Evaluation of bottom temperature from GLORYS12 and EN4 for North American continental shelf waters: from the North Atlantic, to the Arctic, to the North Pacific Oceans

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2023

Canadian Technical Report of Hydrography and Ocean Sciences 355

Fisheries and Oceans Canada Pêches et Océans Canada

Canada

Canadian Technical Report of Hydrography and Ocean Sciences

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Canadian Technical Report of

Hydrography and Ocean Sciences 355

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EVALUATION OF BOTTOM TEMPERATURE FROM GLORYS12 AND EN4 FOR NORTH AMERICAN CONTINENTAL SHELF WATERS: FROM THE NORTH ATLANTIC, TO THE ARCTIC, TO THE NORTH PACIFIC OCEANS

by

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Cat. No. Fs97-18/355E-PDF ISBN 978-0-660-49024-3 ISSN 1488-5417

Correct citation for this publication:

McKee, E.,Wang, Z., and DeTracey, B. 2023. Evaluation of Bottom Temperature From GLORYS12 and EN4 for North American Continental Shelf Waters: From the North Atlantic, to the Arctic, to the North Pacific Oceans. Can. Tech. Rep. Hydrogr. Ocean. Sci. 355: vii + 34 p.

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ABSTRACT

McKee, E.,Wang, Z., and DeTracey, B. 2023. Evaluation of Bottom Temperature from GLORYS12 and EN4 for North American Continental Shelf Waters: From the North Atlantic, to the Arctic, to the North Pacific Oceans. Can. Tech. Rep. Hydrogr. Ocean. Sci. 355: vii + 34 p.

Bottom temperature data is an important determinant for the distribution of many marine species. A scarcity of bottom temperature observations in Canadian shelf waters often leads to the use of ocean models and products as alternative sources of data. However, the performance of these products through validation with collected observations is not frequently conducted. We validated the ocean products EN4 and GLORYS12 using available bottom temperature observational data as a baseline comparison. Model bias, correlation, standard deviations, and trends were evaluated for eight regions of the Canadian/North American shelves: the Scotian Shelf, Gulf of St. Lawrence, Newfoundland Shelf, Labrador Shelf, Chukchi Sea, Bering Sea, Alaska Shelf, and the British Columbia Shelf. GLORSY12 out-performed the EN4 product in all regions assessed with the exception of the Gulf of St. Lawrence. Our analyses suggest that regionally averaged bottom temperature of the GLORYS12 could better represent the observed regional mean than the comparison for individual stations.

RÉSUMÉ

McKee, E.,Wang, Z., and DeTracey, B. 2023. Evaluation of Bottom Temperature from GLORYS12 and EN4 for North American Continental Shelf Waters: From the North Atlantic, to the Arctic, to the North Pacific Oceans. Can. Tech. Rep. Hydrogr. Ocean. Sci. 355: vii + 34 p.

Les données sur la température au fond constituent un facteur déterminant pour la répartition de nombreuses espèces marines. La rareté des observations de la température au fond dans les eaux du plateau canadien conduit souvent à une utilisation de modèles et de produits océaniques comme sources de données de rechange. Cependant, on effectue rarement une évaluation du rendement de ces produits au moyen d'une validation avec les observations recueillies. Nous avons évalué les produits océaniques EN4 et GLORYS12 en utilisant les données d'observation de la température au fond disponibles comme base de comparaison. On a évalué le biais, la corrélation, les écarts types et les tendances des modèles pour huit régions des plateaux canadiens et nord-américains : le plateau néo-écossais, le golfe du Saint-Laurent, le plateau de Terre-Neuve, le plateau du Labrador, la mer des Tchouktches, la mer de Béring, le plateau de l'Alaska et le plateau de la Colombie-Britannique. GLORSY12 a obtenu de meilleurs résultats que le produit EN4 dans toutes les régions évaluées, à l'exception du golfe du Saint-Laurent. Selon nos analyses, la moyenne régionale de la température au fond de GLORYS12 pourrait mieux représenter la moyenne régionale observée que la comparaison entre les stations individuelles.

1 Introduction

A Fisheries and Oceans Canada (DFO) CSRF project (Competitive Science Research Fund; CC-22-05-01) titled “The performance and projections of the CMIP6 Earth System Models (ESMs) for Canada’s three oceans” was funded, and the evaluation of bottom temperature for shelf waters is an important component of the project. Continental shelf waters provide habitats for many marine species (e.g., Wang et al., (2020); Greenan et al., (2019); Stanley et al., (2018)). There are substantially fewer bottom temperature data available than those for surface quantities (e.g., sea surface temperature), despite bottom temperature being a critical ocean layer for many marine species that spend part or all of their life cycle near or on the seabed. Due to sparsity of observed bottom temperature data, bottom temperatures from modelled ocean products can represent a viable alternative. Routine monitoring surveys at periodic intervals on the continental shelf provide invaluable data for the evaluation of the products.

The GLORYS12 (details in next section) is a widely used and recognized ocean product with a relatively high resolution (1/12 deg.), among many other attributes (Wang et al., 2020). However, its performance on bottom temperature has not been evaluated as far as we are aware. The EN4 (details in next section) is an observational data based ocean product with a resolution of 1 degree, and this product is globally recognized and used as well (e.g., Wang et al., (2022)). Whether this coarse resolution data-based product can represent variations of the bottom temperature needs to be investigated.

Here, we use bottom temperature observations collected by long-standing oceanographic monitoring programs to validate the accuracy of GLORYS12 and EN4 ocean products in representing bottom temperatures on the North American continental shelves (Figure 1). A pilot work by Wang et al. (2023) evaluated the bottom temperature of the Scotian Shelf using trends from model results and observational data as the metrics to evaluate model solutions. Our current work will introduce additional metrics with the hope of better representing the performances of the GLORYS12 and EN4 ocean products.

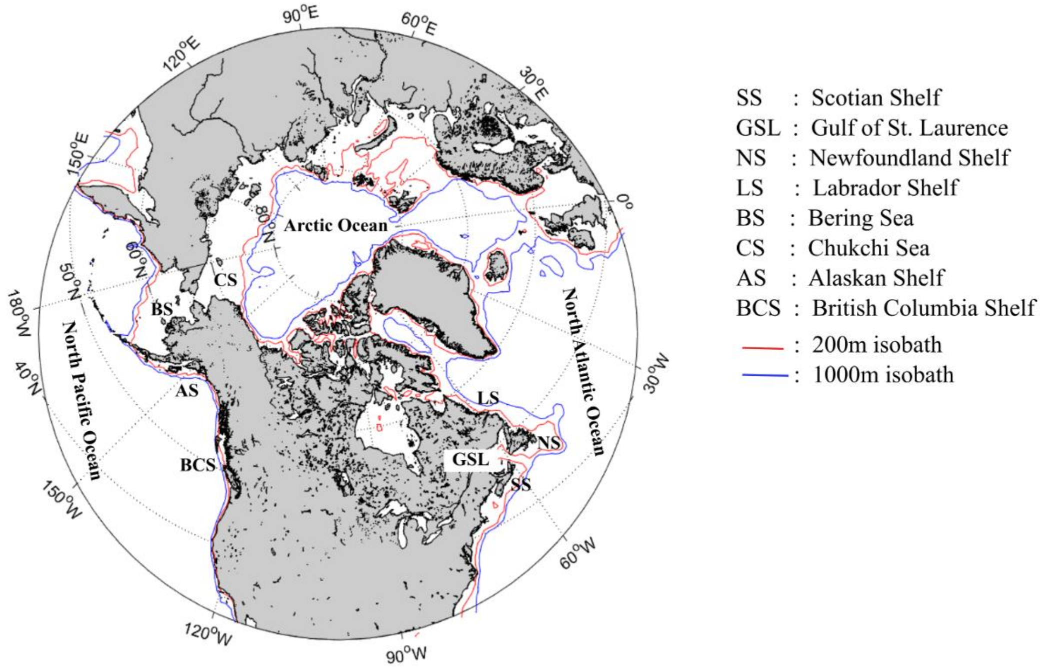

Figure 1: Map of the shelves and areas of interest surrounding Canada

2 Data Sources and Methodology

2.1 Ocean Products

2.1.1 GLORYS12

The GLORYS12 product (version 1) is a global, eddy-resolving, physical ocean and sea ice reanalysis on a 1/12 degree resolution covering the 1993-present altimetry period. GLORYS12 (referred to as GLORYS from herein) is restricted to this altimetry period as the observational network before this time is not informative enough, particularly on the mesoscale. A reduced-order Kalman filter is used to assimilate ocean observations. Track altimeter sea level anomaly, satellite sea surface temperature and sea ice concentration, as well as in-situ temperature and salinity vertical profiles are jointly assimilated. There are 50 vertical levels, with space increasing with depth, with 22 levels within the top 100 m. The GLORYS monthly data were used in this evaluation. For more information on the GLORYS product see Jean-Michel et al. (2021) and Mercator Océan International (2022).

2.1.2 EN4

The EN4 product is the fourth of a series of “EN” ocean products, and is a dataset of monthly, global quality-controlled ocean temperature and salinity profiles which covers from 1900-present on a 1 degree resolution. The main data source used in constructing EN4 is the World Ocean Database

(Boyer et al., 2018), though data from all types of ocean profiling instruments that record temperature and (when applicable) salinity are used to construct EN4. The depth levels are spaced so that observations are approximately 1 m apart in the top 100 m, and 10 m apart above 1500 m depth. These data are preprocessed (see Good, Martin, and Rayner (2013) for more information on preprocessing techniques), and are then used to produce a monthly objective analysis of the oceans' temperature and salinity. For this evaluation data from 1955-2017 were used. See Good, Martin, and Rayner (2013) for more information on the EN4 product.

2.2 Observed Bottom Temperature Data

2.2.1 North Atlantic

The Scotian Shelf (Figure 2) data used in this technical report were collected by the Atlantic Zone Monitoring Program (AZMP) during the Summer Research Vessel (RV) Survey that typically occurs in July each year and it is the only Fisheries and Oceans Canada (DFO) survey that provides complete spatial coverage for the Scotian Shelf (Claytor et al., 2014; Hebert et al., 2021). Full water column (to within 5m of the bottom) Conductivity-Temperature-Depth (CTD) profiles are collected using a SeaBird SBE 25 CTD and 12-bottle rosette at every primary fishing location, which are selected on a depth-stratified random design. Data collected from surveys spanning from 1970-2019 were interpolated to a 0.2° by 0.2° grid (approx. 22 km latitude by 16 km longitude) by Chantelle Layton (DFO) and extracted for use in this study. In this report, we defined several shelf subareas, and the bottom temperatures within these subareas were spatially averaged to examine the ocean products.

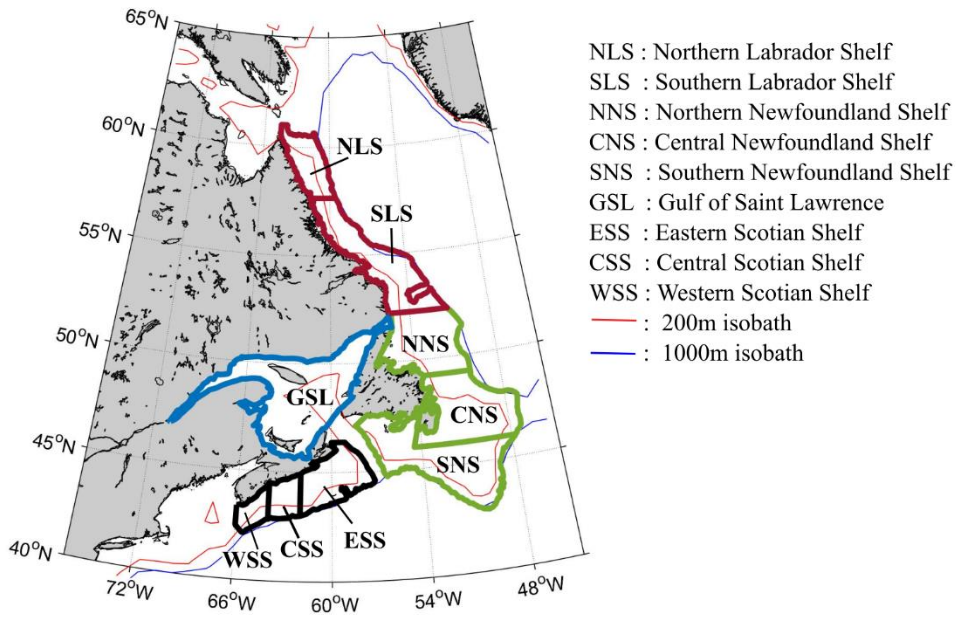

Figure 2: Map of the shelves and areas of interest around Canada in the North Atlantic Ocean.

The Gulf of Saint Lawrence (Figure 2) temperature data were averaged for various depths using a method by Petrie et al. (1996), but for the geographical Gulf of St. Lawrence region. Using this method, all of the available data within the region are averaged together for each year at each chosen depth. From there, the monthly averages are averaged into regional yearly time series. For more information on this dataset see Galbraith et al. (2021). The data provided were averaged temperatures at 150 m and 300 m for the Gulf of St. Laurence, and so we used the data at these two layers to investigate performance of the ocean products. Since the two layers are all deep layers, we assume they could represent variations of temperature for deep water zones. It should be noted that, while they were not used in this report, bottom temperature data have been collected in the Gulf of St. Lawrence.

For the Newfoundland and Labrador Shelves (Figure 2), the method used to obtain the bottom temperature data used in this report was introduced by Cyr et al. (2019). As part of this method, all available annual temperature profiles were arranged in 5 m vertical bins, and any empty bins were filled with vertical interpolation. Then, all data were averaged on a 0.1° latitude by 0.1° longitude grid for each season (April-June for spring, September-December for autumn). The data were horizontally interpolated to fill any gaps in the grid. For each point on the grid where the deepest recorded temperature was deeper than 10 m, the bottom temperature was considered to be the closest depth to the GEBCO 2014 Grid Bathymetry (version 20141103) to a maximum 50 m difference. Observations deeper than 1000 m were removed as to only focus on the shelf. This method was used for all years between 1980 and 2019 (Cyr & Galbraith, 2021).

2.2.2 Arctic

The Chukchi Sea dataset is a compilation of CTD profiles from the continental shelf of the Chukchi Sea from 1922-2018 (data obtained from DataOne (2021)). Only the data from 1955 onwards were used. The profiles were averaged monthly by 1 m depth layers over a 1° latitude by 2° longitude grid. Due to inconsistent sampling rates across the region, four individual stations were selected (Figure 3) as they had the greatest amount of data during the relevant time period (1955-2019) while being in somewhat different regions within the Chukchi Sea (i.e., the stations were not close to each other). The GLORYS and EN4 data for the arctic (and all individual stations used in this study) were extracted by finding the nearest model grid and using the data from that grid. Data were obtained by Danielson et al. (2020) from the National Centers for Environmental Information (NCEI) World Ocean Database 2018 (WOD18) as well as from recent US oceanographic expeditions where the hydrographic data are not yet incorporated into the WOD18.

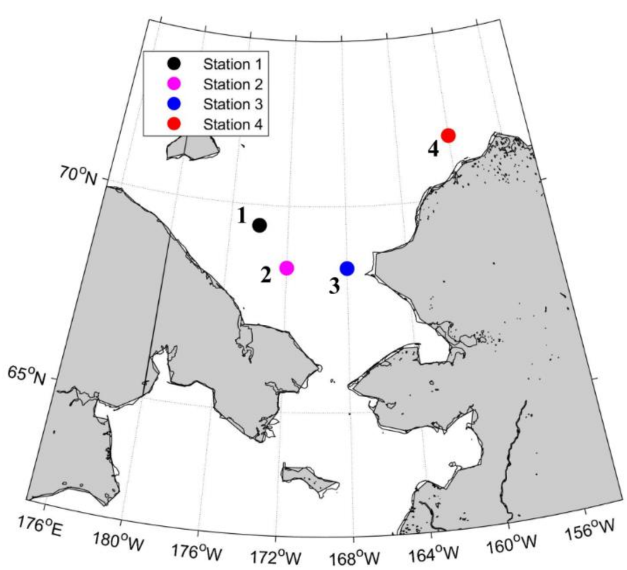

Figure 3: Map showing locations of four stations in the Chukchi Sea.

2.2.3 North Pacific

The Eastern Bering Sea Shelf Survey (Figure 4), from which the bottom temperature data in this report were obtained, has been conducted by National Oceanic and Atmospheric Administration (NOAA) Fisheries to determine the abundance and distribution of various bottom-dwelling species in the Eastern Bering Sea. Beginning in 1982, the aim of these surveys is to resample the same location at the same time of year, every year. The survey grid has not stayed the same over the survey period; the number of sampling stations has increased over time. The survey takes about 2-4 months to complete and is done during the summer (June and July are the most common months). The temperature data were collected with expendable bathythermographs (XBTs) from 1982-1989. From then, the data were collected using digital bathythermograph recorders attached to bottom trawl nets. The bottom temperature data are then averaged to produce a single temperature value per station per year. See Buckly, Greig, and Boldt (2009) and Lauth, Dawson, and Conner (2019) for more information on data collection and post-processing. For more information on this dataset see Kearney (2021).

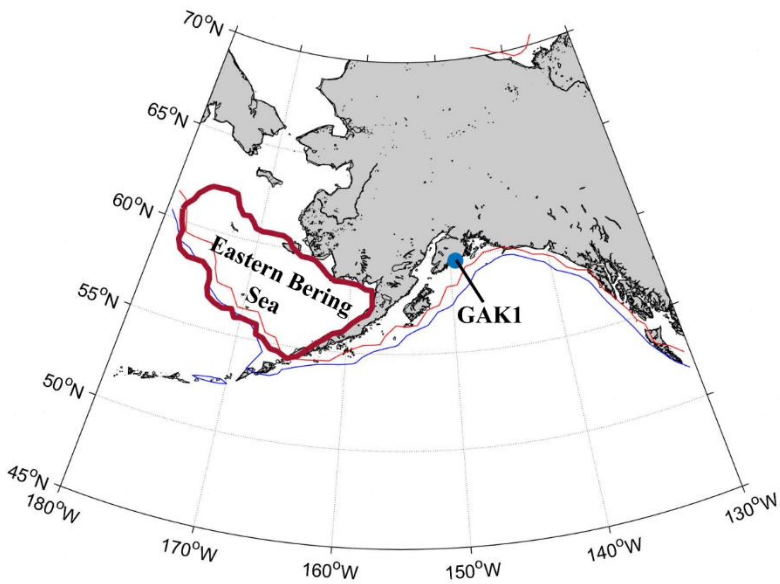

Figure 4: Map of the Bering Sea and Alaska Shelf

Data for the Alaskan Shelf comes from the GAK1 station at the mouth of Resurrection Bay, Alaska (59° 50.7' N, 149° 28.0' W) (Figure 4). From 1970 to 1990 the sampling was mostly done by ships-of-opportunity, thus resulting in inconsistent time intervals between samples. From 1990 onwards, the sampling has been done monthly, usually as a single CTD profile to within 10 m of the bottom (263 m). It is one of the longest running oceanographic time series in the North Pacific. The data are publicly available at Oceanographic Station GAK1 Northern Gulf of Alaska Temperature and Salinity Time Series (uaf.edu).

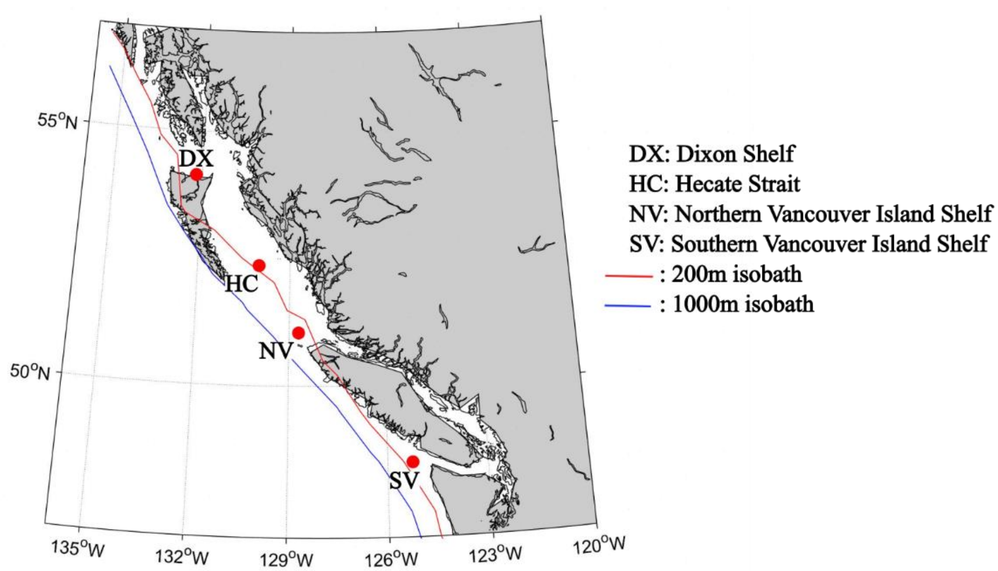

Figure 5: Map of the British Columbia Shelf

The dataset for the British Columbia Shelf (Figure 5) came from Canadian Integrated Ocean Observing System (CIOOS), Pacific (Fisheries and Oceans Canada (DFO), 2022). Four stations were chosen for this study, one on the Dixon Shelf (54.13°N, 132.2°W), one on the Hecate Strait (52.38°N, 130°W), one on the Northern Vancouver Island Shelf (51.06°N, 128.7°W), and one on the Southern Vancouver Island Shelf (48.48°N, 125.25°W). For the Dixon and Hecate stations, where fewer data have been collected, all the available data during the more densely sampled periods (2001-2011, and 2004-2010 for Dixon and Hecate, respectively) are used and compared to the monthly GLORYS and EN4 data. For Northern and Southern Vancouver Island, where there were more data, the data were split into spring (April-June) and autumn (September-November) datasets. The data were measured by CTD loggers deployed by DFO's Institute of Ocean Sciences staff and partner organisations during scientific surveys from 1965-present.

2.3 Methods

This study focuses on long-term changes of bottom temperature, and a criterion for the selection of observational data is that the temporal coverage is no less than 20 years. An exception to this criterion was made on the British Columbia Shelf for the Dixon and Hecate stations as we wanted to see how the products performed along the entire British Columbia Shelf, not just around Vancouver Island. There were three options for comparing the data to the reanalysis/ocean products: using data from the same month each year; using a yearly seasonal mean (averaging 2-4 months); or using all the available data throughout the year.

When possible, bottom temperature observational data were spatially averaged using the mean of each region, as defined in Figures 2 through 4. In regions defined by inconsistent sampling rates, spotty spatial coverage, or the datasets that were not well organised (e.g., on a grid), individual sampling stations were used for the analysis as opposed to using the regional mean values. There were four stations used in the Chukchi Sea, one for the Alaska Shelf, and four for the British Columbia Shelf. Portions of the Newfoundland and Labrador shelves were not evaluated due to a scarcity of data (Northern Newfoundland Shelf spring data, Northern and Southern Labrador Shelf spring data, and Northern Labrador Shelf autumn data).

This report evaluated four values for each comparison: model bias (Bs), correlation (Cr), standard deviation (Std), and the trend (Tr). The model bias describes the difference between the product bottom temperature values and the observational bottom temperature values, and is defined as:

$$Bs = \frac{1}{N}\sum_{year=N1}^{year=N2} Product_n - Data_n \qquad (1)$$

where N=N2-N1+1, N1=first time, N2=last time.

The correlation is a measure of the linear dependence of two variables, and if the two variables have the same number of observations, the Pearson correlation coefficient is defined as

$$\rho(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i - \mu_A}{\sigma_A}\right)\left(\frac{B_i - \mu_B}{\sigma_B}\right) \qquad (2)$$

where μ_A and σ_A are the mean and standard deviation, respectively, of A, and μ_B and σ_B are the mean and standard deviation, respectively, of B, and N is the total number of data points. The correlation function in MatLab (‘corrcoef’) was used to determine the correlation and corresponding *p*-value.

The standard deviation tells us how much the time series deviate from the mean value, and is defined as:

$$\sigma_A = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}|A_i - \mu|^2} \qquad (3)$$

where μ is the mean of A.

The regstats function in MatLab, which performs a multilinear regression of the responses on the predictors, is used to calculate the trend and *p*-value.

The standard deviations and trends were calculated for the entire time series of the observational data and the EN4 and GLORYS products, as well as for the intersect periods (observational and EN4 intersect, and observational and GLORYS intersect), resulting in two standard deviation and trend values each for EN4 and GLORYS, and three standard deviation and trend values for the observational data.

3 Results

3.1 North Atlantic

Both the EN4 and the GLORYS products represent the Scotian Shelf observational data well (Figure 6). The bias between the GLORYS product and the observational data is significantly smaller than the bias between the EN4 product and the observational data, but both products are warmer in the Eastern Scotian Shelf than the observations, and cooler in the central and western regions. The GLORYS product had the strongest correlation for all three regions (Table 1) ranging from 0.89 to 0.99. The EN4 product had its strongest correlation in the central region and had no significant correlation in the western region. The GLORYS product also had higher standard deviations than the EN4 product across all three regions, and were closer to the observational standard deviations than the EN4 standard deviations. The trends on the Scotian Shelf were all positive, though the variations in the values based on the time period they were calculated from makes it difficult to determine if one region is warming faster than the others. The GLORYS trends were better aligned with the observational trends of the same period than the EN4 trends.

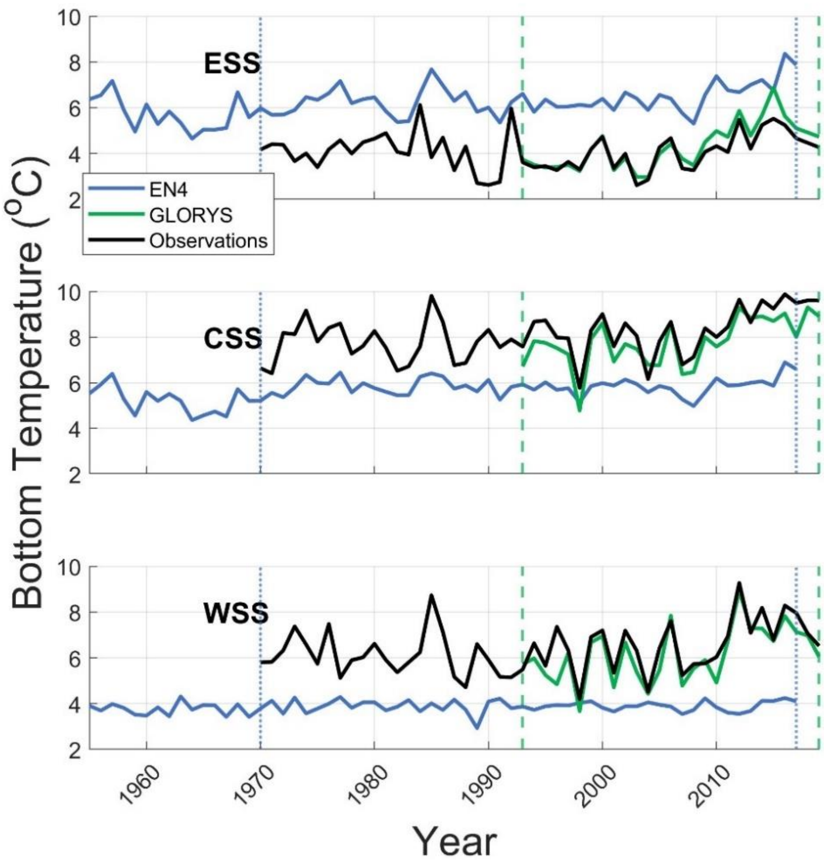

Figure 6: Time series of the July Scotian Shelf bottom temperature from DFO observational data (**1970-2019**) and reanalysis/ocean products for the period of 1955-2029. Dotted blue lines indicate start/end of common EN4/observations period: **1970, 2017**. Dashed green lines indicate start/end of common GLORYS/observations period: **1993, 2019**. ESS = Eastern Scotian Shelf, CSS = Central Scotian Shelf, WSS = Western Scotian Shelf.

Table 1: Scotian Shelf Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (p>0.05). **Black** covers the entire dataset time periods, **1970-2019 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1970-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2019**.

	ESS							
	Bs	**Cr**	**Std**			**Tr**		
OBS	**N/A**	**N/A**	**0.82**	**0.84**	**0.79**	**0.06**	**0.05**	**0.62**
EN4	**2.30**	**0.46**	**0.72**	**0.64**	**N/A**	**0.18**	**0.18**	**N/A**
GLORYS	**0.24**	**0.94**	**0.99**	**N/A**	**0.99**	**0.91**	**N/A**	**0.91**
	CSS							
OBS	**N/A**	**N/A**	**1.01**	**0.98**	**1.06**	**0.29**	**0.25**	**0.72**
EN4	**-2.17**	**0.71**	**0.51**	**0.38**	**N/A**	**0.12**	**0.05**	**N/A**
GLORYS	**-0.57**	**0.92**	**1.06**	**N/A**	**1.06**	**0.77**	**N/A**	**0.77**
	WSS							
OBS	**N/A**	**N/A**	**1.08**	**1.09**	**1.16**	**0.22**	**0.22**	**0.65**
EN4	**-2.48**	**-0.01**	**0.26**	**0.25**	**N/A**	**0.02**	**0.00**	**N/A**
GLORYS	**-0.45**	**0.89**	**1.21**	**N/A**	**1.21**	**0.75**	**N/A**	**0.75**

The results from the Gulf of St. Lawrence were different than the other shelves in Eastern Canada. Here the EN4 product visually fit the observational data better compared to GLORYS (Figure 7). The analyses were done at 150 m and 300 m depths with the trend and standard deviation of the bottom temperature also being done for the products (Table 2). There was no bias between EN4 and the observational data at 150 m depth, and a bias of approximately 0 °C at 300 m depth. The GLORYS products had a bias of about +1 °C at 150 m depth, and almost 0 °C at 300 m depth. The correlation between GLORYS and the observational data was also very strong with a value of 0.85 at 150 m and 0.81 at 300 m, and the correlation between EN4 and the observational data was very strong at 150 m and strong at 300 m with values of 0.86 and 0.64, respectively. The standard deviations of the products matched up fairly well with the standard deviations of the observations with the greatest standard deviation occurring during the entire observational dataset at 150 m, and the smallest standard deviation occurring during the GLORYS intersect period of the observational dataset. There was very little difference between the product standard deviations at 300 m depth and the bottom temperature product data. The trends within the Gulf of St. Lawrence were all positive, with the strongest trend occurring at 150 m depth with the GLORYS product. The 300 m observational and EN4 trends were slightly stronger than at the 150 m depths, while the GLORYS 300 m trend was weaker than at 150 m depth. Again, the bottom temperature trends for EN4 and GLORYS were very similar to those at 300 m.

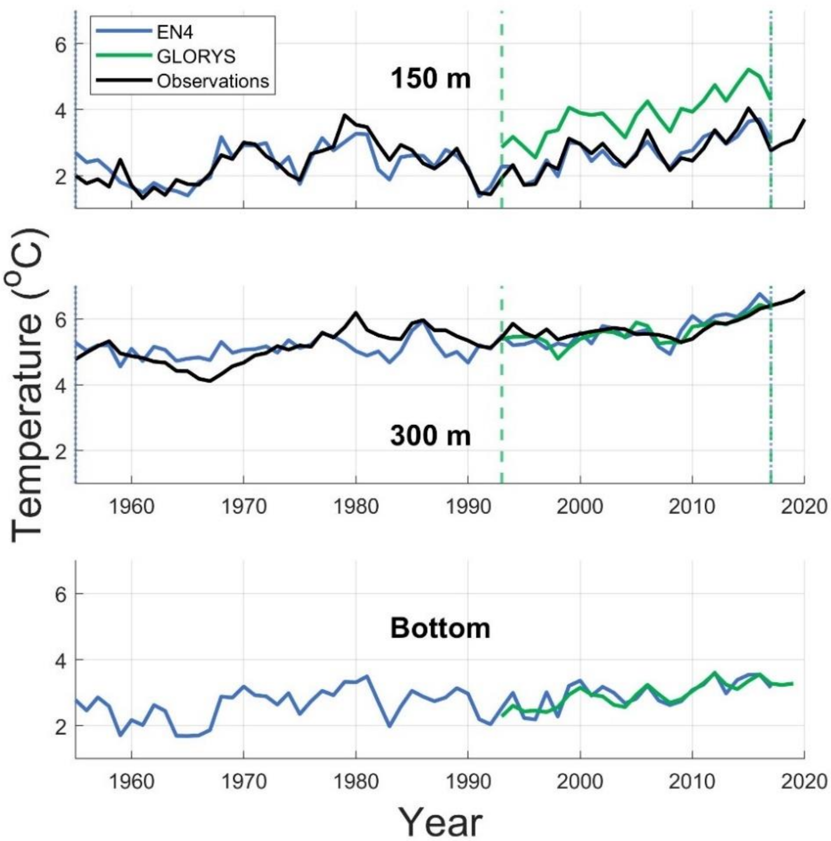

Figure 7: Time series of the Gulf of St. Lawrence water temperature from DFO observational data (**1955-2020**) and reanalysis/ocean products for the period of 1955-2020. Dotted blue lines indicate start/end of common EN4/observations period: **1955, 2017**. Dashed green lines indicate start/end of common GLORYS/observations period: **1993, 2017**.

Table 2: Gulf of St. Lawrence Water Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade. Underlined: confidence level <95% (p>0.05). **Black** covers the entire dataset time periods, **1955-2020 (observations)**, **1955-2017 (EN4)**, **1993-2017 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1955-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2017**.

	GSL 150 m							
	Bs	**Cr**	**Std**			**Tr**		
OBS	**N/A**	**N/A**	**0.70**	**0.63**	**0.58**	**0.21**	**0.17**	**0.53**
EN4	**0.00**	**0.86**	**0.57**	**0.57**	**N/A**	**0.14**	**0.14**	**N/A**
GLORYS	**1.14**	**0.95**	**0.68**	**N/A**	**0.68**	**0.77**	**N/A**	**0.77**
	GSL 300m							
OBS	**N/A**	**N/A**	**0.62**	**0.51**	**0.28**	**0.25**	**0.20**	**0.22**
EN4	**-0.03**	**0.64**	**0.46**	**0.46**	**N/A**	**0.17**	**0.17**	**N/A**
GLORYS	**-0.06**	**0.81**	**0.38**	**N/A**	**0.38**	**0.38**	**N/A**	**0.38**
	GSL Bottom							
EN4	**N/A**	**N/A**	**0.49**	**0.49**	**N/A**	**0.49**	**0.49**	**N/A**
GLORYS	**N/A**	**N/A**	**0.36**	**N/A**	**0.36**	**0.38**	**N/A**	**0.38**

As with the Scotian Shelf, both products represented the observational bottom temperature data well on the Newfoundland Shelf (Figure 8, Figure 9). The EN4 bias was more than 1 °C warmer than the observational data for all regions, spring and autumn (Table 3, Table 4). With the exception of the southern region in autumn, the bias for the GLORYS product was no more than 0.3 °C different than the observations. In the Southern Newfoundland Shelf, the southwestern region was not sampled as often as the rest of the region, resulting in observational data that were cooler than the GLORYS product. The correlation for the GLORYS product was once again stronger than the EN4 correlation for all regions and seasons. The standard deviations for the Newfoundland Shelf were generally lower than those of the Scotian Shelf. The Northern Newfoundland Shelf (autumn) EN4 standard deviation was slightly lower than the observational standard deviations, and the Central Newfoundland Shelf was slightly higher than the observational standard deviations, but all of the other products' standard deviations were similar to the observational standard deviations. The trends for the Newfoundland Shelf were all positive, though the values between the observations and products varied within a region even when the correlations were very strong (Table 3). This could be due to the fact that some of the values were not considered significant at a 95% confidence interval (CI), or it could be due to the time periods used for the calculations as slight differences in the temperature values can cause larger differences in the trend values.

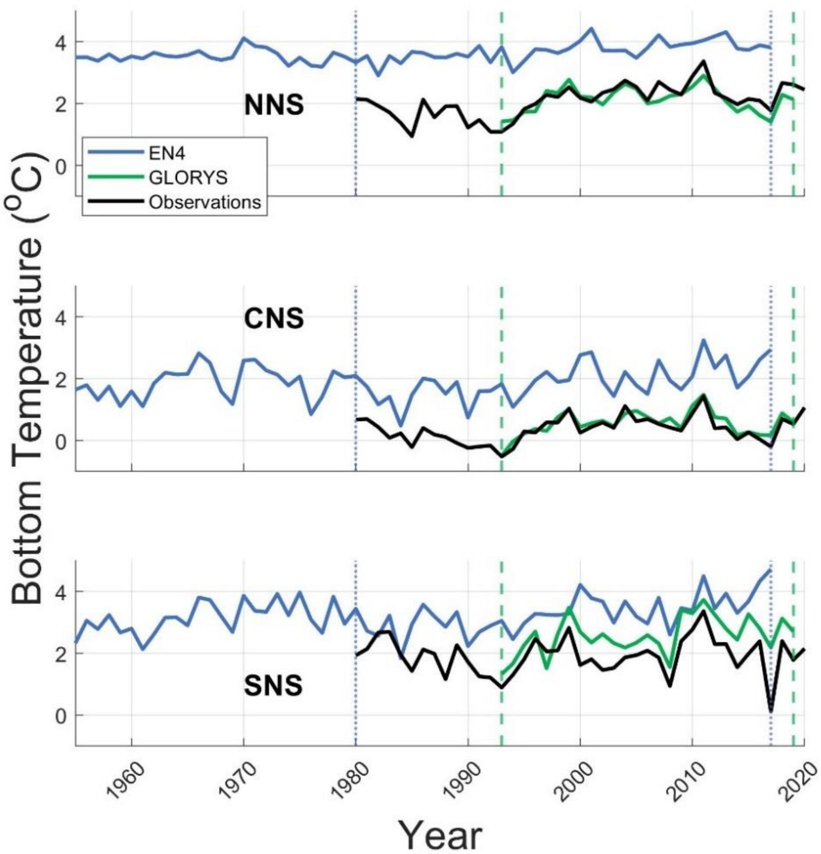

Figure 8: Time series of the autumn Newfoundland Shelf bottom temperature from all available observational data (**1980-2020**) and reanalysis/ocean products for the period of 1955-2020. Dotted blue lines indicate start/end of common EN4/observations period: **1955, 2017**. Dashed green lines indicate start/end of common GLORYS/observations period: **1993, 2019**. NNS = Northern Newfoundland Shelf, CNS = Central Newfoundland Shelf, SNS = Southern Newfoundland Shelf.

Table 3: Newfoundland Shelf Bottom Temperature (autumn): Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (p>0.05). **Black** covers the entire dataset time periods, **1980-2020 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1980-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2019**.

	NNS (autumn)							
	Bs	**Cr**	**Std**			**Tr**		
OBS	**N/A**	**N/A**	**0.52**	**0.52**	**0.46**	**0.25**	**0.25**	**0.24**
EN4	**1.67**	**0.44**	**0.29**	**0.32**	**N/A**	**0.08**	**0.18**	**N/A**
GLORYS	**-0.14**	**0.85**	**0.40**	**N/A**	**0.40**	**0.04**	**N/A**	**0.04**
	CNS (autumn)							
OBS	**N/A**	**N/A**	**0.42**	**0.42**	**0.42**	**0.11**	**0.09**	**0.07**
EN4	**1.58**	**0.37**	**0.56**	**0.59**	**N/A**	**0.09**	**0.30**	**N/A**
GLORYS	**0.11**	**0.92**	**0.40**	**N/A**	**0.40**	**0.14**	**N/A**	**0.14**
	SNS (autumn)							
OBS	**N/A**	**N/A**	**0.60**	**0.62**	**0.66**	**0.02**	**0.00**	**0.09**
EN4	**1.38**	**0.13**	**0.57**	**0.60**	**N/A**	**0.13**	**0.33**	**N/A**
GLORYS	**0.65**	**0.75**	**0.62**	**N/A**	**0.62**	**0.37**	**N/A**	**0.37**

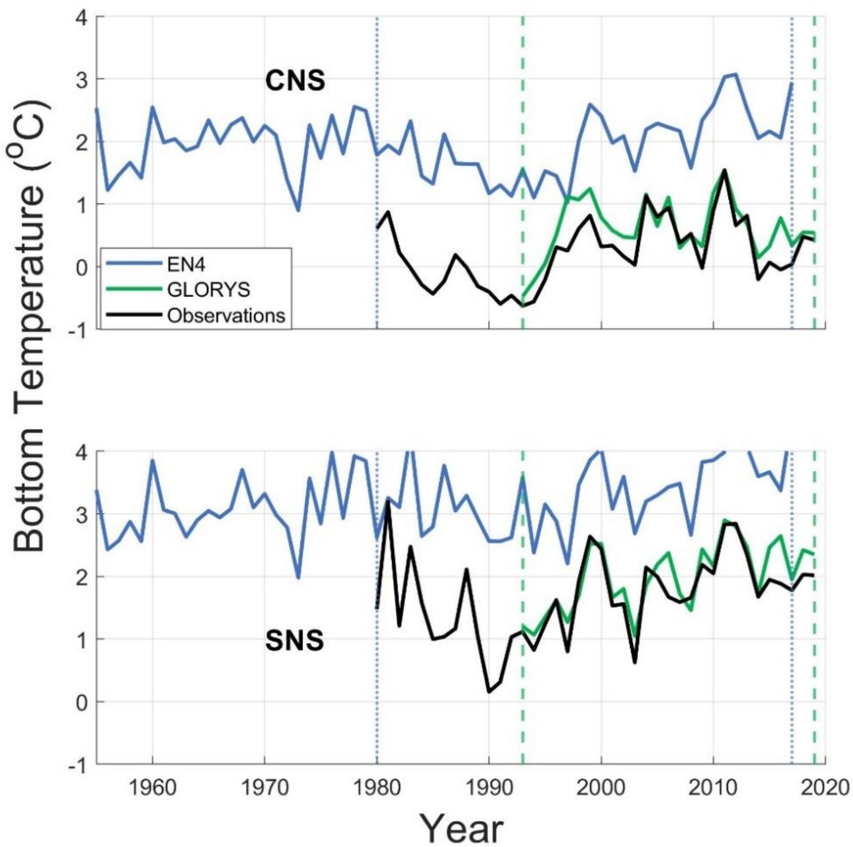

Figure 9: Time series of the spring Newfoundland Shelf bottom temperature from all available observational data (**1980-2020**) and reanalysis/ocean products for the period of 1955-2020. Dotted blue lines indicate start/end of common EN4/observations period: **1955, 2017**. Dashed green lines indicate start/end of common GLORYS/observations period: **1993, 2019**. CNS = Central Newfoundland Shelf, SNS = Southern Newfoundland Shelf.

Table 4: Newfoundland Shelf Bottom Temperature (spring): Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (p>0.05). **Black** covers the entire dataset time periods, **1980-2020 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1980-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2019**.

	CNS (spring)							
	Bs	**Cr**	**Std**			**Tr**		
OBS	N/A	N/A	0.52	0.53	0.50	0.16	0.17	0.16
EN4	1.73	0.64	0.50	0.54	N/A	0.06	0.28	N/A
GLORYS	0.25	0.87	0.46	N/A	0.46	0.10	N/A	0.10
	SNS (spring)							
OBS	N/A	N/A	0.69	0.70	0.57	0.20	0.21	0.34
EN4	1.66	0.70	0.56	0.59	N/A	0.12	0.25	N/A
GLORYS	0.17	0.90	0.55	N/A	0.55	0.43	N/A	0.43

Visually, the results from the Labrador Shelf analysis showed that GLORYS fit the observational data better than EN4 (Figure 10). The analysis (Table 5) also supported this. While the correlations were similar between EN4 and GLORYS, the GLORYS standard deviation was closer to the observational values, and the bias smaller than the same outputs for EN4. The EN4 product had a bias of more than +1.5 °C, while the GLORYS bias was cooler than the observational dataset by <0.3 °C. The correlations between the products and the observational data were nearly identical, but the standard deviations of the EN4 product were much lower than the observational data and GLORYS standard deviations. The observational data during the GLORYS period and GLORYS intersect trends were very similar, though neither were considered significant at a 95% CI, but the EN4 trend was quite different than the respective observational trend and both were considered significant. The EN4 trend during the EN4 intersect period was almost 5 times greater than the trend covering the entire EN4 period, which was likely due to the EN4 intersecting period starting during a time where the EN4 product shows cooler bottom temperatures than the start of the EN4 period.

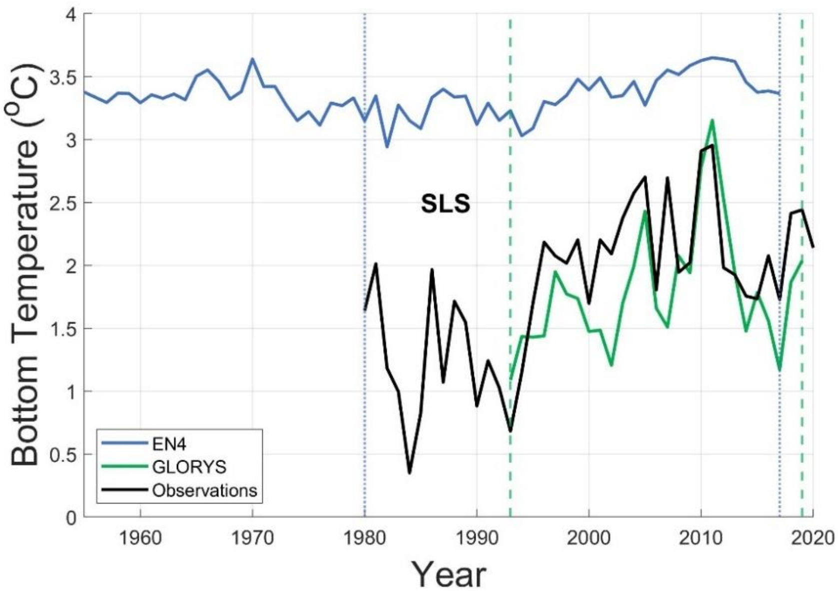

Figure 10: Time series of the autumn Labrador Shelf bottom temperature from all available observational data (**1980-2020**) and reanalysis/ocean products for the period of 1955-2020. Dotted blue lines indicate start/end of common EN4/observations period: **1980, 2017**. Dashed green lines indicate start/end of common GLORYS/observations period: **1993, 2019**. SLS = Southern Labrador Shelf.

Table 5: Labrador Shelf Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (*p*>0.05). **Black** covers the entire dataset time periods, **1980-2020 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1980-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2019**.

	SLS							
	Bs	**Cr**	**Std**			**Tr**		
OBS	**N/A**	**N/A**	**0.61**	**0.62**	**0.50**	**0.32**	**0.33**	**0.22**
EN4	**1.57**	**0.67**	**0.15**	**0.18**	**N/A**	**0.02**	**0.11**	**N/A**
GLORYS	**-0.27**	**0.66**	**0.48**	**N/A**	**0.48**	**0.21**	**N/A**	**0.21**

3.2 Arctic

The Chukchi Sea was analysed using individual stations as opposed to regional averages due to inconsistent/scarce sampling within the region (Figure 3). As well, monthly data were used as opposed to annual or seasonal data as used in other regions. Visually (Figure 11, Figure 12, Figure 13), stations 1-3 in the Chukchi Sea have similar features (e.g., greater variances in the seasonal cycle), while station 4 (Figure 14) differs from stations 1-3 in that the amplitude of the seasonal peaks was much lower. Analysis showed that EN4 ran cooler than the observations at stations 1-3 , but warmer at station 4, whereas the opposite occurred for GLORYS (Table 6). GLORYS had a negative and non-significant correlation with the observational data at station 1, likely because there were few observational data points within the GLORYS intersect period. All of the other correlations were positive, and the only significant correlations had values around 0.5. EN4 had the smallest standard deviations in all four stations, and the observational and GLORYS standard deviations were the largest of all the shelves evaluated in this report. The GLORYS standard deviation and the GLORYS intersect observational standard deviation were most alike at station 1, while the other three stations' standard deviations differed by about 1.0 s.d. While the observational trends could not be calculated due to the inconsistent sampling rates, the GLORYS bottom temperature values showed a higher and positive trend than EN4 at stations 1-3, but a lower positive trend than EN4 at station 4. Based on these analyses, neither the GLORYS nor EN4 products fit the station 4 observational data well. However, caution should be taken when interpreting these results, as the smallest trend values at each station had confidence intervals less than 95%, and trends were calculated using annual averages.

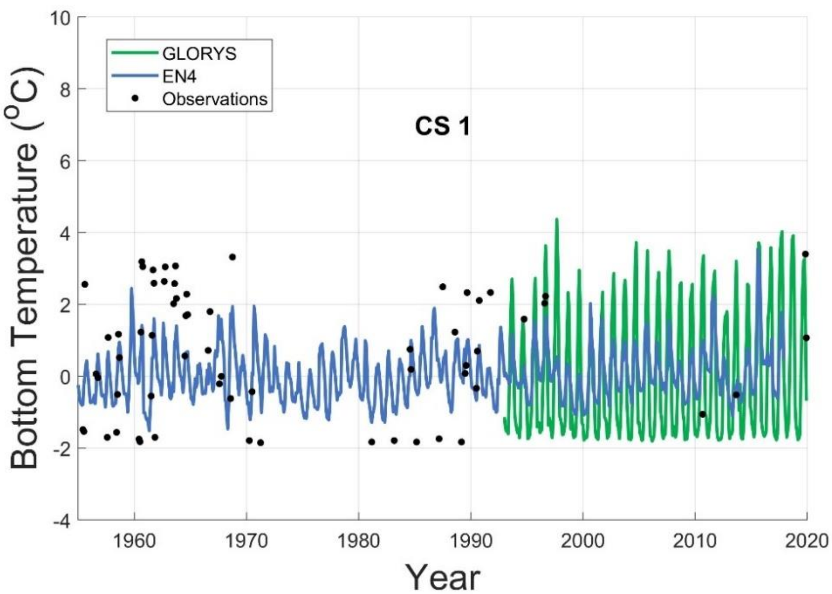

Figure 11: Time series of the bottom temperature from station 1 in the Chukchi Sea (69.5°N, 174°W) and reanalysis/ocean products for the period of 1955-2020. CS = Chukchi Sea.

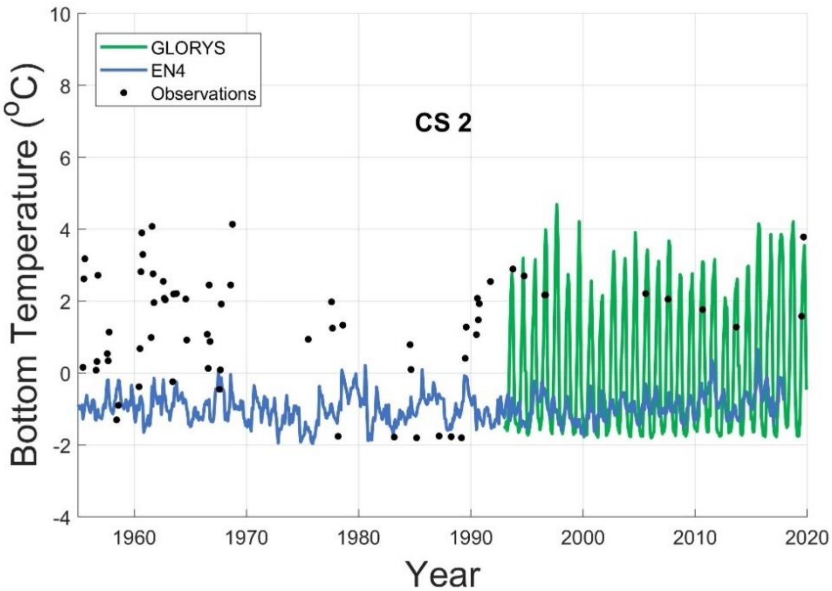

Figure 12: Time series of the bottom temperature from station 2 in the Chukchi Sea (68.6°N, 172°W) and reanalysis/ocean products for the period of 1955-2020. CS = Chukchi Sea.

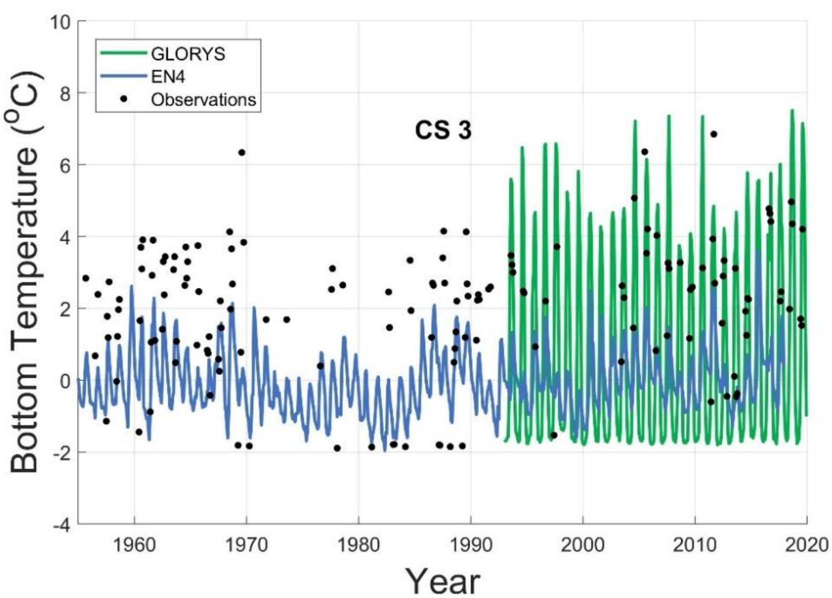

Figure 13: Time series of the bottom temperature from station 3 in the Chukchi Sea (68.5°N, 168°W) and reanalysis/ocean products for the period of 1955-2020. CS = Chukchi Sea.

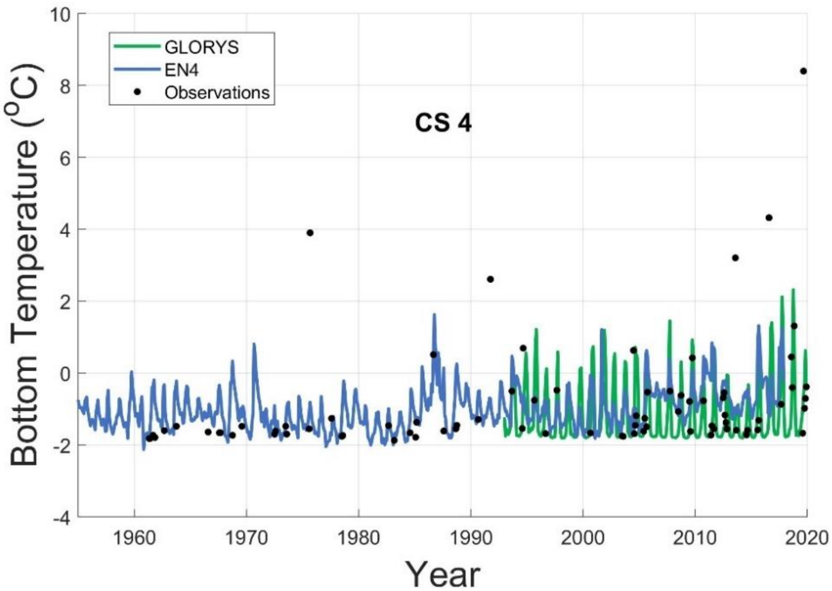

Figure 14: Time series of the bottom temperature from station 4 in the Chukchi Sea (71.5°N,160°W) and reanalysis/ocean products for the period of 1955-2020. CS = Chukchi Sea.

Table 6: Chukchi Sea Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (p>0.05). **Black** covers the entire dataset time periods, **1955-2020 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1955-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2019**.

	CS station 1							
	Bs	**Cr**	**Std**			**Tr**		
OBS	**N/A**	**N/A**	**1.71**	**1.70**	**1.57**	**N/A**	**N/A**	**N/A**
EN4	**-0.18**	**0.56**	**0.72**	**0.72**	**N/A**	**0.04**	**0.04**	**N/A**
GLORYS	**0.73**	**-0.27**	**1.75**	**N/A**	**1.75**	**0.22**	**N/A**	**0.22**
	CS station 2							
OBS	**N/A**	**N/A**	**1.53**	**1.52**	**0.72**	**N/A**	**N/A**	**N/A**
EN4	**-2.02**	**0.16**	**0.40**	**0.40**	**N/A**	**0.02**	**0.02**	**N/A**
GLORYS	**0.36**	**0.13**	**1.88**	**N/A**	**1.88**	**0.17**	**N/A**	**0.17**
	CS station 3							
OBS	**N/A**	**N/A**	**1.82**	**1.82**	**1.72**	**N/A**	**N/A**	**N/A**
EN4	**-1.43**	**0.54**	**0.87**	**0.87**	**N/A**	**0.05**	**0.05**	**N/A**
GLORYS	**1.49**	**0.49**	**2.79**	**N/A**	**2.79**	**0.19**	**N/A**	**0.19**
	CS station 4							
OBS	**N/A**	**N/A**	**1.63**	**1.27**	**1.79**	**N/A**	**N/A**	**N/A**
EN4	**0.46**	**0.05**	**0.58**	**0.58**	**N/A**	**0.11**	**0.11**	**N/A**
GLORYS	**-0.07**	**0.08**	**0.85**	**N/A**	**0.85**	**0.00**	**N/A**	**0.00**

3.3 North Pacific

The plot of the Eastern Bering Sea datasets (Figure 15) showed that both the EN4 and GLORYS products fit the observational data fairly well. Analysis (Table 7) indicated that EN4 had a positive bias of about 0.5°C. This value could likely be contributed mid-2000s to mid-2010s period when EN4 was noticeably warmer than the observational data compared to earlier periods (1980-1990) where EN4 had a small, but negative bias. While the correlation between EN4 and the observational data was moderately strong (0.64), the correlation between GLORYS and the observational data was stronger (0.97). The observational data had the highest standard deviations for all three time periods, and the EN4 and GLORYS standard deviations were similar to each other (0.61 and 0.72, respectively). The observational trends ranged from -0.01 to 0.33 with confidence levels of <95%, which suggests that the trend was quite dependent on the time periods used to calculate it, and that slight annual variations in the bottom temperature values could affect the trend for the whole period. The trends for the reanalysis/ocean products did coincide well with their respective observational trends, and did indicate that there was a positive trend in bottom temperatures in the Eastern Bering Sea with most values ranging from 0.14 - 0.34 °C/decade.

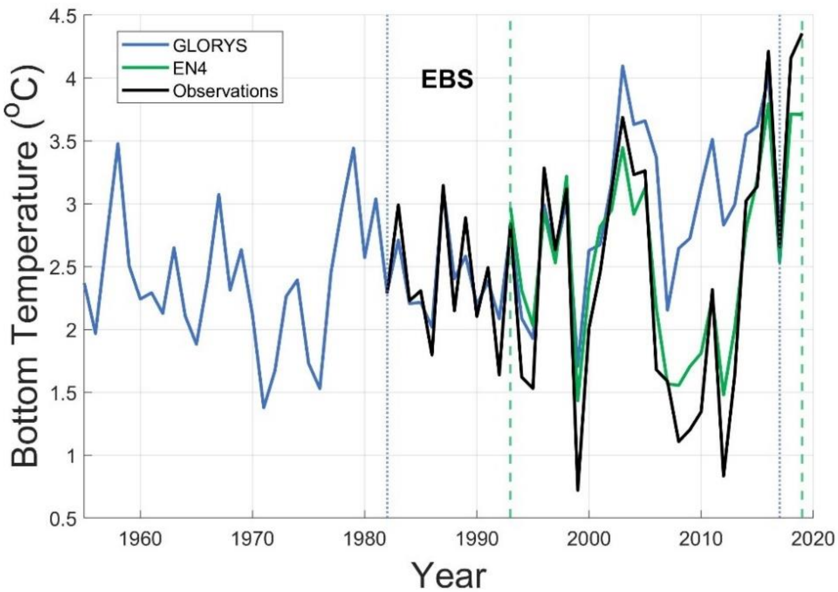

Figure 15: Time series of the Eastern Bering Sea bottom temperature from NOAA observational data (**1982-2019**) and reanalysis/ocean products for the period of 1955-2019. Dotted blue lines indicate start/end of common EN4/observations period: **1982, 2017**. Dashed green lines indicate start/end of common GLORYS/observations period: **1993, 2019**. EBS = Eastern Bering Sea.

Table 7: Eastern Bering Sea Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (*p*>0.05). **Black** covers the entire dataset time periods, **1982-2019 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1982-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2019**.

	EBS							
	Bs	**Cr**	**Std**			**Tr**		
OBS	**N/A**	**N/A**	**0.92**	**0.83**	**1.05**	**0.14**	**-0.01**	**0.33**
EN4	**0.45**	**0.64**	**0.61**	**0.61**	**N/A**	**0.16**	**0.34**	**N/A**
GLORYS	**0.09**	**0.97**	**0.72**	**N/A**	**0.72**	**0.15**	**N/A**	**0.15**

The trend in bottom temperature at GAK1 Station was very similar to that of the EN4 product until the last decade (2010 onward) when the observational temperature trend increased above EN4 (Figure 16). The GLORYS product better fit the upward trend in temperatures, but showed greater amplitudes in the seasonal temperatures than the observational data. Both EN4 and GLORYS had similar biases (-0.35 and -0.25 respectively) (Table 8), and EN4 had a moderate correlation (0.32) while GLORYS had a very strong correlation (0.87). The EN4 standard deviations were at the lower end of the observational standard deviations, and the GLORYS standard deviations were on the higher end. The differences between the observational standard deviations and the products' standard deviations were comparable, with GLORYS being slightly higher than the observational values and EN4 being slightly lower. All trends, with the exception of the EN4 intersecting trend, were positive, although the only trends that were considered significant were the negative EN4 trend and the overall observational trend.

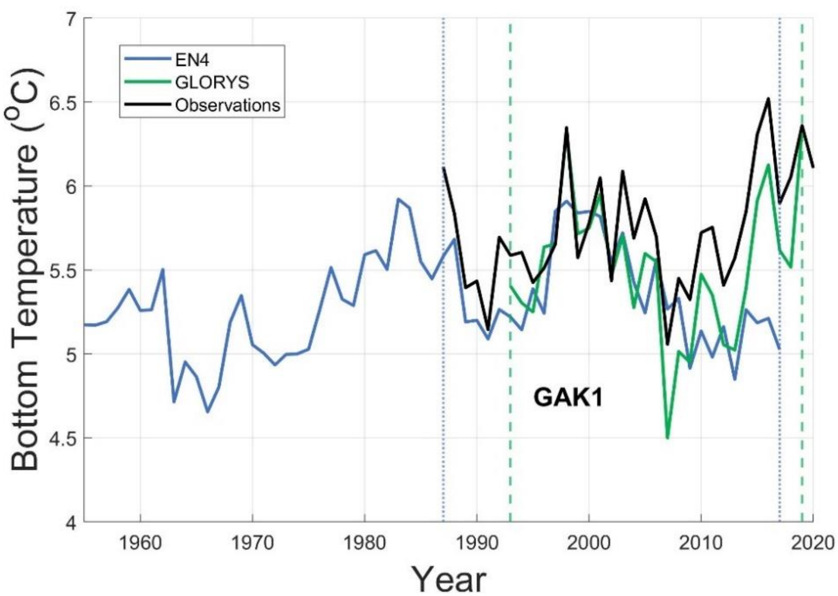

Figure 16: Time series of the GAK1 Station bottom temperature from observational data (**1987-2020**) and reanalysis/ocean products for the period of 1955-2020. Dotted blue lines indicate the start/end of common EN4/observations period: **1987, 2017**. Dashed green lines indicate the start/end of common GLORYS/observations period: **1993, 2019**.

Table 8: GAK1 Station (Alaska) Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (*p*>0.05). **Black** covers the entire dataset time periods, **1987-2020 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1987-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2019**.

	GAK1							
	Bs	Cr	Std			Tr		
OBS	N/A	N/A	0.39	0.37	0.30	0.13	0.21	0.06
EN4	-0.35	0.32	0.31	0.30	N/A	0.04	-0.12	N/A
GLORYS	-0.25	0.87	0.42	N/A	0.42	0.02	N/A	0.02

Keeping in mind that there is a very short period of observational data for the Dixon Shelf (2001-2011), the station on the Dixon Shelf visually matched the GLORYS product better than the EN4 product (Figure 17). The analysis reiterated that finding as GLORYS had a smaller bias than EN4 and, while GLORYS had a weaker correlation at 0.33, EN4 had a moderately strong correlation at -0.51 (Table 9). With regards to the standard deviations, the GLORYS standard deviation was closer to the observational standard deviation than the EN4 standard deviation. The calculated trends were very small for both products, and quite large for the observational data. The differences in the trends were likely the result of the short observational time series.

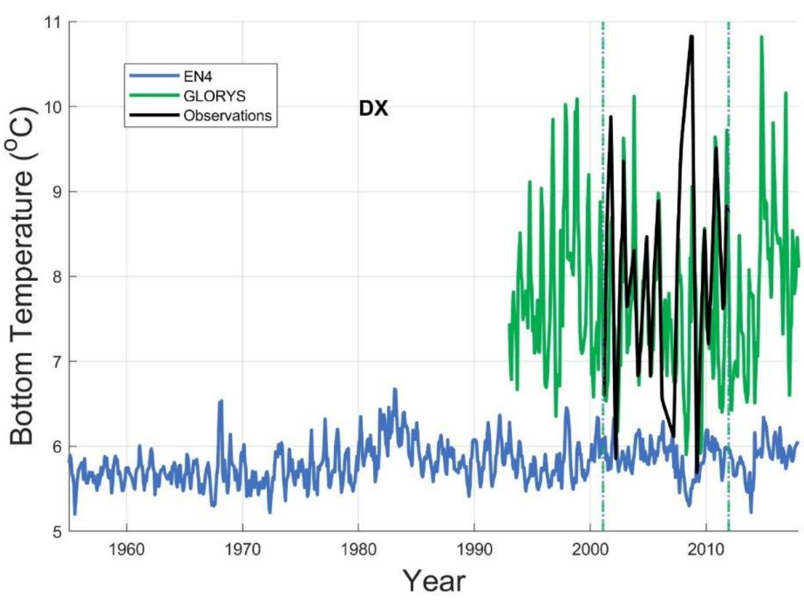

Figure 17: Time series of the Dixon Shelf bottom temperature from observational data (**2001-2011**) and reanalysis/ocean products for the period of 1955-2019. Dotted blue lines indicate start/end of common EN4/observations period: **2001, 2011**. Dashed green lines indicate the start/end of common GLORYS/observations period: **2001, 2011**. DX = Dixon Shelf.

Table 9: Dixon Shelf Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (p>0.05). **Black** covers the entire dataset time periods, **2001-2011 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **2001-2011**; **green** covers the common time period between GLORYS and the observations, **2001-2011**

	DX							
	Bs	Cr	Std			Tr		
OBS	N/A	N/A	1.17	1.17	1.17	0.67	0.67	0.67
EN4	-2.20	-0.51	0.34	0.20	N/A	0.04	<u>-0.10</u>	N/A
GLORYS	-0.49	0.33	0.89	N/A	0.88	<u>0.06</u>	N/A	<u>-0.08</u>

Heading south down the British Columbia Shelf, the Hecate Strait station (which also had a very short period of observational data in relation to other regions in this evaluation (2004-2010)) fit both products slightly better than at the Dixon station (Figure 18). The GLORYS product bias was smaller than the EN4 products bias, but both were within 0.6 °C of the observational data (Table 10). At this station, EN4 had the strongest correlation at 0.43, and GLORYS had a weaker than usual correlation of 0.22. The standard deviations for both products were similar to the observational standard deviations of 0.35, with standard deviations for EN4 and GLORYS being 0.29 and 0.39, respectively, during the common periods. Similar to the Dixon Shelf station, the trends within the intersect period were larger than the trends for the entire product time series, and all three trends were negative during the intersect period while the two product trends were positive when looking at their entire time series.

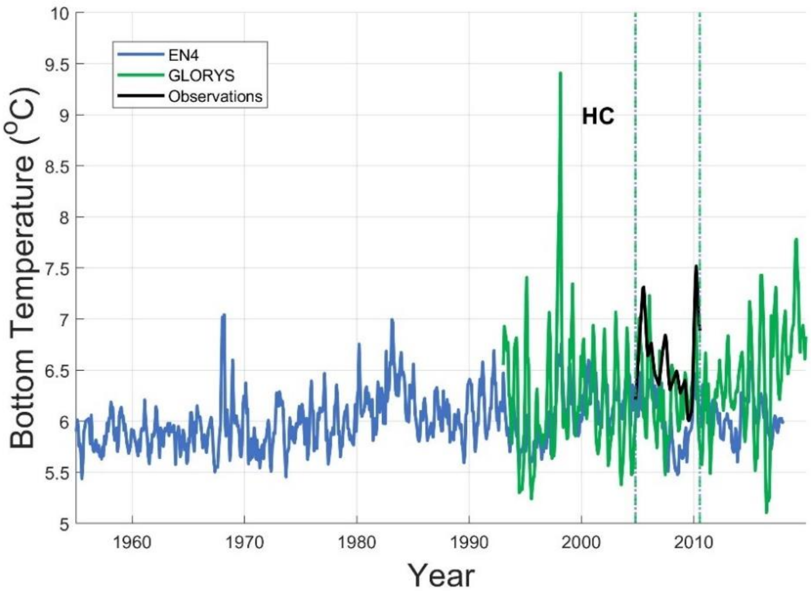

Figure 18: Time series of the Hecate Strait bottom temperature from observational data (**2004-2010**) and reanalysis/ocean products for the period of 1955-2019. Dotted blue lines indicate start/end of common EN4/observations period: **2004, 2010**. Dashed green lines indicate the start/end of common GLORYS/observations period: **2004, 2010**. HC = Hecate Strait.

Table 10: Hecate Strait Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (*p*>0.05). **Black** covers the entire dataset time periods, **2004-2010 (observations)**, **1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **2004-2010**; **green** covers the common time period between GLORYS and the observations, **2004-2010**.

	HC							
	Bs	Cr	Std			Tr		
OBS	N/A	N/A	0.35	0.35	0.35	-0.32	-0.32	-0.32
EN4	-0.56	0.43	0.26	0.29	N/A	0.04	<u>-0.64</u>	N/A
GLORYS	-0.34	<u>0.22</u>	0.55	N/A	0.39	<u>0.14</u>	N/A	<u>-0.17</u>

The North Vancouver Island Shelf station had the available data to do an analysis for both spring and autumn data. During the spring (April-June), the GLORYS product appeared to match the observational data well (Figure 19), and the EN4 product appeared to have a moderate correlation while being at least 1 °C cooler and having less variation than the observational data. During the autumn (September-November), GLORYS and EN4 appeared similar to each other, but neither were similar to the observational data. The analyses seemed to coincide with these visually-based results (Table 11). In the spring, EN4 had a bias which was more than four times greater than the GLORYS bias. Additionally, both correlations were moderately strong with the GLORYS correlation being slightly stronger at 0.73, while the EN4 correlation was 0.63. With regards to the standard deviations during the intersect periods, the GLORYS standard deviation (0.63) was almost the same as the observational standard deviation (0.61), while the EN4 standard deviation (0.25) was much lower than the observational standard deviation (0.64). In both the spring and autumn analyses, the EN4 trends were small, but positive during the entire time series, but around 5-6 times larger and negative during the intersect period, which was similar to the corresponding observational data spring trend, but not the autumn trend. As well, the GLORYS intersect trends were not similar to the corresponding observational intersect trends for either season.

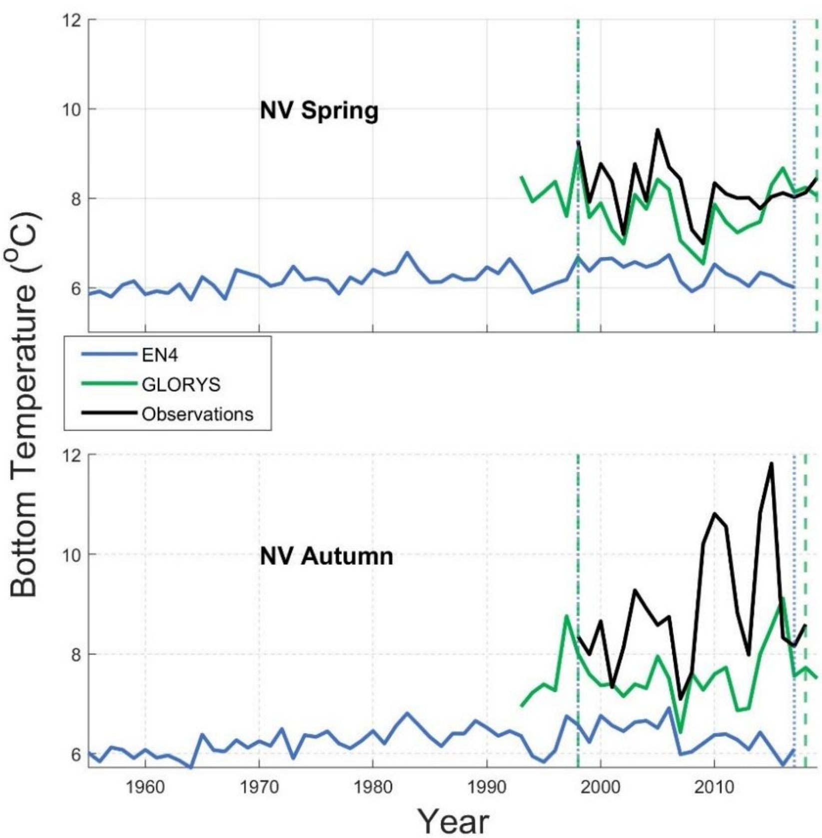

Figure 19: Time series of the Northern Vancouver Island Shelf bottom temperature from observational data (**1998-2018**), (**1998-2017**) and reanalysis/ocean products for the period of 1955-2029. Dotted blue lines indicate start/end of common EN4/observations period: **1998, 2018,** and **1998, 2017**. Dashed green lines indicate the start/end of common GLORYS/observations period: **1993, 2018,** and **1993, 2017**. NV = Northern Vancouver Island Shelf.

Table 11: Northern Vancouver Island Shelf Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (*p*>0.05). **Black** covers the entire dataset time periods, **1998-2019 (spring observations)**, **1998-2018 (autumn observations) 1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1998-2017**; **green** covers the common time period between GLORYS and the observations, **1998-2019 (spring), 1998-2018 (autumn)**.

	NV spring							
	Bs	Cr	Std			Tr		
OBS	N/A	N/A	0.61	0.64	0.61	-0.25	-0.36	-0.25
EN4	-1.83	0.63	0.25	0.25	N/A	0.06	-0.29	N/A
GLORYS	-0.44	0.73	0.60	N/A	0.63	-0.09	N/A	0.08
	NV autumn							
OBS	N/A	N/A	1.26	1.29	1.26	0.72	0.88	0.72
EN4	-2.56	0.09	0.27	0.29	N/A	0.05	-0.30	N/A
GLORYS	-1.32	0.38	0.58	N/A	0.57	0.16	N/A	0.26

The Southern Vancouver Island Shelf station also had enough data to do analyses for both spring and autumn data. The spring (April-June) observational appeared to fit best with the GLORYS spring data (Figure 20), and it was not clear as to whether the GLORYS or EN4 autumn data (September-November) fit the autumn observational data better. The correlation analysis (Table 12) indicated that the product biases were similar to each other in both seasons, with a slightly greater bias occurring in the spring than in the autumn. The GLORYS spring product had the strongest correlation (0.63), with the next strongest correlation being 0.42 with the autumn EN4 product. The EN4 standard deviations during the intersect periods were closer to the corresponding observational standard deviations than the GLORYS standard deviations in both seasons, though the GLORYS standard deviations were not that dissimilar to the observational standard deviations. The observational trends ranged from -0.19 to -0.30 for both seasons, and like the standard deviations, the EN4 intersect trends were closer to the corresponding observational values than the GLORYS trends, which were near zero (0.05 and -0.02 for the spring and autumn GLORYS trends, respectively).

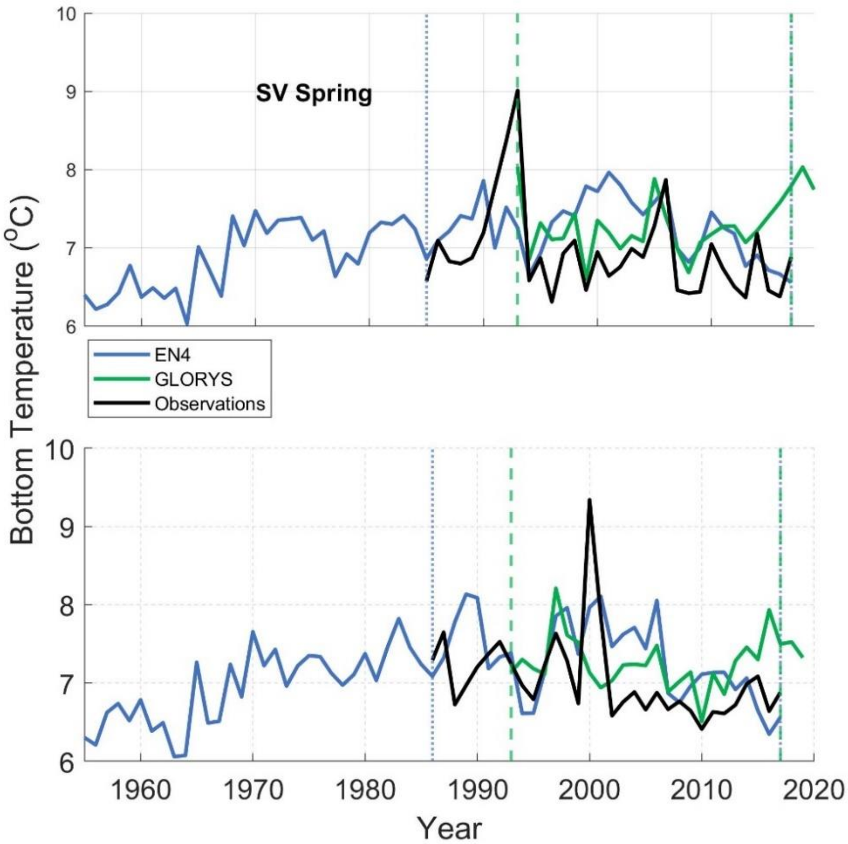

Figure 20: Time series of the Southern Vancouver Island Shelf bottom temperature from observational data (**1985-2017**), (**1986-2017**) and reanalysis/ocean products for the period of 1955-2019. Dotted blue lines indicate start/end of common EN4/observations period: **1985, 2017,** and **1986, 2017**. Dashed green lines indicate the start/end of common GLORYS/observations period: **1993, 2017**. SV = Southern Vancouver Island Shelf.

Table 12: Southern Vancouver Island Shelf Bottom Temperature: Model bias (Bs; unit: °C), correlation coefficients (Cr), standard deviations (Std), and trends (Tr; unit: °C/decade). Underlined: confidence level <95% (*p*>0.05). **Black** covers the entire dataset time periods, **1985-2017 (spring observations)**, **1986-2017 (autumn observations), 1955-2017 (EN4)**, **1993-2019 (GLORYS)**; **blue** covers the common time period between EN4 and the observations, **1985-2017, 1986-2017**; **green** covers the common time period between GLORYS and the observations, **1993-2017**.

	SV spring							
	Bs	**Cr**	**Std**			**Tr**		
OBS	**N/A**	**N/A**	**0.59**	**0.59**	**0.58**	**-0.19**	**-0.19**	**-0.25**
EN4	**0.31**	**0.27**	**0.46**	**0.39**	**N/A**	**0.11**	**-0.12**	**N/A**
GLORYS	**0.38**	**0.63**	**0.37**	**N/A**	**0.34**	**0.14**	**N/A**	**0.05**
	SV autumn							
OBS	**N/A**	**N/A**	**0.55**	**0.55**	**0.59**	**-0.22**	**-0.22**	**-0.30**
EN4	**0.25**	**0.42**	**0.52**	**0.51**	**N/A**	**0.10**	**-0.25**	**N/A**
GLORYS	**0.26**	**0.14**	**0.34**	**N/A**	**0.35**	**0.01**	**N/A**	**-0.02**

4 Conclusions

Our analysis of the EN4 and GLORYS products against the observational data collected on the Canadian/North American continental shelves has revealed that overall, the GLORYS reanalysis product performed better than EN4 for modelling bottom temperatures. The EN4 product generally had weaker correlations with the observational data compared to GLORYS, and smaller standard deviations, suggesting it did not capture the full extent of the temperature variations in these regions. A benefit of the GLORYS product is that it has a finer grid than the EN4 product, suggesting it may better represent single station data compared to the EN4 product. The EN4 product covers a longer time period than GLORYS (1955 onward compared to 1993 onward for GLORYS), and therefore may be more useful in providing longer-time trends with decadal oscillations filtered out, while the realism of the EN4 for the whole time period (1955 to 2017) can not be evaluated for most of these subareas due to lack of observational data for the whole period.

In Eastern Canada, GLORYS fit the observational data more closely than EN4 with the exception of the Gulf of St. Lawrence. Here, the trends in EN4 closely match the 150 m depth observations. In the Arctic, there was a wide variation of standard deviations between the stations. In the North Pacific shelves, the EN4 product fit the observational data better at the GAK1 Station and the Eastern Bering

Sea compared to most other regions (Gulf of St. Lawrence excluded). While the GLORYS still performed better at these locations overall, the trends in EN4 were much closer to the observational data until the last 10-15 years when the data trended towards warming.

Acknowledgements

This work is supported by DFO's CSRF project (CC-22-05-01). DFO colleagues, Ms. Chantelle Layton (BIO), Dr. Frederic Cyr (NAFC) and Dr. Peter Galbraith (IML) provided observational data for the North Atlantic Ocean in this report. Ms. Lindsay Beazley and Dr. Li Zhai internally reviewed an earlier version of this report, and provided invaluable comments, which helped improve this report. The section head of the Ocean Monitoring and Observation Section, Andrew Cogswell, carried out a review of the report, and provided detailed comments, and his comments significantly enhanced the quality of this report.

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