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A Numerical Experiment on a New Current, the Ryukyu Current Extension, in the Shikoku Basin
Part II Eddy Generating Model

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Abstract

This paper presents the results of a numerical experiment on a new current, the Ryukyu Current Extension, using the eddy generating model, following the Part I with the models of linear and weak nonlinear ranges. It is shown that four types of current patterns exist in the Shikoku Basin: the Super Nonlinear Pattern with a strong zonal flow, the Nonlinear Pattern with the formation of an anticyclonic eddy, and the External and Internal Two Eddies Patterns with a spin-up and spin-down of the cyclonic eddy. In the External Two-Eddies Pattern, the cyclonic eddy is formed by the topographic effect of the Izu Ridge, but the cyclonic eddy is induced only by the anticyclonic eddy in the Shikoku Basin in the Internal Two Eddies Pattern. Selection of the current pattern depends on the Rossby number, which is controlled by the depth of the model ocean. However, since the Super Nonlinear Pattern with a significantly amplified meander with large volume transport is very different from the observed feature, the model parameter is not suitable for actual oceanic conditions. Results show that a chaotic change from the External Two-Eddies Pattern to the Nonlinear Pattern occurs and a multi-steady state is suggested among these flow patterns.

Key Words: Ryukyu Current, western boundary current, numerical modeling

1. Introduction

In Part I[1] of this study, the existence of the Ryukyu Current Extension was predicted as the connecting current between the two barotropic western boundary current along the eastern continental slope off Nansei Islands and that along the eastern side of the Izu Ridge. Then, some numerical experiments with a linear and weak nonlinear parameter range were carried out in Part I, assuming the larger velues of horizontal eddy viscosity.

It was shown in Part I that there exist four type of the current patterns in the Shikoku Basin, which are referred to as the Munk Pattern, the Moore Pattern, the Nonlinear Pattern and the Super Nonlinear Pattern. In the case of the Munk Pattern, the Ryukyu Current Extension appears as a weak and wide zonal flow in the Shikoku Basin. The zonal flow becomes strong and narrow in Moore Pattern. In the case of Nonlinear Pattern, an enhanced anticyclonic eddy occupied the Shikoku Basin and a mean flow along the Japanese coast is formed. Only a strong eastward zonal flow appears in the Super Nonlinear Pattern.

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Therefore, the Ryukyu Current Extension is not formed in these two cases.

It is also shown in Part I[1] that, if a large coefficient of the horizontal eddy viscosity is assumed, only the Munk Pattern is formed. If the eddy viscosity is decreased, the Moore pattern is formed in case driven by the small in- and outflow, while the Nonlinear Pattern and Super Nonlinear Pattern appear in the models driven by the intermediate and the large in- and outflow, respectively. However, because of the assumption of large eddy viscosity, effect of meso-scale eddies have not been well examined. Therefore, in the present study, a numerical experiment on the Ryukyu Current Extension is carried out, using the eddy generating model as a Part II of this study, and the results of these numerical models are presented in this paper. In the following, the description of the numerical model will be made in the next section. Results of the numerical models will be mentioned in sections 3 and 4. Summary and discussion will be made in section 5.

2. Numerical Model

The domain of the barotropic ocean model (Fig. 1), the basic equations and the boundary conditions are the same as in Part I[1]. The system is driven by the in- and outflow estimated as the monthly mean Sverdrup transport in January and in April given at 160° E by use of the wind stress data over 1961-1984 presented by Kutsuwada and Teramoto[2]. The coefficient of the horizontal eddy viscosity (Ah) is assumed to be 5×10^6 $cm^2 sec^{-1}$, which is in the range of the eddy generating model[3]. As in part I[1], dependence on

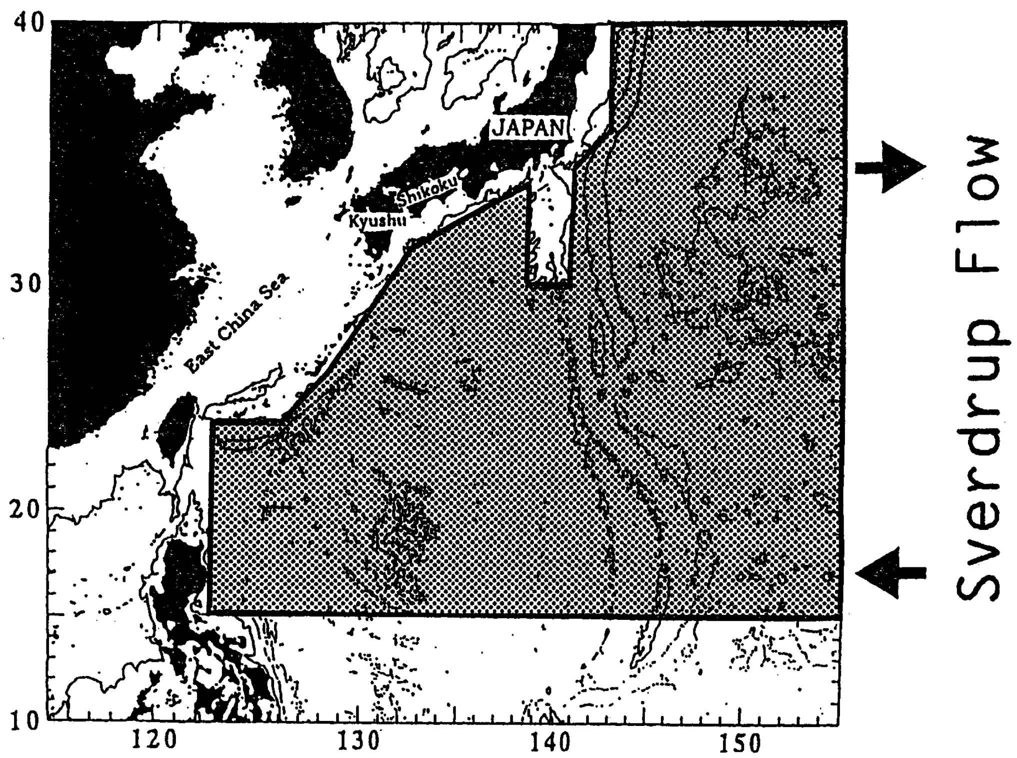


Fig. 1 Schematic view of the model ocean. In- and outflow estimated as the Sverdrup transport is given at along 160° E.

the Rossby number (intensity of the mean flow) is examined by changing the depth of the ocean such as 500m, 1000m , 2000m 4000m, 6000m and 8000m. Because of small eddy viscosity in comparison with Part I[1] with 5×10^7 cm^{2}sec^{-1} and 5×10^8 cm^{2}sec^{-1}, Reynolds number is 10 times (100 times) larger than those of Part I[1].

In the present study, 12 cases of numerical models with different model parameter are examined. In the first step, Sverdrup transport in January is assumed at the eastern boundary and six models with different depths is examined. These models with the depth of 500m, 1000m, 2000m, 4000m, 6000m and 8000m are referred to as W05SE, W10SE, W20SE, W40SE, W60SE and W80SE, respectively. In the second step, the same two Sverdrup in- and outflows in April are given and similar six models with different depths are performed. They are referred to as S05SE, S10SE, S20SE, S40SE, S60SE and S80SE, in which initial letter S (spring) is used in stead of W (winter) in the previous cases.

3. Results of the models drive by winter Sverdrup In- and outflow

Result of W05SE is shown in Fig. 2. A remarkably large meander of the mean flow with large volume transport more than 100 Sv (1 Sv$=10^6$ m^{3}sec^{-1}) is formed. The meander is furthermore amplified by the lapse of time (Fig. 2b) and a wide strong westward flow is generated in the Shikoku Basin, which is referred to as the Super Nonlinear Pattern.

Similar flow pattern to W05SE is obtained in W10SE (Fig. 3). A larger transport (more than 200 Sv) and a larger amplitude meander are also generated. A stationary state is not obtained for these two models and the prominent time change in the volume transport function is maintained stationary. It is clear that the total flow patterns of W05SE and W10SE are significantly different from the observational feature of the Kuroshio and the Kuroshio Extension, which implies that the parameter range of these two models is unsuitable for the actual ocean condition. Similar significant nonliear model appears in the study on the geophysical fluid dynamics[4], however their model is also unsuitable for the observed ocean condition.

The Nonlinear Pattern with a prominent anticylonic circulation in the Shikoku Basin defined in Part I[1] is obtained in W20SE (Fig. 4). A strong coastal flow is formed along the coastal topographies of Kyushu and Shikoku, which corresponds to the observed Kuroshio. Therefore, the Ryukyu Current Extension is not formed in this case. Large meander east of Japan is furthermore amplified after 100 days (Fig. 4b), however the Nonlinear Pattern is essentially maintained stationary and the Ryukyu Current Extension is not formed in this case.

In W40SE shown in Fig. 5a, the Moore Pattern defined in Part I[1], similar to the analytical solution presented by Moore[5], is obtained at 20 days. However, the anticyclonic circulation shifts northward and the antcyclonic eddy occupies a northern area in the Shikoku Basin. From 40 days to 50 days, a cyclonic eddy in the east of the Izu Ridge is enhanced and it separates from the Izu Ridge. The cyclonic eddy intrudes into the Shikoku Basin and interacts with the anticyclonic eddy in 60-70 days. Then, the anticyclonic eddy is weakened and the cyclonic eddy occupys the Shikoku Basin. However, the cyclonic eddy shifts southwestward and decays at 100 days.

The flow pattern of W40SE at 110 days (Fig. 5b) is almost same as that of 40 days (Fig. 5a) and a new cyclonic eddy develops in southwest to the Izu Ridge at 120 days. The similar variation in the cyclonic eddy is repeated after 160 days (Fig. 5c) and the repeated process is hereafter referred to as Two eddies

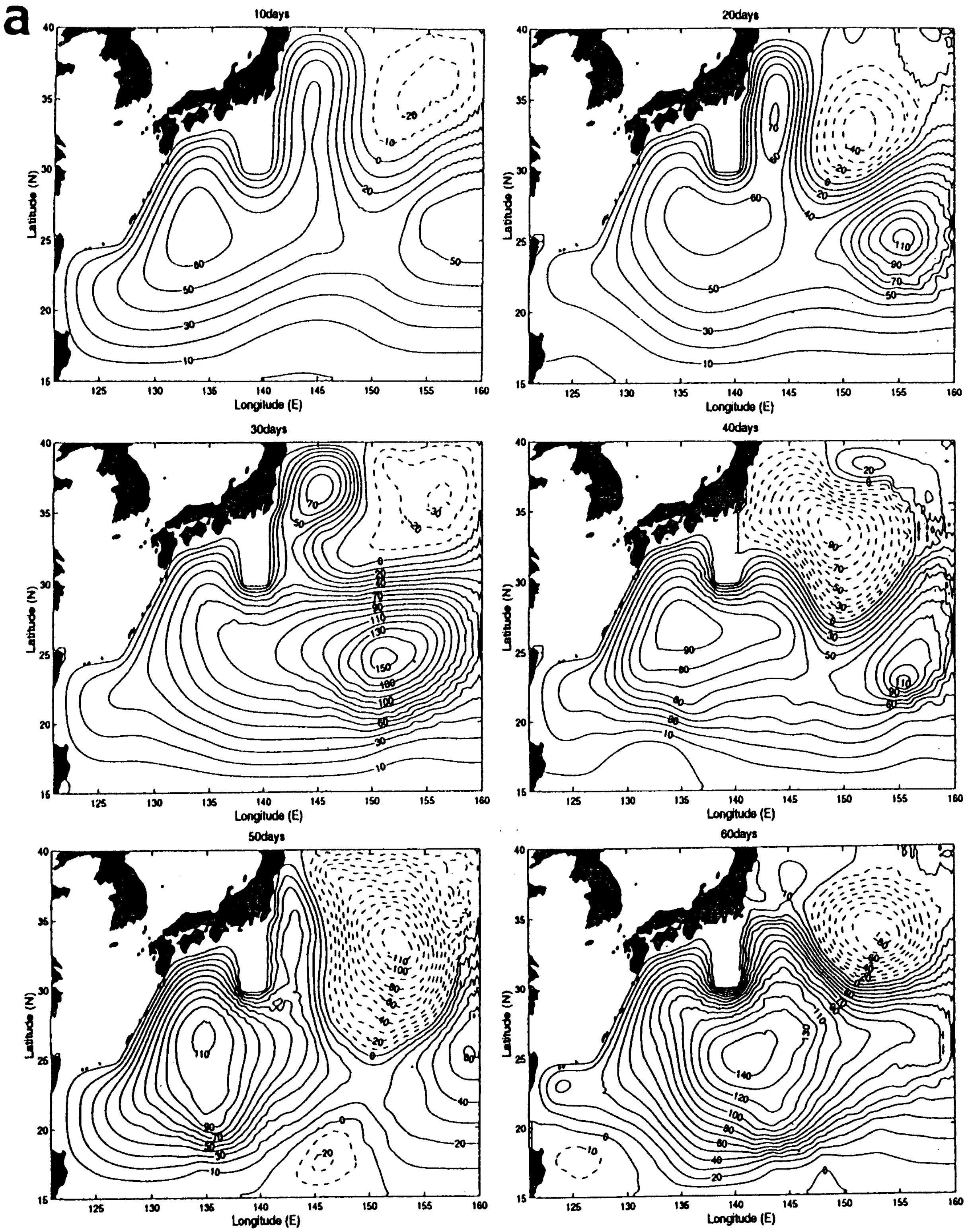
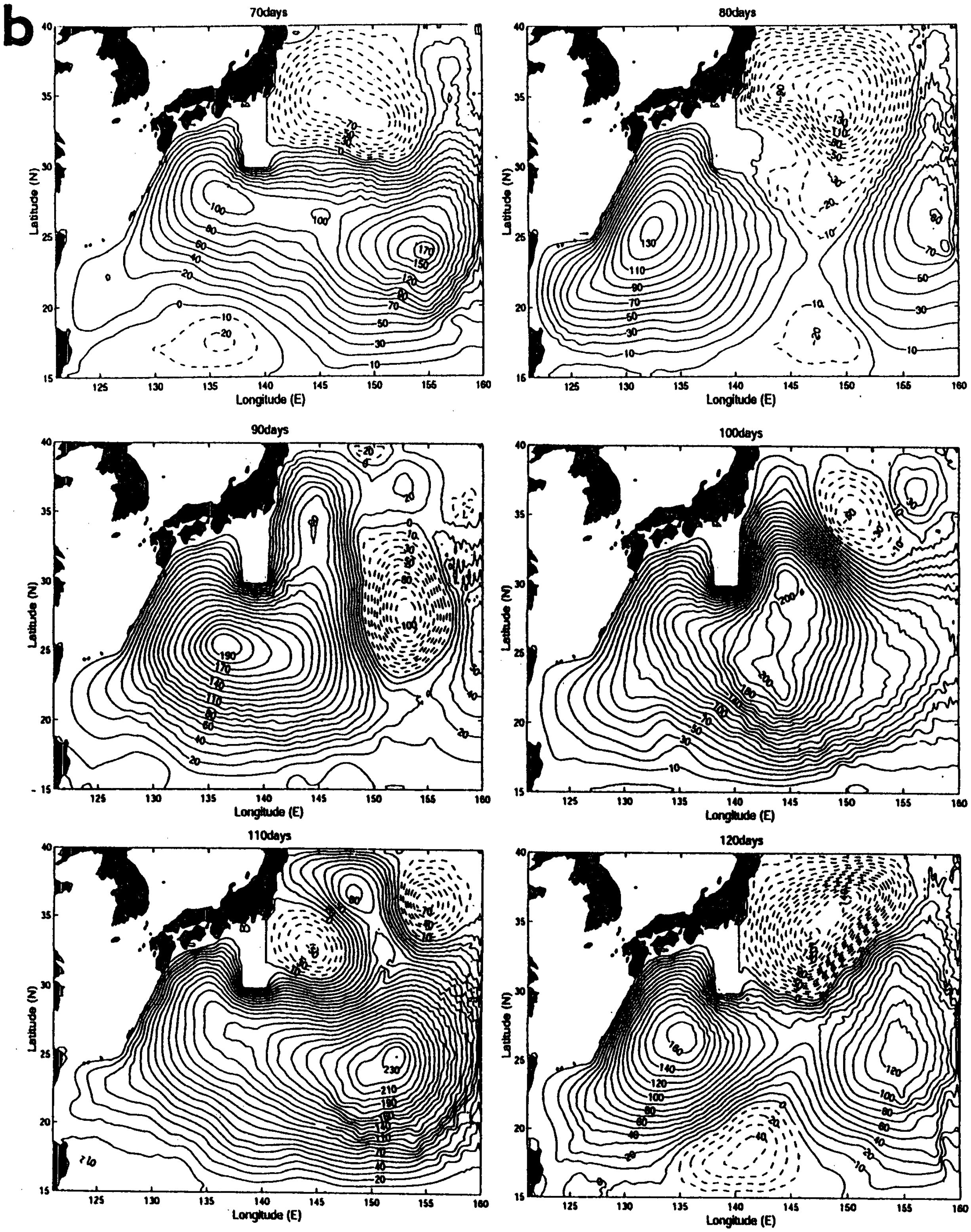


Fig. 2 Results of the numerical model of W05SE shown by the isopleth of the volume transport function, during (a) from 10 days to 60 days and (b) from 70 days to 120 days. The contour interval of the volume transport function is 10 Sv. Regions with negative volume transport function are shown by broken lines. The integrated time period is shown at the top of each panel.

Fig. 2 (continued)



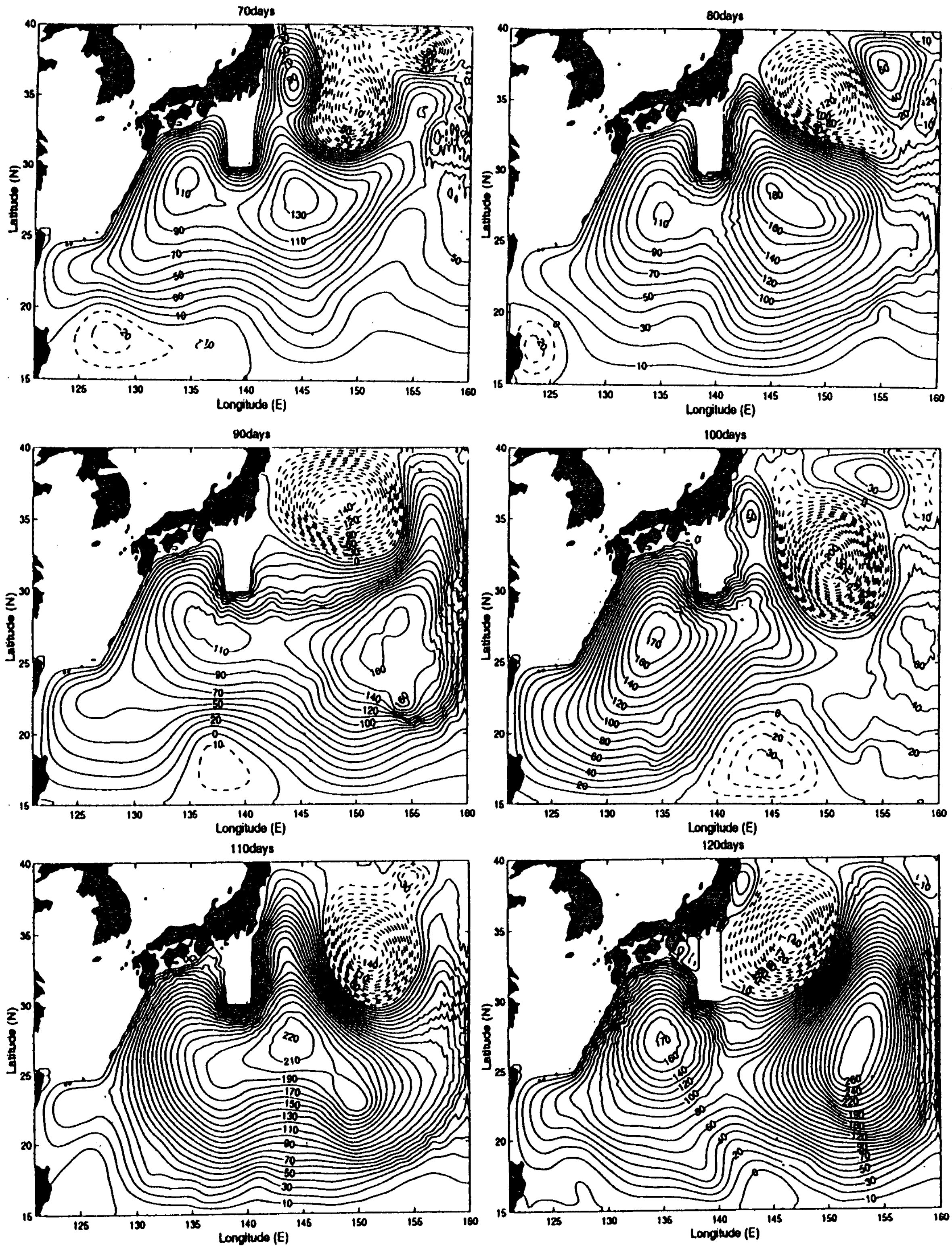


Fig. 3 As in Fig. 2, but for W10SE.

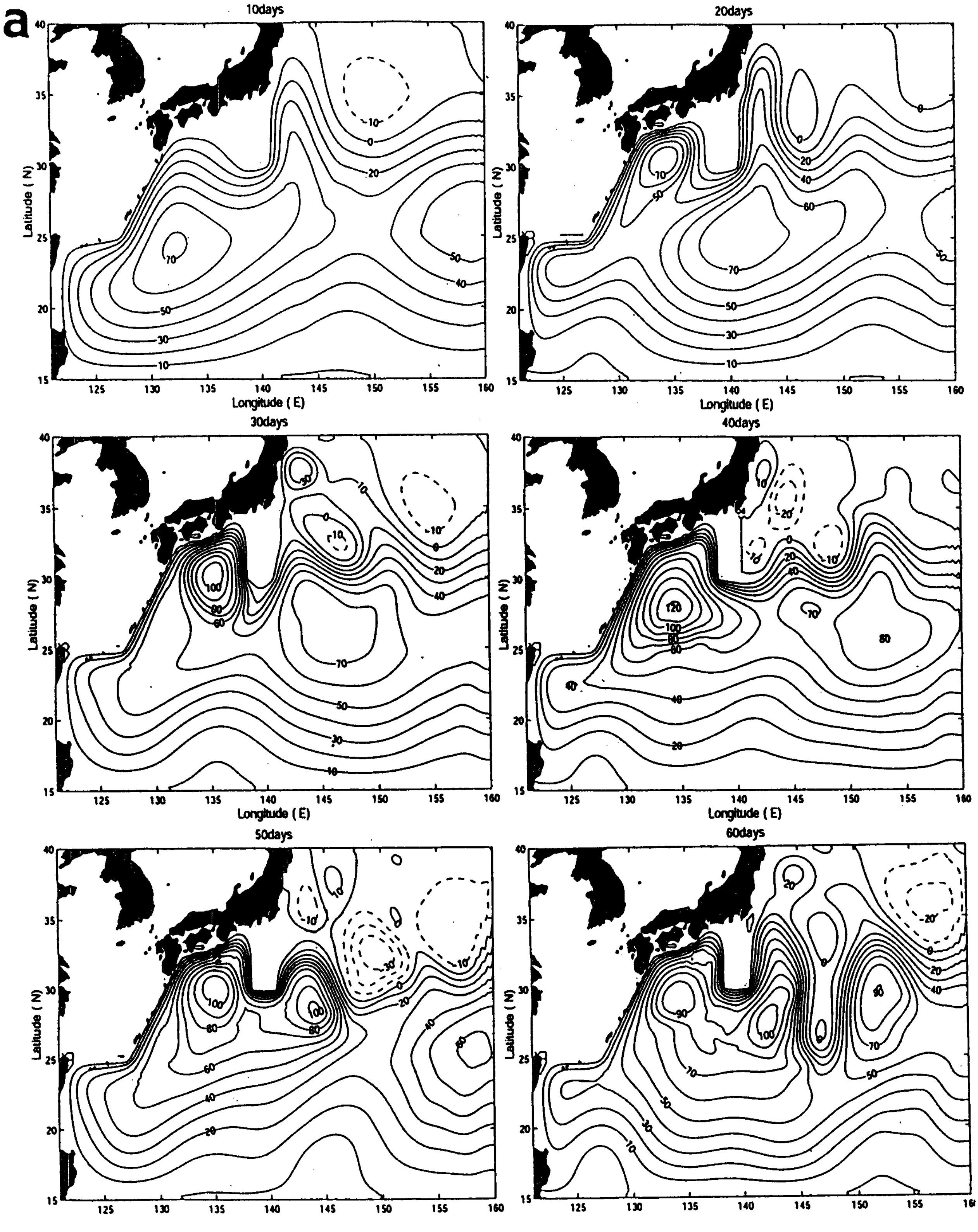
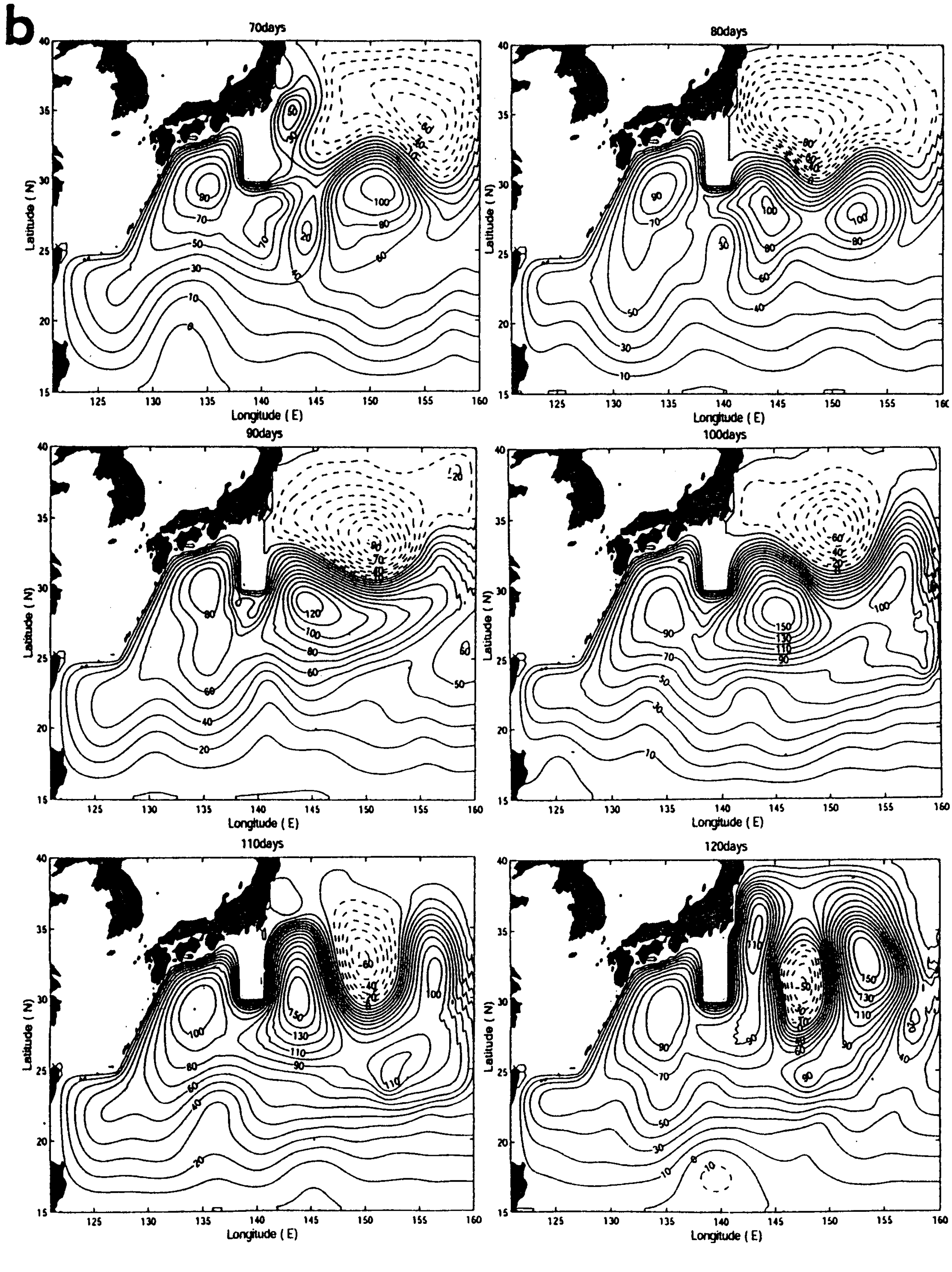


Fig. 4 As in Fig. 2, but for W20SE, during (a) from 10 days to 60 days and (b) from 70 days to 120 days.

Fig. 4 (continued)



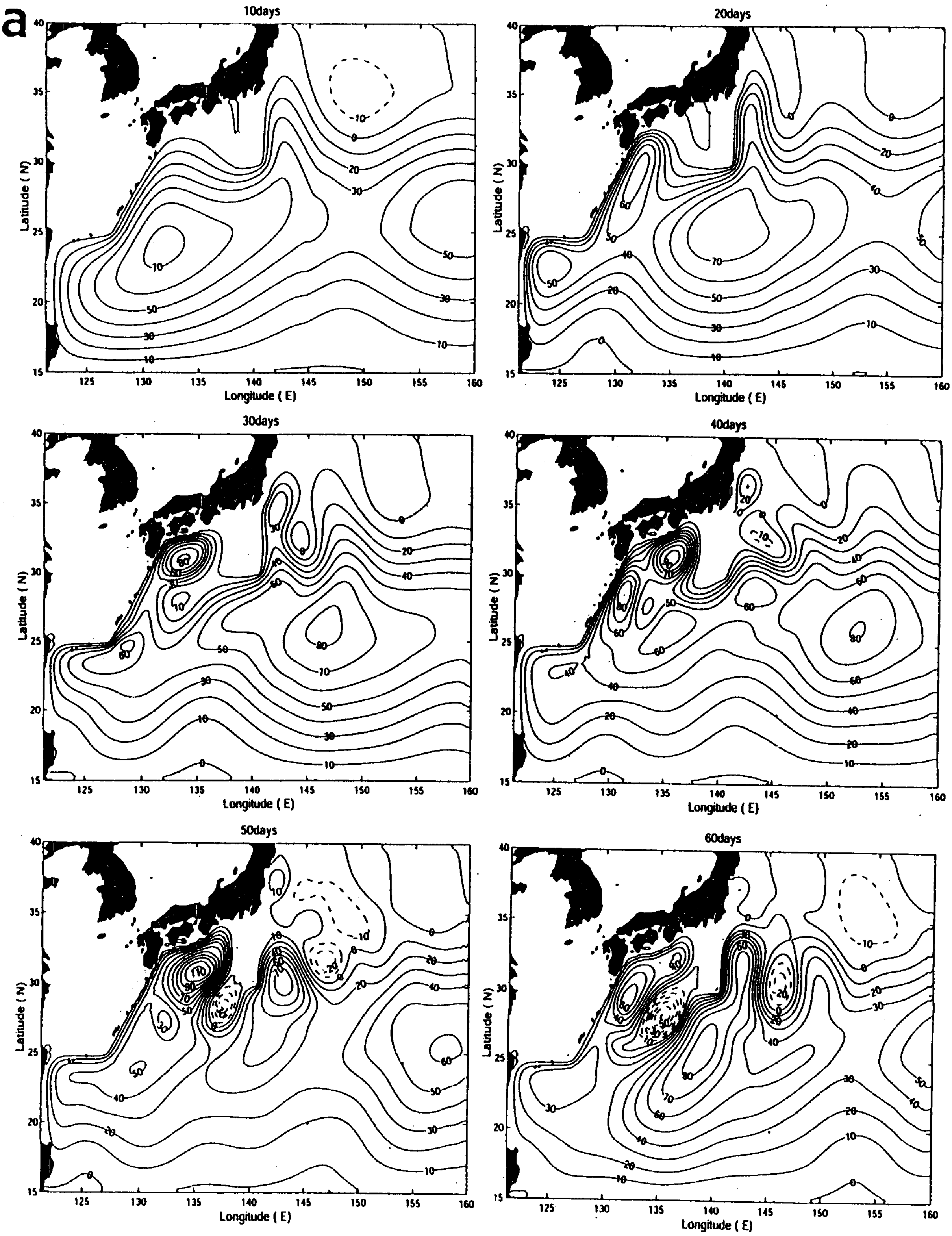


Fig. 5 As in Fig. 2, but for W40SE, during (a) from 10 days to 60 days, (b) from 70 days to 120 days and (c) from 130 days to 180 days.

Fig. 5 (continued)

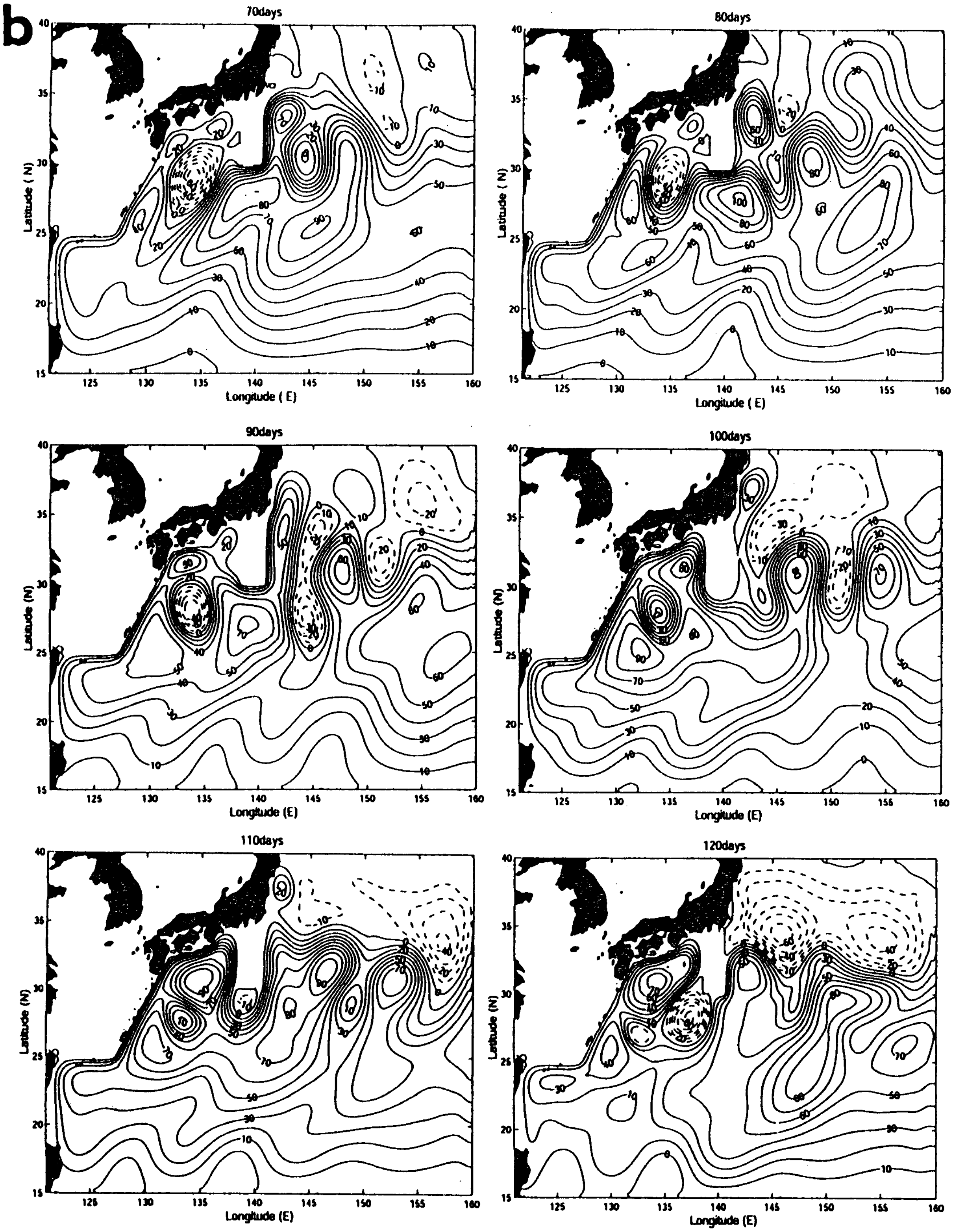
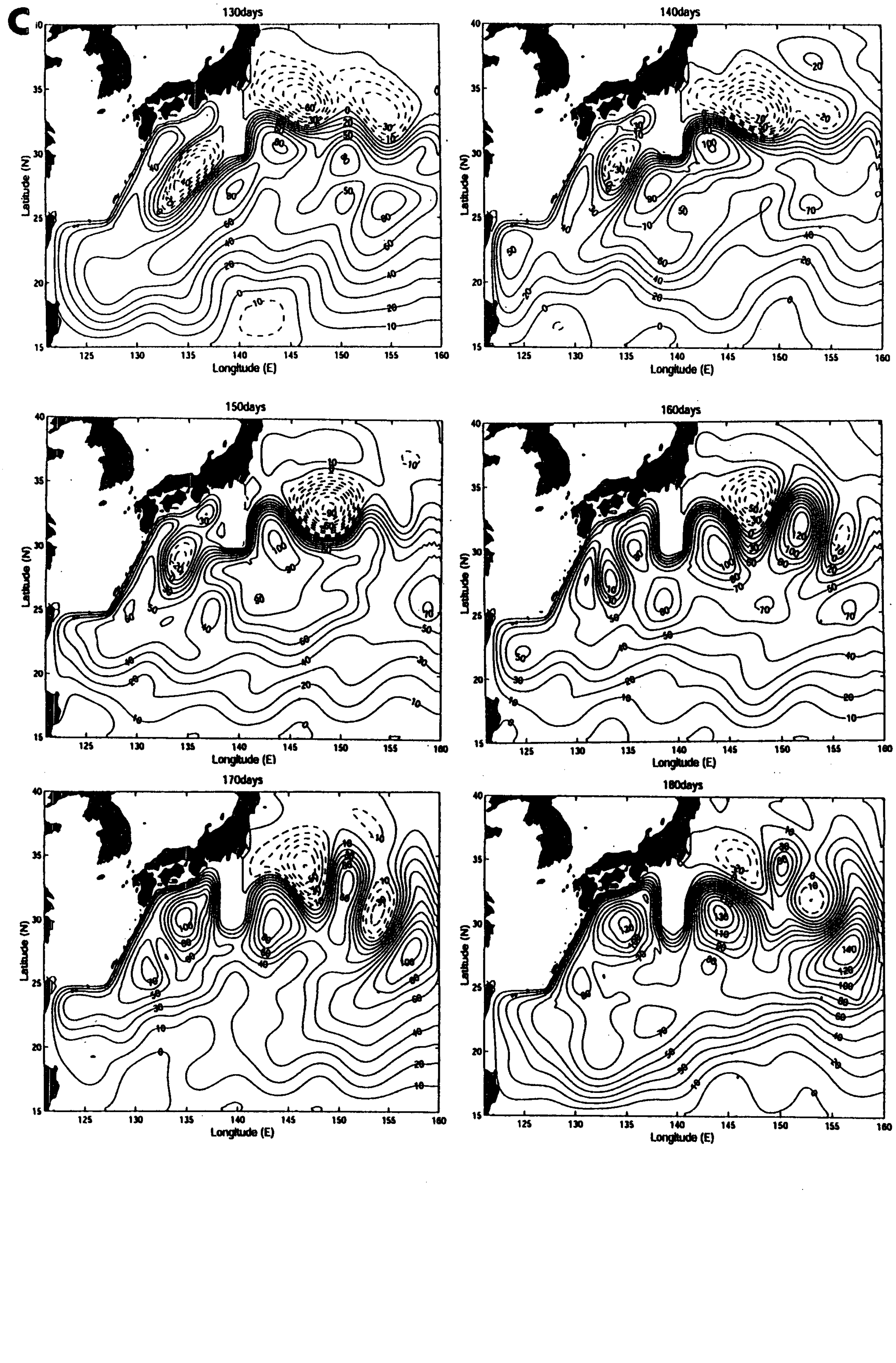


Fig. 5 (continued)



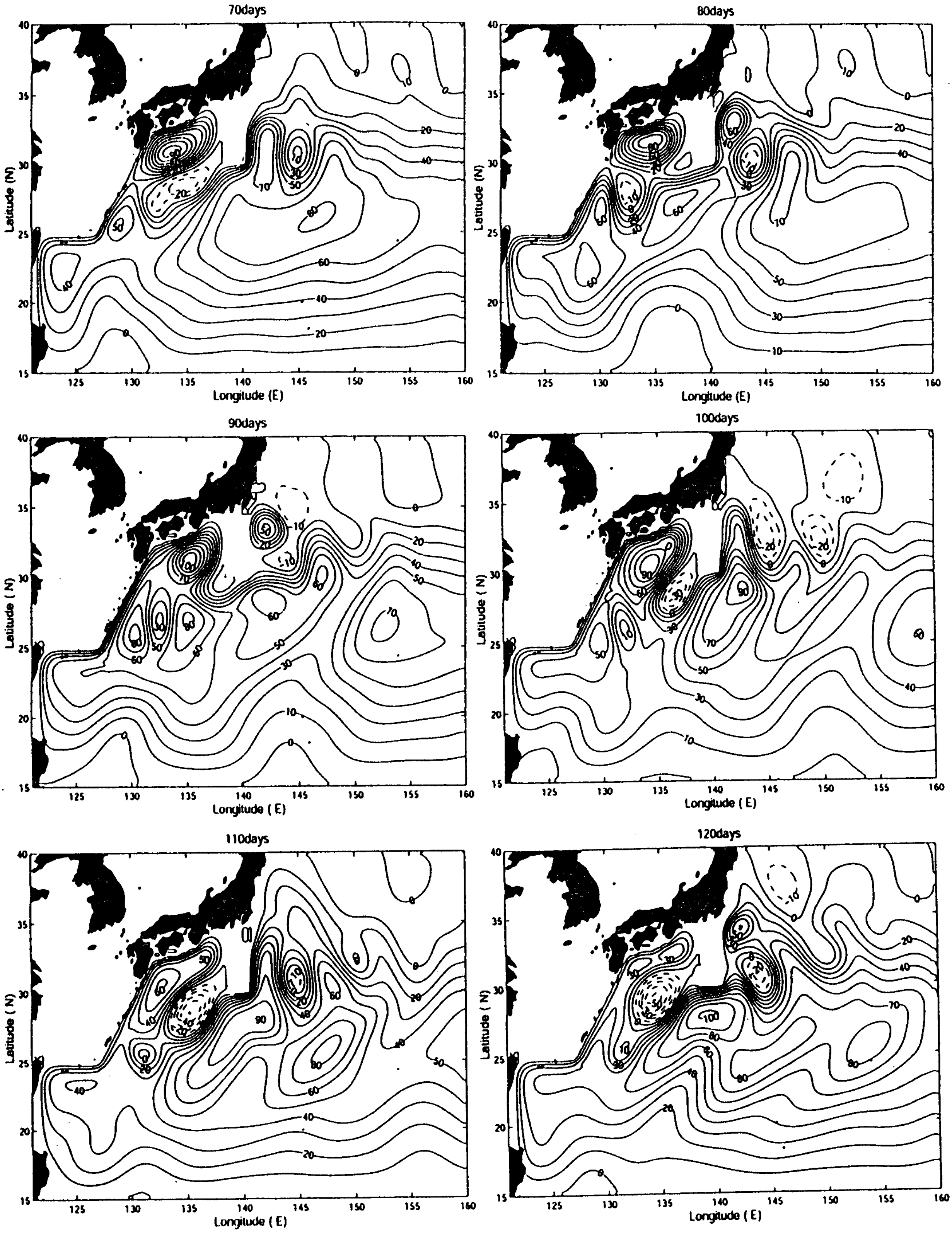


Fig. 6 As in Fig. 2, but for the case of W60SE.

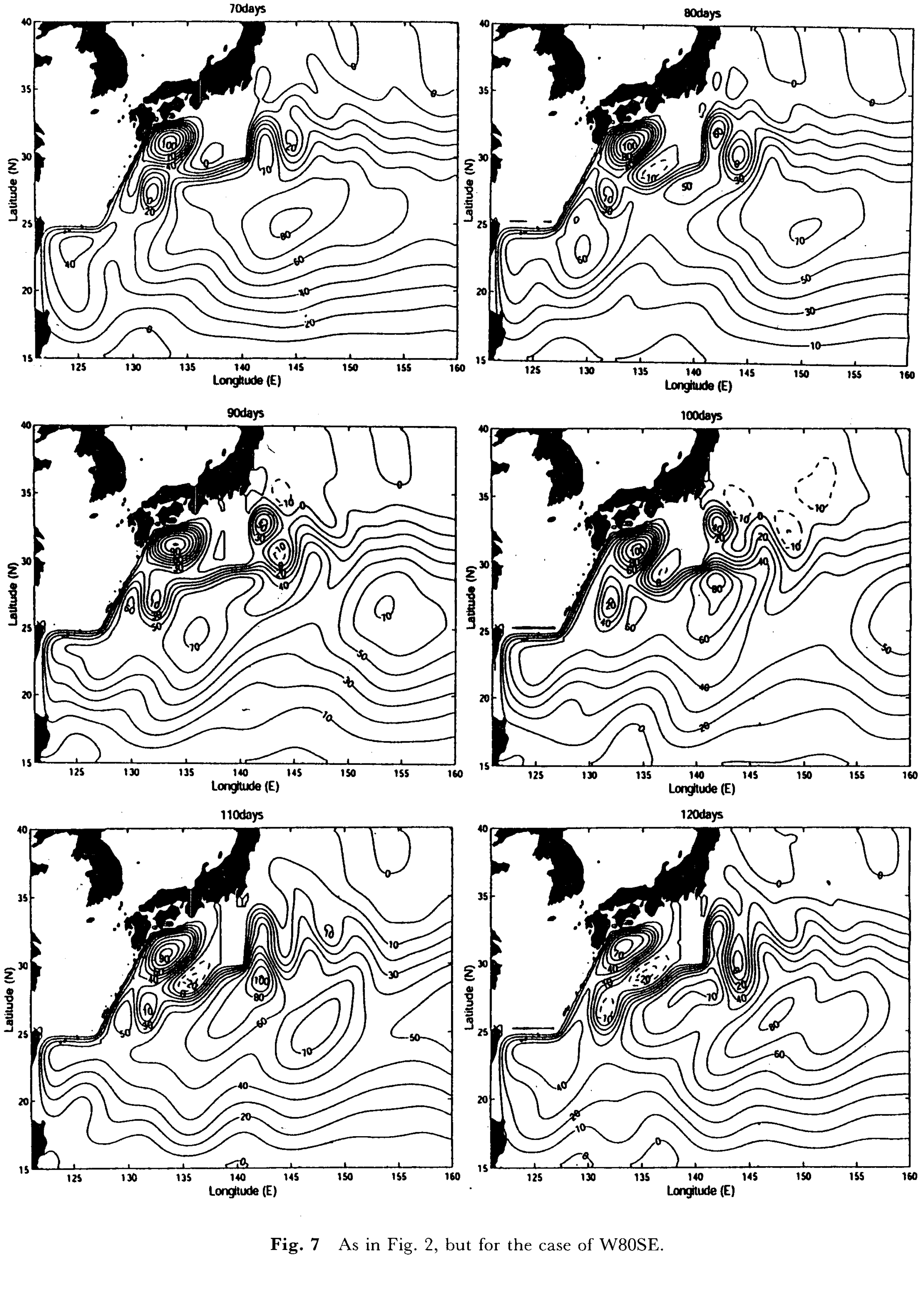


Fig. 7 As in Fig. 2, but for the case of W80SE.

pattern. The lifetime of the cyclonic eddy is about 55 days. However, after 170 days, a strong anticyclonic eddy is formed in the Shikoku Basin and the cyclonic eddy does not intrude into the western side of the Izu Ridge. In the later time, the Nonlinear Pattern is formed in the Shikoku Basin. It is thus suggested that the chaotic change from the Two Eddies Pattern to the Nonlinear Pattern occurs in this case.

The stationary Two Eddies Pattern is also formed in W60SE (Fig. 6) and in W80SE (Fig. 7). The time period of the repeated process with the spin-up and spin-down of the cyclonic eddy of W60SE and W80SE is about 30 days and 20 days, respectively, which is shorter than that of W40SE. It is thus resulted that the lifetime of the cyclonic eddy in W60SE and W80SE is decreased as the Rossby number (depth of the ocean) is decreased (increased). Because of the small kinetic energy of the subtropical circulation and the weak anticyclonic eddy in the Shikoku Basin, a weak cyclonic eddy is formed in W60SE and W80SE. The weak cyclonic eddy has a tendency to shift westward as a barotropic Rossby wave, while a strong cyclonic eddy formed in W40SE has a tendency to shift northward by the nonlinear effect. It is thus pointed out that the westward shift of the weak cyclonic eddy soon reaches to the western boundary region, which results in its short lifetime.

4. Results with the spring Sverdrup in- and outflow

Result of S05SE is shown in Fig. 8. In comparison with the remarkably large meander with large volume transport of W05SE (Fig. 2), the subtropical circulation is relatively weak and its northward intensification is rather significant. Because the strong zonal flow is not formed in the Shikoku Basin and the coastal flow along is rather dominant, it implies that the Nonlinear Pattern appears in this case. The amplification of the large meander east of Japan is gradually enhanced (Fig. 8b), while the volume transport of the anticyclonic eddy in the Shikoku Basin is not increased.

A clear Nonlinear pattern with an anticyclonic circulation in the Shikoku Basin is formed in S10SE (Fig. 9a) and the volume transport of the anticyclonic eddy is much larger than that of S05SE. The large meander east of Japan is furthermore amplified (Fig. 9b) and the total flow pattern is almost similar to W10SE (Fig. 2), except for the smaller volume transport in the southern part of the subtropical circulation. It is suggested from these models that the eastward velocity of the subtropical circulation of S05SE is larger than the westward Rossby wave and the generated eddies are advected downstream direction, conversely the westward velocity of the Rossby wave of S10SE is larger than the eastward circulation velocity and the generated eddies are trapped in the meander region east of Japan, which increases the volume transport of the eddies.

Two Eddies Pattern is formed in the initial stage of S20SE (Fig. 10a). A cyclonic eddy is generated by the topographic effect of the Izu Ridge and it shifts southwestward at 50 days and decays at 70 days. However, the anticyclonic eddy in the Shikoku Basin is enhanced in later time (Fig. 10b) and the Nonlinear Pattern with the enhanced anticyclonic eddy is formed stationary. However, a large cyclonic eddy is formed by the Izu Ridge at 200 days (not shown) and it develops southwestward to the Shikoku basin. The anticyclonic eddy is weakened by the northward shift of the cyclonic eddy, while the anticyclonic eddy develops again and the Nonlinear path is maintained stationary.

Moore pattern is formed in the initial stage of S40SE (Fig. 11) and the the anticyclonic eddy in the Shikoku Basin shifts northward after 30 days. In the later time, the anticyclonic eddy induces the cyclonic

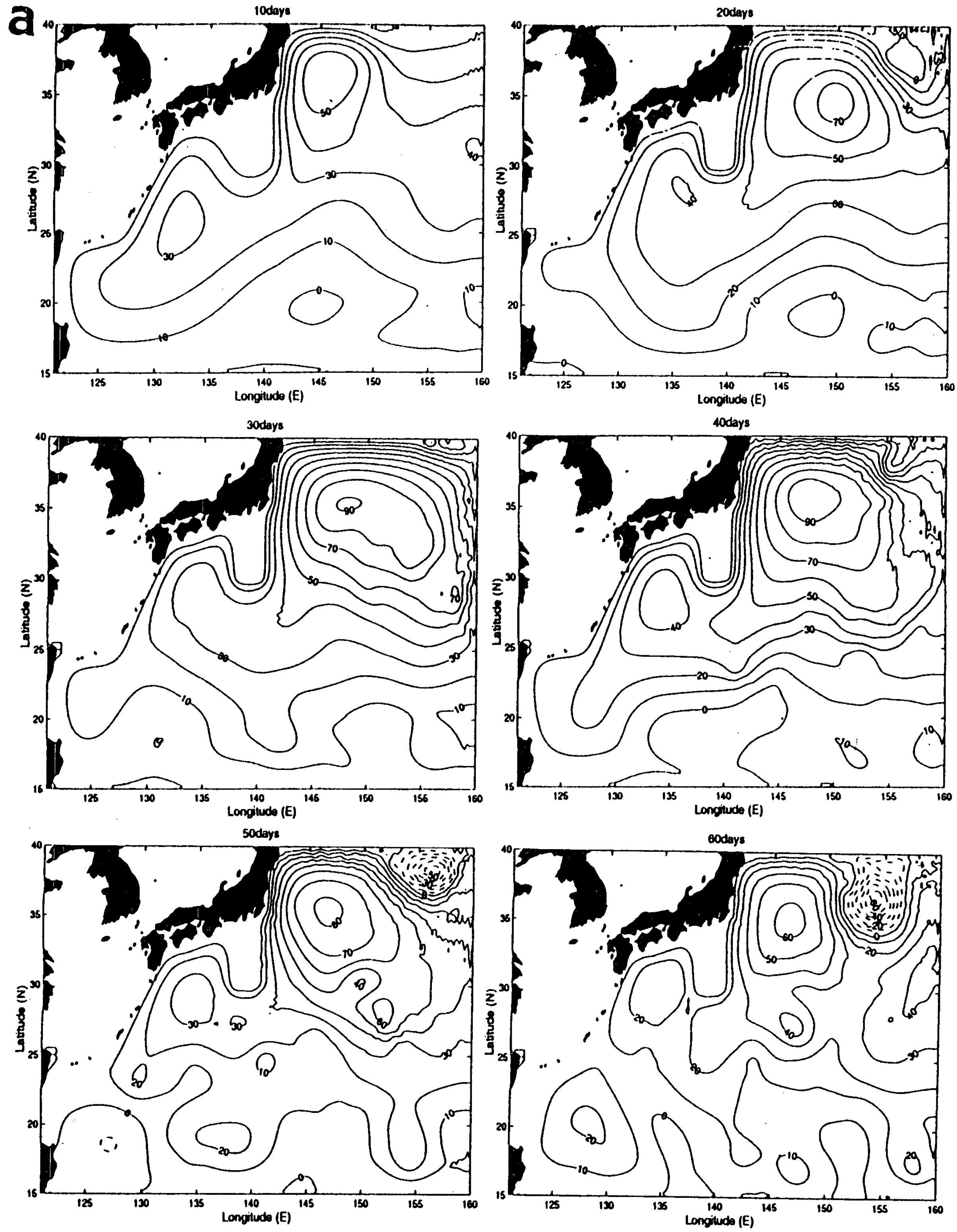
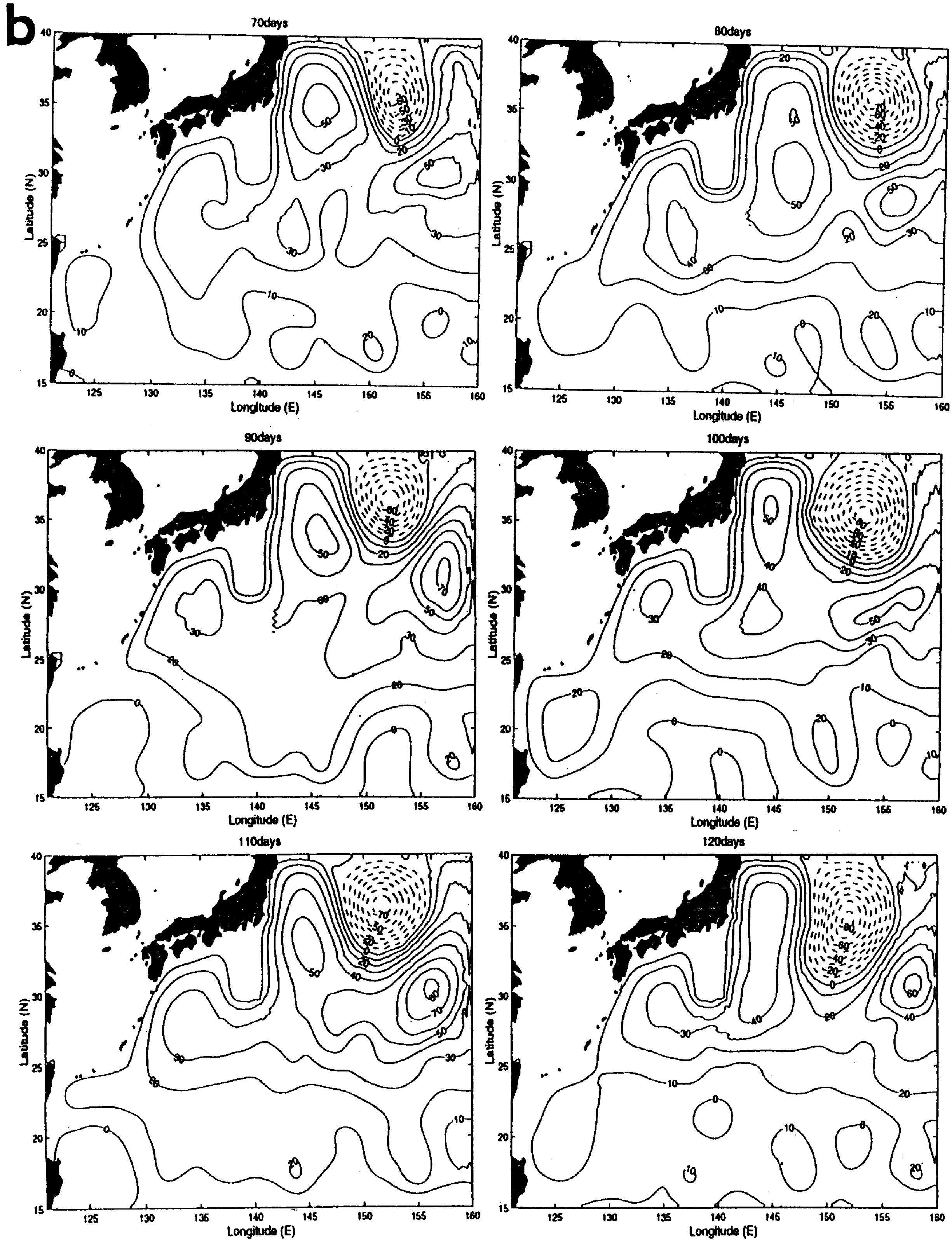


Fig. 8 As in Fig. 2, but for S05SE, during (a) from 10 days to 60 days and (b) from 70 days to 120 days.

Fig. 8 (continued)



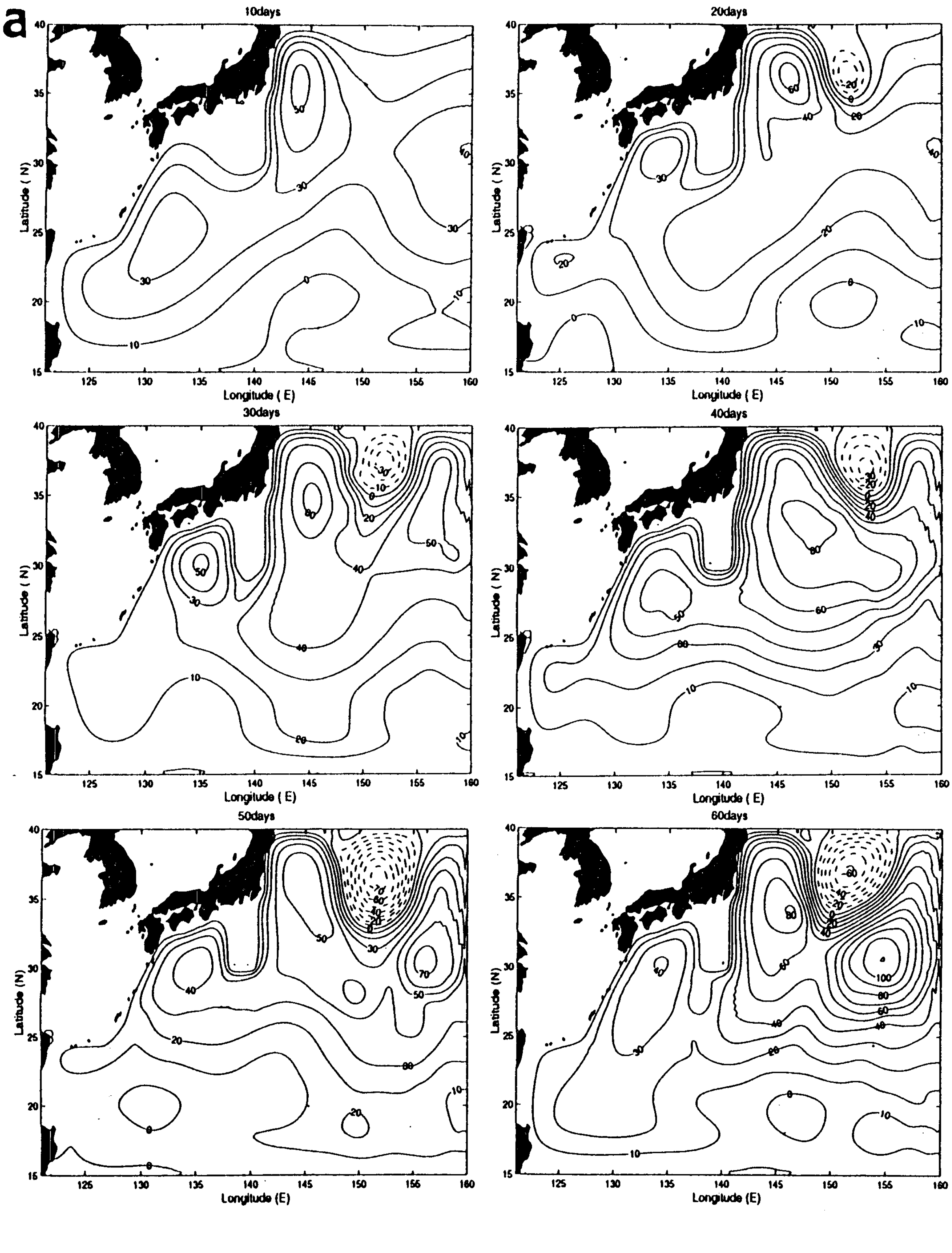
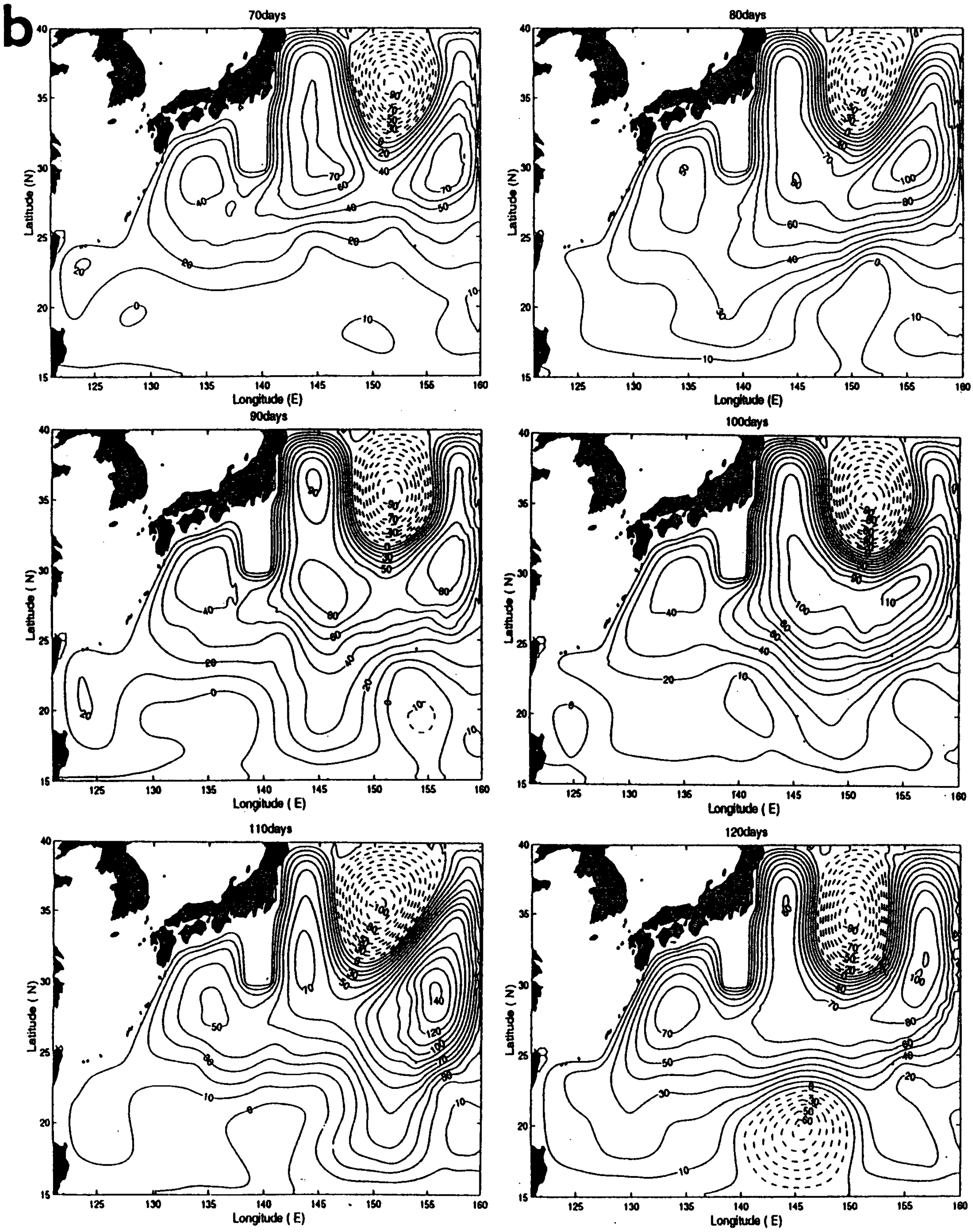


Fig. 9 As in Fig. 2, but for S10SE, during (a) from 10 days to 60 days and (b) from 70 days to 120 days.

Fig. 9 (continued)



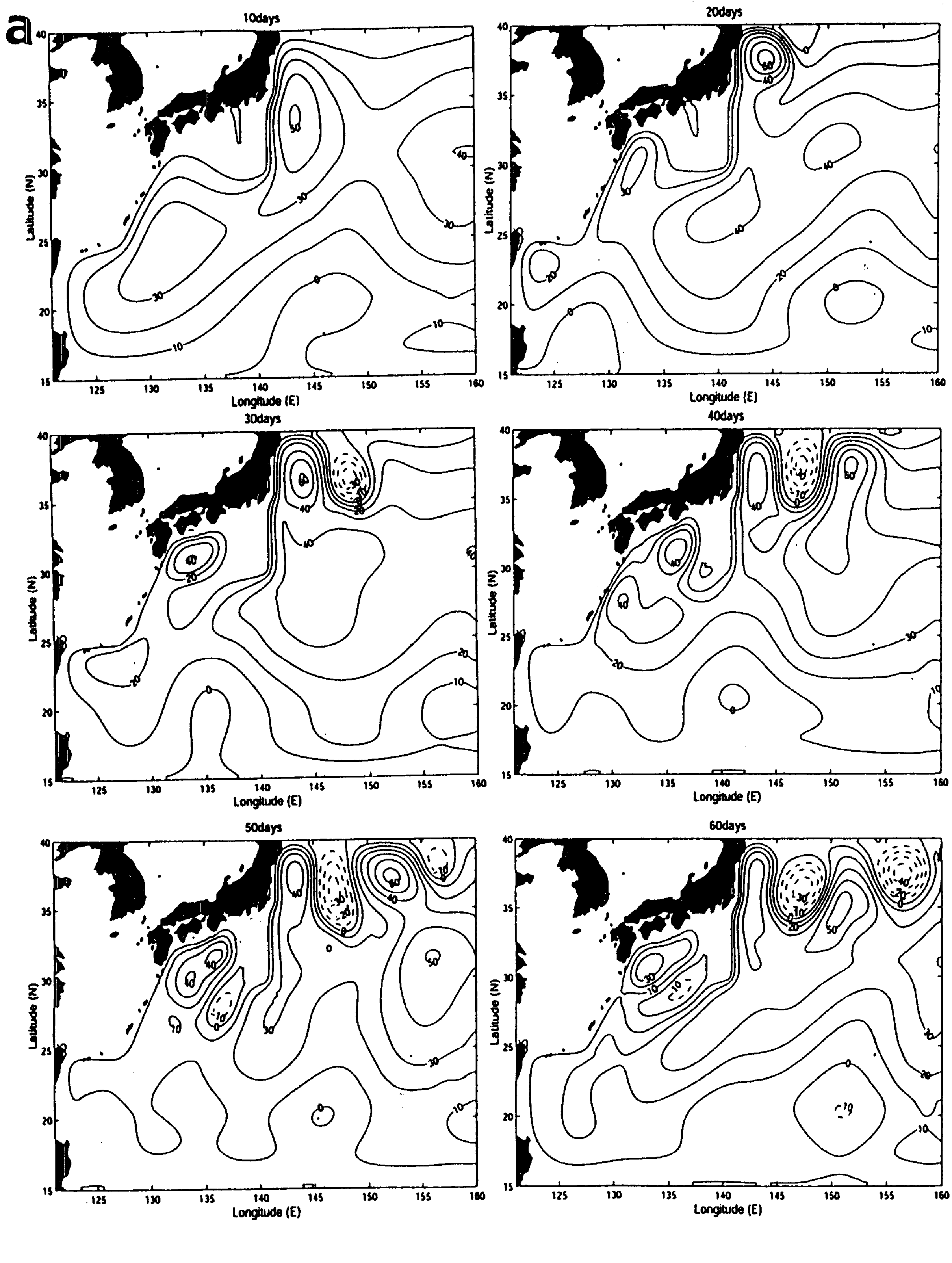
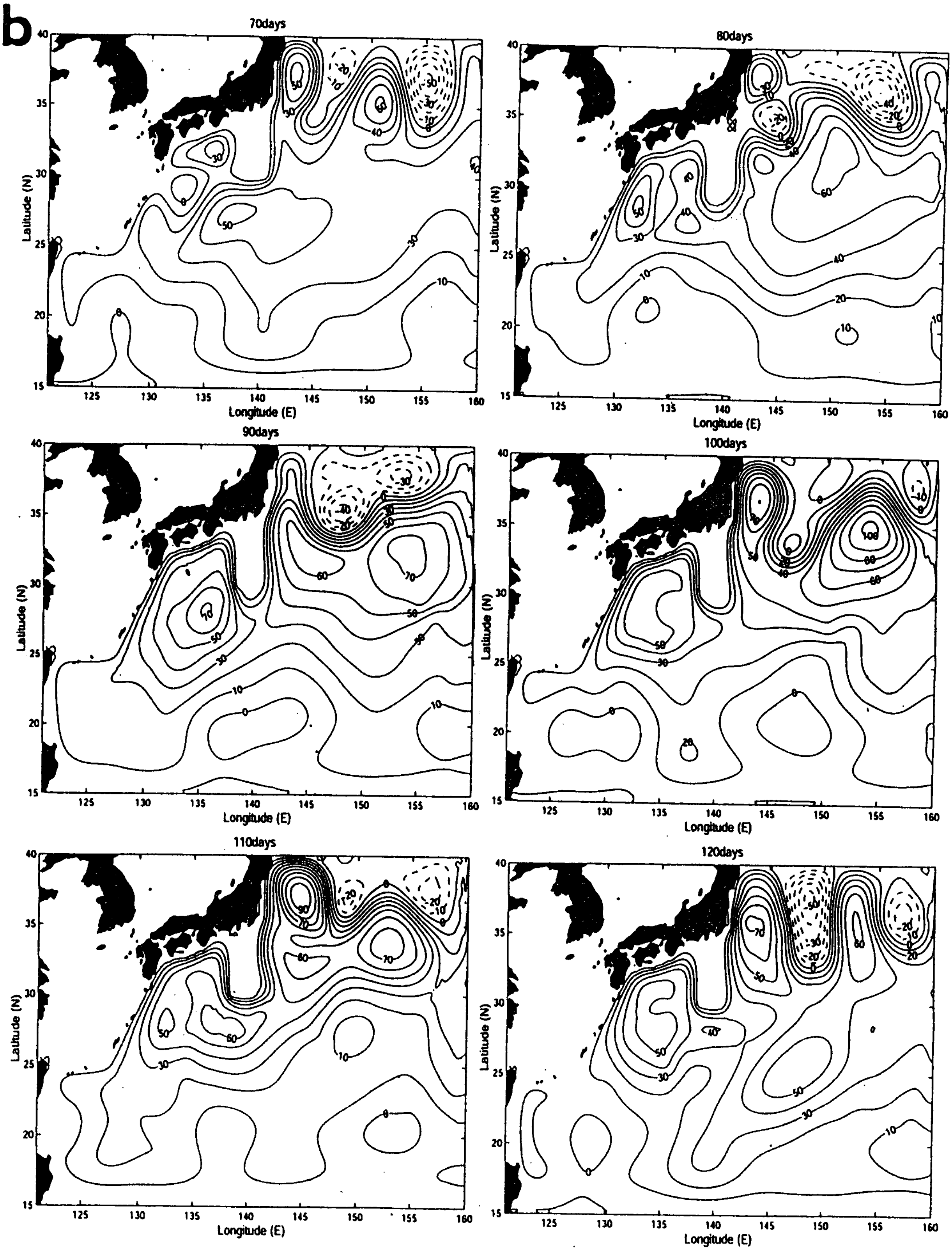


Fig. 10 As in Fig. 2, but for S20SE, during (a) from 10 days to 60 days, (b) from 70 days to 120 days.

Fig. 10 (continued)



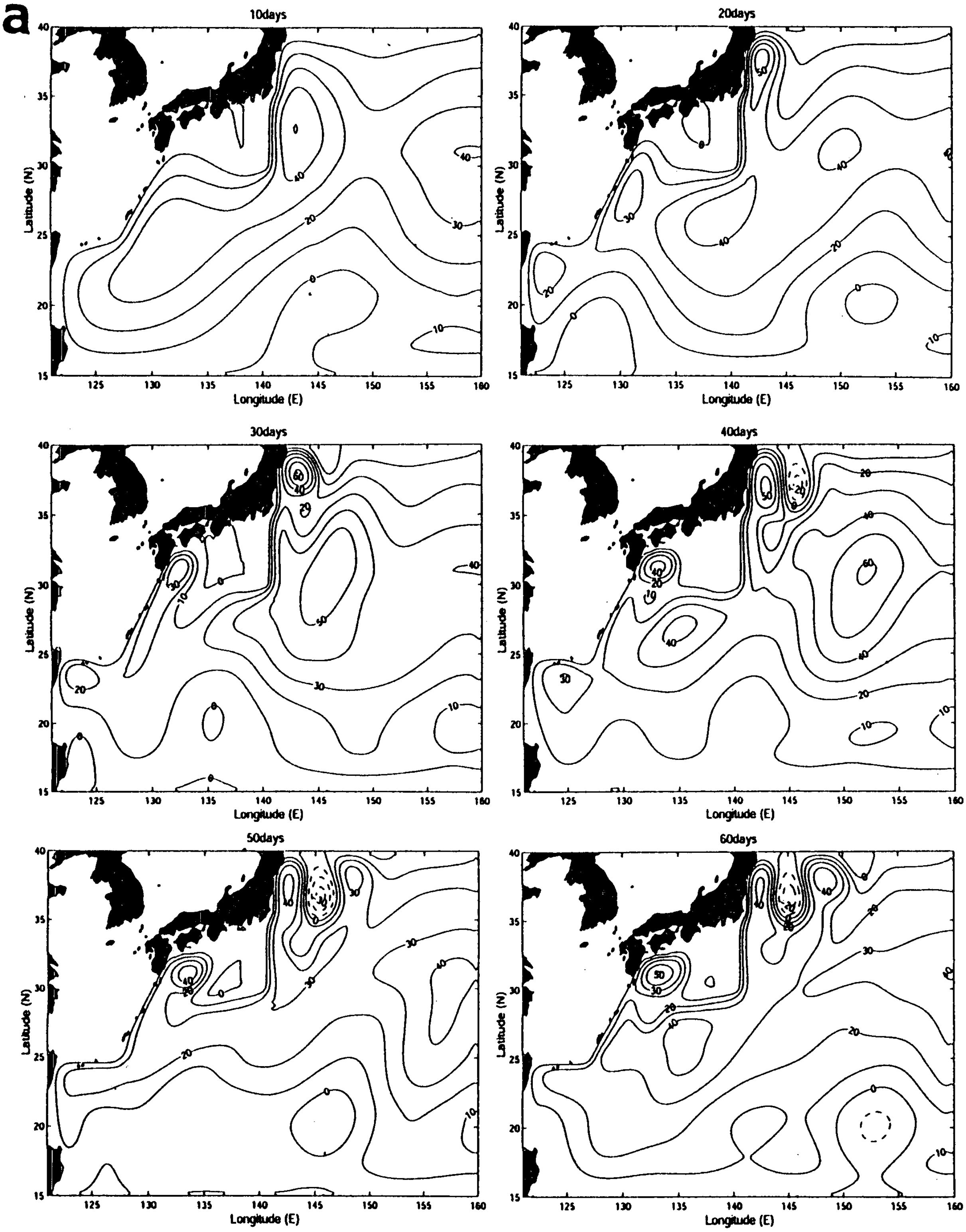
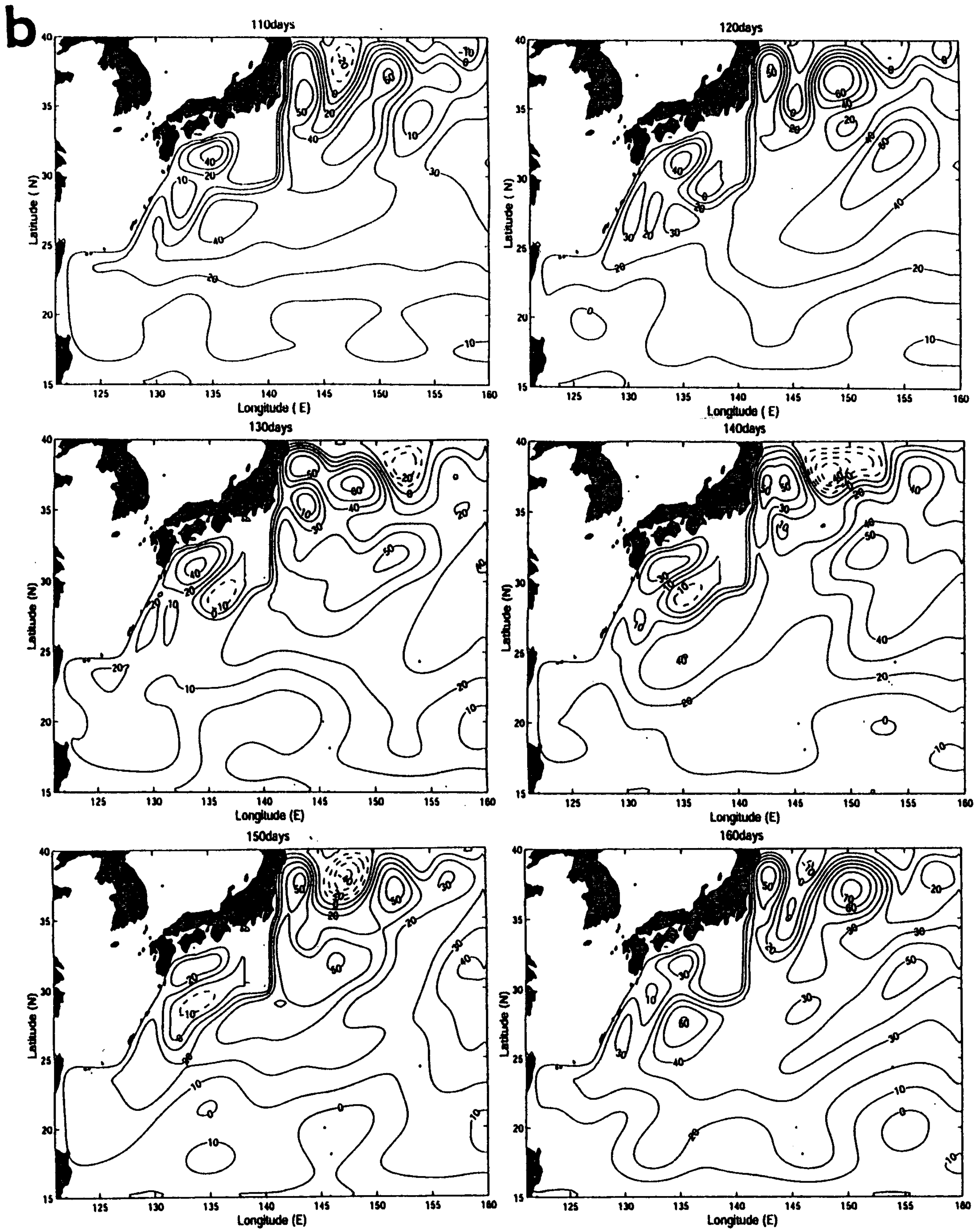


Fig. 11 As in Fig. 2, but for S40SE, during (a) from 10 days to 60 days and (b) from 70 days to 120 days.

Fig. 11 (continued)



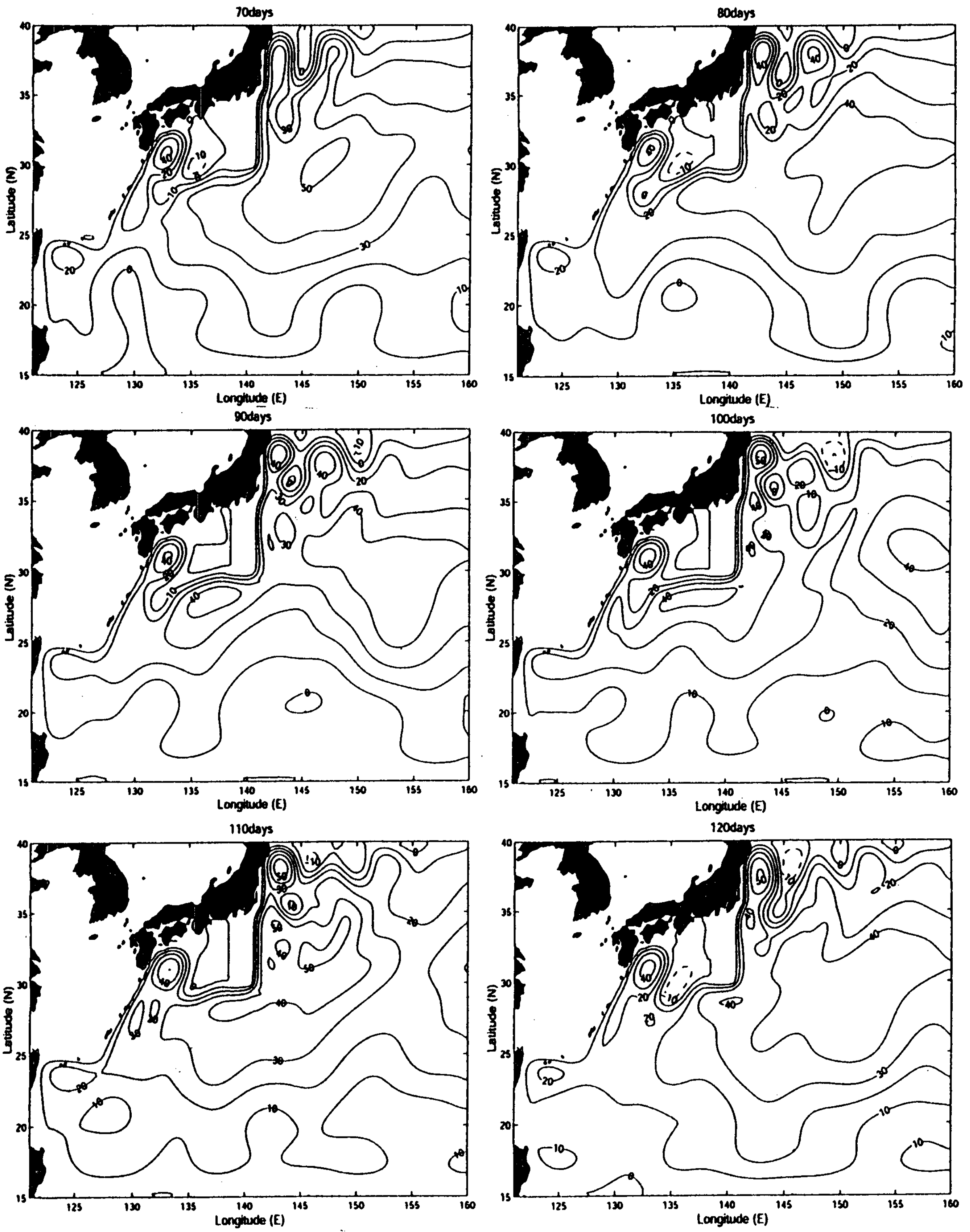


Fig. 12 As in Fig. 2, but for S60SE.

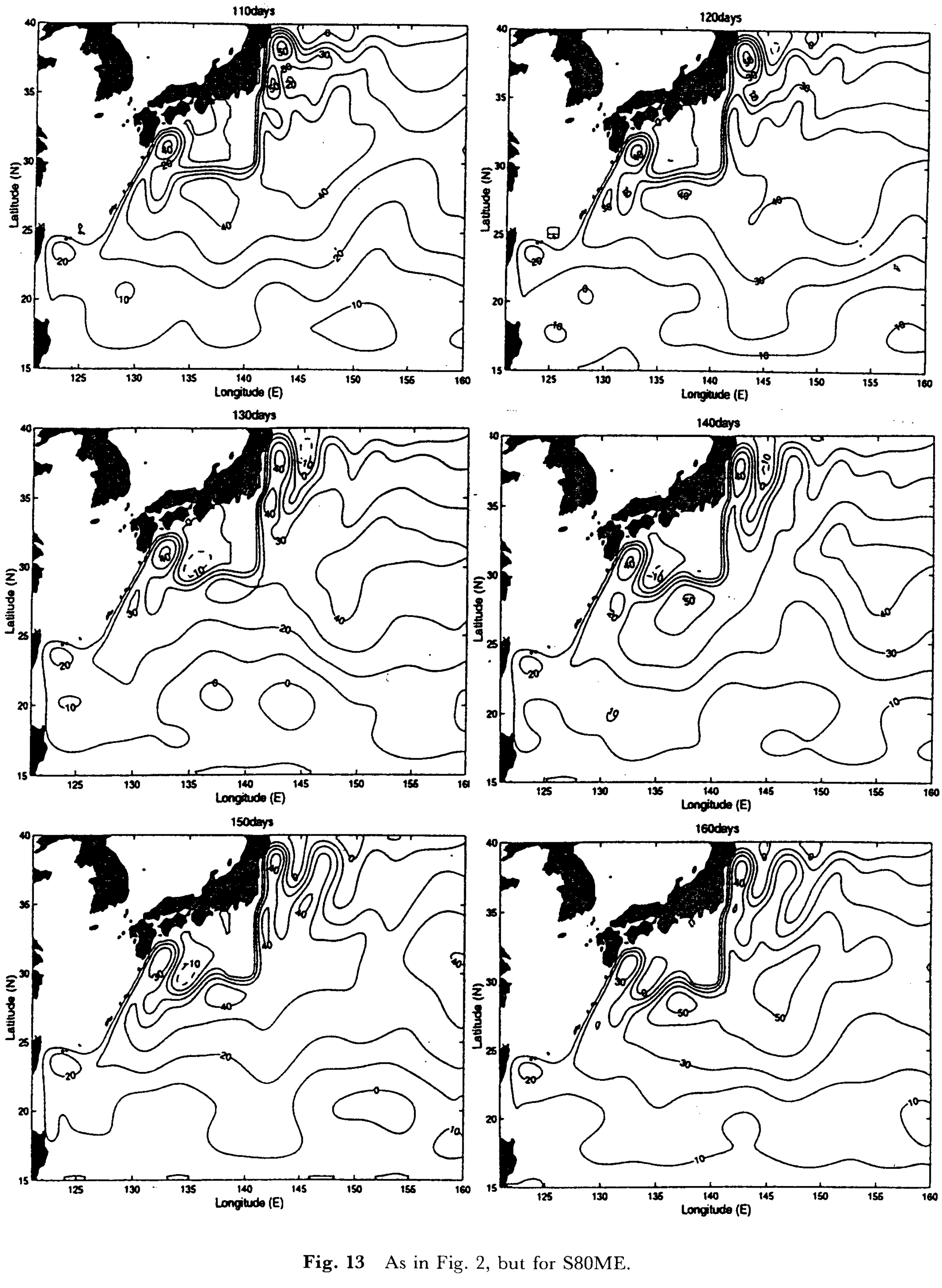


Fig. 13 As in Fig. 2, but for S80ME.

eddy and Two Eddies Pattern is formed at 120 days (Fig. 11b). It should be noticed that the cyclonic eddy is induced by the southwestward advection of the anticyclonic eddy in the Shikoku Basin, which is common to W60SE (Fig. 6) and W80SE (Fig. 7). However, it is difficult from S20SE (Fig. 10c) and W40SE (Fig. 5) with the formation by the topographic effect of the Izu Ridge. It is demonstrated that if the anticyclonic eddy is sufficiently large and occupies all the area of the Shikoku Basin, the cyclonic eddy will be mainly formed by the topographic effect of the Izu Ridge. On the other hand, if the anticyclonic eddy is small and locates at the western part of the Shikoku Basin, the cyclonic eddy will be formed by the southwestward advection by the anticyclonic eddy. Therefore, the Two Eddies Pattern should be classified into two cases by the different formation of the cyclonic eddy; the former case formed by the topographic effect of the Izu Ridge is referred to as the External Two eddies pattern and the latter case formed by the anticyclonic eddy is referred to as the Internal Two Eddies Pattern.

The Internal Two Eddies Pattern is formed in S60SE (Fig. 12) and S80SE (Fig. 13). The flow pattern of S60SE is almost equal to W40SE (Fig. 11) and the lifetime of the cyclonic eddy is about 40 days. The anticyclonic eddy of S80SE in the Shikoku Basin is not completely separated from the western boundary current off Kyushu and it has a characteristics of Moore Pattern. Even though, the anticyclonic eddy induces the cyclonic eddy as the Internal Two Eddies Pattern, which is different from the Moore pattern shown in Part I[1] with larger eddy viscosity. The lifetime of the cyclonic eddy is 50 days. The longer lifetime of the cyclonic eddy in these cases is due to the weak spin-up by the anticyclonic eddy, which takes a long time to spin-up. On the whole, the flow pattern of S40SE, S60SE and S80SE shows the clear appearance of the Ryuku Current Extension, except during the period of the development of the cyclonic eddy.

5. Summary and discussion

Flow characteristics of the Ryukyu Current Extension is examined by use of eddy generating models. Main results of the numerical experiment are summarized as follows:

(1) There exist essentially four current patterns in the Shikoku Basin; the Super Nonlinear Pattern, Nonlinear Pattern, External Two Eddies Pattern and Internal Two Eddies Pattern, depending on the Rossby number represented by the depth of the ocean. The appearance of the Ryukyu Current Extension is clear in the External and Internal Two eddies pattern, however, the Ryukyu Current Extension is not formed in the Super Nonlinear Pattern and Nonlinear Pattern. The multi-steady state is suggested among these patterns.

(2) Because the Super Nonlinear Pattern with the large amplitude and volume transport more than 100 Sv is significantly different from the observational features, model parameters are not suitable for the Kuroshio and the Kuroshio Extension. Similar flow pattern is also shown by other geophysical flow models[4], it is suggested that these models are also unsuitable for the actual ocean condition.

(3) The eastward velocity of the subtropical circulation of the Super Nonlinear Pattern is larger than the westward Rossby wave and the anticyclonic eddy is not formed. Conversely the westward velocity of the Rossby wave is larger than the eastward velocity and the anticyclonic eddy is formed in the Nonlinear Pattern. The similar phenomenon is also detecetd in the development of the anticyclonic eddy in the Shikoku Basin.

(4) In case of the External Eddies Pattern, a large anticyclonic eddy is formed in the Shikoku Basin and

the cyclonic eddy is formed by the topographic effect of the Izu Ridge. On the other hand, for the case of Internal Two Eddies Pattern, a small anticyclonic eddy is generated and the cyclonic eddy is induced by the southwestward advection by the anticyconic eddy in the Shikoku Basin.

Together with the results with Part I[1], it is concluded that there exists essentially six flow patterns in the Shikoku Basin; they are flow patterns of The Super Nonlinear, Nonlinear, External Two Eddies, Internal Two Eddies, Moore and Munk, as the Rossby number is decreased and the Reynolds number is increased. As noted in (1), the multi-steady state is suggested among these patterns.

It was pointed out by Sekine and Chen[6] that the distance of the main Kuroshio axis from Japanese coast is relatively small between off Asizuri-misaki and off Shiono-misaki. If the anticyclonic circulation is formed in the western side of the Shikoku Basin as the Moore Pattern or External and Internal Two eddies Patterns, it is recognized that the offshore distance of the Kuroshio is short off Shikoku by the northward shift of the anticyclonic eddy.

To draw firm conclusion on the flow pattern of the Ryukyu Current Extension, more detailed discussion on the model parameter and the resulted numerical solution is needed and it will be made in a near future. The specified observation on the Ryushu Current Extension is also strongly needed.

Acknowledgment

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新しい海流である琉球海流続流に関する数値モデル実験
第2部　渦解像モデル

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渦解像モデルを用いた琉球海流続流に関する数値モデルの結果について，第一部の線形および弱非線形モデルの結果に続いてまとめた。その結果，四国海盆では強い東向流を生じる超非線形型，高気圧渦を生じる非線形型，伊豆海嶺の地形効果で低気圧渦が生じて四国海盆に流入する外部二渦型と四国海盆内部の高気圧が低気圧渦を励起する内部二渦型の 4 つの流れのパターンが存在することが示された。これらの 4 つの型の出現はモデルの水深で制御される流れの大きさに依存する。超非線形型の場合には異常に大きい流量を持つ蛇行が生じて，モデルのパラメータ化が現実の海の状況には合わないことが示された。外部二渦型から非線形型へのカオス的な変化が発生し，4 つの流れのパターンの中には多重平衡状態の存在が示された。