Mechanisms for the Emergence of Ocean Striations in the North Pacific

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In preparation for

Geophysical Research Letters

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KEY POINTS

NEP striations form as coastal vorticity propagates offshore via beta-plumes.

Vorticity is anchored by coastal geometry, so striations remain stationary.

Striation magnitude is constrained at the shelf by potential vorticity trapping.

Abstract

Recent observations suggest that the mean mesoscale oceanic zonal velocity field is dominated by alternating jet-like features often referred to as striations. Here the generating dynamics of Northeast Pacific striations are explored with a set of 120-year eddy-permitting model simulations. Simulations are conducted with decreasing complexity towards idealized configurations retaining the essential dynamics and forcing necessary for striation development. For each simulation, we diagnose the spin-up of the ocean model and the sensitivity of striation generation to topography, coastal geometry, and the wind stress, which modulates the gyre circulation and the nonlinearity of the flow field.

Results indicate that Northeast Pacific striations develop predominantly at the eastern boundary and migrate westward in congruence with beta-plumes both in the nonlinear and quasi-linear regimes. Mean striations have their source in the coastline geometry, which provides quasi-steady vorticity sources energized by eastern boundary current instabilities.

INDEX TERMS

Numerical modeling

Continental shelf and slope processes

Time series experiment

1. INTRODUCTION

Observations have determined that the mean mesoscale oceanic zonal velocity field is dominated by quasi-permanent jet-like features commonly referred to as striations (Maximenko et al., 2005; 2008; Huang et al., 2007; Ivanov et al., 2009; van Sebille et al., 2011; Buckingham and Cornillon, 2013). These features have also been detected in high-resolution ocean models (Nakano and Hasumi, 2005; Richards et al., 2006; Kamenkovich et al., 2009) including the Regional Ocean Modeling System (ROMS) (Huang et al., 2007). Although mechanisms for the emergence of mean zonal jets have been suggested using theory and idealized models (Rhines 1975; Maltrud and Vallis 1991; Panetta 1993; Rhines, 1994; Cho and Polvani, 1996; Galperin et al., 2006; Nadiga, 2006; Baldwin et al., 2007; Dritschel and McIntyre, 2008), the dynamics of striations remain uncertain.

Scott et al. (2008) showed that mesoscale eddies follow preferred pathways and so may produce the striated features seen in mean zonal velocity. Schlax and Chelton (2008) suggested that striations are an artifact of time-averaging large random mesoscale eddies. Melnichenko et al. (2010) showed, however, that eddies contribute to the potential vorticity (PV) variance of striations, indicating that they are dynamically distinct. Hristova et al. (2008) hypothesized that striations might be related to radiating instabilities of eastern boundary currents (EBC's). Wang et al. (2012) showed using a simple single-layer quasi-geostrophic model that radiating modes excited nonlinearly within an EBC do trigger striations.

Centurioni et al. (2008) reconstructed the time-mean map of geostrophic velocities at 15 m depth using drifters and satellite altimetry and found zonal currents connected to permanent meanders of the California Current System (CCS). They proposed that vorticity associated with these meanders radiates Rossby waves that form stationary jets known as beta-plumes (Rhines, 1994; Afanasyev et al., 2012; Belmadani et al., 2013).

Here we test this hypothesis with sensitivity experiments using model output. By altering the model bathymetry, we remove the effect of topographic features and a continental slope. We then decrease the strength of atmospheric forcing by an order of magnitude to test the role of nonlinear dynamics, as well as coarsen the resolution of the model to 40 km to test the role of eddy variability. Finally, we replace the eastern boundary coastline with a flat meridional wall to test the effects of coastal geometry.

2. Ocean Model and Experimental setup

This analysis employs a set of 120-year ROMS integrations (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008, Curchitser et al., 2005) over 180°W-105°W; 9°N-53°N with a horizontal resolution of 20 km and 30 vertical layers. This configuration has captured both the mean and variability of the CCS (Marchesiello et al. 2003; Di Lorenzo et al., 2008; Di Lorenzo et al., 2009). Vertical diffusion is parameterized according to the Large/McWilliams/Doney scheme (Large et al., 1994). Forcing is a climatological NCEP wind stress (Kistler et al., 2001) without buoyancy fluxes. NCEP heat fluxes are employed with a nudging toward NOAA extended sea surface temperatures (SST's) (Smith and Reynolds, 2004) in order to avoid drifts in model SST (Josey, 2001). Horizontal boundaries are closed walls, and the control topography is extracted from Smith and Sandwell (1994). Integrations begin from rest with a uniform density profile extracted from the World Ocean Atlas 2005 (Locarnini et al., 2006; Antonov et al., 2006).

Striations are diagnosed using zonal currents at 300 m, where the signature of the gyre circulation is reduced.

The role of topography is explored in a set of experiments (*flat+slope)* (Table 1), in which a uniform bottom depth (5000 m) is prescribed everywhere except along the eastern boundary (and around the Hawaiian and Aleutian islands). Here a uniform shelf slope was applied. The slope was taken from the average continental slope between 30°N and 40°N. Within the *flat+slope* set, the role of nonlinearity was determined by reducing the strength of the forcing by a factor of ten (*flat+slope*, weakly nonlinear). The role of mesoscale eddies was determined by further coarsening the grid to 40 km (*flat+slope*, weakly nonlinear, non-eddy resolving). In the *flat* runs, sensitivity to topography was determined by removing the continental shelf and prescribing a uniform 5000 m bottom depth. In the *wall* run, the coastlines are replaced with a meridional wall at 125°W. The *control*, *flat+slope*, *flat*, and *wall* integrations are all able to reproduce the gyre circulation (Figs. 1a, 1b, 1c, and 1d).

3. SPIN-UP OF STRIATIONS FROM THE CALIFORNIA CURRENT

Progressive means of 300 m zonal velocities from the *control* run over the first 6, 12, and 120 months (Figs. 2a, 2b, and 2c) indicate that striations emerge as zonal plumes generated offshore from notable topographic features, as well as features of the California coastline, consistent with observations (Centurioni et al., 2008).

Progressive averages from the *flat+slope* experiment (using the idealized bathymetry and slope describes in Section 2) with full forcing and 20 km resolution (Figs. 2d, 2e, and 2f), show that, in the absence of topographic forcing, striations emerge on similar time scales and have similar magnitude, but evince more spatial coherence. This suggests that topography plays a significant, but lesser influence on offshore striations, in agreement with South Pacific observations (Buckingham and Cornillon 2013). It is, however, clear that the primary source of striation energy is located near the eastern boundary and that striation development is kinematically consistent with beta-plumes.

To determine the sensitivity of striation development to nonlinear background velocity regimes, we examine two additional *flat+slope* experiments, the first in which the magnitude of the wind forcing is reduced by a factor of ten (i.e. weakly nonlinear), and a second in which the resolution of the model is additionally coarsened to 40 km (i.e. weakly nonlinear and non-eddy-resolving). The results of these experiments are indistinguishable visually (not shown) and images are derived from the weakly nonlinear/eddy-resolving case (Figs. 2g, 2h, and 2i). Model output still evinces development of apparent eastern boundary beta-plumes. Striations still dominate 300 m zonal velocity and are maintained at a comparable magnitude to that of the full forcing case. Meanders take longer to develop with the reduced wind energy input (Fig. 2e and 2h), and striations are more strongly zonal due to a decreased large-scale circulation.

To evaluate the importance of the continental slope in the formation of striations, we performed three experiments with uniform 5000 m bottom depth and vertical continental boundaries (*flat* experiments, Table 1). When we remove the continental sole in the *flat* experiment, the magnitude of striations decreases to roughly half that of the *control* and *flat+slope* runs (Figs. 3a, 3b, and 3c) even though the wind forcing is the same, and the gyre circulation is maintained at the same magnitude (Figs. 1b and 1c). The meanders that are sources of vorticity for striations are weaker in the *flat* run (Fig.1c), which may explain the reduced striation magnitude. Continental slopes also impose a dynamical boundary to the offshore propagation of potential vorticity anomalies, so that anomalies from the coast are “trapped” on the shelf and unable to propagate freely offshore until they reach a critical magnitude. Although we do not examine the dynamics of this potential vorticity trapping in detail, we hypothesize that the absence of the continental slope in the *flat* run allows beta plumes to propagate westward independently of their magnitude. Consistent with this hypothesis, when we reduce the wind magnitude by a factor of ten in the *flat* weakly nonlinear experiment (Table 1), striation strength is also reduced by an order of magnitude (Figs. 3d, 3e, and 3f). This linear response to the wind magnitude is not observed in the *flat+slope* case, where reducing the wind forcing by an order of magnitude only reduces striation strength by a small fraction (Figs. 2f and 2i). This leads us to conclude that without a continental slope, striations freely propagate offshore as they develop, whereas in the slope case, anomalies must reach a critical magnitude in order to escape. Despite the slower spin-up of the CCS in the weakly nonlinear *flat+slope* experiment, the magnitude enforced by the slope ensures that striations remain strong in the mean (Fig. 2i). The results of the *flat* weakly nonlinear non-eddy-resolving experiments are again visually indistinguishable and are not presented.

The role of coastal geometry was further explored in the *wall* experiments (Table 1) by removing the coastline and setting a wall along the eastern boundary (125°W) (Fig. 1d). While the spin-up is characterized by the formation of striations, they are short-lived in the mean, and their signature eventually disappears (Figs. 3g, 3h, and 3i). Striations are subsumed in the mean because meanders are no longer anchored to coastal features and propagate freely, consistent with the Wang et al. (2012) model.

4. Conceptual Model for Striations in the Eastern North Pacific

By analyzing the spin-up of the ROMS model, we showed that Northeast Pacific striations are not necessarily forced by surface fluxes of momentum or buoyancy, but can develop from vorticity sources associated with topography and/or instabilities along the eastern boundary, a process for which we propose the following mechanism.

EBC flow is unstable (Walker and Pedlosky 2002, Hristova et al. 2008, Wang et al. 2012), and generates meanders that are anchored to coastal features (Batteen, 1997; Centurioni et al., 2008). The associated vorticity propagates westward as a beta-plume, consistent with observations of striation attachment to CCS meanders (Centurioni et al. 2008). It also agrees with the two most basic observations presented here: that persistent striations are energized within the boundary current as it spins up, and that they develop primarily in response to coastal geometry. This progression is most clear in the *flat* experiment (Figs. 3a, 3b, and 3c), where jet patterns remain in the absence of bottom topography and continental slope, and in the *wall* experiment, in which permanent striations could not develop without coastal features to anchor vorticity anomalies.

These results strongly suggest that intense striations arise at the coast. The fact that striations emerge in a non-eddying regime indicates that they are unlikely to result solely from time-averaged mesoscale eddy tracks, consistently with recent results from idealized models (Nadiga and Straub, 2010) and observations (Ivanov et al., 2012; Buckingham and Cornillon, 2013). The extreme contrast in magnitude between the *flat+slope* weakly nonlinear and *flat* weakly nonlinear experiments indicates that potential vorticity trapping constrains striation strength.

There are a number of significant idealizations in our model. Climatological wind forcing precludes small-scale winds that may modulate striations (Chelton et al., 2004; Taguchi et al., 2012). NCEP winds also produce biases in EBC's (Colas et al., 2012; Cambon et al., 2013), which may alter stratification and associated coastal instabilities. A purely kinematic treatment is also limited in its ability to determine the wider role of striations in the mean circulation, as well as to generalize to other basins. Further study that focuses on the dynamics and vorticity budgets of striations will be vital an understanding of the dynamical balances associated with their generation.

ACKNOWLEDGEMENTS

This research was partly supported by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), by NASA through grant No.NNX07AG53G, and by NOAA through grant No. NA11NMF4320128, which sponsor research at the International Pacific Research Center. . Additional support was provided by the NASA Grant NNX08AR49G. This is the International Pacific Research Center/School of Ocean and Earth Science and Technology Publication Number XXXX/YYYY.

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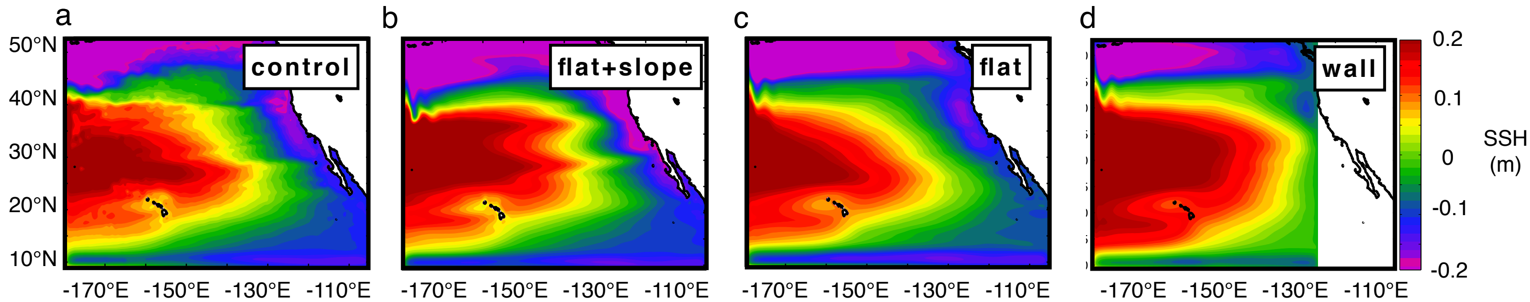
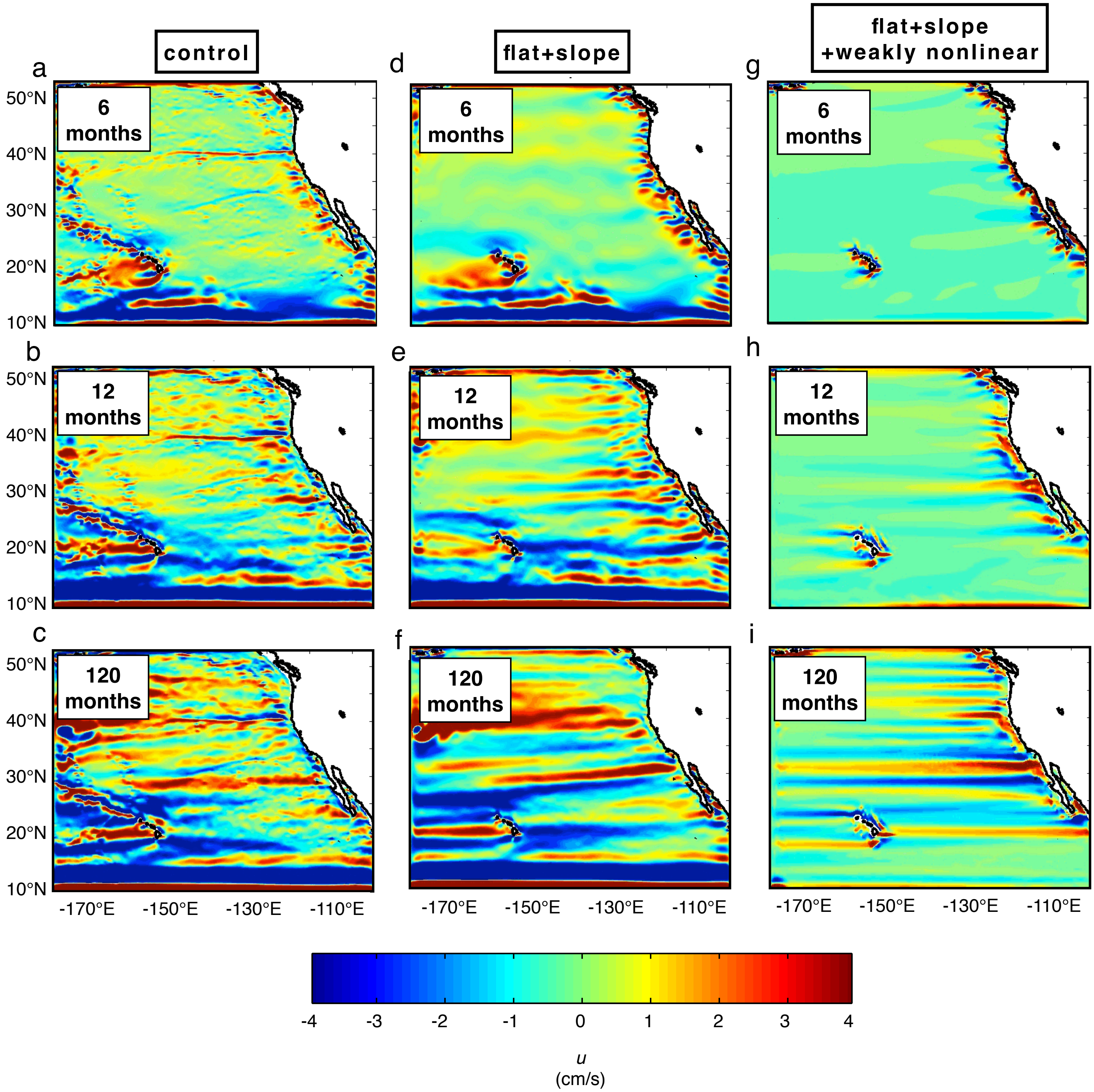
FIGURE CAPTIONS

Figure 1. - 1a , 1b, 1c, and 1d show the 120 year means of sea surface height (SSH) from our *control, flat+slope, flat,* and *wall* experiments, respectively.

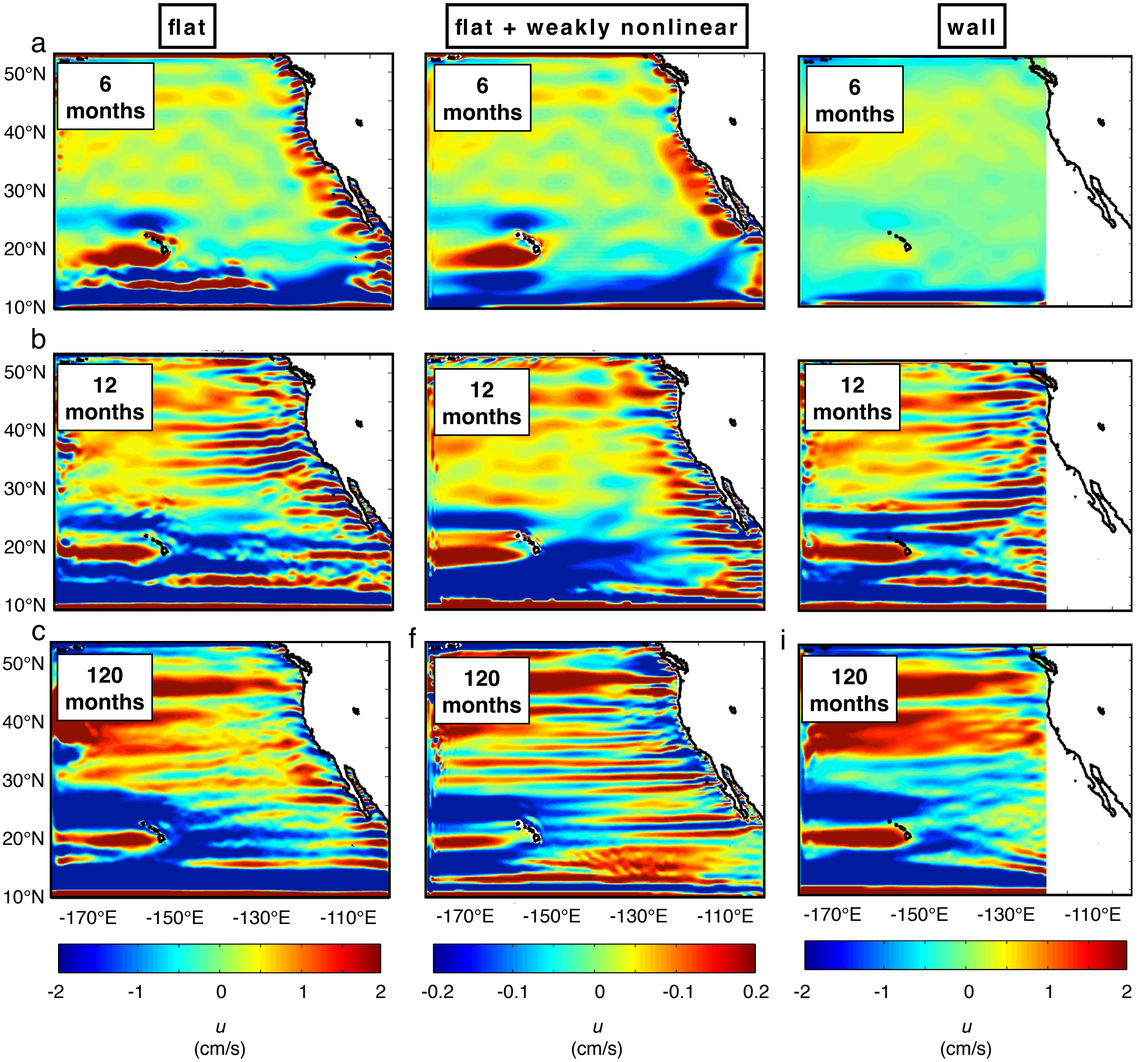
Figure 2. - 2a-2c show progressive averages of 300 m depth zonal currents (*u*) at 6, 12, and 120 months, respectively, from our *control* experiment . 2d-2f are the corresponding plots for the *flat+slope* case, while 2g-2i show similar plots for the *flat +slope* weakly nonlinear experiment.

Figure 3. - 3a-3c show progressive averages of 300 m *u* at 6, 12, and 120 months, respectively, from our *flat* experiment . 3d-3f correspond to the *flat* weakly nonlinear case. 3g-3i corespond to the *wall* experiment.


a
b
c
d
control
flat+slope
flat
wall
50°N
40°N
30°N
20°N
10°N
-170°E
-150°E
-130°E
-110°E
0.2
0.1
0
-0.1
-0.2
SSH
(m)



control
flat+slope
flat+slope
+weakly nonlinear
a
b
c
d
e
f
g
h
i
6
months
12
months
120
months
50°N
40°N
30°N
20°N
10°N
-170°E
-150°E
-130°E
-110°E
-4
-3
-2
-1
0
1
2
3
4
u
(cm/s)



flat
flat + weakly nonlinear
wall
a
b
c
f
i
6 months
12 months
120 months
50°N
40°N
30°N
20°N
10°N
-170°E
-150°E
-130°E
-110°E
-2
-1
0
1
2
-0.2
-0.1
0
-0.1
0.2
u (cm/s)

Exp. Name	**Geometry**	**Forcing**	**Resolution**
control	Full topography	full	20 km
flat+slope	Flat bottom at 5000 m with	full	40 km
flat+slope, weakly nonlinear	uniform continental shelf	full/10	40 km
flat+slope, weakly nonlinear, non-eddy-resolving	along the eastern boundary	full/10	40 km
flat	Flat bottom at 5000 m	full	20 km
flat, weakly nonlinear		full/10	40 km
flat, weakly nonlinear, non-eddy-resolving		full/10	40 km
wall	Flat bottom at 5000 m with eastern boundary meridional wall	full	20 km