Ice-ocean coupled model for operational predictions of sea ice and sea level conditions in the Arctic Ocean marginal seas

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Sea ice conditions and level changes along the Northern Sea Route (shallow arctic marginal the Barents, Kara, Laptev, East Siberian and Chukchi Seas) are influenced significantly by storm surges and tides.
These parameters are important for navigation and have been operationally predicted by AARI since later 1980s using a 2-D coupled ice-ocean model with horizontal resolution of 55.5 km. Here we present a new 3-D coupled ice-ocean model with improved physics and increased horizontal resolution (13.89 km). This model is forced by winds (ECMWF forecasts) and tidal forcing. The 5-day operational forecasts are provided to all users via internet (http://www.aari.ru/main.php)

Equations of motion

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=-\frac{1}{\rho_0}\frac{\partial P}{\partial x}+\frac{\partial}{\partial z}A_z\frac{\partial u}{\partial z}+\frac{\partial}{\partial x}A_L\frac{\partial u}{\partial x}+\frac{\partial}{\partial y}A_L\frac{\partial u}{\partial y};$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-\frac{1}{\rho_0}\frac{\partial P}{\partial y}+\frac{\partial}{\partial z}A_z\frac{\partial v}{\partial z}+\frac{\partial}{\partial x}A_L\frac{\partial v}{\partial x}+\frac{\partial}{\partial y}A_L\frac{\partial v}{\partial y};$$

$$\frac{\partial P}{\partial z}=\rho g;$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0;$$

$$\frac{\partial(T,S)}{\partial t}+u\frac{\partial(T,S)}{\partial x}+v\frac{\partial(T,S)}{\partial y}+w\frac{\partial(T,S)}{\partial z}=\frac{\partial}{\partial z}\nu\frac{\partial(T,S)}{\partial z}+\frac{\partial}{\partial x}\mu\frac{\partial(T,S)}{\partial x}+\frac{\partial}{\partial y}\mu\frac{\partial(T,S)}{\partial y};$$

$$\rho=f(T,S,P);$$

where: u, v, w are the (x, y, z) components of currents velocity vector,
f is Coriolis parameter, P is pressure,
T, S, ρ are sea water temperature, salinity, density respectively,
A_z, A_L are coefficients of turbulent exchange by momentum along vertical and horizontal axes,
ν, μ are vertical and horizontal diffusivity coefficients

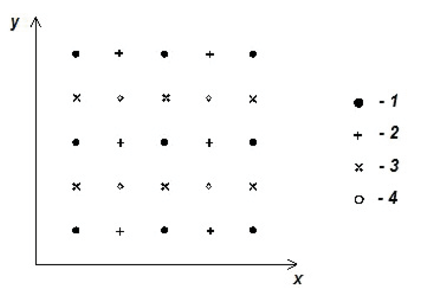
Depth-integrated equations

$$\frac{\partial U}{\partial t}-fV=-gH\frac{\partial\xi}{\partial x}-\frac{g}{\rho_0}\int_0^H\int_0^z\frac{\partial\rho}{\partial x}dzdz+\frac{\tau^0_x}{\rho_o}\quad\frac{\tau^B_x}{\rho_0}+\frac{\partial}{\partial x}\mu\frac{\partial U}{\partial x}+\frac{\partial}{\partial y}\mu\frac{\partial U}{\partial y},$$

$$\frac{\partial V}{\partial t}+fU=-gH\frac{\partial\xi}{\partial y}-\frac{g}{\rho_0}\int_0^H\int_0^z\frac{\partial\rho}{\partial y}dzdz+\frac{\tau^0_y}{\rho_o}\quad\frac{\tau^B_y}{\rho_0}+\frac{\partial}{\partial x}\mu\frac{\partial V}{\partial x}+\frac{\partial}{\partial y}\mu\frac{\partial V}{\partial y},$$

$$U=\int_0^H udz\qquad V=\int_0^H vdz$$

$$\frac{\partial\xi}{\partial t}=-\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right)$$



Placement of variables on the grid

$1-\xi,\ \rho,\ T,\ S, w;\ 2-U,\ \ 3-V;\ \ 4-u,v$

Splitting of 3-D mode

1.
$$\frac{\partial u}{\partial t}-fv=-g\frac{\partial\xi}{\partial x}-\frac{g}{\rho_0}\int_0^z\frac{\partial\rho}{\partial x}dz+\frac{\partial}{\partial z}\varepsilon\frac{\partial u}{\partial z}$$

$$\frac{\partial v}{\partial t}+fu=-g\frac{\partial\xi}{\partial y}-\frac{g}{\rho_0}\int_0^z\frac{\partial\rho}{\partial y}dz+\frac{\partial}{\partial z}\varepsilon\frac{\partial v}{\partial z}$$

$$W=u+iv,$$

$$\frac{\partial W}{\partial t}+ifW=-g\left[\left(\frac{\partial\xi}{\partial x}+i\frac{\partial\xi}{\partial y}\right)+\frac{1}{\rho_0}\left(\int_0^z\frac{\partial\rho}{\partial x}dz+i\int_0^z\frac{\partial\rho}{\partial y}dz\right)\right]+\frac{\partial}{\partial z}\varepsilon\frac{\partial W}{\partial z}$$

2.
$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=0$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=0$$

3.
$$\frac{\partial u}{\partial t}=\frac{\partial}{\partial x}\mu\frac{\partial u}{\partial x}+\frac{\partial}{\partial y}\mu\frac{\partial u}{\partial y}$$

$$\frac{\partial v}{\partial t}=\frac{\partial}{\partial x}\mu\frac{\partial v}{\partial x}+\frac{\partial}{\partial y}\mu\frac{\partial v}{\partial y}$$

Ice model

$$\frac{\partial u_i}{\partial t}=fv_i-g\frac{\partial\xi}{\partial x}+\frac{1}{\rho_i h}\left(\tau^i_x-\tau^w_x\right)+F_x$$

$$\frac{\partial v_i}{\partial t}=-fu_i-g\frac{\partial\xi}{\partial y}+\frac{1}{\rho_i h}\left(\tau^i_y-\tau^w_y\right)+F_y$$

$$\frac{\partial C}{\partial t}=-\frac{\partial u_iC}{\partial t}-\frac{\partial v_iC}{\partial t}$$

$$F_x=m\left(A_i\frac{\partial^2u_i}{\partial x^2}+\eta\frac{\partial}{\partial x}(\mathrm{div}V_i)-\frac{\partial P_i}{\partial x}\right)$$

$$F_y=m\left(A_i\frac{\partial^2v_i}{\partial y^2}+\eta\frac{\partial}{\partial y}(\mathrm{div}V_i)-\frac{\partial P_i}{\partial y}\right)$$

$$P_i=-\eta_1\mathrm{div}V_i,\qquad\text{for }\mathrm{div}V_i<0$$

$$P_i=0,\qquad\text{for }\mathrm{div}V_i\geq 0$$

$$A_i=\eta;\qquad\eta_1\cong 10\eta$$

Boundary conditions

At the sea surface $z=\xi(x,y,t)$

$$\rho_0A_z\frac{\partial u}{\partial z}=-\tau_x,\quad\rho_0A_z\frac{\partial v}{\partial z}=-\tau_y$$

$$\rho_0\mu_T\frac{\partial T}{\partial z}=-\frac{Q_T}{C_p},\quad\rho_0\mu_S\frac{\partial S}{\partial z}=Q_S$$

$$w=-\left(\frac{\partial\xi}{\partial t}+u\frac{\partial\xi}{\partial x}+v\frac{\partial\xi}{\partial y}\right);$$

At the bottom $z=H(x,y)$

$$u=v=w=0$$

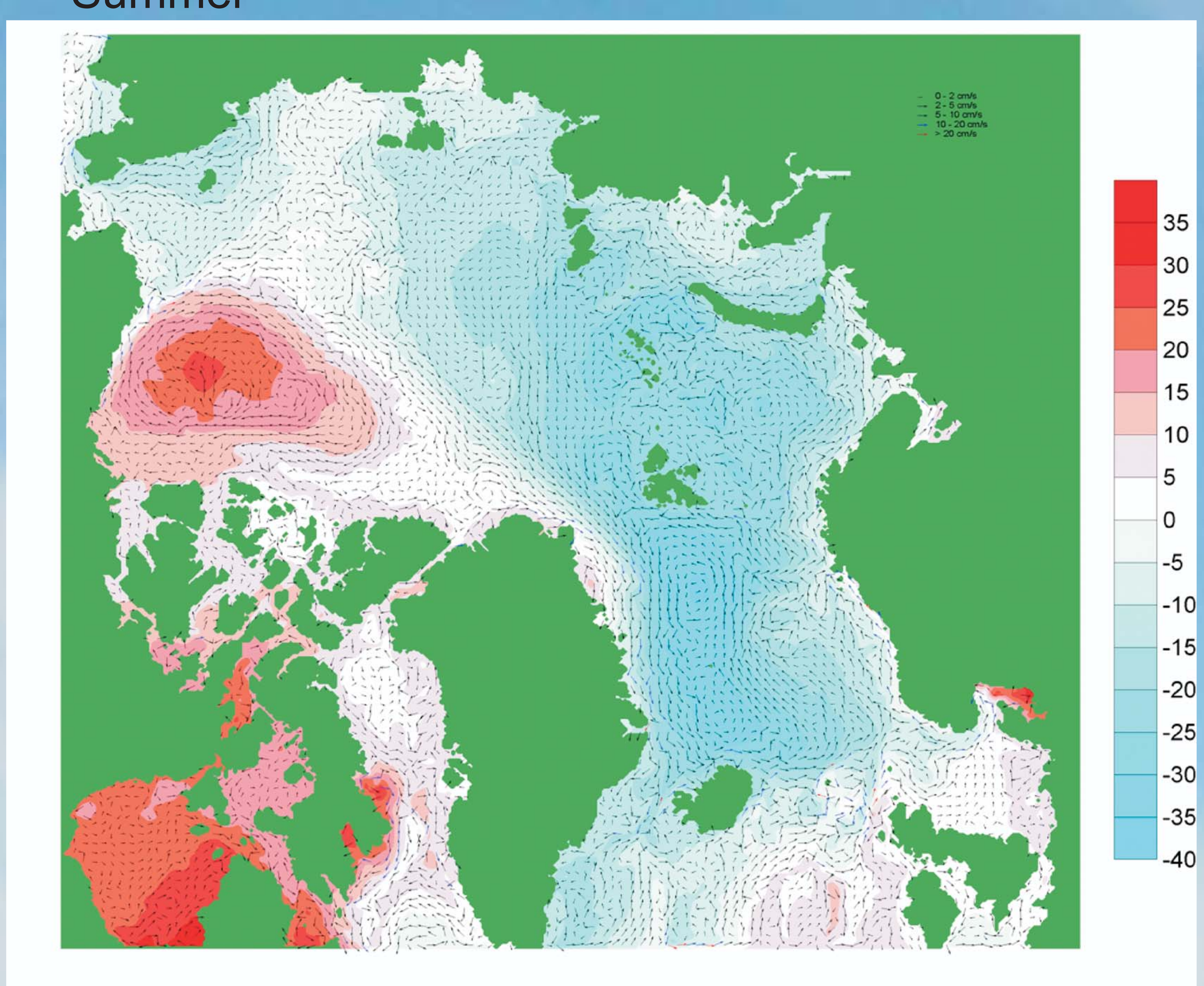
$$\rho_0\mu_T\frac{\partial T}{\partial z}=0,\quad\rho_0\mu_S\frac{\partial S}{\partial z}=0$$

Here:
$\tau_{x,y}$ – is vector components of tangential stress at sea surface,
Q_T, Q_S are surface heat and salt fluxes,
ξ - is deviation of sea surface from undisturbed state.

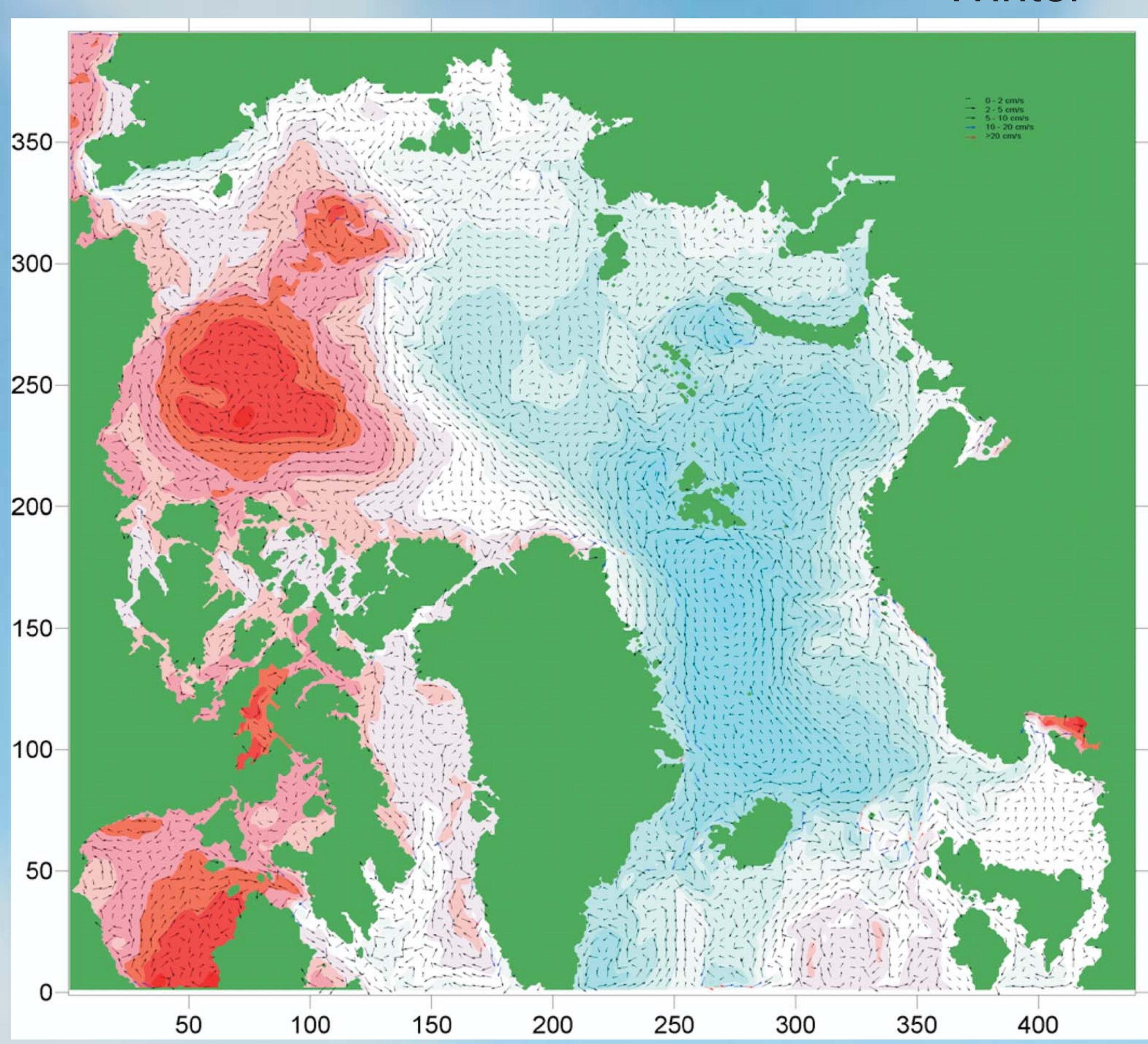
Wind stresses at sea surface and sea ice are calculated based on balk formulas recommended by AOMIP and are assumed to be identical. Frictional terms at sea ice and ocean interface are proportional to the second order of sea ice and ocean velocities difference. Sea ice internal interaction forces are calculated in a viscous form proposed by Rothrock (1975). The observed sea ice concentration is used as initial condition at the beginning of predictions. Ocean state parameters (T, S, currents) after long-term model run under climatologic forcing are used as initial conditions for operational forecasts. Sea ice thickness is 2 meters everywhere and does not change in time.

Climatologic surface water circulation due to T and S forcing

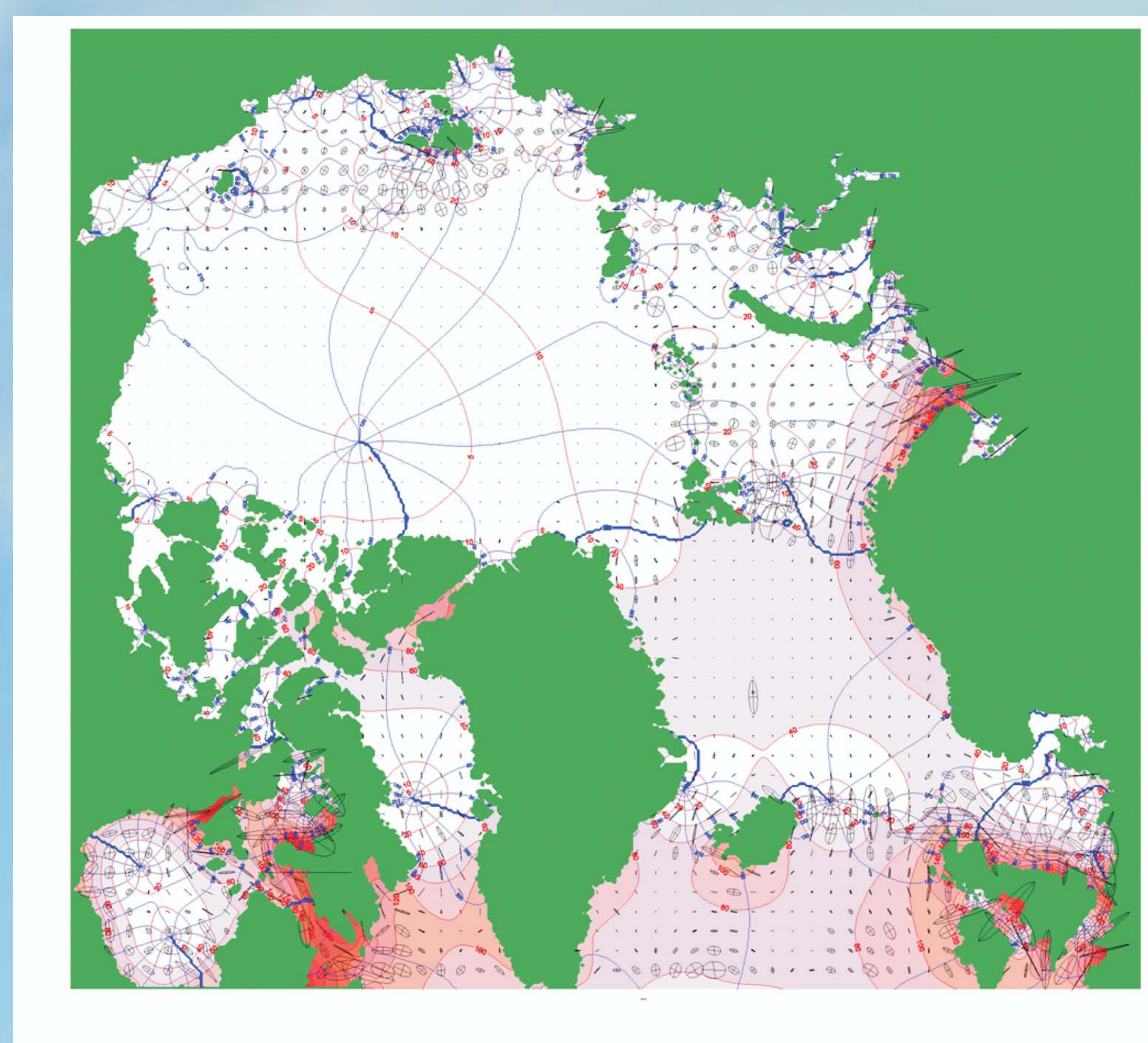
Summer



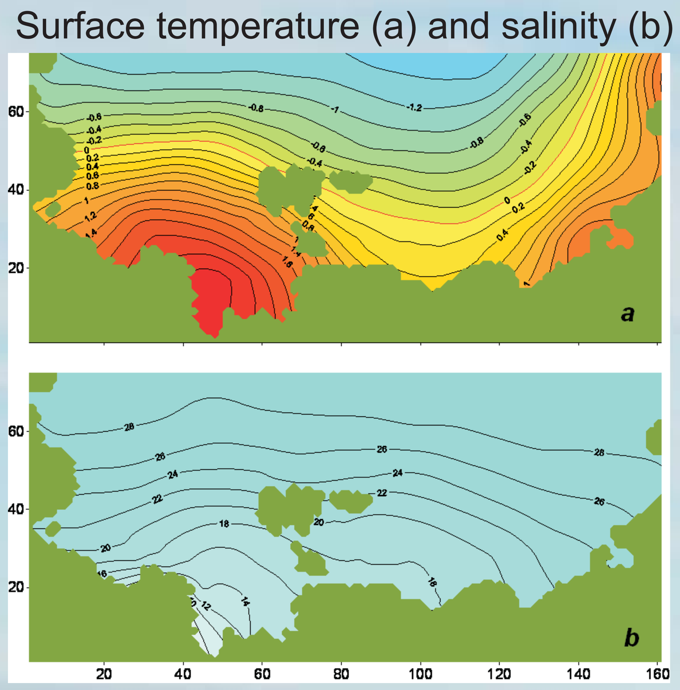
Winter



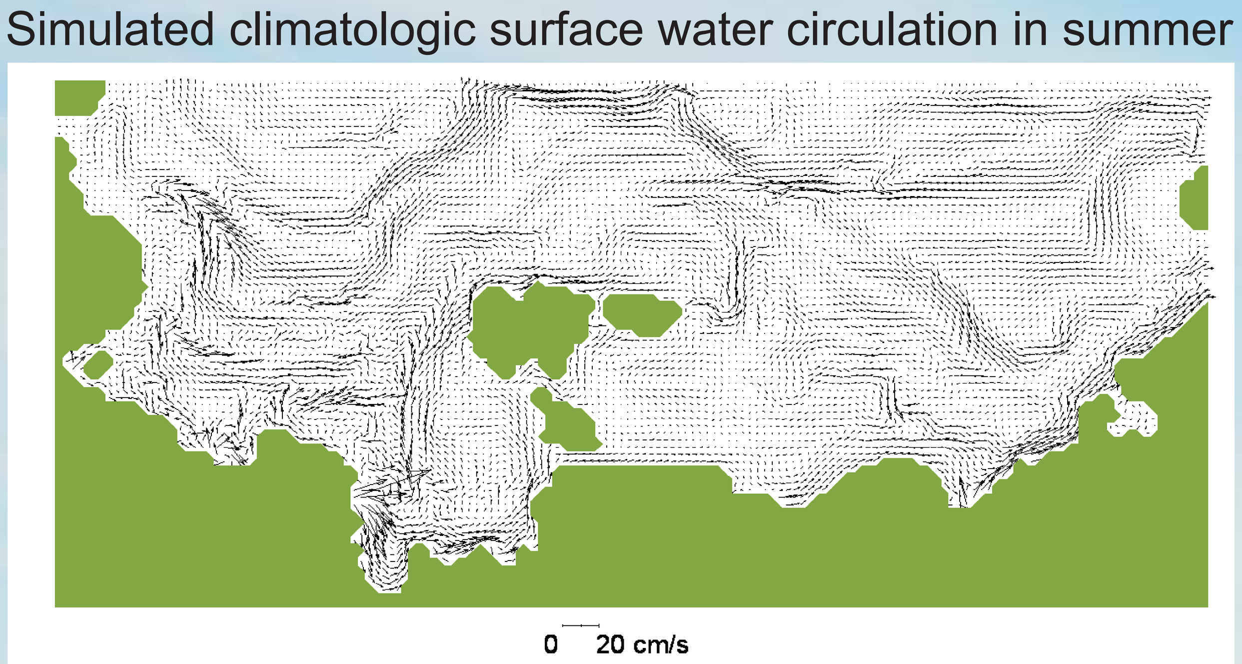
Calculated tidal wave M_2



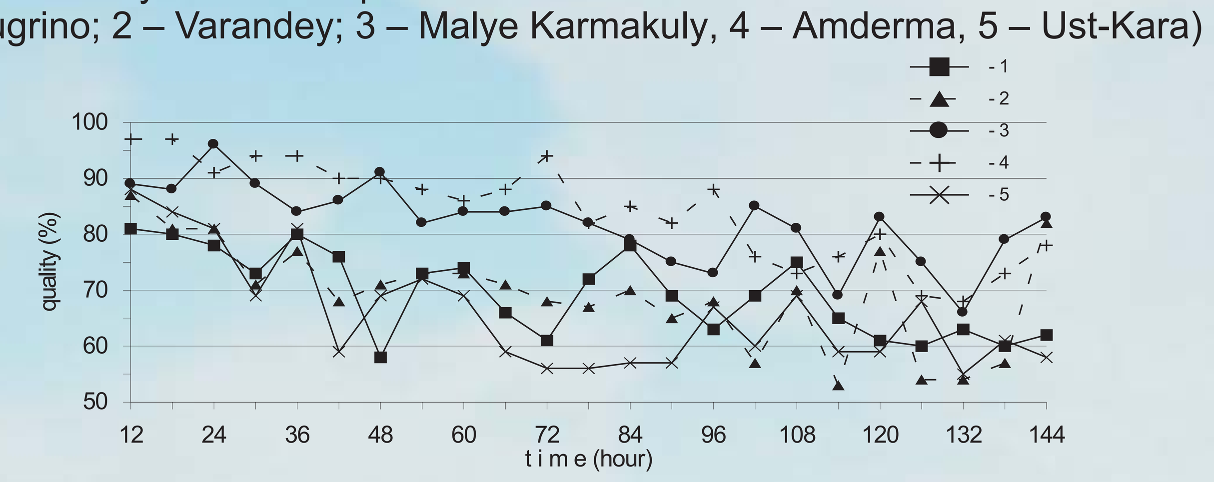
Surface temperature (a) and salinity (b)



Simulated climatologic surface water circulation in summer

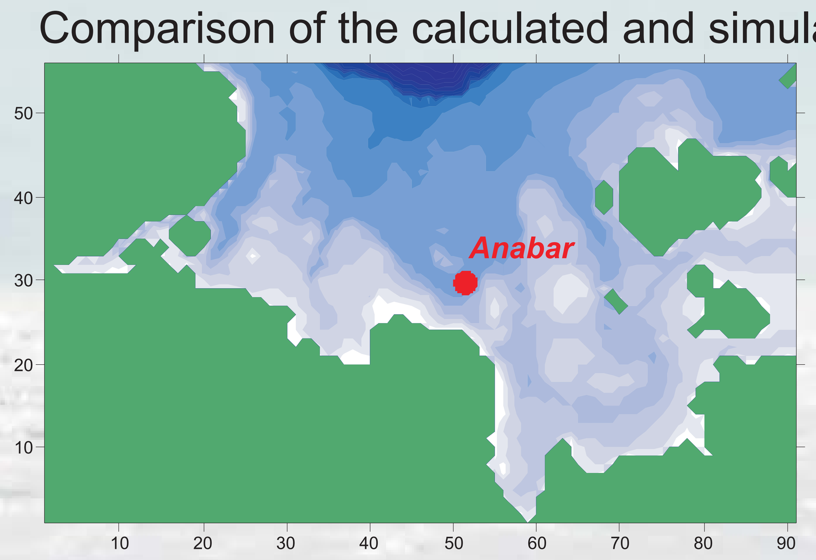


Qualityof sea level predictions in the Barents and Kara Seas
(1 – Bugrino; 2 – Varandey; 3 – Malye Karmakuly, 4 – Amderma, 5 – Ust-Kara)

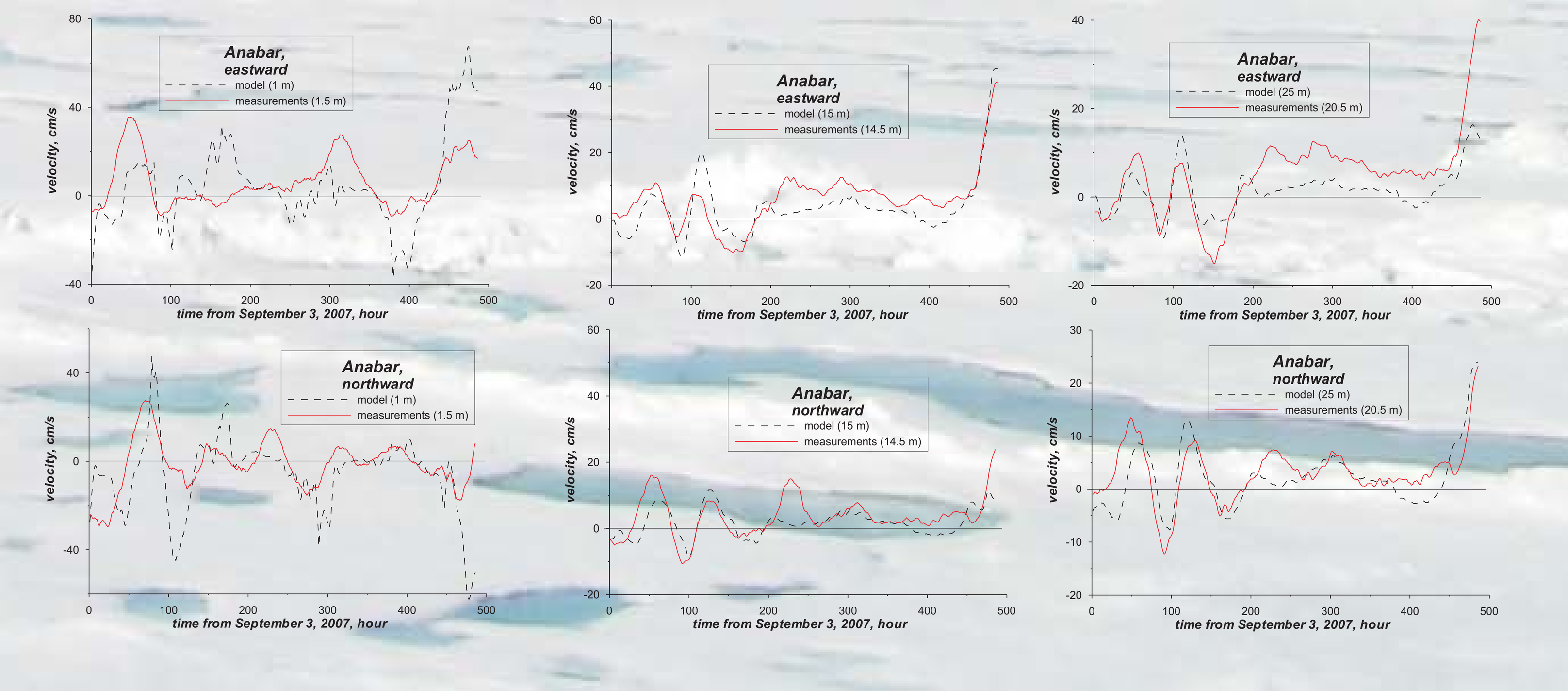


The accuracy of the sea level reproduction has been estimated for both diagnostic (based on observed forcing) and predicted (based on 6-day ECMWF forecasts of sea level atmospheric pressure) simulations. The accuracy of sea level calculations depends mostly on the accuracy of external forcing. The Root Mean Square Error (RMSE) of the predicted sea levels is approximately 17 cm for the 3-day predictions and it increases to 22 cm for the redictions between 3 and 6 days in advance.

Comparison of the calculated and simulated currents at "ANABAR" mooring



TRANSDRIFT XII /BARKALAV2007
Mooring "ANABAR", Sept. 2007 – Sept. 2008
Deployed: 2007-09-02, 05:46 UTC
Recovered:2008-09-07, 06:00 UTC
Position: 74 19.934 N, 128 00.027 E
Depth: 32m
Sensors:
ADCP Teledyne-RDI Workhorse Sentinel 300 kHz WHS300-I-UG135
Memory: 64 Mbyte Flash-memory
Serial: 9226
Transducers 3,20 m above seafloor, up looking
ADCP Teledyne-RDI Workhorse Sentinel 1200 kHz WHSZ1200-I;
Memory: 64 Mbyte Flash-memory
Serial: 9208
Transducers 5,30 m above seafloor, down looking



Comparison of the calculated sea level oscillation and the data of coastal stations