Katabatic wind-driven exchange in Greenland fjords

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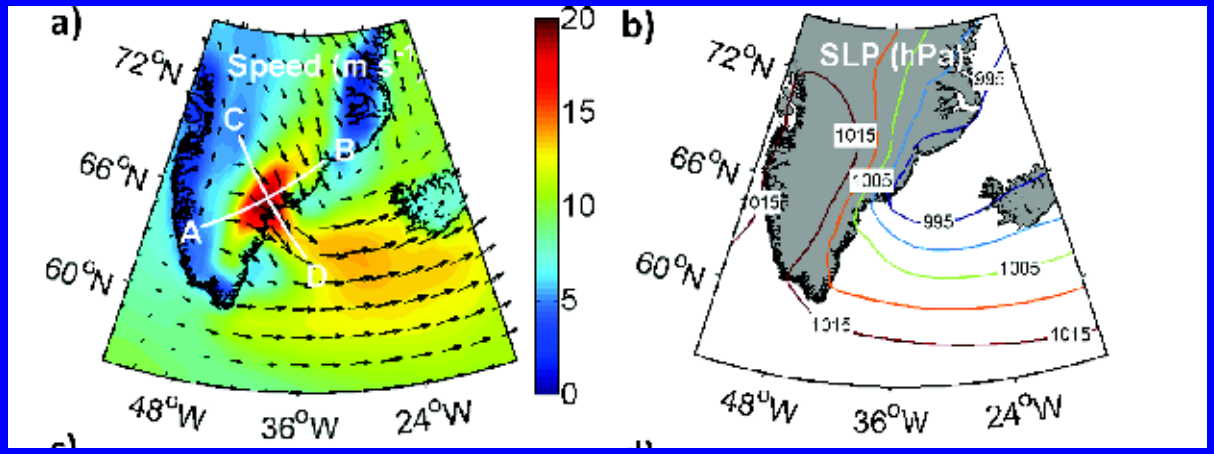


(Oltmanns et al., 2014)

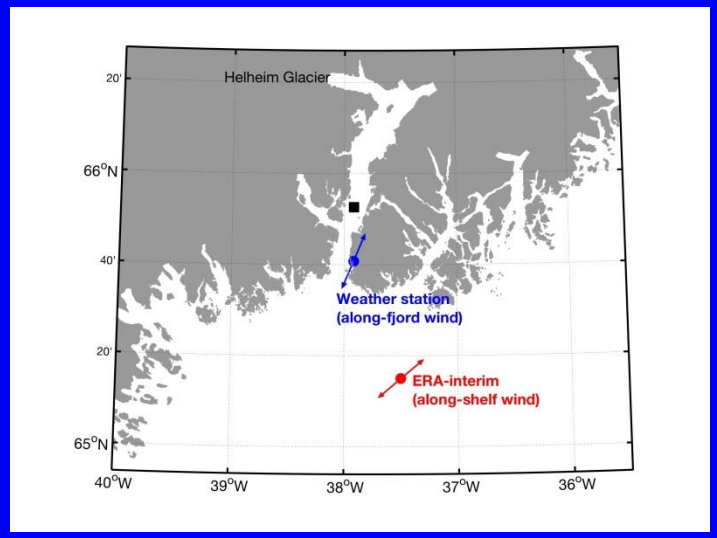
wind speed (m/s) sea level pressure

Passage of low pressure systems east of Greenland often drive katabatic wind events

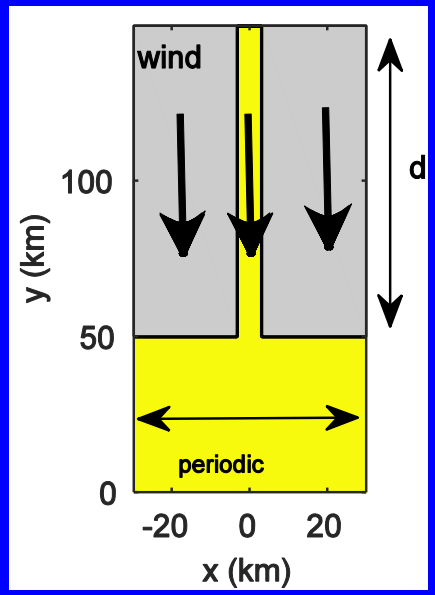
> typically winds in excess of 20 m/s

> duration 1-2 days, 5-10 events per year

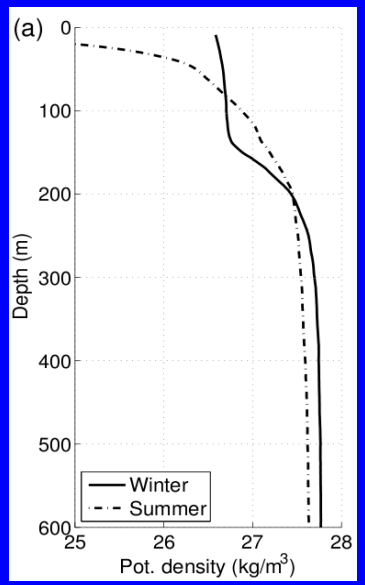
> anomalously cold atmospheric temperatures



Sermilik fjord



model domain



Observed density profile

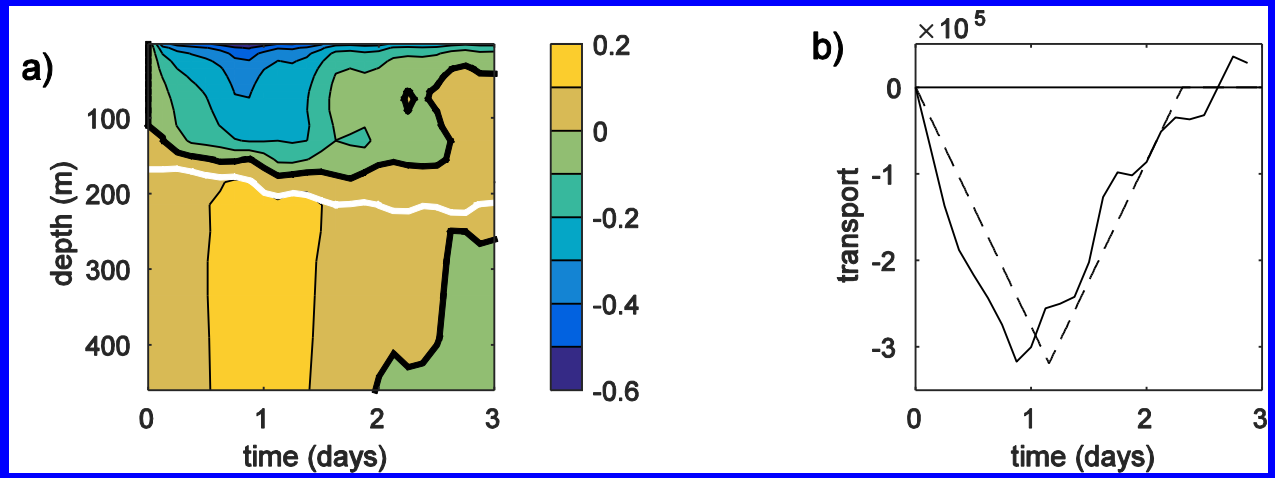
<u>Consider a very idealized fjord connected to a periodic shelf</u>

For the central case the fjord is 100 km long, 6.5 km wide, and 500 m deep
The initial state is at rest and approximately a 2 layer system with a transition from S_1 = 31 to S_2 = 32.125 at h_1 = 150 m depth
The baroclinic wave speed C = 1 m/s, deformation radius is 8.3 km

Spatially uniform wind is turned on at time 0 and held constant for 3 days

Solved with MITgcm, dx=250 m, 20 levels, KPP mixing, Smagorinsky viscosity

Example of exchange at fjord mouth



meridional velocity
(white line is salinity interface)

outflowing transport
solid line – model
dashed line – Farmer theory

$$\phi(t) = \frac{\tau h_2}{\rho_0 (h_1 + h_2)} \int_0^t \left[-\mathrm{H}(t' - y/C) + 0.5\mathrm{H}(t' - (y + d/C)) - 0.5\mathrm{H}(t' - (d - y)/C + \mathrm{H}(t') \right] dt'$$

Farmer (1976)

where H is the Heaviside step function, *d* is fjord length, *C* is wave speed, *y* is latitude

Flow spins up on *d/C* time scale, relaxes back to zero when the pressure gradient balances the wind stress. Friction and rotation are neglected.

When does friction become important ?

Assume for very narrow fjord the balance is between wind and friction

$$Av_{xx} = \frac{\tau}{\rho_0 h_1}$$

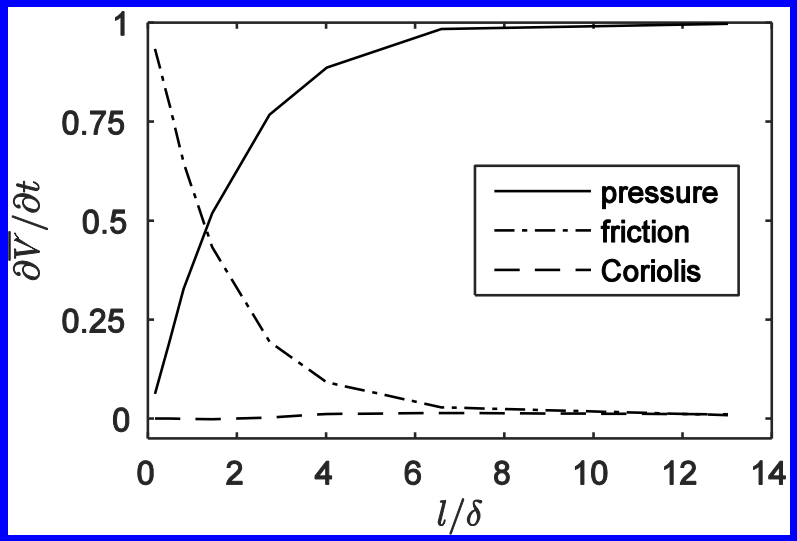
For Smagorinsky viscosity:
where Δ is grid spacing
V_m is max velocity in interior
δ is boundary layer thickness

$$A = \left(\frac{\upsilon\Delta}{\pi}\right)^2 v_x \approx \left(\frac{\upsilon\Delta}{\pi}\right)^2 \frac{V_m}{\delta}$$

Combine with Farmer theory:

$$\delta = \left[\left(\frac{\upsilon\Delta}{\pi}\right)^2 \frac{\tau}{\rho_0 h_1}\left(\frac{dh_2}{C(h_1+h_2)}\right)^2\right]^{1/3} \qquad V_0 = \left[\left(\frac{\pi}{\upsilon\Delta}\right)^2 \frac{\tau}{\rho_0 h_1} l^3\right]^{1/2}$$

l is fjord half-width, V_0 ($< V_m$) is the maximum velocity when $l < \delta$

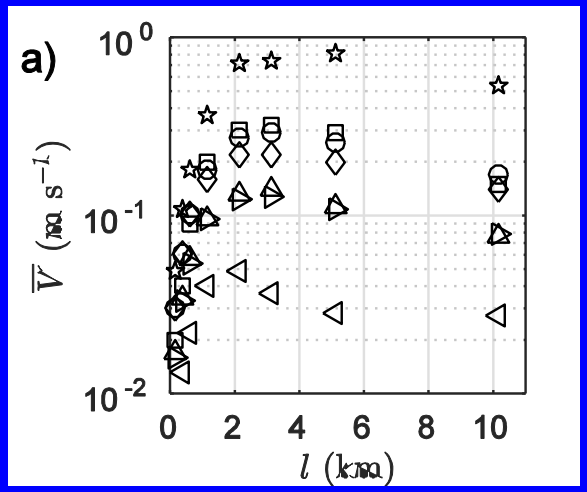


Run a series of calculations with different fjord widths, diagnose terms that balance wind stress (=1)

> Dominant balance is between wind and friction for $l/\delta < 1$
wind and pressure for $l/\delta > 1$

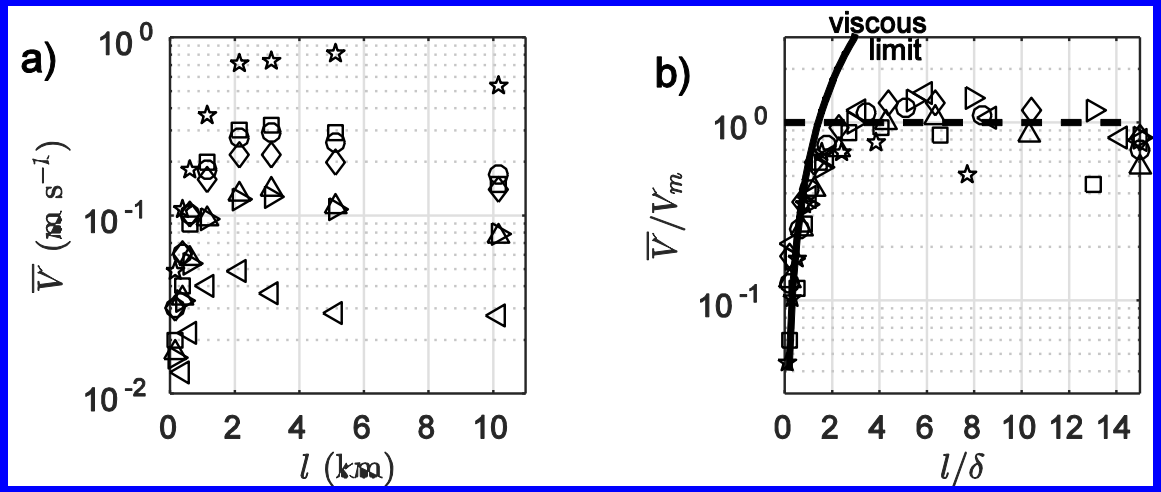
> Coriolis remains small even when $l > L_d$
(because of zonal return flow below Ekman layer in layer 1)

> Validates the assumption used to derive boundary layer scaling



Diagnosed maximum velocity ranges from 2 cm/s to 80 cm/s for a range of stratification, fjord lengths, fjord widths (symbols)

Now scale max velocity by V_m and l by δ

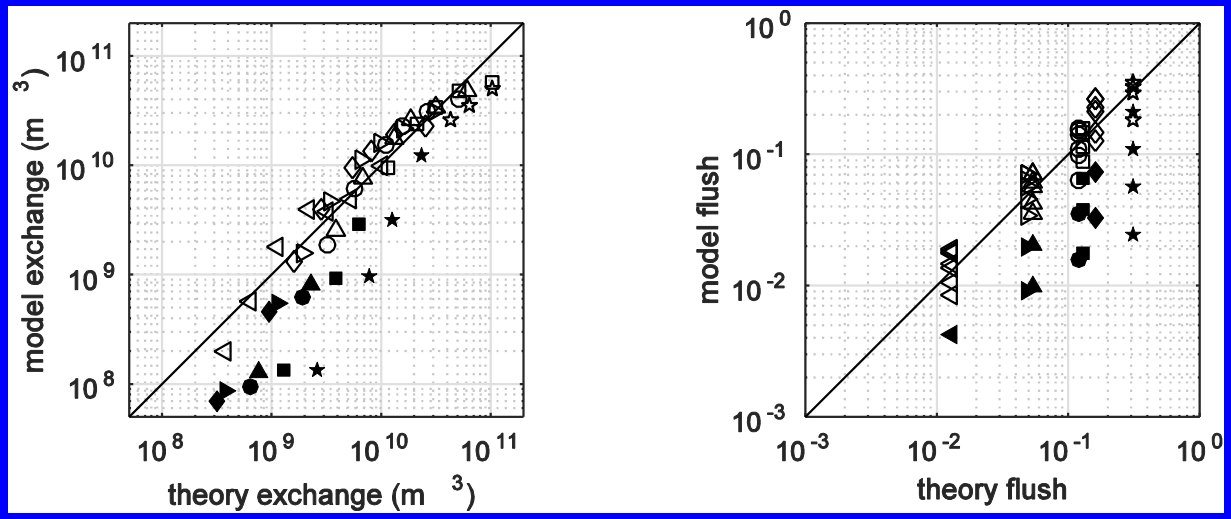


Test Farmer and scaling theories for maximum velocity in the fjord

Compares well with Farmer V_m when $l/\delta > 1$ (dashed line)

Compares well with boundary layer theory when $l/\delta < 1$ (solid line)

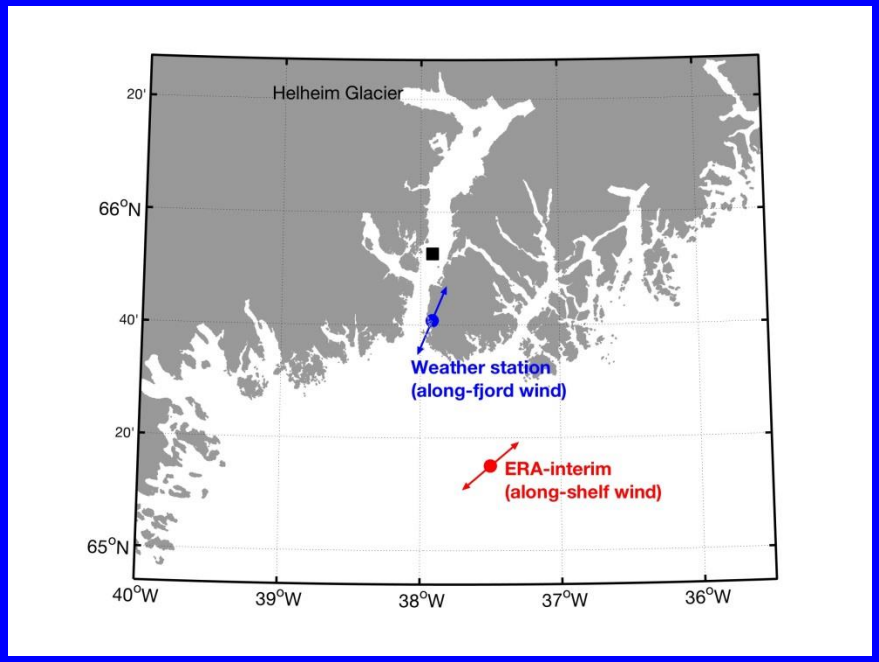
Total exchange over time 2 d/C

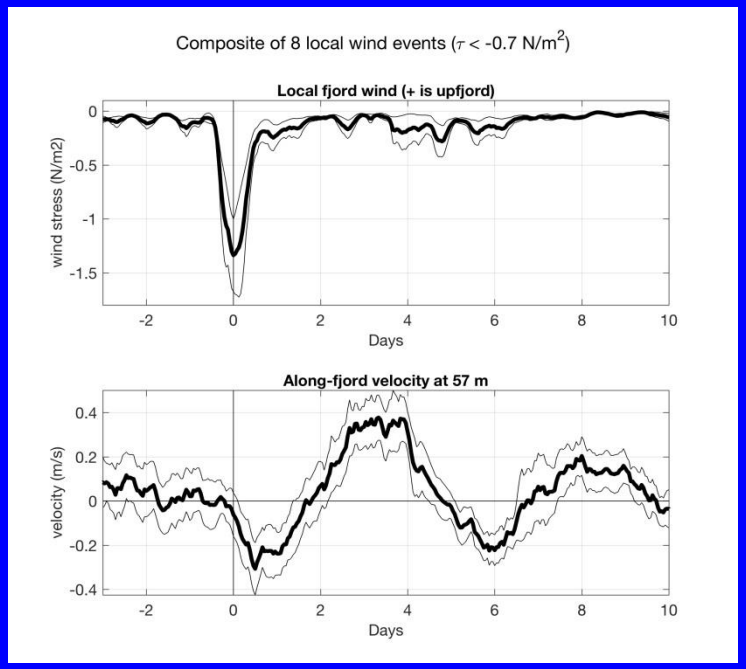


Integrated model exchange close to inviscid theory when $l/\delta > 1$ (open symbols)

Percentage of initial layer 1 volume that gets flushed out over time *d/C* ranges from a few (weak winds) to 10-20 % (realistic winds) for wide fjords

Implies that katabatic wind-driven exchange can represent an important mechanism for exchange between fjords and the ocean shelf



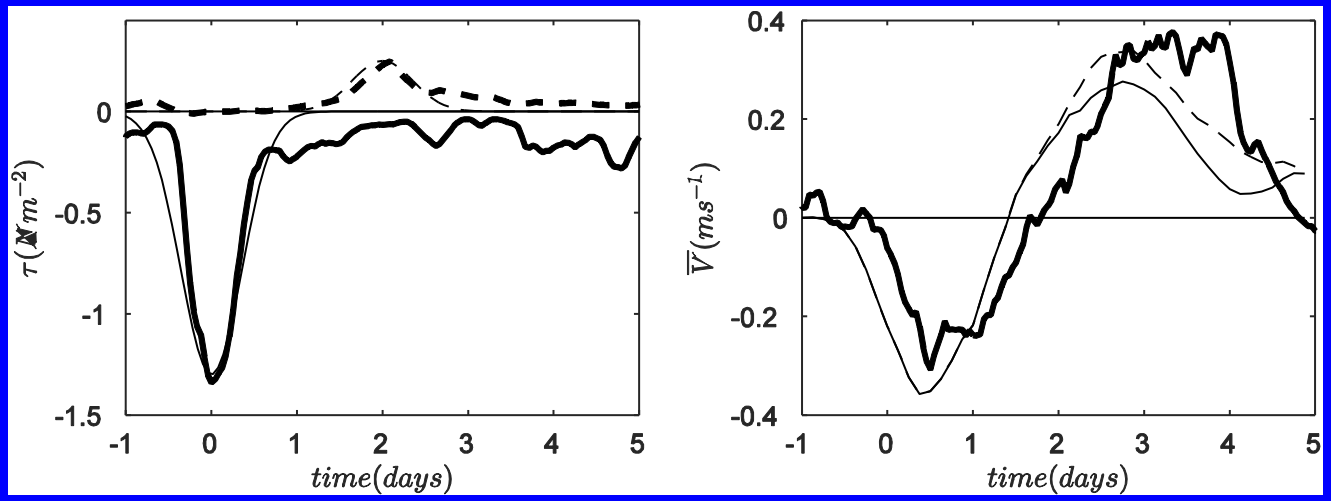


Compare numerical model with observations in Sermilik fjord

Composite of 8 katabatic wind events based on weather station data

Mooring observations (square) show outflow following winds, with inflow 2-4 days after the wind peak

There also tends to be a weaker along-shelf wind event a few days after the katabatic wind event (not shown here)



Wind forcing:
thick = obs, thin = model
solid – along fjord τ
dashed – along-shelf τ

Outflow at 57 m:
thick = observations
thin = numerical model
(solid is without weak along-shelf wind event)

Gross characteristics of the observations are reproduced by the model, including outflow of O(30 cm/s) for 1.5 days, inflow of similar magnitude for another 2 days. Along-shelf wind event strengthens and prolongs the inflow.

Summary

- Katabatic wind events are common along east Greenland fjords

- Numerical models and simple theories suggest two limits:
  - exchange in fjords narrower than the boundary layer thickness δ is limited by friction, nonlinear function of geometry, stratification, forcing
  - exchange in wide fjords is well predicted by the linear, nonrotating, inviscid two-layer theory of Farmer (1976)

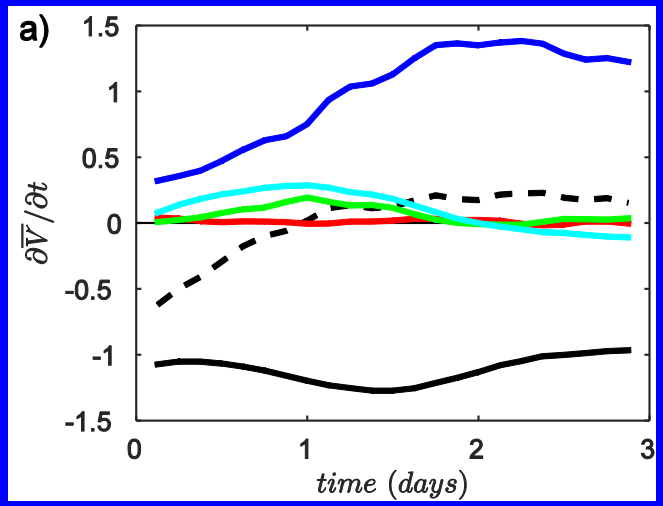
- Typical parameters yield exchange of O(10%) of the low salinity volume in a single wind event

- The idealized model reproduces the observed upper layer velocity reasonably well

Meridional momentum equation balance (integrated over upper layer in the fjord)

$$v_t = -uv_x - vv_y - wv_z - fu - P_y / \rho_0 + F$$

tendency nonlinear Coriolis pressure friction



blue – pressure
black – wind
dashed – tendency
green – nonlinear
cyan – friction
red - Coriolis

Dominant balance is between pressure gradient and wind
friction is isolated within δ of boundaries
Coriolis is small (because is zonal return flow below the Ekman layer)