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Monthly maps of optimally interpolated in situ hydrography in the North Sea from 1948 to 2013

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A B S T R A C T

We used a statistical model mainly based on optimal or Gauss–Markov interpolation (OI) to produce monthly maps of in situ hydrography in the North Sea through 66 years (from 1948 to 2013) with a resolution of 0.2° × 0.2°. The in situ hydrography data are approximately 430,000 hydrographic profiles and aggregated thermosalinograph data from various international databases. Duplicates, outliers and vertical density instabilities were removed. Regions with poor OI estimates were replaced with a harmonic reconstruction arising from the most reliable OI estimates. Adjustments for vertical density stability were based on the standards of the World Ocean Atlas. We mapped at 54 depth levels through the water column, focusing on surface and bottom hydrography because this type of map is of particular interest for ecosystem and fisheries research. Average OI temperature and salinity expected errors at the surface are 0.3 °C and 0.1, respectively. OI errors decrease with depth following decrement of signal and noise variances and apparently independent of the data amount (indicating a good data coverage). Alternative error estimates were obtained with the Median Absolute Deviation between our hydrography estimates and time series excluded from the analysis and are on average 0.3 °C and 0.1 salinity units. While our product seems limited for analysis of variability on monthly and seasonal time scales, particularly in the regions of large variability, it is suitable for studies of inter-annual and decadal variability. A comparison with two alternative analyses (KLIWAS and SODA) is discussed. As direct application of our results, we present a new hydrographic climatology of the North Sea at various depths with an improved effective resolution.

1. Introduction

Maps of oceanographic properties have proven to be of great utility as, for example, boundary and initial conditions in numerical circulation models, for verification of ocean numerical simulations and planning of oceanographic expeditions (Locarnini et al., 2010). Gridded hydrography is particularly important for climate studies, which make use of large amounts of maps spanning various decades (see for instance Kaplan et al., 1998). The North Sea (Fig. 1), due to its geographical location, is one of the most extensively explored and exploited seas in the world. Previous climatic studies in the North Sea have shown the need of gridded hydrography in this region spanning a long period (Becker and Pauly, 1996; Becker et al., 1997).

Spatially resolved maps of surface and bottom hydrography in the North Sea have shown to be also useful for ecosystem and fisheries studies because they describe habitats of pelagic and demersal fishes, respectively (Ehrich et al., 2009; Kempf et al., 2013). Such maps also indirectly provide information about life conditions of the fish early-life stages and food availability, which were shown to be particularly sensitive to water temperature (Planque and Fredou, 1999; Beaugrand et al., 2003; Hufnagl and Peck, 2011). The seasonal spawning and migration, stage-specific development, overwintering and feeding strategies of marine organisms, as well as the specific time-scales of fisheries and ecosystem sampling, demand maps of hydrography at quarterly or monthly resolution (ICES, 2012a,b). On the other hand, unless using a topography-following vertical coordinate, a good resolution for the bottom layer can only be achieved with a relatively high vertical resolution.

Due to climate change, the influence of physical variables on ecosystems at the long time-scales of climate studies is gaining increasing importance for fisheries biology and management (Daw et al., 2009). Ecology and fisheries studies related to climate change demand large amounts of gridded hydrography spanning a long period of time, like decades, with a relatively high sampling frequency, like months (Berx et al., 2011). Currently there is not a satisfactory product for such studies in the North Sea, at all depths, with high resolution and freely available to the scientific community.

1. Satellites provide maps of sea surface temperature (SST) at weekly or even daily basis for various decades (Reynolds and Smith, 1994; Reynolds et al., 2002; Hoyer and She, 2007) but no information about deeper water layers or about salinity (until now). Furthermore,

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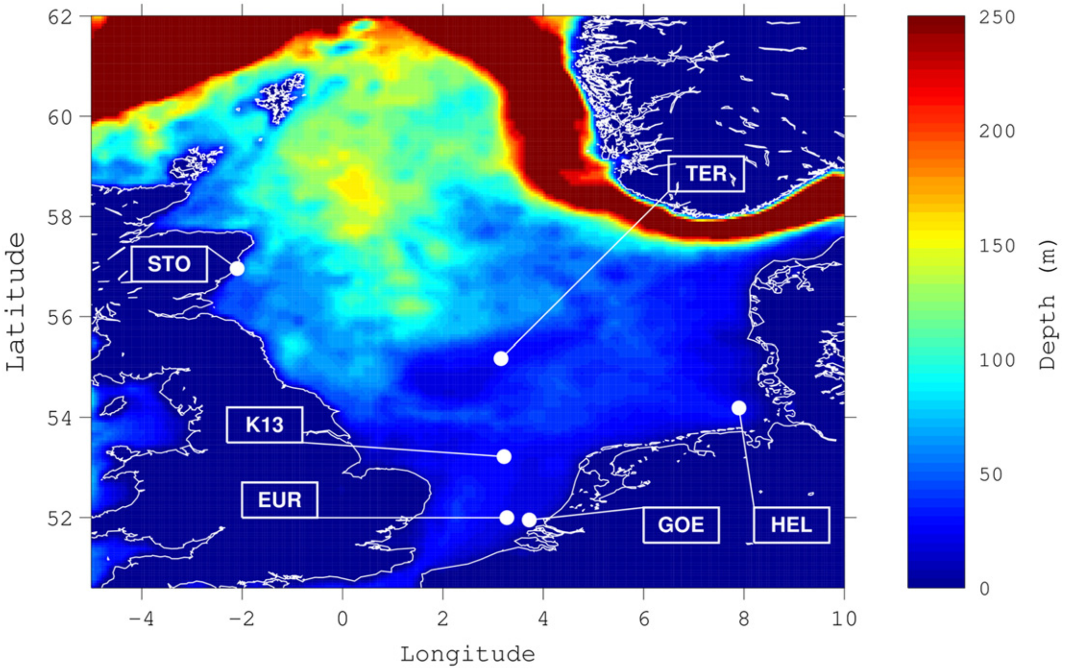

Fig. 1. Study area and ETOPO1 bathymetry decimated to our grid resolution and depth levels. The position of six sampling stations (Table 2) are shown, from where independent time series were taken to validate our analysis.

various ecosystem, fisheries and climate studies demand maps of water characteristics from years previous to the satellite era (Berx et al., 2011), which started in the 1980s.

2. Direct models are relatively computationally cheap methods yielding long-term hindcasts of hydrography (for instance, in the North Sea, the Hamburg Shelf Ocean Model, HAMSOM; Backhaus and Hainbucher, 1987). Such models are valuable tools for variability and dynamical studies at climatic time-scales but modeled hydrography differs considerably from observed values (Delhez et al., 2004). Even though in recent modeling studies (Hjøllo et al., 2009; Meyer et al., 2011) a fair representation of temperature could be achieved, salinity variations are still poorly represented due to the use of long-term monthly mean river run-off (Meyer et al., 2011) or fluxes through open boundaries (Hjøllo et al., 2009). Additionally, approaches more directly related to observations are also relevant to validate direct model runs.
3. High-resolution inverse models or assimilation schemes demand large computational resources, allowing analysis of only few years. Therefore, such studies in the North Sea commonly focus on short-term forecasting (Siddorn et al., 2007; Fu et al., 2011) and not on multi-decade hindcasts. Recent ocean reanalyses spanning various decades have as domain the world ocean (for instance the Simple Ocean Data Assimilation, SODA; Carton and Giese, 2008), achievable only with a relatively coarse space and vertical resolution (0.5° and 24 levels in the North Sea). Furthermore, such elaborate ocean reanalyses depend on model parameterizations, which simplify complex and only partially understood physical phenomena. This makes, again, more simple methods a valuable first step for comparison of results.

These notions point to the need in the North Sea of a computationally cheap but robust gridding of in situ hydrography. One such method is Optimal Interpolation (OI) or Gauss-Markov estimation (Gandin, 1963). OI has been widely used in oceanography to map current velocities, stream function and dynamic height (Freeland and Gould, 1976; Bretherton et al., 1976; McWilliams, 1976; Hiller and Kaese, 1983; Davis, 1985; Denman and Freeland, 1985; Chereskin and Trunnell, 1996), in situ hydrography (Roemmich, 1983; Denman and Freeland, 1985; Kaplan et al., 1998; Meyers et al., 1991; Toompuu and Wulff, 1995; Hosoda et al., 2009), tracers (Sarmiento et al., 1982), SST in the world ocean (Clancy et al., 1990; Reynolds and Smith, 1994; Reynolds et al., 2002) and, with higher resolution, only in the North and Baltic Seas (Hoyer and She, 2007).

The goal of this study was to develop a statistical model, mainly based on OI, to estimate monthly maps of in situ temperature and salinity in the North Sea with a horizontal resolution of 0.2° × 0.2°, from 1948 to 2013. Looking forward to ecology and fisheries studies, we map at various depth levels with a high vertical resolution to satisfactorily resolve bottom hydrography in the horizontal. Our end product will be available to the scientific community linked in the web portal of the Working Group on Operational Oceanographic Data Products for Fisheries and the Environment (WGOOFE) of the International Council for the Exploration of the Seas (ICES), conforming to the recommendations by Berx et al. (2011) relating to data format and meta-data.

2. Data

We analyze approximately 4.3×10^5 hydrographic stations collected from 1948 to 2013 in the region from 50.6°N to 62°N and from 5°W to 10°E (Table 1 and Fig. 1). These are mostly high resolution

Table 1
Number of hydrographic profiles and aggregated thermosalinograph data used in the present study, from 1948 to 2013 in the North Sea (50.6°N to 62°N and 5°W to 10°E). Data sources are shown in the first column. WOD stands for World Ocean Database, ICDC for Integrated Climate Data Center, XBT for eXpendable BathyThermograph, MBT for Mechanical BathyThermograph, ICES for International Council for the Exploration of the Sea and BSH for Bundesamt für Seeschifffahrt und Hydrographie (the German Federal Maritime and Hydrographic Agency). Note many profiles are both temperature and salinity profiles.

Data source	Temperature profiles	Salinity profiles	Total profiles
WOD	271,490	214,879	275,009
ICDC XBT	59	0	59
ICDC MBT	1058	0	1058
Coriolis	970	967	971
ICES	30,143	30,791	32,065
BSH	103,106	98,789	117,152
Total	406,826	345,426	426,314