

Some Tropical Challenges for GCMs

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Some Key Challenges

- Quasi-Biennial Oscillation
- Stratosphere-Troposphere Exchange
- Planetary Boundary Layer Flows in Tropical Cyclones and the ITCZ

Quasi-Biennial Oscillation

- In 1883, Krakatau volcano erupted in Indonesia and sent debris very high into the atmosphere. It circled the globe in 13 days in a westward direction.
 - "Krakatau easterlies"
- In 1908, Berson launched high-altitude balloons from Lake Victoria, Africa and beginning at about 120mb, they traveled in an eastward direction.
 - "Berson's westerlies"
- The conflicting results were resolved when QBO was discovered and documented 50 years ago.
 - Reed et al. (1961), Veryard and Ebdon (1961)

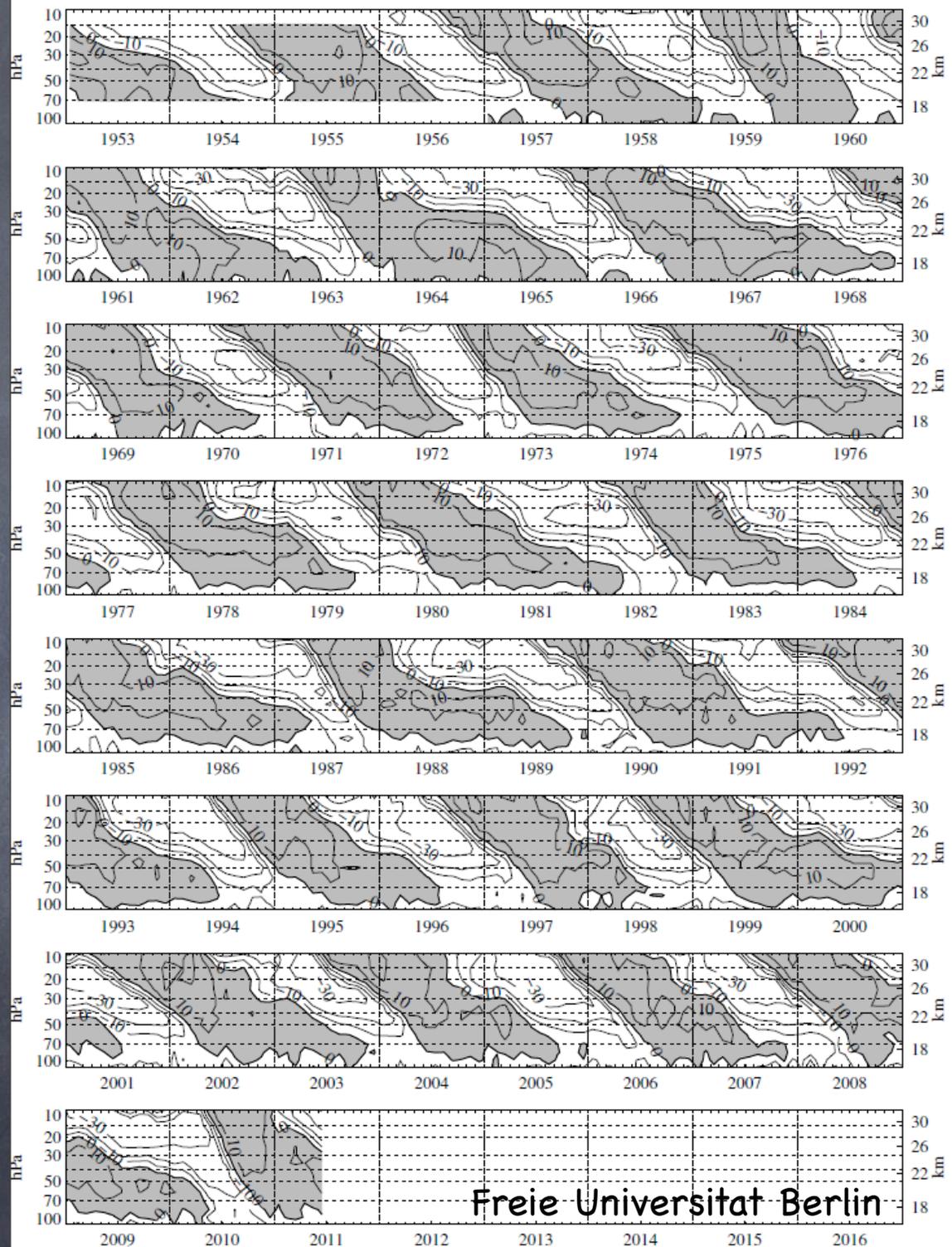


Quasi-Biennial Oscillation

- Periodic shift in equatorial, lower-stratospheric winds
 - Alternating easterly and westerly winds propagate downward at a rate of approx 1 km/month
 - Easterlies propagate downward more irregularly than westerlies
 - Winds reach maximum amplitude of approx 40-50 m/s near an altitude of 20 hPa
 - Average period is about 28 months but with considerable variability (20-36 months)

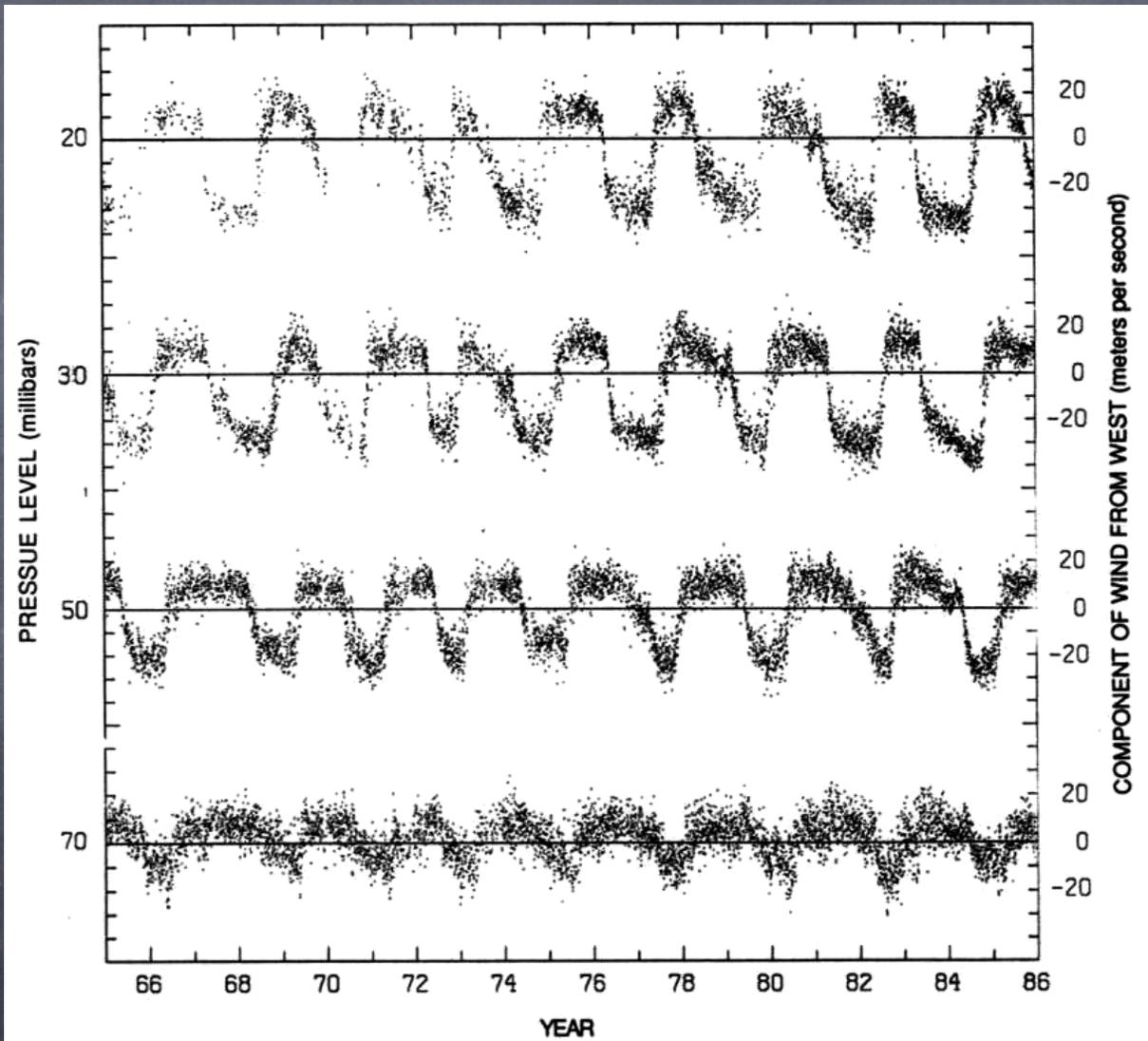
QBO in Observations

- Time-Height diagram with isotachs
- Easterlies: white
- Westerlies: gray
- Contours: 10 m/s
- Utilizes data from 3 different stations over almost 60 years



QBO in Observations

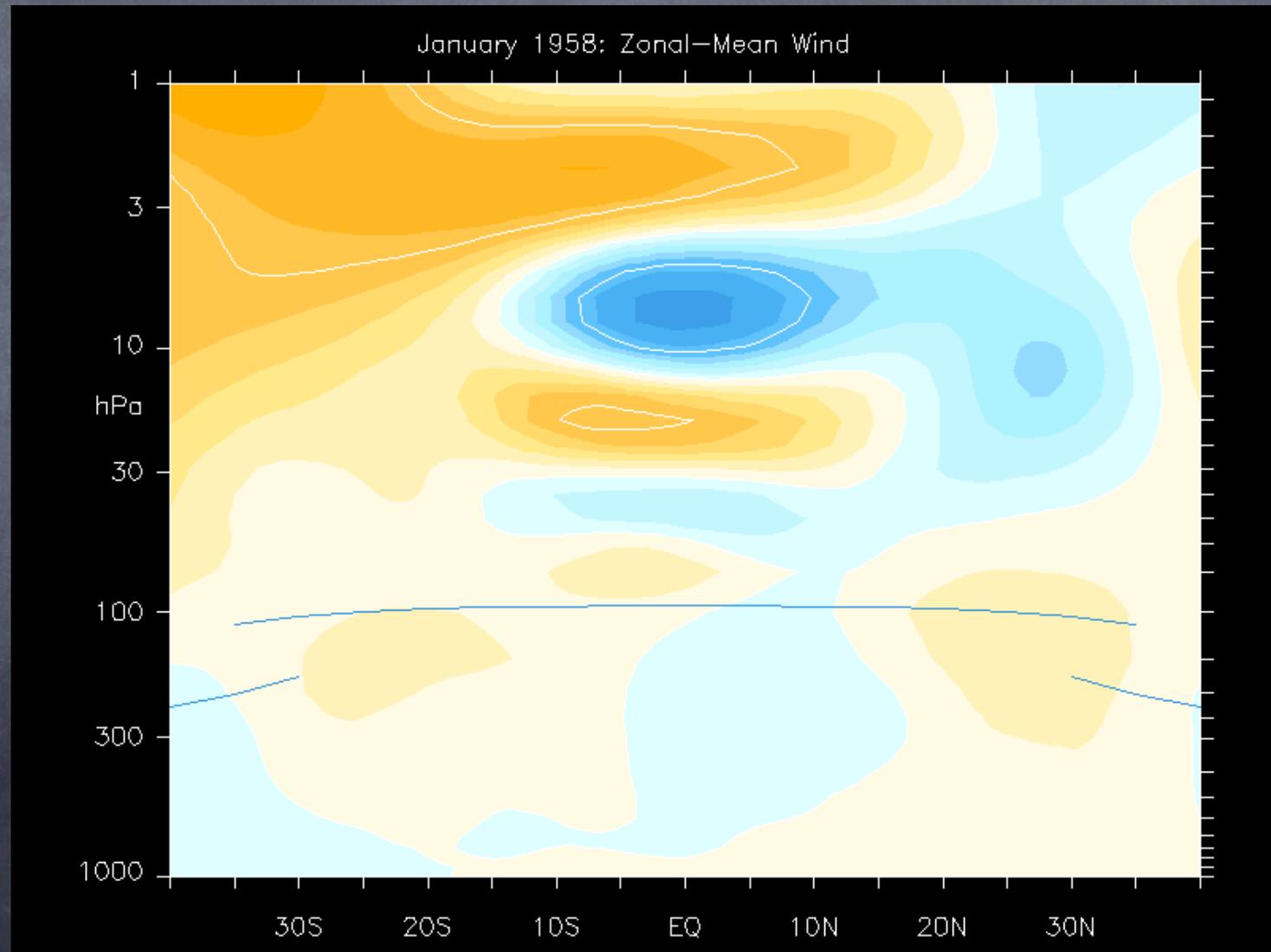
- Daily data points taken from Singapore (1965–1985)
- Shown at 20, 30, 50, and 70 hPa
- Positive is westerly, negative is easterly
- QBO signal is nearly gone at 70 hPa, but very strong at 20 hPa



Lorenz (1993)

QBO in Reanalysis Data

- Zonal mean wind from ERA-40
- Data are deseasoned and 20-month low-pass filtered



Courtesy of Mark Baldwin, NWRA

QBO in Model Simulations

- A challenge since a broad spectrum of vertically propagating waves in the equatorial atmosphere must be accurately simulated.
- Requires at least:
 - Sufficient vertical resolution in stratosphere to allow the representation of equatorial waves at the horizontally resolved scales of the GCM
 - Realistic excitation of resolved waves by simulated tropical weather
 - Parameterization of the effects of unresolved gravity waves



QBO in Model Simulations

- Models dating back to the late 1960s through late 1970s failed to simulate anything resembling a QBO.
 - A known shortcoming, but helped to diagnose what would be needed in future models
- First QBO-capable models developed in early 1980s, and there are dozens now



QBO in Model Simulations

- ◉ Aside from previously mentioned requirements, successful modeling of QBO seems to depend on:
 - ◉ Precipitation amount and type in ITCZ
 - ◉ Moist convective scheme
 - ◉ Horizontal diffusion
 - ◉ Gravity wave drag parameterization

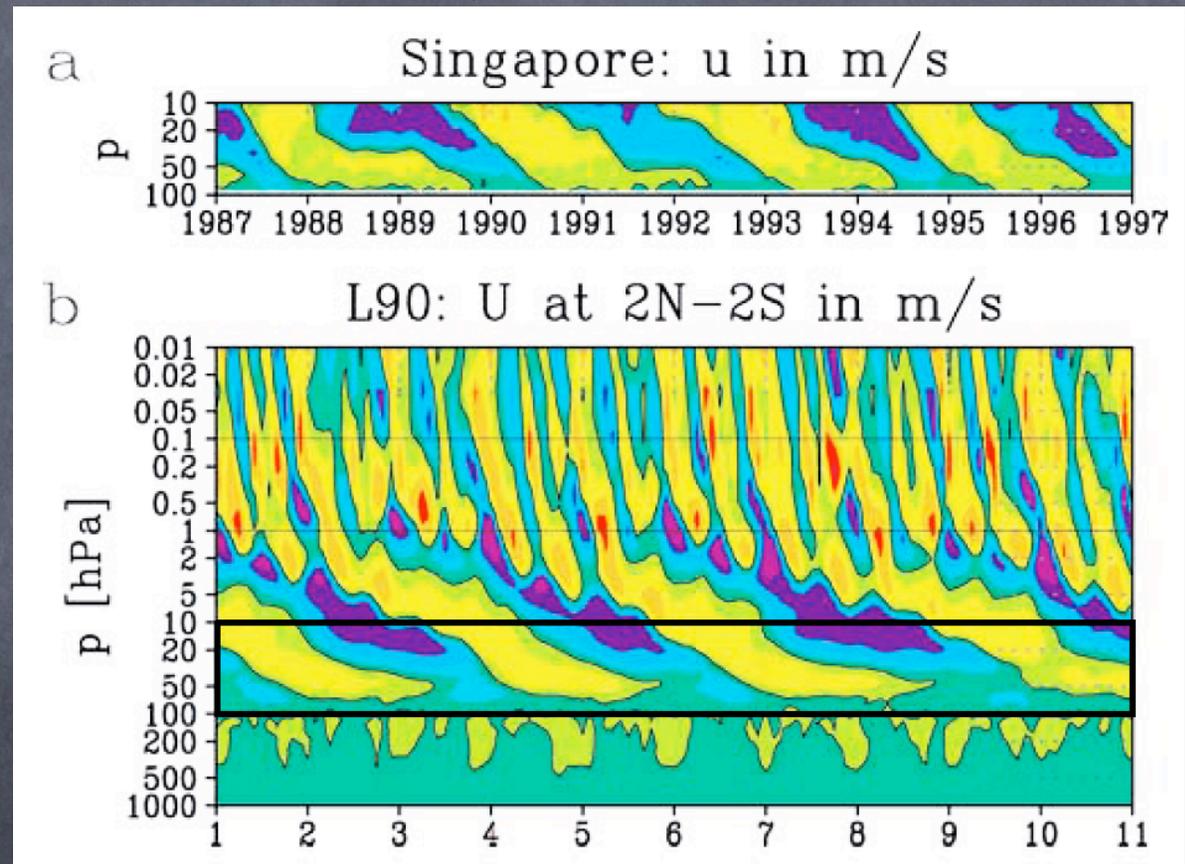
QBO in Model Simulations

- Very promising results have come about within past 10 years (e.g. Giorgetta et al., 2002)
- Middle-atmosphere GCM at Max Plank Institute for Meteorology: MAE-CHAM5 model
 - Vertical resolution: L90 between 1000 to 0.01 hPa (resolves wavelengths ~ 2.8 km in lower stratos)
 - Horizontal resolution: T42 (resolves wavelengths ~ 1000 km)
 - Parameterizations applied at resolution of $\sim 2.8^\circ$



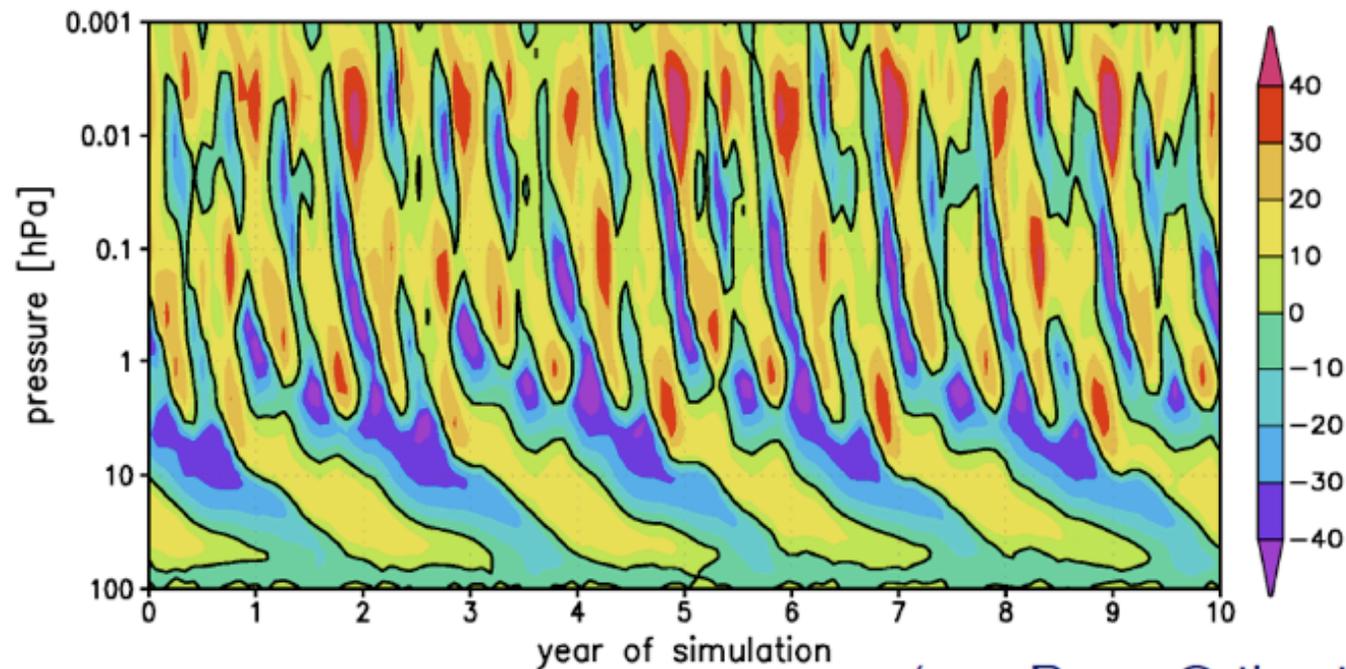
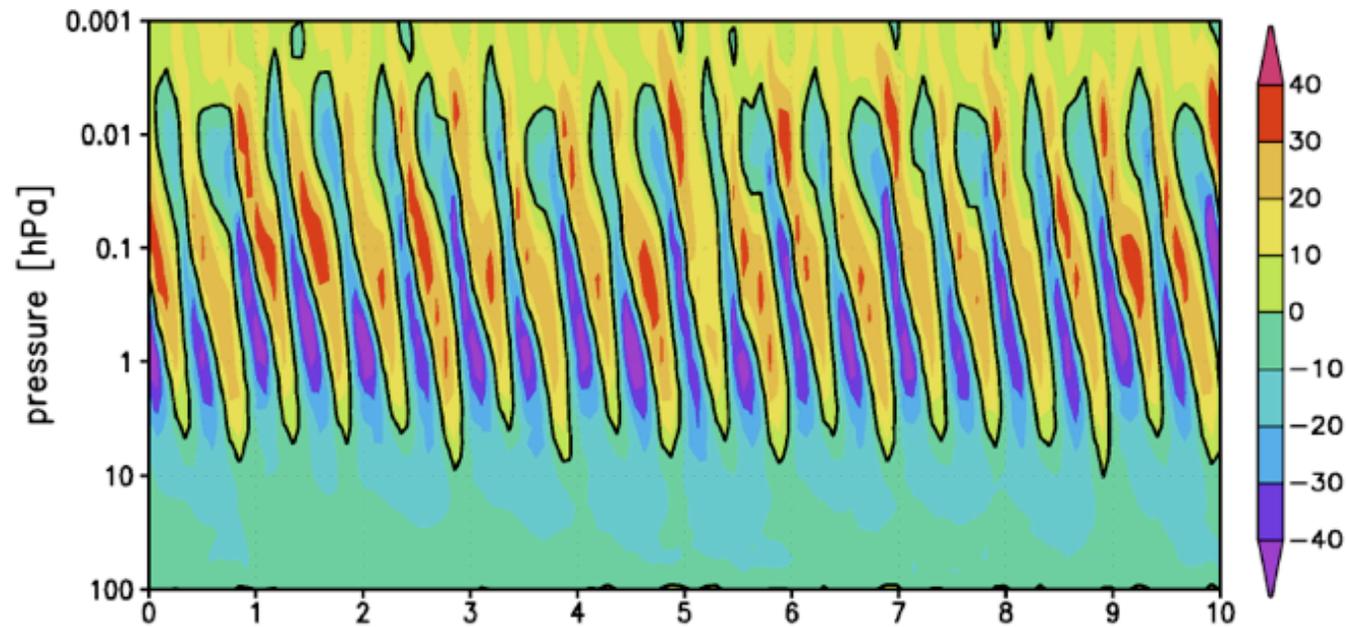
QBO in Model Simulations

- Simulated QBO characteristics
 - period ~ 32 months
 - Westerlies reach 15–20 m/s at 5 hPa, easterlies reach 30+ m/s above 20 hPa
 - Westerlies propagate downward at regular rate, while easterlies can be irregular
 - Temperature anomalies and tropical upwelling speeds also in line with observations



Giorgetta et al. (2002)

Equatorial zonal wind (m/s) in HAMMONIA versions of different vertical resolution



(see Pena-Ortiz et al., JGR, 2010)

Challenge 2: Stratosphere-Troposphere Exchange



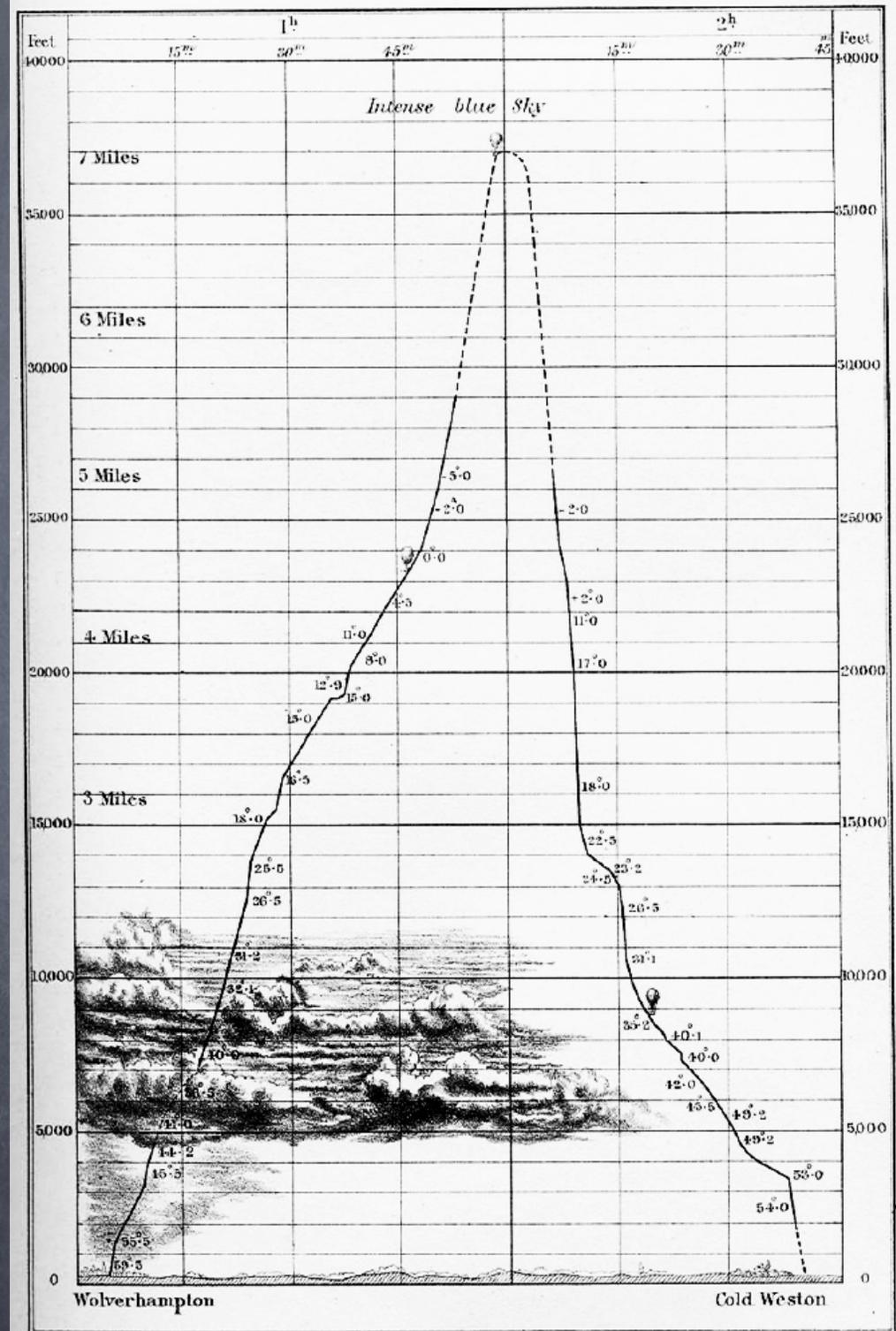
Stratosphere-Troposphere Exchange

- The atmosphere can be dissected ...
 - By lapse rate of temperature yielding the divisions troposphere, stratosphere, mesosphere, etc
 - By potential vorticity and potential temperature yielding the divisions underworld, middleworld, overworld

Discovering the Structure of the Atmosphere

- James Glaisher and Henry Coxwell in manned balloon
- Ascent to 8800m+ over England in Sept 1862
- Both men suffered blindness and paralysis above 5 miles altitude
- Attributed to decompression sickness

Glaisher et al. 1871

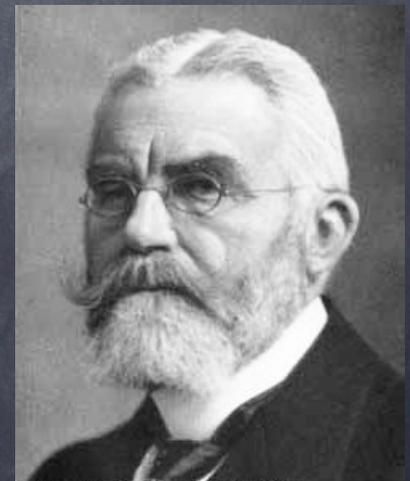


Discovering the Structure of the Atmosphere

- Up until the turn of the last century, we only knew about the part of the atmosphere closest to us, where weather occurs.
- Leon Teisserenc de Bort and Richard Aßmann were meteorologists who discovered another layer of the atmosphere in 1902.



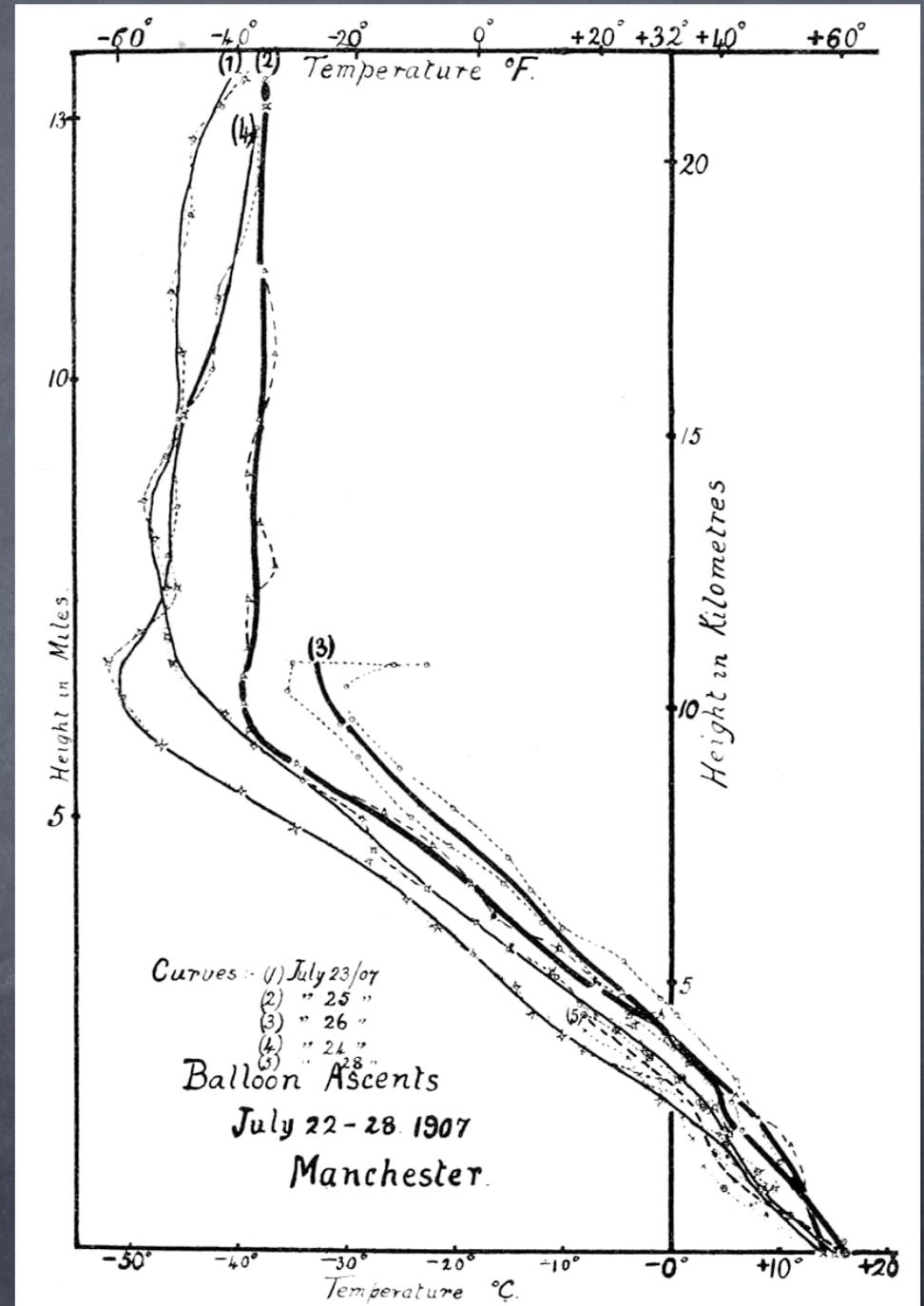
Teisserenc de Bort



Aßmann

Discovering the Structure of the Atmosphere

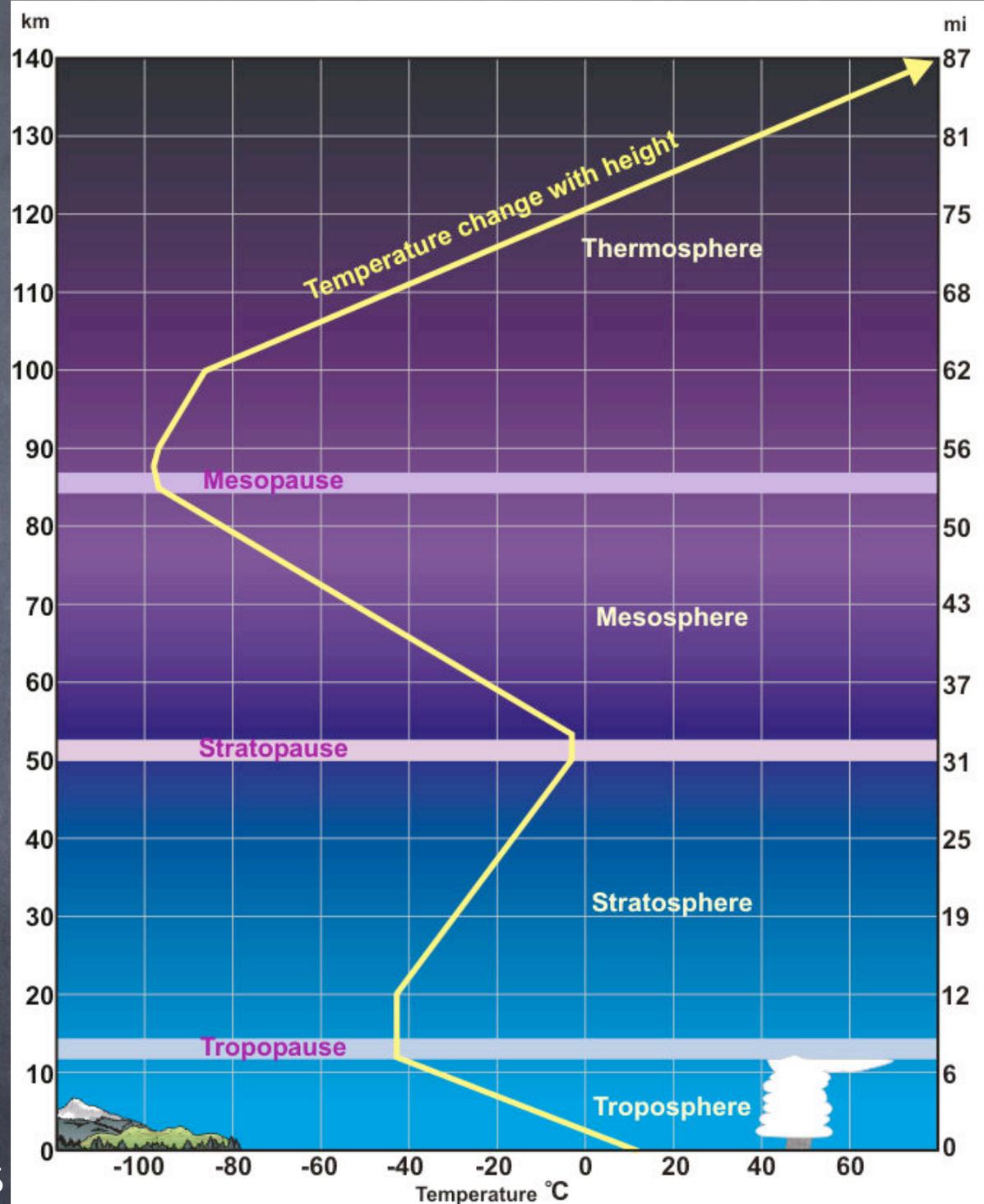
- New layer was isothermal, possibly even warming with height... found using unmanned instrumented balloons
- They named the lowest layer the troposphere (**tropos**=mixing) and the second layer the stratosphere (**strato**=layers)



Petavel and Harwood (1908)

Current Picture

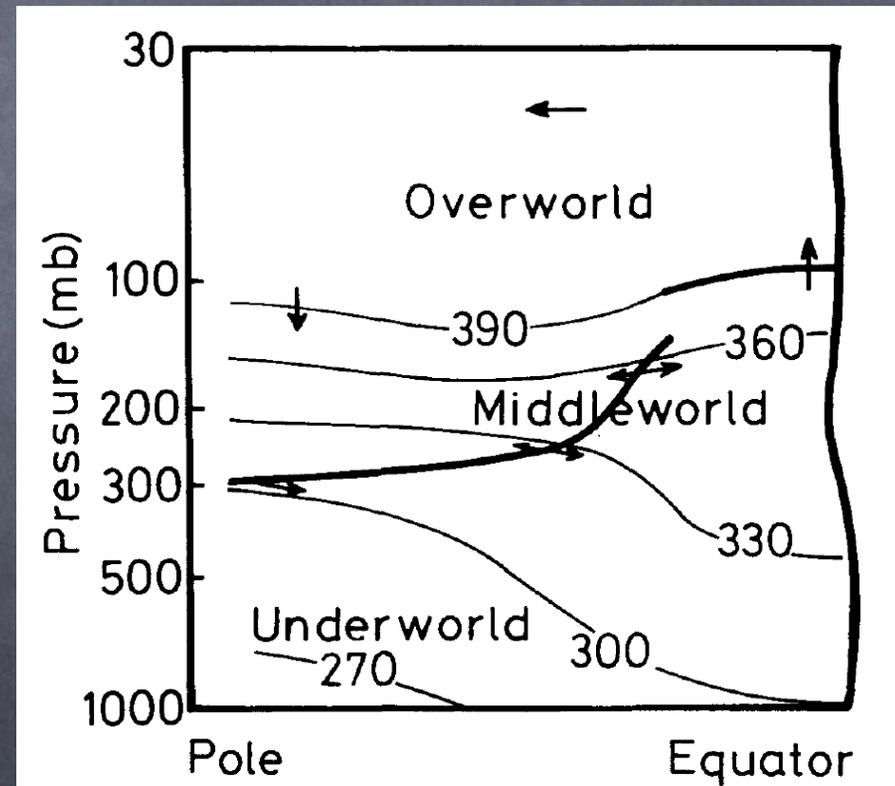
- We now know the thermal structure of the entire atmosphere quite well, due to radiosondes, rockets, and satellites
- There is an isothermal layer just above the tropopause, which reduces the amount of stratification in the lower stratosphere



A Different Model

- Concept of overworld and underworld introduced by Sir Napier Shaw (1930)
- Hoskins (1991) provides schematic with overworld, middleworld, and underworld
 - Overworld: layer of atmosphere where all isentropes lie above the tropopause ($\theta > 390\text{K}$)
 - Middleworld: layer of atmosphere where isentropes intersect the tropopause ($300\text{K} < \theta < 390\text{K}$)
 - Underworld: layer of atmosphere where all isentropes intersect the surface ($\theta < 300\text{K}$)

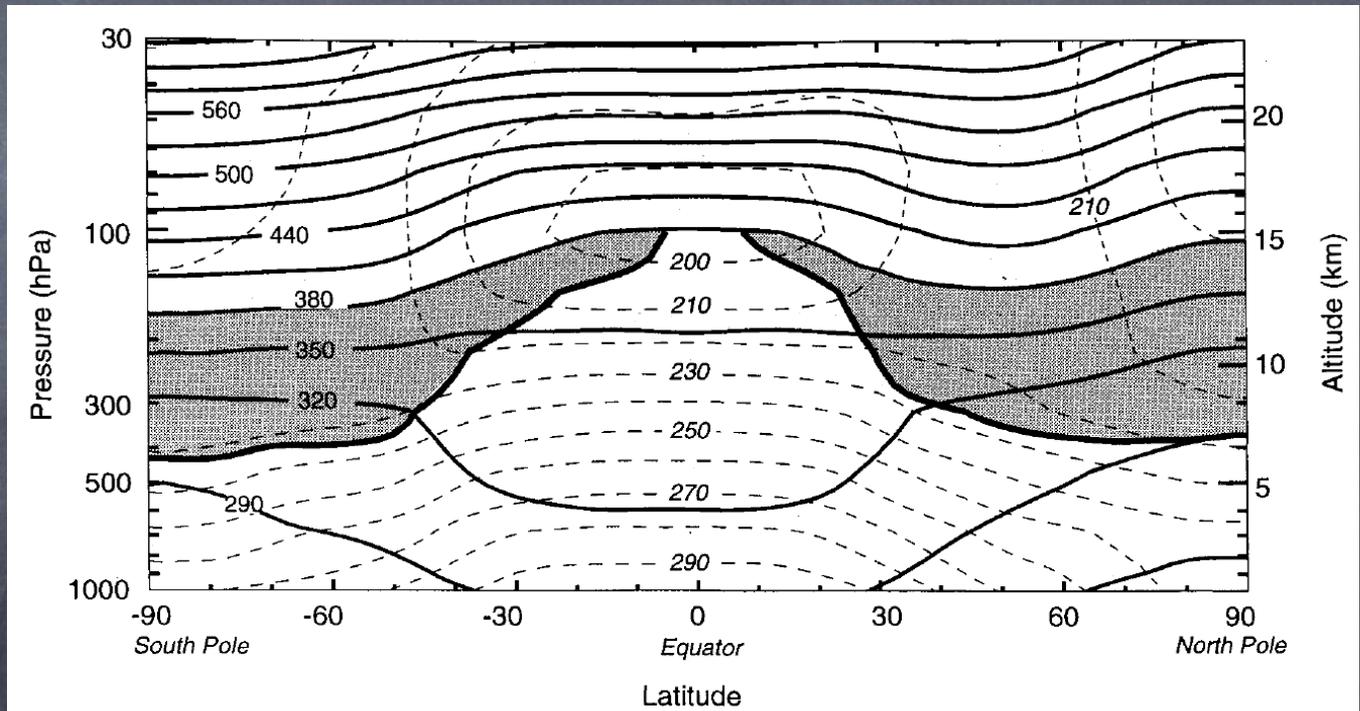
“Air moves along isentropes as easily as fish swim in the sea.”



Hoskins (1991)

3 Worlds in Real Data

- Potential temperature (solid) and temperature (dashed) during Jan 1993.
- Thick line is 2PVU tropopause, gray shading is middleworld where Strat-Trop mixing can readily occur

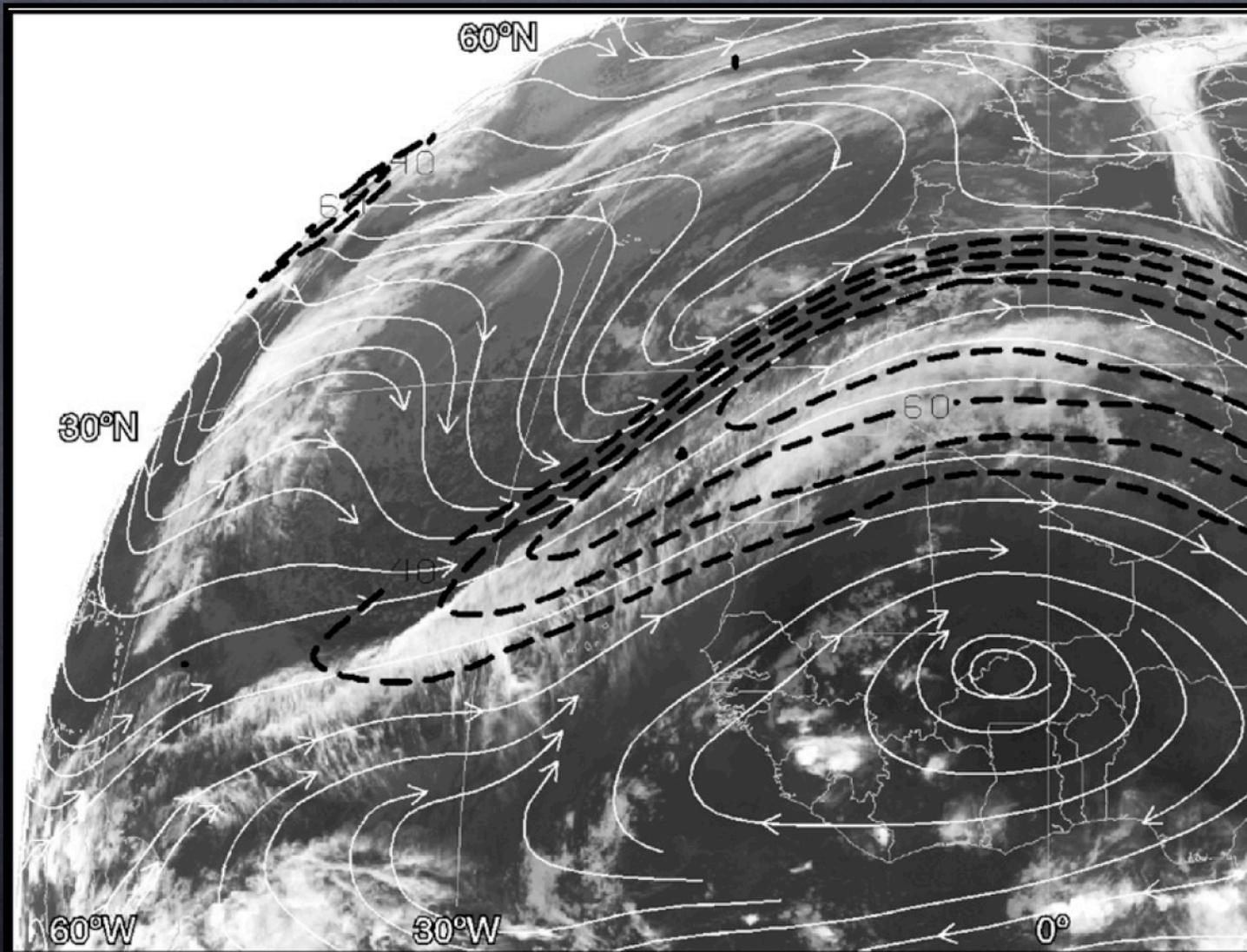


Holton et al. (1995)

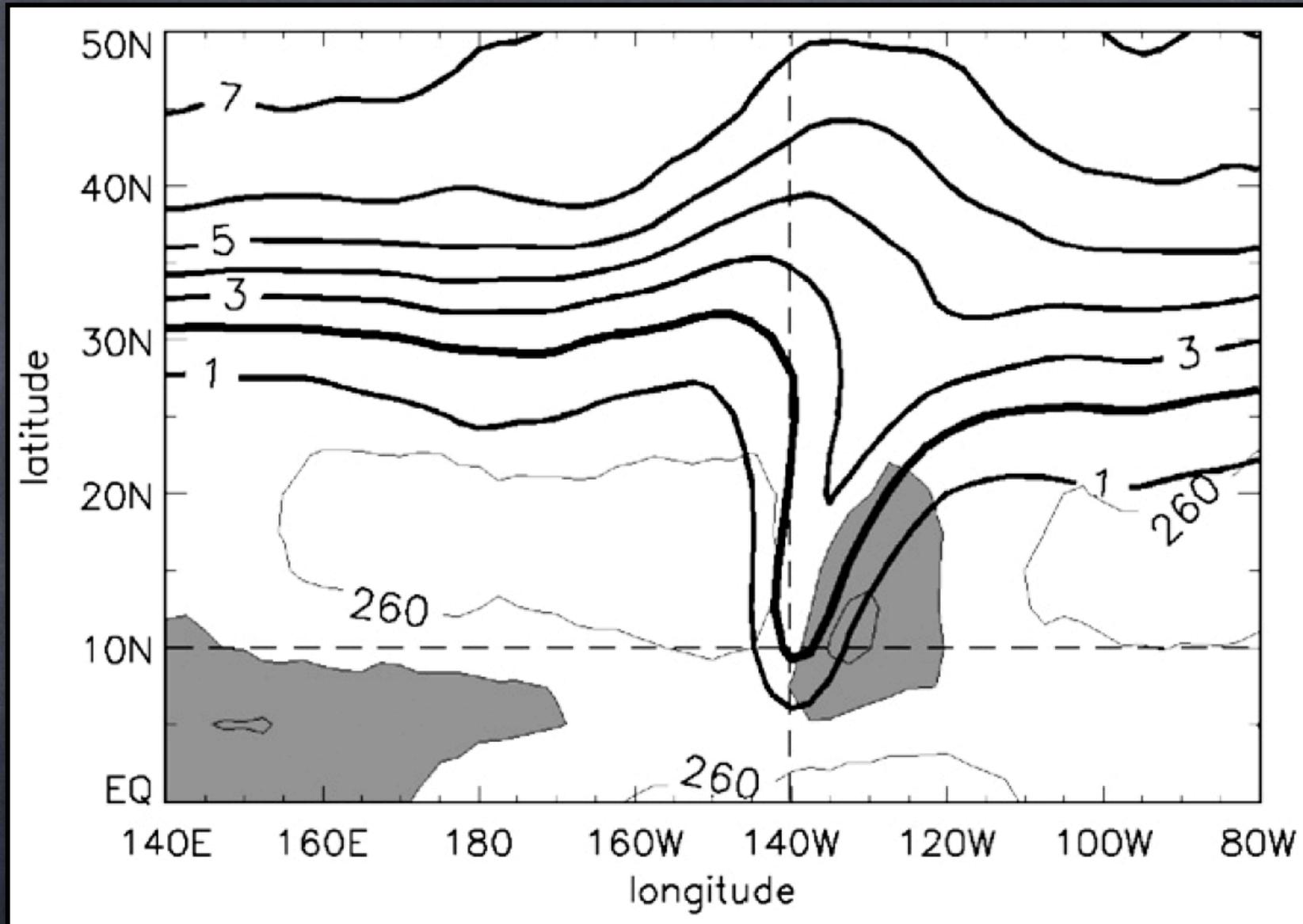
Strat-Trop Exchange

- Because middleworld isentropes lie in both the troposphere and stratosphere, adiabatic motions associated with large-scale cyclones and anticyclones can easily allow for stratosphere-troposphere exchange
- Strat-Trop exchange conserves potential vorticity, making PV an ideal tracer
- Though significant, the folds and filaments can be difficult for a GCM to resolve

Tropical Upper Tropospheric Trough (TUTT)



Low-Latitude PV Intrusion



From Waugh and Funatsu (2003)

Potential Vorticity (PV) Principle

$$\frac{DP}{Dt} = 0$$

PV is materially conserved

Definition of
the PV

$$P = \left(f + \frac{\partial v}{\partial x} \right) \left(-\frac{1}{g} \frac{\partial p}{\partial \theta} \right)^{-1}$$

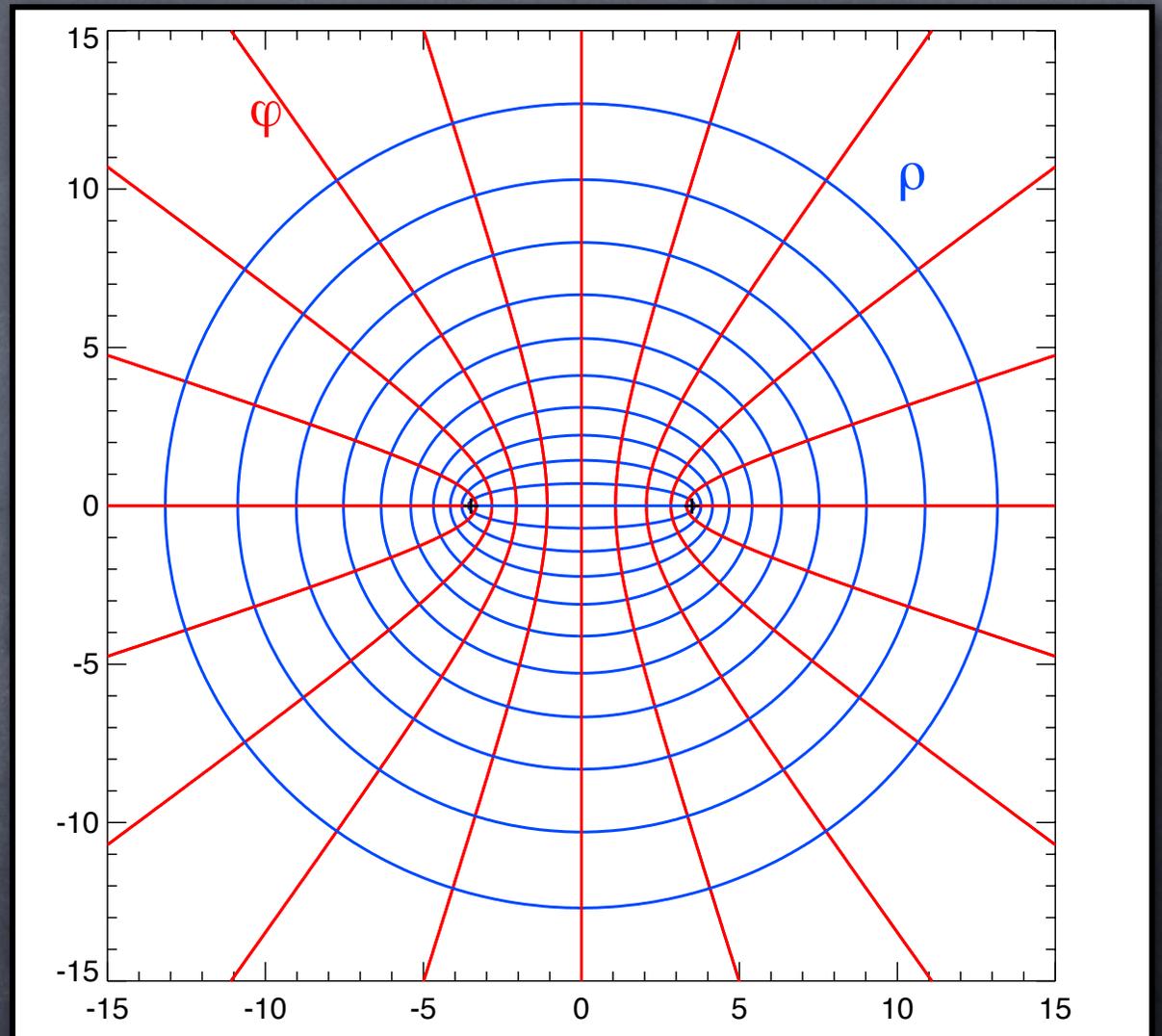
$$\tilde{P} = f \left(-\frac{1}{g} \frac{\partial \tilde{p}}{\partial \theta} \right)^{-1}$$

Far-field PV

Elliptical Coordinates

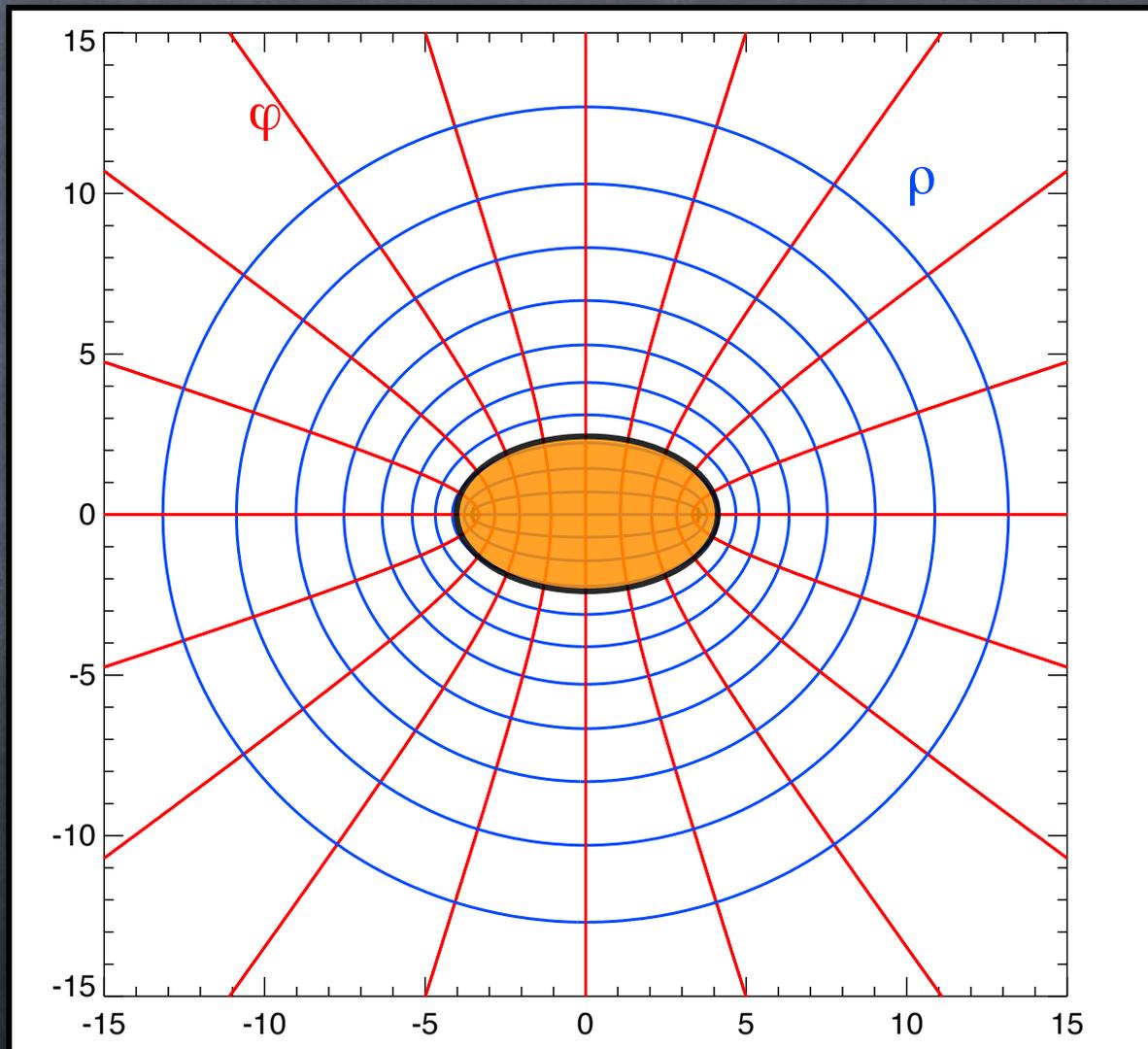
$$x = c \cosh \varrho \cos \varphi$$

$$z = c \sinh \varrho \sin \varphi$$



Prescribed PV Anomaly

$$\frac{P}{\tilde{P}} = \begin{cases} \gamma & \text{if } x^2/a^2 + z^2/b^2 < 1, \\ 1 & \text{if } x^2/a^2 + z^2/b^2 > 1 \end{cases}$$



Cauchy-Riemann Conditions

Inside the PV anomaly:

$$\frac{\partial(v + fx)}{\partial x} + \frac{\theta_c N_c P}{g \tilde{P}} \frac{\partial \Pi}{\partial z} = 0$$

$$\frac{\partial(v + fx)}{\partial z} - \frac{\theta_c N_c}{g} \frac{\partial \Pi}{\partial x} = 0$$

PV Principle

Thermal Wind

Outside the PV anomaly:

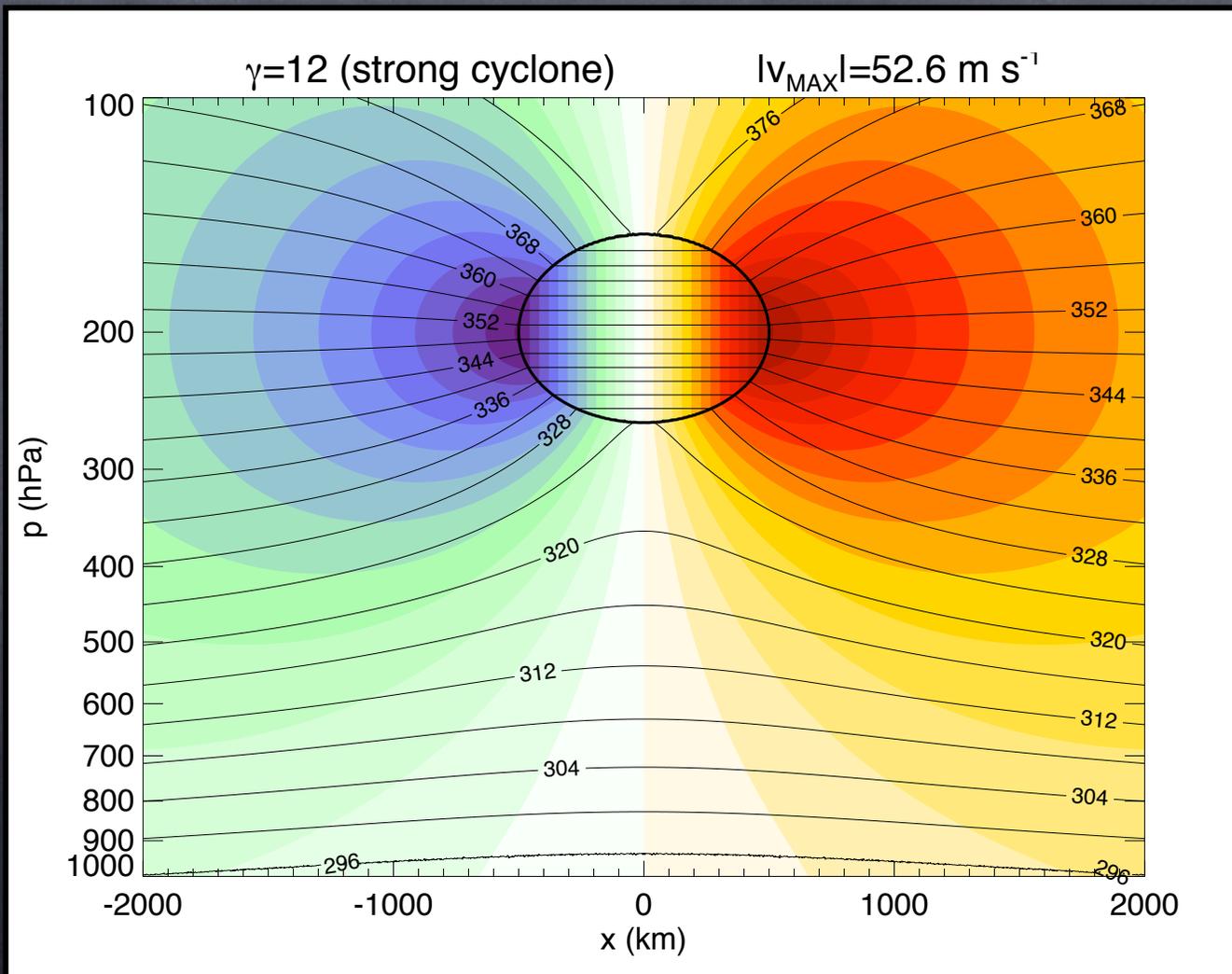
$$\frac{\partial(v + fx)}{\partial \varrho} + \frac{\theta_c N_c}{g} \frac{\partial \Pi}{\partial \varphi} = 0$$

$$\frac{\partial(v + fx)}{\partial \varphi} - \frac{\theta_c N_c}{g} \frac{\partial \Pi}{\partial \varrho} = 0$$

TUTT PV Solutions

$$v(x, z) = \frac{f(\gamma - 1)b}{\gamma a + b} \begin{cases} x & \text{if } \varrho \leq \varrho_0, \\ ae^{\varrho_0 - \varrho} \cos \varphi & \text{if } \varrho \geq \varrho_0 \end{cases}$$

$$\Pi(x, z) = \tilde{\Pi}(z) + \frac{gf(\gamma - 1)a}{\theta_c N_c (\gamma a + b)} \begin{cases} z & \text{if } \varrho \leq \varrho_0, \\ be^{\varrho_0 - \varrho} \sin \varphi & \text{if } \varrho \geq \varrho_0 \end{cases}$$

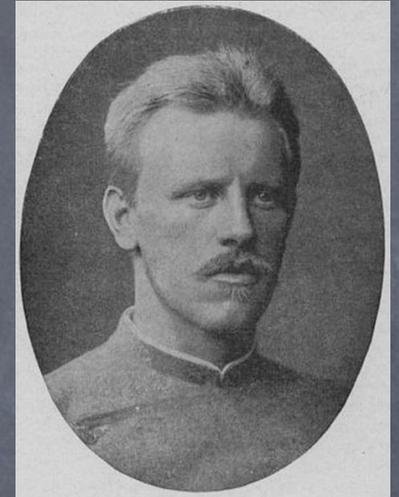


Challenge 3: Planetary Boundary Layer Flows in Tropical Cyclones and the ITCZ



Discovery of Boundary Layer Flows

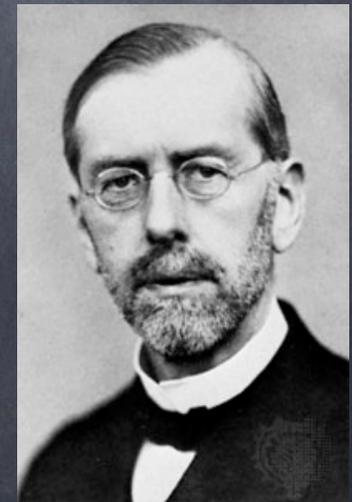
- F. Nansen organized Fram expedition (1893–96) and observed ice drift $20\text{--}40^\circ$ to right of surface wind
- V. Bjerknes (father of J. Bjerknes) put observed ice drift in mathematical framework; passed the problem to his student: V. Ekman
- V. Ekman derived near-surface turning of ocean current with depth in 1905



Fridtjof Nansen



Vilhelm Bjerknes



Vagn Ekman



Discovery of Boundary Layer Flows

1893-96 Fram Expedition Route

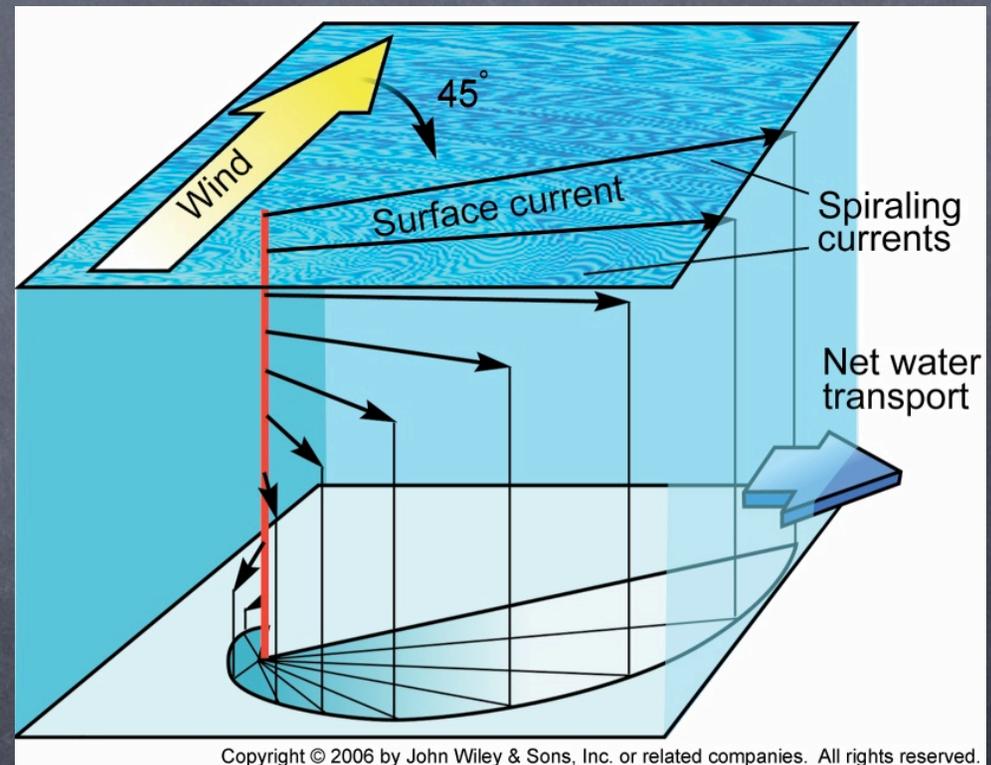


Fram in ice



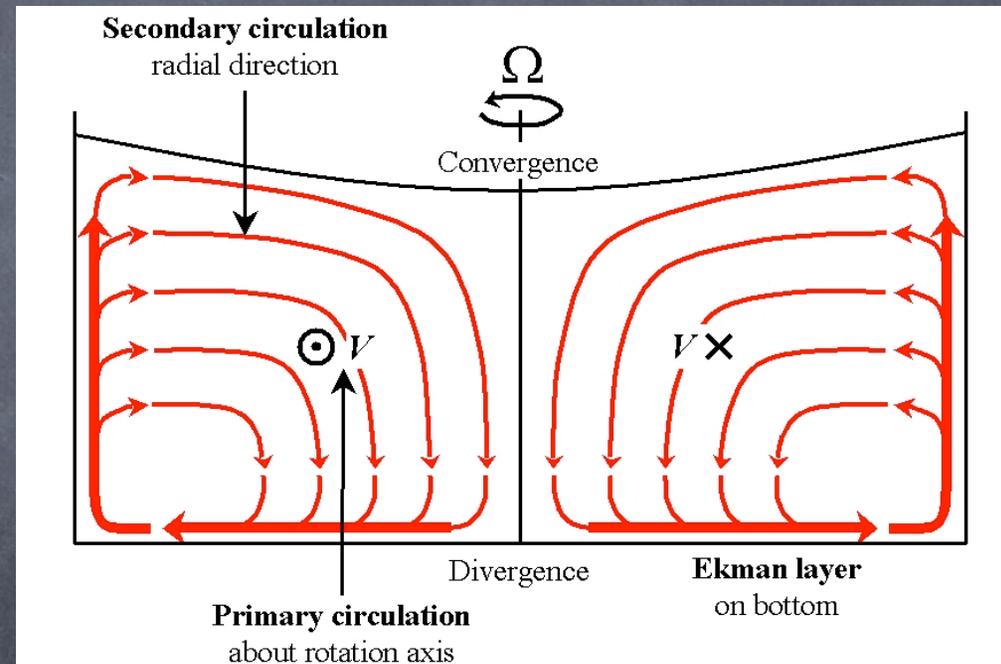
Ekman Spiral

- Icebergs drift 20–40 to right of surface wind because they extend down into the Ekman layer
- Ocean current becomes free of direct atmospheric influence below Ekman layer... approx 50m



Ekman Pumping/Suction

- Atmospheric vortices over the ocean drive a vertical circulation called Ekman Pumping (for cyclones) and Ekman Suction (for anticyclones)
- Effects can be felt through a large depth in the ocean

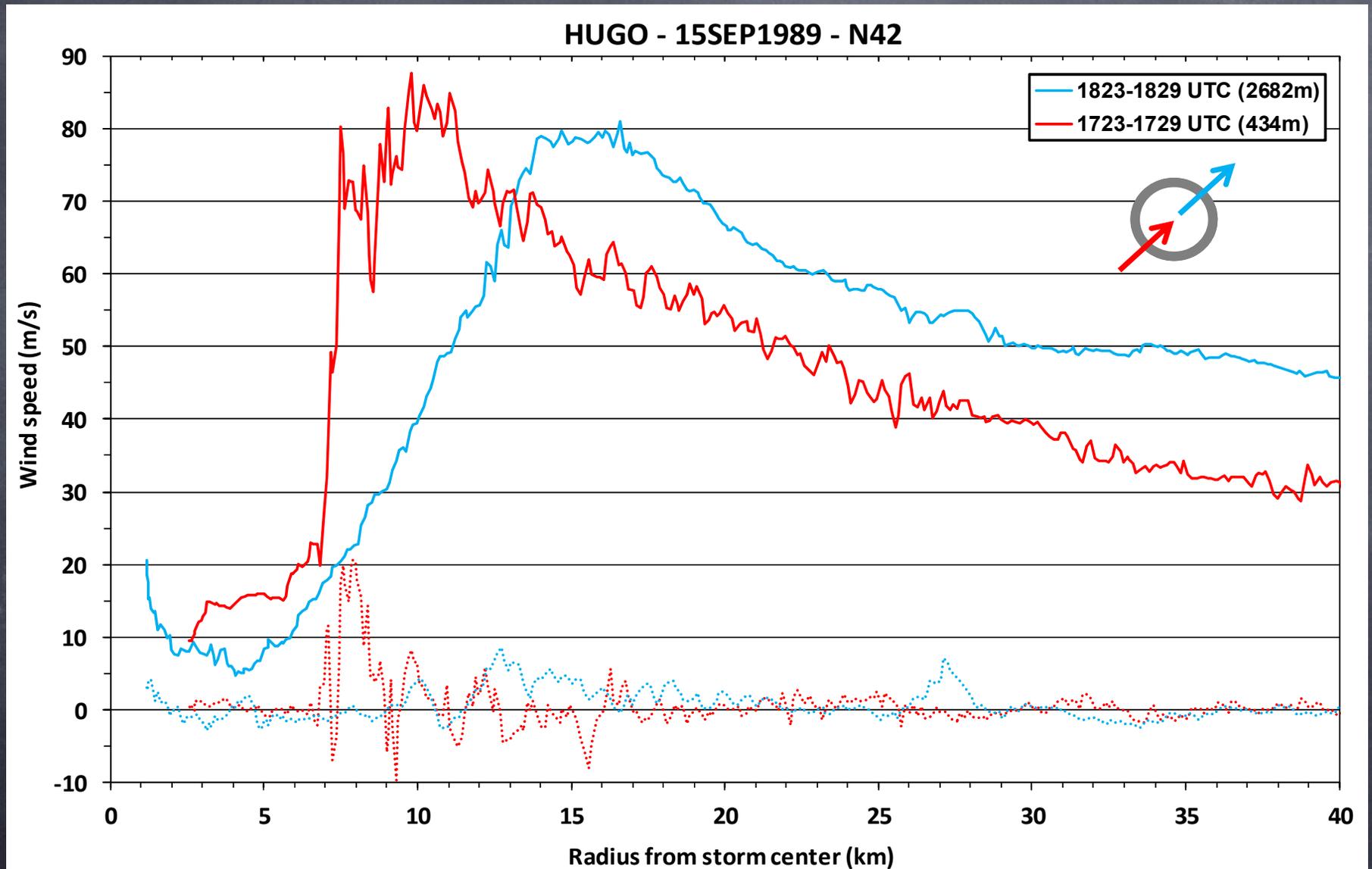


McNoldy et al. (2003)

Ekman Pumping and Shock-Like Structures in the Boundary Layer

- Ekman pumping can create shock-like structures in the boundary layer under certain tropical events
 - Tropical cyclones
 - The ITCZ
- A slab boundary layer model (SBLM) is used to investigate such structures

Hurricane Hugo Flight Data



solid curves: horizontal wind speed
dotted curves: vertical velocity

red curves: inbound, SW, 434 m
blue curves: outbound, NE, 2682 m

SBLM Under a Tropical Cyclone

- Primitive equation, axisymmetric model on the f -plane
- Frictional boundary layer (Ekman layer):
 - slab of constant depth h
 - predict horizontal velocities $u(r,t)$ and $v(r,t)$ within slab
 - diagnose vertical velocity $w(r,t)$ at top of slab
- Overlying layer (the tropical cyclone):
 - radial velocity assumed negligible
 - tangential velocity $v_{gr}(r)$ assumed to be in gradient balance and constant in time

SBLM Under a Tropical Cyclone

f = Coriolis parameter (constant)

K = coefficient of diffusion (constant)

$U = 0.78 (u^2 + v^2)^{1/2}$ = wind speed at 10 m height

c_D = drag coefficient (function of wind speed)

$$w^+ = \frac{1}{2} (|w| + w) = \begin{cases} |w| & \text{if } w \geq 0 \\ 0 & \text{if } w \leq 0 \end{cases}$$

rectified Ekman
pumping

$$w^- = \frac{1}{2} (|w| - w) = \begin{cases} 0 & \text{if } w \geq 0 \\ |w| & \text{if } w \leq 0 \end{cases}$$

rectified Ekman
suction

SBLM Under a Tropical Cyclone

two
predictive
equations

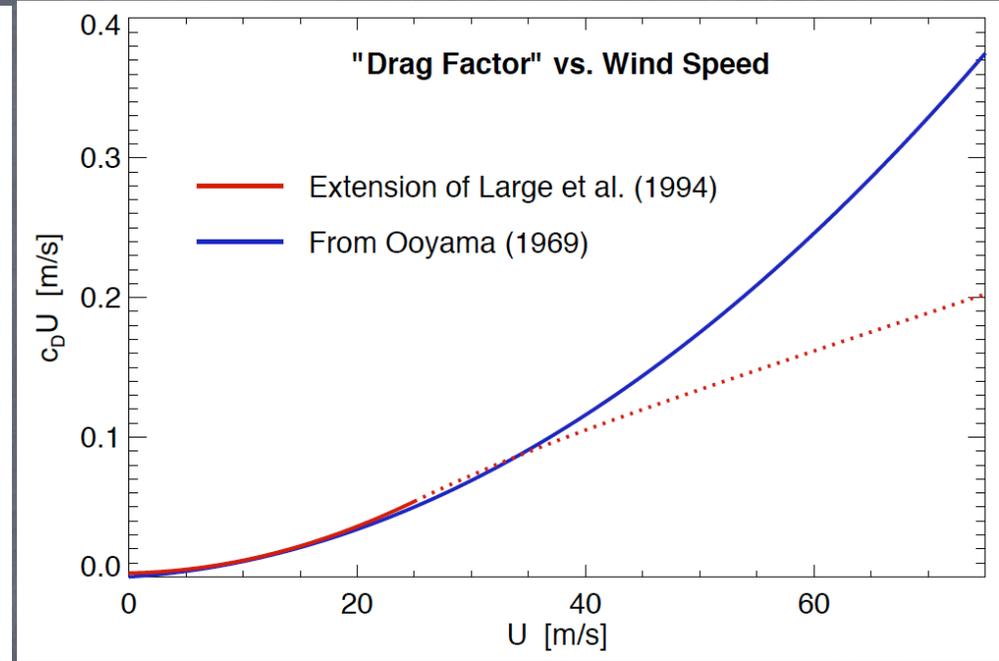
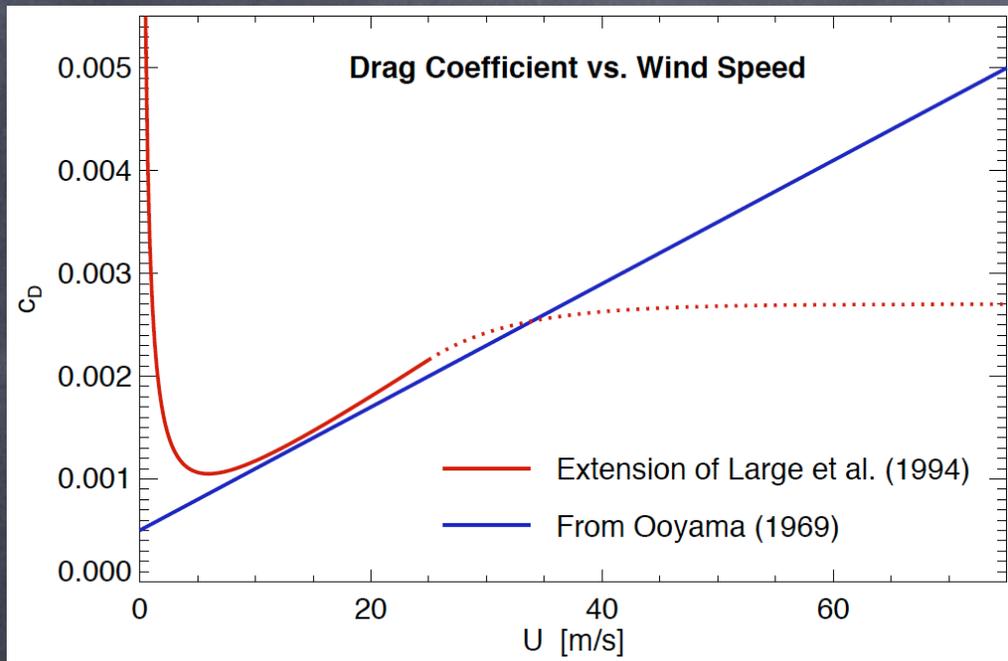
$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial r} - w^- \frac{u}{h} + \left(f + \frac{v + v_{gr}}{r} \right) (v - v_{gr}) - c_D U \frac{u}{h} + K \frac{\partial}{\partial r} \left(\frac{\partial(ru)}{r \partial r} \right)$$

$$\frac{\partial v}{\partial t} = -w^- \left(\frac{v - v_{gr}}{h} \right) - \left(f + \frac{\partial(rv)}{r \partial r} \right) u - c_D U \frac{v}{h} + K \frac{\partial}{\partial r} \left(\frac{\partial(rv)}{r \partial r} \right)$$

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

one diagnostic
equation

Drag Coefficient



- Red curve: extension of Large et al. (1994)

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

- Blue curve: from Ooyama (1969)

$$c_D = 10^{-3} (0.5 + 0.06U)$$



Tropical Cyclone Experiments

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

$$h = 1000 \text{ m}$$

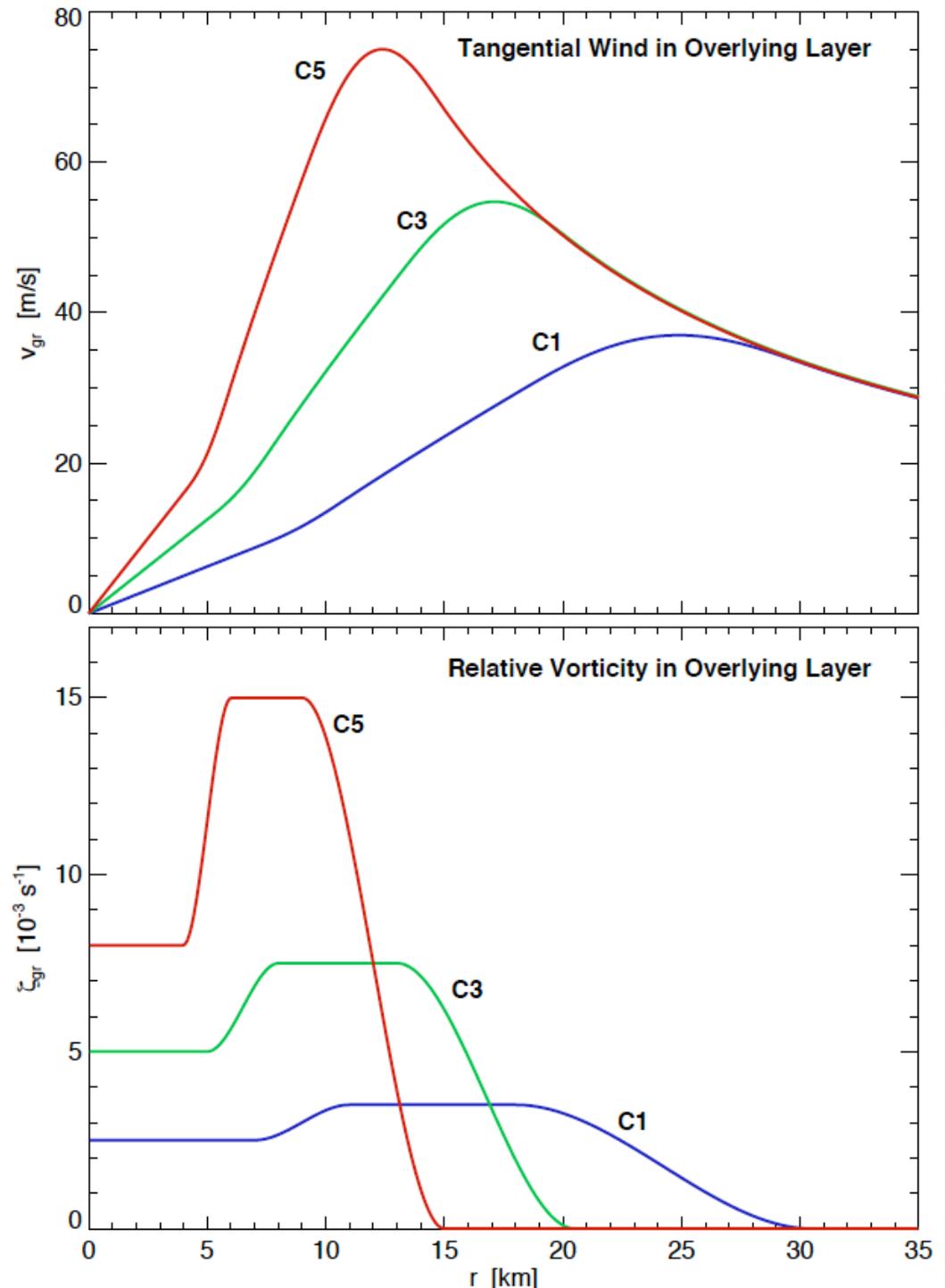
$$K = 4000 \text{ m}^2 \text{ s}^{-1}$$

$$0 \leq r \leq 1500 \text{ km}$$

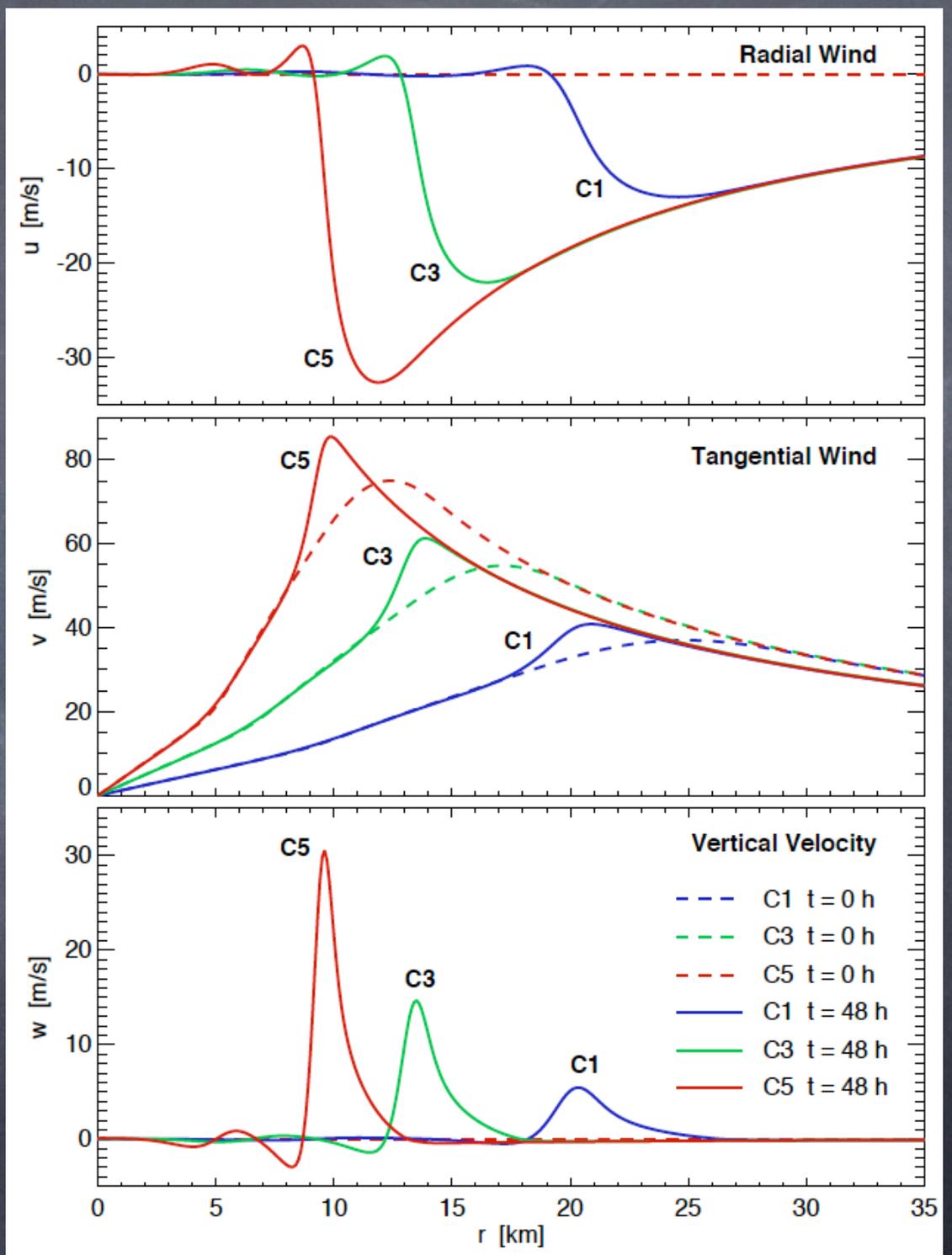
$$0 \leq t \leq 48 \text{ h}$$

$$\Delta r = 100.0 \text{ m}$$

$$\Delta t = 0.5 \text{ s}$$



Tropical Cyclone Results



Summary

- Realistic simulation of the QBO indicates that many things are correct in the GCM, e.g., vertical resolution, damping effects, convective generation of Kelvin and inertia-gravity wave activity.
- Strat-Trop exchange advects high PV air into the tropical upper troposphere. This yields isentropic upglide and atmospheric rivers.
- Tropical cyclone boundary layers can produce fine scale shocks associated with primary and secondary eyewalls. What about the ITCZ?