Journal of Marine Systems 88 (2011) 323–331

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

The influence of increasing water turbidity on the sea surface temperature in the Baltic Sea: A model sensitivity study

Ulrike Löptien *, H.E. Markus Meier

Swedish Meteorological and Hydrological Institute (SMHI), Folkborgsvägen 1, S-601 76 Norrköping, Sweden

ARTICLE INFO

Article history:
Received 18 January 2011
Received in revised form 1 June 2011
Accepted 7 June 2011
Available online 17 June 2011

Keywords:
Baltic Sea
Ocean modeling
Water turbidity
SST trends
Secchi depth

ABSTRACT

The aim of the present study is to investigate the influence of enhanced absorption of sunlight at the sea surface due to increasing water turbidity and its effect on the sea surface temperatures (SST) in the Baltic Sea. The major question behind our investigations is, whether this effect needs to be included in Baltic Sea circulation models or can be neglected. Our investigations cover both, mean state and SST trends during the recent decades. To quantify the impact of water turbidity on the mean state different sensitivity ocean hindcast experiments are performed. The state-of-the art ocean model RCO (Rossby Centre Ocean model) is used to simulate the period from 1962 to 2007. In the first simulation, a spatially and temporally constant value for the attenuation depth is used, while in the second experiment a climatological monthly mean, spatially varying attenuation coefficient is derived from satellite observations of the diffuse attenuation coefficient at 490 nm. The inclusion of a spatially varying light attenuation leads to significant SST changes during summer. Maximum values of +0.5 K are reached in the Gulf of Finland and close to the eastern coasts, when compared to a fixed attenuation of visible light of 0.2 m^{-1}. The temperature anomalies basically match the pattern of increased light attenuation with strongest effects in shallow waters. Secondary effects due to changes in the current system are of minor importance. Similar results are obtained when considering trends. In the absence of long-term basin wide observations of attenuation coefficients, some idealizations have to be applied when investigating the possible influence of long-term changes in water turbidity on the SST. Two additional sensitivity experiments are based on a combination of long-term Secchi depth station observations and the present day pattern of water turbidity, as observed by satellite. We show the potential of increased water turbidity to affect the summer SST trends in the Baltic Sea significantly, while the estimated effect is apparently too small to explain the overall extreme summer trends observed in the Baltic Sea.

1. Introduction

The Baltic Sea is located in central Europe and about 85 million people live in its drainage basin (e.g. Leppäranta and Myrberg, 2009). The shallow, brackish sea is of crucial importance for the bordering countries, e.g. concerning fishery and tourism. The Baltic Sea changed considerably during the recent decades, which is partly due to human influence. Several studies have indicated that the temperature of the Baltic Sea has risen substantially during the last 100 years while the reasons for this warming are still unclear (e.g. Belkin, 2009; Bradtk et al., 2010; Leppäranta and Myrberg, 2009; MacKenzie and Schiedeck, 2007; Siegel et al., 2006). Belkin (2009) found warming trends during 1982–2006 in the Baltic and North Sea that exceeded the surrounding seas by 0.5–0.6 K. Furthermore, the analysis of daily station data from long-term monitoring programs since the 1860s reported an unprecedented warm period during the mid 1990s (MacKenzie and Schiedeck, 2007). From 1985 to the early 2000s the temperature rose on average 0.6 K with a significantly higher increase in summer (>1.4 K). Also, Siegel et al. (2006) report strong positive trends during the summer month for the period 1990–2004 with a maximum slope in the Bothnian Sea. According to their findings, the Gotland Sea warmed by 0.15–0.18 K per year (July–September) which is close to the values reported by MacKenzie and Schiedeck (2007) for the period 1985 to the early 2000s. This warming can partly be explained by the atmospheric conditions. However, in particular, the summer warming is higher than what could be expected on the basis of the consensus view of global increase of air temperatures. Due to the strong warming large ecological consequences might occur (MacKenzie and Schiedeck, 2007).

Besides, one of the most serious environmental problems in the Baltic Sea is eutrophication (e.g. Boesch et al., 2006; Boesch et al., 2008; Jansson and Dahlberg, 1999; Nehring, 1992; Pawlak et al., 2009; Wasmund and Uhlig, 2003; Wulff et al., 1999). This is caused by increased nutrient input from the intensively cultivated catchment area, resulting in an increase in biomass and a reduction in water

* Corresponding author now at: Leibniz Institute of Marine Sciences (IFM-GEOMAR), Düsternbrooker Weg 20, D-24105 Kiel, Germany. Tel.: +49 431 600 4283; fax: +49 431 600 4469.
E-mail address: ulrike.loptien@smhi.se (U. Löptien).

0924-7963/$ – see front matter
doi:10.1016/j.jmarsys.2011.06.001

transparency (Sanden and Håkansson, 1996). The decrease in water transparency is mainly illustrated by long-term Secchi depth measurements, which is the depth at which a white disk disappears from the observers' view as it is lowered into the water. Secchi depth measurements exist since the beginning of the last century at single locations (Aarup, 2002; Sanden and Håkansson, 1996) and apparently Secchi depth experienced a remarkable decrease during the last 100 years (Leppäranta and Myrberg, 2009; Sanden and Håkansson, 1996). While the present level is 5–10 m, some measurements indicate that it has almost halved at numerous locations since the beginning of the last century (Laamanen et al., 2004). Empirical studies found a good correlation between water transparency and the state of eutrophication (Elmgren and Larson, 2001; Nielsen et al., 2002; Sand-Jensen and Borum, 1991). Note, that the Baltic Sea is optically a multi-componental water (coastal water, Type 1–5) and the decrease in Secchi depth might possibly be influenced by changes in yellow substances or suspended organic matter, besides chlorophyll (Kratzer and Tett, 2009; Siegel et al., 2005). However, regardless of the reasons for the observed increase in water turbidity, it can be assumed to feed back on the sea surface temperature (SST). Kahru et al. (1993) report a substantial feedback of cyanobacterial blooms and their accumulation on SST. Satellite data indicate a local SST increase by up to 1.5 K due to cyanobacterial blooms. Also, it is well known that optically active substances, such as chlorophyll and yellow substances, strongly absorb light in the blue and red parts of the spectrum. Through this, the vertical distribution of radiative heating can be modified which results in enhanced surface warming and sub-surface cooling (Chang and Dickey, 2004; Oschlies, 2004). State-of-the-art Baltic Sea models neglect the temporal and spatial variability in the attenuation of light and assume for simplicity a fixed, mean attenuation (e.g. Meier and Faxen, 2002; Rudolph and Lehmann, 2006; Schrum et al., 2003; Wilhelmsson, 2002). Thus, the effect of changing water transparency is not included. The present study is a first attempt to introduce a more complex attenuation of light into a Baltic Sea climate model, investigate the effects and quantify the importance. To test the impact of spatial variability of light attenuation, we focus on the visible part, since water itself is highly absorbing in the near infrared spectrum. Our new parametrization of visible light (KD_v) is based on the mean seasonal cycle of measurements of the diffuse attenuation coefficient at 490 nm (KD(490)), which is measured directly by satellites and closely related to Secchi depth. The conversion to KD_v follows the results of Pierson et al. (2008) and is especially designed for the Baltic Sea. To estimate the potential of decreased Secchi depth to affect trends in SST, we perform two idealized experiments which are based on station data of Secchi depth. In the absence of basin wide measurements, the station data are combined with a spatial pattern of water turbidity which matches the present day satellite observations. Additionally, we calculate anomalous net heating rates in dependence of KD_v theoretically and compare the results with our model. The paper is organized as follows. The calculation of net heating rates, a description of the three dimensional model, the experimental design and the source of observational data for model validation are described in Section 2. Section 3 addresses the results and is subdivided into three major subsections, comprising of the net heating rates, the mean seasonal cycle and trends. A comprehensive discussion follows in Section 4.

2. Methods

2.1. Net heating rates

To quantify the uncertainties concerning the underlying parameters and the possible effects of varying attenuation coefficients, we consider as a first step the dependency of the anomalous net heating rates on the attenuation of visible light. Net heating rates estimate temperature changes of a water parcel due to radiation neglecting all other physical processes (e.g. diffusion and advection). The calculation follows the formulation given by Sweeney et al. (2005). We consider a profile of downward radiative heat flux, which is represented as

$$I(x,y,z) = I_0(x,y)J(z), \tag{1}$$

where I_0 is the downwelling shortwave radiative flux just below the sea surface (W/m^2) and J(z) is a dimensionless attenuation function exponentially decaying with depth, depending on an attenuation coefficient specifying the profile. J(z) is generally wavelength dependent. While sea water itself is highly absorbing in the near infrared spectrum, visible light penetrates much deeper and can be largely influenced by optically active substances. Thus the focus is, as in the three dimensional experiments, on the visible part of sunlight and an attenuation coefficient of 0.2 m^{-1} is used for KD_v as reference. This value is compared to different parameter settings for KD_v, ranging from 0.15 to 0.36 m^{-1}. The corresponding shortwave heating affects the local temperature T in a Boussinesq fluid according to

$$\frac{\partial T}{\partial t} = -\left(1/\rho C_p\right)\partial/\partial z\left(\rho C_p F^z - I\right). \tag{2}$$

Here, F^z accounts for vertical processes such as advection and diffusion, ρ denotes the density and is set to a mean value. C_p denotes the heat capacity of sea water. From this equation it is possible to separate the net heating rate due to shortwave radiation of a water column between the depth levels Z1 and Z2 by,

$$\left(1/\rho C_p\right)\int_{Z1}^{Z2}\frac{\partial I}{\partial_z}dz = \left(1/\rho C_p\right)(I(Z2) - I(Z1)). \tag{3}$$

2.2. The ocean model

The three-dimensional (3D) ice–ocean model used for all three dimensional sensitivity experiments is the Rossby Centre Regional Ocean model (RCO). RCO was used previously for various ocean and climate studies (e.g. Meier, 2005; Meier, 2006; Meier and Kauker, 2003b) and is described in more detail in Meier et al. (2003) and Meier and Kauker, (2003a). The ocean model is a regionalized version of the Ocean Circulation Climate Advanced Model (OCCAM) (Webb et al., 1997) implemented for the Baltic Sea. It is a Bryan–Cox–Semtner primitive equation model with a free surface coupled to a Hibler-type sea ice model. A prognostic two-equation turbulence closure scheme is embedded. The downward radiative flux in RCO is parametrized by two exponential functions describing the near infrared and visible part of the spectrum. Since the parametrizations vary between the sensitivity experiments, they are explained in more detail in Section 2.3. The model domain covers the Baltic Sea including Kattegat. RCO in this setup has a tendency to produce structured noise and thus different advection schemes were tested. Following Meier et al. (2003) in our study the third-order advection scheme (split-quick) by Webb et al. (1998) is used. This scheme results in comparatively smooth horizontal tracer distributions allowing the calculation of SST trends at a relatively low noise level. The horizontal resolution used here is 2 nautical miles and 41 levels in the vertical. Layer thicknesses ranging from 3 m close to the surface to 12 m near the bottom are used. The model depths are based on a bottom topography taken from Seifert and Kayser (1995). We use open boundaries in the northern Kattegat. In case of inflow, temperature and salinity values at the boundaries were nudged in all simulations towards observed climatological profiles in the southern Skagerrak. In case of outflow, a modified Orlanski radiation condition is utilized (Stevens, 1990). Such a simplified treatment of the open boundary in Kattegat is sufficient since the Kattegat deep water salinity of about 33.2 psu does not change significantly (Meier and Kauker, 2003b). Sea