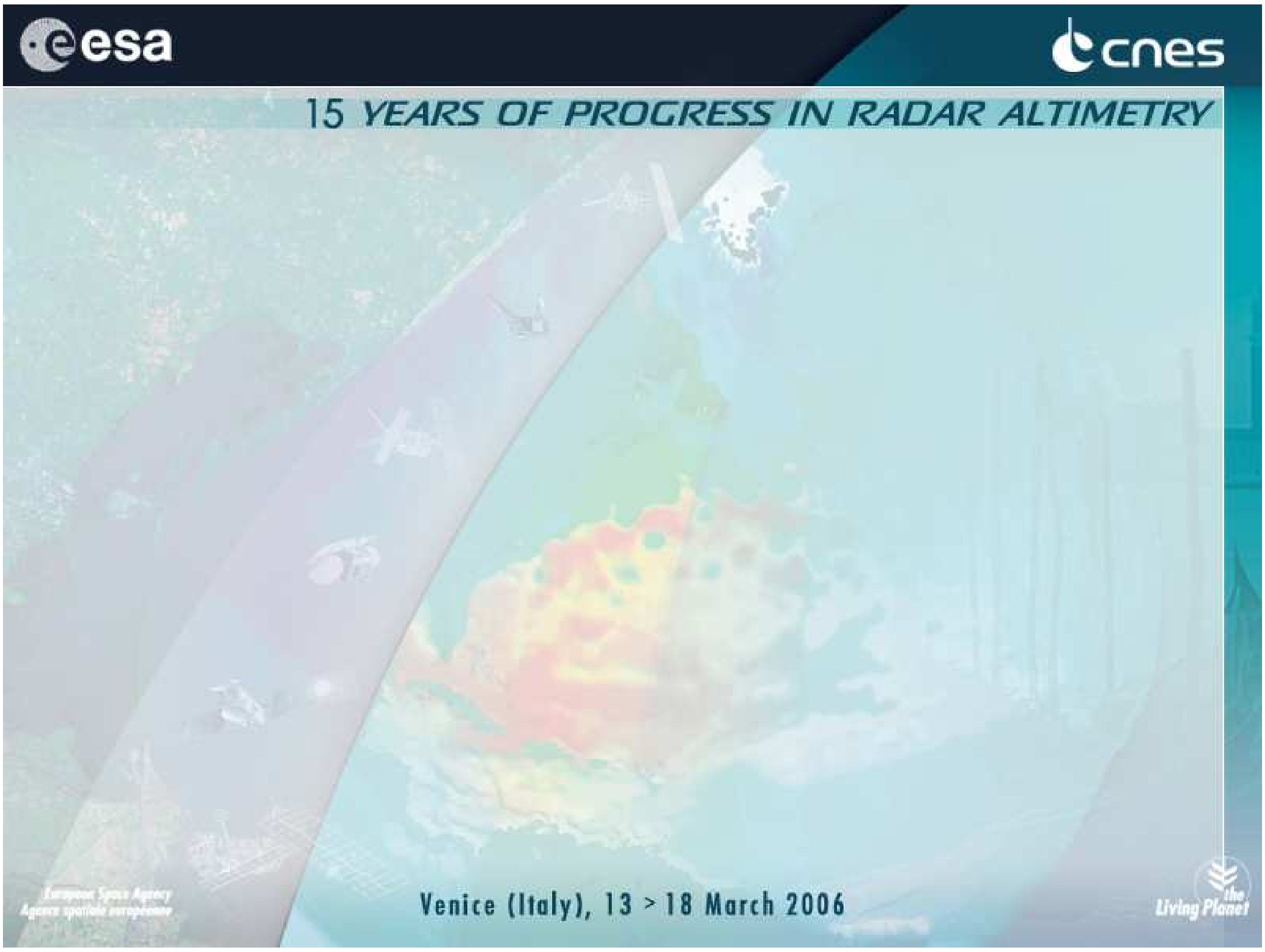
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SEASONAL AND INTERANNUAL VARIABILITY OF THE NORTH PACIFIC OCEAN: MODELING RESULTS AND THEIR VALIDATION THROUGH ALTIMETER DATA

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ABSTRACT/RESUME

Numerical results of process-oriented model studies, successfully validated with altimeter data, have provided new insight into the dynamical functioning of relevant aspects of the seasonal and interannual variability of the North Pacific Ocean. The wind-driven seasonal variability in the eastern tropical North Pacific is found to depend substantially on a remote equatorial forcing due to a teleconnection mechanism known to play a major role in the El Niño dynamics, and on the beta-refraction of baroclinic Rossby waves. Passing to mid-latitudes, an idealized Kuroshio Extension forced by a time-independent climatological wind evidences a decadal chaotic variability in significant agreement with altimeter observations for the period 1992-2004. This suggests that purely internal nonlinear oceanic mechanisms may be the predominant cause of the observed decadal variability of the jet, in contrast with the common opinion that such variability is basically due to wind-driven changes of the Sverdrup return flow.

1. INTRODUCTION

Data from recent altimetric missions (*Topex /Poseidon*, *ERS 1-2*, *Envisat*, *Jason-1*) have provided an unprecedented tool for monitoring and investigating synoptically the variability of the surface oceanic currents and of the ocean heat content. A more precise determination of the geoid (thanks to the new gravity missions such as *GRACE* and *CHAMP*) is now allowing the mean surface circulation to be investigated as well. This has, in general, relevant implications as far as the understanding of the role of the ocean in the global climate is concerned. More specifically, a fundamental application of altimeter measurements concerns the interpretation of some large-scale oceanographic processes that have a surface signature: the validation of theoretical hypotheses regarding their functioning can benefit substantially from the synoptic information (previously lacking) provided by the altimetry.

In connection to this, in the present paper some relevant aspects of the variability of the North Pacific Ocean are discussed in the framework of process-oriented model studies, whose results are successfully validated with altimeter data, namely: the wind-driven seasonal variability in the eastern tropical ocean (section 2), the beta-refraction of baroclinic Rossby waves in the same region (section 3) and the decadal variability of the Kuroshio Extension (Section 4). The details of these analyses can be found in [1,2,3].

2. SEASONAL VARIABILITY OF THE TROPICAL NORTH PACIFIC

2.1. The oceanographical problem and the model implementation

The main periodicity in the large-scale ocean heat content and circulation is the seasonal cycle, due to annual variations of heat, freshwater and momentum exchanges with the atmosphere. In particular, the seasonal variability of the large-scale ocean circulation is mainly driven by the momentum flux associated with the wind, and has very different features for different latitudinal bands. At mid and high latitudes the oceanic response to seasonally varying winds is mainly barotropic and is driven by the Ekman pumping (e.g., [4]), which is proportional to the local wind stress curl. Baroclinic Rossby waves give some contribution for latitudes higher than the critical one for the annual period (φ~35°). On the other hand, in the tropics annual baroclinic Rossby waves, being much faster than those at midlatitudes, are able to shape the wind-driven seasonal variability in the central and eastern tropical Pacific and Atlantic oceans (e.g., [5,6,7,8,9,10]). Still in the tropics, in the central and western part of the basins Ekman pumping and topographic interactions can give important contributions to the seasonal variability.

The most striking (and energetic) aspect of the wind-driven seasonal variability in the eastern tropical Pacific (and for very low latitudes also in the central part of the ocean) is the presence of annual baroclinic Rossby waves radiating from the eastern boundary and yielding a pronounced "beta-refraction" toward the equator due to the dependence of phase speed with latitude. Although this was first recognized through the analysis of *in situ* data (e.g., [5,6,11]), it was only with altimeter data that this prominent seasonal feature could be analyzed synoptically (e.g., [12]). According to a fairly common opinion such waves (and their Atlantic counterpart) are thought to be generated at the oceanic eastern boundary mainly by the local action of seasonally varying winds (e.g., [5,6,7,8,9,10]). However, it is interesting to notice that in [13] wave energy in the eastern Pacific, as observed in *Topex/Poseidon* (T/P) data, was found to be strongly correlated with SSH anomalies at the equator, suggesting a predominantly non local generating mechanism. If that is the case, then such mechanism is presumably due to Rossby wave forcing from poleward propagating coastal Kelvin waves generated in the equatorial region by wind stress anomalies through a teleconnection proposed in [14] in the different context of El Niño dynamics. So the following questions arise: are the annual Rossby waves radiating from the eastern boundary of the North Pacific Ocean generated at the coast mainly through a local or a remote wind forcing? Moreover, in the case of a prevalent remote generation, is the teleconnection cited above the actual physical mechanism that shapes the response?

The process-oriented model study [1] provides plausible answers to these questions: a box model for the wind-driven seasonal variability in the North Pacific Ocean was implemented and the obtained results (validated with the T/P altimeter data presented in [15]) support the hypothesis of a predominant remote forcing associated with the above mentioned teleconnection mechanism, as we are going to discuss.

In [1] a two-layer primitive equation ocean model is implemented in an idealized Pacific spanning the latitudinal range φ=30°S/52°N. The forcing is provided by an idealized seasonally varying wind field obtained from the *European Centre for Medium-Range Weather Forecasts* (*ECMWF*) seasonal climatology presented in [16]. The thin solid lines of Fig. 1a show the meridonal profiles of the 10-m *ECMWF* zonally averaged zonal wind stress over the North Pacific Ocean averaged over December-January-February (line DJF) and June-July-August (line JJA), as digitized from *figure 5* of [16]; the thick solid line shows the meridional profile of the annual mean obtained by averaging the DJF and JJA lines; finally, the thick dashed line represents the meridional profile of the seasonally varying winds while the thin dashed line is the analytical approximation of the thick dashed line, and represents the meridional profile of the seasonally varying zonal wind stress used to force the circulation model.

2.2. Validation with altimeter data

Despite the simplicity of this model, validation of the gross features of the wind-driven seasonal variability in tropical latitudes could be carried out. In [15] meridional transport fluctuations q_{ALT} (obtained, under the assumption of barotropic flow, from more than 2 years of T/P data starting from October 1992) and q_{SVE} (obtained from *ECMWF* winds through the Sverdrup relation) were computed according to:

$$q_{ALT} = D\frac{g}{f}\frac{\partial\eta}{\partial x}; \quad q_{SVE} = \frac{curl_z \boldsymbol{\tau}}{\rho\beta} \qquad (1)$$

where η is the dynamically active sea surface height anomaly (SSH), x is the zonal coordinate, D the water depth, g the acceleration of gravity, f the Coriolis parameter, $\boldsymbol{\tau}$ the *ECMWF* surface wind stress, ρ the mean water density and β gives the planetary beta effect. The r.m.s. of q_{SVE} in a zonal belt centered at 13°N was found to be much smaller than that of q_{ALT} ($\mu = \sigma_{SVE} / \sigma_{ALT} \cong 0.15$), this being a clear symptom that the variability is locally predominantly baroclinic. In [15] those quantities were then integrated spatially: the meridional transports Q_{ALT} and Q_{SVE} obtained by integrating μq_{ALT} and q_{SVE}, respectively, over a zonal belt centered at 13°N with a latitudinal extension of 6° were reported in *figure 5c* of [15].

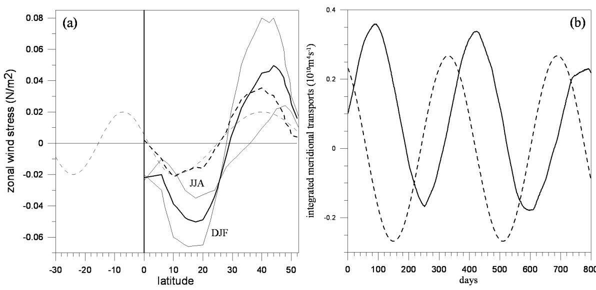

Figure 1. (a): Meridional profiles of the wind stress; the thin dashed line is the profile of the analytical wind field used to force the circulation model (see text). (b): Solid line: numerical Q_{ALT}; dashed line: numerical Q_{SVE} (see text). This figure is directly comparable with figure 5c of [15] (adapted from [1]).

Analogous quantities are computed using the numerical results in [1]. First of all the ratio μ is found to be in very good agreement with the corresponding experimental value: $\mu \cong 0.12$. Moreover, the time series of Q_{ALT} and Q_{SVE} (reported in Fig. 1b) show that Q_{SVE} leads Q_{ALT} with a time lag of about 3 months, again in significant agreement with the altimeter derived data (compare Fig. 1b with *figure 5c* of [15]).

2.3. Dynamical analysis of the numerical results

The successful validation with altimeter data just discussed insures that the model is able to reproduce with sufficient accuracy the main features of the seasonal variability in the eastern tropical North Pacific. Thus, one has a simple modeling tool to investigate the nature of the dynamics that lies behind the signals used for validation (such as those shown in Fig. 1b). A detailed analysis of the results, based also on sensitivity experiments in [1] evidences that the oceanic response in the tropical region is mainly in the form of annual baroclinic Rossby waves (with a strong beta-refraction structure, see next section) radiating from the eastern boundary and generated by the passage of northward propagating coastal Kelvin waves, which are in turn produced remotely by seasonally varying winds in the equatorial wave guide, through a dynamical mechanism known to play a major role in the dynamics of El Niño events. Therefore, these model results suggest that the annual Rossby waves observed in the eastern tropical North Pacific may be mainly generated remotely in the equatorial band rather than by varying winds along the eastern coast, as considered in other studies.

3. SPECTRAL ANALYSIS OF BETA-REFRACTED ROSSBY WAVES

3.1. Beta-refraction as revealed by altimeter data

The model study summarized in the preceding section has evidenced that the oceanic response to seasonally varying winds in the eastern part of the tropical belt is in the form of baroclinic Rossby waves radiating from the eastern boundary that, because of the dependence of Rossby wave-speed with latitude, possess a peculiar funnel-shaped spatial distribution due to the longitudinal confinement produced by the so-called "beta-refraction", studied analytically in [17]. It should be stressed that such mechanism is not limited to annual Rossby waves but is active, in principle, for any subinertial frequency. Due to its large-scale and highly time-dependent structure, only recently beta-refracted Rossby waves could be revealed synoptically thanks to T/P and ERS1-2 data analyses.

In [12] T/P altimeter data showed a weak westward penetration of baroclinic Rossby waves in the form of beta-refracted patterns, although no quantitative analysis was carried out to this respect. In [18] evidence was given of biennial beta-refracted Rossby waves in the Pacific basin from T/P data, but with no quantitative analysis. In [19] time-longitude plots of SSH anomalies derived from T/P altimeter data at 8°N, 14°N and 20°N were presented: the seasonal cycle and El Niño/La Niña events manifest themselves in terms of baroclinic Rossby waves confined in an eastern latitude-dependent band (in that study, again, no explicit reference was made to the beta-refraction). In [20] the authors considered 8 years of T/P altimeter data in the North Pacific Ocean with the seasonal cycle removed. Signatures of coastal Kelvin waves propagating northward from the tropics and of Rossby waves generated by their passage were clearly revealed. Moreover, in order to test the relative importance of Rossby waves generated by the wind in mid ocean and of those generated at the eastern boundary, "boundary-driven" waves were simulated numerically after prescribing the observed coastal variability as boundary forcing. The correlation between the simulated boundary-driven Rossby wave SSH signal and the T/P SSH anomaly were then computed: the map of the correlation coefficients (*figure 4(a)* in [20]) shows a typical beta-refracted Rossby wave pattern (although, once more, such effect was not taken into consideration).

3.2. Numerical results and analysis of the teleconnection mechanism

Although, as seen above, the actual occurrence of the beta-refraction in tropical latitudes is clearly revealed by altimetric observations, a systematic and quantitative study based on altimeter data specifically devoted to analysing beta-refracted boundary-driven baroclinic Rossby waves appears to be still lacking, yet it could provide valuable information on the oceanic variability, particularly in tropical oceans. To this respect, a model study aimed at gaining insight into the spectral features of this part of the variability was carried out in [2] in view of a possible altimetric validation. The same two-layer model implemented in [1] is forced by a white-noise wind stress with a latitudinal dependence shown in Fig. 2 (solid line), and a spectral analysis of the zonal and meridional, barotropic and baroclinic velocity components is carried out. Several dynamical features are identified in terms of boundary-driven Rossby waves, and their spatial structure and frequency dependence are examined.

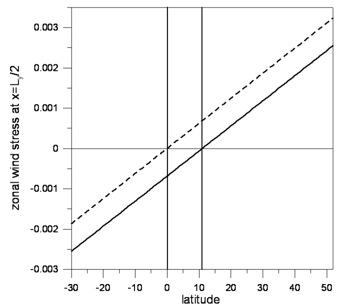

Figure 2. Meridional profiles of the wind stress forcing for φ_0=11° (solid line) and φ_0=0° (dashed line).

How can the beta-refraction of Rossby waves be characterized quantitatively? Although a ray theory of beta-dispersion of low-frequency Rossby waves propagating from meridional and sloping coastlines was developed long ago in [17], it is rather surprising that in recent studies of the tropical variability based on altimeter data, in which beta-refracted waves clearly emerge (as seen in section 3.1), no application of those theoretical results was made. Besides [17] we believe that in [21] a simple, yet powerful criterion to determine the shape of beta-refracted wave patterns was proposed which could be used in interpreting the altimeter-derived oceanic variability in the eastern tropical oceans. In [21] it was shown that the offshore scale of the response produced by fluctuating winds is the internal Rossby deformation radius R_i for forcing frequencies higher than the Rossby cutoff frequency,

$$\bar{\nu} = \beta R_i / 4\pi \qquad (2)$$

(the maximum frequency for which Rossby waves can exist at that latitude), while, for lower forcing frequencies it is equal to the distance covered by a Rossby wave during a period, i.e. to the wavelength for that frequency. In Fig. 3a the blue line, given by

$$\tilde{x} = L_x - \frac{\beta R_i^2}{\nu} \qquad (3)$$

($x=L_x$ corresponds to the eastern boundary), represents the western limit of the low latitude beta-refracted Rossby waves according to this theory for 10°N, while the horizontal black line shows the cutoff frequency $\bar{\nu}$ according to Eq. 2, above which the offshore length scale should be given by the Rossby radius of deformation. In general, the frequency dependent shadow zone obtained in the numerical simulations agrees very well with the theoretical one delimited by the western and northern limits according to Eqs. 2-3, as shown, for example, in the spectral density map of Fig. 3a for 10°N.

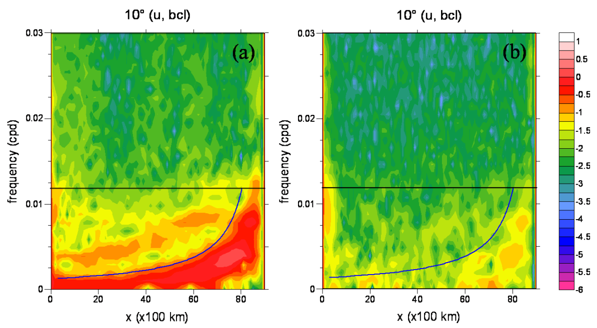

Figure 3. Longitude-frequency maps of Log_{10} of the spectral density of the zonal component of the upper layer baroclinic velocity at 10°N. (a) response to the forcing given by the solid line of Fig. 2; (b) response to the forcing given by the dashed line of Fig. 2. For the black and blue lines see the text (adapted from [2]).

The remote equatorial forcing of boundary-driven beta-refracted Rossby waves (revealed in [1], section 2.3, for the annual frequency) can be verified for a wide range of forcing frequencies by comparing Fig. 3a with Fig. 3b. In the latter the logarithm of the spectral density of the response to a white wind stress having the meridional profile given by the dashed line of Fig. 2 is reported. In this case the latitude φ_0 at which the wind stress vanishes corresponds to the equator, while it is φ_0=11° (solid line of Fig. 2) for the basic numerical experiment (Fig. 3a). The baroclinic signal shown in Fig. 3b is orders of magnitude smaller than that shown in Fig. 3a, despite the fact that the two cases correspond to forcings with exactly the same wind stress curl (it is usually assumed that the large-scale subinertial, "quasi-geostrophic" oceanic response depends only on the curl of the wind stress)!

This apparently paradoxical result can be easily explained according to the remote equatorial forcing mechanism as follows. Referring to Fig. 3a, the zonal winds in the equatorial band are strong and flow, instantaneously, in the same direction North and South of the equator (see the solid line of Fig. 2). The corresponding Ekman transport at the equator produces upwelling (easterly winds) or downwelling (westerly winds) events with consequent formation of eastward propagating equatorial Kelvin waves and the triggering of the teleconnection mechanism described above. On the contrary, referring to Fig. 3b, weak zonal winds are anti-symmetric around the equator (see the dashed line of Fig. 2), and this does not allow for the formation of equatorial Kelvin waves in mid-ocean.

4. LOW-FREQUENCY VARIABILITY OF THE KUROSHIO EXTENSION

4.1. What is the main cause of the low-frequency variability of the Kuroshio Extension as observed by the altimetry?

The Kuroshio Extension (K.E.) is the eastward-flowing, free, inertial meandering jet formed by the confluence of the Kuroshio and Oyashio western boundary currents; it constitutes, therefore, a front separating the warm subtropical and cold subpolar waters of the North Pacific Ocean. The K.E. is a region of the world's ocean where one of the most intense air-sea heat exchanges takes place. It is also the region of the North Pacific with the highest eddy kinetic energy level and in which large-scale interannual changes lead to high temperature anomalies that are capable of enhancing the variability of the midlatitude coupled ocean-atmosphere system, and thus, of strongly affecting North American climate (e.g., [22]). It is therefore very relevant, from a climatic point of view, to investigate the nature of the K.E. system.

T/P and ERS 1-2 altimeter data have clearly revealed ([22,23,24]) that the K.E. undergoes low- frequency (nearly decadal) bimodal oscillations between an "elongated" and a "contracted" state, the former having a stronger meandering path, a larger eastward surface transport, a greater zonal penetration and a more northerly zonal-mean path compared with the latter.

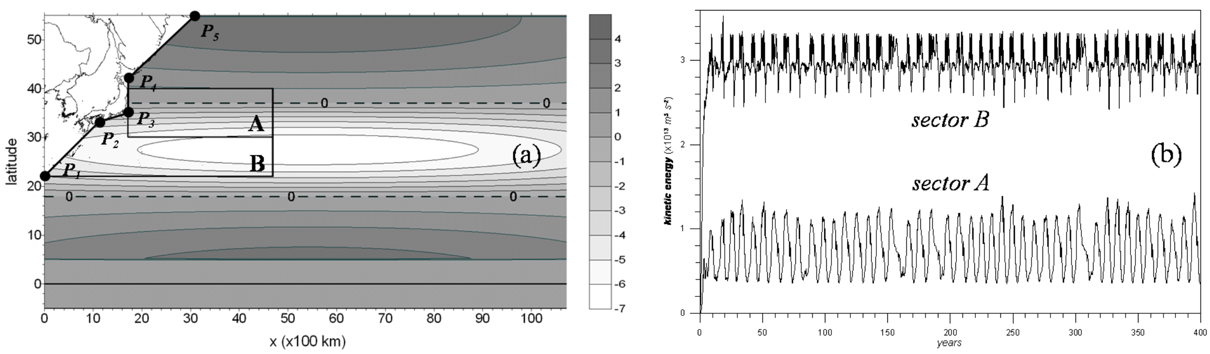

Figure 4. (a): Domain of integration and contour map of the wind stress curl forcing (units in 10^{-8} N/m^3). (b): Time series of the kinetic energy integrated over the sectors A and B (adapted from [3]).

In particular, in [24] such oscillation is documented in great detail for the period 1992-2004 by means of an altimeter data set compiled by the *CLS Space Oceanographic Division* of Toulouse (France), that merges T/P, ERS 1-2 and Jason-1 measurements.

As for the causes of such a decadal variability, it is usually believed (e.g. [23,24]) that it is basically due to the external atmospheric forcing (through the effect of the wind-driven variability of the Sverdrup return flow). On the other hand, it is well known that a highly nonlinear dynamical system may undergo oscillations (of periodic or chaotic nature) induced by purely internal mechanisms. To this respect it is important to notice that the model study in [25] suggests that, in fact, the observed bimodal Kuroshio variability south of Japan may be explained in terms of a self-sustained internal oscillation. So, the question arises as to whether the observed variability of the K.E. may also be affected (more or less substantially) by nonlinear inertial effects, including the possibility that the latter may even be the main cause of the variability.

4.2. The decadal variability of the Kuroshio Extension as a chaotic self-sustained oscillation

The model study [3] strongly supports the hypothesis that the observed decadal variability of the K.E. be mainly due to internal nonlinear mechanisms. A reduced-gravity primitive equation ocean model implemented in the domain shown in Fig. 4a and forced by a time-independent climatological wind stress yields an internal low-frequency variability in terms of a chaotic bimodal oscillation (see Fig. 4b for the time series of the kinetic energy integrated over the sectors *A* and *B* reported in Fig. 4a) between an energetic meandering state and a much weaker state with a reduced zonal penetration. These high and low energy states are found to be very similar to the “elongated” and “contracted” modes of the K.E. discussed in section 4.1. More specifically, the period (of around 10 years) and transition details of a typical bimodal cycle (shown in Fig. 5 through a 9-year sequence of the modelled SSH) are found to be in significant agreement with the altimeter observations relative to the period 1992-2004 presented in [24].

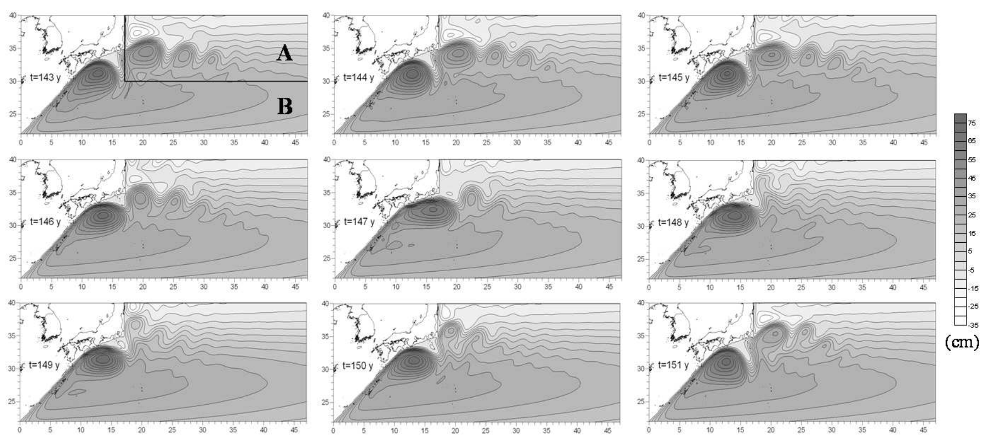

Figure 5. Sequence of snapshots of the modeled SSH for t=143-151 years (adapted from [3]).

Also the strong variability of the upstream K.E. path length and the positive trend of the K.E. latitudinal position observed during the unstable phase of the cycle are recovered in the model results. A dynamical mechanism supporting this self-sustained oscillation of the modeled Kuroshio Extension is proposed in [3], and its strict connection with the bimodal behavior of the Kuroshio south of Japan is analyzed.

On the basis of these modeling results and of their significant altimetric validation, it is therefore hypothesized that the observed bimodal decadal variability of the Kuroshio Extension is basically due to a self-sustained internal oscillation related to the barotropic instability of the Kuroshio south of Japan without any crucial intervention of wind-driven Sverdrup transport fluctuations and of topographic interactions (absent in the model), although such effects may well play an important role in shaping the finer structure and timing of the jet variability.

ACKNOWLEDGMENTS

The research activities presented in this paper were supported by the "*Agenzia Spaziale Italiana*".

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