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QUASI-STATIONARY STRIATIONS IN BASIN-SCALE OCEANIC CIRCULATION: OBSERVATIONS AND A MODEL HINDCAST

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Abstract

Recently, prominent jet-like features of the oceanic circulation, called striations, with meridional scale of O(300-500 km) and extending for thousands of kilometers in length have been detected in satellite and *in situ* observations and high-resolution numerical models. In this paper, we describe quasi-stationary striations, which are best seen when substantial time-averaging is applied. In particular, analysis of the 1992-2002 mean dynamic ocean topography (MDOT) revealed that eastern parts of practically all oceans, in their subtropics, are populated with these anisotropic features, whose orientation is not strictly zonal. The features are slightly tilted relative to the east-west direction with the sign and the angle of the tilt, remarkably, being in accord with the sign and the strength of the meridional component of the large-scale flow. Analysis of more than 20 years of the high-resolution satellite sea surface temperature and historical hydrographic data shows that the quasi-stationary striations are persistent features of the basin-scale oceanic circulation.

To understand dynamics of the quasi-stationary striations we analyze the data of the Ocean General Circulation Model for the Earth Simulator (OFES) in the eastern parts of the subtropical North and South Pacific, where the striations are well pronounced both in the model and in observations. Internal dynamics of the striations is evaluated by assessing individual terms in the local vorticity balance. On the spatial scale of the striations, the dominant terms in the time averaged relative vorticity equation are the local advection of relative vorticity by the large-scale flow, vortex stretching and advection of planetary vorticity by the striations. The estimated balance agrees with one, anticipated for the stationary Rossby waves whose propagation tendency is balanced by the large-scale advection. Analysis of the model data also suggests that quasi-stationary meanders of the eastern boundary currents may induce the formation of the striations.

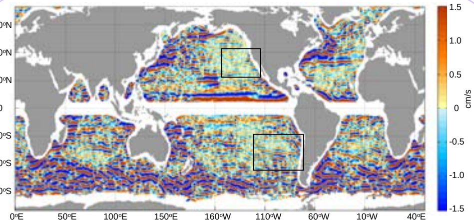


Figure 1. High-pass filtered zonal component of geostrophic velocity derived from the1992-2003 Mean Dynamic Ocean Topography (Maximenko et al., 2008)

Observations: 1992-2002 mean dynamic ocean topography (MDOT); near-surface drifter velocities; Argo float data; historical XBT observations from the World Ocean Database 2005 (WOD'05); Advanced Microwave Scanning Radiometer (AMSR) sea surface temperature (SST); Advanced Very High Resolution Radiometer (AVHRR) SST.

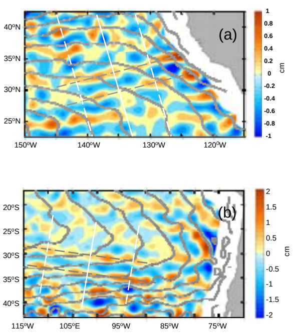


Figure 2. High-pass filtered (2D Hanning window of half-width of 4°) MDOT in the eastern North Pacific **(a)** and in the eastern South Pacific **(b)**. Contours of MDOT (gray solid lines, contour interval is 5 cm) are superimposed. Water parcels following the geostrophic streamlines are only slightly deflected in the direction of the striations. Note the characteristic tilt of the striations relative to the east-west direction (gray dashed lines mark crests). The angle of the tilt is 12-14° in the North Pacific and about 10° in the South Pacific.

Validation of the striations observed in MDOT against other independent data in the eastern North Pacific

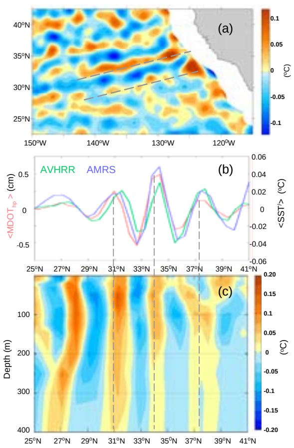
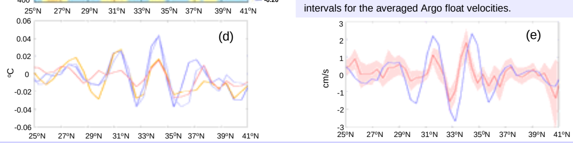


Figure 3. 2002-2007 mean AMSR SST, high-pass filtered with the same window as MDOT **(a)**. Gray dashed lines indicate two consecutive crests in MDOT. Positive SST anomalies correspond well to the crests in MDOT (gray dashed lines).
(b) Red line shows the high-pass filtered MDOT averaged along the direction of the striations. The same procedure was applied to the 1985-2001 mean AVHRR SST and 2002-2007 mean AMSR SST fields, green and blue lines, respectively. Note, that the two mean SST fields are obtained with different sensors (different sources of uncertainties) and the averaging periods do not overlap.
(c) Historical XBT observations accumulated in the NODC World Ocean Database 2005 made it possible to validate the striations against *in situ* data. Mean temperature fields at every standard level from the sea surface to the 400 m depth, reconstructed on the 0.5° grid, were high-pass filtered and then averaged along the direction of the striations (Maximenko et al., 2008). For comparison, three successive crests (positive temperature and dynamic topography anomalies) are marked by the gray dashed lines.
(d) Seasonal mean AVHRR SST (data from 1985 to 2001) high-pass filtered and averaged along the striations. Cold colors indicate fall and winter, and warm colors are chosen for spring and summer. Note that the SST expression of the striations is stronger in cold seasons and much weaker in spring and, especially, in summer (red line) when shallow seasonal thermocline forms. Despite the strong seasonal cycle, the spatial structure of the SST anomalies associated with the striations practically does not vary, corresponding well to the 10-year mean dynamic topography. We suggest that entrainment from the base of a mixed layer is the major source of the SST anomalies.
(e) 0.25° bin-averaged zonal velocity from 1978-2006 near-surface drifter observations (blue curve) and zonal velocity from Argo float subsurface displacements (red curve), both averaged along the direction of the striations. Pink shadow indicates confidence intervals for the averaged Argo float velocities.



Results of the validation of the striations in the eastern part of the subtropical gyre in the South Pacific (not shown) are very similar and lead to the same conclusion. The quasi-stationary striations are persistent features of the basin-scale oceanic circulation.

Hypothesis

The characteristic tilt of the quasi-stationary striations in the eastern parts of the subtropical gyres, in accord with the sign of the meridional component of the large-scale flow, the relative amplitude of the striations, suggest the dynamics similar to that of the stationary Rossby waves. It has been hypothesized that the striations have their source of energy at the easternmost tips of them. Permanent meanders in the eastern boundary currents may provide such a source of energy that propagates westward as β-plumes (Maximenko et al., 2008).

We assume that the large-scale flow and the striations are governed by different dynamics. We separate the scales simply by applying the 2D isotropic filter, so that the large-scale flow and the striations are low-pass and high-pass filtered parts of the circulation, respectively. On the scale of the striations the averaged relative vorticity balance (quasi-geostrophic) can be written as

$$\overline{\mathbf{U}}\cdot\nabla\bar{\zeta} + \bar{\mathbf{u}}\cdot\nabla\bar{\zeta} + \overline{\mathbf{u}'\cdot\nabla\zeta'} = -\beta\bar{v} + f\frac{\partial\bar{w}}{\partial z} + D$$

$\overline{\mathbf{U}}$ - large-scale flow; $\bar{\mathbf{u}}(\bar{u},\bar{v},\bar{w})$, $\bar{\zeta}$ - the striations (velocity and relative vorticity, respectively); $\mathbf{u}'$ - transient motions; D - dissipation.

Geostrophic velocities derived from MDOT are used to estimate different terms in the time-averaged relative vorticity equation.

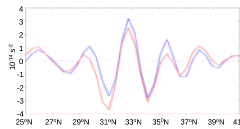


Figure 4. Advection of the striations by the large scale flow (blue curve) is nearly balanced by the β-term (red curve). Self-advection is negligible. Example is for the eastern part of the subtropical North Pacific.

Centuriony et al., 2008, using surface Velocity Program drifter data from 1987 to 2005, NCEP reanalysis wind and Aviso sea level anomalies, reconstructed a time-averaged map of the 15-m-deep geostrophic velocities in the California Current System. They found that bands of alternating of eastward and westward zonal currents are connected to four permanent meanders of the California current. Among several high-resolution OGCM, ROMS (5 km resolution) is found to be in the closest agreement with observations.

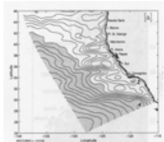


Figure 5, taken from Marchesiello et al., 2003 (their figure 6(a)), shows ROMS annual mean surface heights (contour interval (CI)=2 cm). The time-mean ageostrophic velocity in ROMS is strongest within the cyclonic part of the meanders (Centurioni et al., 2008)

Ocean Model: The OGCM for the Earth Simulator (OFES), based on the Modular Ocean Model (MOM3), was jointly developed by the Earth Simulator Center and Frontier Research Center for Global Change (Japan). The computational domain is near-global (75°S-75°N), 54 vertical levels, horizontal grid spacing is 0.1°. A 50-year spin-up simulation was forced by monthly climatology of NCEP/NCAR reanalysis data, staring from the WOD'98 temperature and salinity fields without motion. A hindcast simulation from 1950 to 2007 was forced by daily mean NCEP/NCAR reanalysis data, starting from the last output of the spin-up simulation (Sasaki et al., 2008). Additional simulation from July 1999 to 2007 was forced by daily mean QuikSCAT wind stress (Sasaki et al., 2006).

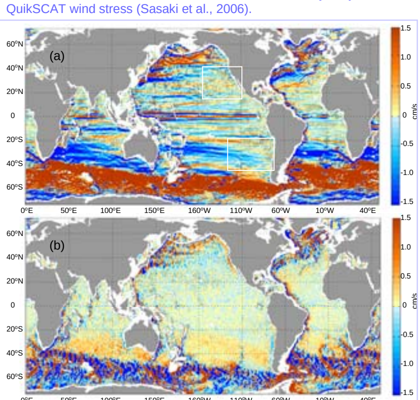


Figure 6. 10-year (1992-2003) mean zonal **(a)** and meridional **(b)** components of velocity at 1000 m depth from the OFES run forced by the NCEP/NCAR reanalysis fluxes. The model quasi-stationary striations qualitatively, although not everywhere quantitatively, resemble the observed features.

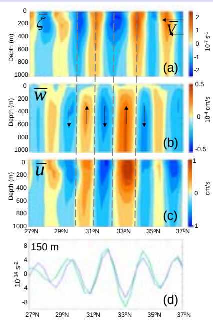


Figure 7. In the eastern **North Pacific** the OFES model forced by the NCEP/NCAR reanalysis fluxes does not reproduce the observed striations (see the panel below), although the time-mean velocities show noticeable anisotropy. The tilt of the apparent striations, which have meridional scale of O(250 km), is close to 0-3°. Vertical cross-sections of zonally averaged relative vorticity **(a)** and high-pass filtered vertical velocity **(b)** reveal the phase shift between them of about 90°. These structures are surface-intensified **(c)** and coherent through the water column. **(d)** The vorticity advection (blue curve) is nearly canceled by the vortex stretching (green curve). A similar zonally averaged mean relative vorticity balance may correspond to the preferred paths of baroclinic, vertically coherent eddies, propagating westward in the presence of large-scale meridional shear.

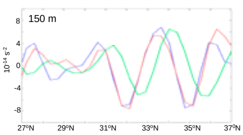


Figure 8. In the model run forced by the QuikSCAT wind stress, the striations, very similar to the observed ones, start to develop. **(e)** The vorticity advection is now nearly balanced by the β-term. Horizontal divergence coincides in phase with the pressure field and should be balanced by dissipation or other terms, implying complex eddy-mean flow interactions.

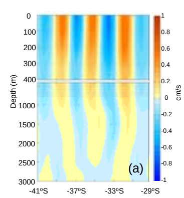
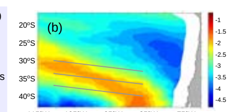


Figure 9. The striations in the eastern **South Pacific** are well reproduced by the OFES hindcast run including the meridional scale of O(400 km), the tilt (~9°) and even the location. The vertical structure of the striations in terms of the zonal component of velocity is shown on figure **(a)**. The striations are coherent trough the water column with the largest contribution from the first baroclinic mode.

(b) Potential vorticity (PV) on σ_θ =27.0 surface. The striations are small-amplitude undulations of the PV contours. Three eastward flowing striations shown above are marked by gray lines. No "PV staircases" were found.



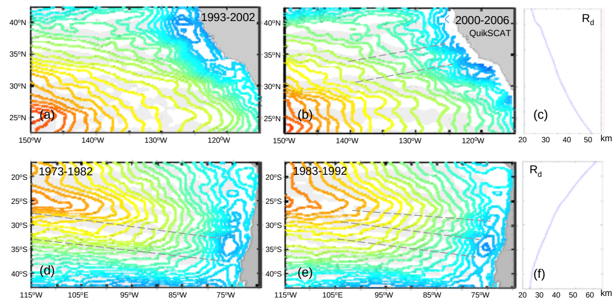


Figure 10. Contours of 10-year mean SSH from the OFES simulations forced by the NCEP/NCAR reanalysis fluxes **(a, d, e)** and the QuikSCAT wind stress **(b)** superimposed on the corresponding high-pass filtered SSH fields (shaded gray indicates negative SSH anomalies). Gray color indicate negative SSH anomalies. Contours of SSH are plotted with 2 cm interval.

The OFES run forced by the NCEP/NCAR reanalysis fluxes does not reproduce the observed striations in the eastern North Pacific. The reason appears to be in the ability of the model to reproduce the permanent meanders of the California Current. The 1993-2002 mean SSH in the eastern North Pacific (fig. **(a)**) shows no clear meanders in the California Current except for the northernmost one at approximately 40°N. Note, however, how this permanent meander causes effective blocking of the eastward flowing North Pacific Current. Changing in the model boundary conditions (QuikSCAT wind stress) led to development of two well pronounced meanders in the California Current (fig. **(b)**), which closely resemble the observed ones. As a consequence, the tilted striated features with meridional scale of O(400 km) develop.

In the eastern South Pacific the model forced by the NCEP/NCAR reanalysis data reproduces the observed striations quite well. All striations are connected to some features in the eastern boundary current. Note changes in the meridional scale of the striations (35-25° S) in two different 10-year mean SSH fields.

Figures **(c)** and **(f)** show latitude dependence of the first baroclinic radius of deformation R_d. Note that the meridional scale of the striations depend rather on the size of the quasi-stationary meanders in the eastern boundary currents, than on R_d. Also the striations seem to be connected to the permanent meanders in the east.

Summary

Analysis of different independent data shows that the quasi-stationary striations are persistent features of the basin-scale oceanic circulation. Even in a presence of a strong seasonal cycle in large-scale oceanographic fields, the striations seem to retain their position. They also seem to retain their coherent structure throughout a wide range of depths. Through the SST signature, the striations may also affect the atmospheric boundary layer.

The modeled quasi-stationary striations qualitatively, although not everywhere quantitatively, resemble the observed features. The realism of the modeled striations in the eastern parts of the subtropical gyres seems to depend on the ability of a model to reproduce the quasi-stationary meanders in the eastern boundary currents. When it happens, the striations are connected to such permanent meanders. The scale and the tilt of the striations on the horizontal plane are determined by the scale of the meanders and the sign and the strength of the meridional component of the large-scale flow. In time-averaged vorticity balance the advection of the striations by the large-scale flow is nearly compensated by the advection of planetary vorticity in the striations as would be expected for stationary long Rossby waves. Distribution of the stretching term suggest non-trivial role of transient motions in maintaining or resisting the striations. Zonal jet-like structures are observed in the ocean under a variety of circumstances. In any particular region the problem of separating different effects, to some extent acting simultaneously, can be difficult. Idealized regional models are needed to isolate dynamical factors responsible for generation and maintenance of the quasi-stationary striations.

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