Katabatic wind-driven exchange in Greenland fjords

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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

(Oltmanns et al., 2014)
Consider a very idealized fjord connected to a periodic shelf.

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.
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

\[ A v_{xx} = \frac{\tau}{\rho_0 h_1} \]

For Smagorinsky viscosity:
where \( \Delta \) is grid spacing
\( V_m \) is max velocity in interior
\( \delta \) is boundary layer thickness

\[ A = \left( \frac{\nu \Delta}{\pi} \right)^2 v_x \approx \left( \frac{\nu \Delta}{\pi} \right)^2 \frac{V_m}{\delta} \]

Combine with Farmer theory:

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

\( l \) is fjord half-width, \( V_0 (\leq V_m) \) 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 $\delta$. 
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)
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 $\tau$
  - dashed – along-shelf $\tau$

**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 $O(30 \text{ cm/s})$ 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 $\delta$ 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)

\[ \nu_t = \ -u\nu_x - v\nu_y - w\nu_z - fu - \frac{P_y}{\rho_0} + F \]

- tendency
- nonlinear
- Coriolis
- pressure
- friction

**Dominant balance is between pressure gradient and wind friction is isolated within \( \delta \) of boundaries**

Coriolis is small (because is zonal return flow below the Ekman layer)