Downfront winds in a coastal environment

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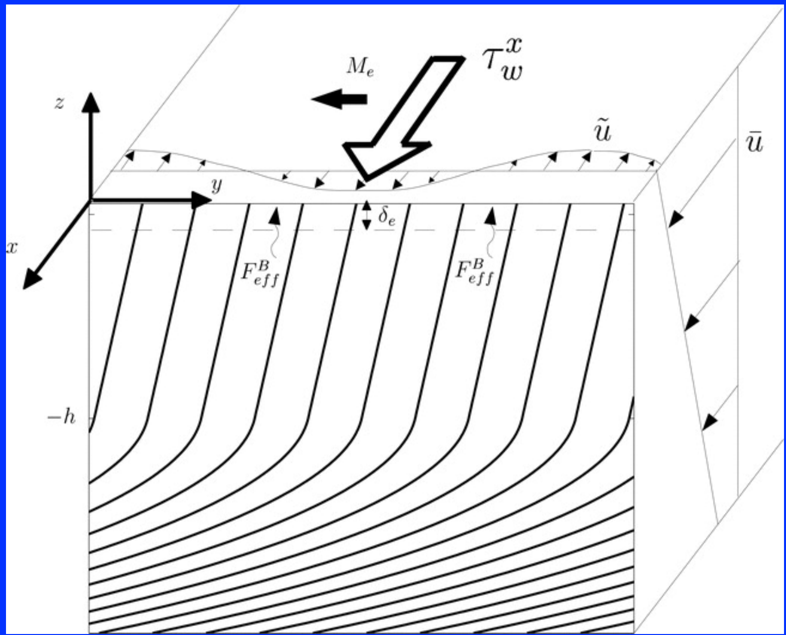
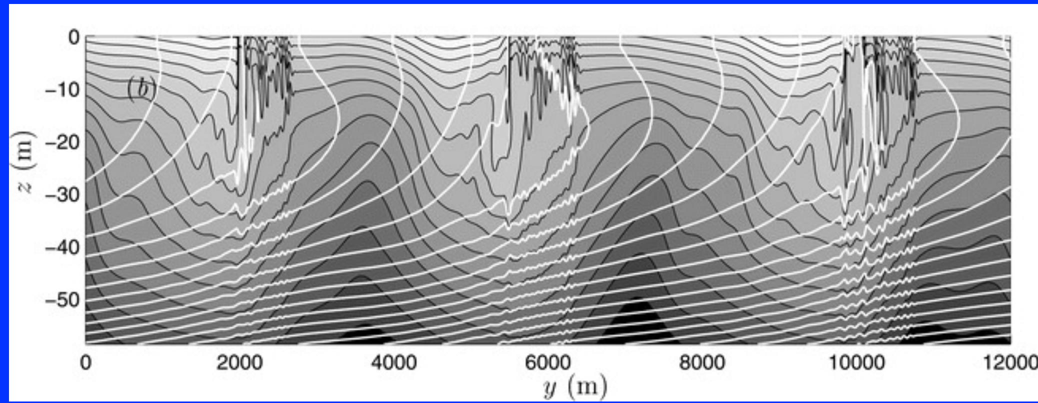
Downfront winds in the open ocean
(Thomas and Lee, 2005)



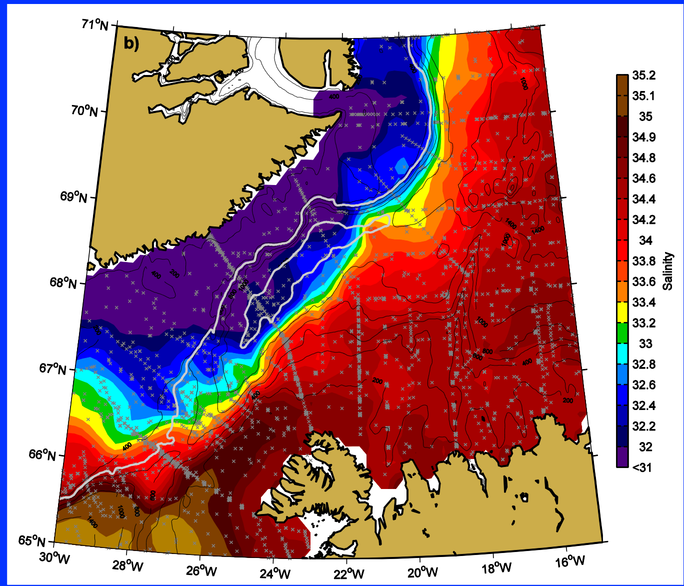
schematic of downfront wind



along-front velocity and density

Downfront wind produces a destabilizing Ekman transport

This provides an effective buoyancy flux to the interior.
Feedbacks between secondary circulations and the nonlinear Ekman layer result in frontogenesis

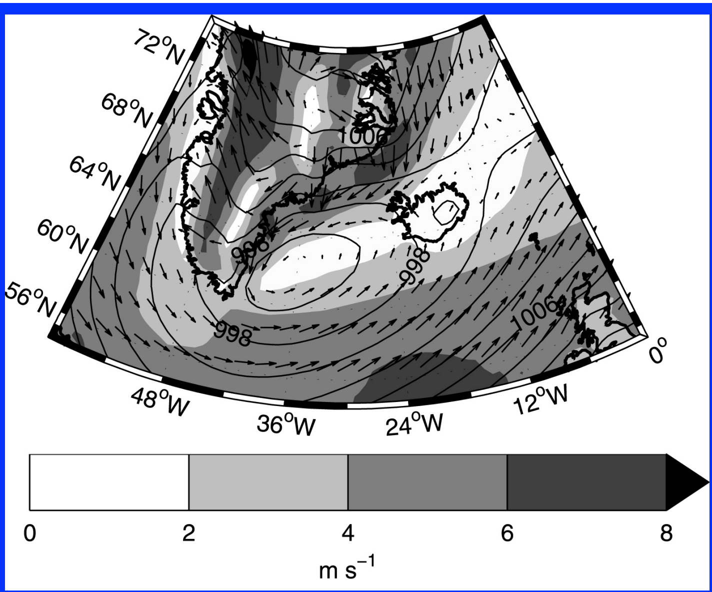


Climatological average
salinity upper 30 m

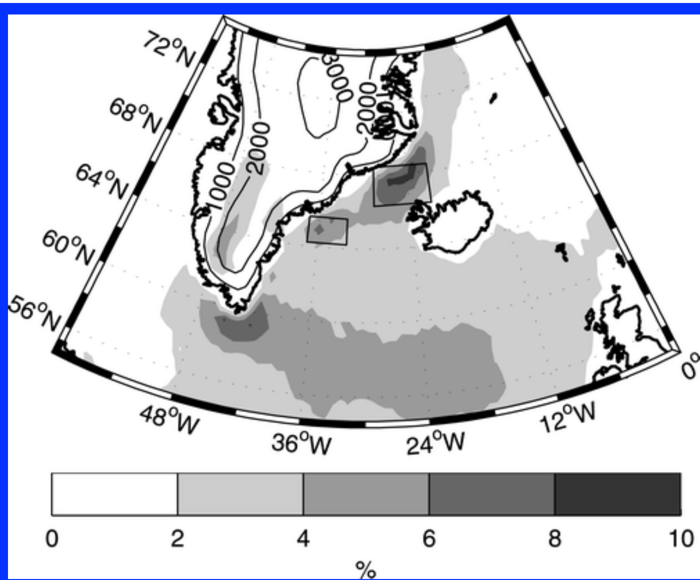
(Vage et al., 2013)

Freshwater is found over the shelf along the east coast of Greenland (black and gray contours are bottom topography)

It is contained on the shelf north of the Blossville Basin but spreads over the deeper water as Denmark Strait is approached



Mean wind speed



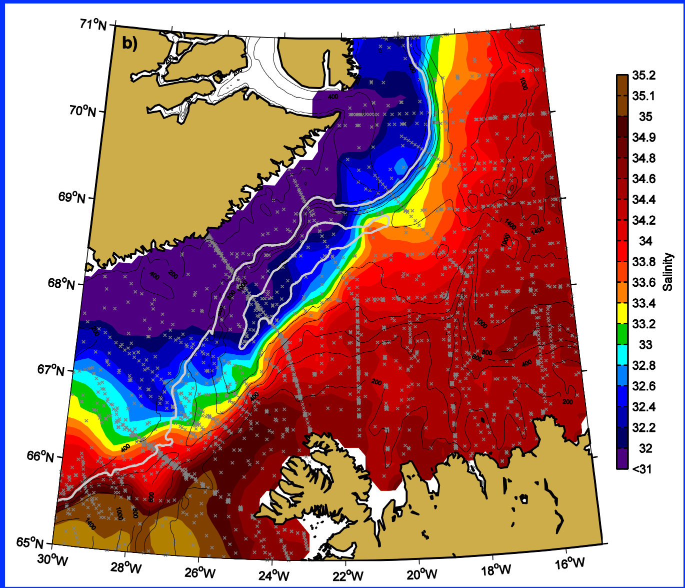
percent > 20 m/s

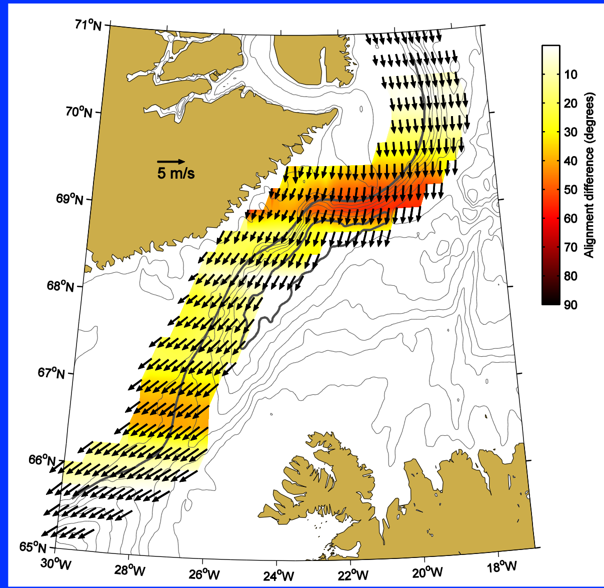
Harden et al 2011

Mean winds approach 8 m/s towards the south over the shelf east of Greenland

The winds exceed 20 m/s approximately 10% of the time

These are barrier wind events resulting from low pressure systems and the tall orography of Greenland

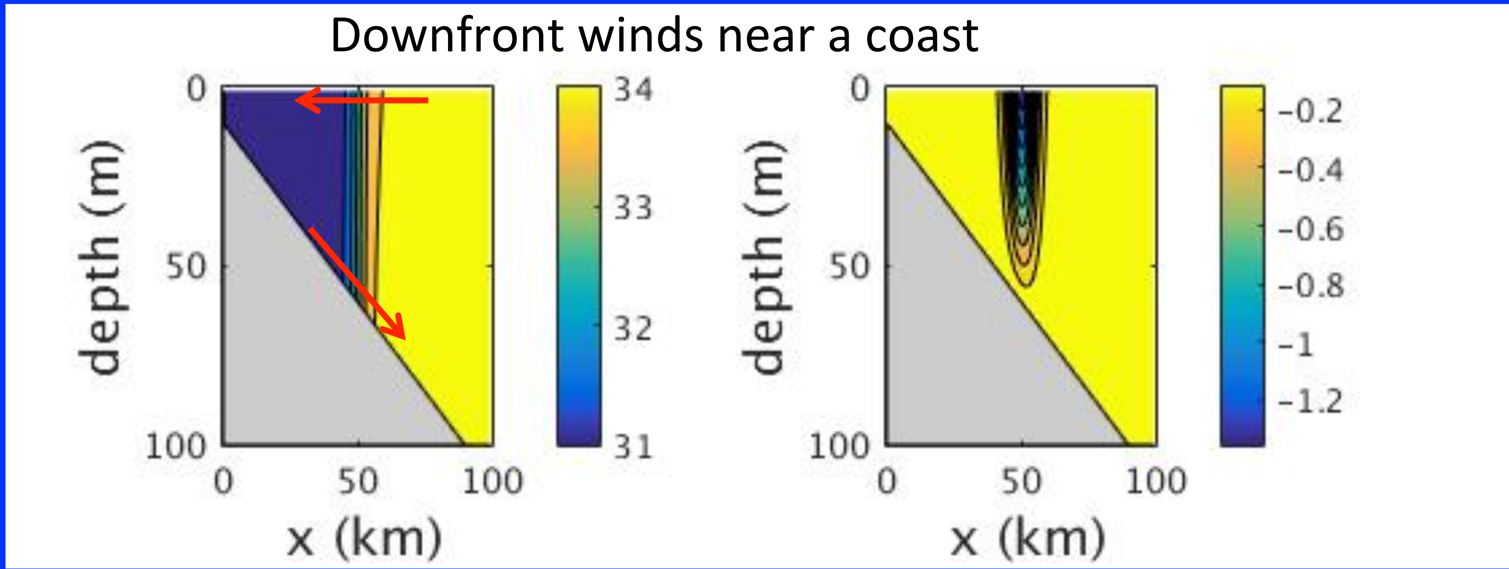




The freshwater leaves the shelf just where the wind is no longer parallel to the shelf break (red colors on right hand panel). Wind can not turn the corner and remain parallel to the tall orography of Greenland

Suggests that the wind is responsible for keeping the freshwater over the shelf, in opposition to baroclinic instability that works to restratify and spread freshwater into the basin interior

How do downfront winds interact with freshwater on the shelf?



salinity meridional velocity

For downfront wind, Ekman transport is towards the coast
drives increase in sea surface height and downwelling

Bottom Ekman layer will develop in response to ssh buildup and
barotropic flow, resulting in offshore flow near the bottom

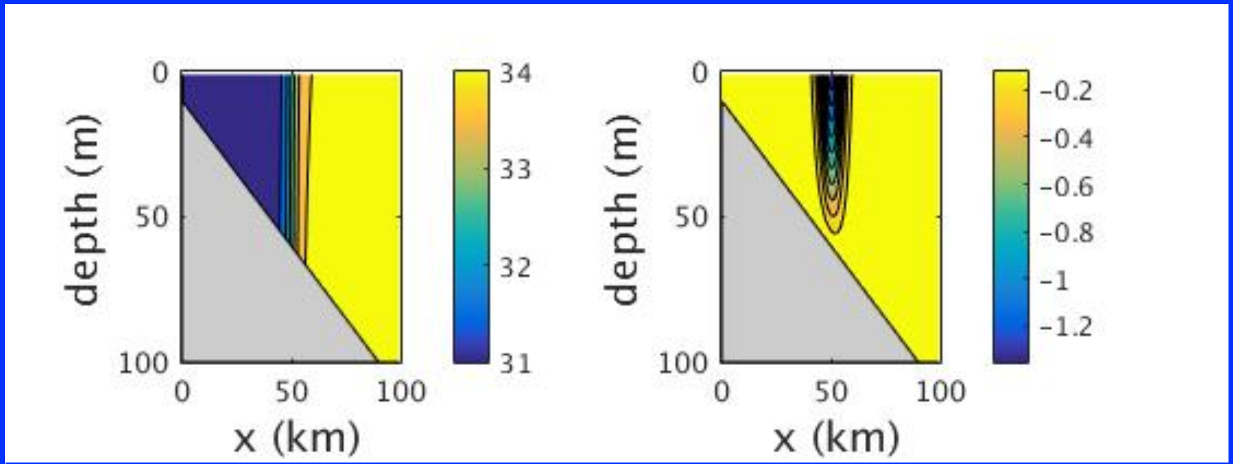
Both Ekman layers are destabilizing

Baroclinic instability attempts to restratify the fluid

We anticipate a balance between Ekman transport and bc instability

MITgcm:

hydrostatic PE
500m grid spacing in x,y
(250 m very similar)
2m grid spacing in z
periodic channel in y
uniformly sloping bottom
100km x 100 km domain
KPP mixing parameterization
Smagorinsky viscosity coefficient 2.5

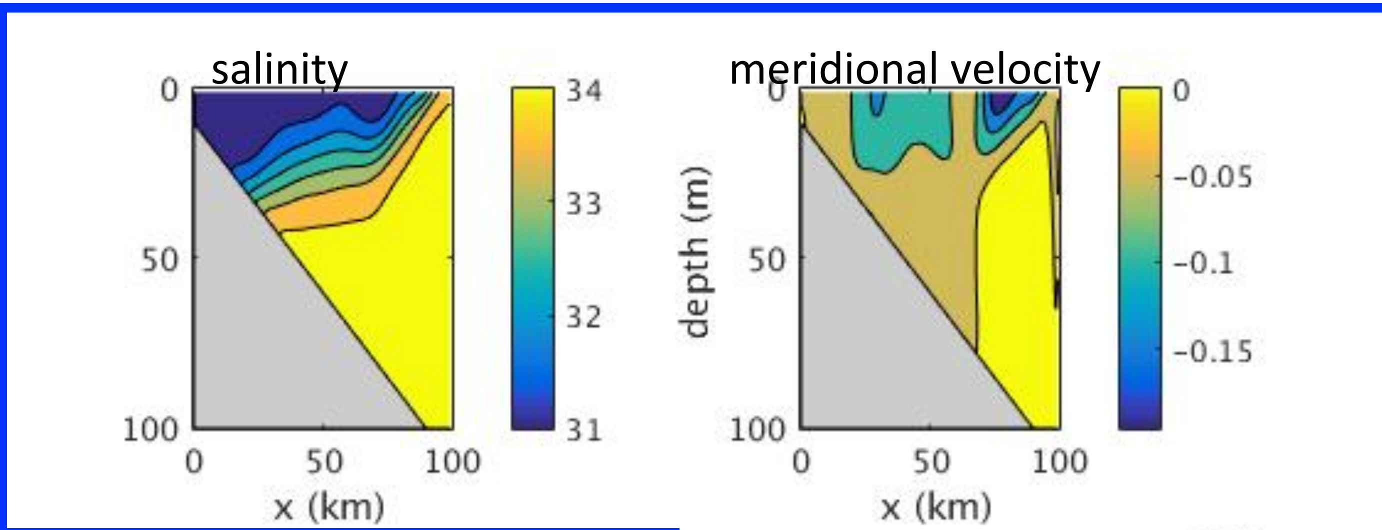


initial salinity

meridional velocity

Initialized with freshwater (31) over inner slope and salty water (34) over outer slope
Velocity is in geostrophic balance

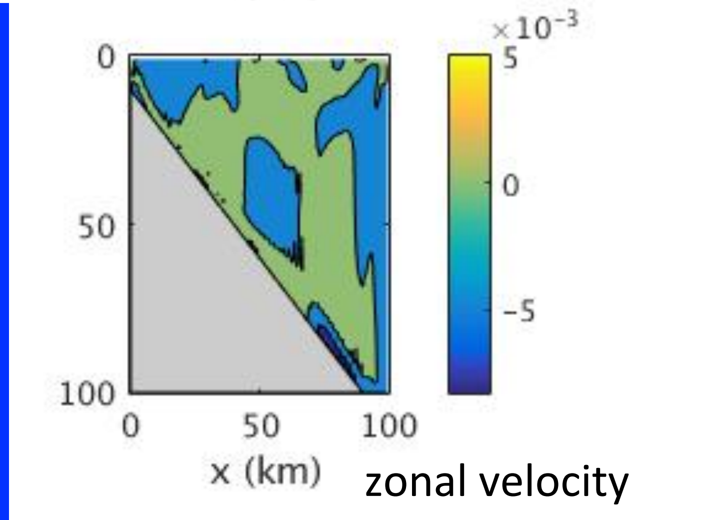
Uniform downfront wind is spun-up over several days then held steady
out to 30 days integration



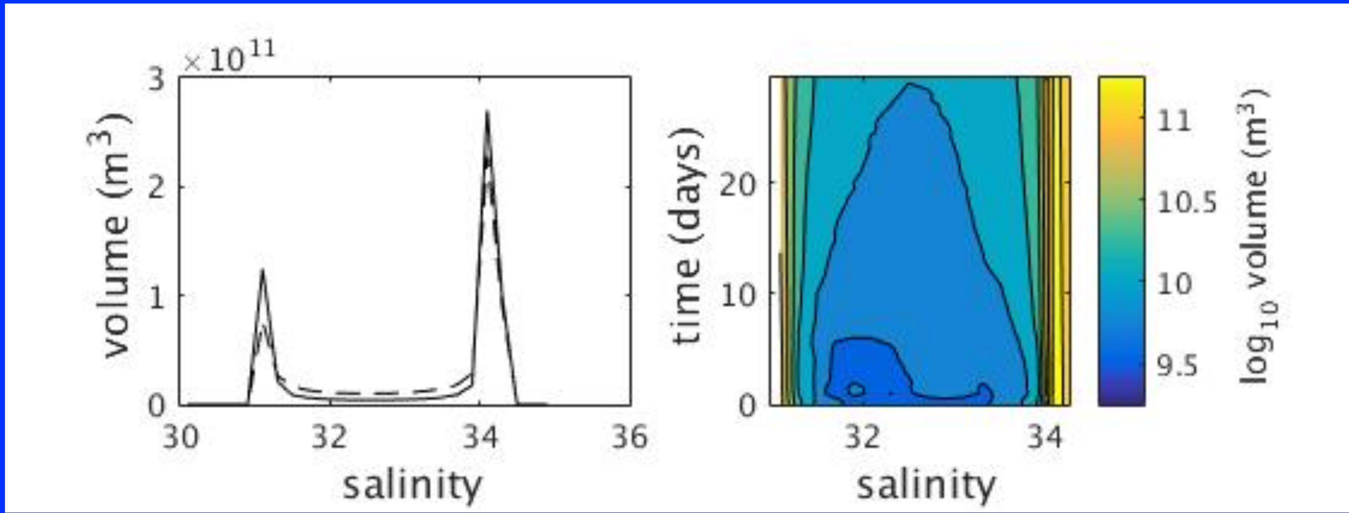
First, run the model for 30 days with no wind

Spin-down with offshore flux of freshwater

Relatively weak velocities in both
along slope (10 cm/s) and
across slope (< 1 cm/s) directions



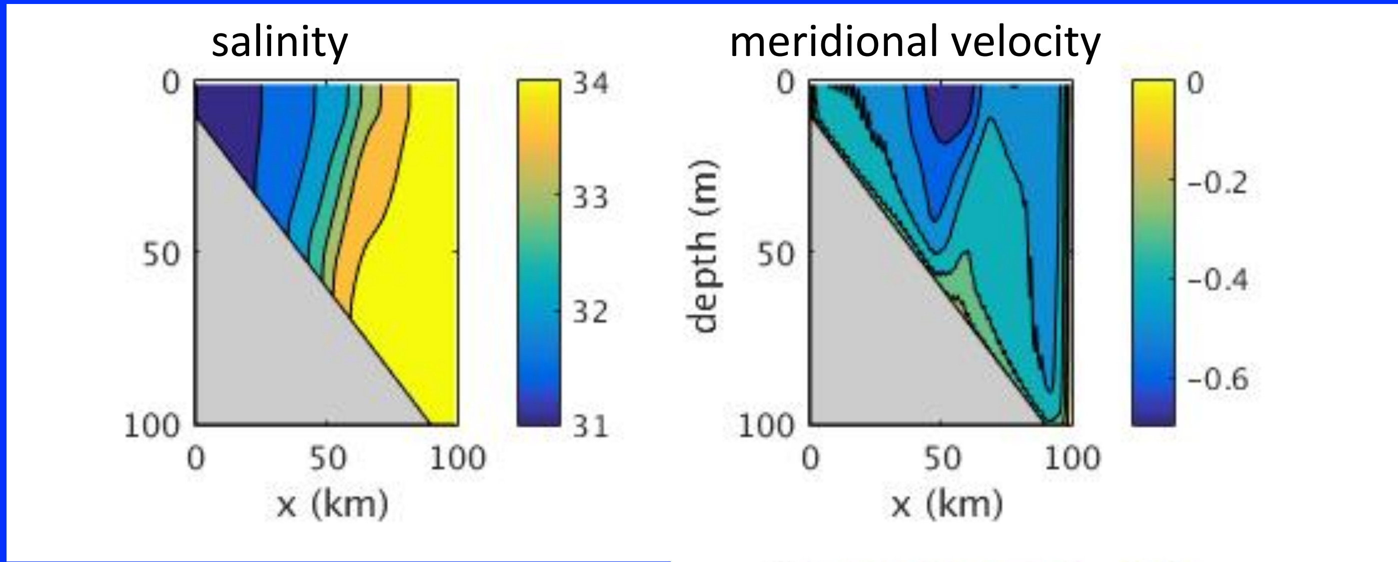
Water mass transformation



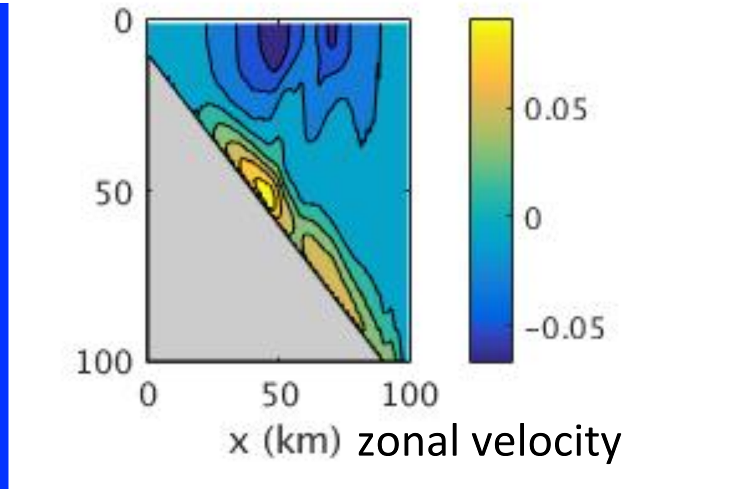
Solid line: initial conditions
Dashed line: after 30 days

There is only very weak mixing of water masses between the fresh and salty water, two modes remain clearly separated

along-slope and
time mean



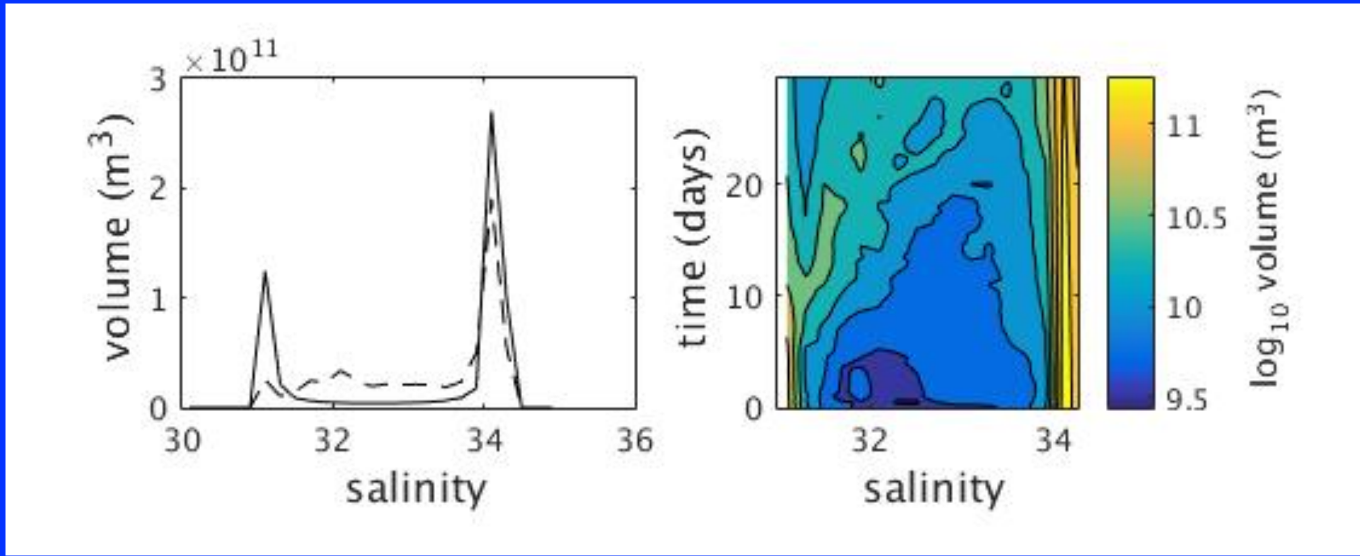
Now apply a uniform wind stress of -0.1 N/m^2



Fresh water remains over shallow slope
Isohalines are nearly vertical
along slope velocity O(60 cm/s)
across slope velocity O(5 cm/s)

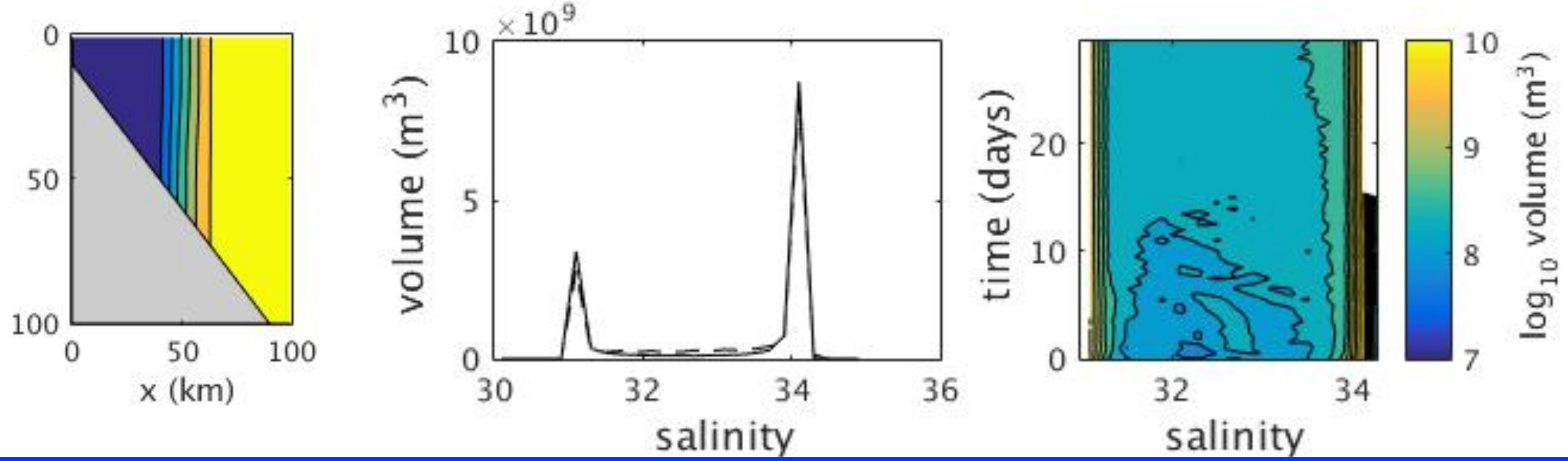
There is now a strong barotropic along slope flow
Cross slope flow carried in surface and bottom Ekman layers
nonlinearity is important, enhanced flow in regions of anticyclonic shear
$\tau/(f+\zeta)$ determines Ekman transport

Water mass transformation



Solid line: initial conditions
Dashed line: after 30 days

Compared to the no-wind case, there is much more mixing of the fresh water, the freshwater peak is now at > 32
This mixing begins around day 8, once baroclinic instability is active

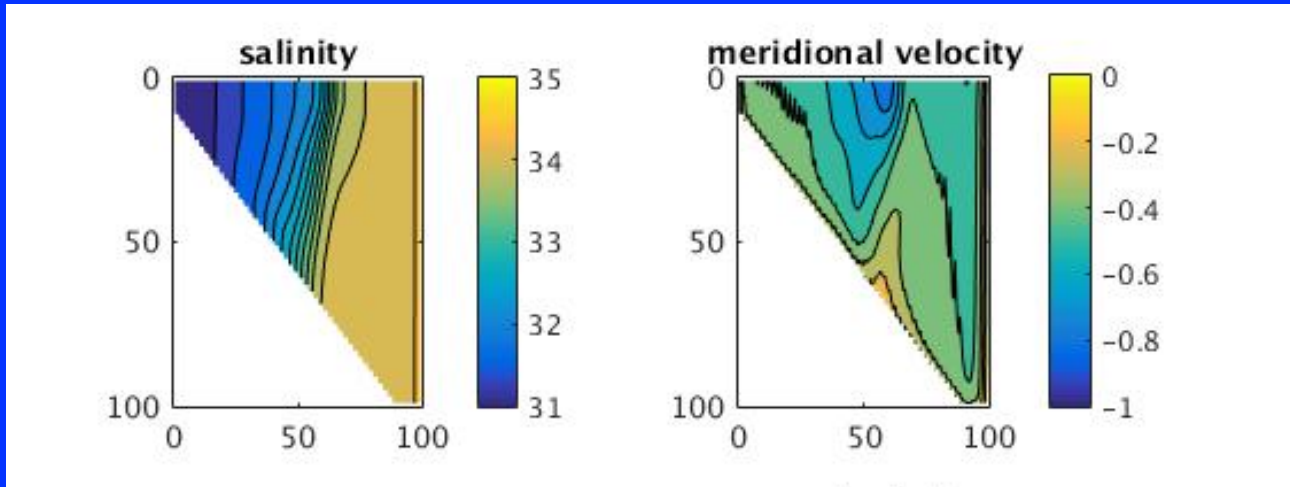


It is not just the wind – a two-dimensional calculation with $\tau = -0.1$ results in no net change in water masses!

This is because the net cross-slope flow is zero and the lateral gradient of salinity is independent of depth (since the isohalines are vertical).

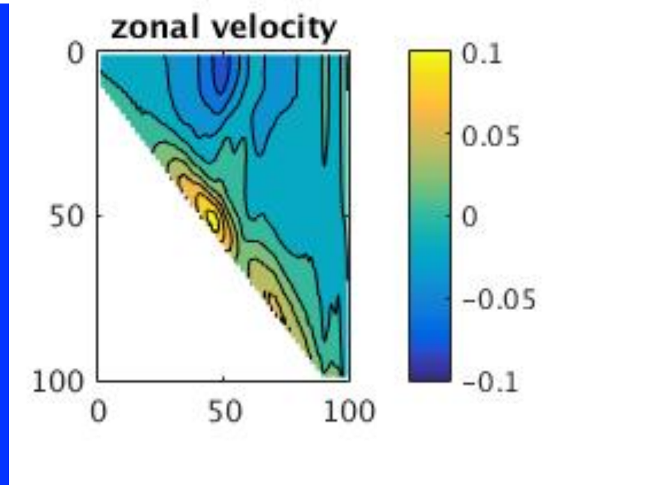
The vertical mixing of salty water exactly balances the vertical mixing of fresh water so there is no change in the volume in each salinity class.

So what is it about baroclinic instability and wind that causes mixing?

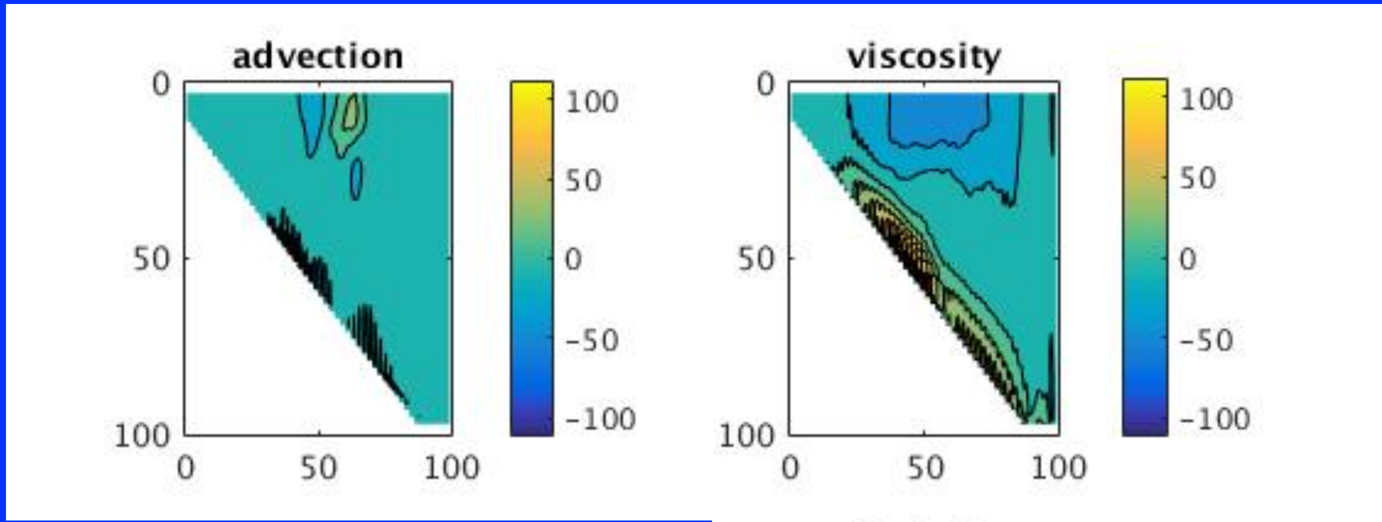


Circulation looks qualitatively similar to
what we expect for a 2-d case:

cross slope overturning in surface and
bottom Ekman layers, near vertical isohalines

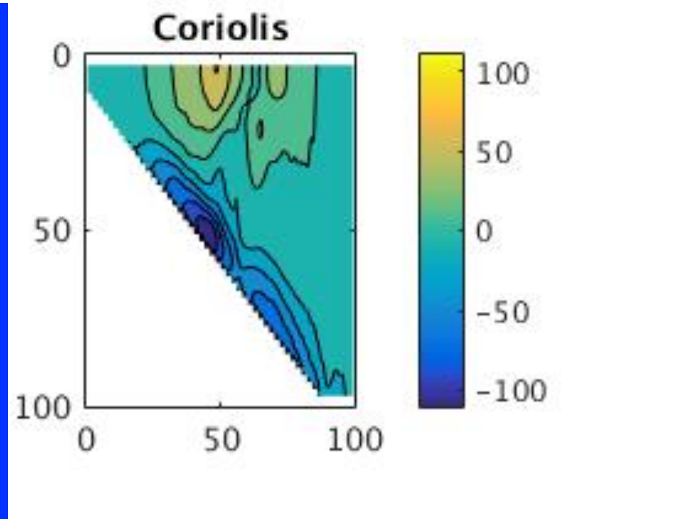


Terms in along slope momentum budget

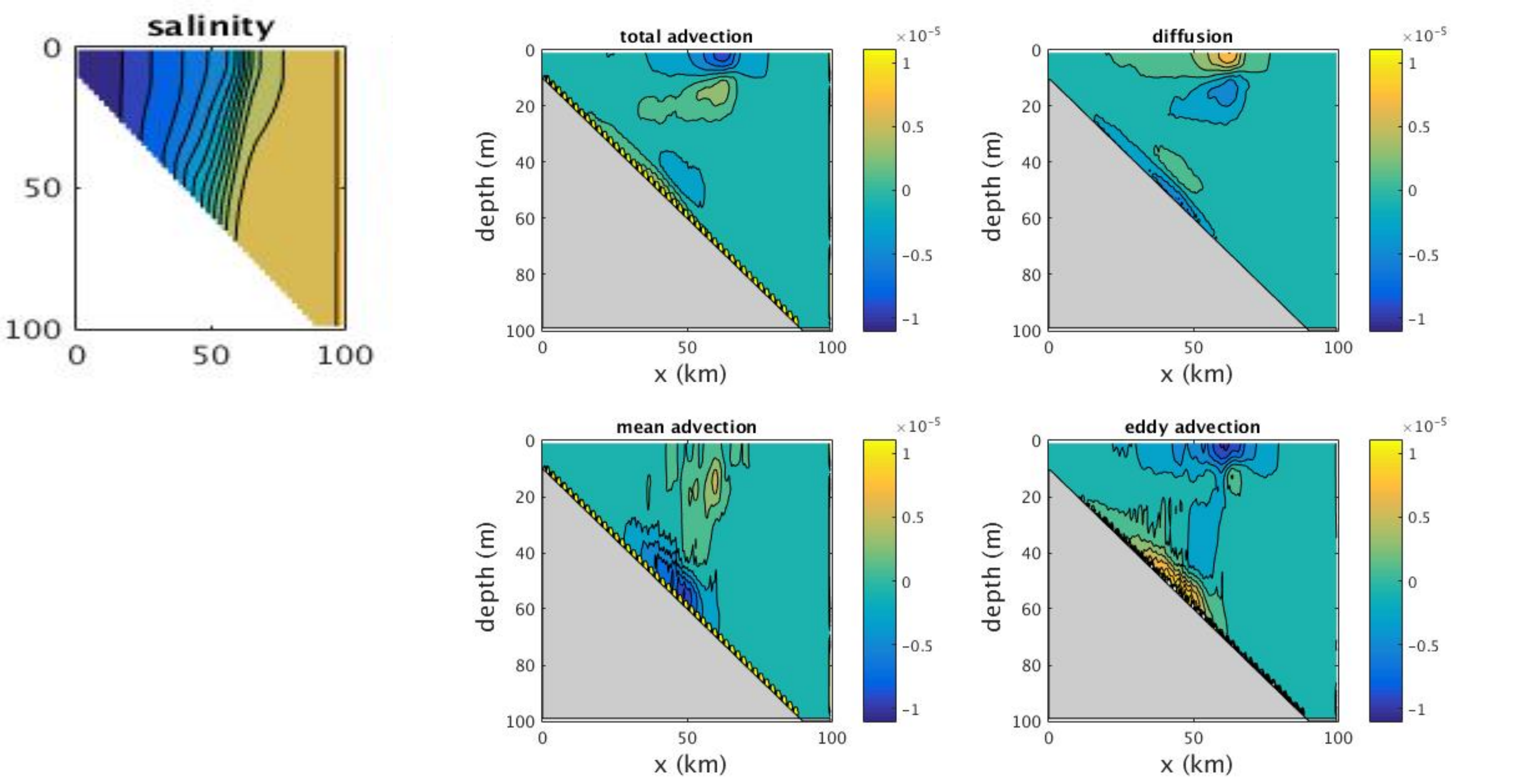


Momentum budget is also consistent with surface and bottom Ekman layers, with weak contribution from nonlinear terms (due to relative vorticity)

The pressure gradient drops out because the domain is periodic in y

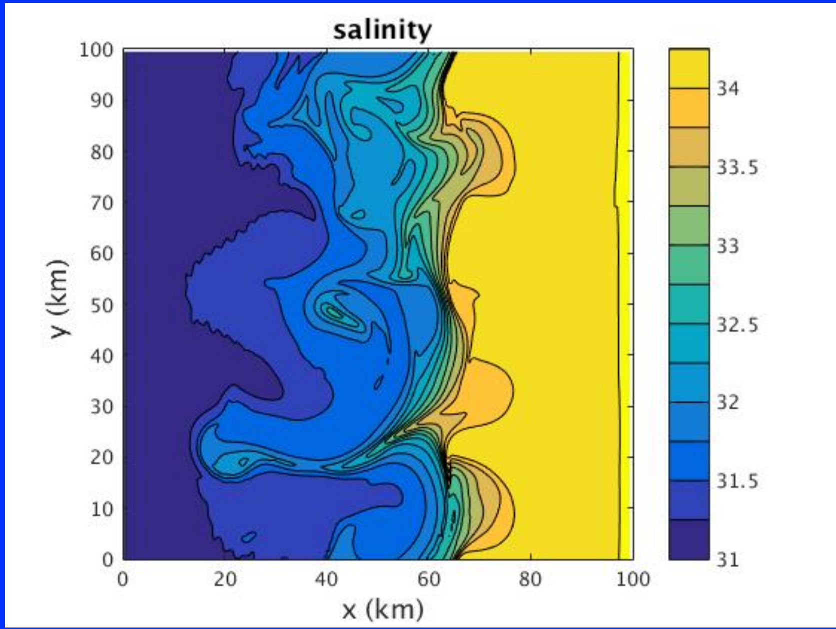


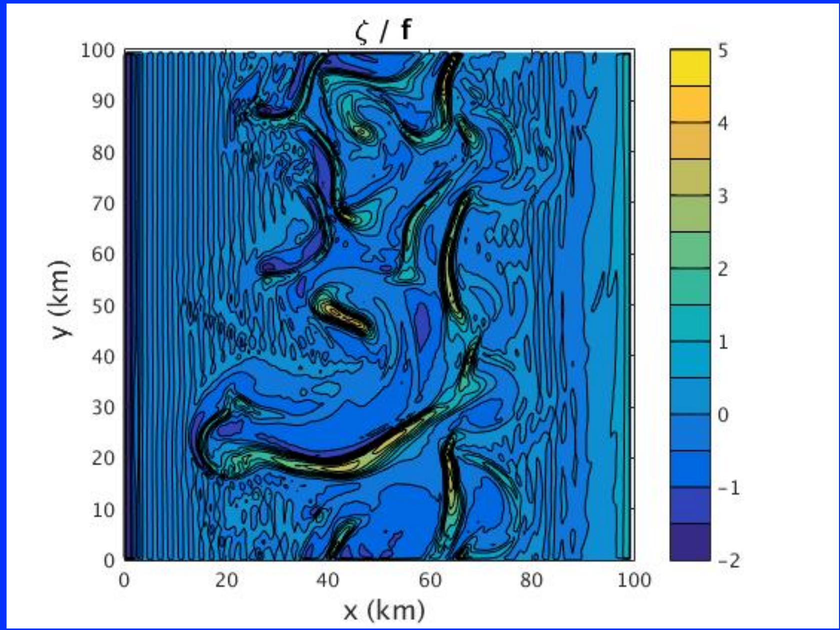
The salinity budget gives a different picture



Advection is making surface fresher and subsurface saltier, balanced by diffusion (opposite from that expected by linear Ekman circulation)

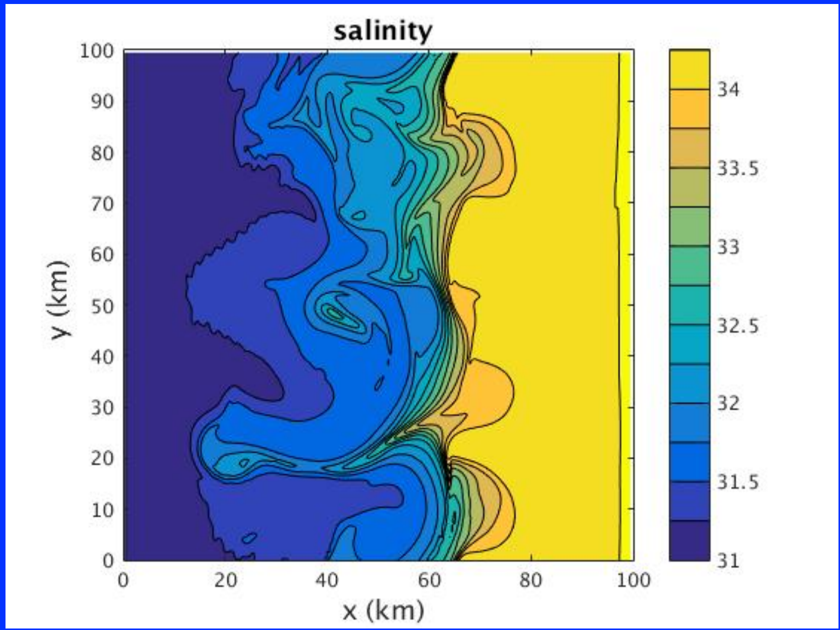
Advection is due to eddies near the surface but mean is important in the interior and near the bottom – most of the transformation takes place near the surface

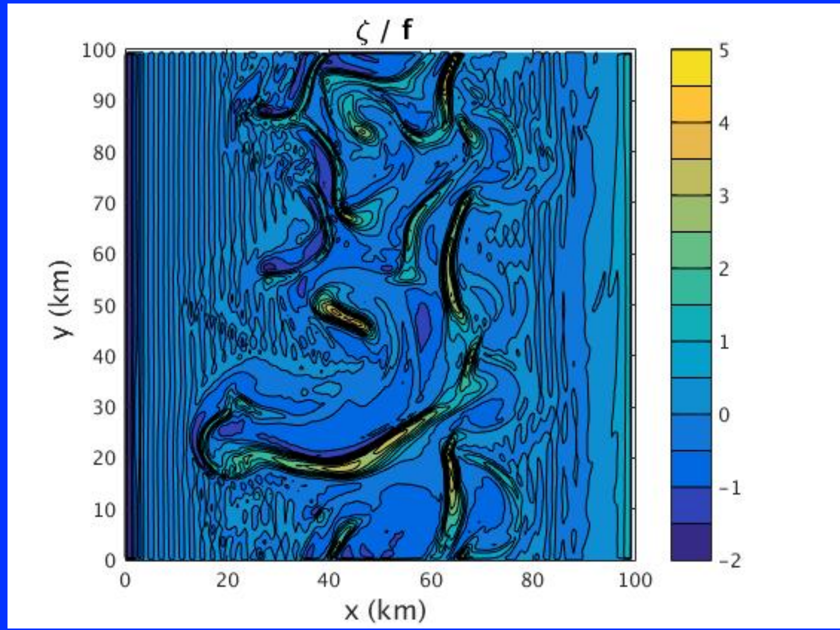




Front is strongly unstable, generates large Rossby number filaments and fronts

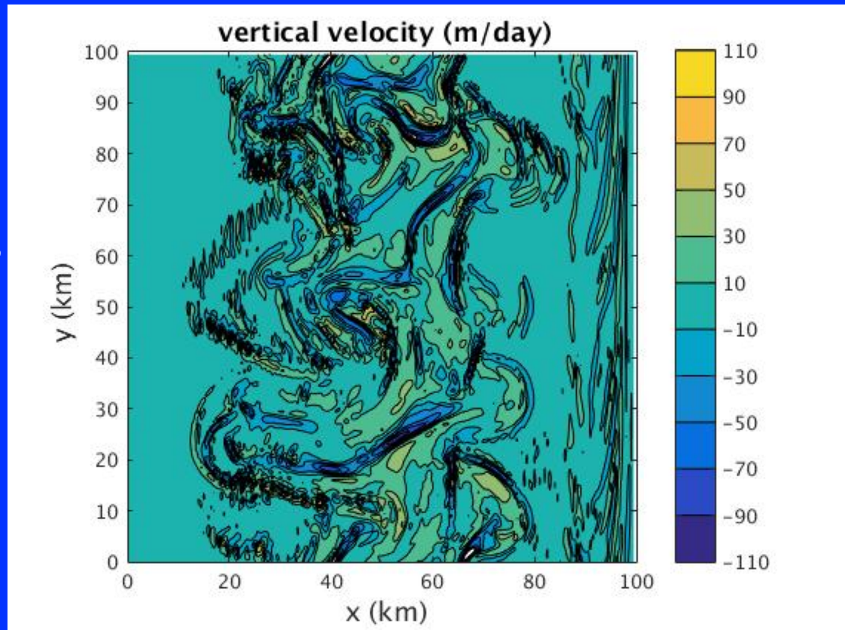
relative vorticity > 4 f

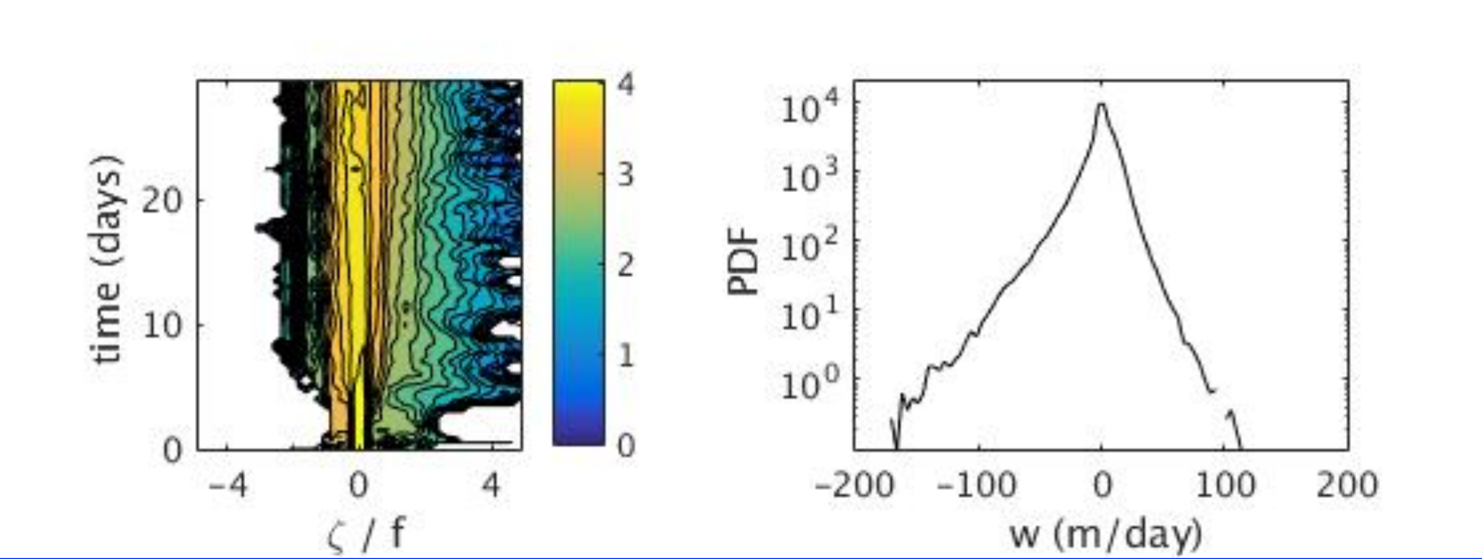




Front is strongly unstable, generates large Rossby number filaments and fronts

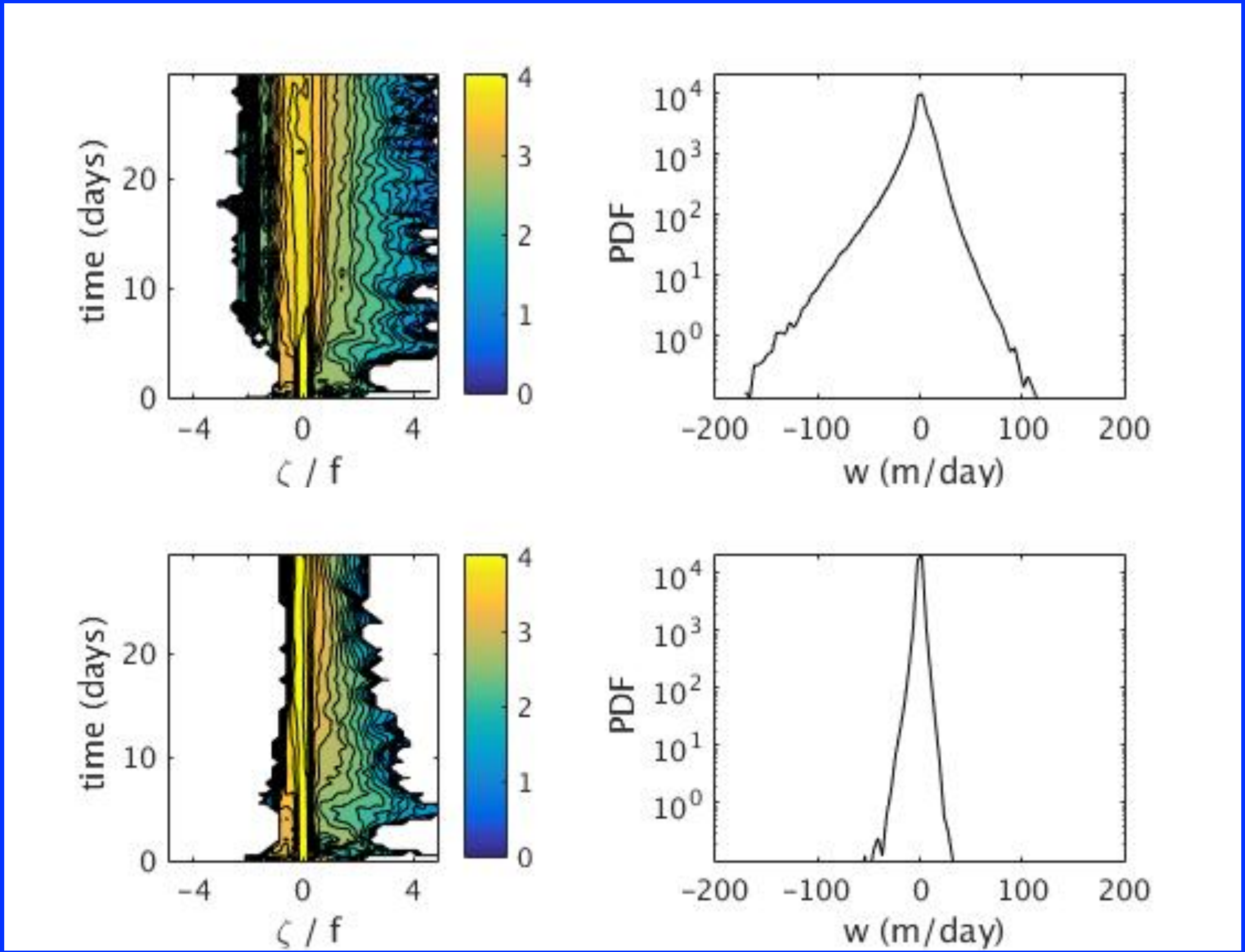
Strong downwelling is found in the regions of large cyclonic vorticity, weak upwelling in anticyclonic regions





Large positive and negative vorticities persist for 30 days

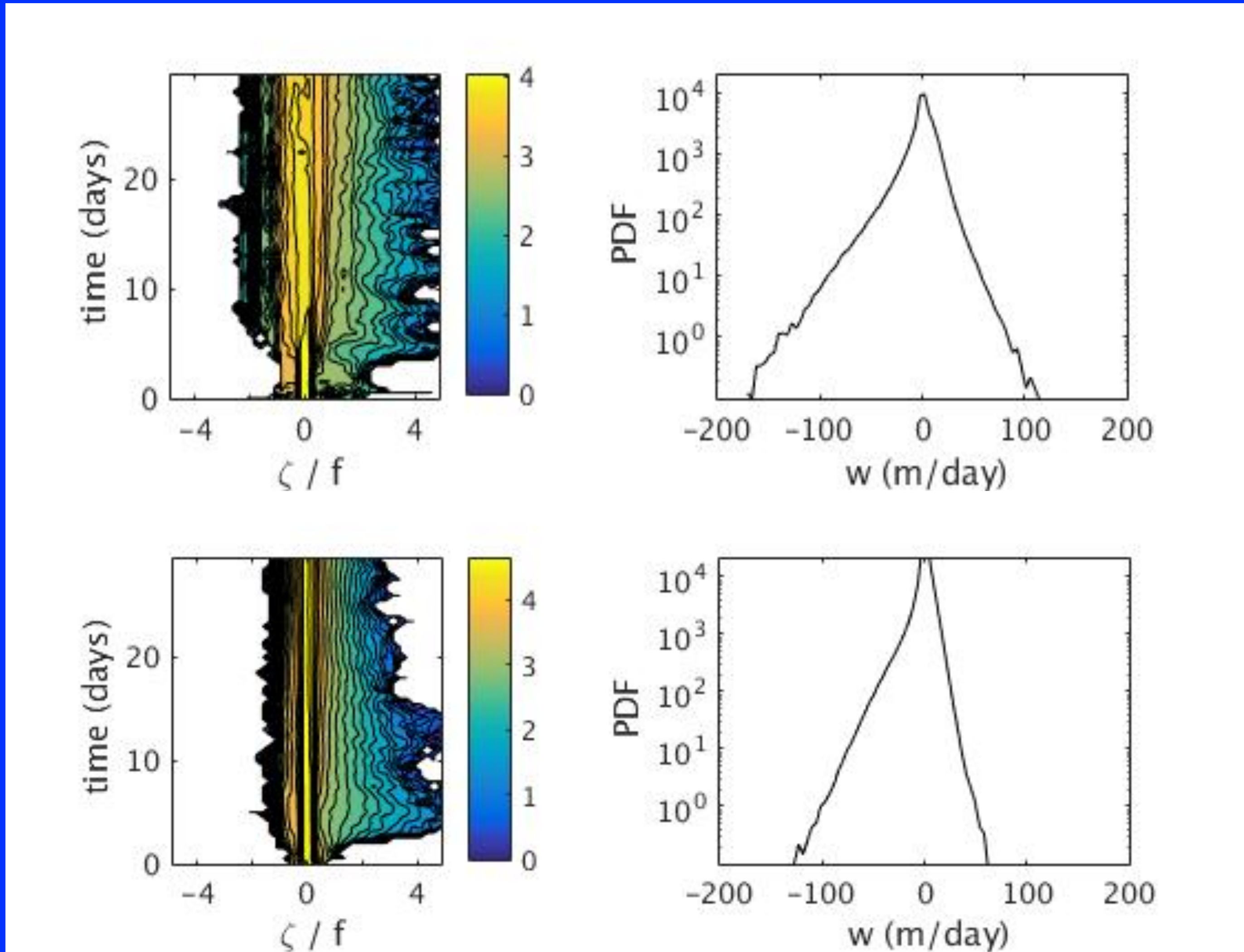
Vertical velocities over 100 m/day are common near the front, downwelling is more intense than upwelling



wind

no wind

Much more intense nonlinearities and vertical motions than found without wind

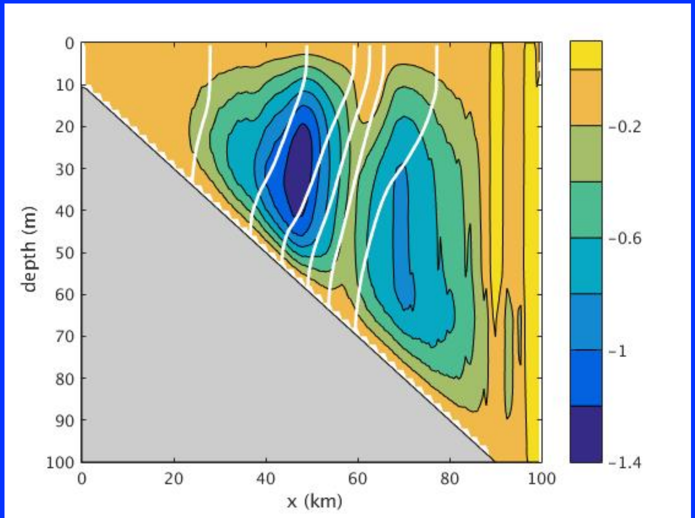


coast

no coast

Also more nonlinear compared to a downfront wind with no coast

Consider the overturning circulation in Eulerian coordinates

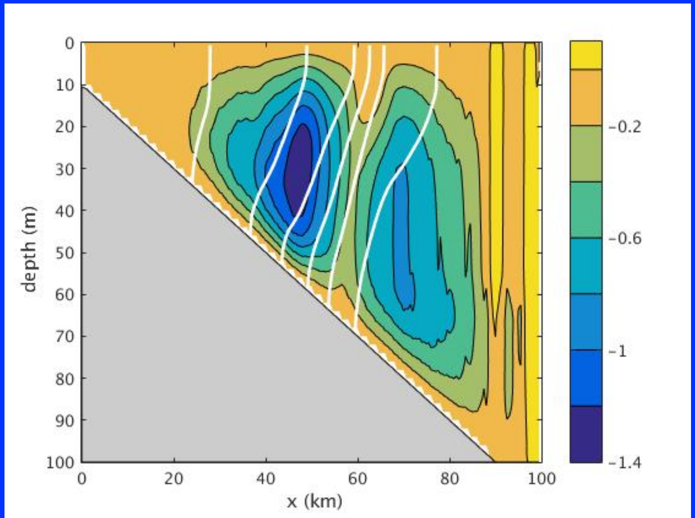


Eulerian streamfunction (Sv)
and mean salinity

In the sense expected from nonlinear Ekman layer dynamics

Nonlinear effects are important near the front, induce upwelling into anticyclonic side and downwelling from cyclonic side.

Compare to that found in density coordinates



Eulerian streamfunction (Sv)
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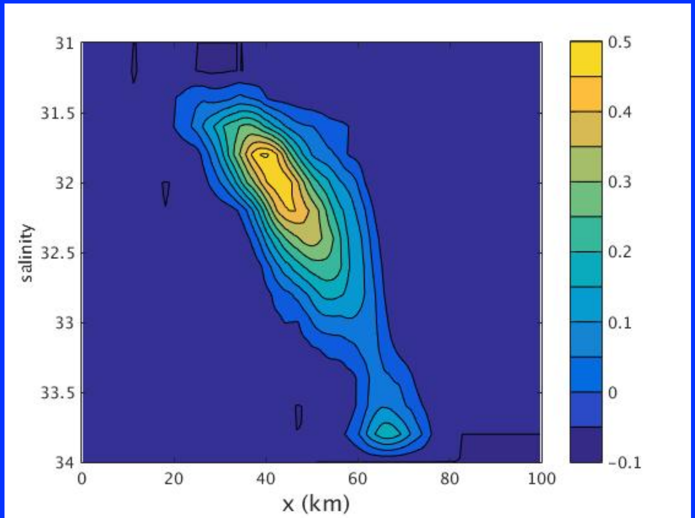
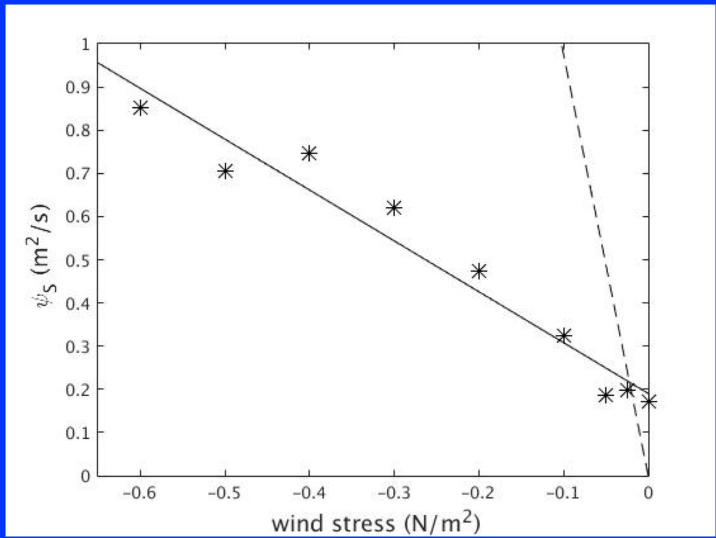


salinity coordinates
streamfunction (Sv)

Eulerian mean gives wrong sense of circulation, parcels are getting saltier over deep water, fresher over shallow water

Strength of transformation is smaller than, but same order of magnitude as the Eulerian transport. Will refer to salinity coordinate streamfunction as the Transformed Eulerian Mean (TEM) streamfunction

How does the strength of transformation depend on forcing τ ?



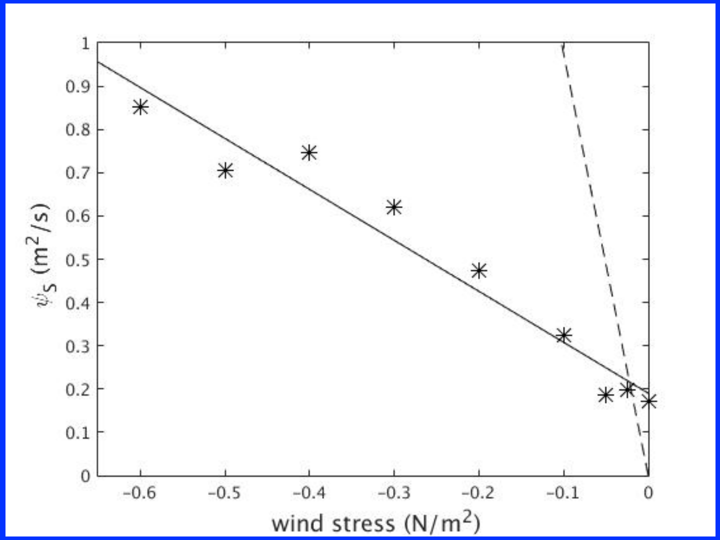
Maximum mean TEM streamfunction

TEM streamfunction increases approximately linearly with wind stress
slope approximately = -1 (case with zero wind is not in equilibrium)

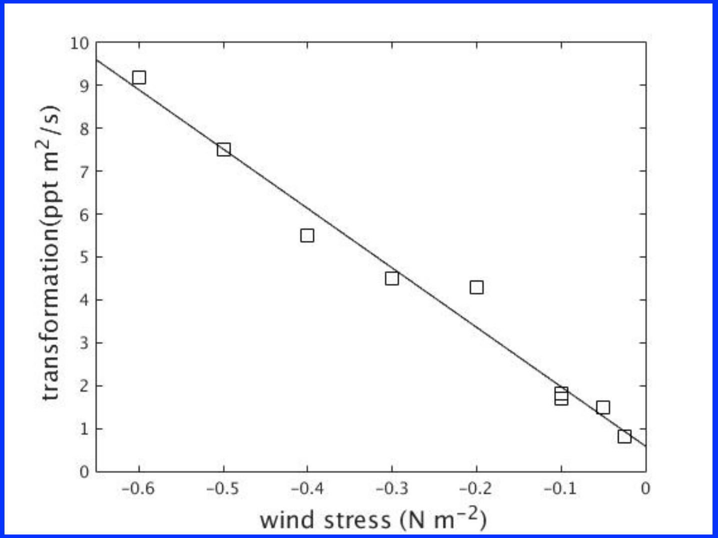
The net overturning in density coordinates is much less than the Ekman transport (dashed line)

But this is different from both the maximum and the global average transformation rate

How does the strength of transformation depend on forcing τ ?



Maximum mean TEM streamfunction

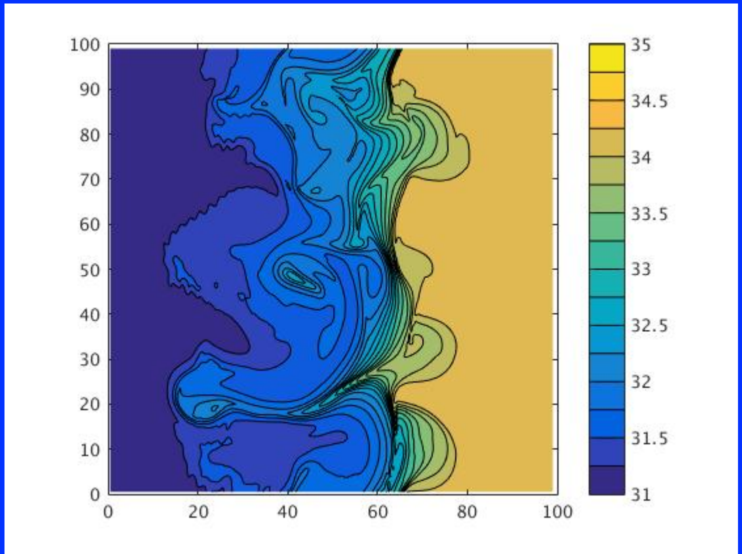


total upper ocean transformation

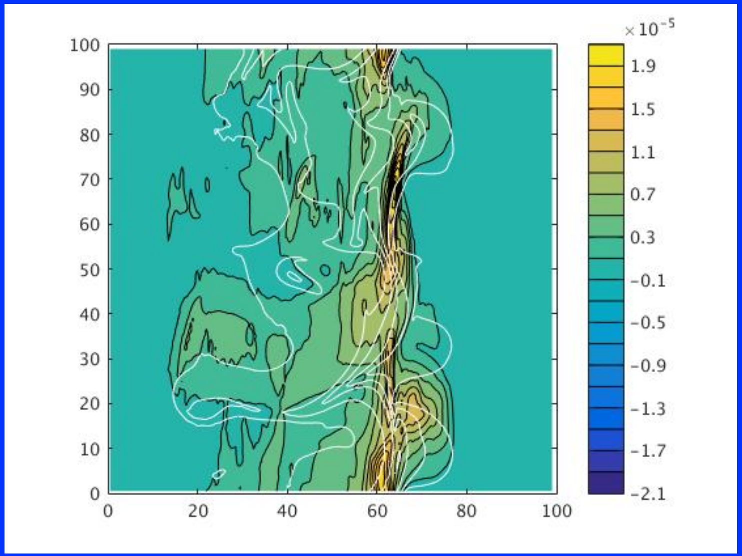
The integrated transformation rate in the upper ocean also increases approximately linearly with wind stress

At the largest stress, this is equivalent to 1 Sv ppt per 100 km of coast

Where does this transformation occur?



sea surface salinity



change in surface salinity due to vertical mixing (not convection)

Water mass transformation is concentrated on the upstream (Ekman sense) side of the front, not in the filaments or regions of large ζ

Depends on mixing parameterization – constant vertical diffusion results in shallow mean Ekman transport (destabilizing) balancing vertical convection

This is very different than the direct eddy-driven cell found here.

Summary

- The ocean response to downfront winds in a coastal region differs from that found in the open ocean in several ways:
  - presence of a coastline allows SSH gradient, stronger along slope velocities, and stronger frontogenesis
  - barotropic flow develops a bottom boundary layer, which is destabilizing
  - the sloping bottom reduces baroclinic instability and mixing

- Combination of baroclinic instability and downfront winds results in significant water mass transformation but does not allow for offshore flux of fresh water in eddies

- TEM transport is in opposite direction to Ekman transport

- TEM transport and water mass transformation increase linearly with wind stress, but is an order of magnitude less than the Ekman transport