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Estimating advective near-surface currents from ocean color satellite images

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ABSTRACT

Improved maximum cross correlation (MCC) techniques are used to retrieve ocean surface currents from the sequential ocean color imagery provided by multiple newer generations of satellite sensors on hourly scales in the Yellow Sea and the U.S. East and Gulf coasts. The MCC calculation is validated in a series of Bio-Optical Forecasting (BioCast) experiments with predetermined synthetic velocities, and its products are evaluated by examining the errors and biases with respect to the High Frequency Radar (HFRadar) measurements. The root-mean-square (RMS) errors in our best current products derived from the overlap of satellite sensor swath between the VIIRS sequential orbits are less than 0.17 m s^{-1} in the evaluation area outside of the Chesapeake Bay. The most accurate current products are those derived from the imagery data of $R_{rs}(551)$, $B_b(551)$ and C(551), while the image sequences of $B_b(551)$ and Z_{eu}_lee are identified as the most suited products for the retrieval of currents because of their best production capacities of valid velocity vectors. Mechanisms between the advective processes and the dynamic changes of bio-optical properties are discussed regarding the performances of various color products on the retrieval of currents. Similarities of velocity distribution in the retrieved vector arrays are collected across different MCC products derived from ocean color datasets that are of different types and derived from different spectral channels of satellite overpasses. The inter-product similarities themselves can be used to characterize the near-surface advection as well and usually have smaller errors than each of the individual MCC currents. Moreover, efforts are also under way to improve the ocean color derived currents by merging several of the MCC products with similarities to increase the total spatial coverage. This study not only seeks the image-derived products best representing the sea surface current structures in coastal areas, but also exploits how these currents can be improved or optimized to support the ocean forecasts.

1. Introduction

The retrieval of surface currents from time sequential satellite imagery has been demonstrated using the maximum cross correlation (hereafter MCC) method by many researches (Emery, Fowler, & Clayson, 1992; Emery, Thomas, Collins, Crawford, & Mackas, 1986; Matthews & Emery, 2009; Wahl & Simpson, 1989, 1990, 1991; Wu, Pairman, McNeill, & Barnes, 1992; Zavialov, Grigorieva, MoLler, Kostianoy, & Gregoire, 2002, etc.). Most of these studies were focused on estimating currents from thermal imagery by the implementation of MCC method and its variants. Although the basic rules are similar, the detailed implementation of this method varied from case to case in the documented studies. For example, Emery et al. (1992) applied statistical significance and next-neighbor filter techniques to remove fictitious current vectors due to the presence of residual clouds; Wahl and Simpson (1991) indirectly estimated the tangential component of the total flow based on vector subtracting of the total flow and the normal component of flow; Zavialov et al. (2002) developed a modified version of the MCC method by allowing small displacements along isolines to be detected between the paired images.

Besides the cross-correlation based methods, several other approaches have been proposed in the literature for extracting the near-surface currents as well. The optical flow algorithm (Horn & Schunck, 1981) is a variational approach with a framework where the optical flow is computed as the solution of a minimization problem. Cote and Tatnall (1994) proposed a different pattern matching method named as Hopfield neutral network to estimate feature movement, which allows the deformation of pattern title and is faster than the conventional cross-correlation based methods. To overcome some weaknesses of the MCC method (e.g. Kamachi, 1989 pointed out the deficiency of not reconstructing rotational and deformational motion patterns), Bannehr, Rohn, and Warnecke (1996) presented a non-statistical functional analytic method to derive displacement vector field under the consideration of neighborhood information.

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In some previous studies (e.g. Chen, Mied, & Shen, 2008; Emery et al., 1992; Vigan, Provost, Bleck, & Courtier, 2000a, 2000b), the derived currents were compared to the ocean model velocity field to examine errors and uncertainties. However, it must be noted that in many situations the velocity outputs from ocean circulation models can be misrepresented because most of the present-day operational ocean models do not assimilate velocity observation and there are often large inter-model differences in the velocity products of different ocean models. Although the large regional scale ocean current observations are a limitation for validation of models especially in remote regions, the development of the HFRadar network as a part of the U.S. coastal observing system has somehow improved this situation. The HFRadar measurement of sea surface currents is being used increasingly in the U.S. coastal waters and regularly provides hourly velocity observation in several spatial resolutions. In the study of the U.S. coastal waters, we no longer evaluate the derived currents with respect to the ocean model currents but instead compare them to the velocities derived by the HFRadar network. In our BioCast experiment, the image-derived currents are directly compared to the pre-established synthetic velocities to validate the retrieval procedure.

The time span between the sequential satellite images should impact the frontal movements associated with ocean processes such as tides, winds and eddies. In coastal areas, river plume fronts are rapidly changing movements and require approximately ~1 hour separation between images. Comparatively, gulf stream and large eddies can have longer time periods, such as days, to response the surface currents.

Sea surface temperature (SST) is a physical parameter that has a direct link to the advection processes and frontal movements and has long been used to track and estimate the surface currents. However, there are issues such as the diurnal heating of surface water, that have influence on the location of frontal movement and thereby the ability to derive currents. The SST products are also limited to time of the year when there are significant gradients for frontal detection. In summer months, not only are there large temperature variations during a full heating and cooling cycle, but also the strong radiance could significantly change the stratification near the sea surface and smooth out many small-scale information which are essentially preferred in executing a typical MCC calculation. In the Gulf of Mexico during the summer months, for example, the SST is sometimes isothermal and can neither resolve frontal location nor be used for defining the surface currents.

The tracking of ocean color fronts such as the chlorophyll fronts from sequential satellite images can also be used to track water mass advection (Crocker, Matthews, Emery, & Baldwin, 2007; Garcia & Robinson, 1989; Svejkovsky, 1988). However, bio-optical products are also influenced by non-advective processes such as growth and decay of phytoplankton blooms which can impact the gradients and frontal locations and thereby the ability to estimate surface movements. These bio-optical processes are dependent on the timing between the sequential images and are assumed to be negligible with the hours (Dickey et al., 1991), therefore the velocity products retrieved from hourly sequential images can be used to represent the advective processes. Besides chlorophyll, there are many ocean color products available which respond to different bio-optical and advective processes, some of which may be more optimally suited for retrieving currents. An inter-product comparison can help identify both the similarities and differences of velocity distribution among various ocean color derived velocity products. On the grounds that these separately derived MCC products are used to represent the same surface advection, it is the inter-product similarities, instead of the differences, that are more likely to link with the surface flow. Because of this, we may not only use the similarities themselves to estimate advective processes besides the individual MCC products, but also merge the multiple MCC products by keeping both their similarities and differences to increase the total spatial coverage of velocity field. One primary reason for carrying out this study is that we can take advantage of the abundance of available ocean color satellite products to support the timely forecasts and the coastal operations in need of surface current information.

The present study uses the sequential ocean color products provided by the Geostationary Ocean Color Imager (GOCI) and Visible Infrared Imaging Radiometer (VIIRS). The visible and infrared spectra measured from these satellite instruments can provide information about dissolved and suspended constituents in water that have optical properties. Many of their remotely sensed products can help define the surface circulation features and one effective way is to use these products to retrieve the advective currents by image processing algorithms such as the MCC method. The objectives of this paper include the following: 1) applying MCC to various ocean color products and evaluating the derived currents to define the optimum products which are best related to surface advection; 2) testing the MCC algorithms for ocean color products using synthetic datasets that are initialized with chlorophyll data and based on a forecast circulation model; 3) demonstrating the retrieval of currents from the VIIRS overlaps; 4) determining the uncertainty and RMS error of the derived currents by comparing with the observed currents from HFRadar network; 5) illustrating that similarities of velocity distribution can be collected through different MCC currents derived from different ocean color products and how these MCC currents with similarities may be merged to increase the total spatial coverage.

In Section 2, the satellite imagery data and the velocity estimating methods are briefly introduced. Case studies of the BioCast experiment follow in Section 3 to validate the MCC retrieval procedure. Section 4 gives an example to illustrate that the high similarities of velocity distribution can be collected between the currents derived from different ocean color products. The evaluation of MCC products in the U.S. East and Gulf coasts with respect to the HFRadar measurements is presented in Section 5. Section 6 describes some techniques of merging multiple derived currents to improve the vector coverage of flow field. The concluding remarks are given in Section 7.

2. Data and approaches

2.1. GOCI and VIIRS satellite imagery

The ocean color imagery used in this study is obtained from the remotely sensed data of the GOCI and VIIRS, which are capable of providing multiple looks per day for each of a number of different types of bio-optical properties. GOCI is a sensor on a Korean telecommunications satellite (i.e. the Communication, Ocean and Meteorological Satellite-1, COMS-1); VIIRS is a sensor on the Suomi National Polar-Orbiting Partnership (S-NPP) satellite. The GOCI is the world's first geostationary orbit satellite sensor over the Yellow Sea for detecting, monitoring and predicting short-term biophysical phenomena. The target area is 2500 km × 2500 km and centered at 130°E, 36°N; a map of its coverage can be found at http://kosc.kordi.re.kr/oceansatellite/coms-goci/specification.kosc. Hourly data for 9 am–3 pm daily are acquired in multispectral bands from 412 to 865 nm and with a spatial resolution of about 500 m. The GOCI can capture the hourly images eight times per day, which is very useful to learning the evolution of the dynamic changes in water masses and bio-optical properties, particularly in coastal waters where the river discharge, tides, winds, and the shape of land and seafloor all play a role in shaping the surface flow.

The VIIRS is a polar orbiting satellite sensor with a 22-band radiometer for collecting imagery and radiometric measurements of the ocean in the visible and infrared bands of electromagnetic spectrum. The VIIRS orbit provides an overlap of the sensor swath so that multiple looks per day and bio-optical products can be collected over the same ocean (Arnone et al., 2013). The overlap between VIIRS sequential orbits is about 100 min and based on the orbital progression. The overlap of VIIRS at the U.S. East coasts does not occur every day. There is enough overlap in this area approximately every 2 days. In Northern hemisphere the spatial resolution increases with latitude and is approximately 750 m at nadir in the U.S. East and Gulf coasts but 1.6 km at