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Mixed layer depth in the Aegean, Marmara, Black and Azov Seas: Part II: Relation to the sonic layer depth

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ABSTRACT

This paper provides the first analysis of the seasonal evolution of the sonic layer depth (SLD) relative to the mixed layer depth (MLD) for the Aegean, Marmara, Black, and Azov Seas. SLD identifies the acoustic ducting capabilities of the upper ocean and is of interest to investigations of upper ocean acoustics. A monthly SLD climatology on a regular 0.25°×0.25° grid is constructed from interpolation of available quality-controlled ocean temperature and salinity profiles using the kriging methodology. A four step pre-processing procedure is designed to reduce noise and the effects of sampling irregularities. Monthly SLD fields are then compared relative to the much more widely studied MLD as computed using four different methods from the recent scientific literature. The goals of this analysis are to characterize the SLD relative to the MLD and provide a means for computing SLD from limited hydrographic information and/or MLD estimates. Very deep SLD values are found during winter, in the Aegean and Black Seas, when the near surface temperature values become lower than the temperature below the permanent pycnocline. When this occurs, the SLD drops to the bottom while the MLD remains much shallower at the seasonal pycnocline. For the months of May through October the SLD tends to be less than 25 m for the entire region. It is demonstrated that MLD obtained from the four methodologies have high correlations with SLD over the annual cycle, indicating a robust relationship. As a result, SLD can be estimated using least squares regression coefficients when salinity is unavailable or when observation profiles do not extend to deeper levels.

1. Introduction

Conditions of the upper ocean often result in a near surface acoustic duct that limits the downward transmission of sound and results in the acoustic spreading to be approximately cylindrical (Urick, 1983). Sound trapped in a surface duct is primarily transmitted outward from the source in an expanding disk. This occurs when the near surface environment is upward refracting due to an increase of sound speed with depth. The depth over which the increasing sound speed penetrates is called the sonic layer depth (SLD) (e.g., Kerman, 1993). The acoustic frequency that can propagate in this type of duct is dependent on the SLD. For a given SLD there is a cutoff frequency above which sound will be trapped in the surface duct. Sound with a lower frequency is not trapped and will spread spherically in all directions, leading to more rapid horizontal attenuation (Etter, 2003). Sound in a duct (with cylindrical spreading) can be transmitted much farther horizontally than in non-ducting environments (with spherical spreading). This phenomenon substantially influences, for example, ocean communications (Siderius et al., 2007), acoustic tomography (Sutton et al., 1993), and naval operations (Urick, 1983).

A parameter related to SLD, the mixed layer depth (MLD), is also important because it identifies the penetration depth of turbulence near the ocean surface and has a wide array of influence on a variety of upper ocean processes from air-sea exchange (e.g., Chen et al., 1994) to biological interactions (e.g., Siegel et al., 2002). For a typical water column, where isothermal and isohaline surface layer depths are equal and temperature decreases below that depth, the MLD and SLD are equal. This is because sound speed increases with depth due only to increasing pressure until a local maximum at the MLD, below which sound speed decreases with decreasing temperature. There are other conditions, however, where the SLD may be lower or higher in the water column than the MLD. The characteristics of how SLD and MLD become different are discussed in this paper because they provide useful information regarding the structure of the upper ocean temperature and salinity fields.

In a recent analysis (Helber et al., 2008), the global deviations of the MLD relative to the SLD were investigated for the annual cycle. It was

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found that in the spring when new stratification events occur, the SLD can be substantially deeper than the MLD. In the present study, we examine differences between SLD and MLD in more detail in a region including a small part of the eastern Mediterranean Sea and the Aegean, Marmara, Black and Azov Seas. This is accomplished by interpolating the SLD and MLD values to a 0.25 × 0.25 grid using kriging (Diggle and Ribeiro, 2007). This region is chosen because there have not been any previous studies quantifying and examining SLD features.

The Black Sea is heavily influenced by river input that along with precipitation exceeds evaporation losses and is balanced by outflow across the Bosphorus (Özsoy and Ünlüata, 1998). As a result, the Black Sea is characterized by fresher surface water residing above warmer saltier deep water (a condition associated with "diffusive convection," e.g., Kantha and Clayson, 2000). Above a permanent pycnocline there exists a cold intermediate layer (CIL) that is replenished in the winter when the seasonal thermocline is deepest (Özsoy and Ünlüata, 1998). The Aegean Sea is influenced by cooler fresher surface water originating in the Black Sea that passes through the Bosphorus and the Marmara Sea and enters the Aegean through the Dardanelles Strait. This water flows across the northern Aegean shelf and southward along the western coastline (Kourafalou and Barbopoulos, 2003; Olson et al., 2007). Cold, saltier Mediterranean water enters the lower layers of the Marmara Sea through the Dardanelles Strait (Beşiktepe et al., 1994). The Sea of Azov is very shallow, with an average depth of 5 m, but stratification does exist (Debolskaya et al., 2008). In all of these regions, to some degree, the surface layers defined by MLD and SLD will be associated with cooler, fresher surface water above saltier, warmer subsurface water. As will be shown, the evaluation of the SLD relative to the MLD is impacted by this unique hydrographic structure, making this an excellent region for studying SLD and its relation to MLD.

Estimating SLD from observation profiles is achieved using a method derived by Helber et al. (2008). We use four methodologies for MLD taken from the recent literature (Kara et al., 2000b; Lorbacher et al., 2006) that are discussed by Kara et al. (2009). For two of the algorithms, temperature-only profiles are used, while the other two select the MLD from density profiles. Comparison of SLD with both temperature and density MLD estimates, all interpolated on a 0.25° grid, provide information regarding the salinity contribution to the upper ocean in addition to characterizing upper ocean acoustics and the penetration depth of surface turbulence. Use of several MLD methods enhances the results by ensuring that the observed phenomena are not an artifact of one MLD methodology.

The differences between the SLD and MLD arise because of differences in the sensitivities of density and sound speed to temperature, salinity, and pressure. For density, salinity variability is often small enough that the MLD is controlled by temperature. Salinity, however, can have a large impact producing, for example, the "barrier layer" (e.g. Kara et al., 2000a), where the salinity contribution results in a MLD that is shallower than temperature alone would dictate. Salinity has a smaller impact on sound speed relative to density because sound speed is more sensitive to temperature than salinity. A fundamental difference between sound speed and density, and therefore SLD and MLD, is that sound speed does not influence turbulence whereas density does. These differences results in a relationship between SLD and MLD that we explore in this analysis.

A major goal of this paper is to identify the conditions under which SLD and MLD differ in time and space in the Aegean, Marmara, Black and Azov Seas region. In addition, statistical relationship between SLD and MLD is exploited in order to provide a means for predicting SLD from MLD estimates. This capability is particularly useful when only temperature profiles or MLD forecasts are available.

In Section 2 we describe the sources of the observation profiles and the quality control and data editing procedures. The methods for estimating MLD, SLD and computing the interpolated fields are described in Section 3. The monthly SLD climatology is described in Section 4 and the differences between SLD and MLD are discussed in Section 5. Section 6 describes the statistical relationship of SLD and MLD and Section 7 concludes the paper. The Appendix A contains information about the data preparation steps taken for producing the interpolated SLD/MLD 0.25° gridded fields.

2. Data

The available historically observed temperature profiles (*T*-only) and paired profiles of temperature and salinity (*T* and *S*) are acquired from the following sources: (1) the World Ocean Database 2005 (WOD05) (Boyer et al., 2006), (2) the U. S. Navy's Master Oceanographic Observation Data Set (MOODS) (Teague et al., 1990), (3) Argo (Gould et al., 2004), and (4) the National Oceanographic Data Center (for the Sea of Azov, Matishov et al., 2006). The reader is referred to Table 1 for the number of profiles of *T*-only and *T* and *S* from each source. The first three sources of data are partially redundant but all are considered, because after the removal of duplicates there are unique data in each. The WOD05 has less stringent quality control (QC) procedures than MOODS but potentially more data sources. There is an approximately 6% increase in data volume with the addition of WOD05 data relative to the MOODS data set alone. Older Argo data are included in the MOODS and WOD05, and the latest Argo data from the Data Acquisition Centers (DAC) have been included with the application of the latest QC recommendations. As an example of the data coverage for observations with profile pairs of *T* and *S*, Fig. 1 shows the locations of usable profiles for all years in the month of October only. Note that for the Marmara and Azov Seas there are very few data points, and therefore the results within these seas is less robust than in the Black and Aegean Seas.

While the data are quality-controlled, there are still some existing errors that include profile location, XBT drop rate, low vertical resolution, etc. In the interest of including as much data as possible, profiles with relatively low vertical resolution or large gaps in the vertical have been retained in the data set. To help minimize these and other sources of potential errors, SLD "outliers" are removed statistically as explained in Appendix A. Errors that are not also "outliers" are statistically undetectable and therefore cannot be removed in this manner.

3. Methods

The SLD algorithm is described in detail in Helber et al. (2008) and will be explained briefly here. The first step in estimating the SLD from *T* and *S* profile pairs is the computation of sound speed at each depth level using the nine-term equation of Mackenzie (1981):

$$\begin{aligned} c = {} & 1448.96 + 4.591T - 5.304\times10^{-2}T^2 + 2.374\times10^{-4}T^3 \\ & + 1.340(S-35) + 1.630\times10^{-2}D + 1.675\times10^{-7}D^2 \\ & - 1.025\times10^{-2}T(S-35) - 7.139\times10^{-13}TD^3 \end{aligned}$$

Sound speed, c (m s^{-1}), is a function of temperature, T (°C), salinity, S (psu), and depth, D (m) and is non-linear. The first three non-constant terms depend only on *T* and are the largest in the upper ocean. Only at depth do the terms including *D* have large

Table 1
The number of total, *T*-only, and *T* and *S* profiles from each source in the analysis domain of Fig. 1 (22.00 E to 41.84 E and 34.50310 N to 47.31377 N).

Source	Total	*T*-only	*T* and *S*
All	105,164	70,516	34,648
Argo	3010	3	3007
WOD05	64,031	53,560	10,471
MOODS	37,659	16,935	20,724
NODC (Azov)	464	18	446