac{\partial (rv)}{r\partial r}\right)$$

- ★ Note the embedded Burgers' equation
- ★ Pressure gradient force: $\frac{1}{\rho}\frac{\partial p}{\partial r} = (f + v_{\text{gr}}/r)\,v_{\text{gr}}$
- ★ Diagnostic equations for vertical velocity at top of slab:

$$w = -h\frac{\partial (ru)}{r\partial r}$$

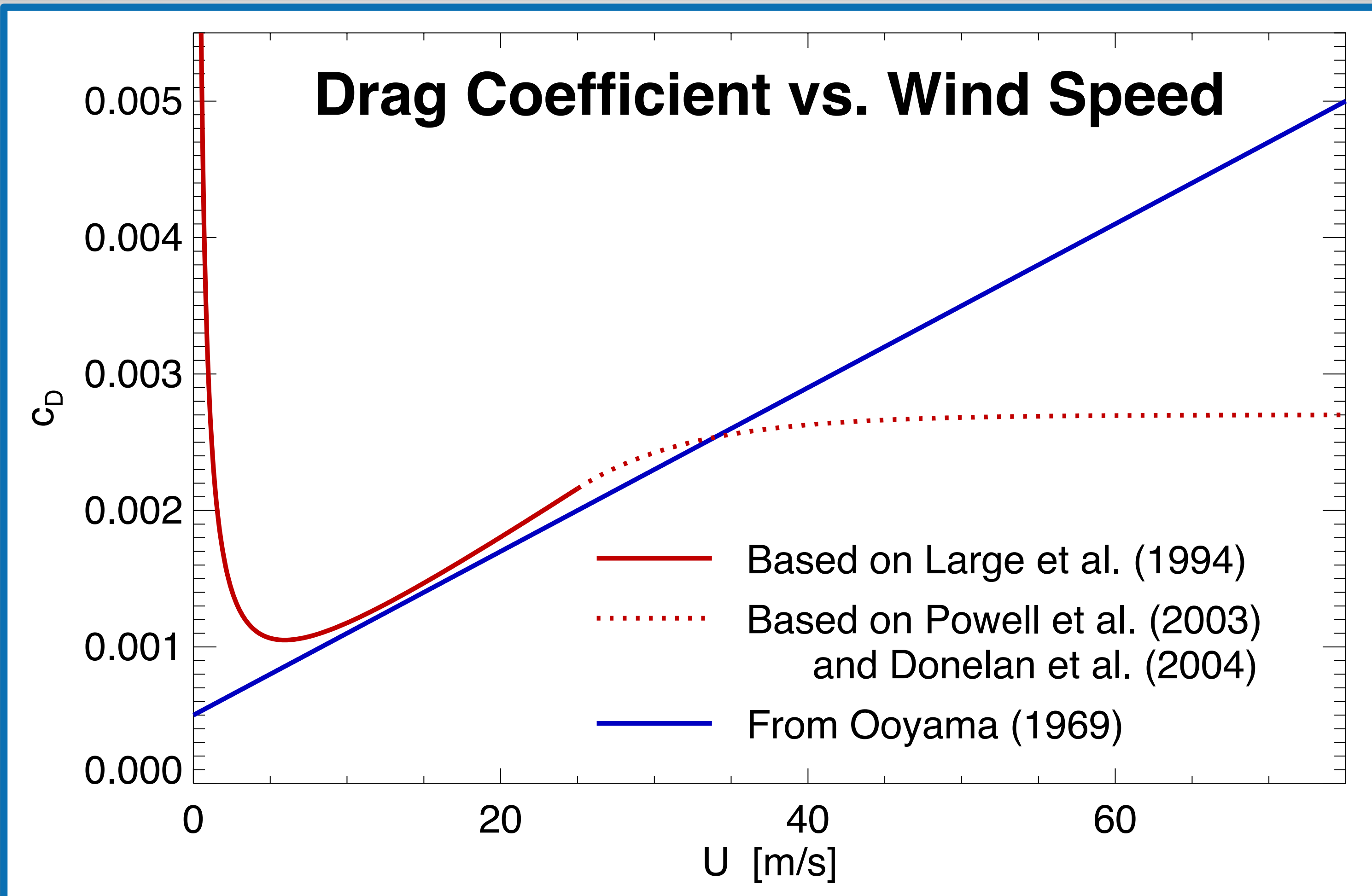
and

$$\alpha = \begin{cases} 1 & \text{if } w \geq 0 \\ 0 & \text{if } w < 0 \end{cases}$$

- ★ Diagnostic equation for wind speed at 10 m height in slab: $U = 0.78\,(u^2 + v^2)^{1/2}$

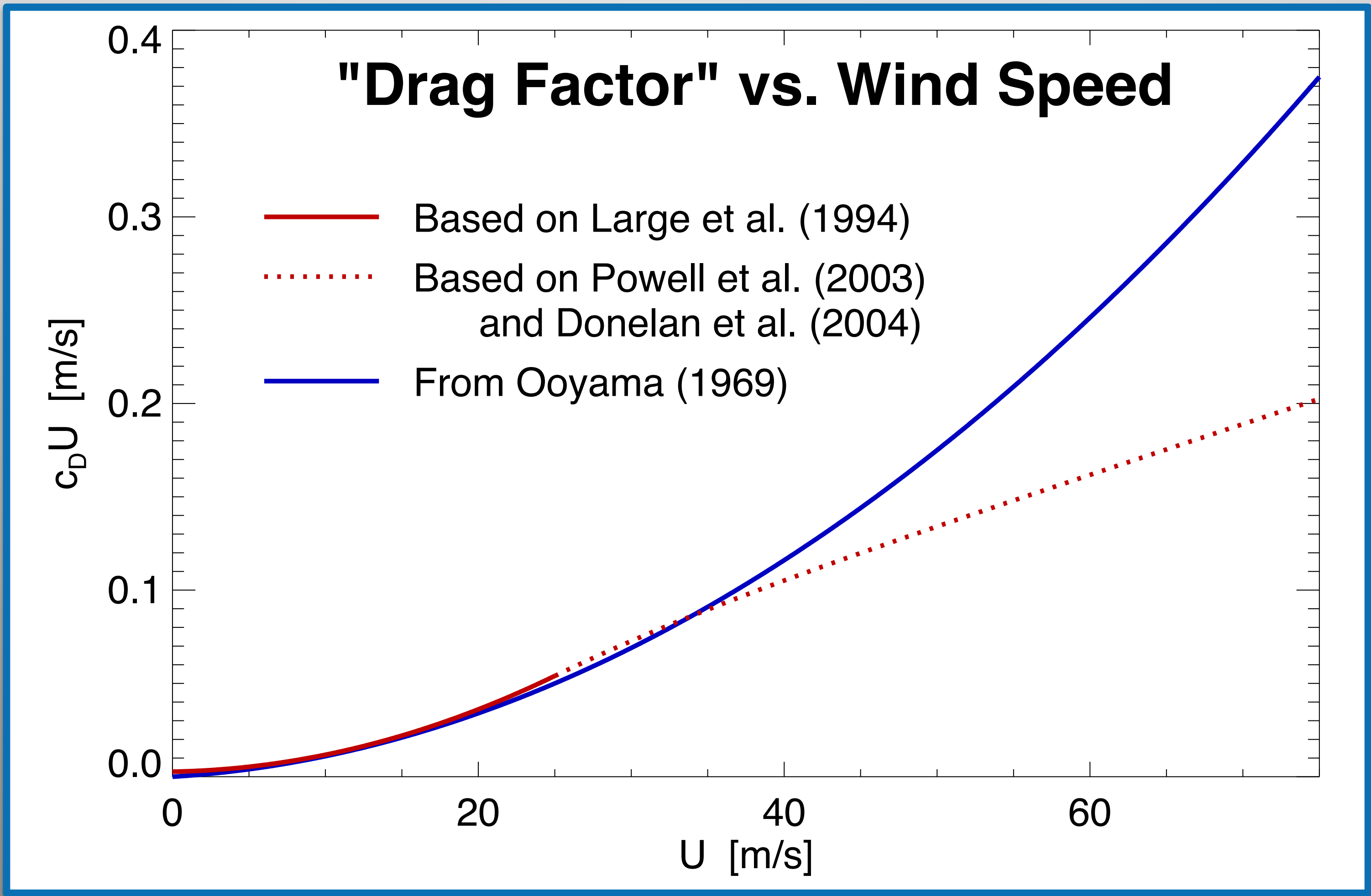
Drag Coefficient

$$c_D(U) = 10^{-3}\begin{cases} 2.70\,U^{-1} + 0.142 + 0.0764\,U & \text{if } U \le 25 \\ 2.16 + 0.5406\,\{1 - \exp[-(U - 25)/7.5]\} & \text{if } U \ge 25 \end{cases}$$

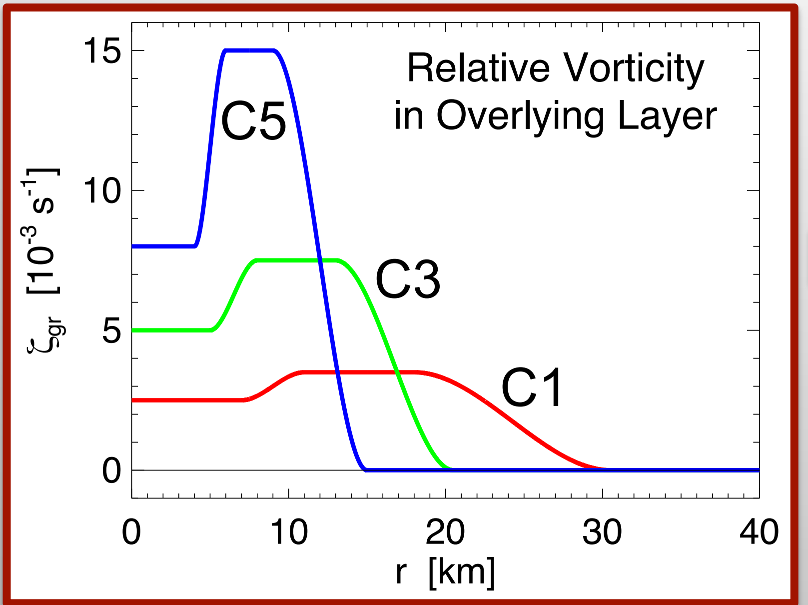


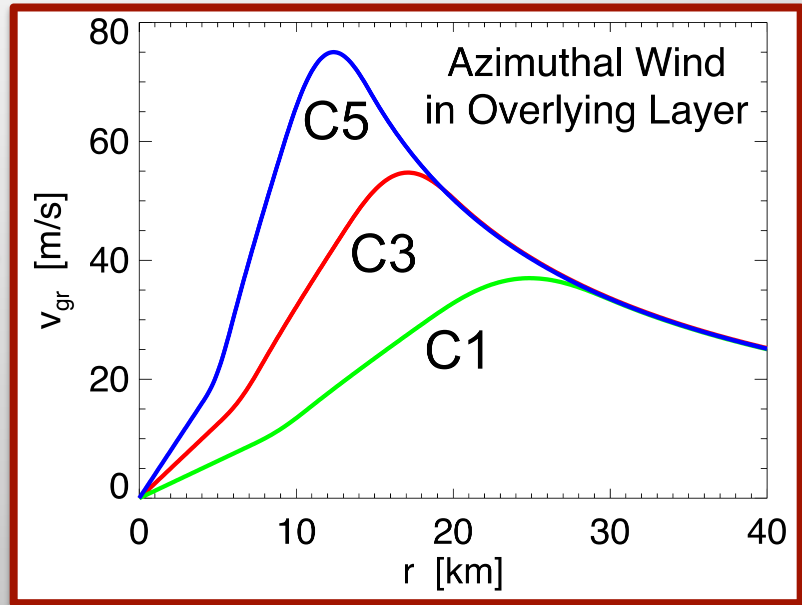
"Drag Factor"

$$c_D(U)U = 10^{-3}\begin{cases} 2.70 + 0.142\,U + 0.0764\,U^2 & \text{if } U \le 25 \\ (2.16 + 0.5406\,\{1 - \exp[-(U-25)/7.5]\})\,U & \text{if } U \ge 25 \end{cases}$$



SBLM-TC Experimental Details





★ Domain:

$$0 \leq r \leq 1000 \ \text{km}$$

★ Resolution:

$$\Delta r = 100 \ \text{m} \quad (10,001 \ \text{gridpts})$$

$$\Delta t = 1 \ \text{s}$$

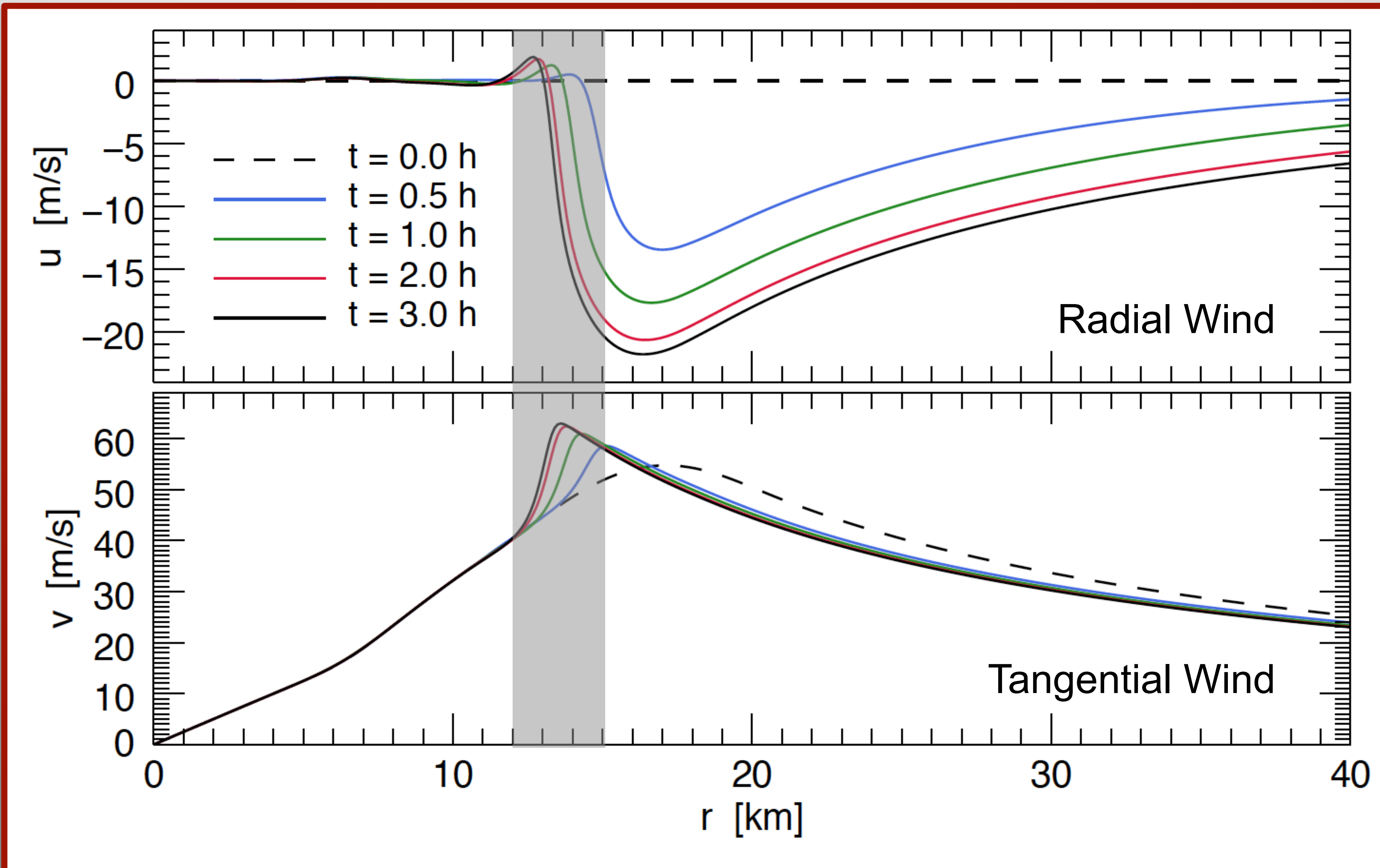
★ Parameters:

$$h = 1 \ \text{km}$$

$$f = 5.0 \times 10^{-5} \ \text{s}^{-1}$$

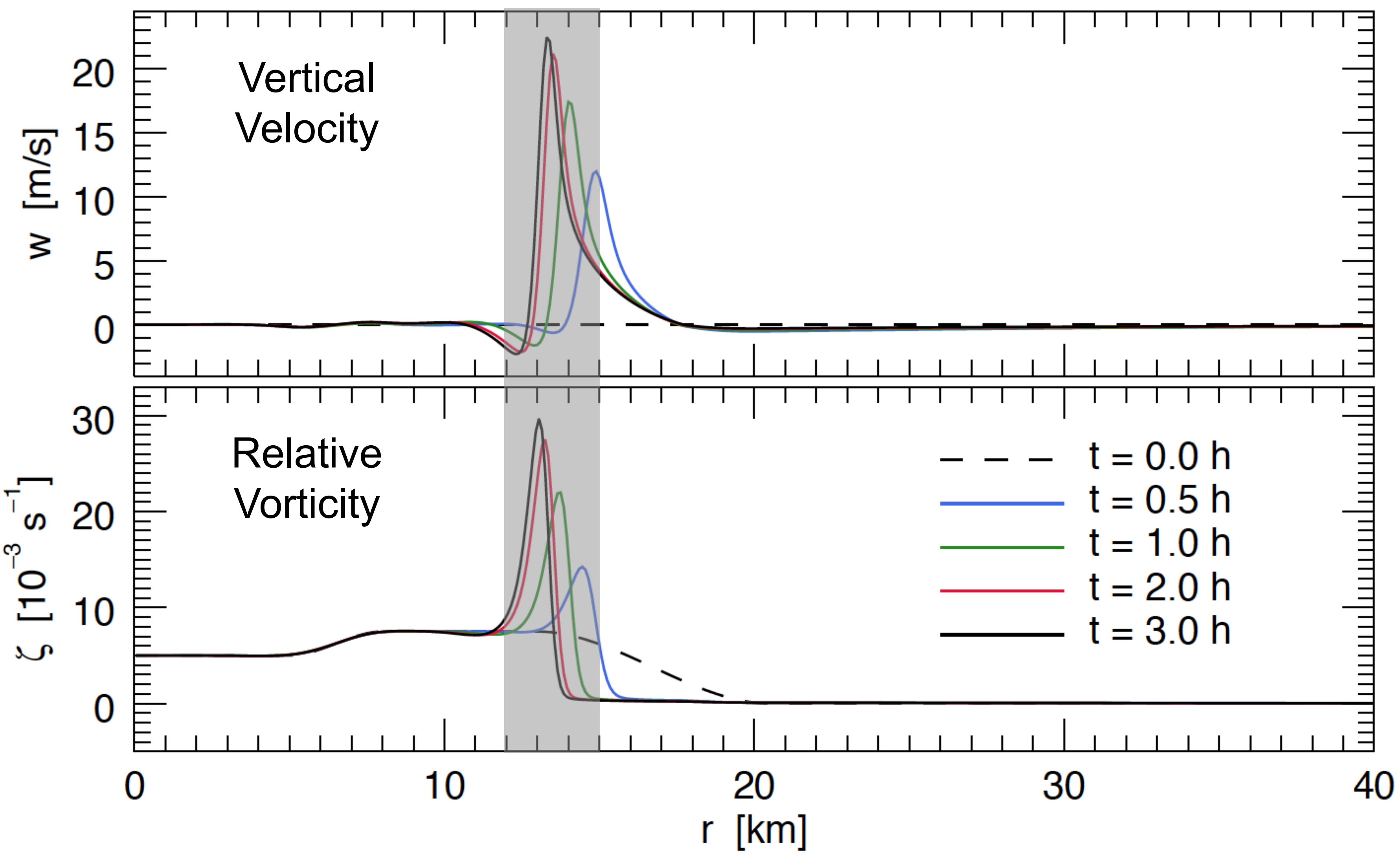
$$K = 1500 \ \text{m}^2\text{s}^{-1}$$

Results from C3 Experiment



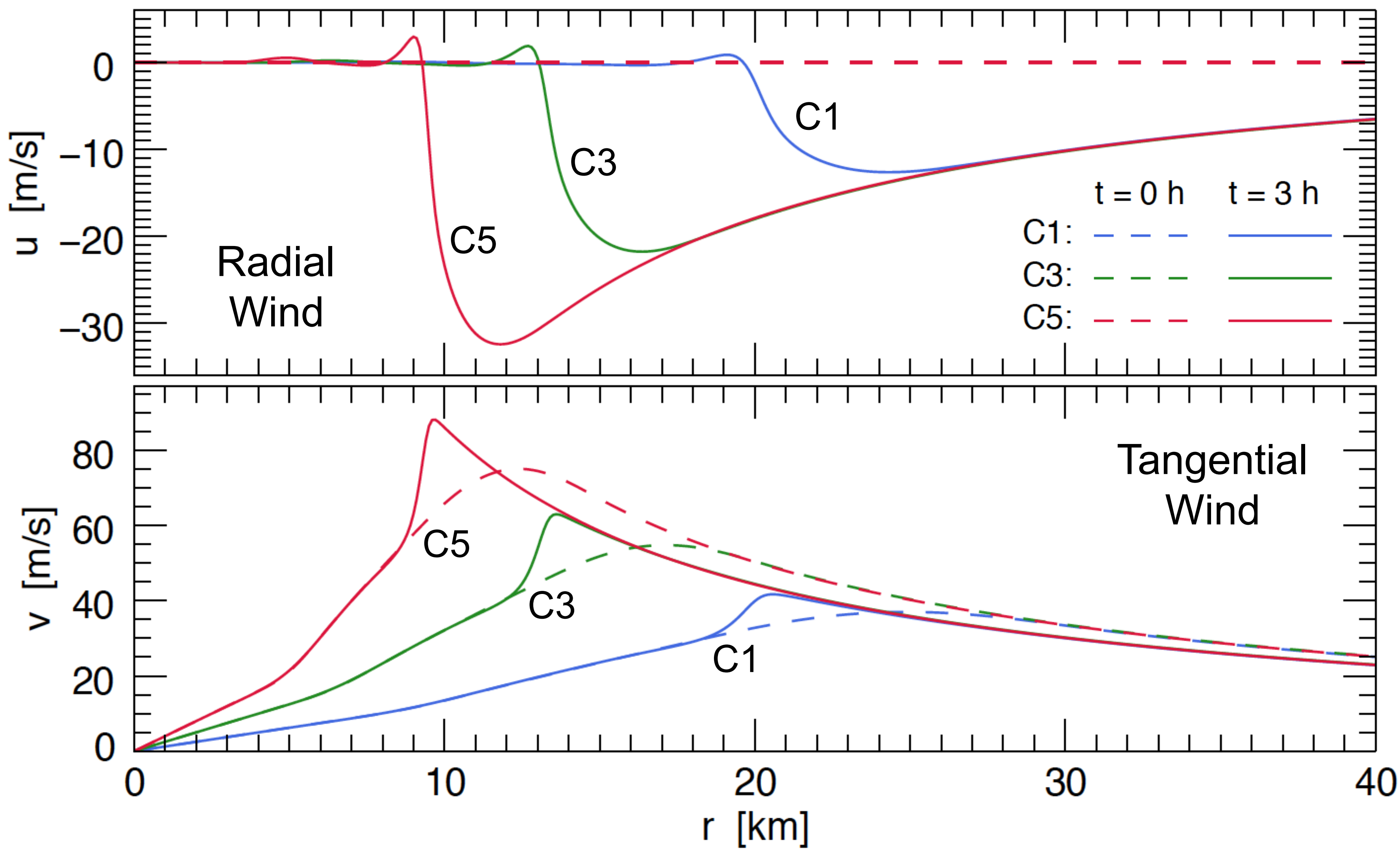
Shock-like steady state quickly develops

Results from C3 Experiment

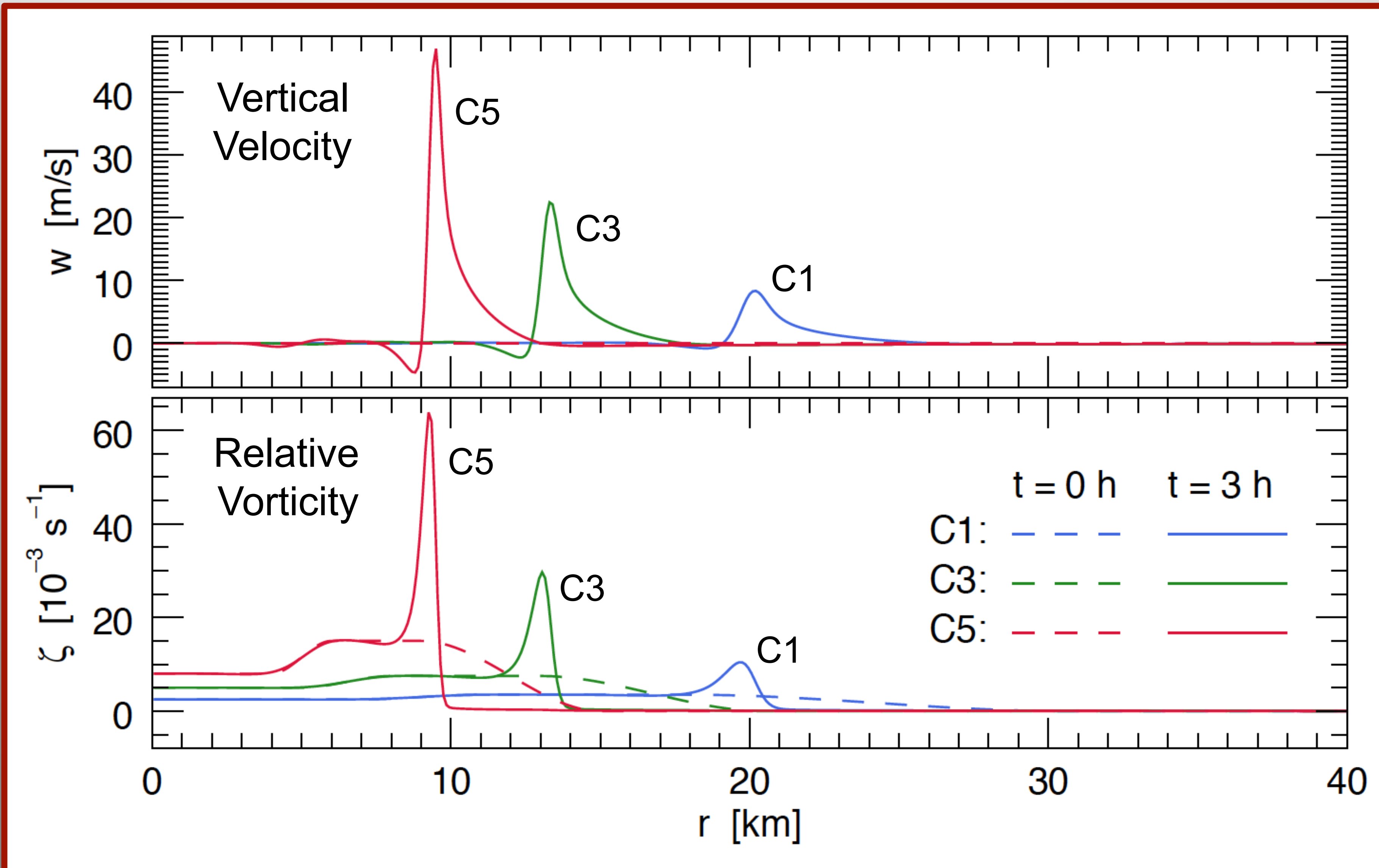


Shock-like steady state quickly develops

Summary of SBLM-TC Experiments



Summary of SBLM-TC Experiments

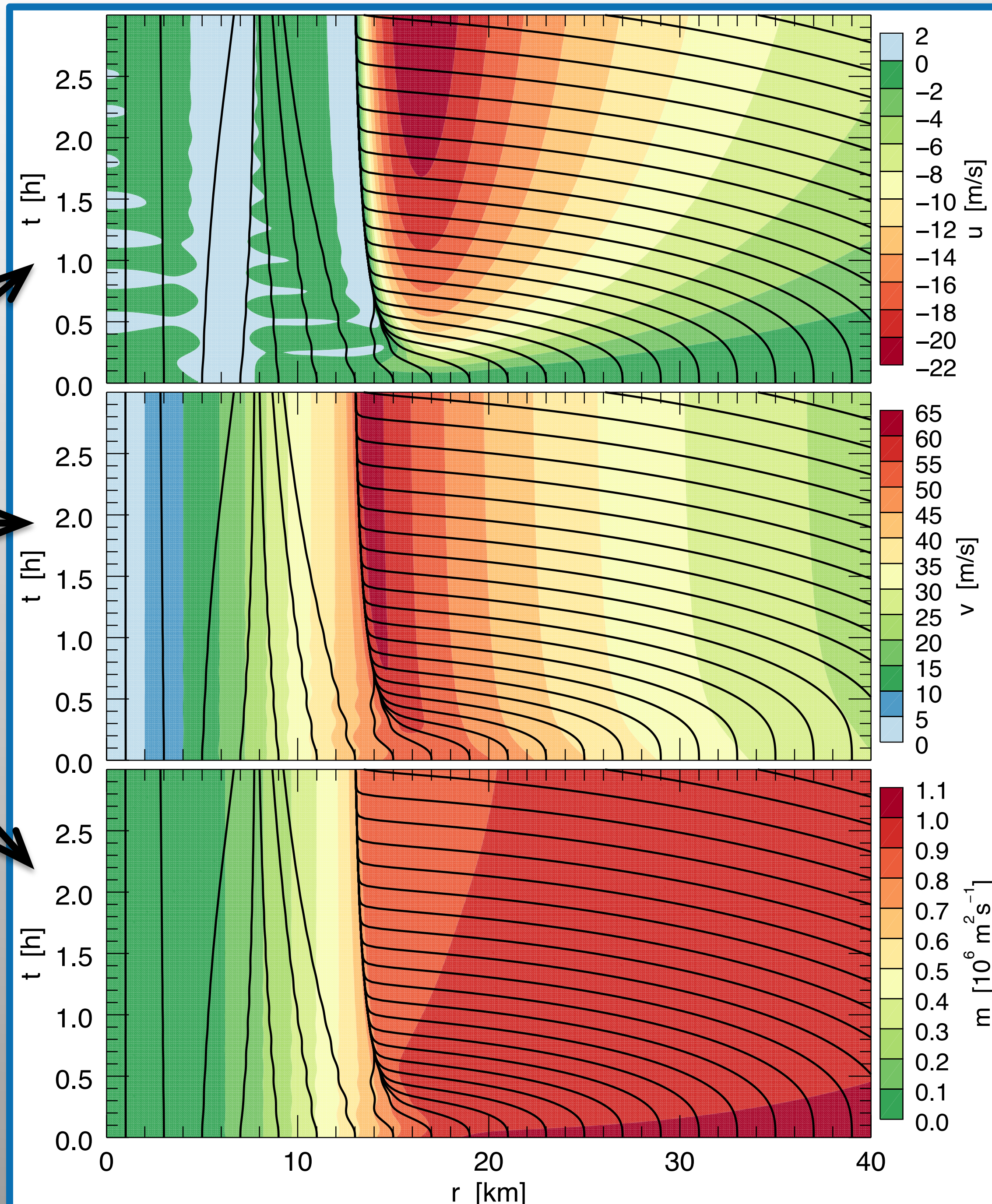


Trajectories for C3 Experiment

Radial Wind

Tangential Wind

Abs. Angular Momentum

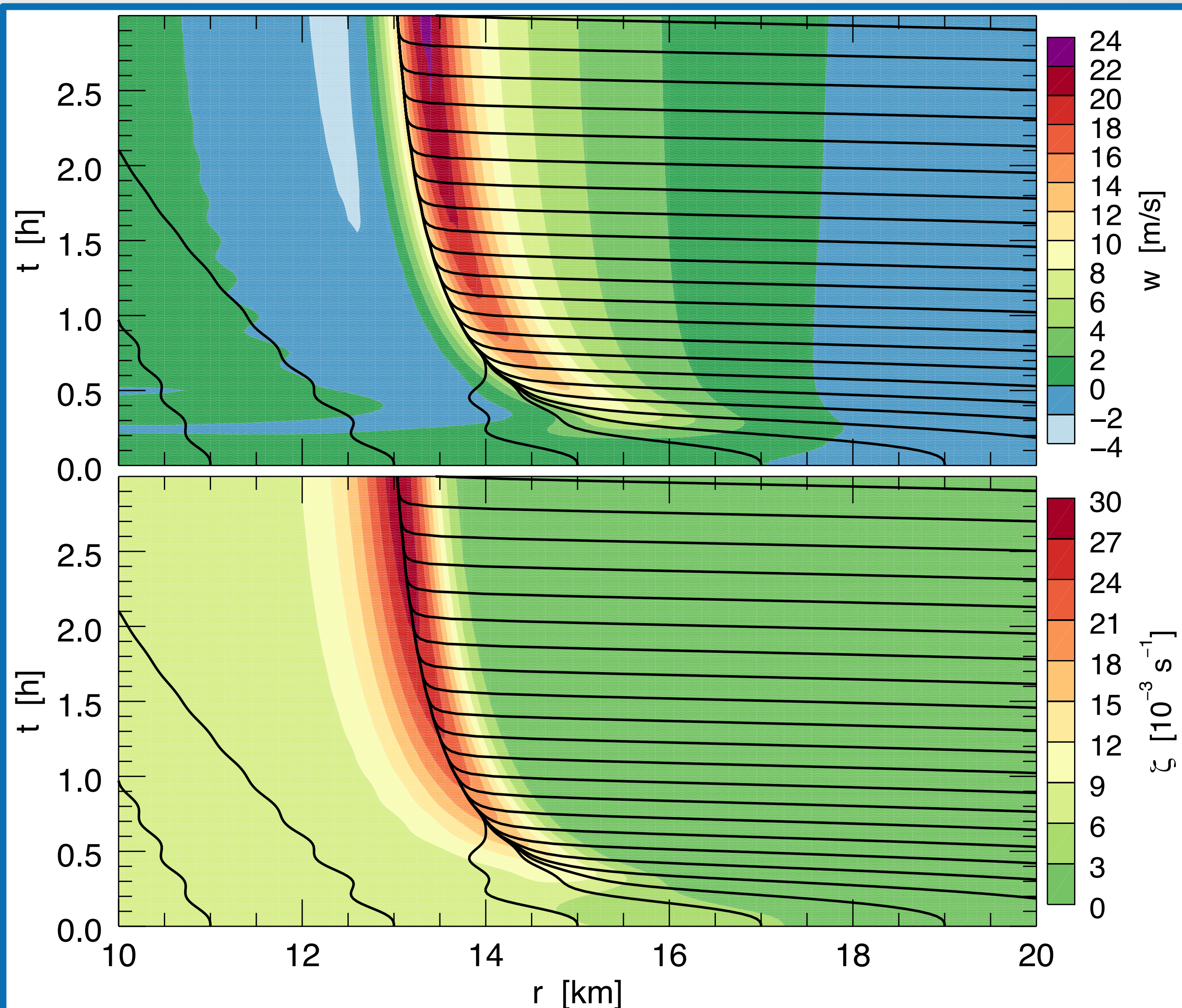


★ Note the clear shock-like feature

Trajectories for C3 Experiment

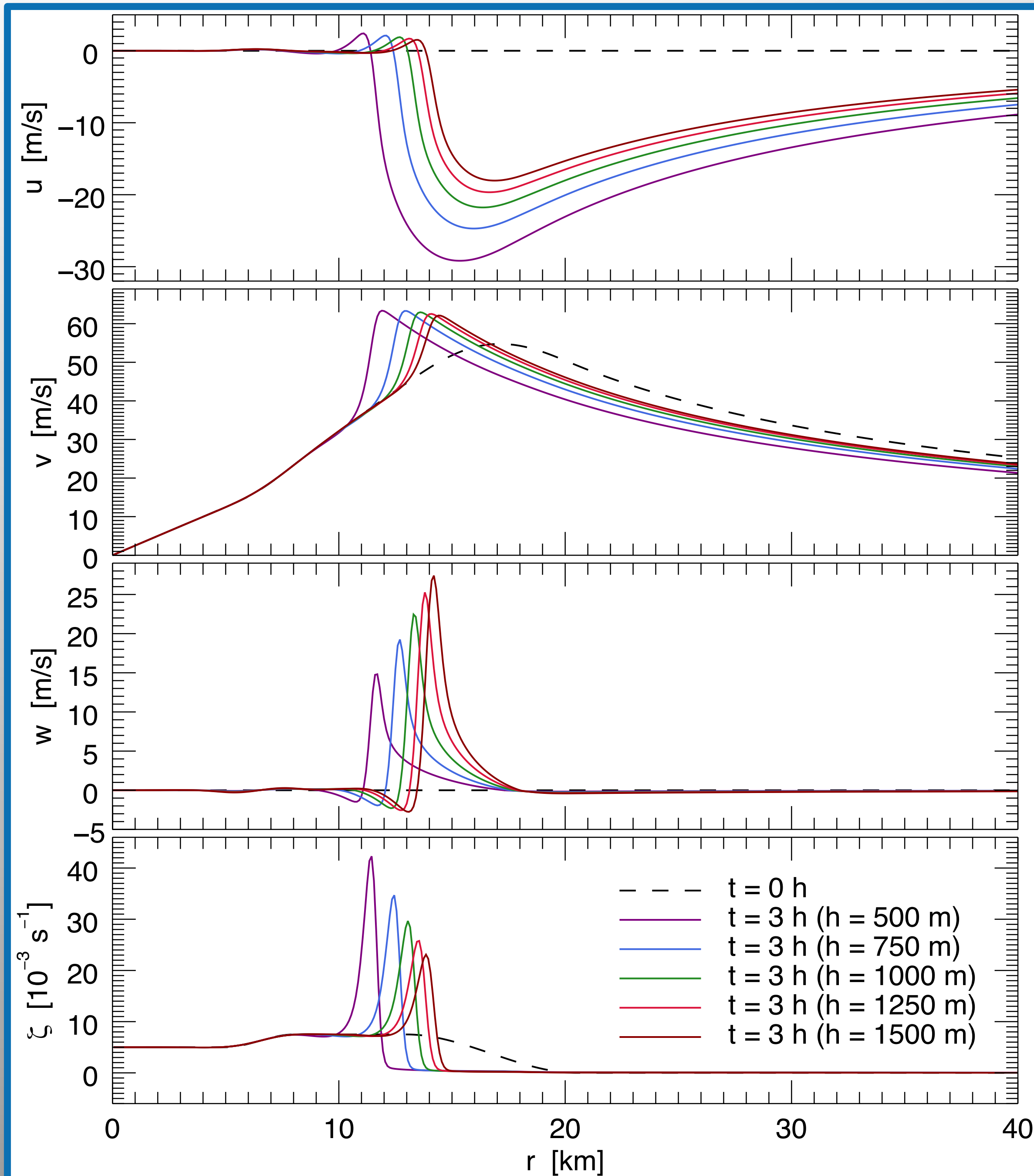
Vertical Velocity

Relative Vorticity



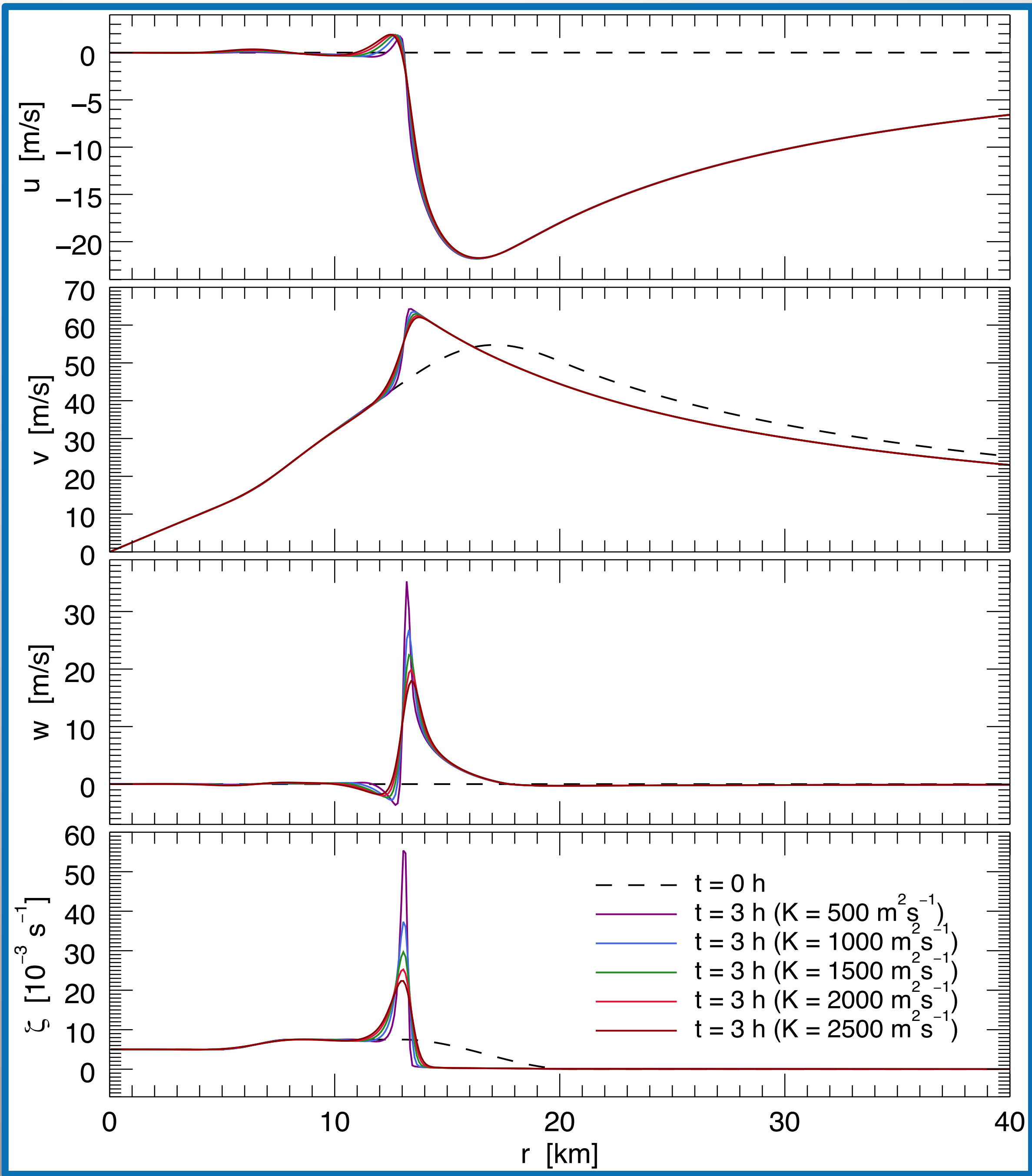
Results vs. Depth (h) for C3 Experiment

★ Depth of the slab affects strength and location of the shock-like structure



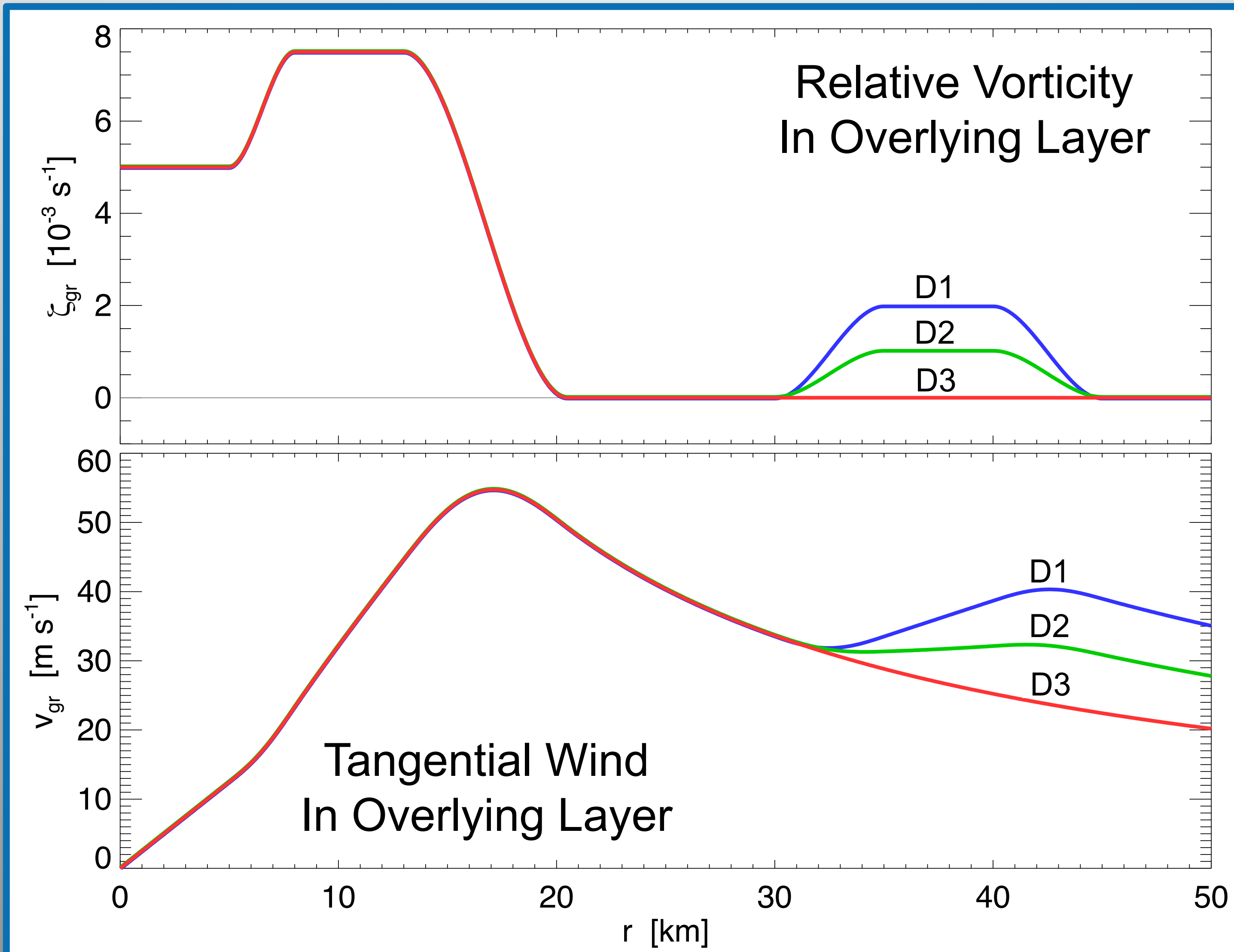
Results vs. Coefficient of Diffusion (K) for C3 Experiment

- ★ Shock-like structure grows in strength as the horizontal diffusion is reduced



What About a Double Eyewall?

★ Experiment 1: Adding a secondary vorticity maximum

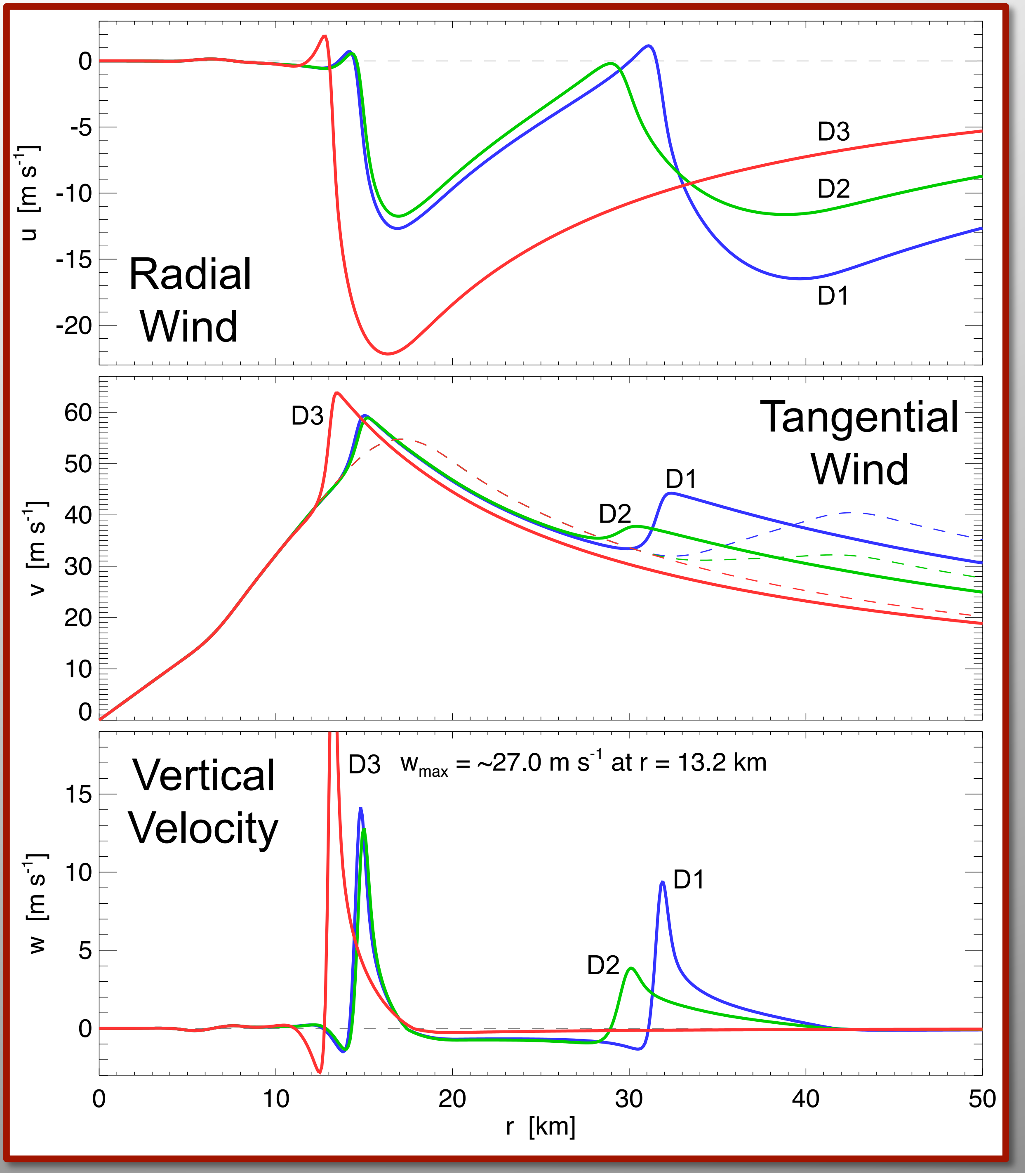


Note:

D3 = C3

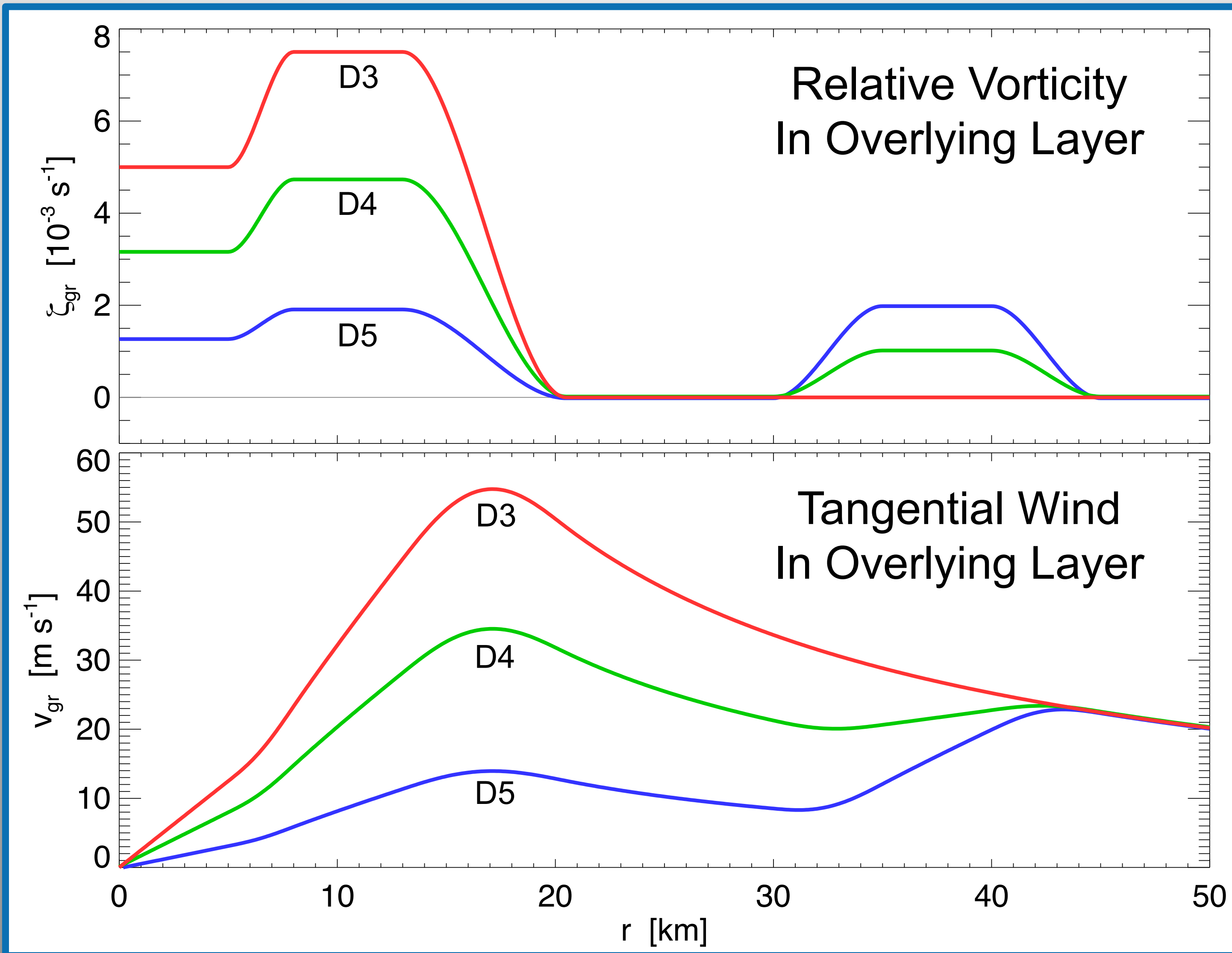
Double Eyewall Experiment 1 Results

- A second outer shock can form and significantly affect the original inner shock



What About a Double Eyewall?

★ Exp. 2: Like Exp. 1, but keep average vorticity the same

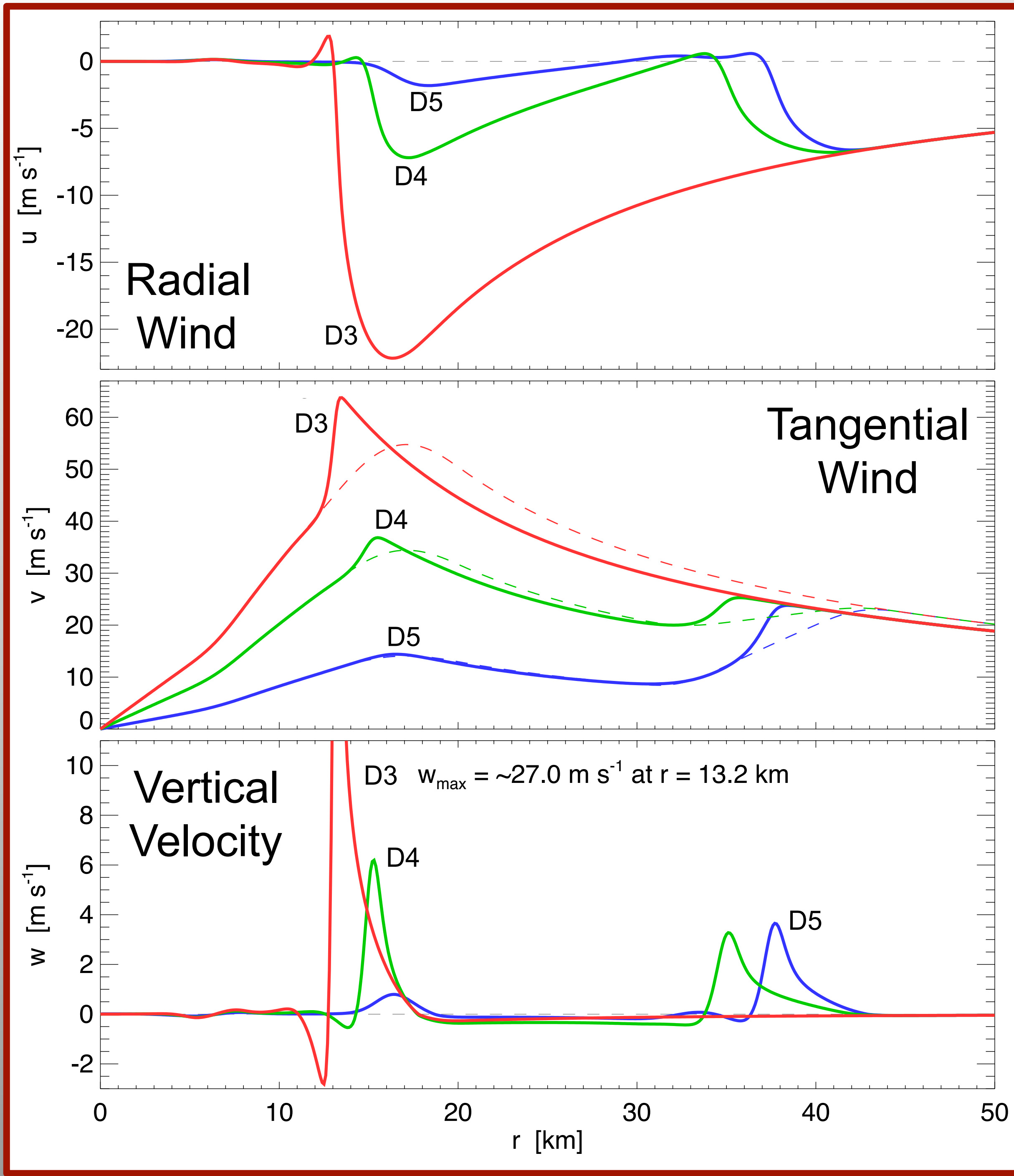


Note:

D3 = C3

Double Eyewall Experiment 2 Results

★ An outer shock can be similar to or even greater than the inner shock



Lessons Learned from SBLM-TC

- ★ The slab boundary layer equations (without diffusion) constitute a hyperbolic system, allowing for the possibility of shock formation.
- ★ Horizontal diffusion is needed to prevent a true shock from forming. Otherwise, standard numerical procedures break down and fail.
- ★ With horizontal diffusion, shock-like structures form in the boundary layer of tropical cyclones, but high spatial resolution is needed to capture these structures well.
- ★ These shock-like structures can help explain how and where single and double eyewalls form and why the maximum tangential winds can occur in the boundary layer.

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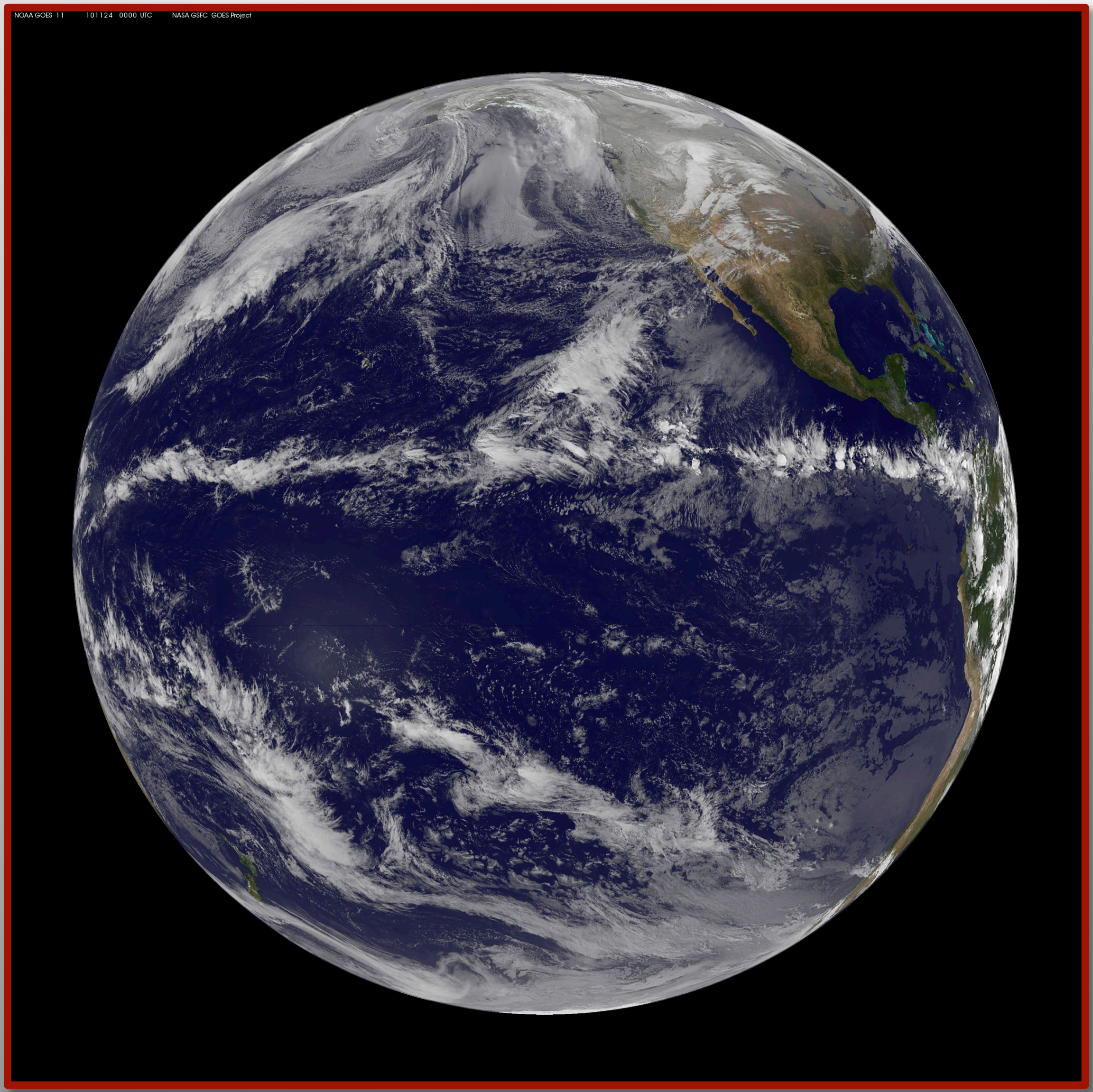
What About the ITCZ?



(from NASA GSFC GOES Project website)

- ★ NOAA GOES VIS/IR Blended Image:

  Nov. 24, 2010
  00:00 UTC

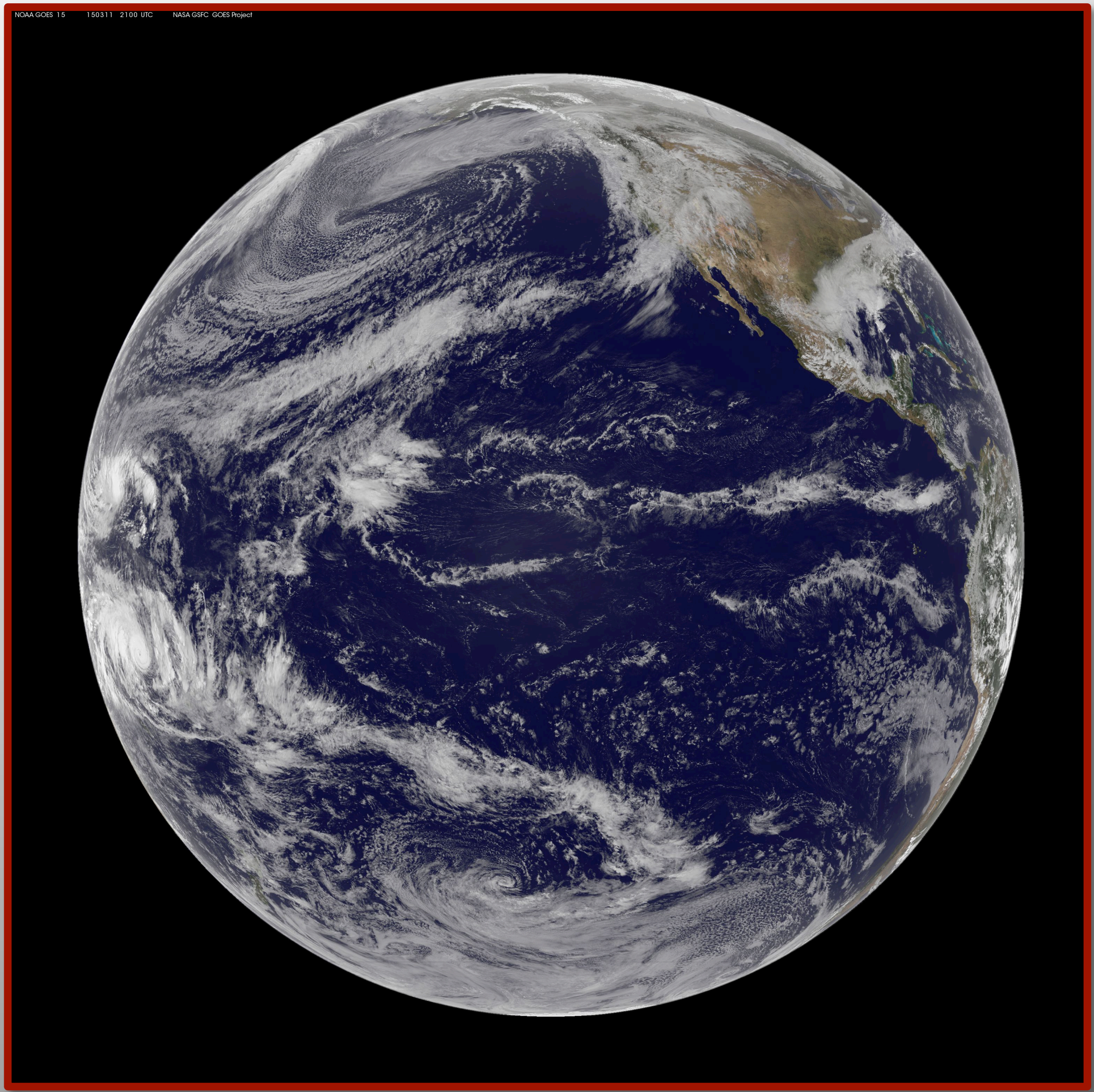
- ★ Do boundary layer shocks play a role in the narrowness of the ITCZ?

What About the ITCZ?

- NOAA GOES VIS/IR Blended Image:

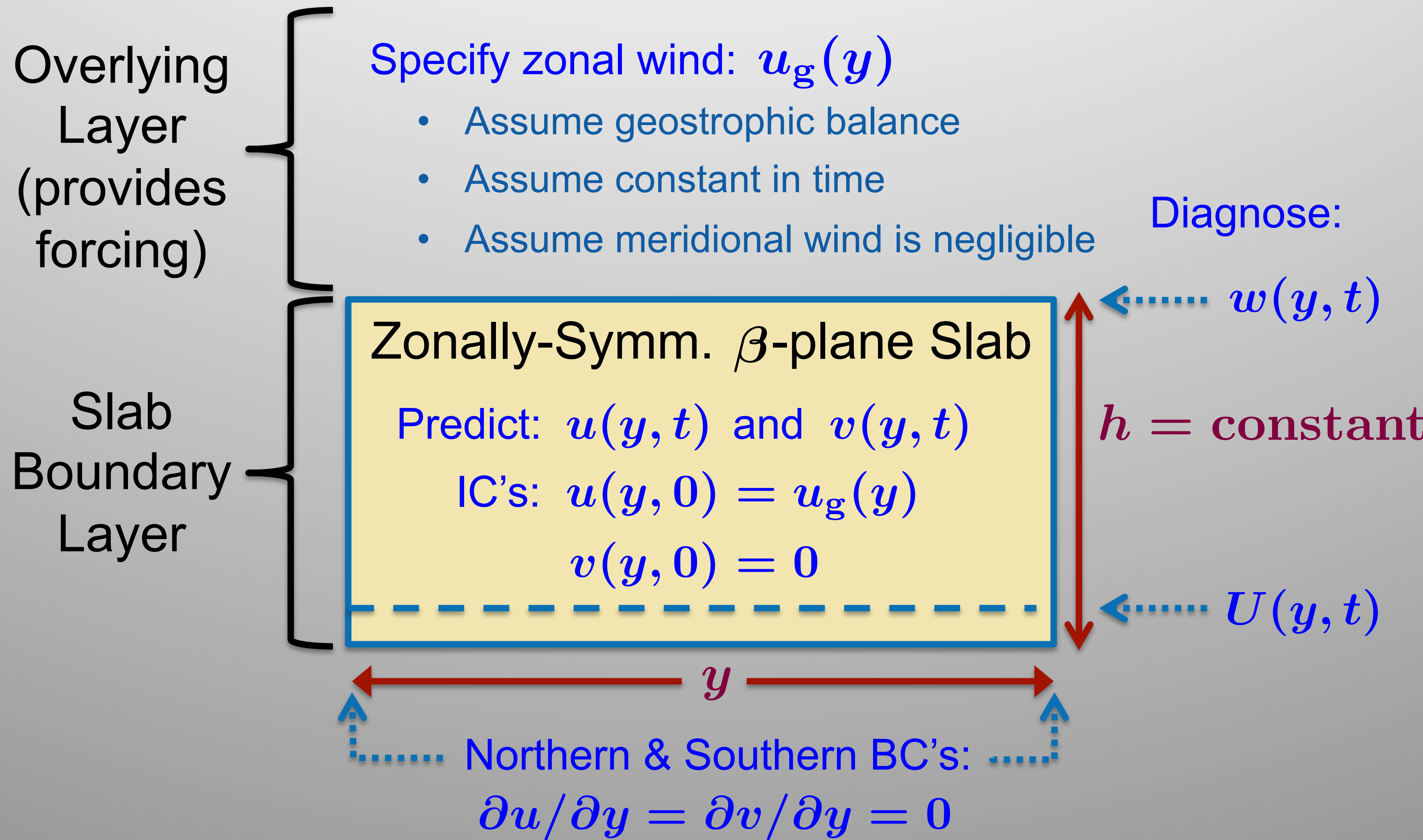
  Mar. 11, 2015
  21:00 UTC

- Does the boundary layer play a role in the determining if the ITCZ is single or double?



(from NASA GSFC GOES Project website)

Slab Boundary Layer Model for the ITCZ (SBLM-ITCZ)



SBLM-ITZC Governing Equations

- 2 predictive equations for the horizontal winds in the slab:

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} - w\,(1-\alpha)\left(\frac{u-u_g}{h}\right) = \beta y v - c_D U\frac{u}{h} + K\frac{\partial^2 u}{\partial y^2}$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial y} - w\,(1-\alpha)\frac{v}{h} = -\beta y u - \frac{1}{\rho}\frac{\partial p}{\partial y} - c_D U\frac{v}{h} + K\frac{\partial^2 v}{\partial y^2}$$

- Note the embedded Burgers' equation
- Pressure gradient force: $-\frac{1}{\rho}\frac{\partial p}{\partial y} = \beta y u_g$
- Diagnostic equations for vertical velocity at top of slab:

$$w = -h\frac{\partial v}{\partial y} \quad \text{and} \quad \alpha = \begin{cases} 1 & \text{if } w \geq 0 \\ 0 & \text{if } w < 0 \end{cases}$$

- Diagnostic equation for wind speed at 10 m height in slab: $U = 0.78\left(u^2+v^2\right)^{1/2}$

Local Ekman Theory

- Slab version on the equatorial β-plane:

$$\begin{pmatrix} \frac{c_D U}{h} & -\beta y \\ \beta y & \frac{c_D U}{h} \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} 0 \\ -\frac{1}{\rho}\frac{\partial p}{\partial y} \end{pmatrix}$$

- Three force balance:
  1. Coriolis force
  2. Surface drag force
  3. Pressure gradient force (y-direction only)
- Note:
  - Pressure field $p(y)$ is specified
  - Solve for $u(y)$ and $v(y)$
  - Requires iteration because $U = (u^2 + v^2)^{1/2}$

SBLM-ITZC Experimental Details

- Domain: $-5000 \leq y \leq 5000 \text{ km}$
- Resolution: $\Delta y = 100 \text{ m} \quad (100,001 \text{ gridpts})$
  $\Delta t = 5 \text{ s}$
- Parameters: $h = 500 \text{ m}$
  $K = 500 \text{ m}^2\text{s}^{-1}$
- 3 Experiments:

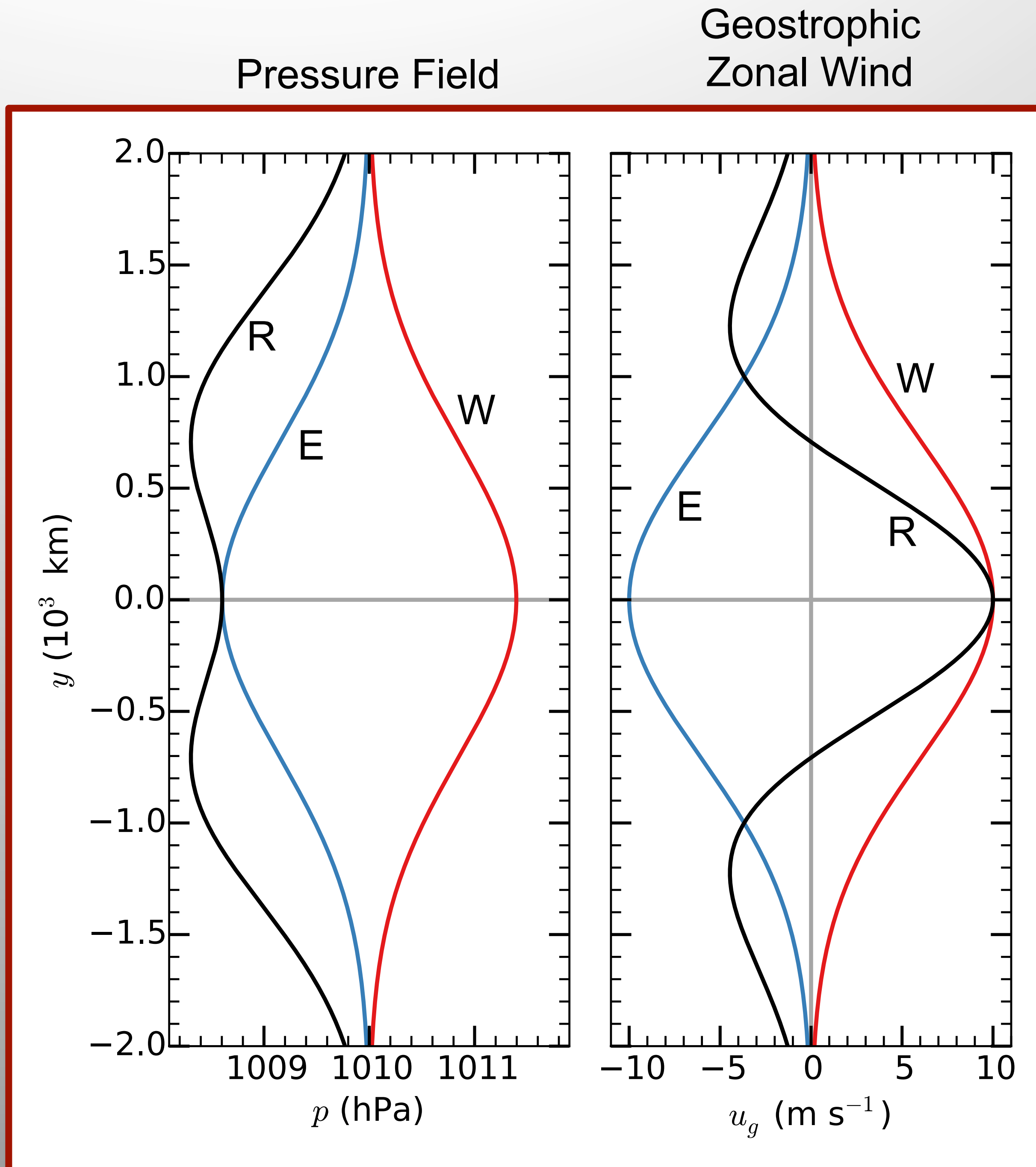
(E)	Easterly Geostrophic Flow	Low pressure on the equator
(W)	Westerly Geostrophic Flow	High pressure on the equator
(R)	Rossby Gyre Case	Low pressure on both sides of the equator

SBLM-ITCZ Experiments

(E) Easterly Geostrophic Flow

(W) Westerly Geostrophic Flow

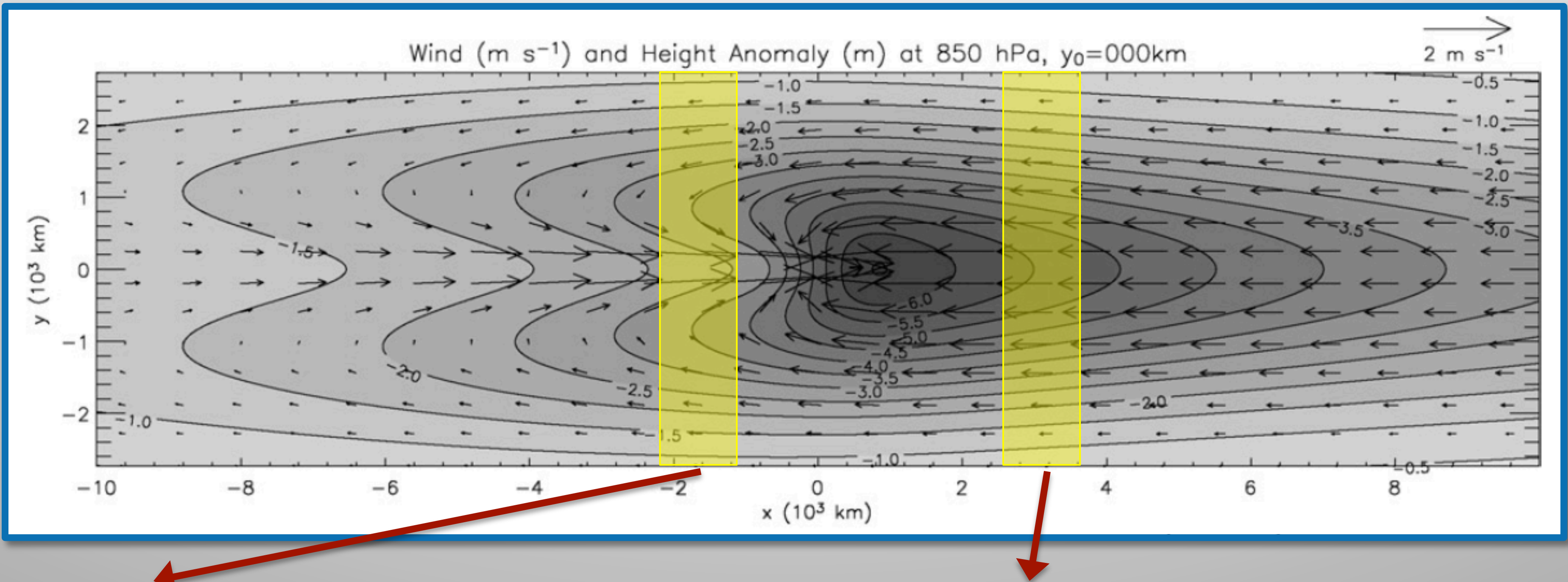
(R) Rossby Gyre Case



Motivation from the MJO

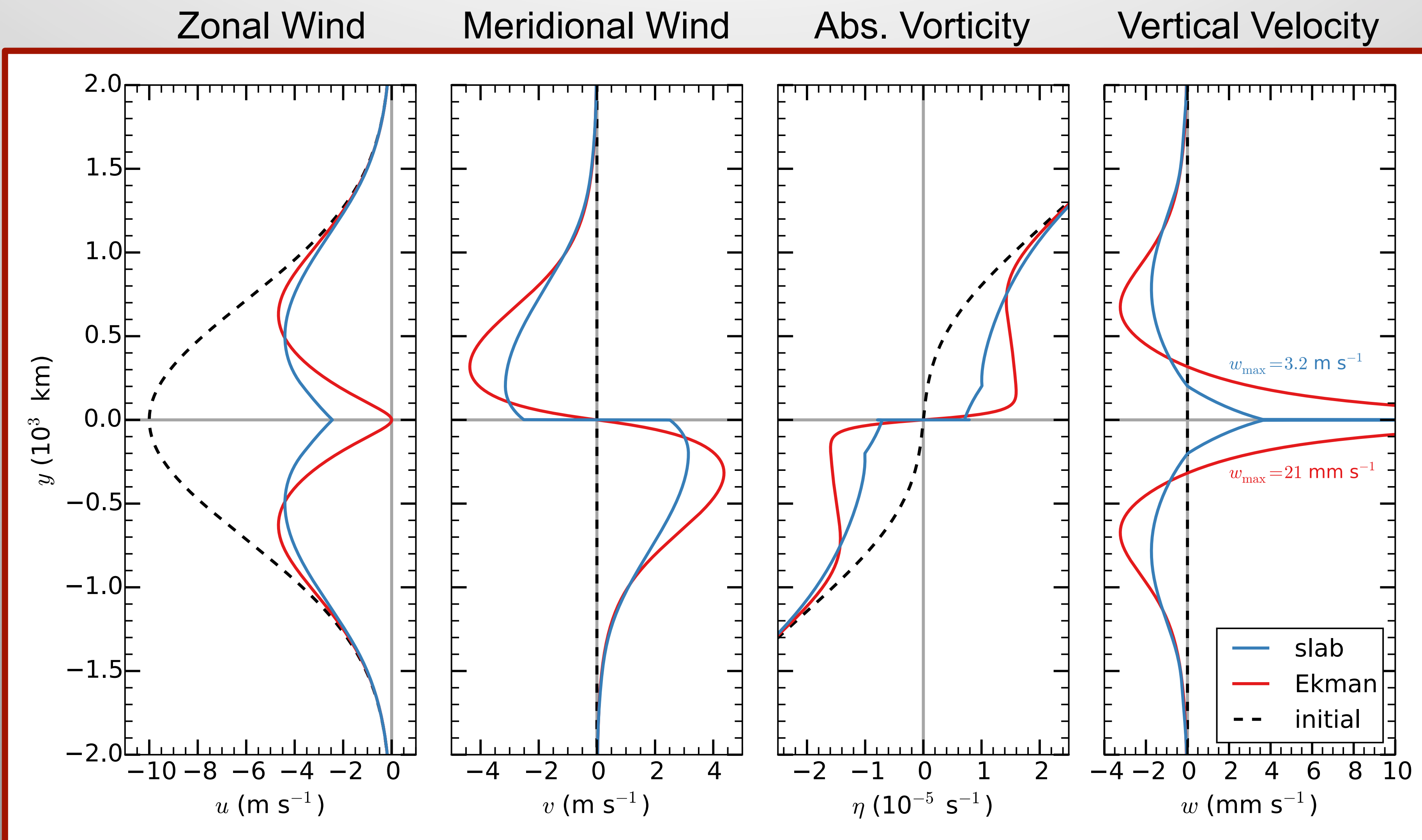
Simulated MJO

(from Schubert and Masarik 2006)



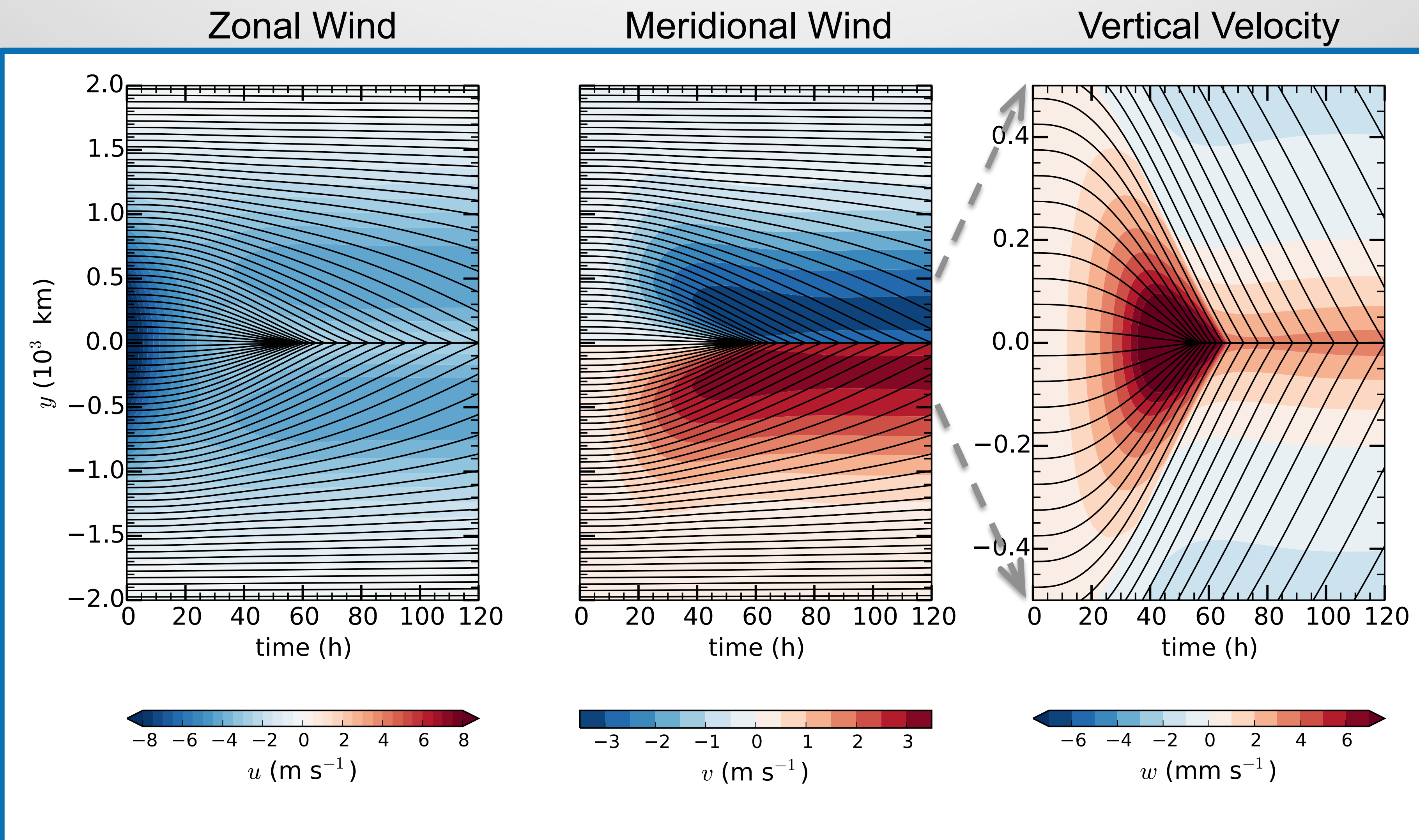
- ★ West of MJO (1st guess) ⇒ (W)
  - Westerly flow
  - High pressure on equator
- ★ East of MJO ⇒ (E)
  - Easterly flow
  - Low pressure on equator
- ★ West of the MJO (better) ⇒ (R)
  - Westerly flow on the equator surrounded by easterly flow
  - Low pressure on both sides of the equator

Easterly Geostrophic Flow Results



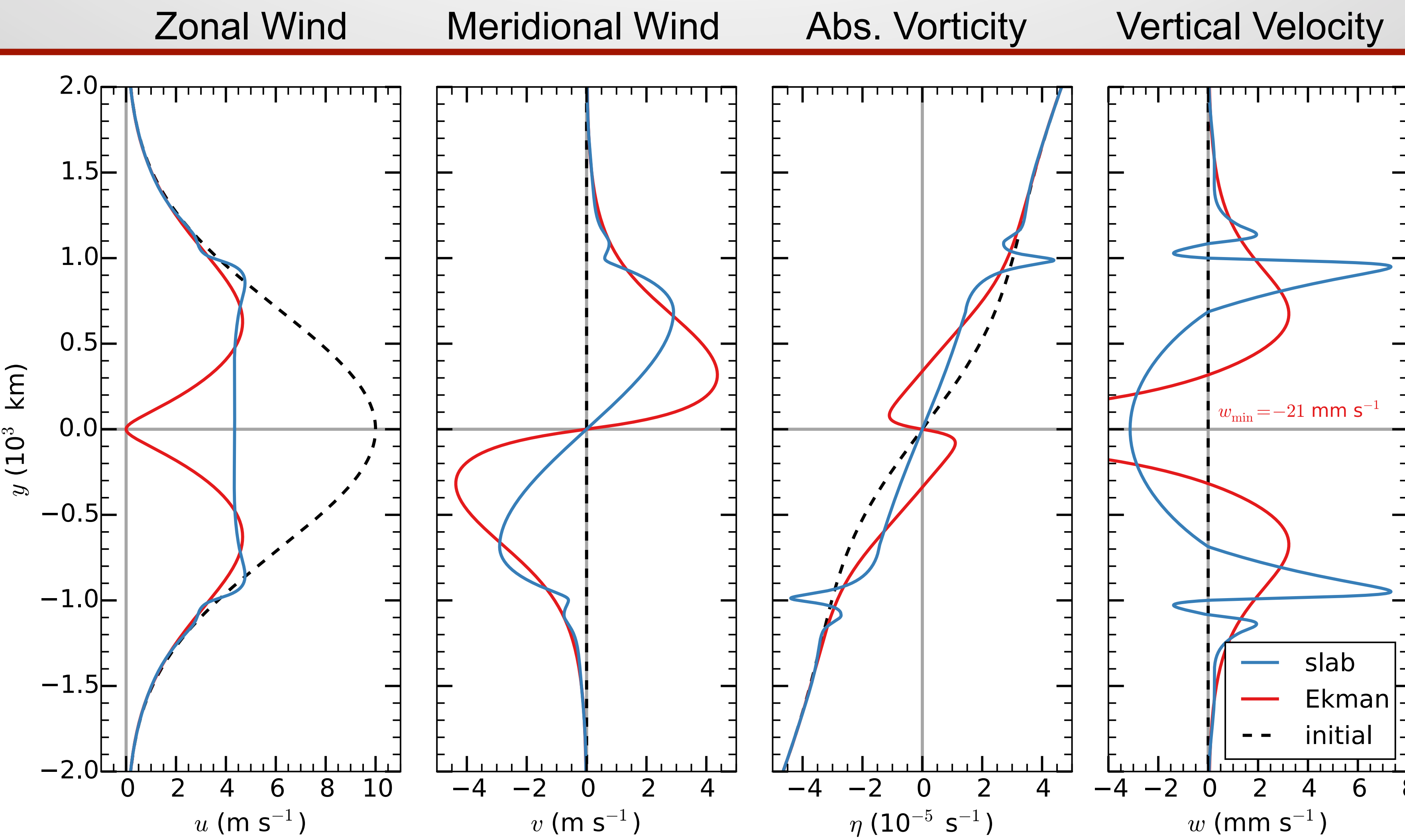
Numerical slab results: Steady-state solutions at t = 120 h

Trajectories for Easterly Case



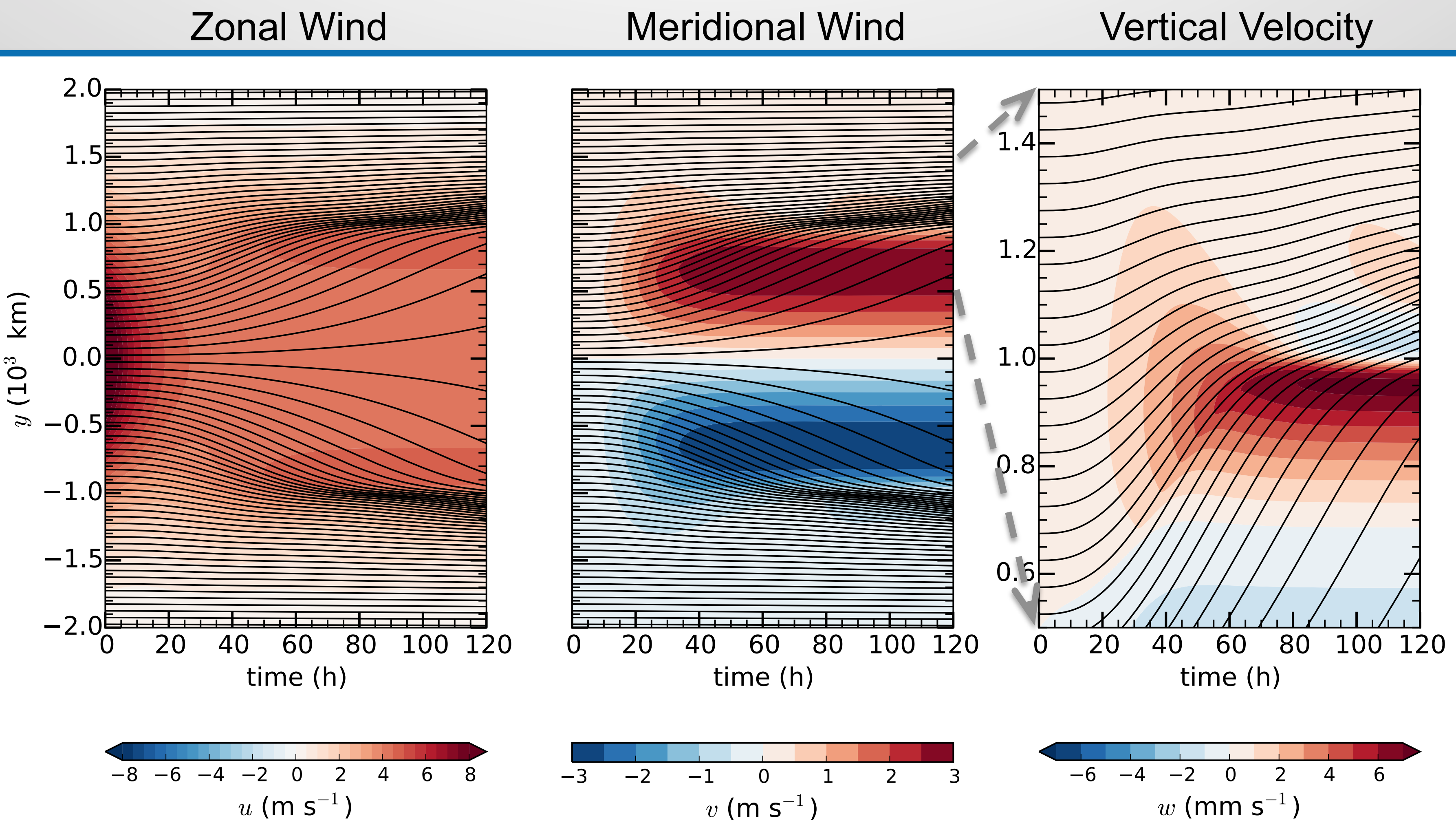
Shock-like feature develops on the equator

Westerly Geostrophic Flow Results



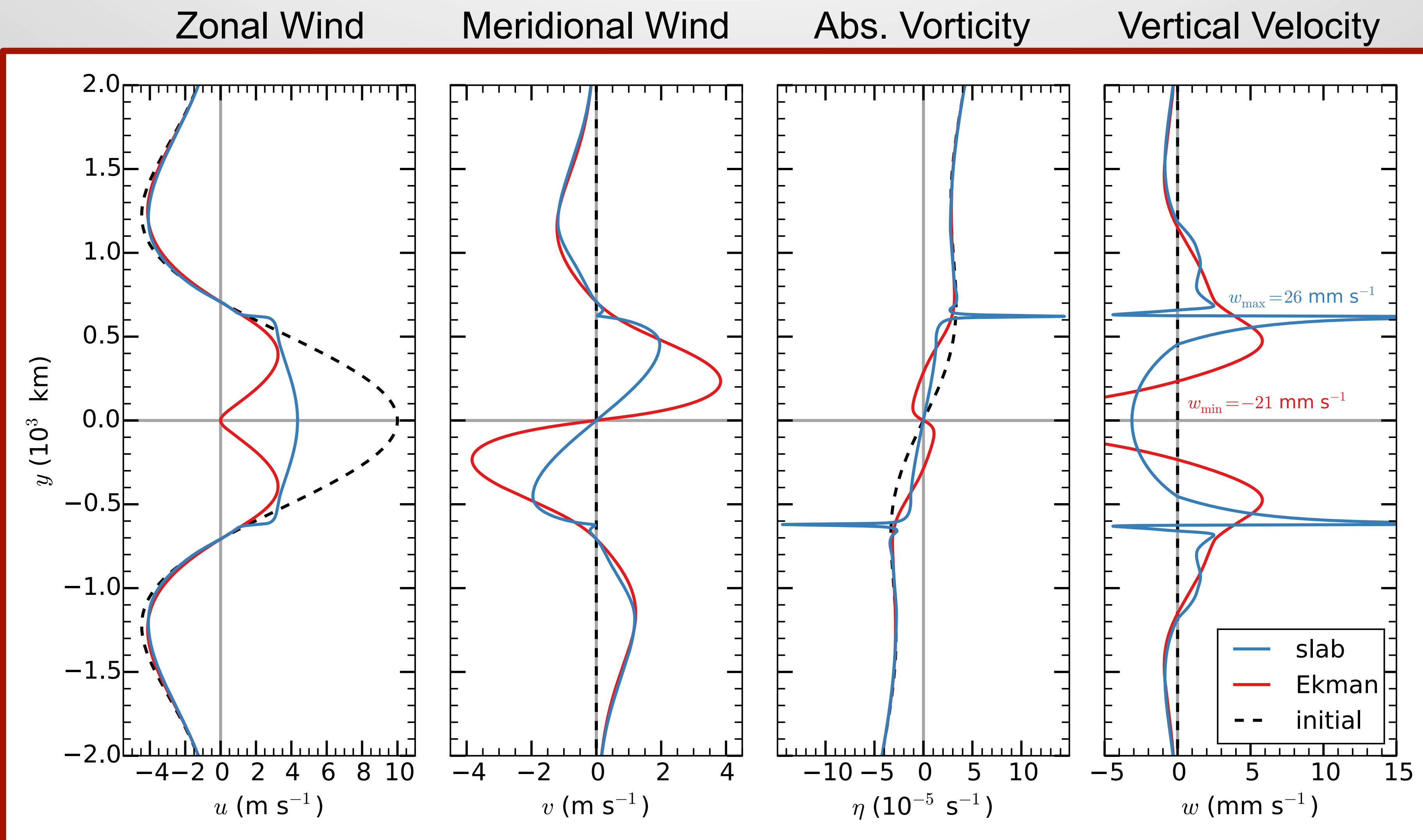
Numerical slab results: Steady-state solutions at t = 120 h

Trajectories for Westerly Case



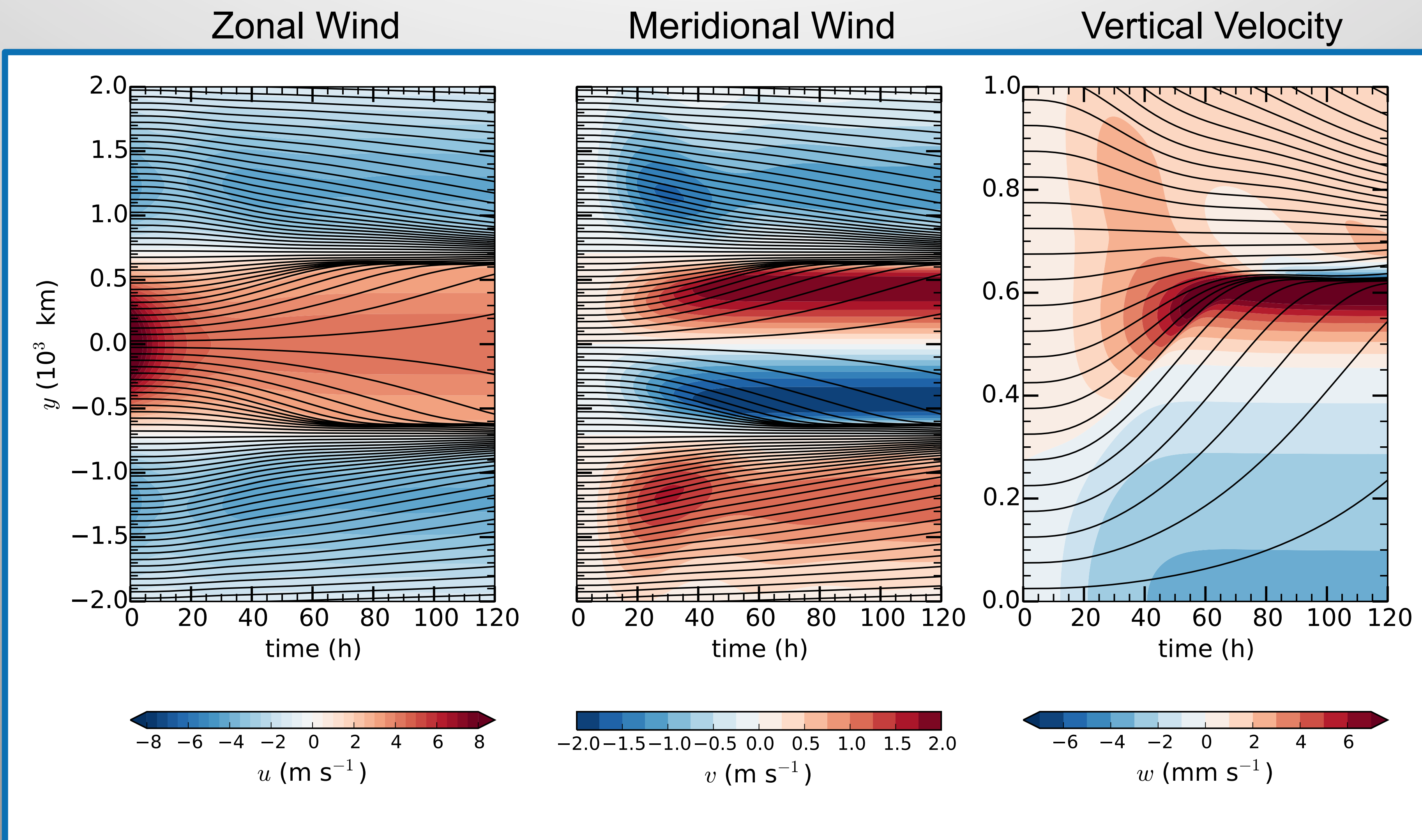
Trajectories converge, but shock-like structures do not form

Results for Rossby Gyre Case



Numerical slab results: Steady-state solutions at t = 120 h

Trajectories for Rossby Gyre Case



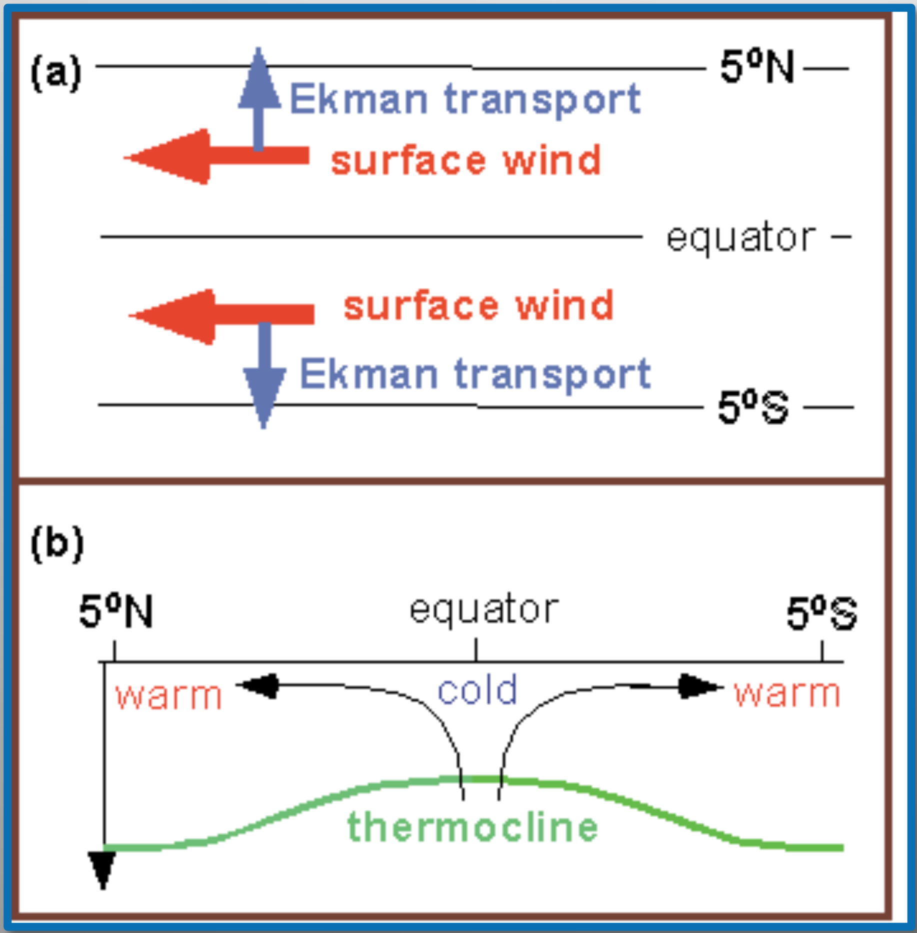
Trajectories strongly converge, but shock-like structures still do not form

Lessons Learned from SBLM-ITCZ

- ★ The slab boundary layer model for the ITCZ (without diffusion) is also a hyperbolic system, allowing for the possibility of shock formation.
- ★ True shock-like structures causing strong Ekman pumping form only with easterly flow (low pressure along the equator).
- ★ Westerly flow (high pressure along the equator) leads to narrow, enhanced Ekman pumping (but not a singularity) and a double ITCZ.

Lessons Still to be Learned

★ Why don't we observe a narrow ITCZ at the equator when there is easterly flow?



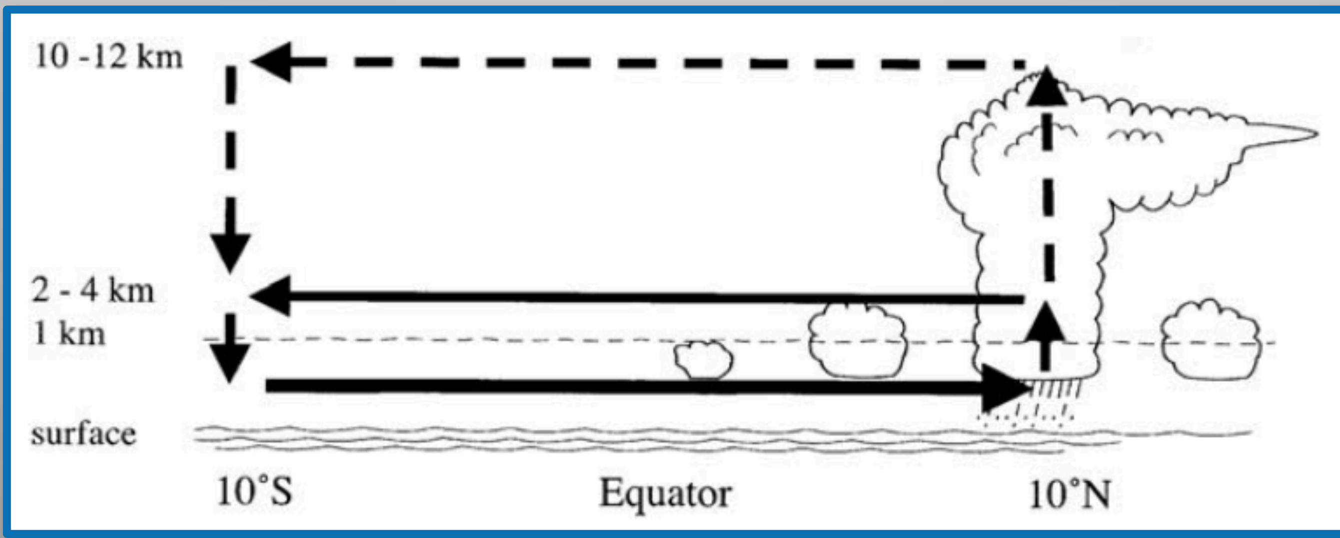
1. Even with strong Ekman pumping at the equator, the associated oceanic upwelling produces cold equatorial surface water, which inhibits deep convection.

(from http://www-das.uwyo.edu/~geerts/cwx/notes/chap11/equat_upwel.html)

Lessons Still to be Learned

★ Why don't we observe a narrow ITCZ at the equator when there is easterly flow?

1. Even with strong Ekman pumping at the equator, the associated oceanic upwelling produces cold equatorial surface water, which inhibits deep convection.
2. Ekman pumping at the equator does not penetrate vertically, since the Rossby depth is small (Rossby length is large).



(adapted from Zhang et al. 2004)

Lessons Still to be Learned

★ Why don’t we observe a narrow ITCZ at the equator when there is easterly flow?

1. Even with strong Ekman pumping at the equator, the associated oceanic upwelling produces cold equatorial surface water, which inhibits deep convection.

2. Ekman pumping at the equator does not penetrate vertically, since the Rossby depth is small (Rossby length is large).

3. Any other ideas?

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References for More Info

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