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Evaluation of shelf -deep ocean exchange in the Arctic Seas

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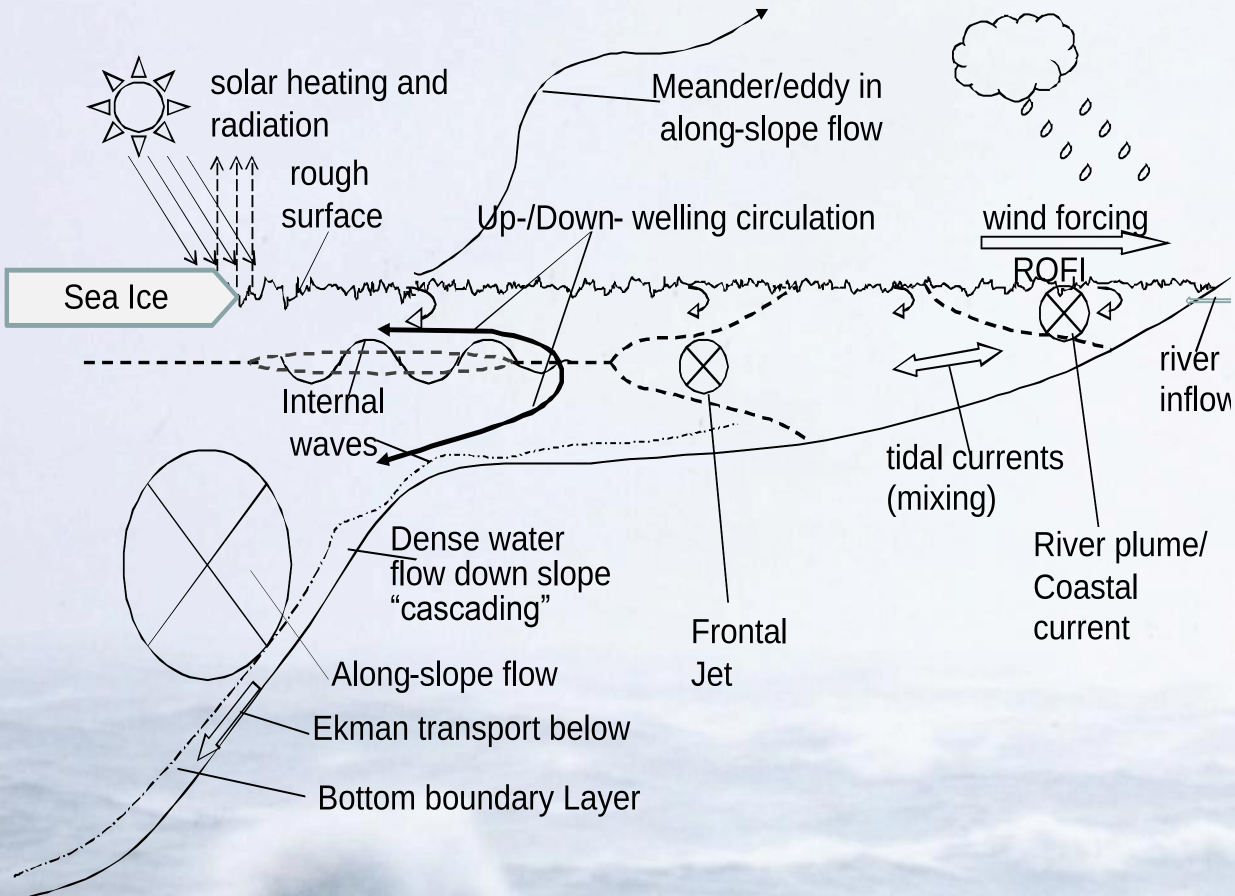
Evaluation of the shelf-ocean exchange in the Arctic Ocean on the multidecadal scale



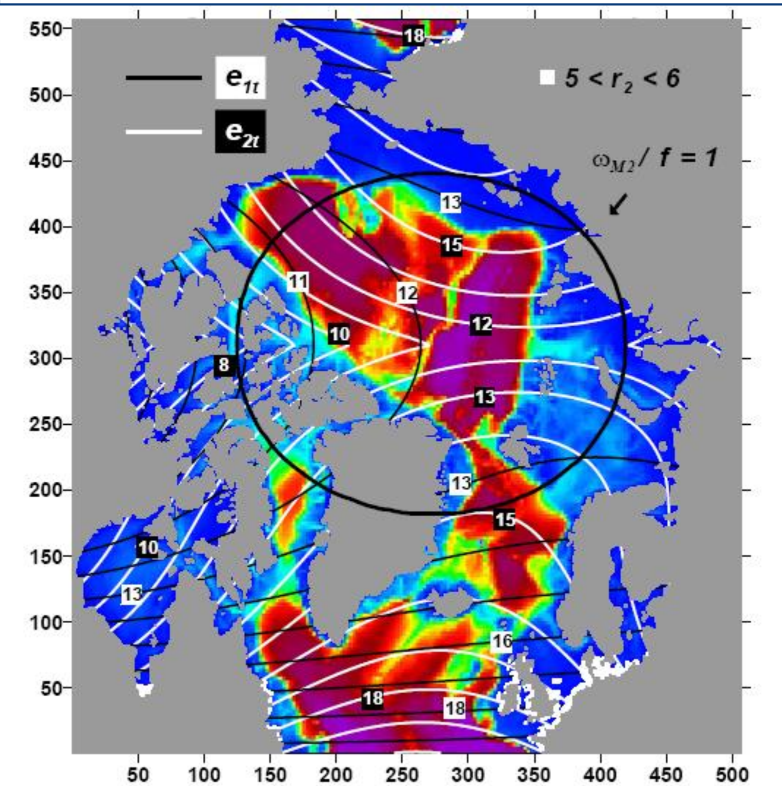
Schematic of Ocean-Shelf Exchange (OSE) processes
(c.f. Huthnance et al 2009)

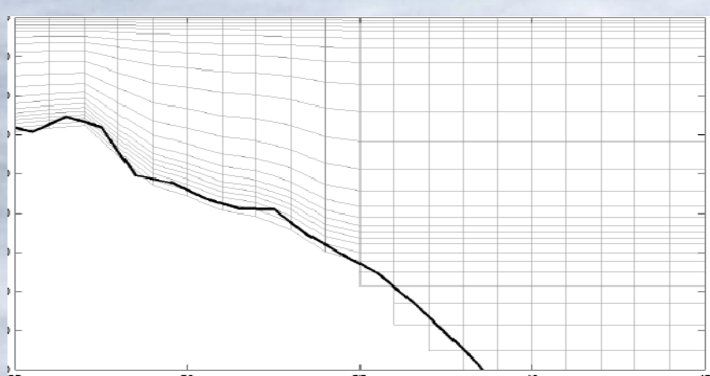
To conserve PV ocean currents follow contours of constant f/h;

The connection between shelf seas and the open ocean is by a series of generally ageostrophic processes that break this constraint:

- Tides;
- Ekman surface drain
- Ekman bottom transport
- River plumes
- Inertial waves
-

NEMO-shelf pan-Arctic model





- NEMOv3.6 with shelf processes included coupled with LIM2 elastic-viscous plastic rheology

O'Dea et al, 2012, Luneva et al, 2015*

¼ resolution based on ORCA-025 tripolar grid (7-15km)

numerical algorithms

- **Vertical coordinates**: Hybrid (s-z) 74 levels
- **Vertical mixing:** k-eps with Canuto, 2001 closure
- **Horizontal mixing:** Smagorinsky lap.
- **Barotropic pressure**: time split
- **prj** (pressure Jacobian) for baroclinic pressure

Physics: tides, 15 harmonics.

Boundary conditions: OTPS, ORCA12

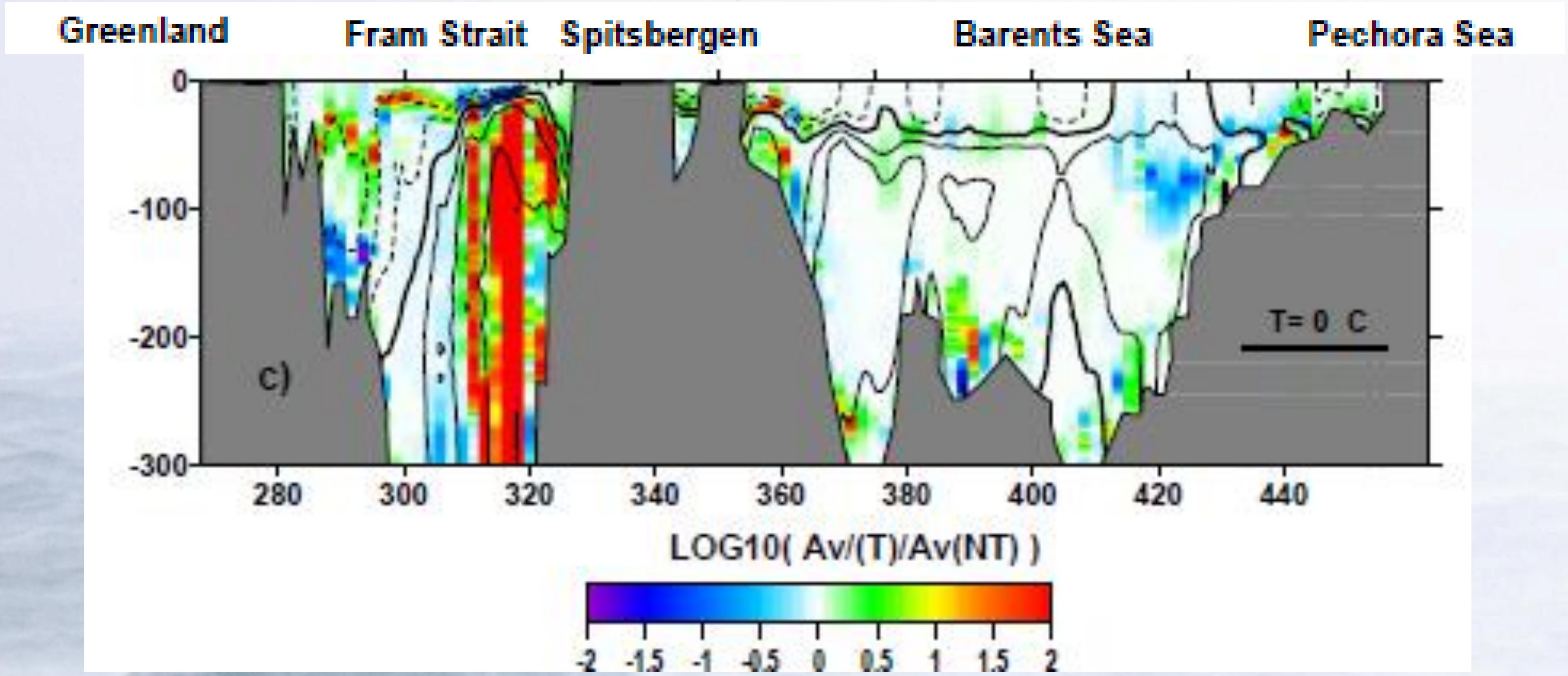
- Model runs: 1980-2010 with tides and without
- Forcing: DFS5.1
- Runoff: climatic or Dai et al, 2009+Bamber 2012

Greenland Glacial melting included,

* Some results are from V3.2 version

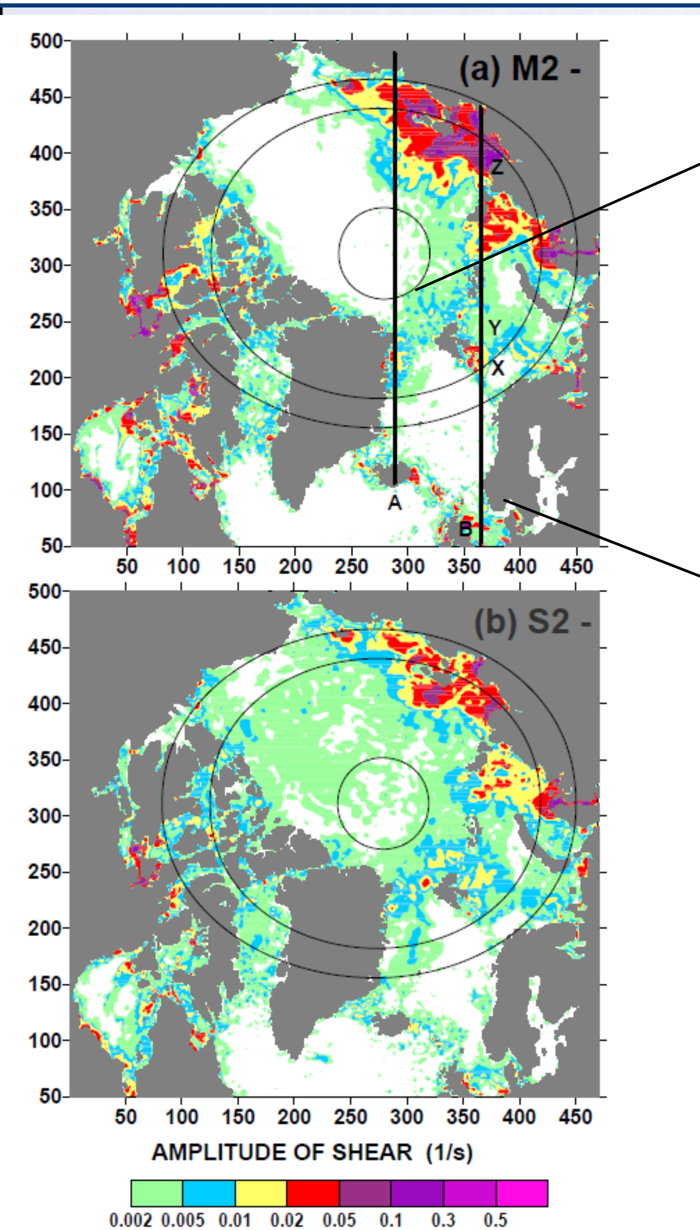
Tidal effects

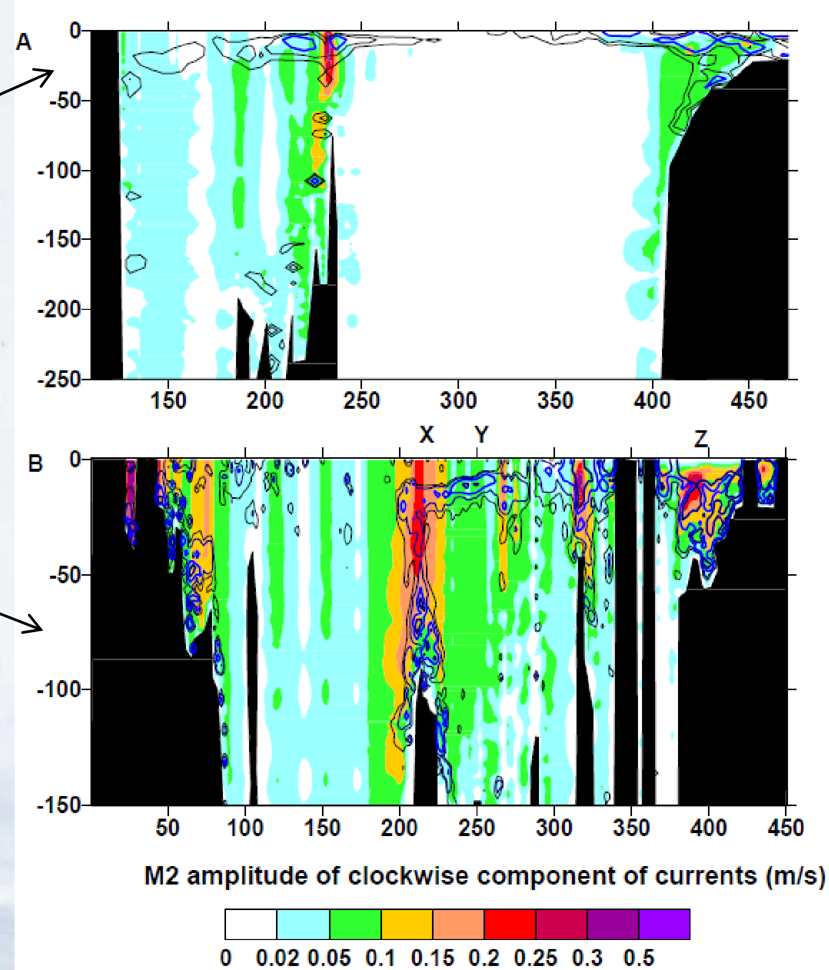
- Thicker benthic and ice-ocean boundary layers, stronger mixing;
- In stratified flow stronger shear in pycnocline/halocline, induces sporadic bursts of mixing
- Rectification currents, induced by nonlinear shear stresses and tidal Reynolds stresses.



Relative difference of vertical diffusivity in simulations with and without tides in logarithmic scale

Tidal shear

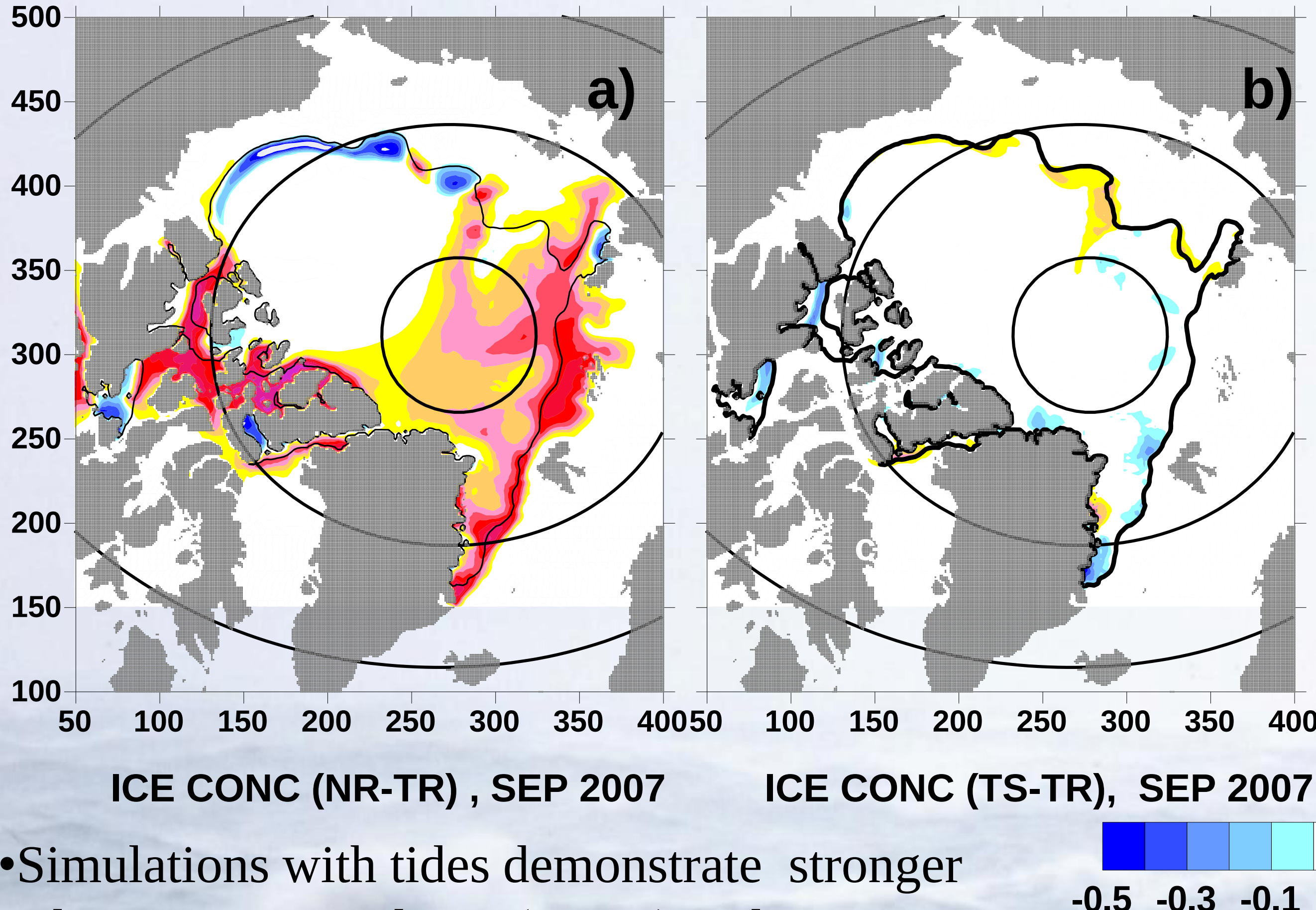




Tides induce a strong shear stresses with maximum located below the surface and over bottom topography anomalies.

As M2 and S2 frequencies are very close to inertial, potential depth of Ekman layer can be very deep: $h_e \sim u^*/|f-\omega|$ or ($h_e \sim (A_v/|f-\omega|)^{1/2}$)

Effect of tides on sea ice.



Runs:

TR: Tides + new riverine

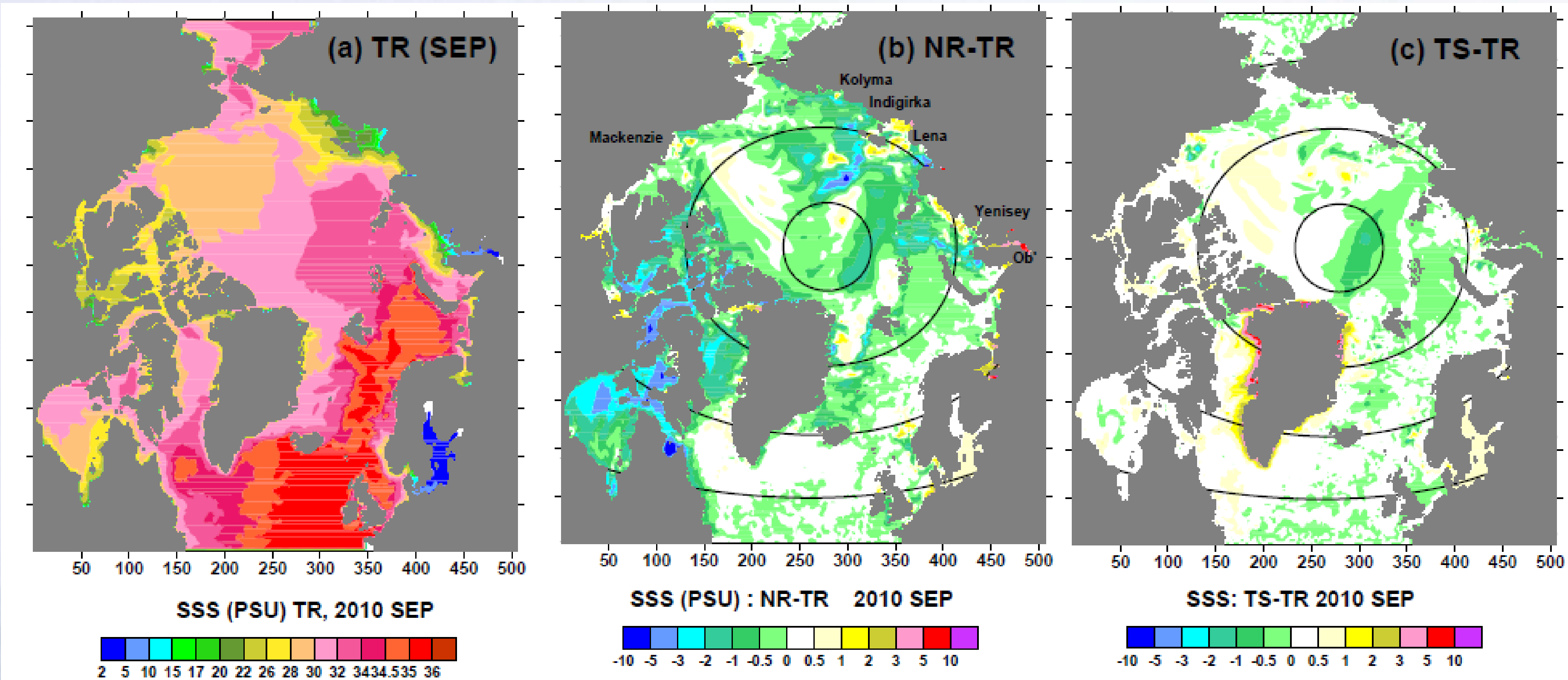
NR: no tides

TS: tides but with climatic runoff

•Simulations with tides demonstrate stronger reduction in ice volume (~15%) and extent (~5%) in comparison with simulation without tides and predicts right trends in comparison with PIOMAS -2.54 x10^3km^3/decade versus -2,55

Variability of runoff forcing has the minor, localised effect on ice volume

Effects of tides on the surface salinity

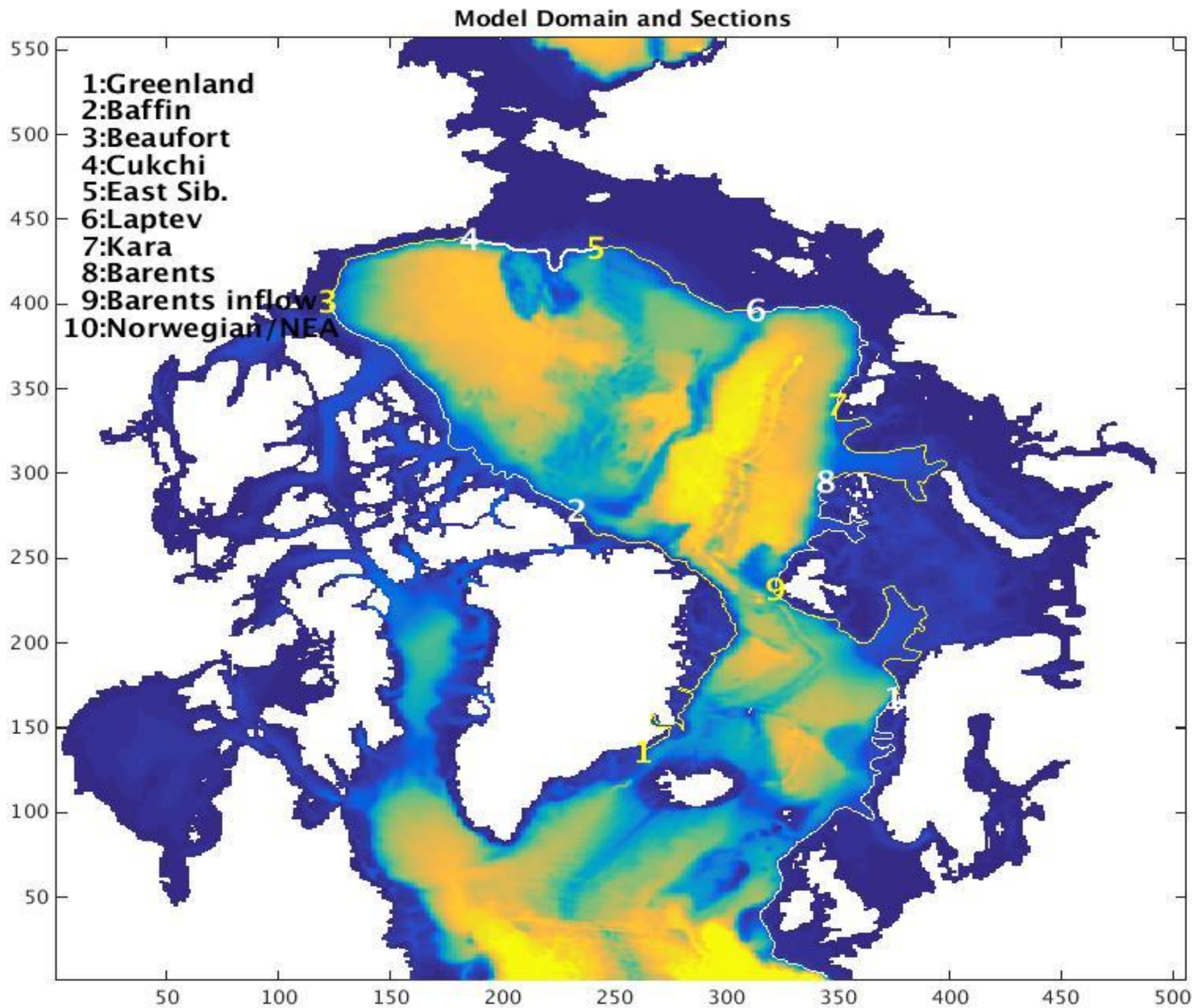


Tidal effects change freshwater pathways and increase surface salinity about 0.5-1 PSU in comparison with simulations without tides.

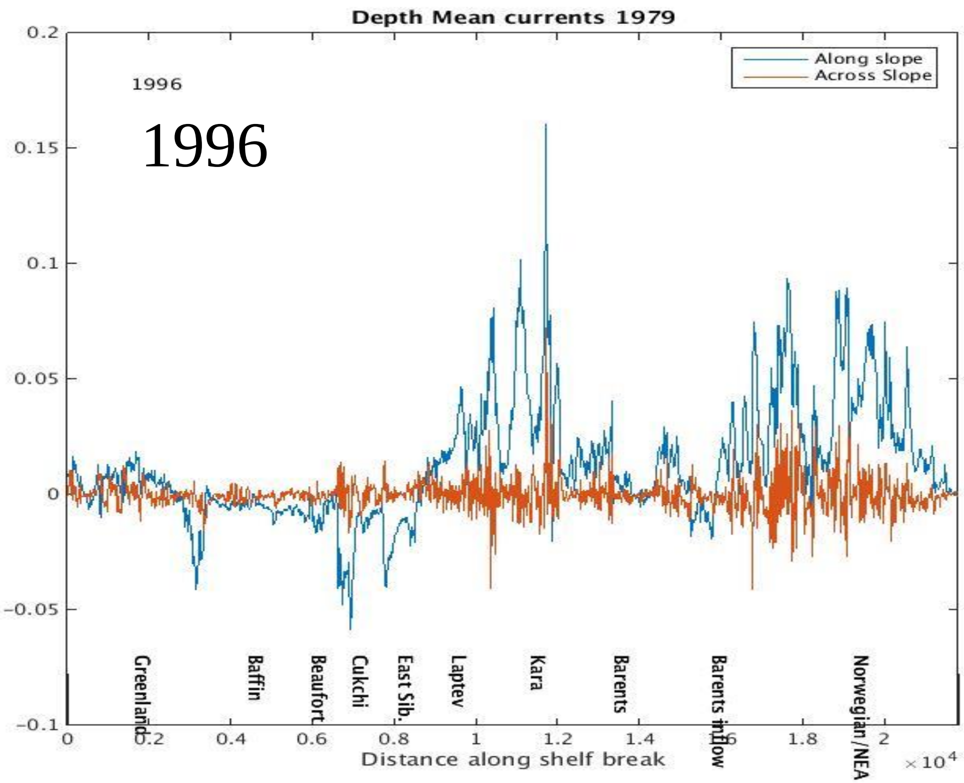
Ice reduction/salinity increase indicate inflow/mixing of warm and saltier Atlantic waters to the surface and increased mixing of river runoff.

Riverine interannual variability result effect is much weaker.

Cross-shelf edge: contour depth 300m



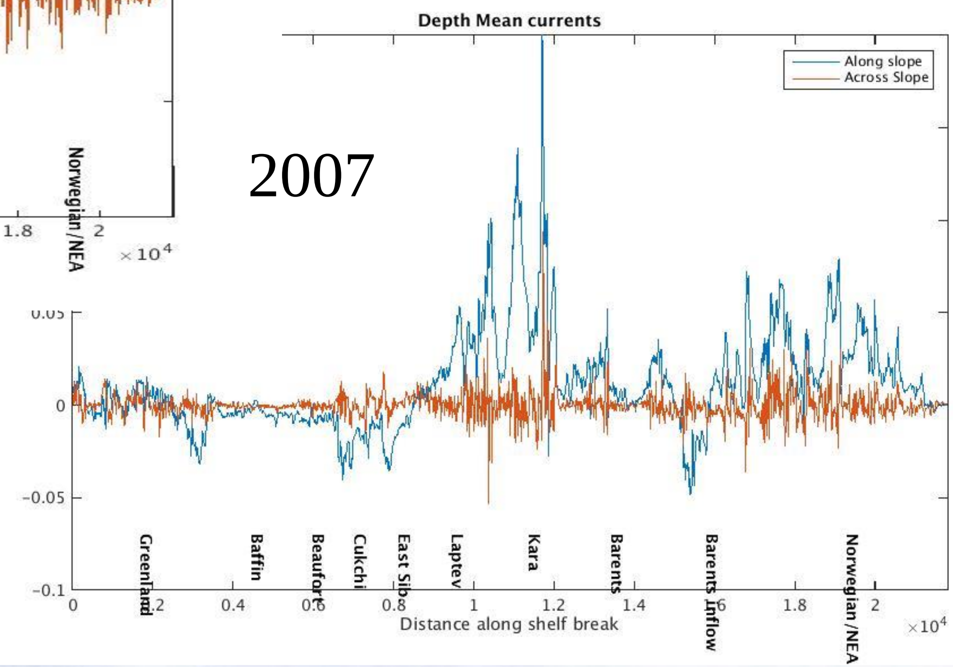
Currents along/across contour



1996

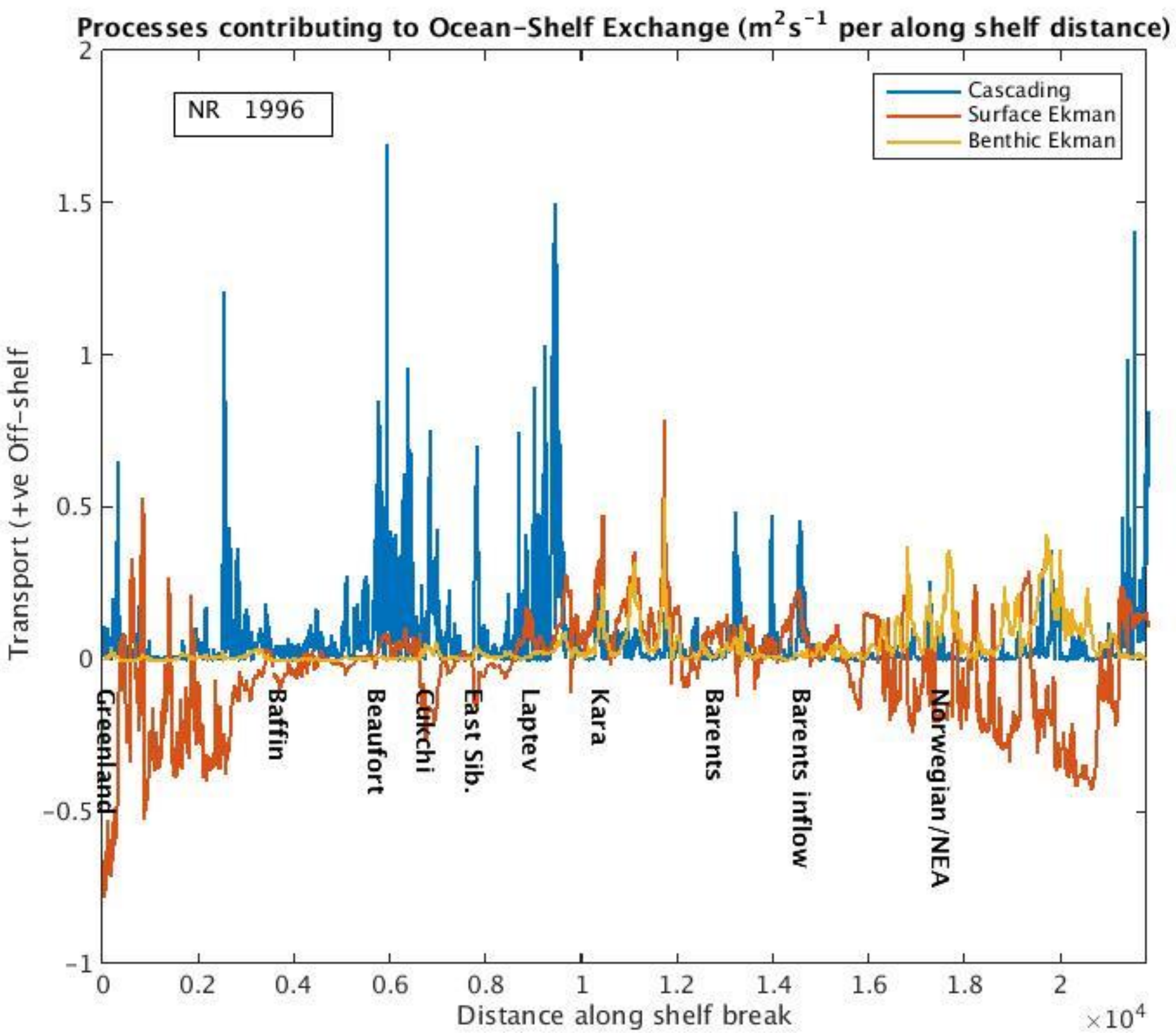
Along slope currents: mostly cyclonic, follow f/h; 0.05-0.15 ms $^{-1}$

2007



Cross shelf currents (shown in scale 0.1 of along slope), positive offshore,
AS- positive cyclonic

Cascading is dominant process, 2-3 times intensive compared with Ekman drain



Cascading: $0.36 h_E g \Delta\rho h_n / f\rho$
Shapiro et al, 2003

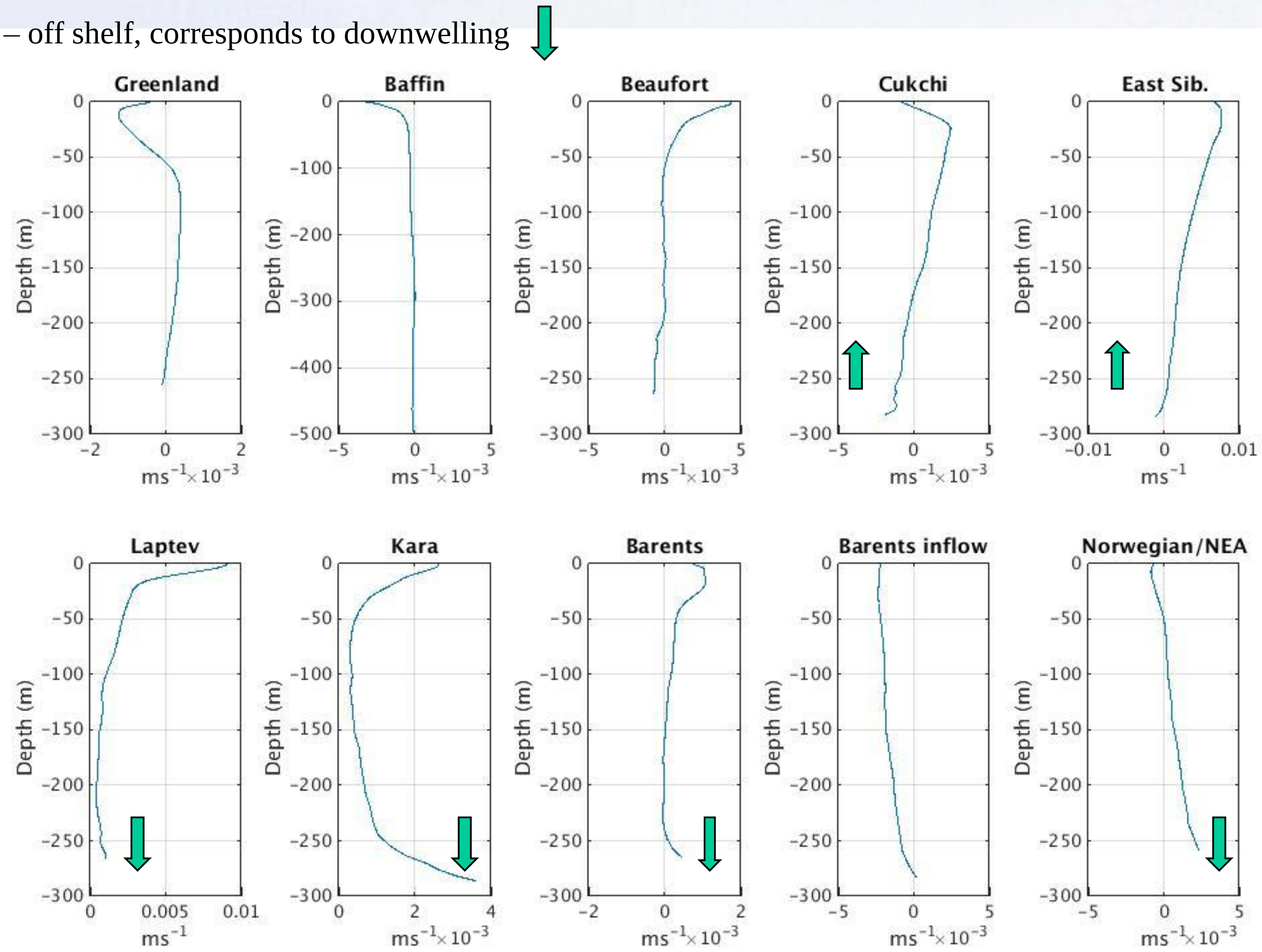
Surface Ekman: $\tau_w / f\rho$

Benthic Ekman: $C_d V.|U|/f$

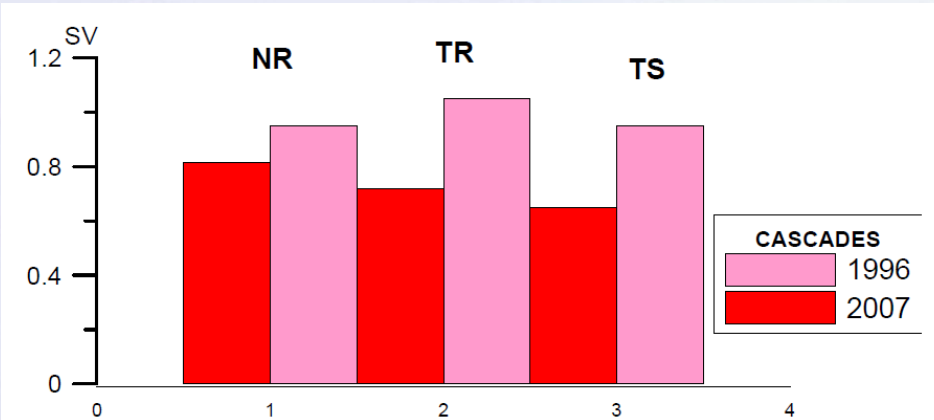
Cascades: denser water lies up-slope of lighter water in the lowest model.
V is along slope current,
U is total current (mean + |tide|),
h_E is Ekman depth ,
h_n is slope. 1 year mean

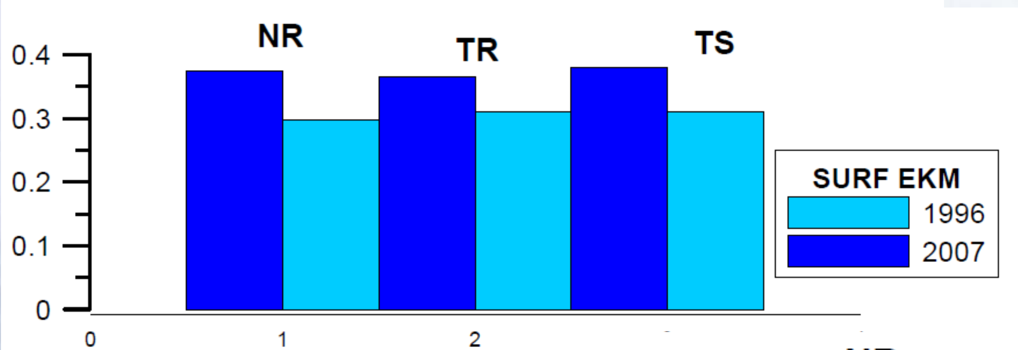
Yearly mean cross-slope currents, ~1-5 mm/s

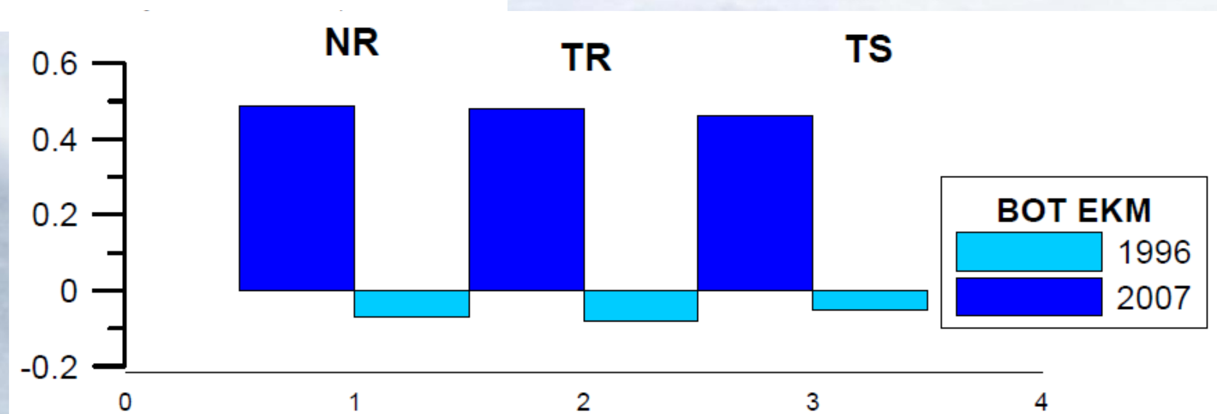
Positive – off shelf, corresponds to downwelling



Effects of tides and riverine on cross-shelf exchange





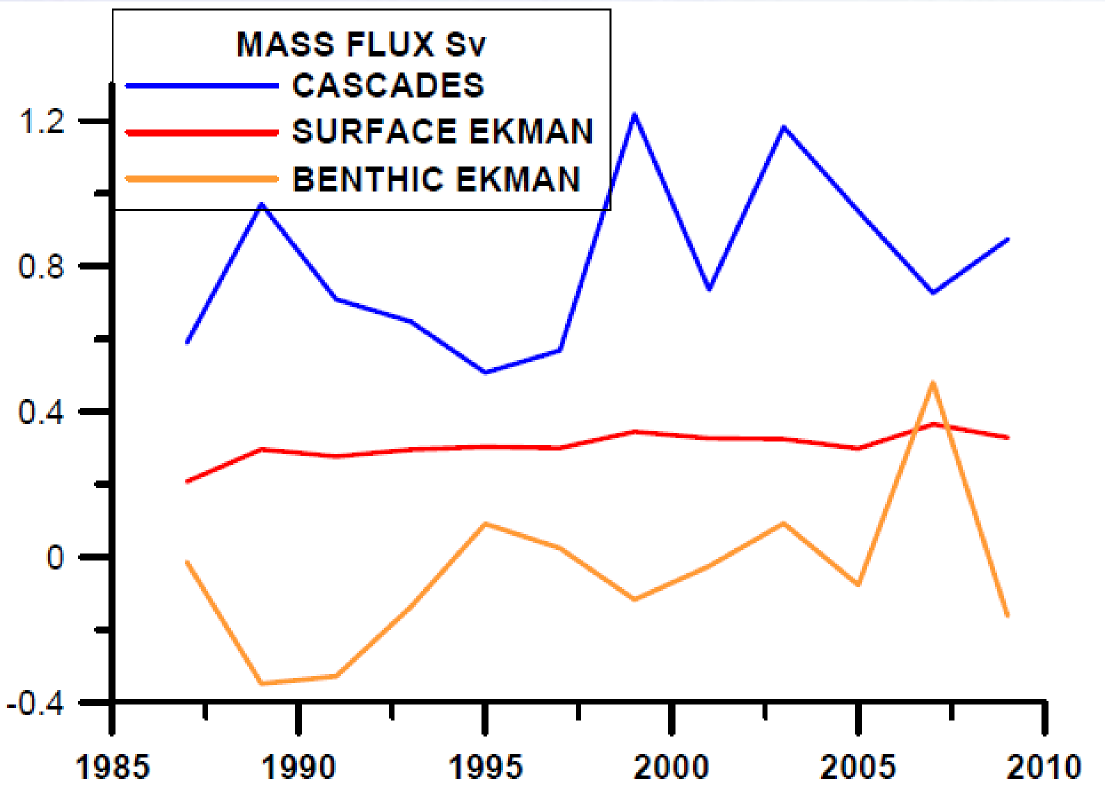


Inter-annual variability is much stronger compared with riverine/tidal effects.

Bottom Ekman pumping – even opposite effect.

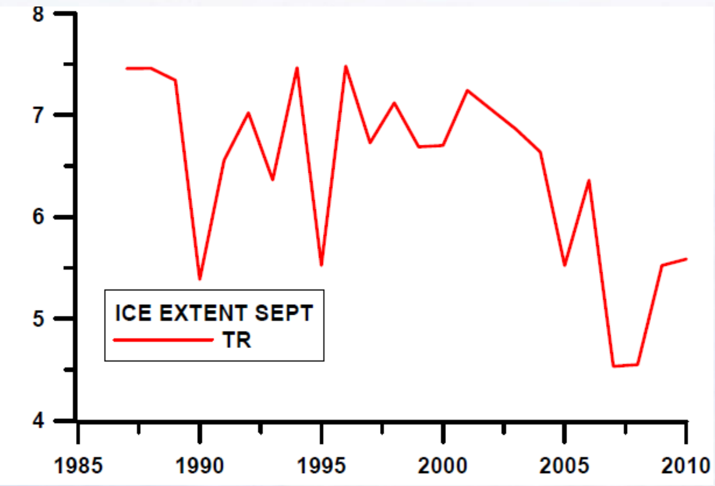
What is the main driver of variability?

Total flux

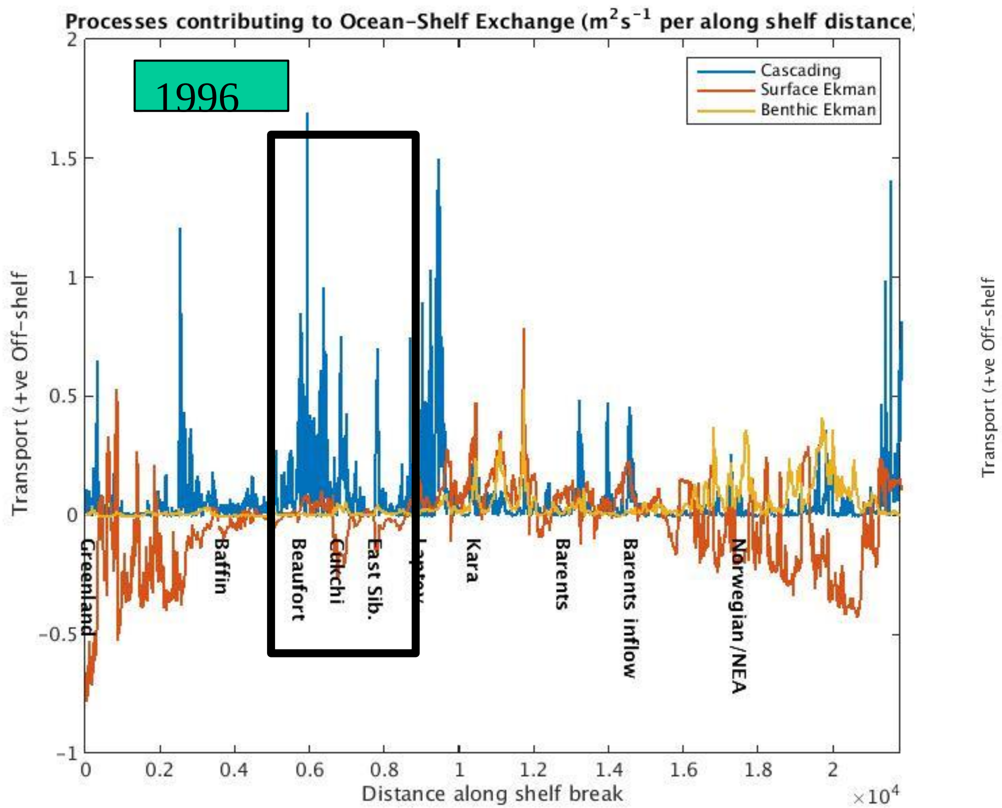


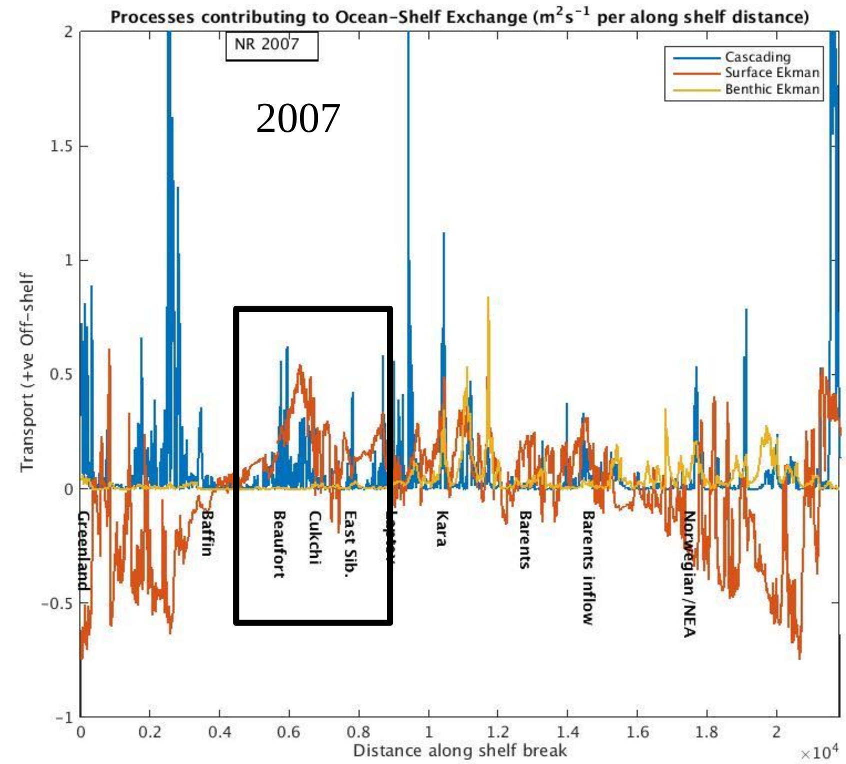
Cascades:
0.65 -1.2 Sv;
Ekman surface:
-0.4 - 0.4 Sv
Ekman bottom:
0.2 - 0.4 Sv

No evident relation with ice extent;
Negative correlations with surface Ekman drain;
Surface Ekman offshore → upwelling→ reduced cascading



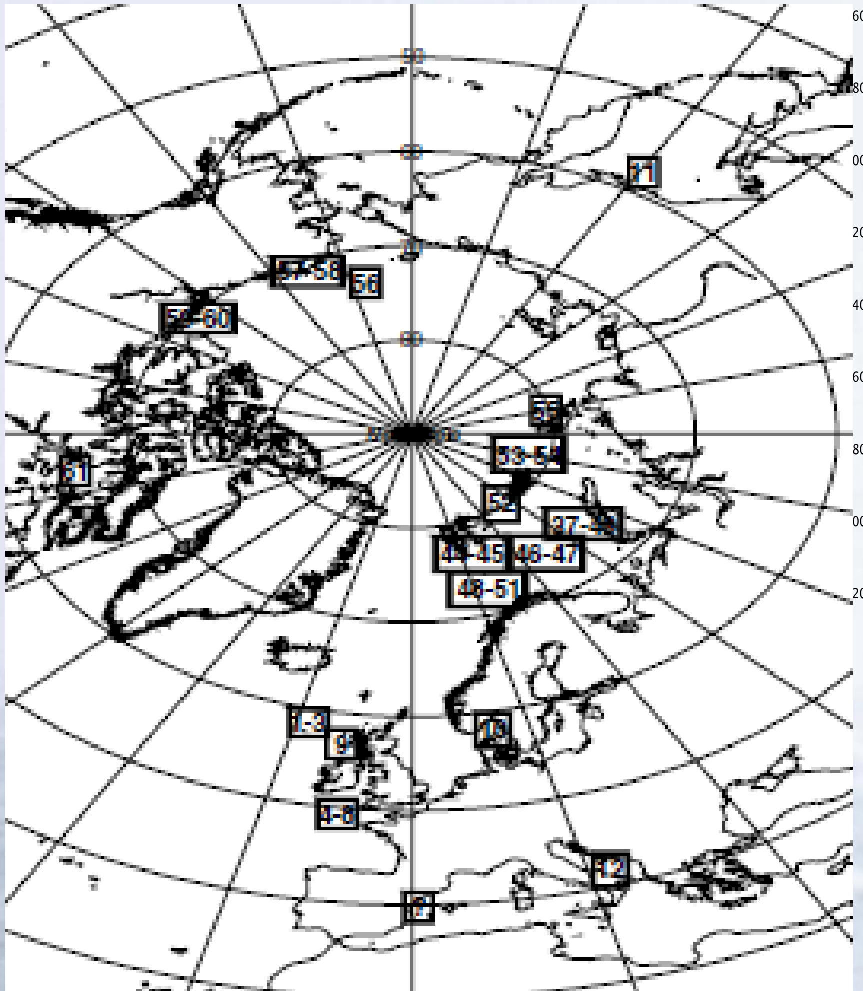
Strong inter-annual variability

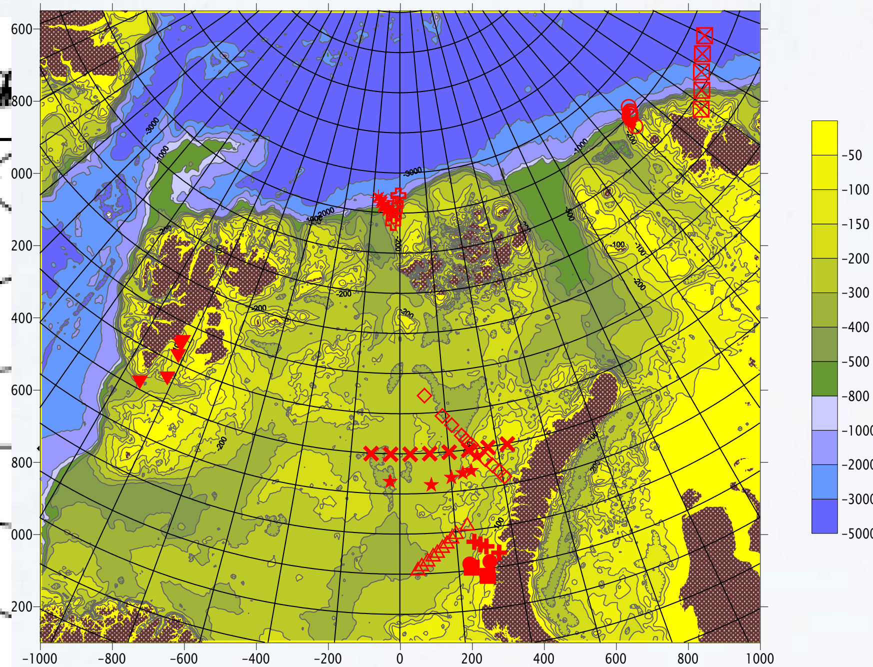


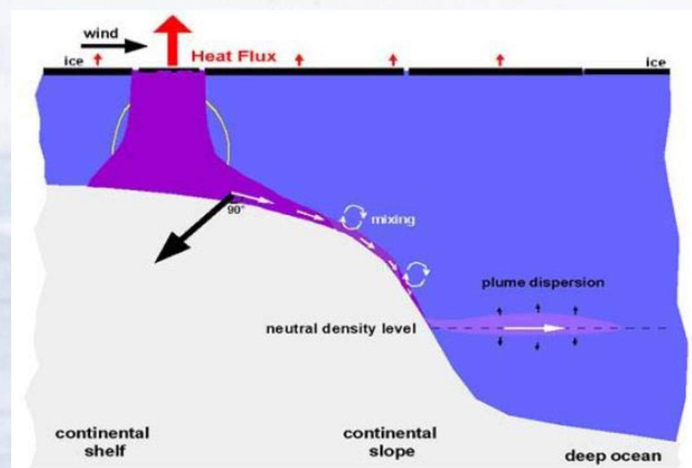


Stronger regional inter-annual variability with 100-200% changes in amplitude;
Positive Ekman surface drain; 5 fold reduction in cascading

Observed cascades (shelf convection) in AO (Ivanov et al, 2004)



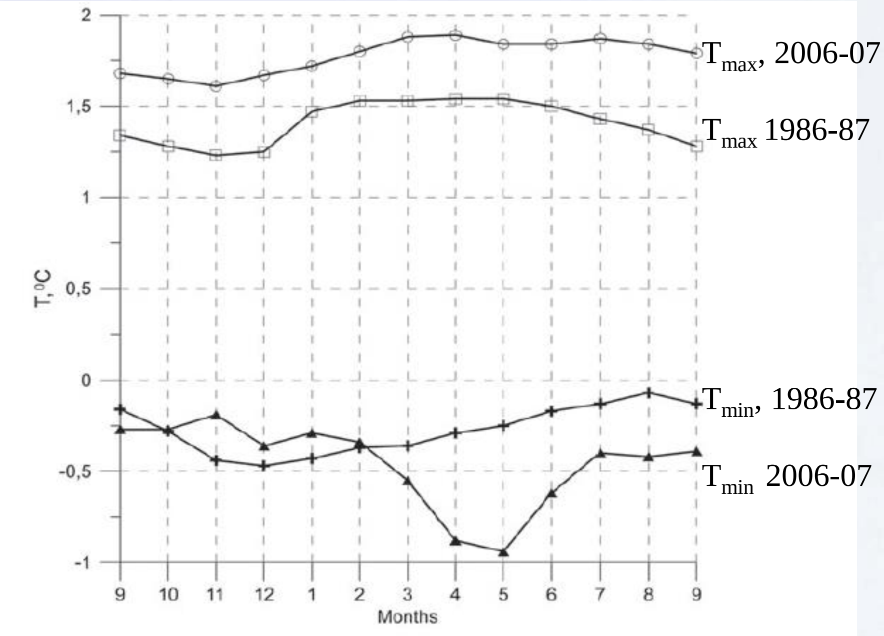




Locations of shelf edge cascades from observations (Shapiro et al, 2003, Ivanov et al, 2004).

Illustration of cascading mechanism

Ivanov et al, 2015: Shelf-basin exchange in the Laptev Sea in the warming climate: a model study.



Time series of max and min temperature at 250m depth

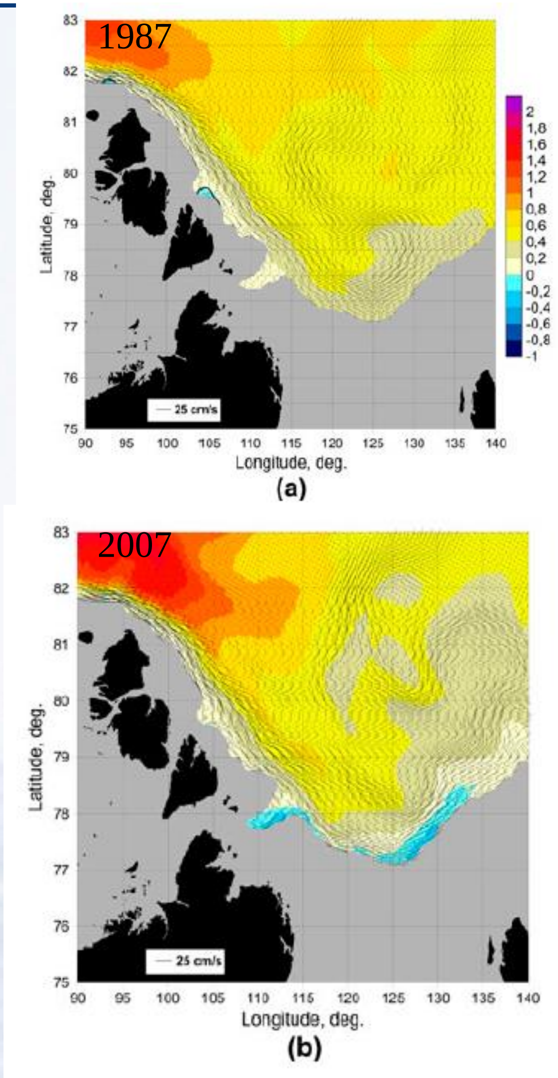
Model: NEMO

Runs: 1958:2007

analysis:

high ice extent 1986-1987

low ice extent 2006-2007



Model distribution of monthly mean temperature and current speed at 250m, September

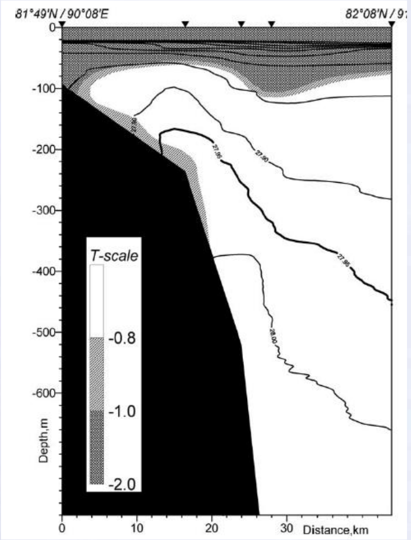
Hypothesys: Dense water production on the Arctic shelves is not likely to cease in warmer climate but rather increase…

!!! Wind-driven shelf exchange is important

Conclusions

- Shelf-exchange fluxes and their inter-annual variability are evaluated;
- Dense water overflow (cascades) is most prominent in the Arctic Ocean, $\sim$ 1Sv with 2-3 times weaker surface Ekman drain;
- Mean cross-shelf velocity $\sim$ 1- mm/s.
- Cascading flux is negatively correlated with surface Ekman drain (wind driven)
- Detailed analysis of wind/cascades/ice cover regional feedbacks is required.

Next steps: Arctic cascades and deep water formation in the warming climate



Temperature and density St. Anna Trough, 1995

The main the hypotheses to test are:

1. Physical conditions for initiation of cascading events can be identified from the output of ocean models.

2. The cumulative effect of cascading events have an important role in ocean-shelf exchange that is significant for global biogeochemical cycles and oceanic water mass formation.

3. The dramatic reduction of seasonal ice, observed in recent years (2007-2015) stimulates cascading, deep water formation and carbon dioxide storage.

4. Wind circulation controls the strength of dense water overflow.

Next steps:

(a) Long-term simulations: model based climatology of cascading: analysis of existing runs, evaluate frequency, locations, mass flux and depth of new water formation, inter-annual variability.

(b) Short term runs: 1 year starting from September high ice year and low –ice year.

add passive tracer with surface boundary condition : concentration=1, or flux proportional to buoyancy flux. Test Shapiro et al. estimate of dense water flux.

- The coupling between the continental shelves and the deep ocean is a key facet of the Earth System.

- Continental shelves are strongly impacted by: terrestrial inputs, tidal mixing, growth of coastal-trapped waves and rapid communication with the atmosphere.

- In the Arctic this issue is modulated by the unique physical oceanographic environment arising from the combination of sea ice, weak currents, weak interior stratification, strong and persistent surface stratification and broad continental shelves. Here we explore the processes mediating this exchange. We examine this with results from a 1/4° pan Arctic model (Luneva et al., 2015), based on an extraction of the NOC global ORCA025 model, but including features appropriate for shelf seas. Modelling the bottom Ekman layer is crucial to these processes and requires tides, sufficient vertical resolution and sophisticated mixing schema. to accurately represent bottom stresses.