OCEAN STRIATIONS

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1. DESCRIPTION

Striations are stripy patterns of oceanic jet-like features recently detected in observations [1, 2, 3] and high-resolution models [4, 5]. Observations of the ocean's surface show at least two different types of striations.

Stationary striations (Fig. 1) are best seen in the long-term mean zonal geostrophic surface velocity after removal of the large-scale component by horizontal high-pass filtering. Together with stronger frontal currents, the striations cover the entire ocean. This pattern is robust with respect to the choice of period of averaging, but is barely distinguishable in snapshots that are dominated by much stronger mesoscale eddies. Typically, striations have an orientation close to zonal, with a meridional wave length of 300-500 km, while their crests retain coherence over zonal distances of thousands of kilometers. Stationary striations are surface-intensified and associated with velocity and sea level amplitudes of about 1 cm/s and 1 cm, respectively. In observations, striations are vertically coherent throughout at least upper 700m. In models, these features cover the entire depth range [3].

Time-variant striations (Fig. 2) have been detected in maps of altimetric sea level anomaly [2] and intermediate-depth model velocities [5, 6]. In subtropical gyres, their characteristic amplitude reaches 5 cm. Time-variant striations appear in groups and propagate slowly towards the equator (Fig. 2c). When approximated by a monochromatic wave, the characteristic wavelength, in the domain shown in Fig. 2a, is about 500 km, the azimuth of wave vector is about 180º + 3.5º, the local period is about 4.9 years, and the equator-ward phase speed is about 0.35 cm/s. The crests and troughs of the time-variant striations are aligned with eddies of corresponding sign. The movements of eddies and striations are synchronized so that eddies remain at all times on the same crests or troughs of striations [7].

2. PHYSICS

The physics of the features is not clear yet, and we therefore, use, at least temporarily, the neutral name 'striations'. A large number of hypotheses have been suggested, none of which, however, explains all properties of the striations. Because water particles move along contours of mean dynamic topography and across the striations (Figs. 1c and 1d), the latter are not inertial jets. Therefore, they are neither the zonal jets, predicted by the classical theory of two-dimensional geophysical turbulence, nor associated with PV (potential vorticity) staircases [8], induced by breaking Rossby waves. In addition, the vertical structure of striations is baroclinic and their horizontal scale is less dependent on latitude and energy than predicted by the 'turbulent' Rhines [9] radius. On the other hand, models show that eddy fluxes are large and correlate with the striations [10, 11], that is inconsistent with the concepts of linear Rossby waves, standing in the meridional large-scale flow [3] and of near-coast beta-plumes induced by the nonlinear interaction between along-coast Ekman current and permanent meanders of the eastern boundary current [12]. Preferred paths of eddies that may be associated with stationary striations [13], but whether the eddies are the cause or the consequence of the striations is not clear. Such organization of eddies also rejects the hypothesis that the striations are an artifact of randomly distributed eddies smeared by the time averaging as they propagate towards the west [14].

The origin of the time-variant striations is unknown. High-resolution OGCM's forced by the monthly climatological fluxes produce realistic striations with periods larger than one year. Therefore, striations must be a product of the internal ocean dynamics, and not the result of the air-sea interaction. The characteristic parameters of the observed striations (Fig. 2) are in good agreement with estimates of the most unstable wave in the quasi-geostrophic model of large-scale spiraling flow with density gradient [15]. Interestingly, similar equator-ward propagating patterns were found in early primitive-equation simulations [16], but were attributed to an unrealistic Rhines' mechanism developing over the model's flat bottom. Wavenumber vectors of typical time-variant striations have large meridional components [17]. Additional observed west-ward component is suggestive of linear Rossby

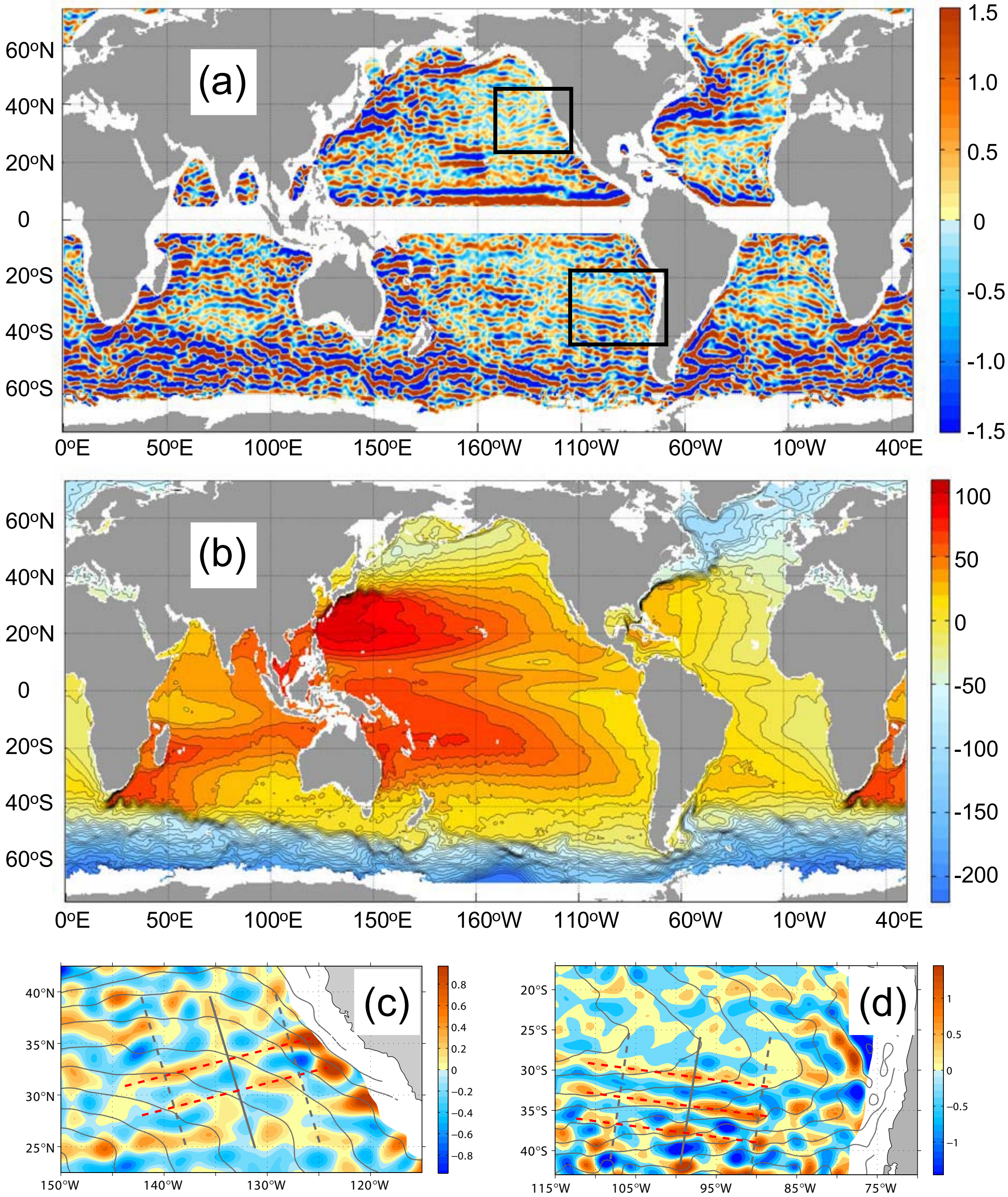

Figure 1. ***Stationary striations.*** *High-pass filtered mean zonal geostrophic velocity (a, [3]), calculated from the 1993-2003 mean dynamic topography (MDT) (b, [7]). Also contours of MDT superposed on striations in the high-pass filtered MDT in the eastern North (c) and South Pacific (d). The filter is two-dimensional Hanning filter of 4^o half-width. Rectangles in (a) show locations of domains (c) and (d). Red dashed lines mark crests of main striations [11]. Units are cm/s (a) and cm (b-d).*

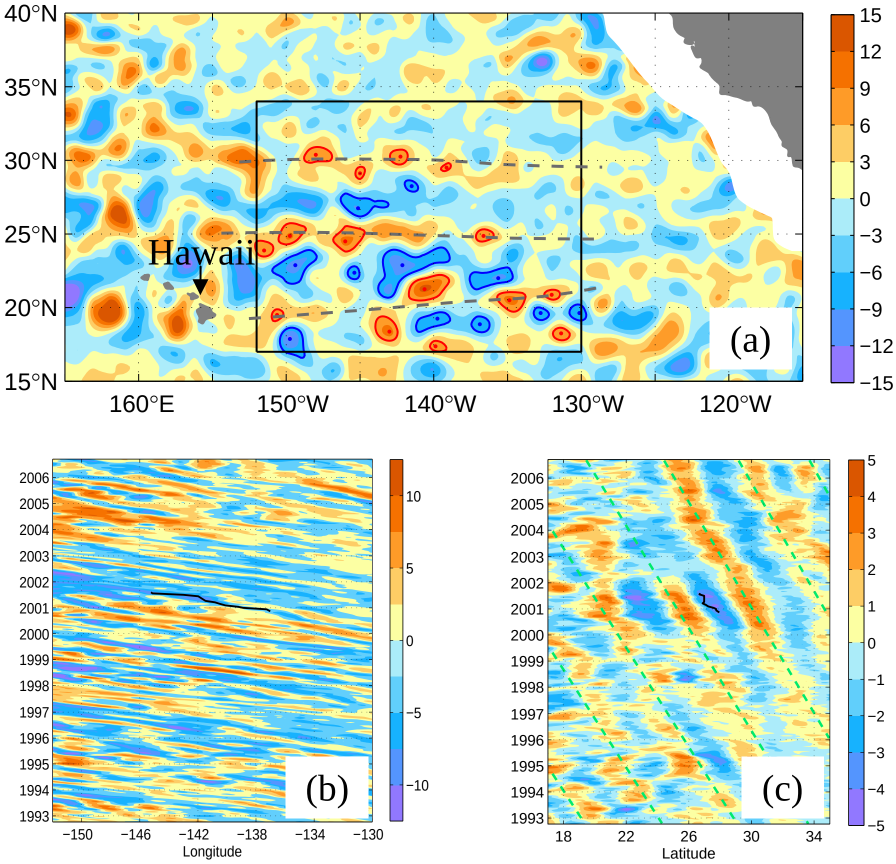

*Figure 2. **Time-variant striations**. (a) August 1, 2001 map of the AVISO sea level anomaly in the eastern North Pacific, high-pass filtered with the two-dimensional Hanning filter of 5^o half-width, (b) Hovmoller longitude-time diagram at 25^{o}N and (c) Hovmoller latitude-time diagram, averaged zonally between 145 and 150^{o}W. Dashed lines in (a) mark crests of striations, and +/- 6 cm contours outline strong eddies. Black lines in (b) and (c) show movement of an individual cyclonic eddy.*

dynamics. However, the alignment of eddies along the striations strongly indicates that nonlinear process are at least as important as linear dynamics.

3. IMPLICATIONS FOR OCEAN AND CLIMATE SCIENCES

Because of their multi-scale (width vs length) structure, the striations link mesoscale eddies and large-scale circulation. Understanding this link is a challenge to modern oceanography. The alignment of existing and the ability of the striations to control the formation of new eddies [18] may indicate that they regularize an otherwise turbulent eddy field by modulating baroclinic instability of the large-scale flow. In this case, oceanic turbulence may be more organized than was previously thought.

Despite their relatively low energy, the anisotropic striations impact horizontal mixing. The distribution of a tracer can be very different with and without striations due to both advection of the tracer by striations and the organization of eddies. Parameterization of these mixing processes may be essential for coarse-resolution coupled climate models.

Ongoing studies suggest that the thermal signature of striations imprints onto the atmospheric planetary boundary layer by changing its stability. This suggests the exciting possibility that striations can modulate the air-sea fluxes on regional and global scales and play a role in the Earth's climate system.

4. OBSERVATIONAL REQUIREMENTS

The study of striations requires high-resolution, basin-scale observations that are continuous for an extended period of time, and it was not possible until satellite data were aggregated into large high-quality data sets. The same striated patterns are detected in historical XBT [3] and drifter data that would not be confident because of high level of eddy noise and random spacing if not the satellite observations in place. In turn, drifter data were critical in providing the absolute reference to the relative dynamic topography measured by satellite altimeters. Striations are best seen in maps of sea level, however, modern nadir-looking satellite radar altimeters may be underestimating their amplitude. Optimal interpolation used to translate the signal from satellite tracks onto two-dimensional grid assumes a correlation function that is characteristic for eddies. Hence, a part of the striated signal is transformed into artificial eddies. Future SWOT mission (wide-swath altimetry) will likely mitigate this problem.

All current high-resolution satellite data are tied to the ocean surface. Little is known about the vertical structure of surface-intensified striations or about striations in the intermediate and deep ocean. The impressive progress made in observational systems such as the array of Argo floats is still insufficient to resolve mesoscale eddies and time-variant striations. Specialized regional experiments are needed to understand the three-dimensional structure and dynamics of the striations.

Resolution and accuracy of air-sea flux observations have to be significantly improved, particularly, in coastal areas, to investigate various kinds of forcing, including beta-plumes, as a possible source of stationary striations, and to carefully assess the impact of striations on atmosphere.

5. REQUIREMENTS TO MODELS

In the foreseeable future, models will likely remain the main tool for exploration of such delicate aspects of mesoscale dynamics as balances of the relative and potential vorticity. Recent improvements in modeling of the upper-ocean circulation need to be accompanied by a comparable progress in simulating, at mesoscale spatiotemporal resolution, intermediate-depth and abyssal currents that currently remain largely unverified.

To evaluate and understand the role that eddies play in the dynamics of striations, basin-wide models have to evolve from eddy-permitting to eddy-resolving and adequately reproduce the internal eddy structure and dynamics. In return, models will greatly benefit from the study of striations. The pattern of striations in Figure 1a provides a dense global grid, every stripe of which is associated with one or more physical processes. Comparison with observations can be used to fine-tune model parameters and to assess model performance on different scales and in different regions.

6. REFERENCES

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