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Review

Using motionally-induced electric signals to indirectly measure ocean velocity: Instrumental and theoretical developments

Zoltan B. Szuts *,[1]

Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany

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ABSTRACT

The motion of conductive sea water through the earth's magnetic field generates electromagnetic (EM) fields through a process called motional induction. Direct measurements of oceanic electric fields can be easily converted to water velocities by application of a first order theory. This technique has been shown to obtain high quality velocities through instrumental advances and an accumulation of experience during the past decades. EM instruments have unique operational considerations and observe, for instance, vertically-averaged horizontal velocity (from stationary sensors) or vertical profiles of horizontal velocity (from expendable probes or autonomous profiling floats). The first order theory describes the dominant electromagnetic response, in which vertically-averaged and vertically-varying horizontal velocities are proportional to electric fields and electric currents, respectively. After discussions of the first order theory and deployment practices, operational capabilities are shown through recently published projects that describe stream-coordinate velocity structure of the Antarctic Circumpolar Current, quickly-evolving overflow events in the Denmark Strait, and time-development of momentum input into the ocean from a hurricane.

A detailed analysis of the Gulf Stream at its separation point from the continental slope serves as a case study for interpreting EM measurements, including the incorporation of geophysical knowledge of the sediment. In addition, the first order approximation is tested by the many features at this location that contradict the approximation's underlying assumptions: sharp horizontal velocity gradients, steep topography, and thick and inhomogeneous sediments. Numerical modeling of this location shows that the first order assumption is accurate to a few percent (a few cm s^{-1}) in almost all cases. The errors in depth-varying velocity are <3% (1–3 cm s^{-1}), are substantiated by the direct observations, and can be corrected by iterative methods. Though errors in the depth-uniform velocity are <2 cm s^{-1} (<10%) at all locations except for the upper continental slope, where apparent but unresolved meander events in water shallower than 500 m can generate depth-uniform errors of order 30%, there are not sufficient observations to confirm these errors directly. Errors in the first order approximation at this location show no non-linear increase due to the joint effect of steep topography and horizontal velocity gradients. Using motional induction in the world's oceans, aside from stationary measurements when depth-uniform ocean currents meander across topography, these results suggest that the first order approximation is accurate to within 1–2 cm s^{-1} or less in almost all regions of the ocean, an error similar to the instrumental accuracy of EM instruments.

Contents

* Tel.: +49 40 411 73 152; fax: +49 40 411 73 366.
E-mail address: zoltan.szuts@zmaw.de

[1] Most of this work was undertaken at the Applied Physics Lab, University of Washington, 1013 NE 40th St, Seattle, WA 98105, United States.

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1. Introduction

Seawater moving through the earth's magnetic field generates electric signals in the ocean through a process called motional induction. Measuring the electric response is a convenient way to indirectly measure ocean velocity. This technique has developed significantly over the past decades and is currently capable of obtaining high quality velocity measurements with unique operational benefits. Technological advances and accumulated experience behind the success of this technique have not been summarized in a readily accessible format, however, and so reviewing current practices is the first goal of this article.

Despite these observational advances, however, the theory of motional induction has not been critically examined when first order assumptions of broad ocean currents and a horizontal seafloor are invalid. To confidently interpret measurements taken in more complex locations, such as near ocean margins where energetic ocean currents flow over steep bathymetry, it is necessary to quantify higher order processes involved in motional induction. A detailed study of the higher order terms in motional induction is the second goal of this article.

The assumption of ocean currents with large width-scales flowing over nearly horizontal bathymetry leads to a dominant and one-dimensional (1D) relationship in the vertical between velocity and electrical signals, which will be called interchangeably a first order or 1D approximation. Physically, the first order approximation is based on water depth being much shorter than horizontal scales, which restricts electric fields and electric currents to flow in a vertical plane. Verification of the 1D approximation against independent velocity measurements (Spain and Sanford, 1987; Luther et al., 1991; Polzin et al., 2002) has proven it to hold within measurement accuracy, though often the reference velocities have lower vertical resolution than the electromagnetic instruments. Instrumental and observational techniques developed through such studies are mature but poorly distributed in oceanography.

Many regions of the ocean with important physical processes strongly violate the 1D assumptions, however, either because of steep bathymetry or fine-scale velocity features. A perturbation analysis treatment of motional induction by Sanford (1971) found that sloping topography and horizontal velocity gradients are only important to second order, though formally this result assumes *a priori* that gradients are weak. On one hand, electric field observations in regions that break the 1D assumptions (Spain and Sanford, 1987; Althaus et al., 2003) have not indicated any observable differences with independent velocity measurements. On the other, recent theoretical work quantified the inaccuracy of the 1D approximation for either extremely narrow velocity features (Szuts, 2010a, hereafter SzI) or extremely steep topography (Szuts, 2010b, hereafter SzII) and found small but measurable errors. In the real ocean, steep topography strongly influences the velocity field, and thus errors in such regions are not expected to simply be a linear combination of the results from SzI and SzII.

In a region where the 1D assumptions are invalidated by steep bottom topography, sharp horizontal velocity gradients, and other factors, I quantify the accuracy of the first order approximation. The study is motivated by observations collected across the Gulf Stream at its separation point from the continental margin. An electromagnetic numerical model (Tyler et al., 2004) is used to resolve the complexities present at Cape Hatteras. With both bottom topography and horizontal velocity gradients present at the same location, their joint perturbation to the 1D approximation is quantified and compared to the observations.

This article starts with a review of motional induction and its application for calculating water velocity. The topic is introduced with a brief historical overview of this technique in physical oceanography and in related fields of geophysics (Section 2). Then the theory and physical basis are presented, both for the 1D approximation and for higher order perturbations (Section 3). Application of the theory to field measurements leads into three examples of observational capabilities from recent field programs (Section 4).

Building on the earlier sections, the accuracy of the 1D approximation is analyzed and quantified at Cape Hatteras (Section 5). Initial interpretations of the observations (Section 5.2) find that the 1D approximation is not entirely sufficient at this location.