Polarforschung 85 (2), 101–105, 2015 (erschienen 2016)

High Resolution Sea-Ice Modelling and Validation of the Arctic with Focus on South Greenland Waters, 2004–2013

by Kristine Skovgaard Madsen[1*], Till Andreas Soya Rasmussen[1], Mads Hvid Ribergaard[1] and Ida Margrethe Ringgaard[1]

Abstract: We introduce an operational model system of the Arctic and Atlantic oceans with a horizontal resolution of about 10 km. The model system consists of the 3D ocean model HYCOM coupled with the sea-ice model CICE. This study presents a hindcast simulation from 2004–2013, which has been continued in operational mode, and is continuously updated with a 6-day operational forecast. We first focus on the general ice cover and thickness simulated by this hindcast. The Arctic Sea ice cover is to a large degree fixed by assimilation and the modelled total sea ice volume is within the uncertainty range of available observations and other models. Then, we zoom in on the ocean around Cape Farewell (the southern tip of Greenland), which is the main focus area for the Ice Charting by the Danish Meteorological Institute (DMI). Simulating the sea-ice conditions in this area is challenging, since it requires correct simulation of the ice export along the East Greenland coast, the interplay between cold Polar and warm Atlantic water masses within the East Greenland Current and the effects of local weather systems. The model replicates the seasonal and interannual ice variability as compared to the DMI ice chart index for Cape Farewell, but the total number of weeks with sea ice is underestimated by the model. Finally, *in situ* profile observations near Fylla Bank off West Greenland are used to validate the properties of the Polar and Atlantic water masses within the West Greenland Current. Despite a warm bias originating at the sea surface, the hindcast reproduces the pulsating nature of the interplay between the two water masses and demonstrates interannual variability in the same range as observed.

Zusammenfassung: Es wird ein operationelles Modellsystem für die Arktis und den Atlantischen Ozean mit einer horizontalen Auflösung von 10 km vorgestellt. Das Modellsystem besteht aus dem 3D Ozeanmodell HYCOM, gekoppelt mit dem Meereismodell CICE. Die Arbeit zeigt eine auf die Periode 2004 bis 2013 zurückschauende Simulation (Hindcast), die im operationellen Modus fortgeführt und kontinuierlich mit sechstägigen operationellen Vorhersagen aktualisiert wurde. Schwerpunkt liegt hierbei auf der Untersuchung der Eisbedeckung und der Eisdicke. Die arktische Meereisbedeckung ist im Modell zu einem Großteil durch Assimilation festgelegt. Das hiermit modellierte, totale Meereisvolumen liegt innerhalb des Unsicherheitsbereiches der vorhandenen Beobachtungen und von anderen Modellen. Der Ozean rund um das Kap Farewell (der südlichste Punkt Grönlands) ist die Hauptfokusregion der Eiskartierung des Dänischen Meterologischen Instituts (DMI). Die Meereissituation dieser Region zu simulieren, stellt eine Herausforderung dar, da korrekte Simulationen des Eisexportes entlang der Ostküste Grönlands benötigt werden und Kenntnisse über das Zusammenspiel zwischen kaltem Polar- und warmem Atlantikwasser innerhalb des Ostgrönlandstroms und Einflüsse lokaler Wettersysteme eine Rolle spielen. Das Modell bildet die saisonale und zwischenjährliche Eisvariabilität, verglichen mit der DMI Eiskarte des Kap Farewell gut ab. Jedoch wird die Gesamtzahl der Wochen mit Meereis durch das Modell unterschätzt. *In situ* Beobachtungen nahe Fylla Bank an der Küste Westgrönlands werden genutzt, um die Eigenschaften des Polar- und Atlantikwassers innerhalb des Westgrönlandstroms zu validieren. Abgesehen von einer Tendenz zu wärmeren Meeresoberflächentemperaturen, bildet die zurückschauende Simulation (Hindcast) den pulsierenden Charakter der Wechselwirkungen zwischen den zwei Wassermassen gut ab und spiegelt die zwischenjährliche Variabilität in derselben Größenordnung wie die Beobachtungen wider.

doi:10.2312/polfor.2016.006

[1] Danish Meteorological Institute, Lyngbyvej 100, 2100 Copenhagen OE Denmark;
[*] Corresponding author <kma@dmi.dk>

This extended abstract was presented as a poster contribution at the Inter-national Conference "Our Climate – Our Future: Regional perspectives on a global challenge", 6–9 October 2014 in Berlin, Germany.
Manuscript received 22 June 2015; accepted in revised form 16 October 2015.

INTRODUCTION

Over the past ten years, the annual Arctic minimum sea-ice extent has been observed to be low and highly variable compared to the 1979–2000 climatology, with record low years in 2007 and again in 2012 (Lavergne et al. 2010, Eastwood et al. 2011, Meier et al. 2013, Peng et al. 2013). The sea-ice volume is not well observed, but model studies of the Arctic show a steady decrease throughout the last decade (e.g., Zhang & Rothrock 2003, updated), making the sea ice weaker and more sensitive to weather and upper ocean heating (Parkinson & Comiso 2013, Zhang et al. 2013). Warming is observed in the Polar Waters that reach tidewater glaciers of the Greenland Ice Sheet, enhancing their retreat (Myers & Ribergaard 2013, Straneo & Heimbach 2013). With the reduction in sea ice, an increasing interest and need is seen for detailed data of the Arctic Ocean and sea-ice conditions for applications in ecology, ice-sheet modelling, shipping, ice charting, oil-spill preparedness, etc. Here, we present a high-resolution ten year ocean and sea-ice hindcast of the Arctic. We place a special focus on the south Greenland Waters, which is one of the hotspots for Arctic development and change, and focus on three research questions:

(1) Is the model suitable to estimate the total sea-ice volume in the Arctic?
(2) Is the model a suitable tool for assessing the sea-ice extent at Cape Farewell (the southern tip of Greenland)?
(3) Are the temperature and salinity properties of the water masses at Fylla Bank, west of Greenland, represented in the model?

In all three cases we discuss the operational aspects. We consider the seasonal and interannual variability of the daily mean variables, except for the sea-ice extent of Cape Farewell, where we match the weekly resolution of the observational index.

MODEL AND MATERIALS, INCLUDING OBSERVATIONS FOR VALIDATION

The model system consists of the HYbrid Coordinate Ocean Model (HYCOM, e.g., Chassignet et al. 2007) and Community Ice CodE (CICE, Hunke & Dukowicz 1997, Hunke 2001) models, coupled with the ESMF coupler. The model resolution is about 10 km to ensure an eddy-permitting model and resolve the coastal shelf, while balancing computational resources and the domain covers the Arctic Ocean and the Atlantic Ocean to approximately 20°S (Fig. 1). The sea-ice model, CICE v4.0, is a Hibler-type model with five ice thickness categories. The thermodynamics of CICE allows for a vertical temperature profile with a resolution of four thermodynamic layers and one layer of snow. The ocean model, HYCOM v2.2.55, explores a hybrid coordinate system, combining isopycnals with z-level coordinates. The vertical mixing is defined by the K-profile parameterisation (KPP) scheme (Large et al. 1994). Our setup of HYCOM has 40 vertical levels, it includes tides, and we have modified the input radiation scheme to correct for inconsistencies of the ice cover between the atmospheric forcing and the model (Rasmussen et al. 2010).

The model is initialized in 1997 with a combined climatology, using the Polar Science Center Hydrographic Climatology (PHC, Steele et al. 2001) in the Arctic and World Ocean Atlas 2001 in 0.25° resolution (Conkright et al. 2002) in the Atlantic, with a 100 km linear transition. The first seven years were considered as spin-up. ERA-Interim was used for atmospheric forcing (Dee et al. 2011). The model domain has two open boundaries in the Barents Strait and in the South Atlantic Ocean, where temperature and salinity are prescribed from the combined climatology, while no volume transports were prescribed at the boundaries. Similarly, tidal forcing is prescribed from Oregon State University TOPEX/Poseidon Global Inverse Solution (TPXO71, Egbert & Erofeeva 2002). In the model interior, body tides are induced using eight constituents.

The model assimilates Ocean and Sea Ice Satellite Application Facility (OSISAF) reanalysed sea-ice concentration (Eastwood et al. 2011) and sea-surface temperature from the Operational SST and Sea Ice Analysis (OSTIA) system (Donlon et al. 2011) for 1997-2010 and from Global Ocean Data Assimilation Experiment High Resolution SST (GHRSST) Level 4 DMI_OI (DMI 2007, Høyer et al. 2014) from 2011 onward, using a nudging scheme with 10 and 30 days relaxation time, respectively. Surface salinity is relaxed towards climatology with 30 days relaxation time. More than 100 rivers are included as monthly climatological discharges obtained from the Global Runoff Data Centre GRDC) and scaled as in Dai & Trenberth (2002).

Only non-flagged OSISAF reanalysed sea-ice observation is used, therefore sea ice is not assimilated in a 20–50 km zone near the coast where the satellite footprint is affected by land. We also do not assimilate where the modelled and observed sea-ice concentration agrees within 10 %, to limit observationally induced noise effects. In these areas, the concentrations are determined purely by the sea ice model physics.

For validation of sea ice conditions in the Cape Farewell area on the southern tip of Greenland, we use an index based on weekly ice charts for south Greenland (pers. com. K. Qvistgaard 2014). The index is set to 1 if sea ice is present west of Cape Farewell at 44°W, and set to 2 if it is present at 48°W and thus fills the Julianehaab Bight (see Fig. 1 for locations).

For validation of the temperature and salinity profile in West Greenland Waters, we use annual in situ observations for Fylla Bank station 4 obtained in June/July (63.8833°N, 53.3683°W, Fig. 1). The data was collected and handled by DMI in collaboration with the Greenland Institute of Natural Resources (Ribergaard 2014).

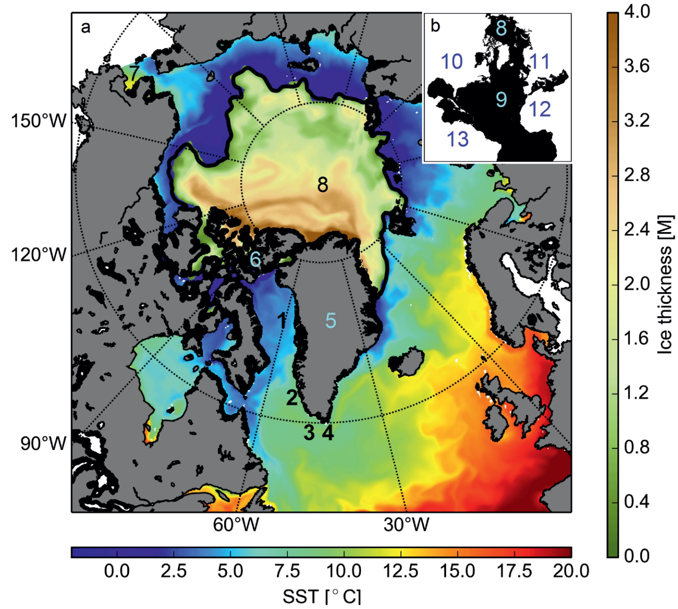

Fig. 1: a) September 2009 mean modelled SST (horizontal colour bar) and sea-ice thickness (vertical colour bar), overlaid with the 15 % contour of OSISAF ice concentration (black). The numbers indicate 1: Baffin Bay, 2: Fylla Bank, 3: Julianehaab Bay, 4: Cape Farewell, 5: Greenland, 6: Canadian Archipelago, 7: Barents Strait. b): Small insert marks the entire model domain. The numbers indicate 8: Arctic Ocean, 9: Atlantic Ocean, 10: North America, 11: Europe, 12: Africa, 13: South America.

Abb. 1: a) Mittlere modellierte Meeresoberflächentemperatur (SST) (horizontale Farbskala) und Meereisdicke (vertikale Farbskala) im September 2009 mit Kontourlinie der 15 % Eiskonzentration des OSISAF überlagert (schwarz). Die Nummern geben spezielle Regionen der Untersuchungen an: 1: Baffin Bay, 2: Fylla Bank, 3: Julianehaab Bay, 4: Cape Farewell, 5: Greenland, 6: Canadian Archipelago, 7: Barents Strait. b) Einlegekarte markiert das gesamte Modellgebiet. Die Ziffern dienen zur geographischen Orientierung 8: Arctic Ocean, 9: Atlantic Ocean, 10: North America, 11: Europe, 12: Africa, 13: South America.

RESULTS

General evaluation

The modelled sea-ice thickness and sea-surface temperatures (SST) averaged for September 2009 are shown in Figure 1.

For this month, the observed and modelled sea ice extents are similar, with small deviations in the western Arctic and the Canadian Archipelago. The SST general patterns indicate that the large-scale ocean currents are captured by the model, with the warm North Atlantic Current up along the European coast, the generally cold sea surface of Baffin Bay and the cold East Greenland Current. This current is responsible for the export of sea ice southwards along the coast of Greenland and down to Cape Farewell in winter and early spring.

The sea-ice thickness distribution in the Arctic is also reasonable with thick ice located near the Canadian Archipelago and the northern coast of Greenland. There are no continuous measurements of the distribution of the thick ice, however, remote sensing results by CryoSat-2 as well as point measurements from the IceBridge-campaign support the modelled ice-thickness distribution and total volume (Farrell et al. 2009, Farrell et al. 2012, Tilling et al. 2015).

The overall sea-ice extent closely follows sea ice observations independently processed by NSIDC (Fig. 2, CAVALIERI et al. 1996). The sea-ice volume, on the other hand, is not fixed by assimilation. At the start of the time series, the seasonal range is 10,000-30,000 km^3, but the volumes decrease to a new level from 2005 to 2008, following the observed loss of Arctic sea ice. The summer minima in 2008 and 2012 are both around 5,000 km^3.

As indicated by the sea-ice extent time series, there are large seasonal variations in the Arctic ice cover. Figure 3 shows the average modelled number of days with at least 15 % ice concentration, displaying how large parts of the Arctic, including coastal zones where satellite observations are lacking, is accessible for the summer season only.

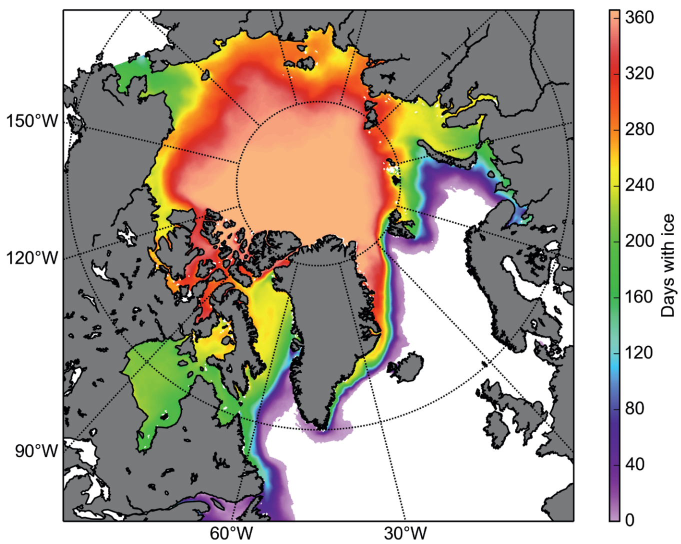

Fig. 3: Modelled average number of days with sea ice, 2004–2013. Points with only one model year with sea ice have been removed.

Abb. 3: Modellierte mittlere Anzahl der Tage mit Meereis, 2004–2013. Punkte mit Meereis in nur einem Modelljahr wurden ausgenommen.

Cape Farewell

In the challenging waters of Cape Farewell, sea-ice assimilation is almost absent due to land effects in the OSISAF products. Nevertheless, the weekly mean modelled sea ice extent captures most interannual variability seen in the ice chart based weekly sea ice index, including an almost complete absence of sea-ice in 2005 and a long period with sea ice in Julianehaab Bight in 2008 (Fig. 4). However, the model has a bias with too early breakup and a following lack of sea ice in June and July.

Fylla Bank

The model is able to reproduce the general vertical structure with low-saline shelf and Polar Waters in the upper ~200 m and warm and saline water masses of subtropical Atlantic origin below 400–500 m (Fig. 5). The seasonality in the two water masses and interannual variations are both captured by the model, but it is not possible to make solid conclusions on changes from one year to another, using one single observa-

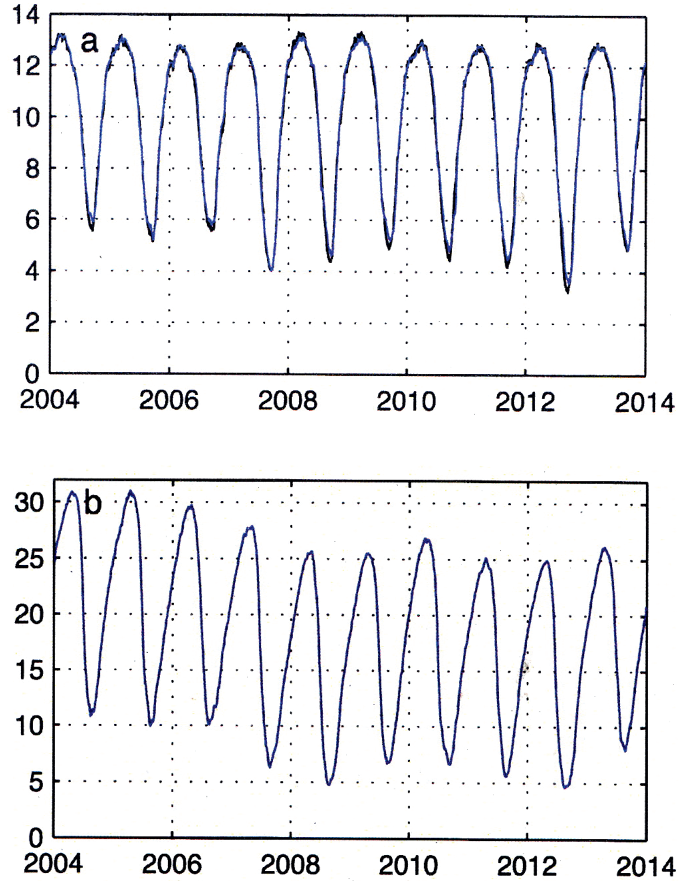

Fig. 2: a): Modelled (blue) and observed (CAVALIERI et al. 1996, black) sea-ice extent (15 % concentration limit) of the entire model domain, daily averages 2004–2013 (million km^2); b): Modelled total sea ice volume, daily average 2004–2013 (thousand km^3).

Abb. 2: a): Modellierte (blau) und beobachtete (CAVALIERI et al. 1996, schwarz) Meereisausdehnung (15 % Meereiskonzentration) im gesamten Modellgebiet, tägliche Mittelwerte 2004–2013 (in Mio. km^2), b): modelliertes Meereisvolumen, tägliche Mittelwerte 2004–2013 (in 1000 km^3).

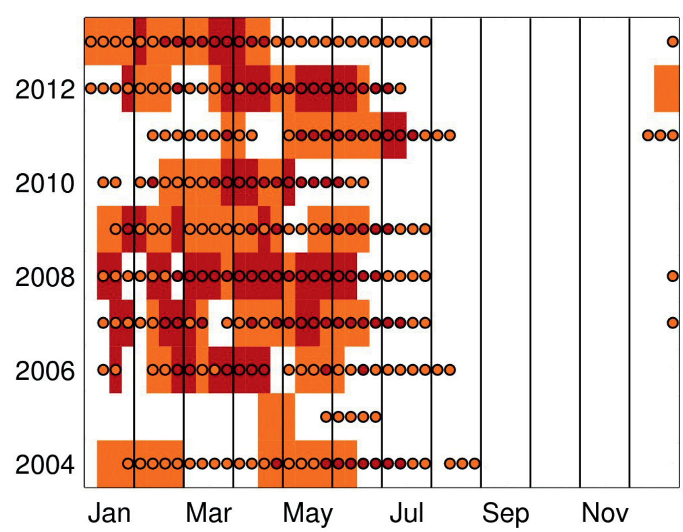

Fig. 4: Weekly sea ice index at Cape Farewell as observed (circles) and as modelled (patches), 2004–2013. White: no sea ice. Orange: sea ice at Cape Farewell. Red: sea ice fills Julianehaab Bight.

Abb. 4: Wöchentlicher Meereisindex am Kap Farewell aus Beobachtungen (Kreise) und Modellierung (farbliche Hintergrundfüllung), 2004–2013. Weiß: kein Meereis. Orange: Meereis am Cape Farewell. Rot: Meereis füllt die Julianehaab Bucht.

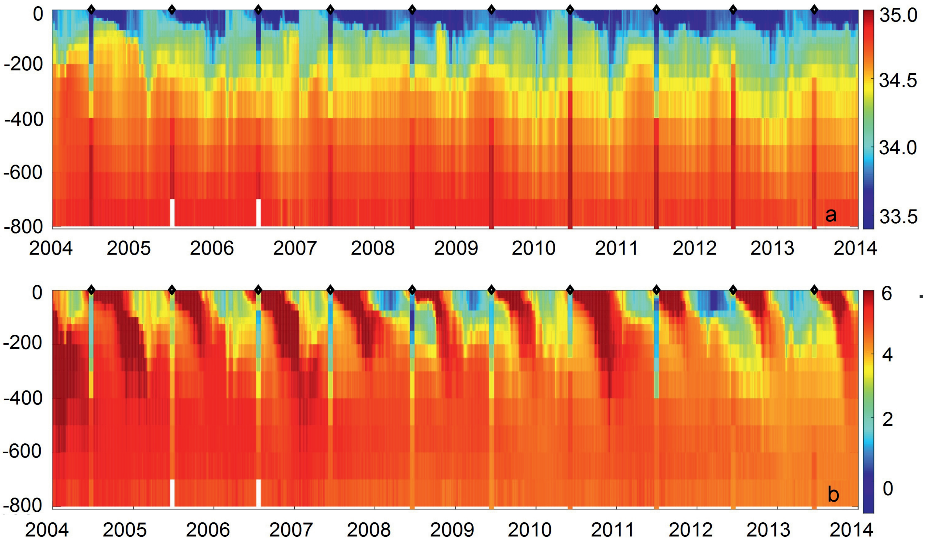

Fig. 5: Hovmöller diagram of modelled salinity (a) and temperature (b) (°C) as a function of depth (m) and time (years). Annual in situ observations in June/July (Ribergaard 2014) are interpolated to the same vertical axis, shown with 20 days width, and marked with black markers at the top.

Abb. 5: Hovmöllerdiagramm der modellierten (a) Salinität und (b) Temperatur (in °C) als Funktion der Tiefe (in m) und Zeit (in Jahren). Jährliche Beobachtungen im Juni/Juli (Ribergaard 2014) wurden auf dieselbe vertikale Achse interpoliert, gezeigt mit 20 Tagen Bandbreite und gekennzeichnet mit schwarzen Markierungen an der Spitze.

tion per year. For example, the observed low temperature and salinity down to almost 400 m in 2011 is likely due to a cold-water eddy. However, compared to June/July observations, the model has higher salinities in the surface waters and slightly lower salinities in the deeper waters. This leads to a lower stratification, as it is mainly determined by its salinity. Likewise, the modelled temperatures are in general higher than observed. This is especially true for the upper waters and is likely related to a too thin and too saline surface layer. In contrast, the Atlantic Water temperature is much closer to the observations.

DISCUSSION AND SUMMARY

The total sea-ice volume (Fig. 2b) is comparable to that of the PIOMAS model (Schweiger et al. 2011, not shown). The seasonality is very similar, but our maximum values are about 4.000 km^3 higher than the PIOMAS estimate, in line with observations by CryoSat-2 (Tilling et al. 2015). Our model reproduces more short-term variability than PIOMAS. The two models differ on the interannual variability of the annual minimum volumes; in particular, the PIOMAS model simulates a larger ice volume in 2008 than in 2012. However, the differences are within the uncertainties of this very poorly constrained parameter.

The model is able to correctly position the ocean currents in the water column off West Greenland, despite bias in the water mass characteristics compared to observations. The differences are likely related to an overly weak stratification due to underestimated fresh water discharge from the Greenland Ice Sheet. An update of the runoff is an obvious improvement of the model performance.

When analysing the sea ice, we have paid special attention to the coastal regions, where the satellite observations have an increased level of uncertainty. Based on the unassimilated model results by Madsen et al. (2016), the model physics are expected to maintain a realistic ice edge without assimilation. This is confirmed by the validation against ice charts at Cape Farewell. However, the modelled amount of summer sea ice in this area is too low, possibly relating to the warm bias detected off West Greenland.

The simulation presented here serves several purposes. It is a scientific baseline for studies of the physical environment of the ocean and the sea ice and its effect on and interaction with the atmosphere, the ecosystem, the cryosphere, etc. It is also the foundation for operationally interesting statistics on ocean and sea-ice conditions that are valuable for ice charting, shipping, and oil-spill response planning among other activities. Since the simulations are continued seamlessly to the present, complete with twice-daily forecasts, the results also serve as a first validation of the operational forecast. However, the assessment of forecast skill and of the impact of the required change of atmospheric forcing to an operational product is left for future studies.

ACKNOWLEDGMENTS

We acknowledge the Ocean and Sea Ice Satellite Application Facility (OSISAF) High Latitude Processing Centre for producing and making available their reprocessing data sets and derived products from the Danish Meteorological Institute (DMI) and the Norwegian Meteorological Institute (MET Norway). We would like to thank Paul Meyers and an anonymous reviewer for fruitful comments improving this manuscript and R. Mottram for language support.

References

GRDC <http://grdc.bafg.de>

Cavalieri, D.J., Parkinson, C.L., Gloersen, P. & Zwally, H.J. (1996: updated yearly): Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1 [2004-2013].- NASA National Snow and Ice Data Center Distributed Active Archive Center. Boulder, Colorado USA, doi:10.5067/8GQ8LZQVL0VL.

Chassignet, E.P., Hurlburt, H.E., Smedstad, O.M., Halliwell, G.R., Hogan, P. J., Wallcraft, A.W., Baraille, R. & Bleck, R. (2007): The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system.- J. Marine Syst. 65: 60-83, doi:10.1016/j.jmarsys.2005.09.016.

Conkright, M.E., Locarnini, R.A., Garcia, H.E., O'Brien, T.D., Boyer, T.P., Stephens, C. & Antonov, J.I. (2002): World Ocean Atlas 2001: Objective Analyses, Data Statistics, and Figures, CD-ROM Documentation.- National Oceanogr. Data Center, Silver Spring, MD, 1-17.

Dai, A. & Trenberth, K.E. (2002): Estimates of freshwater discharge from continents: Latitudinal and seasonal variations.- J. Hydrometeorol. 3: 660-687.

Dee, D.P. & 35 co-authors (2011): The ERA-Interim reanalysis: configuration and performance of the data assimilation system.- Quat. J. Royal Meteorol. Soc., 137: 553-597, doi:10.1002/qj.828.

DMI (2007): GHRSST Level 4 DMI_OI Global Foundation Sea Surface Temperature Analysis (GDS version 2). Ver. 1.0.- PO.DAAC, CA, USA, doi:10.5067/GHGDM-4FD02.

Donlon, C.J., Martin, M., Stark, J.D., Roberts-Jones, J., Fiedler, E. & Wimmer, W. (2011): The Operational Sea Surface Temperature and Sea Ice analysis (OSTIA).- Remote Sensing of the Environment, doi:10.1016/j.rse.2010.10.017.

Eastwood, S., Larsen, K.R., Lavergne, T., Nielsen, E. & Tonboe, R. (2011): Global Sea Ice Concentration Reprocessing.- Product User Manual. Product OSI-409. Document version: 1.3. Data set version: 1.1. Available online <http://osisaf.met.no/docs/pum_seaicereproc_ss2_v1p3.pdf>

Egbert, G.D. & Erofeeva, S.Y. (2002): Efficient inverse modeling of barotropic ocean tides.- J. Atmos. Oceanic Technol. 19: 183-204.

Farrell, S.L., Laxon, S.W., McAdoo, D.C.. Yi, D. & Zwally, H.J. (2009): Five years of Arctic sea ice freeboard measurements from the Ice, Cloud and land elevation Satellite.- J. Geophys. Res. 114: C04008, doi: 10.1029/2008JC005074.

Farrell, S.L., Kurtz, N., Connor, L.N., Elder, B.C., Leuschen, C., Markus, T., McAdoo, D.C., Panzer, B., Richter-Menge, J. & Sonntag, J.G. (2012): A first assessment of IceBridge snow and ice thickness data over Arctic sea ice.- IEEE Transactions on Geoscience and Remote Sensing 50: 2098-2111, doi:10.1109/tgrs.2011.2170843,

Hunke, E.C. (2001): Viscous–plastic sea ice dynamics with the EVP model: linearization issues.- J. Comp. Phys. 170: 18-38, doi: 10.1006/jcph.2001.6710.

Hunke, E.C. & Dukowicz, J.K. (1997): An elastic–viscous–plastic model for sea ice dynamics.- J. Phys. Oceanogr. 27: 1849-1867, doi:10.1175/1520-0485(1997)027<1849:AEVPMF>2.0.CO;2,

Høyer, J.L., Le Borgne, P., & Eastwood, S. (2014): A bias correction method for Arctic satellite sea surface temperature observations.- Remote Sensing of Environment 146: 201-213, doi: 10.1016/j.rse.2013.04.020.

Large, W.G., McWilliams, J.C. & Doney, S.C. (1994): Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization.- Rev. Geophys. 32: 363-403, doi:10.1029/94RG01872.

Lavergne, T., Killie, M.A., Eastwood, S. & Breivik, L.-A. (2010): Extending the CryoClim Arctic sea ice extent time series with operational OSI SAF products from 2008 onwards.- Met. no Note 07/2010.

Madsen, K.S., Mottram, R., Rasmussen, T.A.S. & Ribergaard, M.H. (2016): High resolution sea-ice modelling and validation of the Arctic with focus on South Greenland Waters, 2004–2013.- Polarforschung 85: 85–88.

Meier, W., Fetterer, F., Savoie, M., Mallory, S., Duerr, R. & Stroeve, J. (2013): NOAA/NSIDC climate data record of passive microwave sea ice concentration. Version 2.- Natl. Snow Ice Data Center, Boulder, USA, doi:10.7265/N55M63M.1.

Myers, P.G. & Ribergaard, M.H. (2013): Warming of the Polar water layer in Disko Bay and potential impact on Jakobshavn Isbrae.- J. Phys. Oceanogr., 43: 2629-2640, doi:10.1175/JPO-D-12-051.1.

Parkinson, C.L. & Comiso, J.C. (2013): On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm.- Geophys. Res. Lett. 40: 1356-1361, doi:10.1002/grl.50349.

Peng, G., Meier, W., Scott, D. & Savoie, M. (2013): A long-term and reproducible passive microwave sea ice concentration data record for climate studies and monitoring.- Earth Syst. Sci. Data 5: 311-318, doi: 10.5194/essd-5-311-2013.

Rasmussen, T.A.S., Kliem, N. & Kaas, E. (2010): Modelling the sea ice in the Nares Strait.- Ocean Modelling 35: 161-172, doi:10.1016/j.ocemod.2010.07.003.

Ribergaard, M.H. (2014): Oceanographic investigations off West Greenland 2013.- NAFO Scientific Council Documents, 14/001.

Schweiger, A., Lindsay R., Zhang J., Steele M., Stern H. & Kwok, R. (2011): Uncertainty in modelled Arctic sea ice volume.- J. Geophys. Res. 116: C00D06, doi:10.1029/2011JC007084 (Updated to version 2.1).

Steele, M., Morley, R. & Ermold, W. (2001): PHC: A global ocean hydrography with a high quality Arctic Ocean.- J. Climate 14: 2079-2087 (Updated to PHC 3.0 in 2005).

Straneo, F. & Heimbach, P. (2013): North Atlantic warming and the retreat of Greenland's outlet glaciers.- Nature 504, 36-43, doi: 10.1038/nature12854.

Tilling, R.L., Ridout, A., Shepherd, A. & Wingham, D.J. (2015): Increased Arctic sea ice volume after anomalously low melting in 2013.- Nature Geosci. 8: 643-646, doi:10.1038/ngeo2489.

Zhang, J. & Rothrock, D.A. (2003): Modelling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates.- Mon. Weath. Rev. 131: 681-697 (Updated data available from <http://psc.apl.washington.edu/zhang/IDAO/data_piomas.html>).

Zhang, J., Lindsay, R., Schweiger, A. & Steele, M. (2013): The impact of an intense summer cyclone on 2012 Arctic sea ice retreat.- Geophys. Res. Lett. 40: 720-726, doi:10.1002/grl.50190.