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Dynamic Study of Ocean Striations From Perspective of Satellite Altimetry

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1. Abstract

Accumulation of large, high-quality satellite and in situ data led to significant improvements in the description of the mean dynamic ocean topography (MDOT) by the previous OST Science Team. The new models of MDOT, downscaled to 50-100 km resolution, have not only revealed important details in the complex mesoscale structure of circulation systems such as the Gulf Stream, Kuroshio Extension, and Antarctic Circumpolar Current, but also led to the discovery of new anisotropic jet-like features in ocean circulation referred to as "striations".

While somewhat similar features -- alternating zonal jets, are predicted by a number of theories inspired by the banded cloud patterns in the atmospheres of Jupiter and Saturn, preliminary analysis of satellite and high-resolution ocean models reveal that striations (at least at the sea surface) are inconsistent with two-dimensional, geophysical turbulence, which produces jets through the combination of processes commonly known as the "Rhines mechanism". Equally unlikely is the role of the PV staircases that could be formed by breaking Rossby waves. The uniqueness of the ocean dynamics comes from the existence of the continents and culminates in the generation of large gyres associated with essentially meridional flows. To remain time-invariant in such a flow, striations behave as waves rather than as inertial jets. Once detected, the striations, both stationary and periodic in time, are found to be common throughout the ocean, although their properties varying to different degrees both geographically and interannually.

This paper outlines the main challenges of the striation study project that is part of the new OST Science Team. After a general overview of the striations distribution and properties, we list a set of hypotheses to explain the forcing and dynamics of these striations. In particular, we explore the interaction between striations and mesoscale eddies, and present evidence that striations play an important role in regularizing the otherwise random ensemble of eddies. The striations are shown to be not just an artifact of misinterpreted moving eddies, but a structure retaining its coherence on spatiotemporal scales significantly exceeding the eddy scales (in some reported cases, up to thousands of kilometers and 15 years). We also discuss how striations impact the climate system, both through the ocean dynamics and air-sea interaction and acknowledge that circulation of the intermediate-depth ocean may correspond to the regime different from the one in the upper ocean. We also note that techniques currently employed to map the sea level anomaly, derived from the along-track satellite altimetry, may tend to convert the signal from striations into the one from a train of eddies. We demonstrate the importance of the combined use of data of satellite and in situ observations, and realistic high-resolution global ocean general circulation model along with theoretical analysis and numerical experimenting with the regional ocean model system.

2. Two kinds of striations

At least two different kinds of striations have been detected in data: stationary and propagating.

2.1. Stationary striations

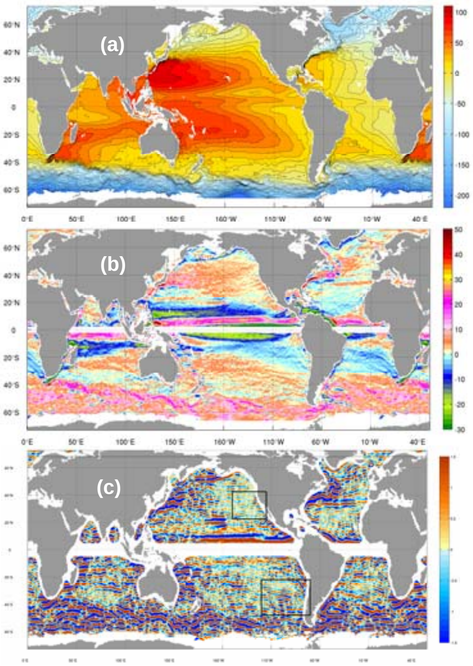

Figure 1. *(a)* 1993-2002 mean dynamic ocean topography (Maximenko and Niiler, 2005), *(b)* mean zonal geostrophic velocity, and *(c)* result of high-pass filtering the latter with a two-dimensional 4-degree space filter. Units are dyn.cm on (a) and cm/s on (b). Red/blue color in (c) corresponds to east/westward current associated with the striations.

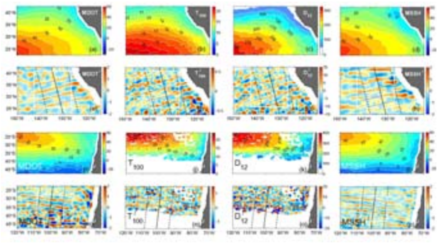

Figure 2. Validation of stationary striations using historical XBT profiles in two domains marked on Fig.1c. MDOT (a,i), T_{100} (b,j), D_{12} (c,k), and MSSH (d,l) in the northern (a-d) and southern (i-l) domains. Panels (e-h) and (m-p) show maps of the fields plotted in (a-d) and (i-l), correspondingly, high-pass filtered with a 4° filter. Units in the four columns of panels are cm, °C, m, and cm, correspondingly. Red lines tilted 13° in (e-h) and -9° (m-p) indicate the crests of striations in MDOT′ (e,m). (Maximenko et al., 2008)

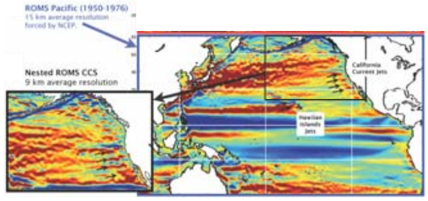

Figure 3. Stationary striations are reproduced in models. Results of preliminary runs of the Pacific and California Current System Regional Ocean Model System are displayed. See the poster of Melnichenko et al. for more details on the OFES (OGCM for Earth Simulator) model results.

2.2. Time-variant (propagating) striations

Systems of nearly zonal striations with crests propagating in time toward the equator are found in the satellite altimeter data.

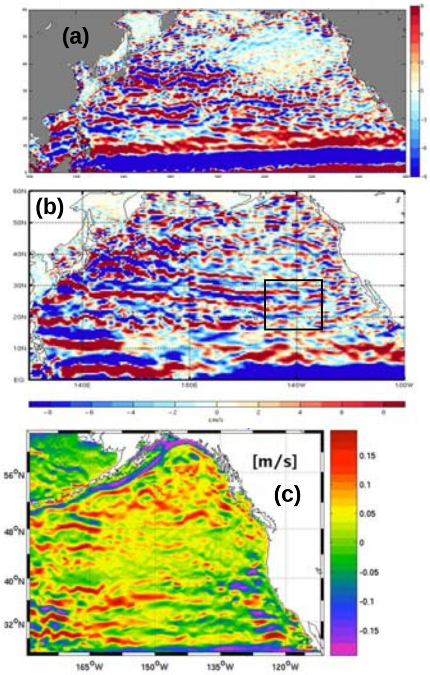

Figure 4. Examples of 4-month averaged zonal surface velocities estimated from satellite altimetry *(a)*, OFES *(b)* , and *ROMS (c).*

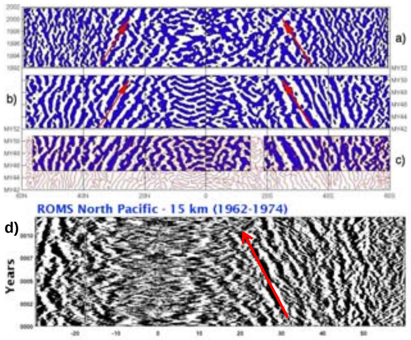

Figure 5. Latitude-time diagram of anomalies of geostrophic vorticity at the sea surface from the Aviso (*a*) and OFES (*b*) data and anomaly of full OFES vorticity *(c)* at 1 km depth. *(d)* shows similar diagram for the surface vorticity in the ROMS (note changes in time period and axes). Anomalies are averaged zonally between 150 and 140°W and in time over about 18 weeks. Negative values are shaded. Contours on *(c)* are zero-contours from *(b)*. Arrows on *(a,b)* mark equator-ward phase propagation at speed 0.45 cm/s.

3. Dynamics of stationary striations

Incomplete list of mechanisms that can induce striations compiled at the 2007 IPRC workshop on jets and fronts includes:

1. 'Rhines mechanism'.
2. PV staircase [Baldwin et al., 2007]
3. β - plume [Stommel, 1982; Pedlosky, 1997]; Tsuchiya jets [Furue et al.]
4. Rossby waves with meridional orientation of wave vector [e.g., Glazman et al.]
5. PV-conserving flow interaction with the bottom topography.
6. Flow interaction with bottom topography: Mixing over the ridge.
7. Instability of meridional flow [Treguier et al., 2003, Spall]
8. Rectification of circulation forced by basin-wide random forcing [Berloff, 2003]
9. Rectification of ocean response to oscillatory local forcing of finite amplitude [Waterman and Jayne, 2005]
10. Wind-induced Rossby modes arrested by friction [Nakano and Suginohara]
11. Preferred paths of mesoscale eddies [e.g., Scott et al.]
12. Local forcing by the wind stress curl [e.g., Xie et al.]
13. Rossby wakes.
14. Flow past mountains/seamounts.
15. Nonlinear interaction between the Ekman current and geostrophic meanders [Centurioni et al., 2008]

While understanding the dynamics of striations is the end goal on this team, preliminary study shows that "Rhines mechanism" is unlikely to be the cause in the upper ocean. Neither PV-staircases are found there. So far most likely candidates is a kind of a β - plume induced in the east by a vorticity source that forms in the presence of the large-scale meridional flow a system of stationary Rossby waves propagating against the flow (Figure 6). A distributed ensemble of different vorticity sources may responsible for the nearly ubiquitous pattern of striations in Figure 1c.

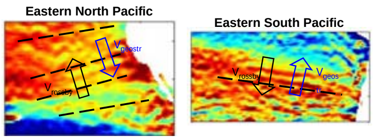

Figure 6. Schematic illustrating interpretation of striations in the eastern North and South Pacific Subtropical Gyres as stationary Rossby waves forced in the near-coastal areas in the east. The key factor in support of this hypothesis is the systematic tilt of the striations.

4. Are striations an artifact of moving eddies smeared by time averaging?

Recently, Huang et al., Qiu et al, Scott et al, Chelton et al. emphasized the sensitivity of the eddy field interpretation to time averaging used in the study. Indeed, while a propagating eddy can be perfectly round on snapshots, averaging the eddy in time produces the "slow shutter" effect that results in a striped signal oriented along the eddy trajectory. The longer the averaging, the larger the degree of an artificial anisotropy [Huan et al, 2007; Qiu et al., 2008]. The effect can be further amplified in the case of extraordinarily rare, strong eddies [Schlax and Chelton, 2008] and if eddies follow preferred paths [Scott et al., 2008]. Given the strength of eddies, the very existence of the striations behind the smeared signal can be questioned [Chelton personal communication]. To separate between eddies striations in the study described below, no time averaging has been used.

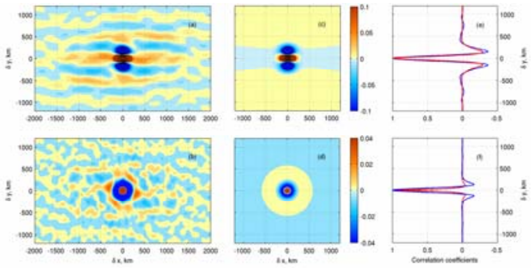

Figure 7. Maps of spatial autocorrelation coefficients of geostrophic zonal velocity R_u (*a*) and vorticity R_ς (*b*) calculated from the Aviso sea level anomaly in the domain shown in Figure 4a, R_{uA} (*c*) and $R_{\varsigma A}$ (*d*) derived from Aviso mapping function at 24°N, sections (*e*) of R_u (blue) and R_{uA} (red) along δ y, and radial structures (*f*) of R_ς (blue) and $R_{\varsigma A}$ (red). Contours on (*a* and *c*) are -0.3, -0.2, -0.1, 0.1, 0.3, 0.5, 0.7, and 0.9. (Maximenko et al., paper in preparation.)

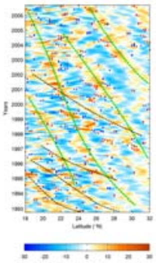

Figure 8. Latitude-time diagram of the zonal component of the Aviso surface geostrophic velocity anomaly averaged zonally between 145 and 150°W. Numbers are cm/s. Dots indicate weekly positions of cyclonic (blue) and anticyclonic (red) mesoscale eddies with the SLA anomaly larger than 8 cm in the longitude range 146.5-147.5°W. Green and black dashed lines indicate crests of eastward-flowing striations' signal propagating toward the equator. (Maximenko et al., paper in preparation.)

Space correlation does not vanish on scale of some thousand kilometers, much larger than the eddy decorrelation scale. In a simplistic way, the striations can be described as via a monochromatic wave with nearly meridional wave vector. Slight westward component of the vector is consistent with the Rossby wave dynamics. On a meridional section, individual crests can be tracked for as long as 15 years, while signal from individual eddies does not last longer than 2 months. Eddies of the corresponding sign are aligned along crests and troughs of the striations. Multiple "envelopes "of striations are observed, with characteristics varying between years and locations. **Such a complex self-organization of an ensemble of eddies is unlikely. Even though the exact nature of instability inducing the striations is not yet known, the striations seem to be the mechanism regularizing the formation mechanism of new eddies.**

Note: at small lag, the correlation function on Figure 7a resembles suspiciously well the one estimated from the mapping correlation function assumed by Aviso (Fig.7c). It is not impossible that Aviso interpolation scheme dictates the properties of the resulting eddies (whose structure thus cannot be studied using Aviso maps) and favors eddies against striations.

5. Implication for climate system

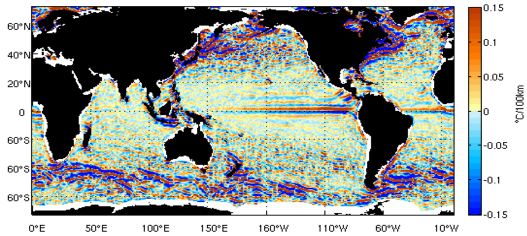

Figure 9. Striations in the meridional gradient of the 1985-2001 mean AVHRR SST high-pass filtered with the two-dimensional 4-degree filter analogous to the one used in Figure 1c. Predictably enough, striated signal in the ocean dynamic topography reflects in the sea surface temperature and thus affects the air-sea fluxes, the key parameter for the Earth's Climate System.

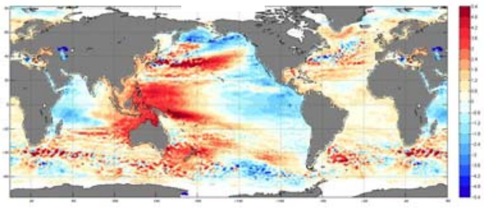

Figure 10. 1993-2003 decadal trend in the altimetric sea level. Basin scale striations on unknown origin are apperant in many locations.

6. Tasks on the Team for 2008-2012:

-use satellite and in situ data to systemize different kinds of striated features in the ocean;
-use OFES model data to study dynamical balances associated with different kinds of striations;
-classify existing vorticity forcing mechanisms and describe their distribution in the ocean;
-use ROMS to isolate important dynamical factors in regional runs;
-use theoretical and numerical studies to understand interactions between unstable flow, striations and eddies;
-assess the impact of striations on the climate dynamics

7. Acknowledgements

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