

## Salt intrusions in Siberian river estuaries: Observations and model experiments in Ob and Yenisei

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### Abstract

Observations in Siberian river estuaries show a very pronounced vertical stratification during summer. In particular in the Yenisei Estuary, salinity profiles are strongly affected, not only by freshwater runoff, but also by bottom following salt intrusions that penetrate actively into the estuary.

In order to study the estuarine variability and to investigate the physics behind these salt intrusions, two different numerical circulation models are applied to the Kara Sea and the estuaries of Ob and Yenisei. The 3-D, baroclinic models are based on the realistic topography, forced with wind, tides and river runoff.

Model results from summer reveal a general northward flow of river water at the surface out of the estuaries. Near the bottom, however, a south-westward transport of saline water from the Taymyr coast towards the estuaries prevails. A salt intrusion occurs during strong runoff when the direction of the wind-induced offshore transport is aligned with the axis of the estuary. In this case, the enhanced surface flow has to be compensated by an onshore near bottom flow that may penetrate into the estuary.

Salt intrusions occur frequently in the Yenisei Estuary in connection with north-easterly winds, a prevailing wind direction in summer in the Kara Sea. In the Ob Estuary, salt intrusions are almost absent and the haline stratification is weaker than in the Yenisei. This is due to enhanced tidal mixing in the Ob but also due to the orientation and depth profile of the estuary.

### 1 Introduction

The Kara Sea is a marginal shelf sea located in the Eurasian part of the Arctic Ocean. It is influenced by oceanic water masses from the Arctic Ocean, the North Atlantic and the Barents Sea. Additionally, the Kara Sea receives large amounts of freshwater through the Siberian rivers Ob and Yenisei. The rivers drain a catchment area in Siberia and Russia of more than 5 mill. km<sup>2</sup>. The total annual amount of freshwater input into the Kara Sea equals roughly 1200 km<sup>3</sup>/y of which 80% is discharged in spring (May-June) (Pavlov and Pfirman,

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1995). Peak freshwater discharge rates of more than 100,000 m<sup>3</sup>/s lead to a pronounced vertical stratification in the estuaries of Ob and Yenisei. Under specific meteorological conditions, high saline marine waters may penetrate as a bottom following counter flow into the estuary which additionally enhances the stratification.

One goal of the bilateral German/Russian project SIRRO is to study the dispersion and fate of biogeochemical tracers emerging from Ob and Yenisei rivers. In numerical transport models, most of these river tracers cannot be regarded as dissolved and conservative, dispersed only by the circulation. Horizontal and vertical gradients between freshwater and brackish water affect the transport behaviour and form a so called 'marginal filter'. The mixture of river and sea water leads to a settlement of suspended material as well as to the formation of precipitates. Knowing the time and space variability of the vertical stratification and the transition zone between freshwater and marine waters is therefore a prior condition for the investigation of estuarine transport processes.

Several publications were dealing so far with the area and the above described phenomena. Since a complete review of the previous work and the existing literature is out of scope of the present paper we refer only to some important work. The penetration of high saline, marine waters into the Ob and Yenisei estuaries has already been noted in early descriptions of the hydrological regimes of these areas by Antonov (1962) and Antonov and Maslaeva (1965). More recent papers investigated the magnitude of salt water intrusions depending on tides, wind surges and river discharge in the Ob Gulf (Ivanova, 1984; Stanovoy, 1984; Ivanov and Sviyatsky, 1987) and in the Yenisei Gulf (Graevsky, 1997). During intense field studies in summer 1993-1996 in the Kara Sea, different types of data from the region of freshwater influence (ROFI) of Ob and Yenisei were obtained. Results from these campaigns are given e.g. in Johnson et al. (1997) and McClimans et al. (2000). A good reviewing description of the variability in Kara Sea estuaries, based on long term observations, can be found in Stanovoy and Nøst (2002a,b).

Hydrodynamic modelling was previously carried out by e.g. Pavlov (1996) or Harms and Karcher (1999) who investigated more generally the circulation and hydrography of the Kara Sea, but also the river runoff and the transport of river tracers from Ob and Yenisei (Pavlov and Timokhov, 1997); (Harms et al., 2000). Model studies in the Ob Gulf were performed by Ivanov and Sviyatsky (1987) and Doronin and Ivanov (1997), mainly for simulating the magnitude of salt water intrusions depending on the river discharge and its inter-annual variability. Also a laboratory model was applied in order to investigate transport processes in the eastern Barents and Kara Seas (McClimans et al., 1997; McClimans et al., 2000).

## 2 Observations

Regular measurements of water temperature and salinity in the Yenisei Estuary started in the 1930's. Data were collected during summer and winter expeditions, mainly by the Arctic and Antarctic Research Institute (AARI, St. Petersburg) and by the Dikson Hydrometeorological Observatory. Summer observations were carried out from the second half of July until the beginning of October. In wintertime, observations under the ice were carried out from March until the beginning of June.

In general, the historical data showed a permanently existing pycnocline in the estuary but only recent CTD<sup>1</sup>-profiles (from 1993 on) revealed that vertical salinity and temperature gradients may be extremely strong and reach values of up to 5-10 per 10 cm and 1.5-2.0 °C per 10 cm. The average multiyear salinity at the surface and bottom in August and the vertical distribution of temperature and salinity in summer 2001 in the Ob and Yenisei Estuary is shown in Figures 1 and 2. These pictures exhibit a clearly pronounced two-layer structure of the water masses which is the typical situation during summer. It is also apparent that the difference between surface and bottom water salinity is more pronounced in the Yenisei Estuary, where saline bottom water seems to penetrate into the estuary.

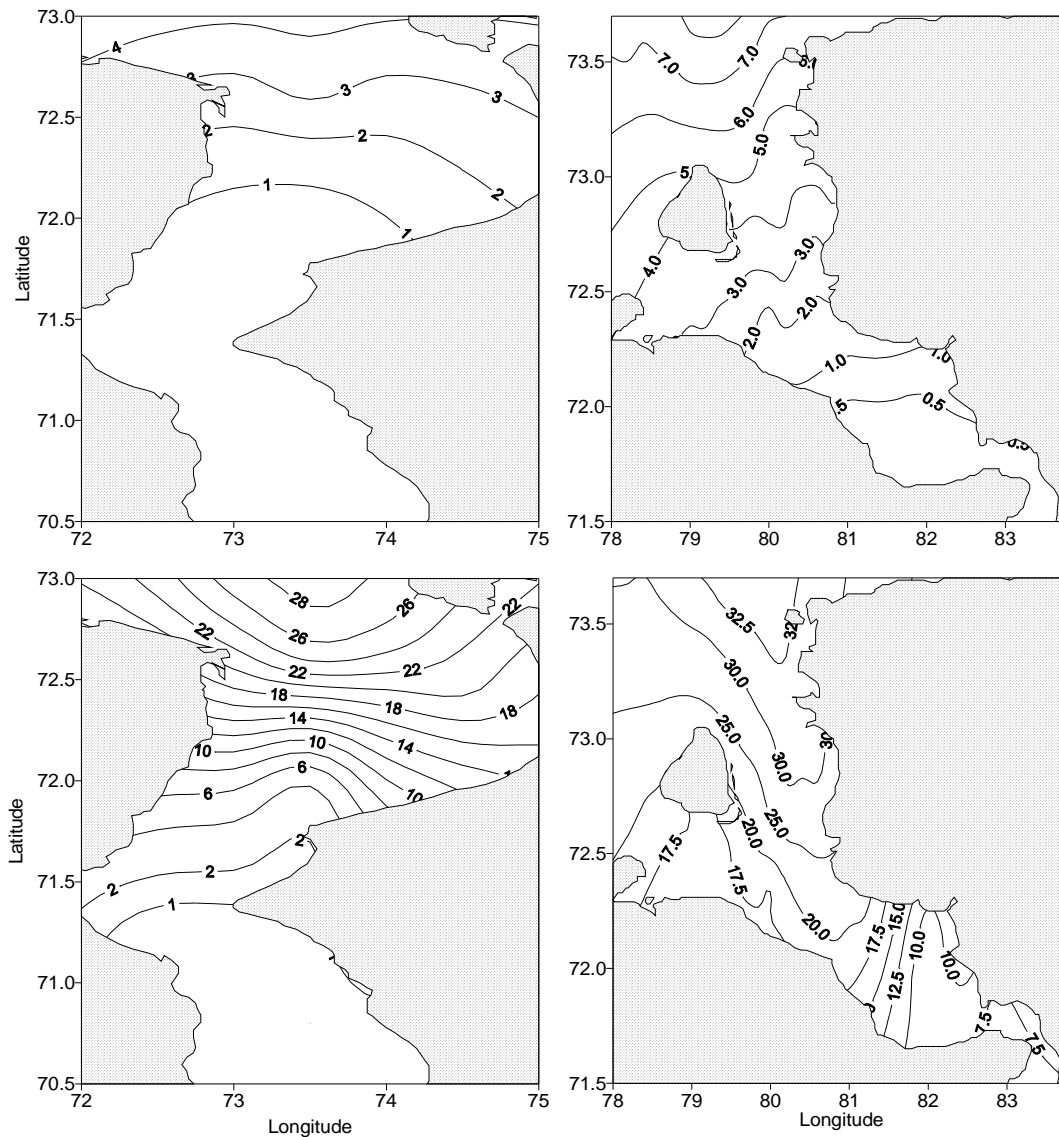


Fig. 1: Average multiyear salinity at the surface (upper panels) and at the bottom (lower panels) in August in the estuaries of Ob (left) and Yenisei (right).

<sup>1</sup> CTD = Conductivity, temperature and depth

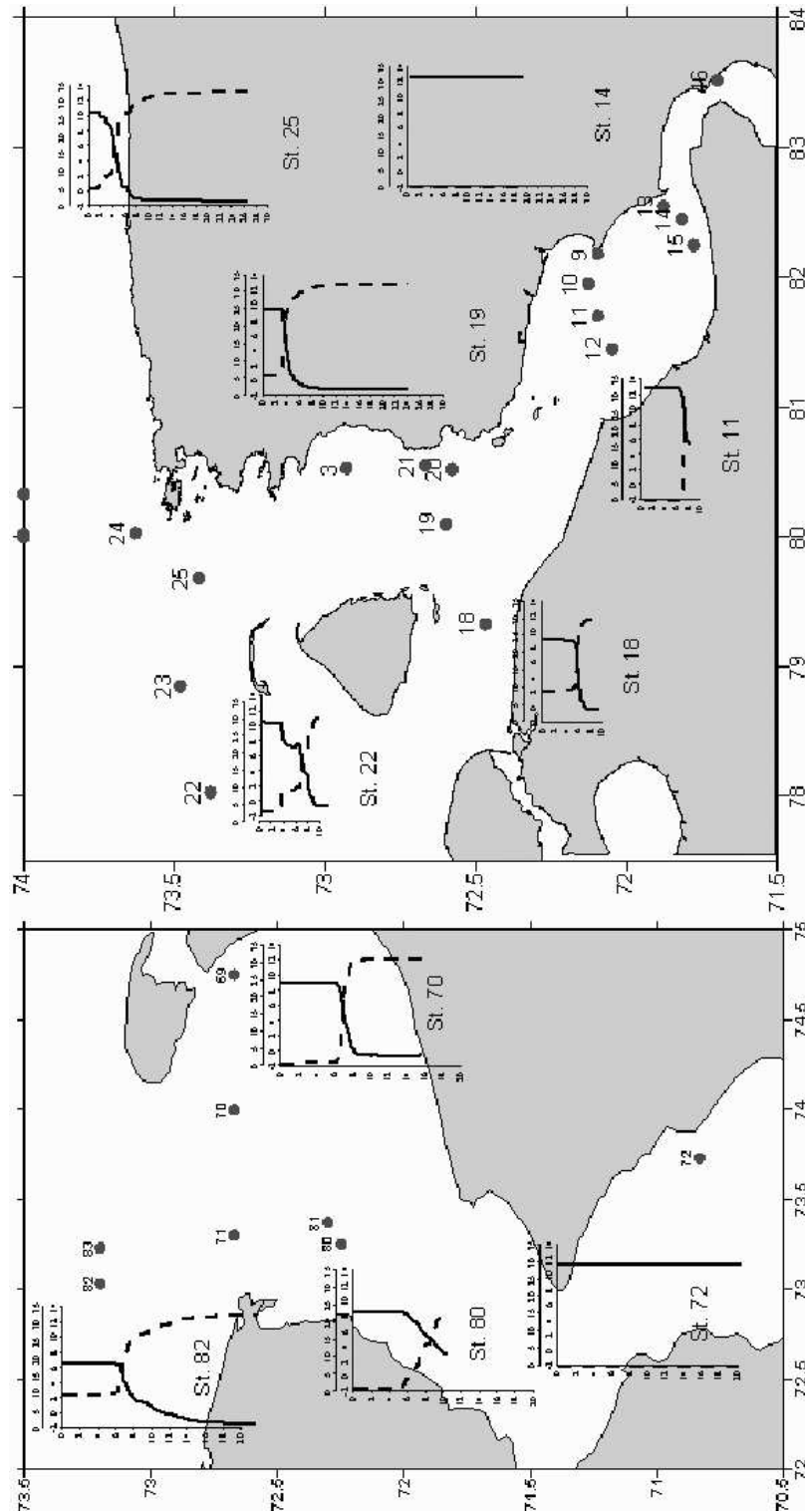


Fig. 2: Selected profiles of temperature (solid lines) and salinity (dashed lines) in summer 2001 in the estuaries of Ob (left) and Yenisei (right).

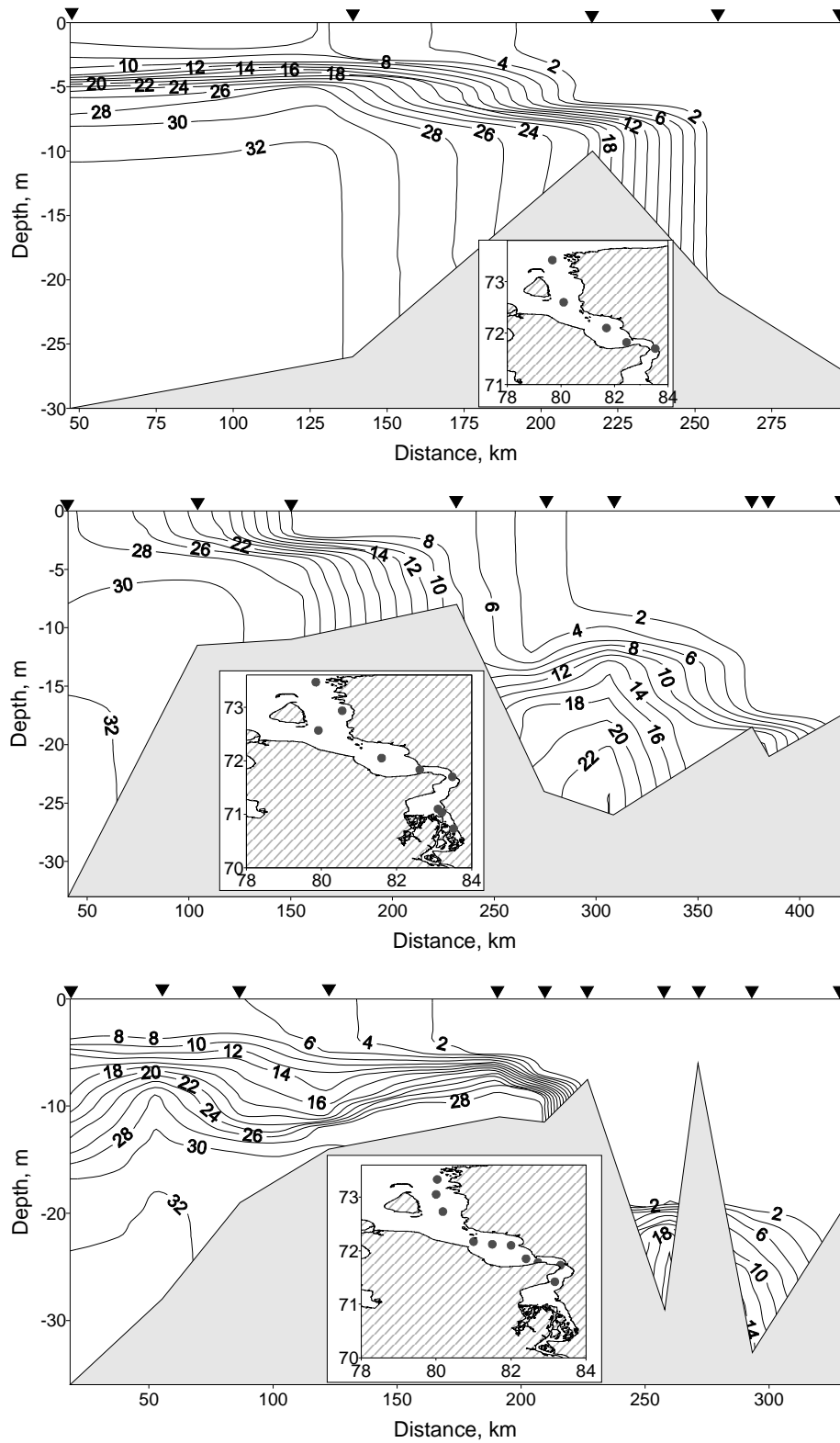


Fig. 3: Salinity sections in the Yenisei Estuary, observed in: (a) summer 2001, (b) summer 2000 and (c) summer 1995. Distance labels start at  $73^{\circ} 50' N$ ;  $80^{\circ} 00' E$

The most rapid freshening of estuarine surface waters in Ob and Yenisei occurs in spring when the spring flood wave passes through. At Dikson Island (outer Yenisei Estuary), for example, a sea surface salinity between 0-2 is observed for 20-30 days in June-July. Horizontal salinity gradients may reach values of up to 0.5 per 1 km. The horizontal transition zone between freshwater and brackish water in summer is located usually in the middle part of the Yenisei Estuary, between 71° 30' and 72° 00' N (Stanovoy and Nøst, 2002b). A typical example of such a distribution was observed during the last cruise of RV "Akademik Boris Petrov" in summer 2001 (Fig. 3a). This section shows clearly the horizontal salinity gradient just above the sill and the strong vertical stratification further seaward. Specific meteorological conditions might enhance the observed stratification shown in Figure 3a considerably. Driven by an on-shore counter flow at the bottom, saline bottom water may penetrate into the estuary, leading to so called 'salt intrusions'. Figures 3b and c show this phenomenon on two Yenisei sections taken in summer 1995 and 2000. In both figures, high saline bottom water has moved upstream of the sill, into the river delta, however, with different intensity.

The apparent interannual variability of salt intrusions is depicted more clearly in Figure 4, which shows the bottom water salinity for August, September and the winter season in the Yenisei river delta, north of the large sand bank.

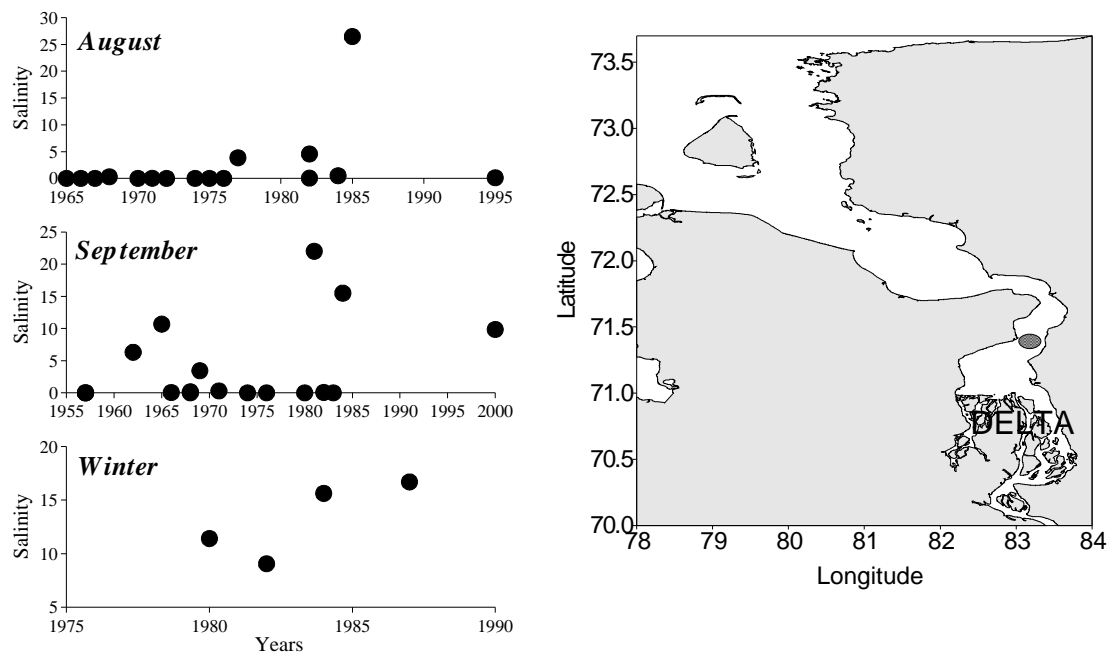


Fig. 4: Observed interannual variability of bottom water salinity for August, September and winter season (left) at 71° 24' N, Yenisei Estuary (right panel, dot).

All available observations carried out during the last 50 years were used. An extremely high value occurred in August 1985 but the number of salt intrusions seems to be higher in September, even if the absolute values are lower compared to August. Also in winter, the bottom water salinity varies considerable from year to year. The fact that the winter values are partly higher than the summer values can be attributed to a much weaker stratification in

winter and a general southward shift of the transition zone between freshwater and brackish water (Stanovoy and Nøst, 2002b).

These observations suggest that salt intrusions vary significantly on inter-annual time scales depending on the meteorological situation. We therefore expect also variations on shorter time scales. However, due to sparse data, it is difficult to assess the seasonal or monthly variability of salt intrusions from observations. In this situation, numerical models can be a valuable tool to give a more complete view of the variability in that region and the physics behind.

### 3 Model Experiments

Two well established hydrodynamic models are used to investigate circulation and stratification in the estuaries of Ob and Yenisei. Although the area of investigation is the same, the model types and the scope of the model applications are different: the HAMSOM/VOM application is focused on multi-year runs based on climatological, monthly mean forcing whereas the SCRUM application investigates only the ice free period in summer based on synoptic 12-hourly forcing. The aim of this paper is not to evaluate the model types or approaches but to interpret the model results in comparison with observations.

The following two sections describe the model type and configuration of the HAMSOM/VOM and the SCRUM approach.

#### 3.1 HAMSOM / VOM application

At the Institute for Oceanography, University Hamburg, the shelf sea modelling group applies a high resolution baroclinic 3-D circulation and sea ice model to the Kara Sea (Fig. 5). The horizontal grid resolution is 9.4 km. The model is based on the coding of the Hamburg Shelf Ocean Model HAMSOM, introduced by Backhaus (1985), and previously applied to the Barents and Kara Sea by Harms (1997a, b); Harms and Karcher (1999) and Harms et al. (2000). HAMSOM is based on non-linear primitive equations of motion, invoking the hydrostatic approximation and the equation of continuity, which serves to predict the elevation of the free surface from the divergence of the depth mean transport. The numerical scheme is semi-implicit and the equations are discretised as finite differences on an Arakawa C-grid (Stronach et al., 1993).

The circulation model is coupled to a thermodynamic and dynamic sea ice model, which calculates space and time dependent variations of ice thickness and ice concentration (Hibler, 1979). Sea surface heat fluxes, calculated with bulk formulae (Maykut, 1986), are used to determine prognostically the ocean temperature and thermodynamic ice formation (Parkinson and Washington, 1979). The circulation model includes an Eulerian transport algorithm for temperature, salinity and passive tracers, based on the advection-diffusion equation.

In order to handle complex bathymetries and to reproduce more realistically topographic effects on circulation and hydrography, the coding was vectorised and supplied with a vertical adaptive gridding technique (Backhaus, pers. com.). The Vector Ocean Model (VOM) is a level type model but the vertical adaptive grid implies that the number of levels and the thickness depends on the topography. The Kara Sea grid provides a high resolution in critical areas such as shallow estuaries, slopes and topographic obstacles. Surface and bottom following boundary layers are resolved uniformly in 4 m intervals (Fig. 5). This allows for a

better reproduction of estuary and shelf processes such as vertical stratification, stratified flows or current shear due to surface and bottom friction.

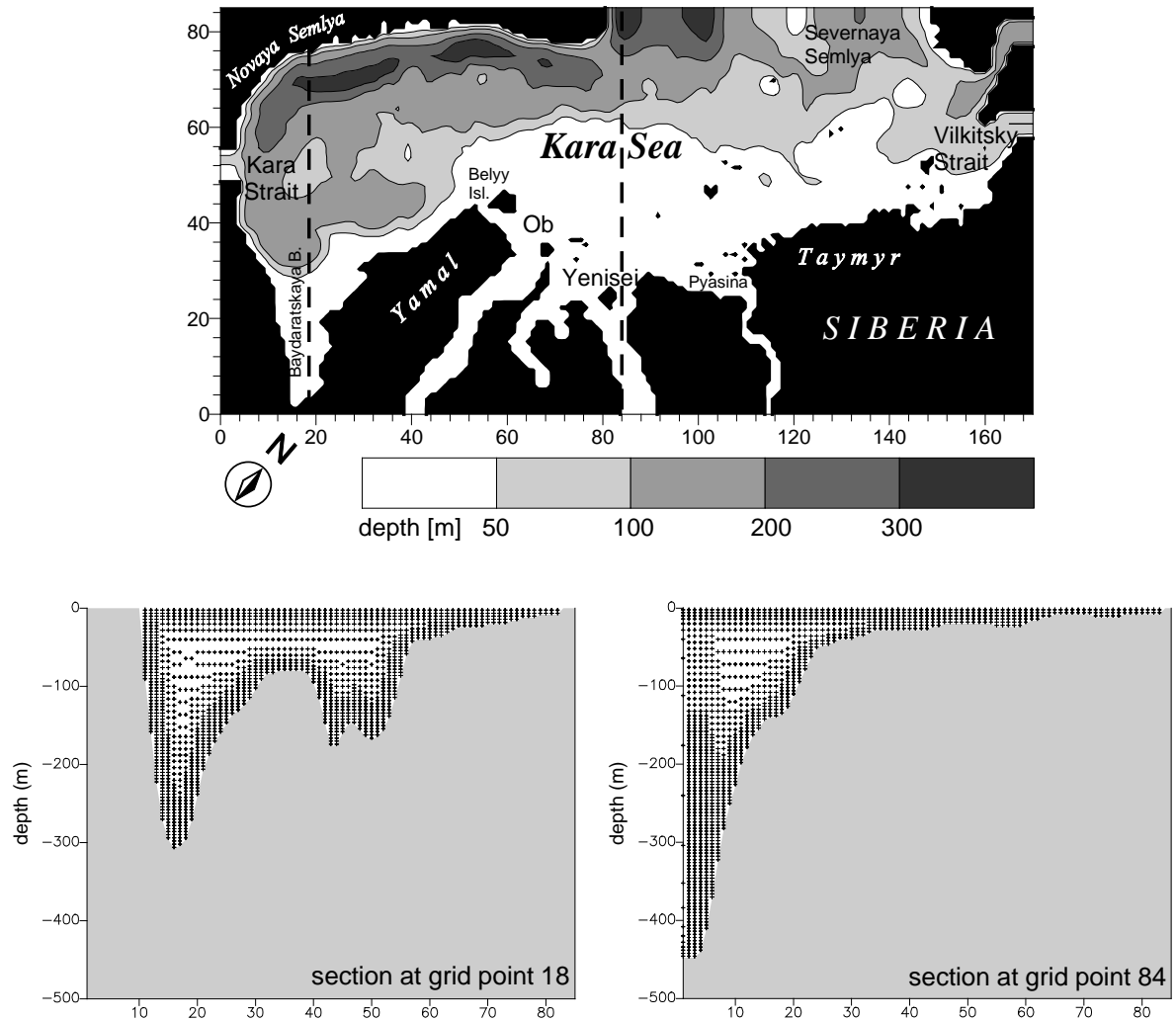


Fig. 5: Domain and topography of the HAMSOM/VOM Kara Sea Model (upper panel) and vertical grid resolution (lower panels) on two selected sections (dashed lines).

Our present studies are forced with realistic atmospheric winds, heat fluxes, river runoff and tides. The wind forcing is based on a climatological year prepared by Trenberth et al. (1989) from ECMWF data (ECMWF, 1988) for the period 1980-1989. Monthly mean climatological air temperature, humidity and cloud cover data were compiled by Aukrust and Oberhuber (1995) from ECMWF-data for the period 1985-1990. River runoff rates for Ob (incl. tributaries Taz and Pur), Yenisei and Pyasina are prescribed as daily mean volume fluxes in  $\text{m}^3/\text{s}$ , interpolated from 10-day mean values. Information on runoff to the Kara Sea was taken from a data review on the hydrology of Arctic rivers, described in more detail in Harms and Karcher (1999). The Kara Sea Model accounts for the dominant  $M_2$ -tidal constituent. Amplitudes and phases were taken from tidal models of the Arctic Ocean (Gjevik



and Straume, 1989; Kowalik and Proshutinsky, 1993; 1994) and applied to the open boundaries. A detailed description of the tidal solution is given in Harms and Karcher (1999). The simulation of the climatological year was started at 1<sup>st</sup> of January using initial temperature and salinity distributions from validated previous model runs (Harms and Karcher, 1999). The model was run in a prognostic mode allowing for three-dimensional temperature and salinity advection including sea surface heat fluxes and ice formation.

### 3.2 SCRUM application

The modelling group at AARI, St. Petersburg applies a Kara Sea model based on the coding of the S-Coordinate Rutgers University Model SCRUM, developed at the Institute of Marine and Coastal Sciences at Rutgers University. Hedstrom (1997) gives a detailed description of SCRUM with some applications. The main goal of the SCRUM application to the Kara Sea is to study estuarine processes on synoptic time scales during the ice-free period. Therefore this model application does not include an ice model.

The principal attributes of SCRUM are very similar to HAMSOM: SCRUM applies primitive equations with hydrostatic and Boussinesq approximation to calculate the 3-D flow field and the free surface. The discretisation is based on the Arakawa C grid. Advection schemes allow for a prognostic transport of tracers (potential temperature, salinity, etc). Also the horizontal resolution (10 km) and the model domain of the SCRUM Kara Sea Model is very similar to the HAMSOM/VOM Kara Sea model (c.f. Fig. 5). The main and important difference to HAMSOM however, is the vertical grid approximation: SCRUM is a layer type model that uses terrain-following, stretched coordinates. The vertical scale is resolved uniformly with 10 layers which means that in shallow areas each layer thickness is much smaller than in deeper areas.

The initial temperature and salinity data for winter and the river runoff to the Kara Sea were taken from the Joint Russian-US Atlas of the Arctic Ocean. The river runoff is prescribed as monthly mean discharge rates of the Ob and Yenisei rivers. The surface wind stress at 10 m height above the sea surface is prescribed twice a day (12 hourly forcing), based on NCEP/NCAR reanalysis data.

## 4 Model Results

In order to study the variability of the vertical stratification and to detect possible salt intrusions, we analysed the HAMSOM/VOM daily mean fields of salinity of the climatological year. An example for a typical summer situation is depicted in Figure 6 for the 5<sup>th</sup> of August. At the surface, the low saline river plume shows its largest extent, spreading in the entire central Kara Sea from the estuaries almost up to the Novaya Semlya coast. At the bottom, however, the extent of the freshwater plume is much smaller and shows several branches with higher saline water reaching from the north-east into the estuaries. In particular in the Yenisei, a salt intrusion penetrates deep into the estuary and the river delta.

The intensity of vertical stratification is different for Ob and Yenisei. Looking at the salinity differences between surface and bottom (Fig. 7), it becomes clear that the stratification is most pronounced in the Yenisei where the difference between surface and bottom salinity exceeds 20. The stratification in the Ob is weaker and the salt intrusion does not penetrate very far into the estuary.

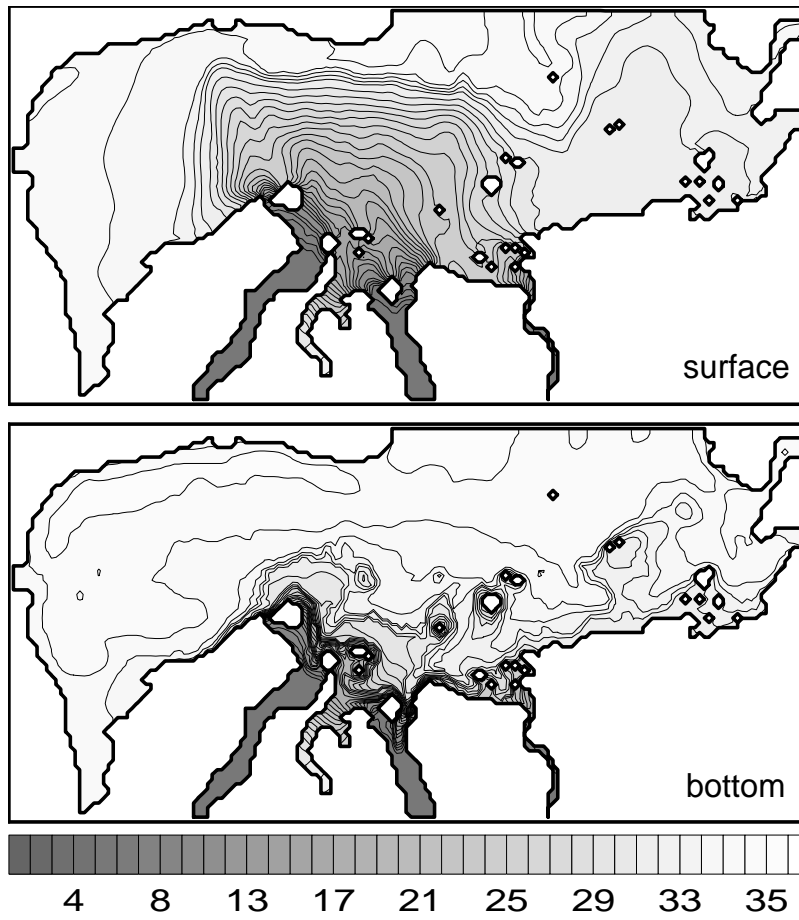


Fig. 6: Simulated salinity distribution (HAMSOM/VOM) at the surface and at the bottom for the 5<sup>th</sup> of August, climatological year.

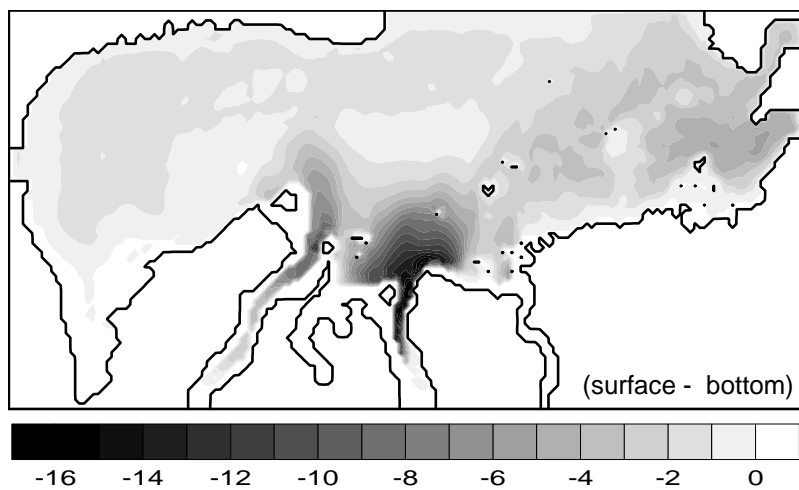


Fig. 7: Simulated salinity difference (surface-bottom, c.f. Fig. 5) at the 5<sup>th</sup> of August, climatological year.

The reason for estuarine salt intrusions can be found in the vertical distribution of the circulation field depicted in Figures 8 a and b for the 5<sup>th</sup> of August. The surface flow (a) is dominated by the runoff from the Ob and Yenisei. In the estuaries, intense north-westward flows drive the surface freshwater into the central Kara Sea where the front of the plume is visible as a slight discontinuity in the flow field. A striking feature at the bottom (b), however, is the south-westward flow along the Taymyr coast which is stronger than the corresponding surface flow and partly in the opposite direction. This model result reflects the reality very well: vertical current shear with north-westerly flows at the surface and south-westerly flows at the bottom were also reported by Johnson et al. (1997) and McClimans et al. (2000) from observations in that area. McClimans et al. (1997) found very similar flow patterns in laboratory model results, although this model had no wind forcing. Since the simulated south-westward bottom current at the Taymyr coast is very persistent during summer, we assume that this flow brings saline water from the north-eastern Kara Sea towards the estuaries thus enhancing the vertical stratification and forming a pool of saline bottom water in front of the river mouths. The pool of saline water may feed a bottom current in the estuary itself, leading to a salt intrusion in the river delta. Such a situation is clearly visible in Figure 8 b for the Yenisei.

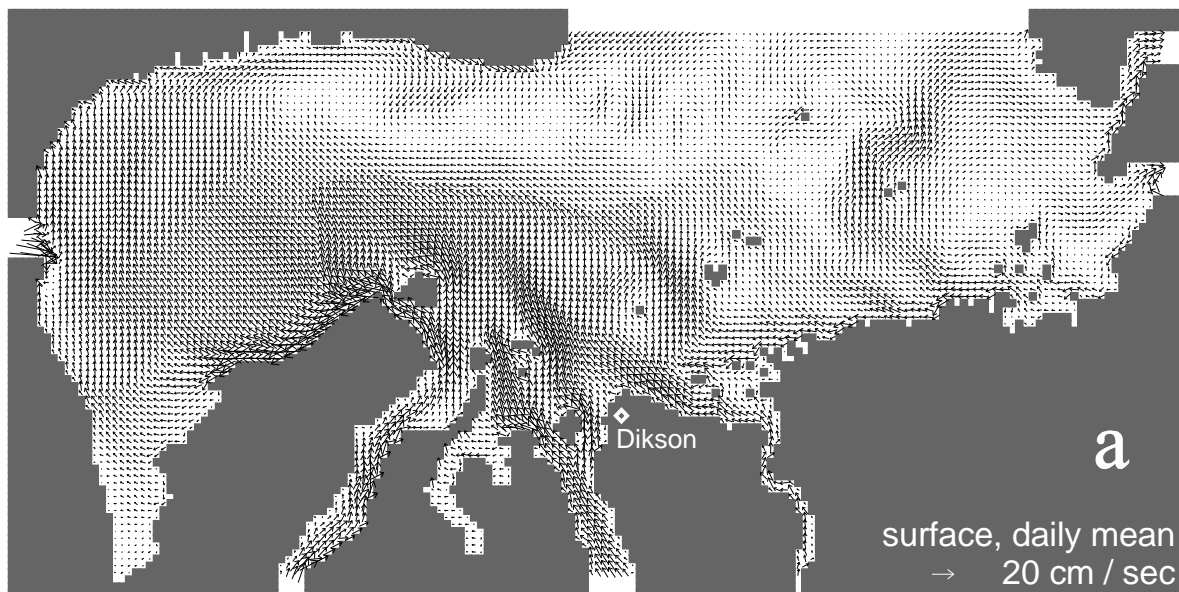


Fig. 8a: Simulated, de-tided and daily averaged surface flow (HAMSOM/VOM) at the 12<sup>th</sup> of July, climatological year.

In particular in the eastern part of the estuary, the bottom flow opposes the surface flow, forming a counter current that penetrates partly into the estuary. A time series of surface and bottom flows on a section in the eastern Yenisei Estuary (Fig. 9) suggests that the bottom counter current (shaded areas) compensates strong off-shore flow at the surface. Both flows reveal a significant inverse correlation: a southward bottom flow usually appears together with a northward surface flow and vice versa.

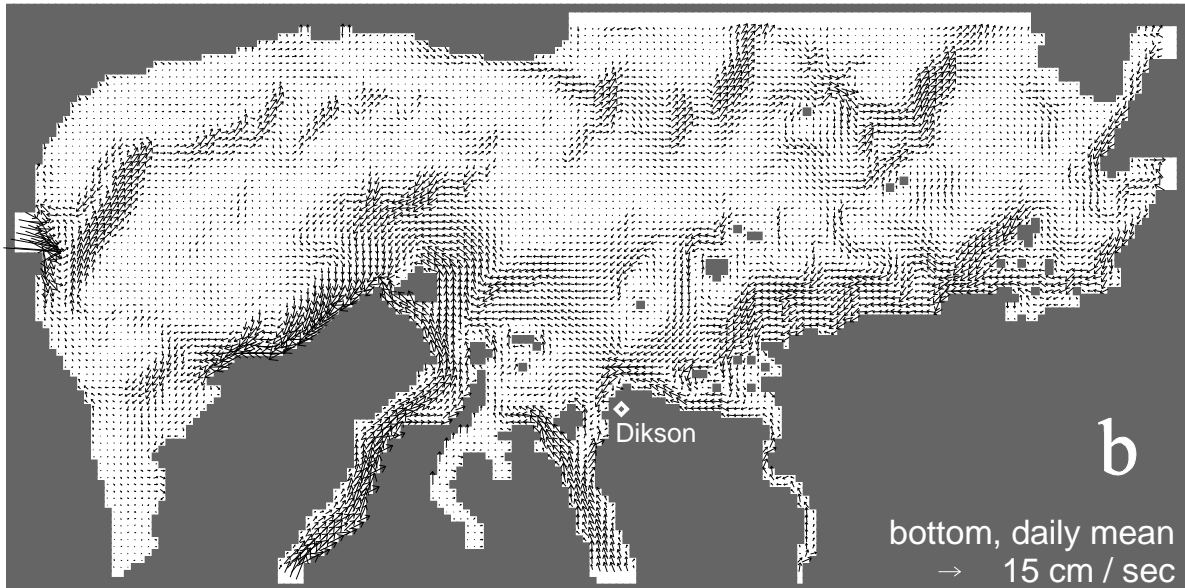


Fig. 8b: Simulated, de-tided and daily averaged bottom flow (HAMSOM/VOM) at the 12<sup>th</sup> of July, climatological year.

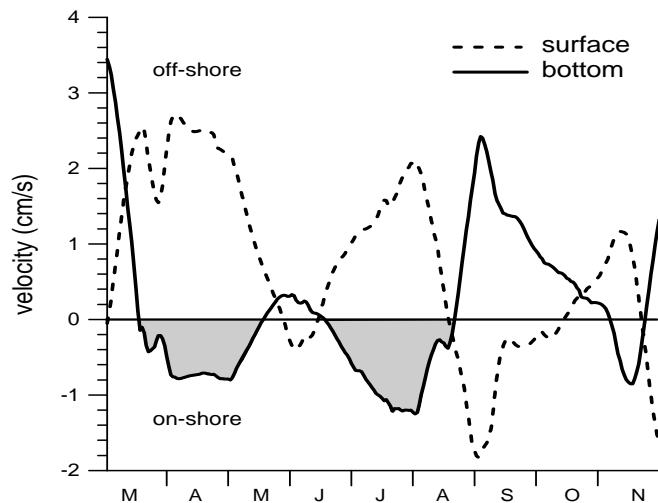


Fig. 9: Time series of de-tided bottom and surface flow in the outer Yenisei Estuary, near Dikson (see Fig. 7), from 1<sup>st</sup> of March to 30<sup>th</sup> of November, climatological year (HAMSOM/VOM). Shaded areas denote periods and strength of on-shore bottom flow.

The main driving force for this anti-correlated flow regime is the surface wind stress in the Kara Sea. The applied climatological ECMWF wind patterns show strong, monsoon-like variability due to the seasonal air pressure distribution over the Arctic. In winter, cyclonic vorticity prevails over the Barents and Kara Seas area with main local wind directions from south to south west. In summer, however, the wind fields show anti-cyclonic vorticity with dominating north to north-easterly winds in the southern Kara Sea (Harms and Karcher, 1999). Since the wind induced mass transport on the northern hemisphere is between 45° and

90° to the right of the wind direction, north-easterly winds cause a north-westerly off-shore surface transport away from the Taymyr coast and out of the Yenisei delta. As a result, the coastal sea level drops and a compensatory bottom flow may penetrate into the estuary.

Very similar results were obtained by the modelling group at AARI St. Petersburg. A characteristic example for the onshore, near bottom flow in the Yenisei Estuary simulated with SCRUM is presented in Figure 10 for the 29<sup>th</sup> of August 1978. Like with the climatological ECMWF data, the NCEP/NCAR wind patterns at that time (Fig. 10a) are characterised by an anticyclonic rotation over the Kara Sea, with strong north-easterly components over the Yenisei Estuary. This drives a surface flow of more than 40 cm/s out of the estuary whereas a near bottom counter current flows at 20 cm/s in the opposite direction (Figs. 10 b and c). The onshore current at the bottom is most pronounced in the deep eastern part of the Yenisei Estuary, which is also seen in the HAMSOM/VOM simulations.

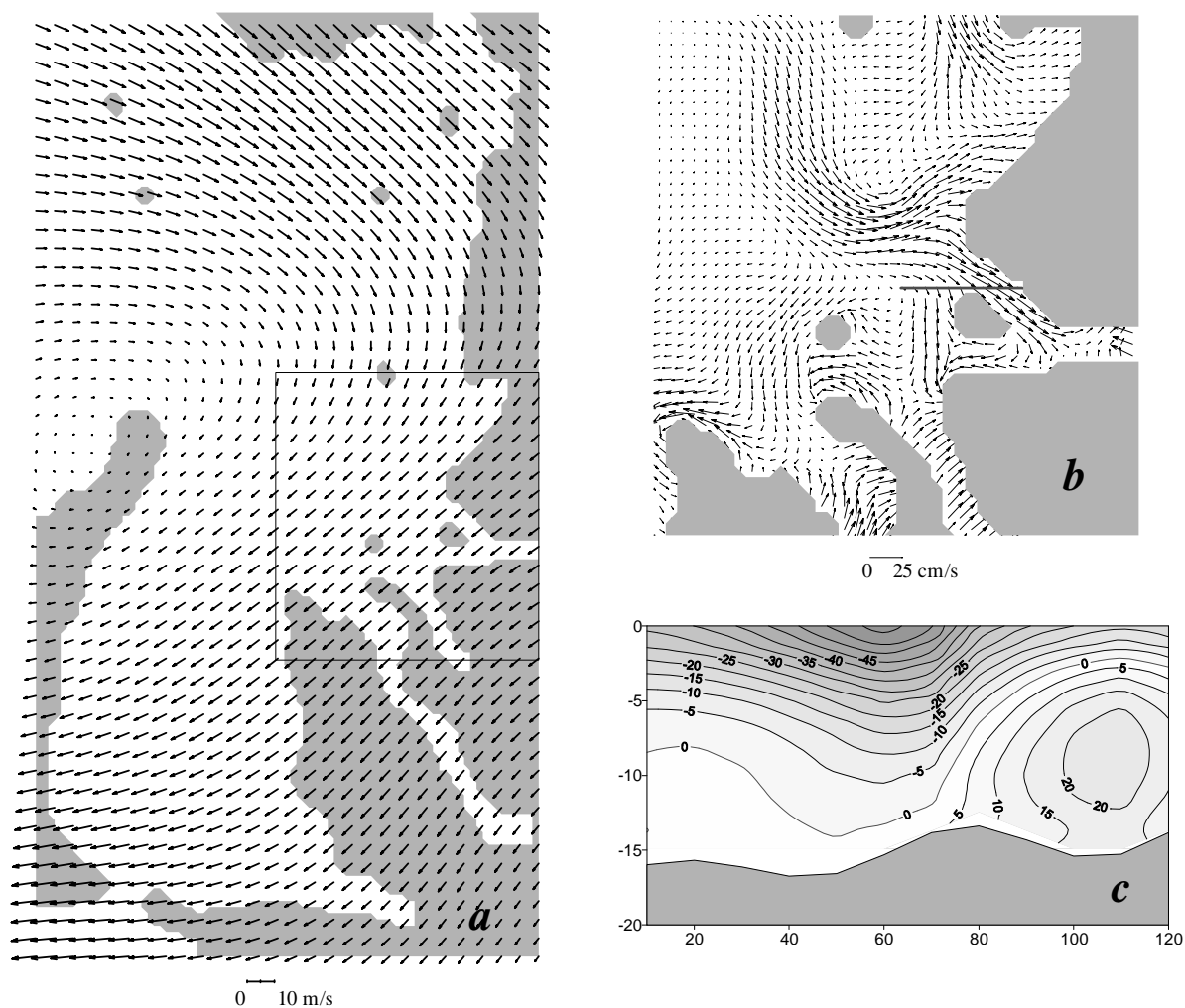


Fig. 10: Applied wind patterns (a), bottom flows (b) and along section components of current speed (c) at the 29<sup>th</sup> of August 1978, simulated with the SCRUM Kara Sea Model.

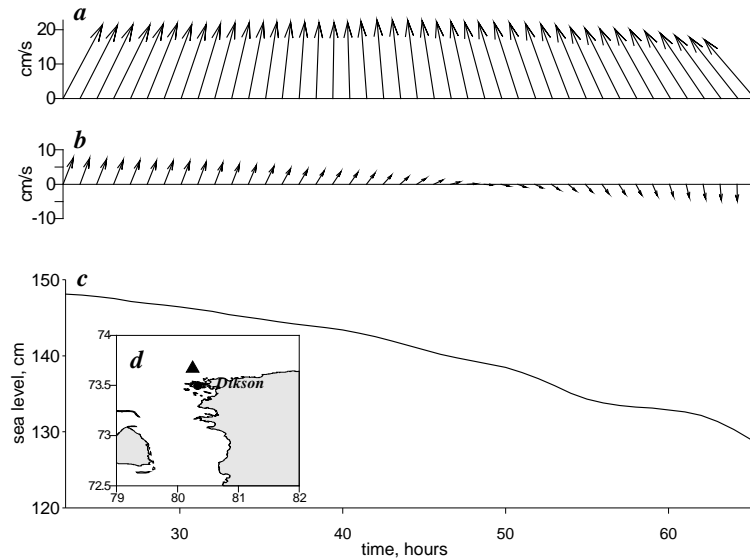


Fig. 11: Current vector time series from 8<sup>th</sup> to 9<sup>th</sup> of August 1975 for 9 m (a) and 22 m (b) depth, and sea level elevation at Dikson (c). Inlay (d) shows the position of the mooring (triangle) and the coastal station Dikson.

The simulated circulation from both models can be compared qualitatively with direct current measurements in the outer Yenisei Estuary, close to Dikson, from 8<sup>th</sup> and 9<sup>th</sup> of August 1975 (Fig. 11). The current meter mooring reveals a wind induced shift of the surface flow from north-east to north-west within two days. The north-westerly flow drives surface waters out of the Yenisei which causes a drop of the coastal sea level at Dikson. At the same time, the bottom flow shifts from off-shore to on-shore directions, finally forming a compensatory counter current that flows at 5 cm/s into the estuary. Although the time series covers only a short period, it illustrates the physics behind the salt intrusions and supports clearly the model findings.

## 5 Discussion

The applied horizontal model grid size of 9-10 km is still too coarse to trace salt intrusions further upstream of the sill and in the inner parts of the river delta. However, both models provide a high vertical resolution which is the main reason for their principal capability in reproducing observed Arctic coastal and estuarine dynamics and hydrography. SCRUM simulations for example show that calculated daily sea level elevations at coastal stations compare reasonably well with observations during the ice-free period (Fig. 12). A salinity section, simulated with HAMSOM/VOM (Fig. 13), is in qualitative agreement with salinity measurements presented in part I (c.f. Figs. 3a, b and c). Since direct current measurements are scarce and mostly not available for model comparison, the reproduction of single hydrographic observations, like sea levels, profiles or sections, constitutes a valuable model validation. These kinds of comparisons give confidence in using other model scenarios and parameters, not covered by measurements. Although the number of comparisons is very few, the reasonable agreement with hydrographic observations justifies the use of our model

results for the investigation of flow variability and physics that determine estuarine processes in Arctic Shelf Seas.

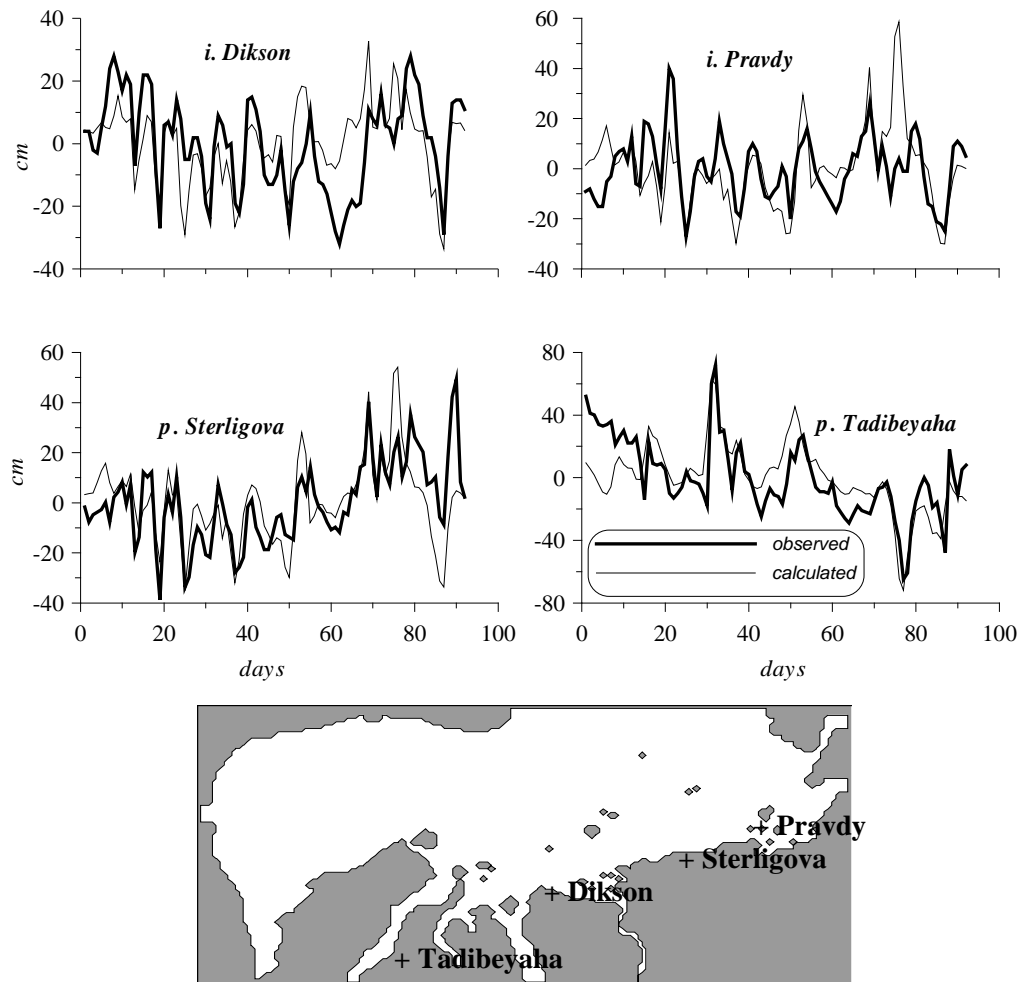


Fig. 12: Comparison of calculated (SCRUM) and observed sea surface elevations at coastal stations from July to September 1994.

The HAMSOM/VOM results depicted in Figure 9 suggest, that the summer flow regime is quite sensitive to the local wind directions over the Yenisei Estuary. In spite of the wind-induced input of anti-cyclonic vorticity at the surface from April to August, the summer flow regime is suppressed and almost reversed during a two weeks period in late May to early June. The reason is that the wind directions in June deviate slightly from the north-easterly direction and show more northerly components. Although the wind stress is very weak, northerly directions are able to slow down the surface off-shore flow which also affects the counter current.

An important point in this respect is the fact that the applied wind forcing is based on a climatological year which is purely artificial. Monthly mean values are very smooth due to averaging in the time domain and they do not reflect synoptic atmospheric variability at all. Although based on climatological forcing, the model results show that the estuarine summer

circulation is quite sensitive and responds directly to local wind effects. It can be assumed therefore that deviations from the typical summer circulation caused by small scale atmospheric variability occur more often and at shorter time scales than simulated.

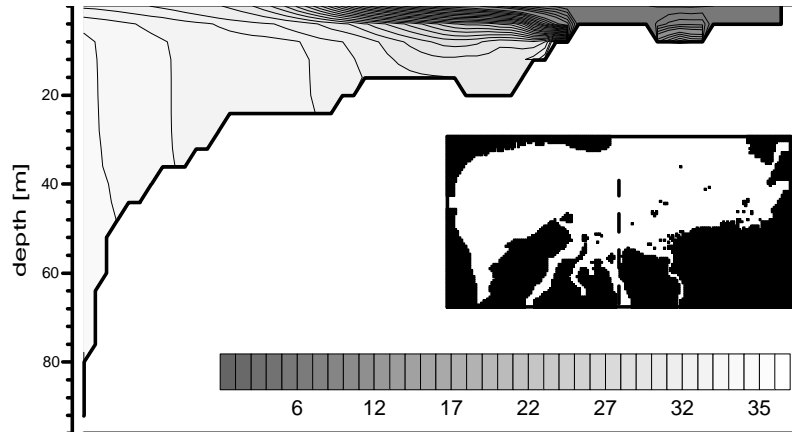


Fig. 13: Simulated salinity section in the Yenisei Estuary (see dashed line) for July, climatological year (HAMSOM/VOM).

Apart from the simulated blocking situation in May/June, the outlined summer circulation regime in the Yenisei prevails from April to August with peak intensities in April and July. However, the most interesting period with respect to variability of vertical stratification is probably late summer when the circulation regime changes from summer to winter. In the climatological HAMSOM/VOM simulation, the first half of August is still dominated by the summer situation with prevailing off-shore transport at the surface and on-shore flow at the bottom. The hydrography is characterised by high saline winter water at the bottom which is overlaid by large amounts of fresh water at the surface (c.f. Fig. 6). The vertical stratification is extreme due to salt intrusion at the bottom of the Yenisei delta. At mid August, however, the summer circulation breaks down and changes to the opposite, winter type flow. Salt intrusions vanish rapidly and the vertical stratification is eroded. If this dramatic change occurs during measurements in the estuary, the interpretation of the data might become difficult. In fact, most expeditions are carried out during the ice free season in July, August and/or September. It is therefore important not only to measure classical hydrographic parameters, but also to observe meteorological conditions and the resulting circulation by means of e.g. current meters or ADCPs<sup>2</sup>.

As outlined above, simulated salt intrusions are more pronounced in the Yenisei than in the Ob Estuary. The model results suggest that this is first of all due to the tidal mixing which is weaker in the Yenisei than in the Ob. Another important feature affecting salt intrusions is the shape of the sea bed of the estuary, which should be narrow and deep as with the Yenisei rather than shallow and broad as with the Ob. Also the geographical orientation of the estuary plays a role. The runoff direction in the Yenisei is more or less 90° to the right of prevailing north-easterly wind directions in summer that results in a maximum off-shore volume

<sup>2</sup> ADCP = Acoustic Doppler Current Profiler



transport. The orientation of the Ob Estuary is different and the same effect for the Ob would require south-easterly winds that are probably less frequent.

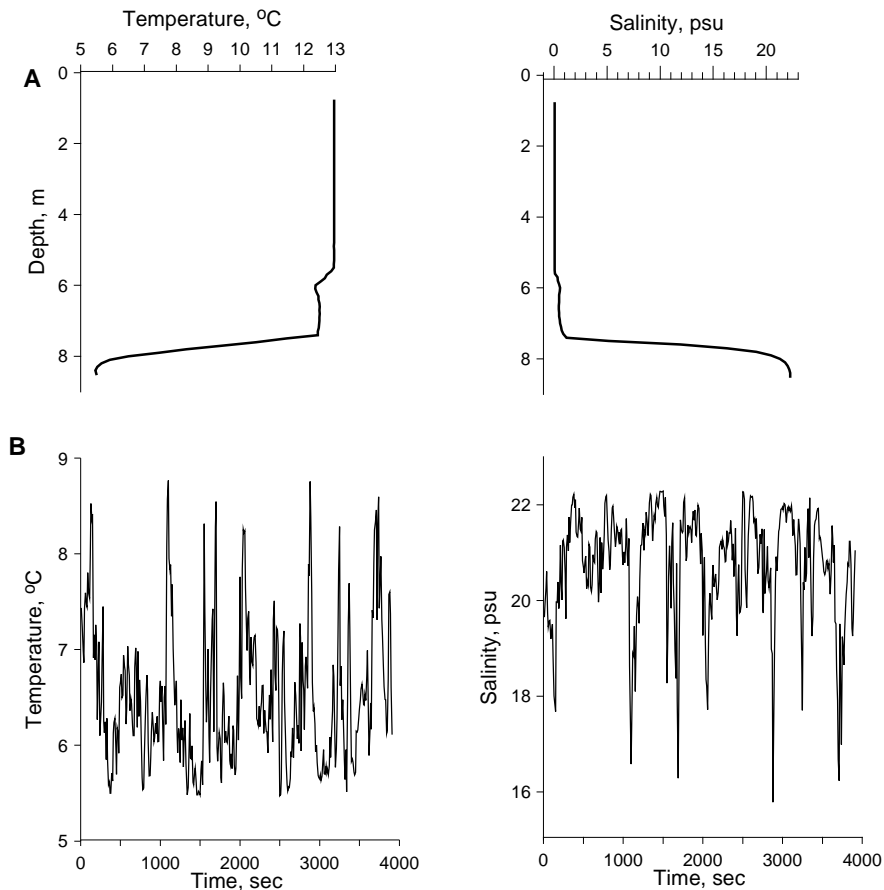


Fig. 14: Vertical profile of temperature and salinity (A) and oscillations of temperature and salinity at the 7.5 m depth horizon (B) at station 11 ( $72^{\circ} 06'N$ ;  $81^{\circ} 42'E$ ) in summer 2001.

The tidal influence on estuarine processes is mainly through horizontal and vertical mixing, internal wave activity and tidal residual flow due to non-linear bottom stress. Simulated residual currents (Harms and Karcher, 1999) were only found in the Ob Estuary, north of the Yamal peninsula and in the Baydaratskaya Bay. Around Belyy Island, residual currents form a weak anticyclonic circulation, however, the velocities here are generally small and remain below 2 cm/s. In the Yenisei Estuary, residual advection due to tidal activity plays an insignificant role. Also the upstream Stokes drift in the bottom layer, induced by the incoming tidal wave, is very weak in the Yenisei and remains in the range of 1 cm/s. Although the tidally induced advective transport is very weak, both processes, residual flow and Stokes drift, have to be regarded as permanent features in the whole system that contribute to estuarine dynamics but do not control e.g. salt intrusions.

The most important effect of tides on estuarine transport processes is through horizontal and vertical mixing. Strong tidal currents near the Ob Estuary provide a constant source for mixing in this area. Simulated  $M_2$ -tidal elevations usually remain below 20 cm in the Kara

Sea except two regions: the southern Baydaratskaya Bay, where tidal resonance causes amplitudes of more than 70 cm, and the area north of Yamal peninsula around Belyy Island (30-35 cm). North-east of the Yamal peninsula and in the small strait between Yamal peninsula and Belyy Island, simulated tidal currents may exceed 50 cm/s due to considerable horizontal gradients in tidal elevation. Stanovoy and Nøst (2002b) note that in the north-western Ob Estuary tidal elevations reach up to 1.8 m with tidal currents between 70 – 80 cm/s. Tracer simulations showed that these areas are significantly influenced by tidal mixing (Harms et al., 2000). In all other regions, in particular in the eastern Kara Sea and along the Taymyr coast, tidal mixing is much weaker.

Tides are also an important source for mixing and entrainment through the process of vertical instability and breaking of internal waves. Measurements carried out in summer 2001, showed very pronounced and classical examples of internal waves with periods of 8-12 min and 2-5 min in the Yenisei Estuary (Stanovoy and Shmelkov, 2002) (Fig. 14). The probability of dynamic instability and internal wave breaking is high for wave periods of 2-5 minutes. This could result in turbulent mixing and pycnocline erosion. As opposed to meteorologically induced features, all these tidal processes occur permanently to influence estuarine dynamics and hydrography.

Although the wind stress may vary slightly between Ob and Yenisei, the overall meteorological situation is very similar for both estuaries and cannot be responsible for large spatial variability. The observed and simulated difference between Ob and Yenisei in terms of vertical stratification and intensity of salt intrusions must be attributed to the different topography and the tidal influence, in particular tidal mixing. Future model studies should take these points into consideration.

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