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Review

Subsurface and deeper ocean remote sensing from satellites: An overview and new results

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ABSTRACT

Satellite remote sensors cannot see far beneath the surface layers of the ocean. Yet many important ocean processes and features are located well below the surface and at considerable depths. Examples include Mediterranean Eddies (meddies), mixed layer depth, internal waves, and bottom topography. Deeper ocean remote sensing is becoming even more important because recent data seem to indicate that the deeper ocean is responding to climate variability and change. Many of these subsurface phenomena have surface manifestations which can be interpreted with the help of models to derive key parameters of deeper ocean processes. The objective of this paper is to provide an overview of satellite remote sensing and modeling techniques which enable scientists to characterize subsurface and deeper ocean processes and features and to present some new results.

Contents

1. Introduction

For several decades satellite sensors have been providing sea surface observations at various spatial and temporal scales. For instance, thermal infrared sensors are mapping sea surface temperatures, microwave radiometers are measuring sea surface salinity, radar imagers are mapping surface wave fields and oil slicks and radar scatterometers are measuring sea surface winds. However, many important processes and structures are located below the surface or at greater depths. Examples may include deep-ocean thermal and haline structure variations, Mediterranean eddies (meddies), internal waves and bottom topography. Because they cannot be directly observed from satellites, most of the research on ocean interior characteristics has traditionally relied on models and in situ measurements that are not able to provide suitably wide coverage in near-real time. While there are many direct and indirect applications of satellite measurements of ocean dynamics at the sea surface, there are few studies of subsurface thermal and haline structures using satellite measurements on a global scale.

Global sea surface changes have been mapped with satellite altimetry over the last two decades, and water mass changes and subsurface density fields with Gravity Recovery and Climate Experiment (GRACE) measurements and Argo floats over several years. The missing information between sea surface height changes, water mass, and density field changes is ocean interior variability. The estimation of the 3-D global thermohaline and density structures can be critically important not only to physical oceanographers, but also to biological and chemical oceanographers,

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because they can estimate subsurface flow fields, allowing them to compute horizontal and vertical advection in the ocean interior (Wilson and Coles, 2005). This is becoming especially important, because there are indications that the deeper ocean is responding to global warming, climate variability and change.

Improvements are needed in the accuracy of large-scale subsurface thermal structure in near-real time assimilation models. As an alternative to obtaining subsurface information from assimilation models, satellite measurements can be used if special algorithms/techniques are developed. Recently, new algorithms are being developed to estimate ocean interior thermal and thermohaline structures and subsurface flow fields using satellite and in situ measurements and to improve the spatial resolution of these physical properties. The algorithm development is based on the hypothesis that thermocline depth changes can quantify the variability of air–sea interactions in the upper layer and mass changes in the lower layer (Jo and Yan, 2013). The objective of this paper is to provide an overview of satellite remote sensing and modeling techniques which enable oceanographers to characterize subsurface and deeper ocean processes.

2. Ocean thermal structure

Determination of the 3-D global thermohaline and density structures can be critically important, because they enable oceanographers to estimate subsurface flow fields and thus to compute horizontal and vertical advection in the ocean interior. Deeper ocean monitoring has become particularly important because recent data show significant warming of the deep ocean (Song and Colberg, 2011). As shown in Fig. 1, in a recent observation-based reanalysis of the time evolution of the global ocean heat content for 1958–2009, Balmaseda et al. (2013) determined that in the last decade about 30% of the ocean warming has occurred below 700 m. Note in Fig. 1 the rapidly accelerating deep ocean heat content, which contributes significantly to the acceleration of the global ocean warming trend. The vertical bars in Fig. 1 indicate a 2 year interval following volcanic eruptions with a 6 month lead (owing to the 12 month running mean), and the 1997–1998 El Nino event again with 6 months on either side. On lower right, the linear slope for a set of global heating rates (W/sq m) is given. The authors showed via sensitivity experiments that surface wind variability is largely responsible for the changing ocean heat vertical distribution. These results may help explain the uncertainties in the ocean's role in the Earth's energy budget and transient climate sensitivity exposed by the elusive nature of the post-2004 upper ocean warming (Balmaseda et al., 2013).

Subsurface thermal information can be obtained from in situ measurements using Expendable Bathythermograph (XBT), Conductivity–Temperature–Depth (CTD), Argo float data, etc., and through numerical modeling that assimilates these data. Unfortunately, the in situ measurements are not able to provide suitably wide coverage in near-real time (Fiedler, 1988). Thus improvements in the accuracy of large-scale subsurface thermal structure in near-real time assimilation models are needed. As an alternative to obtaining subsurface information from assimilation models, satellite measurements can be used, if special algorithms/techniques are developed.

Khedouri et al. (1983) attempted to estimate subsurface temperature from satellite altimetry. They found that there are high correlations between subsurface temperature measured by XBT and sea level height variability measured from the Geostationary Operational Environmental Satellite (GOES)-3 in the Gulf Stream region. Thus, they showed that the relationship between subsurface temperature and sea level height in the Gulf Stream region can be used to infer subsurface thermal structure.

Sea surface temperature (SST) measurements have also been used to estimate subsurface temperature. Chu et al. (2000) showed that a parametric model could determine the subsurface thermal structure from satellite SST observations. The parametric model transforms a vertical profile of subsurface temperature into SST, Mixed Layer Depth (MLD), thermocline bottom depth, thermocline temperature gradient, and deep layer stratification. The study used the U.S. Navy's Master Oceanographic Observation Data Set (MOODS) in the South China Sea during May 1932–1994. Their RMS error was 0.72 °C, and the correlation between the inverted and observed profiles was 0.79.

Using both sea surface height anomaly (SSHA) and SST anomaly (SSTA), Fischer (2000) estimated the vertical thermal structure at the equator. The study showed that a multivariate projection of sea surface measurements could be used to determine subsurface thermal structure. He used the SSTA and SSHA data to compute regression matrices that were obtained from a forced integration of the Modular Ocean Model (MOM). Fischer (2000) found that there were two different vertical temperature modes during the ENSO cycle using both SSH and SST measurements. He also showed that the multivariate projection method provided significantly better results when compared to a univariate method.

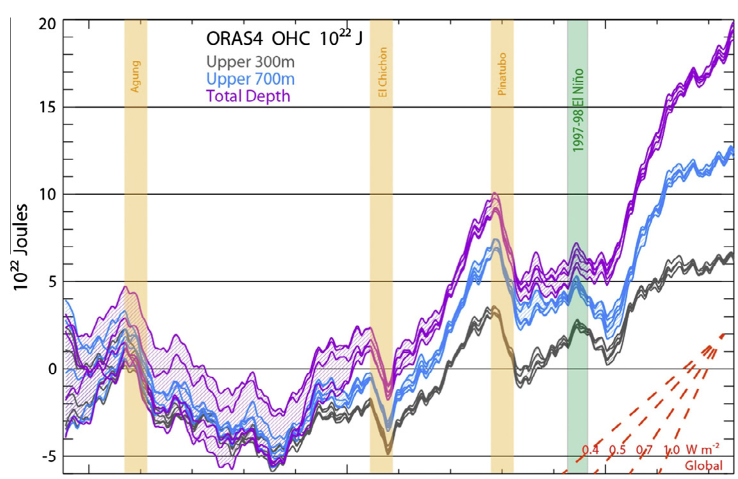

Fig. 1. Ocean heat content integrated from 0 to 300 m (gray), 700 m (blue), and total depth (violet) from ORAS4, as represented by its 5 ensemble members. The time series show monthly anomaly smoothed with a 12-month running mean, with respect to the 1958–1965 base period. Hatching extends over the range of the ensemble members and hence the spread gives a measure of the uncertainty as represented by ORAS4 (Balmaseda et al., 2013). With permission from John Wiley & Sons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)