Ocean and Coastal Research

Brief Communication
Special Article Collection
Collins,C.A.; Castro,R.; Silveira,I.C.A. (Eds.)
Advances in Physical Oceanography
honoring Prof. Affonso Mascarenhas
http://doi.org/10.1590/2675-2824070.22020lfno
ISSN 2675-2824

Evidence of submesoscale coastal eddies inside Todos Santos Bay, Baja California, México

Luis Felipe Navarro-Olache[1], Rafael Hernandez-Walls[1,*], Ruben Castro[1], Reginaldo Durazo[1], Xavier Flores-Vidal[1], Ana Laura Flores-Morales[1], Beatriz Martin-Atienza[1]

[1] Universidad Autónoma de Baja California - Facultad de Ciencias Marinas (Carretera Ensenada-Tijuana No. 3917 - Playitas - Ensenada Baja California - 22860 - Mexico)

* Corresponding author: rwalls@uabc.edu.mx

Abstract

Submesoscale eddies (1-10 km diameter) were identified using surface velocity observations obtained from a high-frequency radar system (HFR) operated in Todos Santos Bay (TSB), Baja California, Mexico. Eddies were detected through a special case of the Okubo-Weiss parameter for divergent flows in the form of eigenvalues of the Jacobian matrix. The detection method, applied for a surface velocity grid, shows encouraging results in the recognition and tracking of submesoscale features in TSB. The detection method is rapid and efficient. Results show the formation and persistence of an eddy structure inside the Bay in December 6, 2010, displaying a trajectory from NE to SW until disappearing at the center of the Bay. The eddy is approximately 4 km in diameter with a frequency of ~0.1f (f is the Coriolis parameter). The real part of the Okubo-Weiss parameter ranged between -4×10^{-9} to -1×10^{-9} s^{-2}, and outlined the eddy for approximately 9 hours. Although it is difficult to identify the origin of the detected submesoscale eddy, its appearance coincided with a drop in relative atmospheric humidity suggesting land-ocean Santa Ana winds as a possible generating mechanism.

Descriptors: HF velocity data, Submesoscale, Okubo-Weiss parameter, Todos Santos bay.

A high density of velocity data either on the surface or in any area of the ocean is key to the detection of flow structures in the ocean, such as eddies, filaments, or fronts. Eddies are common structures in the ocean and play a significant role as a modulator of mass and heat transport, accounting for more than 50% of the ocean's variability (Chelton et al., 2007; Isern-Fontanet et al., 2017). They engulf and transport ocean water and its properties from one side of the ocean to another. Detection and monitoring of mesoscale eddies has boomed in recent decades as high-density observations have become available using satellite images, altimeters (e.g., Chelton and Schlax, 2003), floating elements or debris and, in some cases, temperature differences. Images commonly reveal plentiful of clockwise or counterclockwise rotating isolated eddies in the ocean. Radius of surface mesoscale eddies range from tens of kilometers or less, while submesoscale eddies can be hundreds of meters in diameter and survive for periods of hours to days (Levy et al., 2018; Isern-Fontanet et al., 2004; Chelton et al., 2007; Liu et al., 2020).

The use of high frequency (HF) radar has allowed the generation of large amounts of current velocity data for extensive coastal areas and in nearly real time. HF radar data show high spatial and temporal resolution, allowing enhanced observation of the complex surface circulation of the ocean and coastal zones, compared with traditional observations, such as

Submitted: 22-Mar-2022
Approved: 14-Sept-2022

Associate Editor: Curtis Collins

floating drifters or several single points velocimeters (Alvarez et al., 1988, Paduan and Washburn, 2013). Surface velocity data from HF radar, which is usually obtained at high temporal and spatial resolutions (< 1 hour, < 1 km), allows the study of the kinematics of coastal currents by means of differential operators such as divergence, rotation or deformation rates (Kim, 2010). In semi enclosed seas as Todos Santos Bay, short-lived submesoscale eddies may be generated by horizontal shear instabilities caused by the interaction of currents with coastal morphology and shallow depths, and wind blowing from the coast to the ocean. Detection and following of such structures are carried out by means of automated algorithms that characterize the velocity fields (Liu et al., 2020). One of the most common methods of detection is the Okubo-Weiss parameter which compare the strain and vorticity in a two-dimensional velocity field. The parameter highlights regions where eddy-like structures exist on scales resolved by the data base. Although the method has been used extensively (Yang et al., 2001), some false positives can result near coastal induced horizontal gradients. Here, we use hourly surface velocities measured during 2010 using an HF radar system in Todos Santos Bay (TSB, Figure 1), located on the NW coast of Mexico (Flores-Vidal et al., 2014; Flores-Vidal et al., 2018; Navarro-Olache et al., 2021).

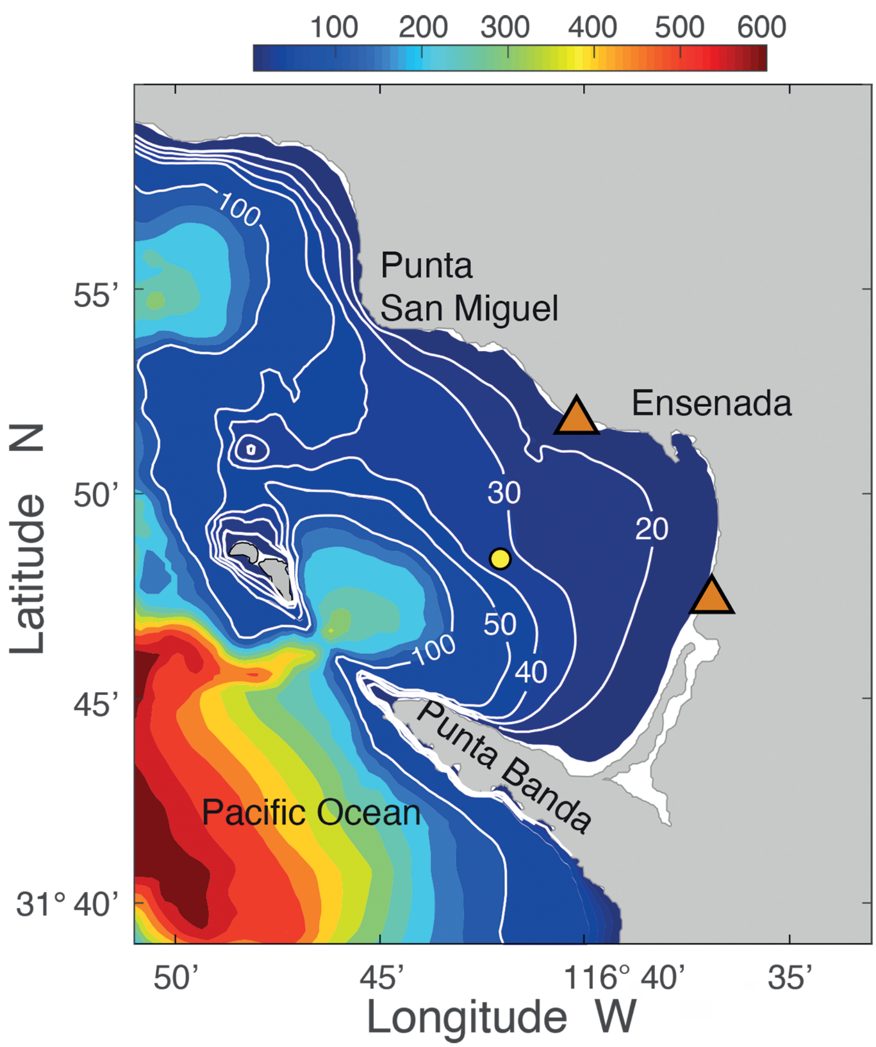

Figure 1. Chart of Todos Santos Bay, México. Depth in meters is indicated by white isobaths as well as by the color bar at the top of the figure. The location of the two high frequency radar stations used in this study are indicated by orange triangles at the coast. The yellow circle at the center of the Bay indicates the location of the time series shown in figure 3.

In this communication, high-density surface velocity data, from a two-HF-radar system in Todos Santos Bay, Baja California, Mexico, are used to study the flow kinematic characteristics inside the Bay. The data are organized in an hourly structured grid of 272 points. In this study, a grid of 17x16 surface velocity points was built with a resolution of less than 500 m (Flores-Vidal et al., 2018). Velocity observations and differential operators, such as divergence, vorticity, and deformation, are examined hourly. Additionally, and more importantly, an alternative method to detect and follow eddy-like structures is implemented to observe features hidden in the large grid of surface velocity data inside TSB. The method used HF radar data, and the Okubo-Weiss parameter for divergent flows and the eigenvalues of the horizontal Jacobian matrix as a variant of the Okubo-Weiss parameter. This procedure is possible since HF radar data do not have zero divergence restrictions, as in other works the non-divergence constraint must remain (Cippola and Blacke, 1997, Isern-Fontaneta, 2004). While the parameter can be written in three different ways (Chang and Lie-Yauw, 2014), we demonstrate the use of the eigenvalues of the Jacobian matrix to detect eddies in TSB and show clear evidence of the presence of submesoscale scale features.

Let $\vec{v}(x,y)$ be the vector field of surface velocities with horizontal components (u,v). We can find a 2-D tensor of the horizontal gradient velocities, also known as Jacobian matrix (J). This is given by the gradient of both horizontal fields (Cipolla and Blake, 1997),

$$J = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix}. \tag{1}$$

The Jacobian matrix is used to detect flow characteristics (Haimes and Kenwright, 1999) by using the differential operators obtained by the matrix components such as divergence $(div(\vec{v}))$, rotation $(\zeta(\vec{v}))$ and deformation $(def(\vec{v}))$. Also solving the Jacobian matrix determinant $(det(J))$, the eigenvalues (λ_1, λ_2) can be obtained, providing additional information on eddy like structures, which is explained below. The eigenvalues of the matrix J are given by the equation,

$$\lambda_{1,2} = \frac{div(\vec{v}) \pm \sqrt{div^2(\vec{v}) - 4det(J)}}{2}, \tag{2}$$

in which λ_1 and λ_2 are the primary and secondary eigenvalues, respectively.

One way to study the dynamic behavior of a fluid is through the Okubo-Weiss (Q) parameter, which is based on the Jacobian matrix (Chang and Lie-Yauw, 2014). The parameter Q, for a divergent flow, is given by (Lukovich and Shepherd, 2005),

$$Q = \tfrac{1}{4}(div^2(\vec{v}) + def^2(\vec{v}) - \zeta^2(\vec{v}) + 2div(\vec{v})\sqrt{def^2(\vec{v}) - \zeta^2(\vec{v})}. \tag{3}$$

It is worth mentioning that this definition also includes the Okubo-Weiss parameter version for non-divergent flows $(div(\vec{v}) = 0)$. Now, the Q parameter can also be written in terms of divergence and $det(J)$, given the relationship

$$det(J) = \tfrac{1}{4}(\zeta^2(\vec{v}) + div^2(\vec{v}) - def^2(\vec{v})), \tag{4}$$

which provides the expression

$$Q = \tfrac{1}{4}(2div^2(\vec{v}) - 4\,det(J) + 2div^2(\vec{v})\sqrt{div^2(\vec{v}) - det(J)}). \tag{5}$$

It can be shown that Q is directly related to the eigenvalues of J. This is possible by remembering that the matrix determinant is given by the product of the eigenvalues, while the trace of a matrix is given by the sum of the eigenvalues. For divergent flows, the Okubo-Weiss parameter is given by the square of the principal eigenvalue, which represents the principal eigenvalue of the Jacobian matrix, namely

$$Q = \lambda_1^2 \tag{6}$$

Given that Q is a complex number, we suggest using only the real part. The Q parameter for non-divergent flows is widely used for eddy detection (Isern-Fontaneta et al., 2004; Gan and Ho, 2007; Zheng et al., 2020). False positives may result because the deformation effect disturbs the information of the velocity gradient tensor (Kolar and Sistek, 2015). Expression (6) provides a simple and elegant way to obtain the Okubo-Weiss parameter and detect eddy like structures based on surface velocity data operators. To assess the method accuracy from the equations above, we use a set of analytic eddies where Q was evaluated in both divergent and non-divergent flows. Similar results were obtained.

The method was evaluated using the HFR data base inside TSB. Negative eigenvalues $(R(\lambda) < 0)$ represent flow convergence linked to eddies. By analyzing such eigenvalues we noted a considerable number of submesoscale eddies that appear and disappear within the 1-hour measuring time step. Surface velocity data on the regular grid was used to calculate spatial derivatives at each node. In our case, a function based on the original MATLAB routine **gradient.m** (Mathworks, 2006) was used, which was modified to include the calculation of second-order derivatives, both on the borders and the center of the mesh. Using this new version of the gradient function it was possible to construct the divergence, rotational and deformation operators for each point of the mesh from the Jacobian matrix J. The kinematic parameters were calculated for all the points of the surface velocity field within TSB.

A particular study case is shown for December 6, 2010 (day 340) in Figure 2A. Arrows indicating flow directions depict areas of convergence and divergence (positive and negative), and other eddy-like structures and velocity gradients. These kinematic parameters are shown as divergence (figure 2B), vorticity (figure 2C) and deformation (figure 2D), overlaid on the velocity vectors. In each of the figures, positive (darker colors) and negative (lighter colors) areas are shown, limited by the zero contour. These fields can be combined

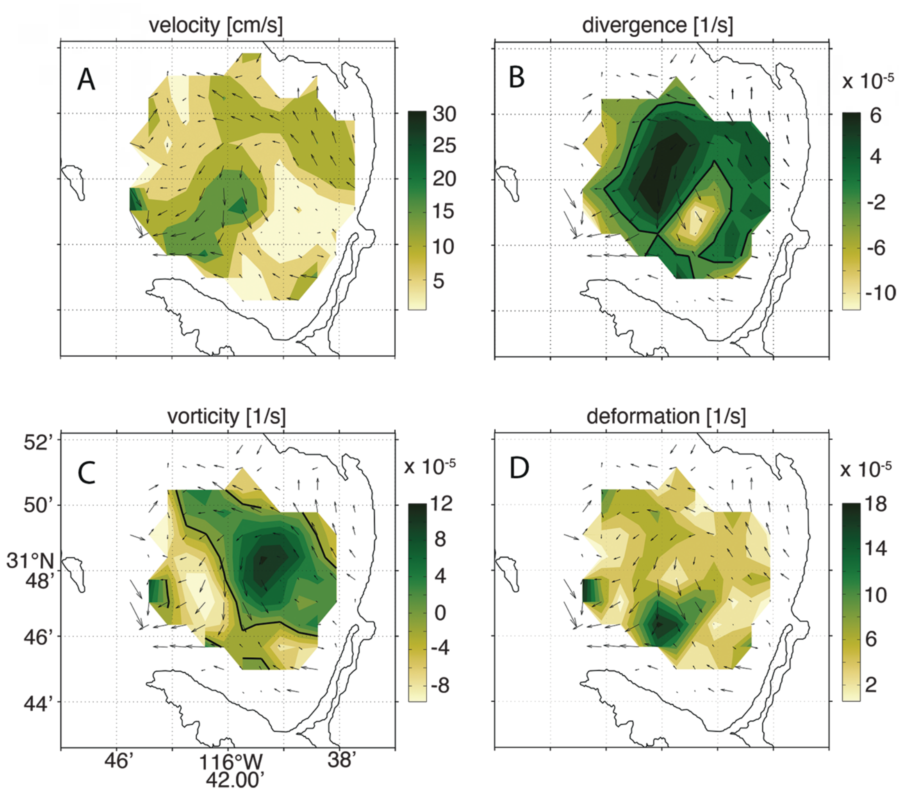

Figure 2. Chart of surface velocity (arrows) and related fields at 23:00 on December 6, 2010. Color bars along the right ordinate indicate the magnitude of each variable as (A) Surface velocity (cm s^{-1}), (B) Divergence (s^{-1}), (C) Vorticity (s^{-1}), (D) Deformation (s^{-1}). Thick black contours in panels B, C and D indicate the zero value. Note the color scale is different on each frame.

to compute the Okubo-Weiss parameter to detect submesoscale eddies through time.

For a specific location we can extract the time series of each calculated operator. An example is shown in figure 3 which shows the time evolution of the operators at a point within TSB. Note that the order of magnitude of the vorticity and divergence operators are similar, between -1 and 1 × $10^{-4}s^{-1}$, indicating the typical highly dynamic conditions within the Bay (Kawai, 1985). The value of vorticity and deformation in figure 3, when normalized by the Coriolis parameter, fall within the cyclonic regime discussed by Buckingham (2021), their figure 1, suggesting the influence of straight fronts in the generation of eddies. Thus, the use of the Q parameter within TSB (eq. 6) is the preferred one since it may be indistinctly used if flows are divergent or non-divergent.

In this study we used the vector field of the surface currents obtained with an HF radar system. We explore the possibility of using the divergent version of Q for eddy detection. The parameter, in the form of eigenvalues, was calculated for a special case when the genesis of a submesoscale eddy was observed (broken gray line in figure 3). It was observed that the real part of Q predicted the existence of this eddy, which can be readily observed in the velocity field in figure 4. To delimit the contours of the eddy, solid thick contours of the real part of Q were drawn between the values of -4 × 10^{-9} to -1 × $10^{-9}s^{-2}$, which distinguished the eddy for 9 hours, from its origin north of the Bay and later displacement south toward the center of the Bay, where it weakens and disappears (figure 4). This submesoscale eddy had an approximate diameter of 4 km and a rotation rate of 0.1f. When trying to determine the cause of the submesoscale eddy, meteorological records showed that during the detection of the eddy, an increase of atmosphere temperature, low values of humidity and a change of direction of winds (towards the ocean) was observed. This condition is direct related with a local Santa Ana wind event in TSB, which partly could explain an eddy generation event (Zatsepin et al., 2019).

One of the main results of this work is that when searching for eddies, it is desirable to calculate only the eigenvalues of the Jacobian matrix, because the Jacobian determinant and the matrix trace can be calculated from them. A special case of the method is that the product $\lambda_1\lambda_2$ is equivalent to the Okubo-Weiss parameter for non-divergent flows.

In highly dynamic regimes as TSB, other forcing such as strong tidal currents (Flores-Vidal et al., 2014) may be interacting with bathymetry to generate submesoscale eddies. Under these fast-changing conditions, the calculation of the Q parameter has a strong potential to detect and follow

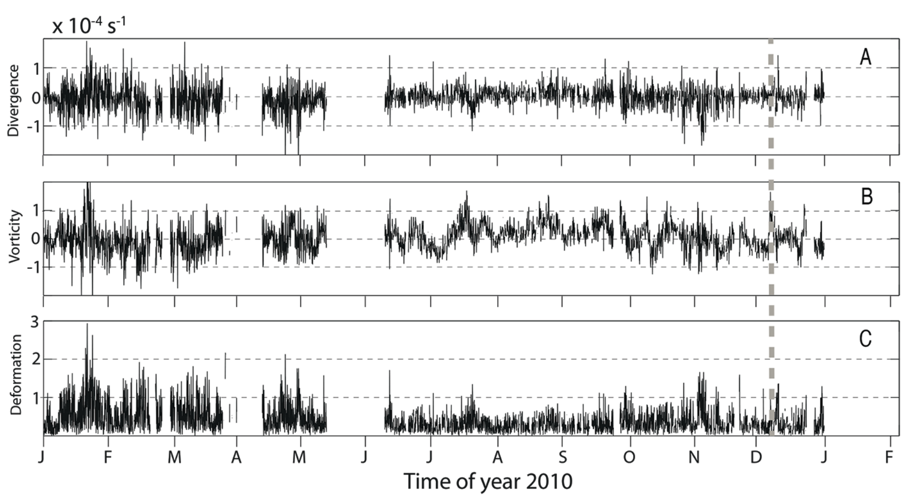

Figure 3. Time series of (A) divergence, (B) vorticity and (C) deformation during the year 2010. The series were built near the center of the Bay, at the location of the yellow dot depicted in Figure 1. The gray broken line indicates year day 340 corresponding to December 6.

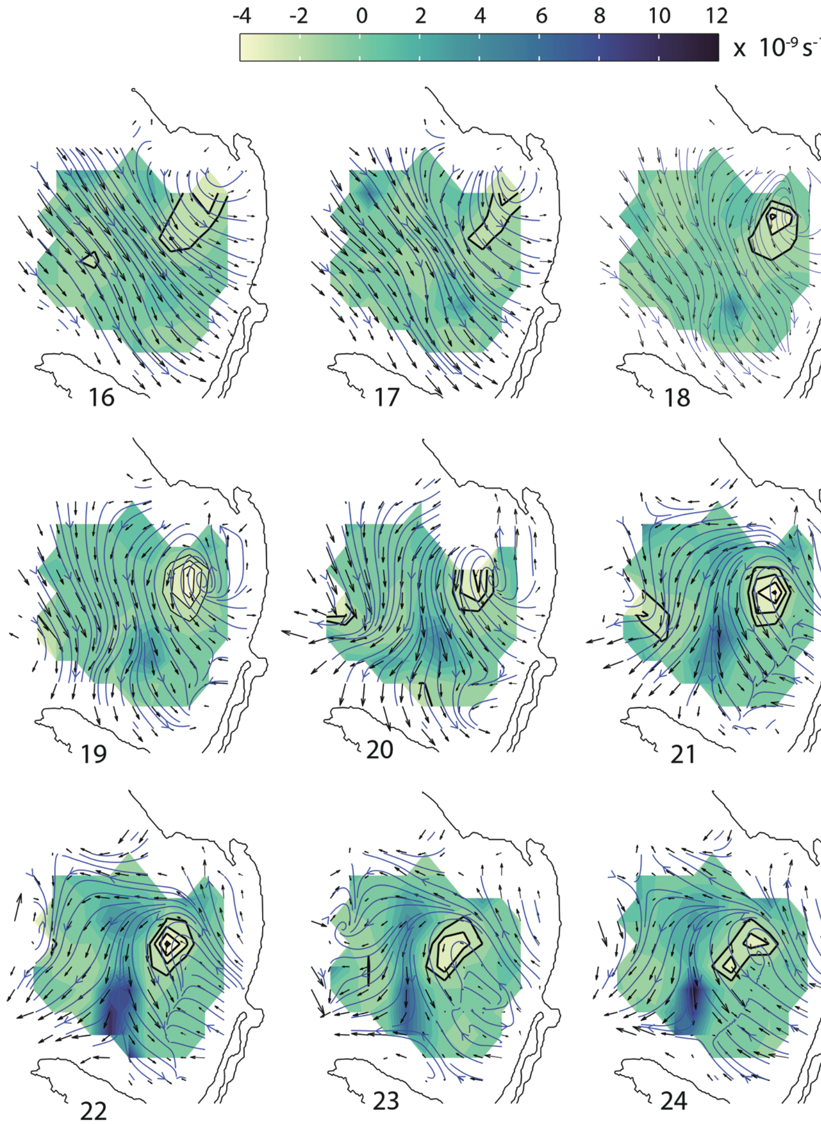

Figure 4. Tracking of a submesoscale eddy in Todos Santos Bay, from 16:00 to 24:00 on December 6, 2010. Numbers at the bottom of each panel indicate the hour. The colorbar at the top indicates the real part of the eigenvalue λ_1. The eddy is marked by black contours of negative values of λ_1. Black arrows and blue contours indicate the pattern of the surface flow.

these eddies. However, fast-disappearing eddies make tracking difficult at times, likely due to the strong horizontal velocity gradients such as those near Todos Santos Island. An improvement in the detection method would provide robust statistics if we achieve greater accuracy in the measurement of surface velocities. This would give a better estimate of the origin and tracking of small-scale eddies allowing consistent statistics of submesoscale features.

ACKNOWLEDGMENTS

The authors wish to deeply thank Professor Affonso da Silveira Mascarenhas who generated the sources of financing, ideas, and a lot of work to initiate in Mexico the study of surface currents using high frequency radars. His enthusiasm and proactive thinking will be always remembered. Also, we thank the students and technicians involved in the installation and retrieval of information from the HF radar system. This study was made possible thanks to the funds received by the 17th internal University of Baja California proposal. The authors also wish to thank the UABC (PREDEPA) and the SEP (PRODEP) for the support received via the mobility program in 2017.

AUTHOR CONTRIBUTIONS

L.F.N.O: Conceptualization; methodology; investigation; writing - original draft; Writing - review & editing;

R.H.W.: Conceptualization; methodology; software; formal analysis; investigation; writing - original draft; writing - review & editing;

R.C. writing - original draft; writing - review & editing;

R.D.: Resources; Project administration; funding acquisition; writing - review & editing;

X.F.V., A.L.F.M., B.M.A.: Investigation; writing - review & editing.

REFERENCES

ALVAREZ, L. G., HERNANDEZ-WALLS, R. & DURAZO--ARVIZU, R. 1988. Patrones de deriva de trazadores lagrangeanos en la Bahia de todos Santos. *Ciencias Marinas*, 14(4), 135-162, DOI: https://doi.org/10.7773/cm.v14i4.609

BUCKINGHAM, C. E. 2021. *Submesoscale potential vorticity.* Washington: ESSOAr (Earth and Space Science Open Archive), DOI: https://doi.org/10.1002/essoar.10508902.1

CHANG, Y. L. & LIE-YAUW, O. E. Y. 2014. Analysis of STCC eddies using the Okubo-Weiss parameter on model and satellite data. *Ocean Dynamics*, 64, 259-271, DOI: https://doi.org/10.1007/s10236-013-0680-7

CHELTON, D. B. & SCHLAX, M. G. 2003. The accuracies of smoothed sea surface height fields constructed from tandem altimeter datasets. *Journal of Atmospheric and Oceanic Technology,* 20(9), 1276-1302, DOI: https://doi.org/10.1175/1520-0426(2003)020<1276:TAOSSS>2.0.CO;2

CHELTON, D. B., SCHLAX, M. G., SAMELSON, R. M. & SZOEKE R. A. 2007. Global observations of large oceanic eddies. *Geophysical Research Letters*, 34(15), L15606, DOI: https://doi.org/10.1029/2007GL030812

CIPOLLA, R. & BLAKE, A. 1997. Image divergence and deformation from closed curves. *International Journal of Robotics Research*, 16(1), 77-96, DOI: https://doi.org/10.1177/027836499701600106

FLORES-VIDAL, X., DURAZO, R., CASTRO, R., NAVARRO, L. F., DOMINGUEZ, F. & GIL, E. 2015. Fine-scale tidal and subtidal variability of an upwelling-influenced bay as measured by the Mexican high frequency radar observing system. *In:* LIU, Y., KERKERING, H. & WEISBERG, R. H. (eds.). *Coastal ocean observing systems: advances and syntheses*. Cambridge: Academic Press, pp. 209-228, DOI: https://doi.org/10.1016/B978-0-12-802022-7.00012-2

FLORES-VIDAL, X., GONZALEZ-MONTES, S., ZERTUCHECHANES, R., RODRGUEZ-PADILLA, I., MARTI, C. L., IMBERGER, J., MEJA-TREJO, A., DURAZO-ARVIZU, R. & NAVARRO-OLACHE, L. 2018. Three-dimensional exchange flows in a semi-enclosed Bay: numerical simulations and high-frequency radar observations. *Estuarine, Coastal and Shelf Science*, 210, 26-35, DOI: https://doi.org/10.1016/j.ecss.2018.05.027

GAN, J. & HO, H. S. 2007. Identification of spatial variability and eddies in the circulation of the South China Sea. *Advances in Geosciences*, 12, 243-26, DOI: https://doi.org/10.1142/9789812836168_0016

HAIMES, R. & KENWRIGHT, D. 1999. *A99-33495 - On the velocity gradient tensor and fluid feature extraction.* Reston: American Institute of Aeronautics & Astronautics, DOI: https://doi.org/10.2514/6.1999-3288

ISERN-FONTANET, J., BALLABRERA-POY, J., TURIEL, A. & GARCÍA LADONA, E. 2017. Remote sensing of ocean surface currents: a review of what is being observed and what is being assimilated. *Nonlinear Processes in Geophysics*, 24(4), 613-643, DOI: https://doi.org/10.5194/npg-24-613-2017

ISERN-FONTANETA, J., FONTA, J., GARCIA-LADONAA, E., EMELIANOVA, M., MILLOTB, C. & TAUPIER-LETAGE, I. 2004. Spatial structure of anticyclonic eddies in the Algerian basin (Mediterranean Sea) analyzed using the Okubo-Weiss parameter. *Deep Sea Research Part II: Tropical Studies in Oceanography*, 51(25-26), 3009-3028, DOI: https://doi.org/10.1016/j.dsr2.2004.09.013

KAWAI, H. 1985. Scale dependence of divergence and vorticity of near-surface flows in the sea. *Journal of the Oceanographical Society of Japan*, 41, 157-166, DOI: https://doi.org/10.1007/BF02111115

KIM, S. Y. 2010. Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities. *Continental Shelf Research*, 30(15), 1639-1655, DOI: https://doi.org/10.1016/j.csr.2010.06.011

KOLAR, V. & SISTEK, J. 2015. Corotational and compressibility aspects leading to a modification of the vortex--identification Q-Criterion. *AIAA Journal*, 53(8), 2406-2410, DOI: https://doi.org/10.2514/1.J053697

LEVY, M., FRANKS, P. J. S. & SHAFER, K. 2018. The role of submesoscale currents in structuring marine ecosystems. *Nature Communications*, 9(1), 4758, DOI: https://doi.org/10.1038/s41467-018-07059-3

LIU, F., ZHOU, H., HUANG, W. & WEN, B. 2020. Submesoscale eddies observation using high-frequency radars: a case study in the northern south China Sea. *IEEE Journal of Oceanic Engineering*, 46(2), 624-633, DOI: http://doi.org/10.1109/JOE.2020.2986175

LUKOVICH, J. V. & SHEPHERD, T. G. 2005. Stirring and mixing in two-dimensional divergent flow. *Journal of the Atmospheric Science,* 62(11), 3933-3954, DOI: https://doi.org/10.1175/JAS3580.1

MATHWORKS. 2006. *Gradiant* [online]. Portola Valley: MathWorks, Inc. Available at: https://www.mathworks.com/help/matlab/ref/gradient.html [Accessed: 2022 Mar 02].

NAVARRO-OLACHE, L. F., CASTRO, R., DURAZO, R., HERNANDEZ-WALLS, R., MEJIA-TREJO, A., FLORES-VIDAL, X. & FLORES-MORALES, A. L. 2021. Influence of Santa Ana winds on the surface circulation of Todos Santos Bay, Baja California, Mexico. *Atmosfera*, 43(1), 97-109, DOI: https://doi.org/10.20937/atm.52719

PADUAN, J. D., KOSRO, P. M. & GLENN, S. M. 2004. A national coastal ocean surface current mapping system for the United States. *Mar. Technology Society Journal,* 38(2), 102-108, DOI: https://doi.org/10.4031/002533204787522839

PADUAN, J. D. & WASHBURN, L. 2013. High-frequency radar observations of ocean surface currents. *Annual Review of Marine Science*, 5, 115-136, DOI: https//doi.org/10.1146/annurev-marine-121211-172315

YANG, Q., PARVIN, B. & MARIANO, A. 2001. Detection of vortices and saddle points in SST data. *Geophysical Research Letters*, 28(2), 331-334, DOI: https://doi.org/10.1029/2000GL011408

ZATSEPIN, A., KUBRYAKOV, A., ALESKEROVA, A., ELKIN, D. & KUKLEVE, O. 2019. Physical mechanisms of submesoscale eddies generation: evidences from laboratory modeling and satellite data in the Black Sea. *Ocean Dynamics*, 69, 253-266, DOI: https://doi.org/10.1007/s10236-018-1239-4

ZHENG, Q., XIE, L., XIONG, X., HU, X. & CHEN, L. 2020. Progress in research of submesoscale processes in the South China Sea. *Acta Oceanologica Sinica*, 39, 1-13, DOI: https://doi.org/10.1007/s13131-019-1521-4