

Ocean Surface Current Monitoring from Space: Methodology and Progress

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ABSTRACT

Monitoring the ocean surface currents is a primary application of the highly successful satellite altimetry missions that started 15 years ago. This symposium coincides with the implementation of a significant achievement of the NOAA Ocean Surface Current Analyses Real-time project (OSCAR, <http://www.oscar.noaa.gov>), namely the extension of satellite-derived surface current processing, and its associated datacenter, to the global ocean. We present a synthesis of the efforts resulting in the estimation of surface currents from satellite within the framework of OSCAR. We summarize the methodology associated with OSCAR, particularly emphasizing the respective contributions of satellite altimeter and scatterometer data to the diagnostic calculations of surface currents. Additionally, we show how the methodology is extended from the tropics, where it was initially developed, to the mid and high latitudes. Finally, we underline the near real-time characteristic of the space-based monitoring of the ocean currents and their validation. This would not be possible without the continuous and on-going satellite coverage of the ocean surface height and winds. Concomitant with the present and future altimetry missions, the OSCAR web site and data server will continue to be updated and will provide an account of any extreme surface current change occurring in the global ocean.

1. INTRODUCTION

Ocean surface currents play an important role in climate regulation and changes, as well as in human activities. Large efforts are devoted to monitor surface currents on medium-to-large scales, and, since a few years, globally. Ocean Surface Current Analyses Real-time (OSCAR) is a project and quasi-operational product for the estimation of ocean surface currents from space. Its coverage is now becoming global. Most of the applications of the OSCAR data are oceanography and

climate studies. They will be also used at an operational level to assess the surface circulation and its variations, as a support to search and rescue missions of the US Coast Guards.

In a similar context, the Global Ocean Data Assimilation Experiment (GODAE) is another program which scope, including ocean surface velocity, goes beyond the surface currents. Its various actors are driven by the requirement of providing comprehensive ocean maps and data, in nowcast and forecast modes, for the benefit of social and economical activities.

Altimetry satellite data constitute the most important measurements that are used in diagnostic calculations such as OSCAR, and that are assimilated in the GODAE general circulation models (GCMs). Although various other datasets are part of the assimilation process in GCMs, currents are rarely assimilated. Hence ocean surface currents constitute one of the crucial dynamic fields in GCMs that can still be evaluated with independent observation (e.g. drifting and moored buoy data). As the GCM-based predictive systems constitute comprehensive and state-of-the-art operational oceanography applications, it is important to evaluate their surface currents in any of the reanalysis, nowcast and forecast modes. Diagnostic calculated data such as OSCAR, joined to independent *in situ* reference observations, can be a useful tool for evaluating the strengths and weaknesses of GCM-based nowcast and forecast systems.

2. A RETROSPECTIVE OF SATELLITE-DERIVED CURRENTS

2.1. Geostrophic velocity

From GEOSAT and TOPEX/Poseidon to the present altimetry satellite constellation including Jason-1, geostrophic velocity maps were constructed. In theory,

the geostrophic approximation is derived from low Rossby number dynamics. However, its application was extended to descriptions of circulation features that are not necessarily in geostrophic equilibrium. For example geostrophic calculations were used to monitor long waves or, at least, their signature.

In principle, the geostrophic approximation becomes singular near and at the equator, as the Coriolis parameter f goes to zero. However, since the beginning of satellite altimetry, zonal geostrophic currents on the equator were successfully estimated from sea surface height (SSH). This was done primarily in the Pacific in the context of El Nino/La Nina (ENSO) studies [1]. The technique to overcome the equatorial $1/f$ singularity was based on applying the meridional derivative operator to the geostrophic balance, yielding the following non-singular zonal velocity formulation:

$$uG_{eq} = -\frac{g}{\beta} \frac{\partial^2 SSH}{\partial y^2} \text{ for } y = 0 \quad (1)$$

Then, the meridional structure of velocity across the equator was built by applying a fitting function linking uG_{eq} to the classical geostrophic velocity far enough from the equator:

$$uG = -\frac{g}{\beta y} \frac{\partial SSH}{\partial y} \text{ for } |y| > \delta \quad (2)$$

Zonal velocity calculated with this method compares well in general with *in situ* data in the western and central equatorial Pacific. Hence, fruitful results on the ENSO dynamics were found, notably on the mechanism of the zonal displacements of the warm-pool [2]. However, there are several issues related to this technique that limit its extension: the correlations with mooring data in the eastern Pacific are usually much less significant; the fine meridional structure of the currents around the equator is filtered out by applying the fitting function; although meridional geostrophic velocity can also be calculated similarly to (1) and (2), e.g.

$$vG_{eq} = \frac{g}{\beta} \frac{\partial^2 SSH}{\partial x \partial y} \text{ for } y = 0, \quad (3)$$

the geostrophic approximation alone does not provide any good estimate of the meridional current near the equator.

2.2. Ekman velocity

The Ekman approximation also derives from low Rossby number dynamics, and is necessary to explain the part of the ageostrophic currents that is related to the effect of local wind friction on the ocean surface. This is a particularly crucial component near the equator. In parallel with the altimetry missions, sea winds from several satellite scatterometer missions were collected

(from ERS, SSMI to QuikScat), and provided gridded datasets for estimating the Ekman contribution. Like the geostrophic approximation, the classical Ekman formulation becomes singular in the near-equatorial region. It was nevertheless possible to calibrate an empirical non-singular ‘‘Ekman’’ velocity relative to the 30m-depth surface layer, using the 15m-drogued drifter deployment data (drifter drogues usually extends from 10 to 20m) [3]. As the resulting wind-driven component was combined with the geostrophic velocity calculated in 2.1, a surface velocity vector field was obtained, that continuously extended across the equator. This was particularly helpful for the description of large-scale surface current variations during El Nino/La Nina 1997-98 [4]. However, low correlations with *in situ* observations in the eastern equatorial Pacific prevailed.

2.3. The OSCAR diagnostic model

Although the OSCAR system for estimating satellite-derived currents is now applied globally, its primary research and application were focused on the equatorial Pacific area [5]. In earlier analyses, issues were identified, which mainly concerned the accuracy of the velocity meridional structure across the equator. This is a particularly important matter, as equatorial surface currents control SST variations to a large extent. Another motivation for further analyses was the extension of velocity calculations to levels closer to the surface ($h < 10m$) for operational applications.

A major cause for inaccuracy near the equator is that the decomposition of total velocity into separate geostrophic and wind-driven components is not mathematically valid there. Indeed, as soon as the meridional slope of SSH is non-zero at $y=0$, the meridional structure of geostrophic velocity is rigorously singular across the equator. While the fitting function mentioned in 2.1 filters out the singularity, it also dampens the fine current structure. This problem is particularly intensified in the eastern Pacific, where, for example, the methods in 2.1 and 2.2 do not allow to replicate the two-branch system, and yield much too weak spring reversals of the currents. Yet, this type of analyses have still much potential. As opposed to prognostic calculations involving a complete numerical model, diagnostic analyses are carried out practically within the framework of quasi-steady and linear assumptions. In this framework, the maps of the diagnostic datasets for a particular period are sufficient to produce the velocity calculations of that period. In particular, this does not require large computer facilities, and remains a fully empirical approach with a small number of parameters to calibrate. Hence the following question: is it possible to derive more accurate near-surface currents by still using this kind of diagnostic model?

The OSCAR model is derived from a complete set of simplified momentum equations, that inherently includes geostrophic, Ekman/Stommel and thermal wind approximations [5]. The reference to Stommel comes from his study of the wind-induced vertical shear of the horizontal current at the equator, which is naturally part of the OSCAR velocity solution [6]. In this framework, a balance must be reached on the equator, between the pressure-gradient forces and the turbulent drag force produced by the wind. This is a necessary condition for calculating a non-singular velocity structure across the equator, and this condition involves the sum of all the momentum terms \mathbf{F} . Thus, individual terms (SSH gradient force for geostrophy, surface buoyancy gradient force for thermal wind, drag force for wind-driven component) cannot be considered separately. This momentum balance is analyzed empirically for the mean flow in the equatorial basins, and optimally adjusted by fixing the value of a depth-scale parameter H . If this equilibrium were perfectly satisfied at all longitude and time, then we would have $\mathbf{F}(y) = y\partial\mathbf{F}/\partial y$, near and at $y = 0$. The velocity would simply be obtained from

$$\mathbf{U} = \frac{\mathbf{F}}{\mathbf{i}\beta y}, \quad (4)$$

seeing that $\mathbf{U}_{eq} = \frac{1}{\mathbf{i}\beta} \frac{\partial\mathbf{F}}{\partial y}(0)$ is the natural extension of (4) to $y = 0$. The momentum equilibrium is optimized on the equator, but cannot be expected to hold at all time. Therefore, function fitting is still used in order to filter out any transient singularity. However, in this case it is applied to the whole sum \mathbf{F} . Moreover, the fitting functions constitute a special set of orthogonal polynomials that naturally derive from the weak formulation of the simplified momentum equations between 8N and 8S. The first 12 polynomials are retained to closely reproduce the fine meridional structure of the currents across the equator.

The locally wind-driven component UWh depends on an eddy viscosity A , characteristic of the momentum vertical mixing, and that itself is parameterized as a linear function of the wind speed squared:

$$A = a(|\mathbf{W}|/W_0)^2 \quad (5)$$

The proportionality constant a was empirically evaluated in the central equatorial Pacific by [7]. Away from the equator, the Stommel model UWh is a generalization of the classical Ekman model, and depends on both parameters a and H , instead of only a for the Ekman model. A particularly interesting property of UWh is that although it is singular on the equator, its combination with the geostrophic velocity near the equator is mathematically appropriate,

contrarily to the classical Ekman model [5]. In theory, the thermal-wind component is a function of the vertical profile of the horizontal density gradient at all locations. Rigorously evaluating this term would require to not only know the vertical profile of the temperature gradient, but also that of the salinity gradient. At this time, this information is available neither with the appropriate resolution nor in near-real time, and a pragmatic approach is adopted. This term is assumed to be function of the horizontal sea surface temperature (SST) gradient only.

In summary, the OSCAR diagnostic model is, at the same time, a generalization and the combination of all classical approximations that derive from low-Rossby number assumptions.

2.4. Data and applications

All the datasets utilized to calculate the OSCAR velocity field are primarily based on satellite observations, and to some extent on *in situ* data. The SSH anomaly data product merges the observations from multiple satellite missions including TOPEX/Poseidon, ERS1-2, Jason-1, GFO and Envisat (from AVISO, Collect Localisation Satellites – CLS); the surface wind data are from the SSMI and QuikScat scatterometers (QuikScat gridding analysis is processed by FSU-COAPS); the sea surface temperature data are from the NOAA optimum interpolation v.2 analysis.

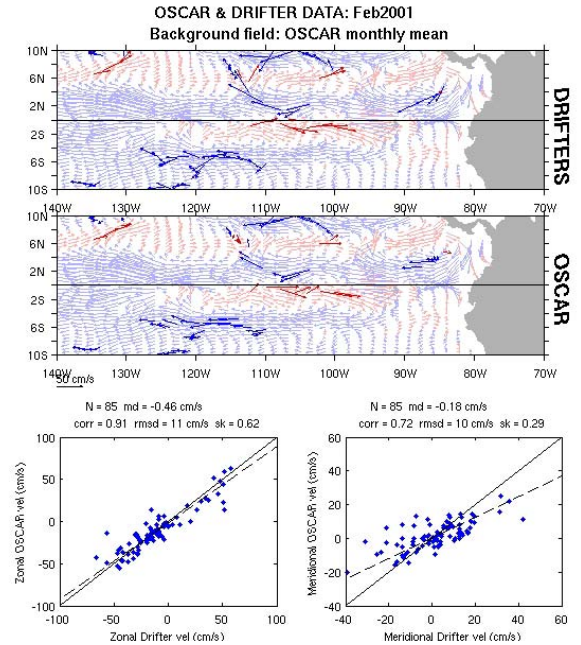


Figure 1: Drifter data and OSCAR calculations (bright arrows in the top 2 panels, red for eastward, blue for westward), during Feb. 2001. OSCAR monthly mean is drawn in the background (faded arrows). Scatterplots for the zonal and meridional components (bottom panels), and comparison coefficients.

Additional datasets are required to complete the total velocity field: the mean dynamic topography from [8], notably incorporating results from the Gravity Recovery and Climate Experiment (GRACE) mission, is used to analyze the equatorial momentum equilibrium and to complete the absolute geostrophic field.

The drifting buoy global deployment data are used to calibrate the OSCAR diagnostic model (see) within a certain time period, and to validate the OSCAR calculations during an independent time period.

As mentioned in 2.3, the OSCAR diagnostic model is capable of reproducing the fine meridional structure and variations of the near-equatorial currents. As an example, Figure 1 illustrates the comparison between the OSCAR and drifting buoy data in the eastern equatorial Pacific, at the early stage of the spring reversal of 2001 (this particular month two drifters were close to the equator during the reversal). Figure 2 shows the comparisons between the OSCAR currents and the Tropical Atmosphere Ocean (TAO) series at the 0N, 110W mooring, and at several depth levels. All series were smoothed using a 1-month running mean, and correlations between OSCAR and TAO are indicated in brackets. The sampling of the TAO series varies much with depth, and influences the correlation significant level (0.3-0.4). However, this figure shows fairly good correlation, better than what was obtained in the past. It also indicates the dynamics complexity at a single point of the ocean, and the challenge this represents to infer this dynamics from remote-sensing data, which overall spatiotemporal resolution is no higher than ~300km and ~10 days. For the meridional component, the overall agreement between OSCAR and TAO is less significant, probably because of the higher frequency variability of the meridional flow along the equator. On the other hand, relatively good agreement is found with the drifter data when considering a large domain (e.g. Figure 1), or with the TAO currents in regions even slightly beyond the equator.

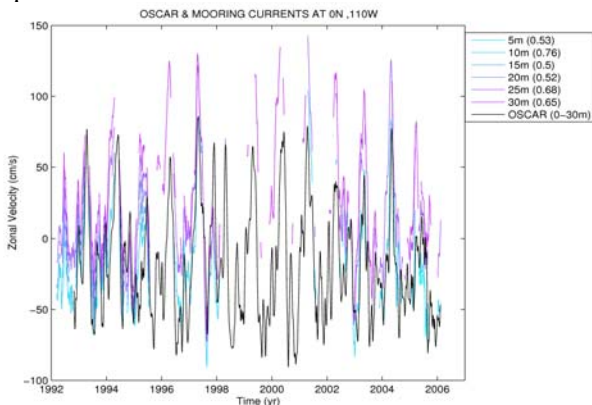


Figure 2: TAO mooring series and OSCAR currents at 0N, 110W for zonal velocity.

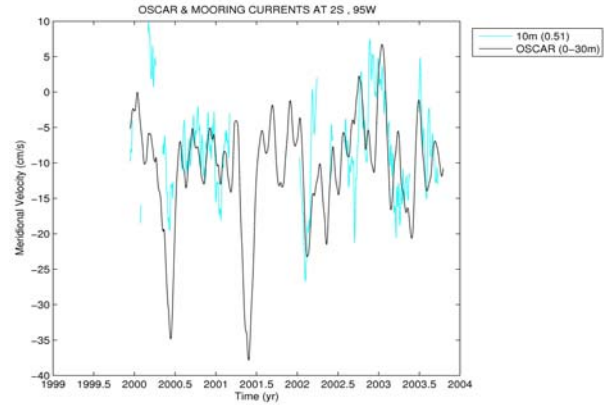


Figure 3: Same as Figure 2, at 2S, 95W for meridional velocity.

3. THE GLOBAL EXTENSION OF OSCAR

In this section we present the main developments of the extension of OSCAR toward the poles. We are not discussing the results here since they are preliminary. Instead, this section should be considered as a description of the methodology of the OSCAR geographical expansion.

Regarding the extension of OSCAR to the other basins, the calculation in the equatorial Atlantic is much similar to that in the equatorial Pacific. In the Indian Ocean, the equatorial momentum balance introduced in 2.3 is complicated by the fact that the surface winds are highly variable (monsoon regime) and very weak on average, and that the east-west slope of the SSH on the equator is small. Although this configuration does not prevent satellite-derived velocity to be estimated with much significant skill in the Indian equatorial region, ongoing research is currently being carried out on this particular subject.

3.1. Geostrophic skill with latitude

The length scale (or span) that is used to compute the SSH gradient is analyzed in function of latitude, using the drifting buoy data as the reference data. In most latitudes, the smallest possible span (75km) allowed by the SSH dataset resolution yields the best agreement with the drifter data. However, within several specific latitude regions including the near-equatorial area ($2.5^\circ < |y| < 7.5^\circ$), larger span produces better skill.

Note: the skill coefficient is defined as $sk = 1 - \text{rms}(|U_{oscar} - U_{drifter}|) / \text{rms}(|U_{drifter}|)$, where rms is the root mean squared. Notably, the meridional geostrophic component is particularly sensitive to span variations. Substantial increase of skill (+0.3) at some locations will result from the appropriate implementation of a latitude-varying span function in the velocity processing.

3.2. Calibration of the locally wind-driven component

As explained in 2.3, the OSCAR diagnostic model depends on two parameters, the coefficient a (also called, as A , the eddy coefficient) and the depth scale H . Beyond the equator, a and H can be considered as free parameters of the diagnostic model. We assume that these parameters are independent of time. Thus, they are adjusted using all the source datasets to calculate the OSCAR velocity (2.2.4), and using the drifting buoy data as the reference observations. The QuikScat gridded field starts in mid-1999, and the adjustment is done from this time on until December 2004.

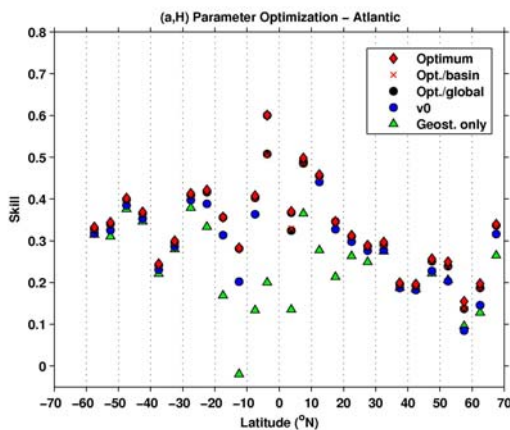


Figure 4: maximized skill in function of latitude, relative to the parameter (a , H) optimization (see text).

The optimum analysis of a and H is carried out in different cases in order to test the sensitivity of these parameters: global, in each basin (Pacific, Atlantic, Indian), and within 5-degree-latitude bands from 2.5° to 65° . Results relative to the optimization procedures are shown in Figure 4 for the Atlantic Ocean. There is a large similarity between the results in the Atlantic and those in the other oceans. Green triangles indicate the skill (as defined in 3.1) when only the geostrophic component is considered. In general, the skill level relative to the geostrophic component is not very high (maximum around 0.4). The red diamonds indicate the skill when the optimized wind-driven component is added to the geostrophic velocity, and when the optimization is done within each latitude band. The improvement of the calculated velocity is particularly large between 20°N and 20°S , where the skill increases by at least 0.15 up to 0.4 (significant level of skill is around 0.1). Red crosses and black circles show the skill when the optimization is done once within the entire basin and within the global ocean respectively (in those two cases, only one value is obtained for each of the parameters independent of latitude). Hence, as the optimized skills from the 3 cases are close to each other, the model is not much sensitive to the parameters. In conclusion, the

effect of the surface wind and of its variability have a strong influence on the surface currents.

3.3. Global validation

The OSCAR calculated currents relative to the 0-30m layer are systematically compared to the buoy drifter data, in an ensemble of predefined boxes covering the major part of the open ocean. As the diagnostic model is calibrated during the 1999-2004 period, completely independent comparisons with drifter data are carried out for the period after 2004. Extensive comparisons with drifters are already provided to users and anyone online for the tropical Pacific. They are updated every month in near-real time for the previous month (February 2006 at the time of this conference). Comparisons with the current data of the TAO/TRITON/PIRATA array will also be regularly updated and available online.

4. CONCLUSION

OSCAR is a project to monitor global surface currents from space. It is based on an empirical methodology that includes observation-based calibration and direct comparisons to independent *in situ* data. Surface current maps can be displayed and downloaded online and in near-real time for the tropical Pacific Ocean. This capability will be available very soon for the global open ocean.

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