Assimilation of sea-ice velocity in a Finite Element Sea-Ice Model

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Introduction

The Singular Evolutive Interpolated Kalman (SEIK) Filter has been used to assimilate Quikscat and SSM/I derived sea-ice drift data in a Finite Element Sea-Ice Model (FESIM) of the Arctic region. A simulation of four month with data assimilation on every 3rd day was performed. The assimilation affects not only drift, but also ice thickness distribution. Compared to the ice thickness or concentration the ice drift changes very frequently, depending on wind, ocean, and internal ice stress. Since inertia of sea ice is small compared to the stresses, the system has very little memory beyond each assimilation step, making corrections by the filter very short-lived. Even a perfectly corrected drift field has very little effect on the model state in the next model integration step. However, ice-drift history is stored in the ice thickness and ice concentration distributions. A modified ice thickness distribution in turn affects the sea-ice drift.

Model Description

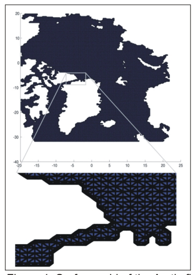


Figure 1: Surface grid of the Arctic finite element sea ice ocean model

The finite-element dynamic-thermodynamic sea-ice model (FESIM) is based on the work of Hibler (1979), but uses the EVP rheology of Hunke & Dukowicz (1997). Momentum balance and advection are solved with the finite element method. The thermodynamic part solves the one-dimensional energy budget and is based on Semtner (1976) and Parkinson and Washington (1979). A prognostic snow layer (Owens and Lemke, 1990) with snow-ice conversion (flooding) is included. Model time step is 2h. The momentum balance is computed with explicit time stepping. The model grid covers the entire Arctic (Fig. 1). It is almost regular and has a mean resolution of about 25 km. The model is forced by daily NCEP/NCAR reanalysis data for air temperature and wind velocities, by monthly means of humidity and dew point temperature and by climatological means of cloudiness and precipitation. Monthly means of ocean currents derived from coupled simulations are prescribed. Vertical ocean heat flux follows a turbulent mixing approach.

Filter Method

A comparison of Kalman filter types (EnKF, SEEK and SEIK) done by Nerger et al. (2005) revealed advantages for the Singular Evolutive Interpolated Kalman Filter (SEIK) with respect to computing time for large ensembles. The SEIK filter is applied with 23 ensemble states (rank=22; dimension of one model state is approx. 1.7 M) and with a forgetting factor $\rho = 0.8$. Observations are 3 day mean sea-ice drift fields derived from Quikscat and SSM/I satellite data (from CERSAT/Ifremer) so every 3rd day an update of model state is computed.

SEIK Algorithm:

INITIALISATION of FESIM and SEIK

↓ Generating a state ensemble of minimum size whose ensemble statistics yield exactly the low-rank covariance matrix **P** in a decomposed form: $P_0 = L_0 U_0 L_0^T$ which is representative of estimated model variance.

model state ensemble (initial or analysed, SEIK)

↓ analysed single ensemble member

↓ **Model FORECAST (FESIM)** x_k^f

↓ forcasted single ensemble member

communication interface SEIK ⟷ FESIM

↓ **forecasted model state ensemble (SEIK)**

↓ **ANALYSIS (SEIK)**

When observations y^0 are available compute the updated **U** which only implicitly relates the model deviation to the observation error R. The model state update x^a finally is given by

$$x^a = \bar{x}^f + LUL^T H^T R^{-1} \left(y^o - H\left[\bar{x}^f\right]\right)$$

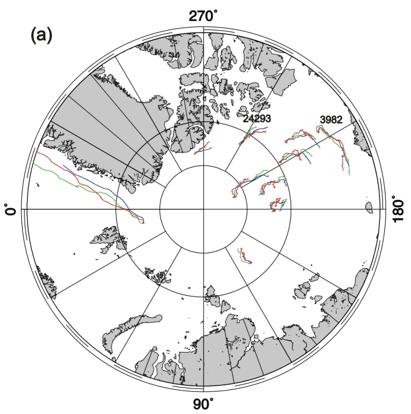
RESAMPLING (SEIK)

Resample state ensemble with updated covariance matrix $P^a = LUL^T$ which represents the updated model variance.

Conclusion

The SEIK filter is able to improve sea-ice model results by assimilation of sea-ice drift. Comparison with buoy data shows sea-ice drift improvement in many cases. The SEIK filter achieves sea-ice drift correction by a modification of the sea-ice thickness (every 3rd day) which leads to fluctuations in the sea-ice thickness distribution and shows a more realistic winter mean sea-ice thickness distribution. This tool enables us to improve sea-ice drift and even sea-ice thickness within a limited period of time without assimilating any sea-ice thickness data directly. The sea-ice thickness distribution as a result from sea-ice drift assimilation is closer to observations than the FESIM only results, restricted to the mentioned period. We assume that a better sea-ice thickness estimates over a longer period may be achieved if a constant covariance matrix is used because a larger model error estimation results in a broader spread of ensemble members. Then the SEIK filter is no longer restricted to the small error estimation of the forecast results due to a underestimated ensemble spread and can update the model state closer to the observation. However, the assimilation of ice drift can already be applied to estimate a real sea-ice thickness distribution for short-term ice forecast in operational systems.

Drift Validation



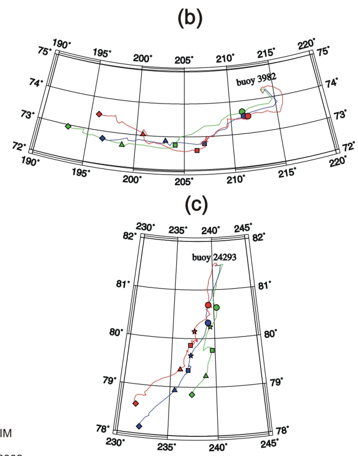


Figure 4: Buoy trajectories; red deployed buoys, green computed trajectories from FESIM results, blue from assimilation results; (a) trajectories of several buoys in the Arctic, (b) trajectory of buoy 24293, same symbols mark same days, (c) same as (b) for buoy 3982

Sea-ice buoy drift data were used to validate assimilation results (Fig. 4). Both model only and assimilated drift (green and blue) are very close to the buoy drift (red). Fig. 4b and 4c show that assimilation results in an improvement of drift direction and speed. In some cases the FESIM and assimilation derived trajectories stay close to each other and the improvement is small. This is due to a small ensemble spread (i.e. small deviations between observation and forecast which result in a smaller model error estimation) so that after some assimilation steps the filter has more "confidence" to the modelled drift than to the observation which can have a larger observation error. On top of that, the filter only can influence drift sustainable by changing ice thickness (with respect to the updated covariance matrix) to accelerate or slow down the velocity. Nevertheless, the SEIK filter corrects the drift such that the result is closer to the observations.

Ice Thickness

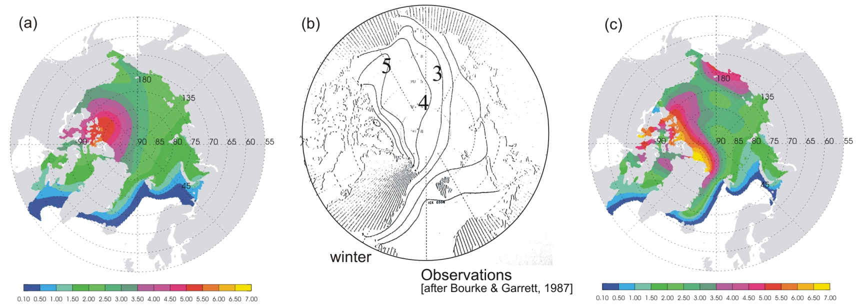


Figure 3: Mean ice thickness distribution: (a) from 20th January to 29th February 2004 (day 20 to 60) FESIM only results; (b) ULS derived ice draft map for annual winter mean; (c) same as (a) with data assimilation results.

Sea-ice thickness is modified every 3rd day during the resampling phase of the SEIK filter based on the updated ensemble mean state and updated covariance matrix. The mean ice thickness distribution in Fig. 3a shows a good result of ice thickness of the model only run but, compared with observations (Fig 3b) it does not show the typical winter pattern of the narrow band of very thick ice close to the Canadian Archipelago. In contrast to that, Fig. 3c agrees remarkably good with the winter mean ice draft map (Fig. 3b) derived from upward looking sonar (ULS) data (Bourke and Garrett, 1987) and is more realistic than the FESIM only thickness distribution. The isolated minimum in the East Siberian Sea is an averaging artefact. The time period of Fig. 3a and 3c corresponds to a 40 day period (20th January to 29th February) in which the ensemble spread of ice thickness estimation is constantly small. The spread increases with ongoing assimilation after the 60th day; compared with the ULS-derived thickness maps the results become worse. We conclude that for the presented filter setup the simulated ice thickness can be improved for a period of up to several weeks.