

# Mean dynamic topography and currents in Persian Gulf and Indian Ocean using altimetry and GOCE data

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## ABSTRACT

Getting to know the oceans Mean Dynamic Topography (MDT) derived from the satellite altimetry data helps to study climates and steady state currents in the oceans. A MDT model named as MDT\_IAU\_TN\_2014, including steady state surface currents was developed by the Islamic Azad University of IRAN, Tehran-North branch, hydrography group. The model includes magnitudes and directions of currents in the region of Persian Gulf and Indian Ocean given in a grid with 2'x2' arc minutes spacing in the latitude and longitude directions. To build up the model, a Mean Sea Surface (MSS) model should be subtracted from a Geoid heights model. An MSS called MSS\_IAU\_TN\_2014, is derive using observations of 21 years of 6 altimetry satellites: Topex-Poseidon (T/P); ERS (E1) and (E2); Jason (J1) and (J2); Geosat Follow-On (GFO). MSS\_IAU\_TN\_2014 differences relative to the MSS\_CNES\_CLS\_2011 has 0.1 m RMS. Also a series of global geopotential coefficients estimated from four years of GOCE data is used to compute the geoid. A truncated Gaussian Filter with truncation radius of 1.386 arc degrees was used to match the spectral content of both MSS and Geoid. Sea Level Anomaly (SLA) an In-Situ data could be used to make the MDT\_IAU\_TN\_2014 independent from any other models. At last, MDT\_IAU\_TN\_2014 was compared with MDT\_CNES\_CLS09 0.51m RMS and MDT\_DTU\_2010 with 0.033m RMS. Velocity vectors from MDT\_IAU\_TN\_2014 shows near coast currents perfectly, but there is some weakness in Oman Sea gyres details.

## 1. Introduction

The Mean Dynamic Topography (MDT) is a quantity comes from subtracting the Geoid Height (GH) from the Mean Sea Surface (MSS) at every point on sea. Then, the MDT's slope (relative to the geoid) would determine the direction of geostrophic currents. Two MDT models data were available by the time of this research: Mean Dynamic Topography Denmark Technical University 2010 (MDT\_DTU\_2010) given on geographical grid of 2 arc minutes spacing [1]. This model is based on the mean sea surface topography model MSS\_DTU\_2010 and the 2 month

of GOCE geopotential data for the geoid as the reference surface. One of the advantages of this model is global coverage in a network of 2-minute points, and one of its disadvantages is the lack of north-south and east-west vectors of currents. In this model, after the difference between the two average levels of the seas and the geoid from each other, a type of Gaussian filter is used, this covers up to 111 km in terms of longitude and latitude. The second model is the Mean Dynamic Topography Centre National d'Etudes Spatiales collected localization satellites 2009 (MDT\_CNES\_CLS09) with 15 minutes' resolution [2]. This model contains the east-west and north-south

geostrophic current components with itself as well. It is based on MSS\_CLS01 [3] and 4.5 years of GRACE Geopotential data used for the reference geoid. Model MDT\_CNES\_CLS\_2009 does not provide accurate information on medium dynamic topography due to its low resolution (15 minutes) near the shore. In contrast, the high-resolution (2 minutes) MDT\_DTU\_2010 shows the average dynamic topography in the study area well. MDT\_CNES\_CLS\_2009 estimated changes in average dynamic topography from 0.43 m to 0.8 m, while MDT\_DTU\_2010 estimated this range from 0.21 m to 0.88 m.

In this research, a series of GOCE geopotential coefficients resulted from the collection of 4 years of GOCE observations was used to estimate the reference geoid in Persian Gulf, Oman Sea and Indian Ocean, i.e., in the area of interest. A mean sea surface topography model is also derived from observations of six altimetry satellites; T/P, E1, E2, J1, J2, GFO in study area of a geographical grid with spacing of 2'x2' arc minute. It is called the MSS\_IAU\_TN\_2014. Both the MSS\_IAU\_TN\_2014 and the geoidal height quantities are referred to the same datum (the Topex mission ellipsoid) and are in Mean tide system [4]. Since the reference ellipsoid is not a level surface, the derived MSS surface (referred to the ellipsoid) cannot be used for steady state current (water flow) investigation on sea. To make it useful or to change it to a dynamic (topography) surface, the reference surface has to be exchanged from the ellipsoid to the above mentioned geoid a level surface. Then, the MSS surface is so exchanged to a dynamic surface called here as MDT\_IAU\_TN\_2014.

A filtering needed in order to eliminate the short scale (higher degree) geoidal errors. The Truncated Gaussian filter with half-width at half-maximum 1.386 degree in space domain was used in this research [2]. For the regional dynamic topography applications, the space domain methods are likely to be more efficient and accurate than spectral methods [1,5]. More information about Truncated Gaussian filter and its kernel is found at GUT User Guide and Algorithm Descriptions [6]. The aim of this study is to find the average dynamic topography using 21 years of altimeter data as well as 4 years of gravity data of GOCE satellite in the Persian Gulf region, Oman Sea and part of the Indian Ocean. Another goal is to obtain geostrophic current vectors in the study area.

## 2. Materials and Methods

There is a wealth of altimetry data collected from the year 1992 to 2013 (21 years) by T/P, J1, J2, GFO satellites Geophysical Data Record (GDR) and E1 (Geodetic Mission Phase E and F), E2 satellites Ocean Product Record (OPR) available for any user. It is used to derive the MSS\_IAU\_TN\_2014 model. There are researches conducted in 1998 to apply corrections to the ERS data by CERSAT [7], which improves ERS orbit computation since then (RA/ATSR products - User Manual) [8]. But, there was no correct information about the location of ERS-ERS and ERS-T/P (especially E1) crossover points at the time in order to further improvement of orbits. The first step for the Mean Sea Surface (MSS) computation is to calculate the mean of Sea Surface Heights (SSH) along the repeated (in time) sub-tracks of altimetry satellites over the years available in the area of interest. The SSH quantity is computed from altimetry data (Range) as shown in equation 1.

$$\text{SSH} = \text{Altimeter altitude from ellipsoid} - \text{measured Range} + \text{Corrections} \quad (1)$$

The mean value of SSHs over time in a same track is then called Mean Height (MH). The Basic Radar Altimetry Toolbox (BRAT) version 3.1.0 was used for the MH computation. The correction term in equation 1 includes the tidal periodic variations, physical earth corrections such as troposphere, ionosphere, and sea state biases. All of these corrections are considered from the satellite handbooks T/P (AVISO/Altimetry) [9], J1 (AVISO and PODAAC user Handbook) [10], J2 (OSTM/Jason-2 Products Handbook) [11], ERS (RA/ATSR products - User Manual) [8], GFO (GEOSAT Follow-On GDR User's Handbook) [12]. Among altimetry satellites, T/P (J1 and J2) has the highest orbit and longest data sets so it has been selected as a reference for corrections. After calculating all MHs in the area of interest, ERS MHs have been transformed from WGS84 ellipsoid to the Topex ellipsoid using the datum transformation formula given by Vanicek & Krakiwsky [13].

In order to take a full advantage of all satellite data in the region of interest and for the sake of homogeneity, the compatibility of different data sets (E1, E2, T/P, J1 and J2) are first tested. For this, some points called here as of test points in the number of about 5000 have been distinguished in the region to be in positions onto which the MH quantities can be

precisely derived from all different data sets. Then the differences of the MHs quantities coming from different data sets are computed in the test points relative to the T/P MHs after the unification of datum's. The differences are classified and tested for their fit to the normal Gaussian curve. Most outliers (200 out of 5831), based on the 95% confidence level, are found among the differences of E1 relative to the T/P MHs, concerning that the spacing of the E1 sub-tracks along the equator is about 8 km while for T/P it is about 315 km. The least amount of outliers (50 out of 16174) are found among differences of J1 MHs relative to the T/P MHs, concerning that their orbits are common with the T/P's. In computing the MH in other points (other than 5000) in the region, an average MH is selected out of different MHs obtained from data sets but accounting for the threshold of outliers experienced in the test points. Fig. 1 shows the map of MSSs derived from MHs values on the sub-track points by a linear interpolation on the 2'x2' arc degree grid already positioned in the region of interest. The solution is named as MSS\_IAU\_TN\_2014. The root mean squares (RMS) differences between the solution and the already available model of MSS\_CNES\_CLS\_2011 are estimated to be 0.1 m in maximum.

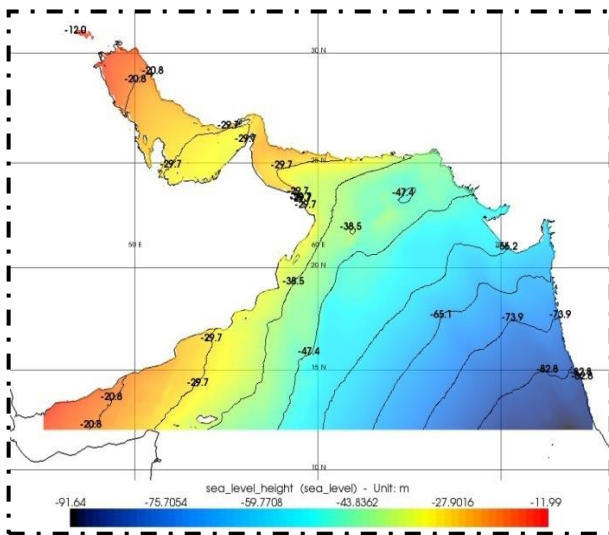


Fig. 1. The MSS\_IAU\_TN\_2014 solution of mean sea surface referred to the reference ellipsoid of T/P satellite.

Precise geoidal heights are now derived from the Gravity field and Ocean Circulation Explorer (GOCE) geopotential model. GOCE has been orbiting the earth since 2009 and gathering higher resolution gravity data compared to the GRACE and facilitating ocean

circulation study as the mission has been set for (ESA SP-1233) [14]. The GOCE DIR 4th generation data could compute the geoidal height in the form of a series of spherical harmonics up to the harmonic degree and order of 260. This computation leaves a higher degree error called omission error as a result of disregarding higher degree (higher than 260) in the gravity field. In addition, there will be another source of errors called the commission errors as the result of least squares estimation method used for the estimation of the geopotential coefficients.

Geoidal heights in the region are calculated from the GOCE level 2 geopotential data (EGM\_GOC\_2) using DIR method [15]. This solution is called GOCE\_DIR4th. By the time of research, the latest version of the data was the 4th generation from November 2009 until October 2012 with a global coverage. The maximum number of spherical harmonic coefficients used is 260. The GOCE User Toolbox (GUT) version 2.1 was used to get the GOCE\_DIR4th solution. The formula used for the geoid computation is completely described in ESA-GUT-AD-001 as it is referenced, (GUT User Guide and Algorithm Descriptions) [6].

### 3. Results and Discussion

The GOCE geoidal height model is subtracted from the MSS\_IAU\_TN\_2014; the result is given in Fig. 2-a [16,17]. A Truncated Gaussian Filter with the averaging radius of 1.386 arc degree is then applied to filter out the higher order (>260) features surviving the subtraction, (Fig. 2-b). The MSS model so determined is lacking higher order (>260) information. To bring in the information, the MDT\_DTU\_2010, Fig. 2 c), is used. For this, the truncated Gaussian filter is applied, once more, to the MDT\_DTU\_2010 model, and the result is subtracted from the model itself to separate the higher order information needed, Fig. 2 d). Table 1 shows statistical differences between the MDT\_IAU\_TN\_2014 relative to the MDT\_DTU\_2010 and MDT\_CNES\_CLS09 models.

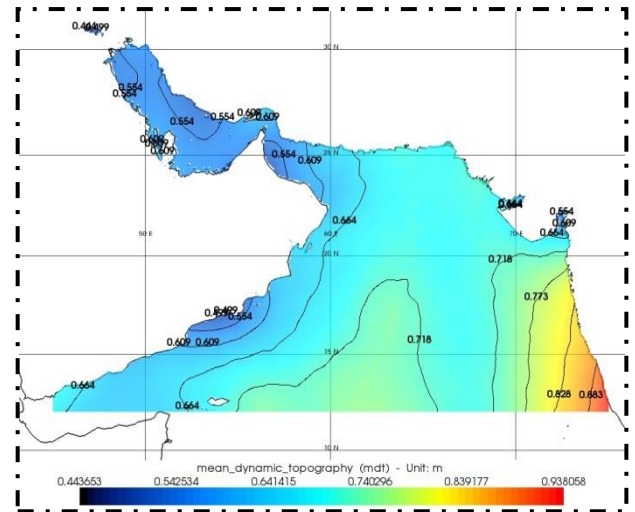
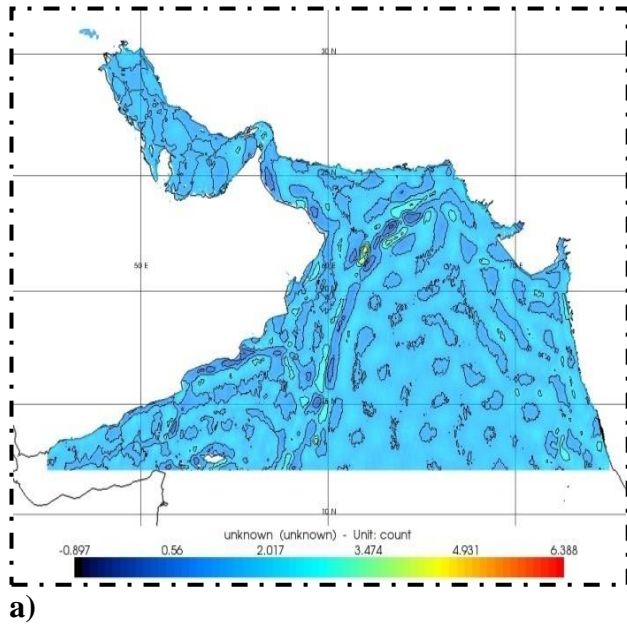
Table 1. statistics of the three MDT models

	MDT_IAU_TN _2014	MDT_DTU_ 2010	MDT_CNES_C LS09
Resoluti on	2'*2'	2'*2'	15'*15'
Min(m)	0.305	0.212	0.436
Max(m)	0.910	0.890	0.800
RMS(m )	Compare to DTU_2010 0.033	Compare to CNES_CLS0 9 0.054	
	Compare to CNES_CLS09 0.051		

To derive the geostrophic currents on the sea surface, the gradients of the mean dynamic topography in the east and north directions ( $\frac{\partial \zeta}{\partial y}$ ,  $\frac{\partial \zeta}{\partial x}$ ) are used in the equations (2a, 2b), [18]:

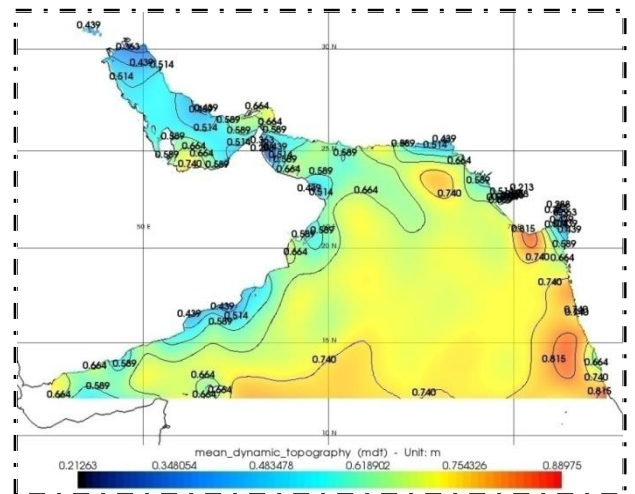
$$u = -\frac{g}{f} \frac{\partial \zeta}{\partial y}, \tag{2-a}$$

$$v = \frac{g}{f} \frac{\partial \zeta}{\partial x}, \tag{2-b}$$

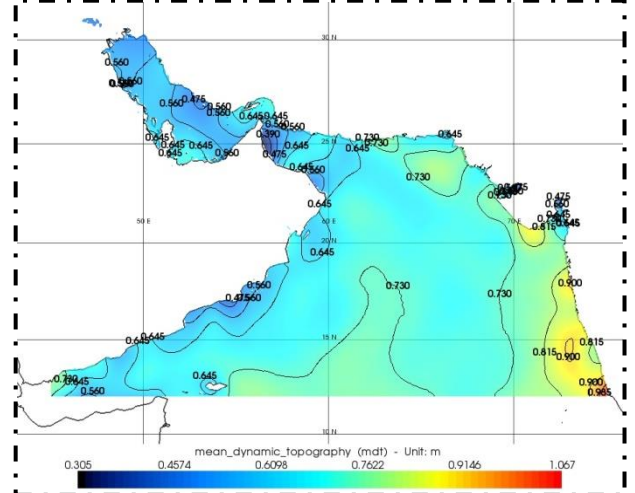


b)

c)

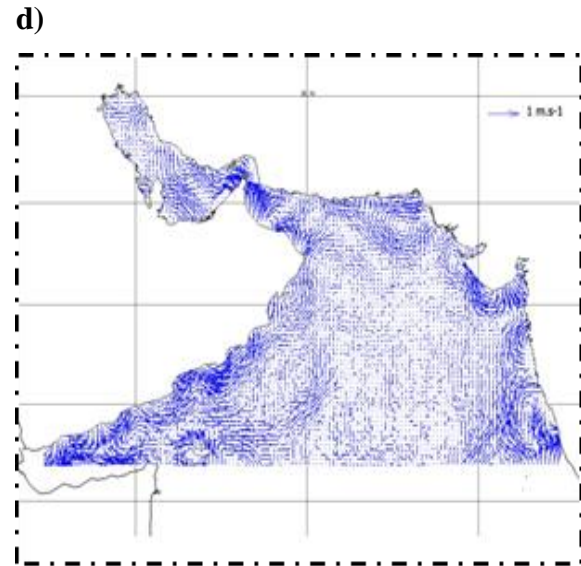
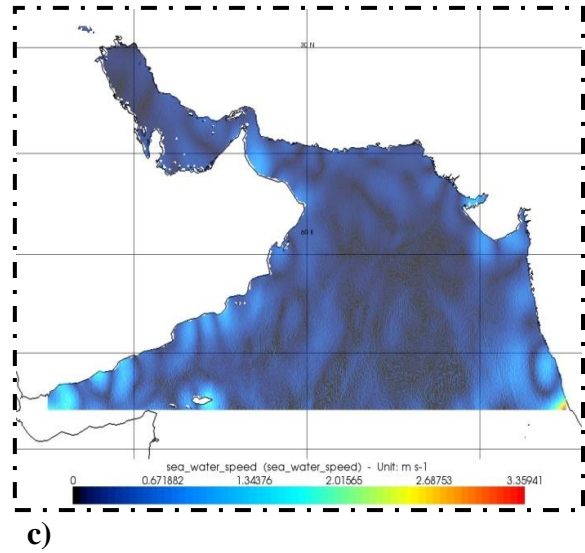
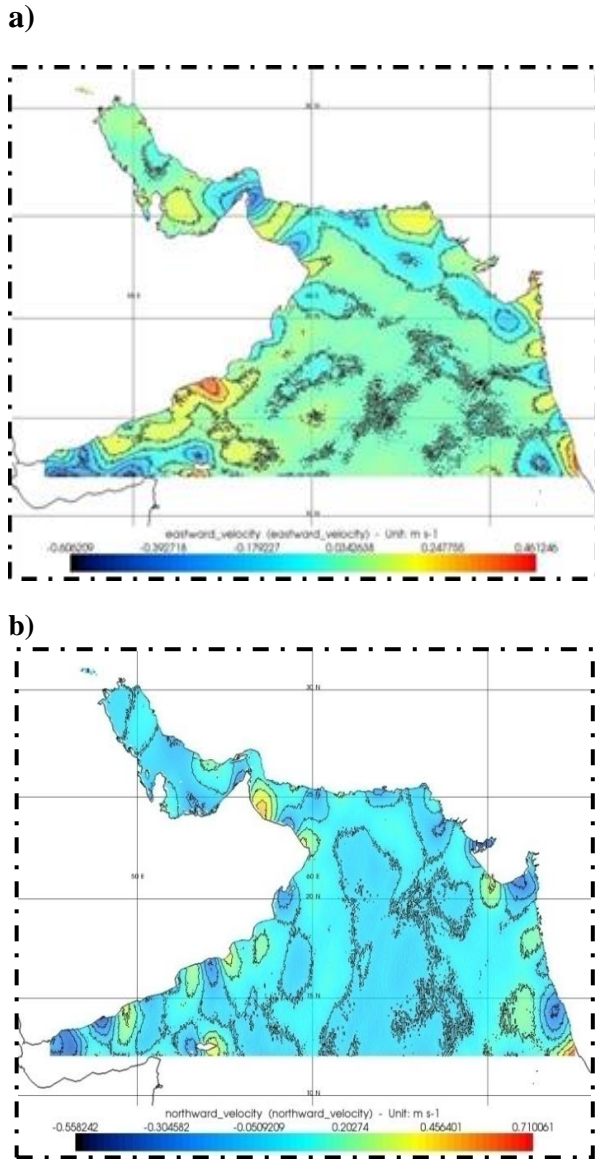


d)



**Fig. 2.** a) MSS\_IAU\_TN\_2014 subtraction from GOCE geoid, a) Repaired GOCE MDT using Truncated Gaussian Filter with 1.386-degree radius. b) MDT\_IAU\_TN\_2014. c) MDT\_DTU\_2010.

The equations are the results of compensations between surface pressure gradients and the Coriolis acceleration on sea surface, where  $u$  and  $v$  are the east-west, Fig. 3 a), and north-south, Fig. 3 b), components of the current.  $\zeta$  is the MDT\_IAU\_TN\_2014 mean dynamic topography,  $g$  is the gravity,  $f$  is the Coriolis parameter which is equal to  $2\Omega \sin \varphi$  and  $|\Omega| = 7.292 \times 10^{-5}$  radians/s angular velocity of the earth rotation. The speeds of resultant geostrophic currents  $V = \sqrt{u^2 + v^2}$  are shown in Fig. 3 c) and the velocity vectors are shown in Fig. 3 d).



**Fig. 3.** a) MDT\_IAU\_TN\_2014 east-west components, b) MDT\_IAU\_TN\_2014 north-south components, c) Geostrophic values, d) Geostrophic currents.

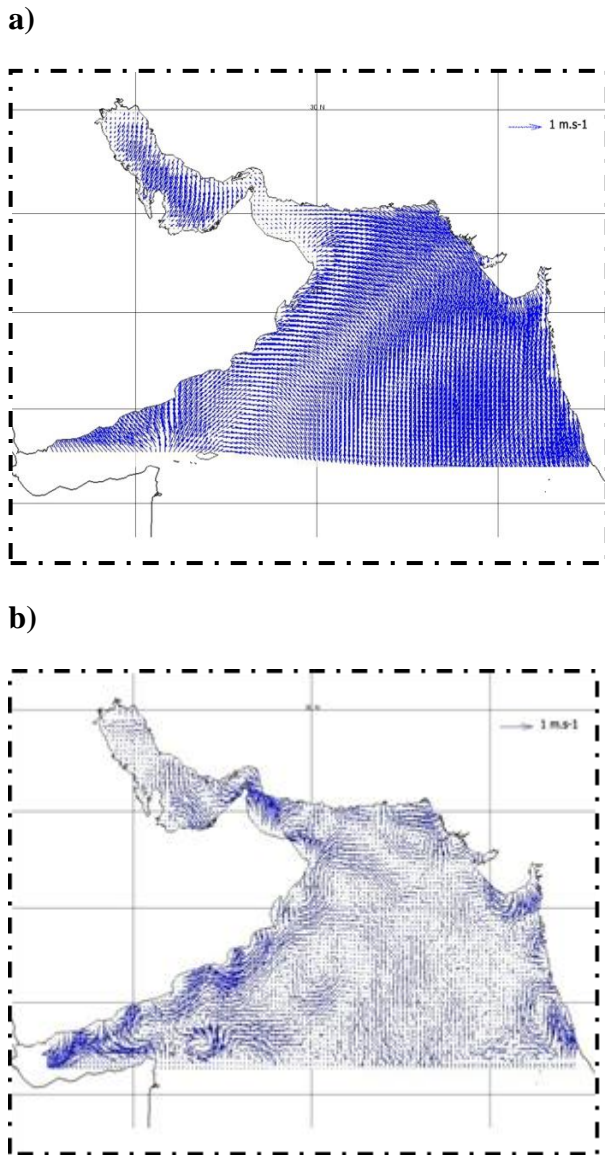
At last, the mean Ekman currents calculated from 22 years of surface wind stress components, Fig. 4 a), in the Eq. 3 are added to the MDT\_IAU\_TN\_2014 Geostrophic currents components to derive the total steady state currents, Fig. 4 b).

$$[u(z)^2 + v(z)^2]^{1/2} = V_0 e^{az} \quad (3)$$

$u$  and  $v$  here are the Ekman current components in the east-west and north-south directions,

$$a = \sqrt{\frac{f}{2A_z}}, V_0 = \frac{T}{\sqrt{\rho_w^2 f A_z}}, \text{ which } T = T_{yz} \text{ when}$$

wind blows to north direction (T is wind stress).



**Fig. 4.** a) Ekman current from 22 years wind stress data, b) Steady state currents from MDT\_IAU\_TN\_2014 and Ekman currents.

OSCAR data is used to validate global coverage [19], which can be measured at 1 degree over time. Of course, only in the south of the study area does this data cover. OSCAR is a product of satellite data that shows marine surface currents in Ref. [20].

#### 4. Conclusions

Among altimetry satellites used in this research, J2 and GFO satellites have ability to measure shallow water altimetry's. Hence, the data provided by these

satellites in shallow waters, i.e. Persian Gulf are valuable. MHs differences between E1 and T/P are larger than the MHs of other satellites in comparison with the T/P, because there are differences between the two missions, i.e., there are 8 km distances between E1 sub-tracks at equator but long repeatability period of 35 days of data acquisition time and T/P sub-tracks spacing are 315 km at equator and short repeatability period of 9.9 days. Also, the orbit elevations are different: T/P at altitude of 1336 km and E1 at altitude of 785 km. Inclusion of E1 data in the MSS\_IAU\_TN\_2014 solution would globally decrease the RMS difference of the solution relative to the MSS\_CNES\_CLS\_2011 model from 0.4 m (without E1 data) to 0.1 m. This improvement by the E1 data is probably due to the higher resolution (8 km spacing) of the data in the region of interest. Changing the filtering radius of 1.386 degree down to lower degrees until 1 degree would increase the MDT\_IAU\_TN\_2014 differences (relative to the MDT\_DTU\_2010) and MDT\_CNES\_CLS09 from 0.033m and 0.051m RMS up to larger values. At the 1.386 degree, the differences are at least. For filtering radiuses of more than 1.386 degree the MDT surface would become unreasonably much smoother and the RMS difference would increase.

Ekman currents were computed from 22 years of wind stress data. These currents are added to the MDT\_IAU\_TN\_2014 geostrophic currents to come up with total currents. The total currents vary between 0 to 0.61 m/s in the region of interest. Using model MDT\_DTU\_2010 and applying equations 2 give the range of variations between 0 to 0.70 m/s. The currents from MDT\_CNES\_CLS09 model show variations between 0.001 to 0.62 m/s. The comparison shows that all three models show almost the same range of variations in the region of interest [21,22,23, 24]. As it is shown in Fig. 4 b), there are currents parallel to Oman coast with an average value of 0.7 m/s, as this is also confirmed by two other models. Some ocean gyres could be seen in Oman Sea in this model, which it could be seen in MDT\_DTU\_2010 and MDT\_CNES\_CLS09, too. The MDT\_CNES\_CLS09 would not show any currents in Persian Gulf but the MDT\_IAU\_TN\_2014 would show very slow currents in this region. The fact that the MDT\_IAU\_TN\_2014 would show Persian Gulf currents is because the J2 and GFO data in this region. Compared to OSCAR data with total currents of MDT\_IAU\_TN\_2014 at 116 common points in 1 degree dimensions, in the east-west direction of RMS

the differences are 0.031 m / s and in the north-south direction of RMS the differences are 0.047 m / s.

Sea Level Anomaly (SLA) an In-Situ data could be used to make the MDT\_IAU\_TN\_2014 independent from any other models. The lack of In-Situ data in the region of interest forced MDT\_IAU\_TN\_2014 to use MDT\_DTU\_2010 to cover filtered parts. Also using other gravity models with higher Spherical harmonic coefficients degree and orders such as EIGEN-6c and EGM08 would make filtering not needed in the dynamic modeling.

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