An adjoint data assimilation method for optimizing frictional parameters on the afterslip area

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Afterslip sometimes triggers subsequent earthquakes within a timescale of days to several years. Thus, it may be possible to predict the occurrence of such a triggered earthquake by simulating the spatio-temporal evolution of afterslip with estimated frictional parameters. To demonstrate the feasibility of this idea, we consider a plate interface model where afterslip propagates between two asperities following a rate-and-state friction law, and we adopt an adjoint data assimilation method to optimize frictional parameters. Synthetic observation data are sampled as the slip velocities on the plate interface during 20 days. It is found that: (1) all frictional parameters are optimized if the data sets consists not only of the early phase of afterslip or acceleration, but also of the decaying phase or deceleration; and (2) the prediction of the timing of the triggered earthquake is improved by using adjusted frictional parameters.

Key words: Afterslip, frictional parameters, data assimilation, earthquake cycle simulation, adjoint method.

1. Introduction

The prediction of the occurrence time of earthquakes, based on physics-based models, is a highly challenging goal of earthquake science (e.g., Kato, 2008). Difficulties are rooted in the following facts: (1) the governing equations may not be sufficiently accurate to forecast the temporal evolution of the stress and the slip velocity; (2) it generally takes several hundred years to obtain observations over multiple cycles; and (3) differential equations are so stiff, and therefore the period when we might observe any precursory signals would be quite limited, so that, to date, unambiguous precursory signals have never been observed.

Nevertheless, this does not mean that all earthquakes are entirely unpredictable. An earthquake leads to a stress increase around the rupture region, which may either trigger another earthquake or induce afterslips. Continuous GPS measurements have revealed that afterslip lasts for several years following giant (M 8–9) earthquakes (e.g., Heki *et al.*, 1997). Such afterslip would load another asperity (a strongly-coupled area on the fault), if it exists, and consequently another earthquake would be induced there, depending on the stress state on the asperity, the amplitude of perturbation and the relative distance between asperities. For example, Uchida *et al.* (2009) suggested that afterslip east of the 2003 Tokachi-oki earthquake rupture region had propagated eastward and triggered the 2004 Kushiro-oki earthquake. Thus, if we trace the spatio-temporal evolution of afterslip, it may be possible to predict the occurrence of such a triggered earthquake.

In order to predict the occurrence time of a subsequent earthquake, it is essential to know the reasonable frictional property on the fault and to develop accurate physical models. Frictional properties in afterslip areas have been estimated based on kinematic inversions of GPS data (Miyazaki *et al.*, 2004; Hsu *et al.*, 2006) or dynamic model-based simulations, which provide constraints on the evolution of slip and the stress state (e.g., Marone *et al.*, 1991; Hearn *et al.*, 2002; Montési, 2004; Perfettini and Avouac, 2004, 2007; Perfettini *et al.*, 2005; Johnson *et al.*, 2006; Fukuda *et al.*, 2009; Mitsui *et al.*, 2010). It should be noted that all of these studies have employed a rate- and state-dependent friction law (e.g. Dieterich, 1979; Ruina, 1983). Although kinematic inversion is a simple technique, it is limited to estimating only $(a - b)\sigma_{\text{eff}}$, where a and b are constitutive frictional parameters (Eq. (1)) and σ_{eff} is the effective normal stress. Fukuda *et al.* (2009) developed a Markov chain Monte Carlo (MCMC)-based method (e.g., Metropolis *et al.*, 1953). Their study represented the Kurile Trench with a one-degree-of-freedom spring-slider system, and estimated $(a-b)\sigma_{\text{eff}}$, $a\sigma_{\text{eff}}$ and L (L is the characteristic length (Eqs. (1)–(2)). Mitsui *et al.* (2010) applied a Sequential Importance Sampling (SIS) method (e.g., Liu *et al.*, 2000) to a two-degrees-of-freedom cell model and demonstrated with synthetic afterslip data that the method worked for estimating $a - b$ and L. These previous studies are notable because the probability density functions (PDFs) are successfully reproduced given a numerical model with 10^6 ensemble members (Fukuda *et al.*, 2009). However, if we recall that earthquake simulations with a continuum medium require significant computational resources, (e.g., a single calculation by Ohtani *et al.* (submitted to *Geophysical Research Letters*, 2013) required approximately 10^7s of CPU time), the realization of 10^6 ensemble members is not practical. Thus, a

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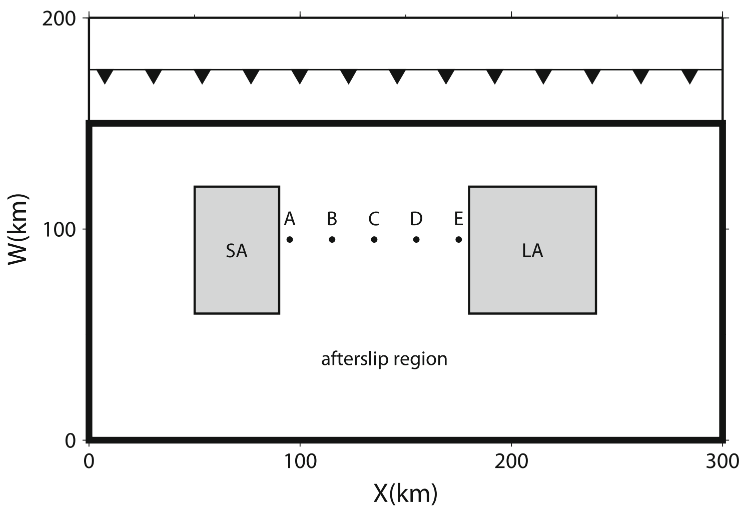

Fig. 1. Plate model domain used in this study. The thick rectangle is the fault area. The two shaded regions represent a large (LA) and small (SA) asperity, respectively. The region around the asperities is assumed to accommodate afterslip. The plate is subducting at a dip angle of 20°. The solid triangles with thin lines schematically show the trench.

computationally-efficient method is required for estimating frictional parameters which enables a realistic model.

Kano *et al.* (2010) utilized an efficient dynamic model-based method, "An Adjoint Data Assimilation Method" (e.g., Lewis and Derber, 1985). Adjoint methods have been extensively applied to realistic models with 10^6–10^{10} variables in the fields of meteorology and oceanography for real-time and long-term forecasting. Kano *et al.* (2010) first applied an adjoint method to earthquake simulations with a three-degrees-of-freedom cell fault model and estimated $a - b$, a and L. They confirmed that the method is computationally much more efficient than MCMC and SIS, whilst providing nearly identical results. They also found that $a-b$ is always constrained. However, the initial phase data of decaying afterslip is required to constrain L, and a was not constrained under any conditions.

Although Kano *et al.* (2010) estimated frictional parameters for three cell faults, they did not investigate the potential impact on earthquake prediction. Nevertheless, their work has motivated us to test the feasibility of predicting future afterslip propagation and its triggering of another earthquake with a realistic continuum fault model based on an adjoint method. In this work, we perform a synthetic data assimilation experiment with the fault model. A rate- and state-dependent friction law and the slowness law (Dieterich, 1979) are used as governing equations for data assimilation. Although this fault model is still simplified in many aspects, it constitutes an important step toward predicting an actual triggered earthquake by evaluating the potential impact of efficient data assimilation.

In Section 2, the numerical model, synthetic afterslip data and the data assimilation system are described. Numerical results are given in Section 3. Section 4 provides a summary and discusses potential challenges for practical application.

2. Setting

2.1 Forward model

2.1.1 Fault model and frictional properties The model region of the plate boundary at the Kurile Trench is represented as one rectangular fault (300-km long, 150-km wide) with a dip angle of 20° (Fig. 1). The model region involves two asperities, one large (60-km long, 60-km wide, hereafter LA) and one small (40-km long, 60-km wide, hereafter SA), representing asperities for the Tokachi-oki earthquake and the Kushiro-oki earthquake, respectively. The remainder of the region, subdivided into 10 × 10-km subfaults, is the aseismic slip region where afterslip is expected to occur.

2.1.2 Governing equations The governing equations consist of a rate- and state-dependent friction law (Eq. (1)), a slowness law (Eq. (2)), and the time derivative of a quasi-dynamic equation of motion (Eq. (3)) as shown below:

$$\mu_i \sigma_i = \mu_{0i}\sigma_i + a_i\sigma_i \ln\left(\frac{V_i}{V_{0i}}\right) + b_i\sigma_i \ln\left(\frac{V_{0i}\theta_i}{L_i}\right), \quad (1)$$

$$\frac{d\theta_i}{dt} = 1 - \frac{V_i\theta_i}{L_i}, \quad (2)$$

$$\sigma_i \frac{d\mu_i}{dt} = \sum_j k_{ij}\left(V_{\rm pl} - V_j\right) - \frac{G}{2c}\frac{dV_i}{dt}, \quad (3)$$

where μ_i is a frictional coefficient, V_i is the slip velocity, θ_i is a state variable, σ_i is the effective normal stress, V_{0i} is a reference velocity, μ_{0i} is a reference frictional coefficient when $V_i = V_{0i}$ at steady state, and a_i, b_i, L_i are frictional parameters (hereafter, we use $A_i = a_i\sigma_i$, $B_i = b_i\sigma_i$) at cell i. In addition, $V_{\rm pl}$ is the plate velocity, G is the shear modulus, and c is the shear wave velocity. The slip response function k_{ij} represents shear stress changes at cell i due to the unit slip at cell j, and is calculated by Okada (1992). The second term on the right-hand side of Eq. (3) is a radiation damping term that represents energy loss by shear wave radiation (Rice, 1993). This set of equations is solved for μ_i, V_i and θ_i. We set $V_{\rm pl}$ = 9 cm/yr (DeMets *et al.*, 1994), G = 30 GPa, c = 3 km/s, μ_{0i} = 0.6, and $V_{0i} = V_{\rm pl}$ (= 9 cm/yr). We set the effective normal stress σ_i = 100 MPa in the asperity region and σ_i = 20 MPa in the afterslip region, which may be small compared to the lithostatic pressure.

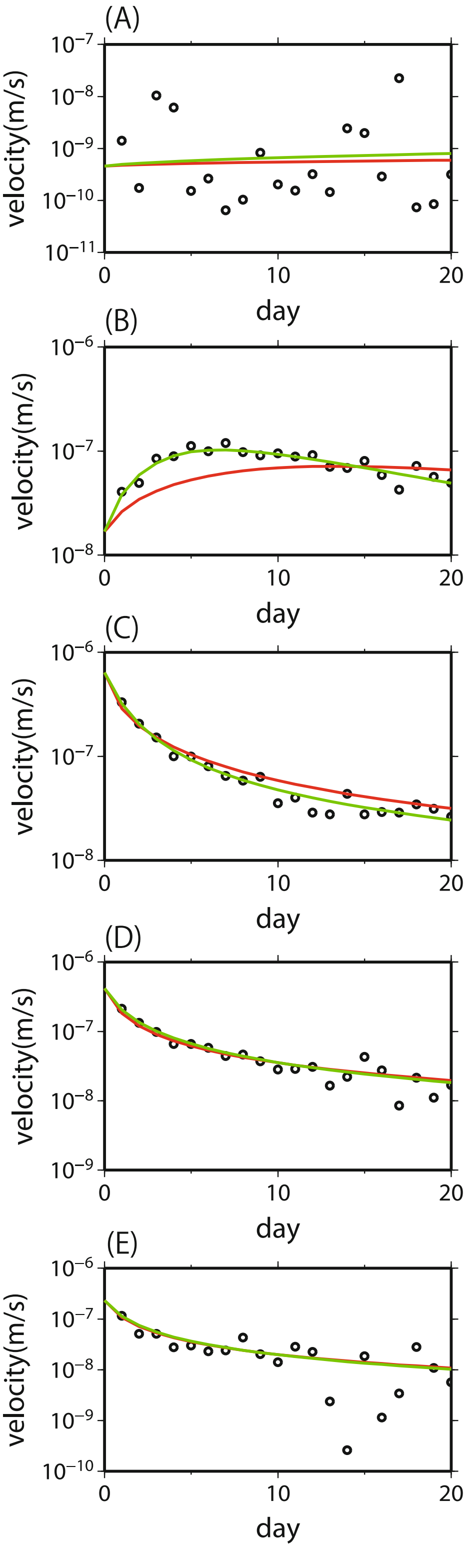

Fig. 2. Time series of slip velocity at points A–E in Fig. 1 with those calculated with first-guess and estimated values. Circles show the synthetic observation data. Red and green lines show the calculated slip velocity with first-guess and estimated values in Table 1, respectively.

We first calculate the spatio-temporal evolution of afterslip with the frictional parameters ($A-B$, A, L) estimated from the subdaily GPS time series following the 2003 Tokachi-oki earthquake by Fukuda *et al.* (2009). However, afterslip does not propagate more than 40 km in the strike region using their values of ($A-B$ (kPa), A (kPa), L (mm)) = (218, 300, 1.00). This is because the single spring-slider system used in their work is not realistic. We found that a low effective normal stress with high pore pressure is essential for afterslip to propagate at a similar depth to seismogenic zones (e.g., Ariyoshi *et al.*, 2007). Equations (1) to (3) are numerically solved with an adaptive time-step Runge-Kutta method (Press *et al.*, 1996) under the initial conditions of $V_i = 0.9V_{\rm pl}$ and $\theta_i = L_i/V_i$.

2.1.3 True state We adopt a one model realization with frictional parameters (($A-B$ (kPa), A (kPa), L (mm)) = (−100, 40.0, 40.0) in LA, (−80.0, 40.0, 40.0) in SA, and (5.00, 40.0, 40.0) in the afterslip regions, as a 'true' state. This is obtained from forward time integration of the above governing equations.

The true state indicates that large earthquakes occur quasi-periodically in the LA region at approximately 100-year intervals, and medium-sized earthquakes occur in the SA region with an average interval of 60 years, depending on the stress interactions between the two asperities (throughout this paper, we regard a fault slip as an earthquake when the slip velocity exceeds 1 cm/s). This is a typical timescale for thrust-type earthquakes at the Kurile Trench (e.g., Sawai *et al.*, 2009).

Hereafter, we focus on one particular earthquake in the LA region which occurred 894 years after the initial time. The subsequent afterslip triggered an earthquake at SA 3.83 years after the first earthquake. Hereafter, the timeframe refers to one day after the initiation of the first earthquake. Figure 2 shows the time series of the slip velocity due to afterslip, showing that the accelerating phase is found at point B. The triggered earthquake occurred at $t = 3.83$ years.

2.2 Synthetic data and simulation run

We investigate whether synthetic observations are sufficient to specify the frictional parameters over the afterslip region. Synthetic slip velocity observation on the fault is sampled from the true state during days 1–20 at all cells in the afterslip area. We then added a Gaussian error with zero mean and standard deviation 1.0×10^{-8} m/s (Miyazaki *et al.*, 2004). We assimilate these synthetic slip velocity data through the adjoint data assimilation method to check whether the "first-guess" parameter values are updated to their true values.

In actual cases, accurate frictional parameters are rarely known. However, it may be reasonable to provide a first-guess value within the order of parameters that is predetermined by, for example, kinematic inversions. In this study, we perform a time integration with the first-guess frictional parameter values in the afterslip region (hereafter, simulation run). In this work, we perturb the true frictional parameters by 100% to generate the first-guess values, as shown in Table 1. Note that the frictional parameters in the two asperities and the initial values of shear stress and slip velocity are fixed to their true values throughout the experiment.

2.3 Adjoint data assimilation method

The adjoint-based data assimilation is outlined in this section. More detailed explanations are given in Lewis *et al.* (2006) and Ito *et al.* (2011). The basic idea is to define a cost function that quantifies the total misfit between the model

Table 1. Table of true, first-guess and estimated values of frictional parameters, cost function, and occurrence time of the triggered earthquake.

	$A - B$ (kPa)	A (kPa)	L (mm)	Cost function	Occurrence time of the triggered earthquake (year)
True value	5.00	40.0	40.0	3000	3.83
First-guess value	10.0	80.0	80.0	12500	10.9
Estimated value	5.37	40.5	40.8	3010	3.92

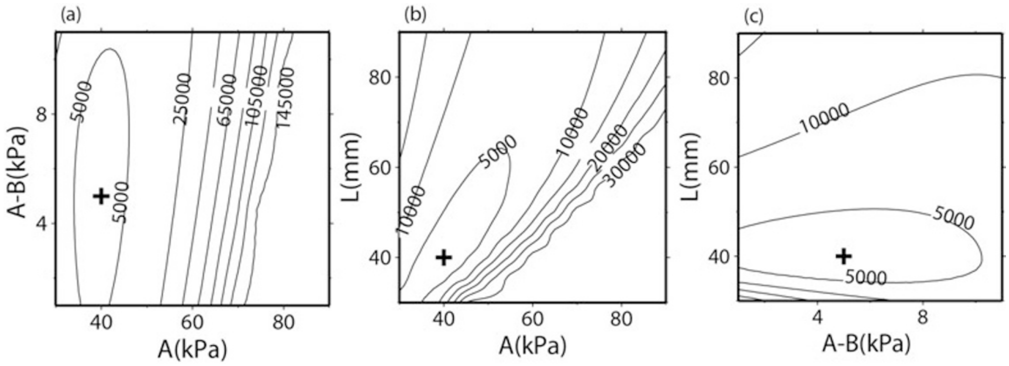

Fig. 3. Contour maps of cost function: (a) $A : A - B$, (b) $A : L$, and (c) $A - B : L$ planes. The crosses show the true values.

results and the observations. The adjoint model, which is the adjoint of the dynamic model operator linearized about the time trajectory, effectively transforms the misfit into the gradient of the cost function with respect to control variables, i.e. the frictional parameters in this study. The control variables are updated iteratively in order to minimize the cost function, thereby improving estimates and prediction. Note that, in each iteration, the control variables are constant.

The cost function used in this work is defined as follows:

$$J(\mathbf{C}) = \frac{1}{2}\sum_t (\mathbf{V}_t^{\mathrm{sim}}(\mathbf{C}) - \mathbf{V}_t^{\mathrm{obs}})^{\mathrm{T}} \mathbf{R}_t^{-1} (\mathbf{V}_t^{\mathrm{sim}}(\mathbf{C}) - \mathbf{V}_t^{\mathrm{obs}}), \quad (4)$$

where $\mathbf{R}_t$ is an observation error variance-covariance matrix, $\mathbf{C}$ is a vector that consists of frictional parameters, i.e., $\mathbf{C} = [A-B, A, L]^{\mathrm{T}}$, $\mathbf{V}_t^{\mathrm{sim}}$ represents a simulated slip velocity vector at epoch t and $\mathbf{V}_t^{\mathrm{obs}}$ is a corresponding observation vector.

We first perform forward time integration with the first-guess values and then an adjoint model transforms the misfit into the gradient of the cost function with respect to the control variables, $\partial J/\partial \mathbf{C}$. In this work, the control variables are updated as follows:

$$\mathbf{C}_{\mathrm{new}} = \mathbf{C}_{\mathrm{old}} + \alpha_{\mathbf{C}} \left.\frac{\partial J}{\partial \mathbf{C}}\right|_{\mathbf{C}=\mathbf{C}_{\mathrm{old}}}, \quad (5)$$

where $\alpha_{\mathbf{C}}$ is a constant and is different in each parameter, i.e.,

$$\alpha_{A-B} = -2.5 \Big/ \left.\frac{\partial J}{\partial (A-B)}\right|_{\mathrm{iter}=1}, \quad (6)$$

$$\alpha_{A} = -20 \Big/ \left.\frac{\partial J}{\partial A}\right|_{\mathrm{iter}=1}, \quad (7)$$

$$\alpha_{L} = -20 \Big/ \left.\frac{\partial J}{\partial L}\right|_{\mathrm{iter}=1}, \quad (8)$$

We then iterate this calculation either 30 times, or until the updated cost function satisfies the following criteria:

$$\frac{J_{\mathrm{old}} - J_{\mathrm{new}}}{J_{\mathrm{new}}} < 0.001 \quad (9)$$

If J_{new} becomes greater than J_{old}, we change the constant $\alpha_{\mathbf{C}}$ to $\alpha_{\mathbf{C}}/2$ until J_{new} becomes smaller than J_{old}. Note that alpha values do not affect the estimation and convergence rate, and that this convergence condition (Eq. (9)) is sufficient to obtain a robust result.

3. Results

3.1 Optimization of frictional parameters

Table 1 shows the results of data assimilation, "estimated values" and first-guess values. As a result of data assimilation, frictional parameters are updated to ($A - B$ (kPa), A (kPa), L (mm)) = (5.37, 40.5, 40.8), which are close to the true parameters, (5.00, 40.0, 40.0). Figure 2 shows that the updated state of the slip velocity is consistent with the observed values at points A–E, whereas those in the simulation run were not. We confirmed, by follow-up experiments, that this result is true within the range of first-guess values which are one-order larger, or smaller, than the true values. This suggests that the rough estimate of first-guess values is sufficient to recover the true frictional parameters. The reason why all frictional parameters are determined, unlike in Kano *et al.* (2010), is presumably that the observation data are available during the accelerating phase of the afterslip. Moreover, we found that only the observations at point B constrain all frictional parameters. Thus, we suggest that if there is at least one observation which contains both the acceleration phase and the decaying phase, all frictional parameters are constrained.

Figure 3 shows J as a function of two frictional parameters, setting the other to its true value. These figures show that, despite the observation error, there are no minimal values except those near the true value. This finding supports

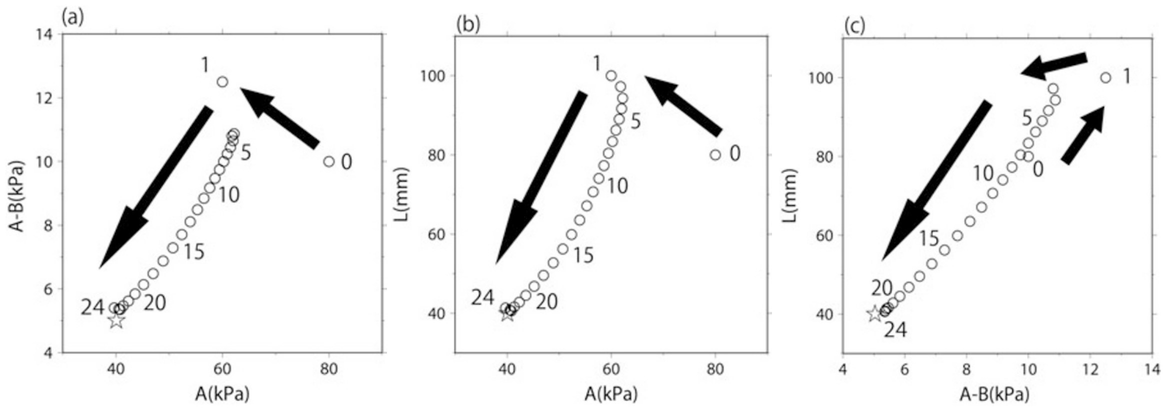

Fig. 4. Updates of the frictional parameters: (a) $A : A - B$, (b) $A : L$, and (c) $A - B : L$ planes. The arrows indicate the updates of the frictional parameters from the first-guess to the estimated values. Circles also indicate the values at each iteration and the number of iterations. Stars indicate the true values.

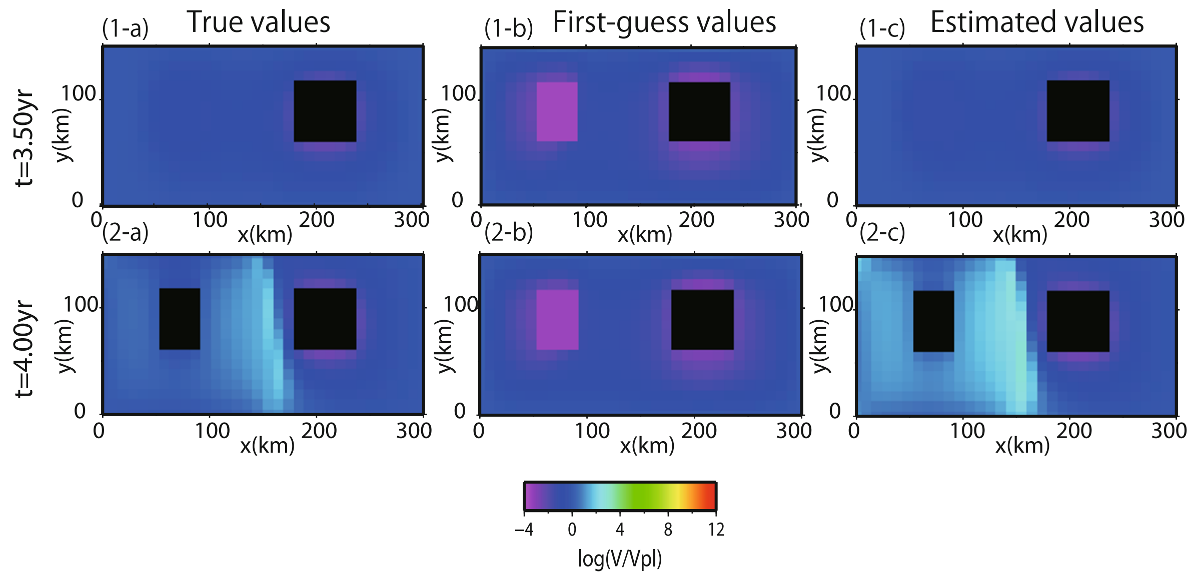

Fig. 5. Snapshots of the slip velocity at (a) $t = 3.50$ yr and (b) $t = 4.00$ yr, respectively. In each figure, the slip velocity is calculated with (1) true, (2) first-guess and (3) estimated values, respectively.

the robustness of the solution. Figure 4 shows three parameter values at each iteration. Parameter values converged only after 24 iterations. The computational cost of each iteration of this data assimilation system is approximately twice that of the forward calculation, and is therefore about 50 times greater in total. This demonstrates the efficiency of an adjoint data assimilation method compared with Monte Carlo-based methods or the explicit illustration of the cost function by iteratively changing frictional parameters as in Fig. 3.

3.2 Prediction of the triggered earthquake in SA

The occurrence time of the triggered earthquake with estimated parameters is $t = 3.92$ year (Table 1). This is close to the true state, $t = 3.83$ year, compared with $t = 10.9$ year without optimization. Figure 5 shows snapshots of the slip velocity at (a) $t = 3.50$ yr and (b) $t = 4.00$ yr, calculated with (1) true values, (2) first-guess values, and (3) estimated values, respectively. This figure shows the weakening of the locked interface at SA and afterslip before, and after, the triggered earthquake in the true state with true values and estimated values, respectively, but not with first-guess values. These results indicate that only the observations during 20 days contribute to improvements in the prediction of the triggered earthquake. Although this data assimilation is an idealized experiment, it encourages us to develop a prediction system for triggered earthquakes with actual data and a more sophisticated fault system.

4. Discussion and Summary

We have developed an efficient data assimilation system to estimate frictional parameters on a fault with the aim of predicting earthquakes triggered by afterslip propagation. Synthetic observation data of the slip velocity on the plate interface are assimilated to a simplified fault model with two asperities through an adjoint data assimilation method. We confirmed that all frictional parameters are well constrained from observations during 20 days, facilitating the enhanced prediction of the triggered earthquake. Moreover, if at least one observation contains both the acceleration phase and the deceleration phase, all frictional parameters are constrained.

In terms of a practical application, several points need to be further verified. First, predictions derived from a data assimilation system are strongly dependent on the base dynamic model. Currently, the dynamic model does not consider the geometry of the plate boundary, structural heterogeneity and visco-elasticity. We assumed uniform frictional parameters over the entire afterslip region. Moreover, it would be essential to estimate the frictional parameters in asperity (Hiyoshi *et al.*, Possible estimates of frictional properties on earthquake and afterslip rupture surfaces with 4D-VAR method, manuscript in preparation, 2013) and other control variables, i.e. the initial slip velocity and the initial state variable (Kano *et al.*, 2010). Our future scope includes improvement of the base model, especially the model of friction, to explain the data well and the optimization of heterogeneous parameters.

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