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Estimating Economic Effects of Political Movements in China[1]

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To measure the economic effects of political movements in China a simple econometric model is constructed. Investment is determined by a central planner maximizing a multiperiod objective function. Political events are modeled by exogenous changes in the shocks to productivity and to investment which affect the time paths of major economic variables. Effects of the events are measured by comparing the time paths generated by the model with and without the changes in the shocks. Without the Great Leap output and consumption per capita would have been 2.0 times as great in 1993, without the Cultural Revolution, 1.2 times as great. *J. Comp. Econom.,* October 1996, **23**(2), pp. 192–208. Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong; and Princeton University, Princeton, New Jersey 08544. © 1996 Academic Press, Inc.

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1. INTRODUCTION

What were the economic effects of the Great Leap Forward Movement in 1958–1962 and the Cultural Revolution in 1966–1969 in China? In other words, if these two events had not occurred, what would have been

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the time paths of the major economic variables such as consumption, real output, and capital stock in the years following 1958? This is an interesting question in economic history. To answer this question one has to compare the historical time paths of these variables with the paths that would have prevailed absent the above events. We first construct an econometric model to explain the growth of the Chinese economy that incorporates the shocks from these two political events. Then the shocks are removed and the hypothetical time paths of the major economic variables are generated from the model. Comparing the hypothetical time paths with the time paths incorporating the shocks provides an answer to our question.

The econometric model has only one sector and includes aggregate output, consumption, investment, physical capital stock and total labor force as major variables. Aggregate output is produced by physical capital and labor according to a Cobb–Douglas production function. Output is divided into consumption and net investment, the latter measured by accumulation in Chinese official statistics. Capital stock increases by the flow of investment. To determine investment, we assume that actual investment equals planned investment plus an error. Planned investment is determined by the assumption that a central planner maximizes a multiperiod objective function with consumption per laborer as argument. The error may be affected by political events. The logarithm of total factor productivity follows a random walk with drift in normal years. In abnormal years such as during the Great Leap and the Cultural Revolution, the residual of the random walk process can also be affected. Thus the effects of political events are modeled by changes in the error of the investment function and in the residual of the random walk process for productivity. Having estimated such a model, one can remove the changes in order to measure the economic effects of the two political events. Section 2 specifies the model and the data. Section 3 presents the method of estimation and the parameter estimates. Section 4 reports on the time paths of major variables obtained by simulating the model absent the shocks from the two political events and provides measures of economic losses attributable to them. Section 5 concludes.

2. MODEL AND DATA

The econometric model consists of four equations. A Cobb–Douglas production function determines aggregate real output Q by physical capital stock K and labor L with constant return to scale. Denoting Q/L and K/L by q and k, respectively, and net investment per laborer by i, we can write the production function, the output identity, the capital accumulation equation, and the equation explaining total factor productivity A as

$$q_t = A_t k_t^{1-\alpha} \tag{1}$$

$$q_t = c_t + i_t \tag{2}$$

$$k_{t+1} = k_t + i_t \tag{3}$$

$$\ln A_{t+1} = \gamma + \ln A_t + \eta_{t+1}, \tag{4}$$

where η is a random shock to the logarithm of total factor productivity A. Note that the capital accumulation equation is obtained by dividing the original identity in aggregate variables by labor L in two adjacent periods and is therefore only an approximation.

The data for aggregate output Q are national income used (*Statistical Yearbook of China* 1994, abbreviated SYB, p. 40) divided by the implicit price deflator of national income. The price deflator is the ratio of national income in current prices (SYB, p. 33; measured in 100 million yuan) to national income in 1952 prices; the latter equals 589 (national income in 1952 in 100 million yuan) times the index of real national income (SYB, p. 34; =100 in 1952) divided by 100. In Chinese official statistics, national income used equals consumption plus accumulation (net investment) in current prices. In our model this identity is assumed to hold in constant prices. We have estimated real national income used Q, real consumption C, and real net investment I by dividing their current values (SYB, p. 40) by the above price deflator. Labor L is total labor force (SYB, p. 88). Given $K = 2213$ (100 million yuan) in 1952 (an estimate from Chow (1993b, p. 821)), we estimate k in 1952 by K/L and k in later years by Eq. (3).

We assume that the Chinese economy evolves as if there were a central planner who, knowing the parameters of the model as we have specified, tries to maximize the following objective function at the beginning of each period t,

$$E_t \sum_{i=1}^{\infty} \beta^{t+i} \log c_{t+i}, \tag{5}$$

subject to the constraints in (1)–(4). This dynamic optimization problem can be solved by defining the control variable as either consumption per laborer c, or investment per laborer i, or even next-period capital stock, as they are related by the identities (2) and (3). This maximization assumption might be questioned. A critic might argue that economic planners in China are not so rational as to have a specific objective function. She would say, just look at what happened to rational economic planning during the Great Leap and the Cultural Revolution. Our response is that during these abnormal periods there were exogenous shocks to the production and investment processes in China, caused to a large extent by the behavior of Chairman Mao, which the economic planners could not control. However, given these shocks, the planners still attempted in each period to maximize the above objective function from that period onward.

Among the possible shortcomings of this model are the treatment of technology, population, and labor force as exogenous and the failure to incorporate possible effects of outcomes on human capital formation. Despite these possible shortcomings, we believe that the present study is an important step toward measuring the economic effects of the two major political events and can serve as a benchmark for incorporating other important effects in future research.

3. STATISTICAL ESTIMATION

As discussed in the last section, the observed Chinese time series data on output, consumption, and capital are interpreted as the outcome of a dynamic optimization process. The solution to the dynamic optimization problem will depend on the parameters (α, β, γ) and the process governing the evolution of productivity. When we estimate the parameters by the method of maximum likelihood, we are in fact searching for a set of parameters for which the solution to the dynamic optimization problem and the observed series are as close as possible. A dynamic optimization problem is thus embedded within each evaluation of the likelihood function. More precisely, calculating the likelihood value for a given parameter setting proceeds in two stages. First, an optimal decision function for investment is determined by assuming that the central planner in China maximizes the objective function (5) subject to the constraints of the model (1)–(4) at each period t. Second, the optimal decision function is combined with the original model to form an econometric model for which the likelihood value can be calculated.

The dynamic optimization problem as stated in (1)–(5) can be converted into an equivalent version involving only stationary processes. The idea is to detrend all variables along their balanced growth paths. After detrending, the model is stationary and econometric problems associated with the unit root in Eq. (4) will be avoided. Define

$$z_t = A_t^{1/\alpha}, \qquad \bar{k}_{t+1} = k_{t+1}/z_t, \qquad \bar{c}_t = c_t/z_t, \qquad \bar{z}_t = z_t/z_{t-1}. \tag{6}$$

Replacing i by $q - c$ and q by the production function, we can write the capital accumulation equation as

$$k_{t+1} = k_t + A_t k_t^{1-\alpha} - c_t,$$

implying

$$k_{t+1}/z_t = (k_t/z_{t-1})z_{t-1}/z_t + k_t^{1-\alpha} z_t^{\alpha-1} - c_t/z_t,$$

or, in terms of the detrended variables defined in (6),

$$\bar{k}_{t+1} = \bar{k}_t \bar{z}_t^{-1} + \bar{k}_t^{1-\alpha} \bar{z}_t^{\alpha-1} - \bar{c}_t. \tag{7}$$

Similarly the productivity Eq. (4) can be written as

$$\ln \bar{z}_t = \mu + \epsilon_t, \tag{8}$$

where

$$\mu = \gamma/\alpha, \qquad \epsilon_t = \eta_t/\alpha.$$

Since z_t is exogenous, we may replace the objective function (5) by

$$E_t \sum_{i=1}^{\infty} \beta^{t+i} \ln \bar{c}_{t+i}. \tag{9}$$

Maximizing (9) subject to (7)–(8) is equivalent to the non-stationary version in (1)–(5). We approach the dynamic optimization problem by first substituting (7) into (9) to eliminate the detrended consumption variable, and then define the control variable to be $\ln \bar{k}_{t+1}$, and two state variables $\ln \bar{z}_t$ and $\ln \bar{k}_t$. With state and control so defined, we obtain numerically an approximate solution in the form of a log-linear first-order difference equation:

$$\ln \bar{k}_t = g + G_1 \ln \bar{z}_{t-1} + G_2 \ln \bar{k}_{t-1}. \tag{10}$$

The coefficients (g, G_1, G_2) may be regarded as reduced form parameters, as they are implicit functions of the three structural parameters (α, β, γ). The solution procedure and numerical algorithm can be found in the Appendix. It is well known that if the capital stock depreciates completely in one year, i.e., if $A_t k_t^{1-\alpha}$ replaces $k_t + A_t k_t^{1-\alpha}$ in the equation determining k_{t+1}, a closed form solution for (10) exists. However, this assumption is a poor approximation to reality and a numerical solution serves our purpose just as well.

Having derived the planned capital stock as described by (10), we allow actual capital stock to differ from planned capital by an error e due partly to failure of the planner to execute the plan and partly to failure of our simple model to capture the complicated economy completely. The econometric model to be estimated consists of two equations, an equation for $\ln \bar{z}_t$ and an equation for $\ln \bar{k}_t$, which can be written as a system of two regression equations,

$$y_t = \Gamma x_t + \xi_t, \tag{11}$$

where $y_t = (\ln \bar{z}_t, \ln \bar{k}_t)'$, $x_t = (1, \ln \bar{z}_{t-1}, \ln \bar{k}_{t-1})'$ and

$$\Gamma = \begin{bmatrix} \mu & 0 & 0 \\ g & G_1 & G_2 \end{bmatrix} \qquad \xi_t = \begin{bmatrix} \epsilon_t \\ e_t \end{bmatrix}. \tag{12}$$

With n observations (11) can be stacked up as

$$Y = X\Gamma + \Xi \tag{13}$$

with the transpose of (11) being the tth row of (13).

Assuming normal and serially uncorrelated residuals, and ξ_t having covariance matrix Σ, we can use the well-known concentrated log-likelihood function (see Chow (1983), pp. 170–171)

$$\ln L = \text{const} - (n/2)\ln|n^{-1}(Y - X\Gamma)'(Y - X\Gamma)| \tag{14}$$

and the maximum likelihood estimate of Σ is given by

$$\hat{\Sigma} = n^{-1}(Y - X\Gamma)'(Y - X\Gamma). \tag{15}$$

The observed variables are $\ln q_t$ and $\ln k_t$, with $\ln z_t$ defined as $[\ln q_t - (1 - \alpha)\ln k_t]/\alpha$. Substituting this definition for $\bar{z}_t = z_t/z_{t-1}$ in Eqs. (8) and (10), we have

$$\ln q_t - (1 - \alpha)\ln k_t = \gamma + \ln q_{t-1} - (1 - \alpha)\ln k_{t-1} + \eta_t \tag{8$'$}$$

$$\begin{aligned}\ln k_t = g + [\ln q_{t-1} - (1-\alpha)\ln k_{t-1}]/\alpha + G_1[\Delta\ln q_{t-1} - (1-\alpha)\Delta \ln k_{t-1}]/\alpha \\ + G_2[\ln k_{t-1} - (\ln q_{t-2} - (1 - \alpha)\ln k_{t-2})/\alpha] + e_t.\end{aligned} \tag{10$'$}$$

The Jacobian of the transformation from $\eta_t = \alpha\epsilon_t$ and e_t to $\ln q_t$ and $\ln k_t$ is

$$J = \begin{vmatrix} 1 & -(1 - \alpha) \\ 0 & 1 \end{vmatrix} = 1$$

which is implicit in the likelihood (14).

To calculate likelihood value for the parameters (α, β, μ) we use these parameters and the data on output and capital to compute z from the production function, $\bar{z}_t$ and $\bar{k}_t$ from Eq. (6), and the coefficients in Γ using Eq. (10). Thus the likelihood function (14) can be computed from the parameters and the data. We maximize the likelihood function in a sequential manner, i.e., $\max_\alpha$-$\max_{\beta,\mu}\ln L(\alpha, \beta, \mu)$. The maximization with respect to (β, μ) is performed by the MAXLIK package in GAUSS, and the linesearch in α is done by Brent's method (see Press et al. (1992, pp. 402–405)). The point estimate and standard error of γ can be recovered from that of α and μ via (8). To make sure that we have indeed located the global maximum, we have also used the simulated annealing algorithm as implemented by Goffe et al. (1991) to maximize the likelihood function. The sample period is from 1954 to 1993.

The maximum likelihood estimates of (α, β, γ), with standard errors given in parentheses, are

$$\begin{aligned}(\hat{\alpha}, \hat{\beta}, \hat{\gamma}) &= [0.7495\ (0.0108),\ 0.9999\ (0.0001),\ 0.0218\ (0.0025)] \\ \text{mean log likelihood} &= 6.6120,\ \text{sample size} = 40.\end{aligned} \tag{16}$$

The estimate 0.7495 for labor elasticity of production is reasonable. It is

TABLE 1

PARAMETER ESTIMATES FOR FIXED VALUES OF α

α	$\hat{\beta}$	$\hat{\gamma}$	Mean log likelihood
0.4	0.9627 (0.0050)	0.0046 (0.0011)	5.9754
0.5	0.9715 (0.0037)	0.0083 (0.0017)	6.2012
0.6	0.9817 (0.0024)	0.0132 (0.0024)	6.3869
0.7	0.9940 (0.0015)	0.0194 (0.0033)	6.5456

somewhat higher than the estimate of about 0.4 reported in Chow (1993b, especially Table VII), but the latter study uses a deterministic trend for log total factor productivity and a sample period ending in 1980 whereas the current estimate is based on a stochastic trend and a sample period extending to 1993. The estimate 0.9999 for the annual discount factor is also reasonable in view of the high value which Chinese planners are supposed to place on future consumption or current investment at the expense of current consumption. This parameter is considered difficult to estimate statistically and is often imposed *a priori* in empirical studies of real business cycles in the United States. The positive drift of log total factor productivity of 0.0218 is also reasonable as the sample includes the post-reform years 1978–1993. It is consistent with Chow (1993b), which found no positive deterministic trend in total factor productivity during the sample period from 1952 to 1980 but a positive trend from 1979 on. Unlike Chow (1993b), the present study not only extends the sample period to 1993 but in estimating model parameters does not exclude any observations that are considered abnormal. This extension is possible partly because a stochastic trend is used for log total productivity rather than a linear deterministic trend as in Chow (1993b).

For sensitivity analysis we present in Table 1 estimates for the remaining two parameters when the labor elasticity parameter is fixed *a priori* at other values sometimes chosen in growth accounting exercises (see, e.g., Li et al. (1995)).

4. MEASURING THE EFFECTS OF TWO POLITICAL EVENTS

To estimate the economic effects of the Great Leap Forward alone we change the estimated residuals of the two reduced form equations in the years 1958–1962 to the mean values of the corresponding residuals in the remaining years; see Figs. 1 and 2. Columns 2 and 3 of Table 2 present actual output per laborer q_t, which can be generated by our model if the estimated residuals are used in the two equations, and simulated output q_t^*, which is generated

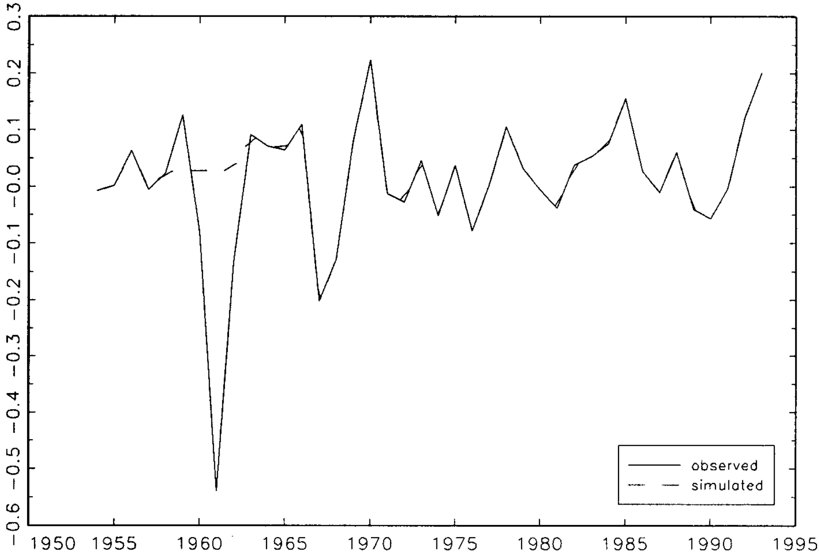

FIG. 1. Observed and simulated residual 1.

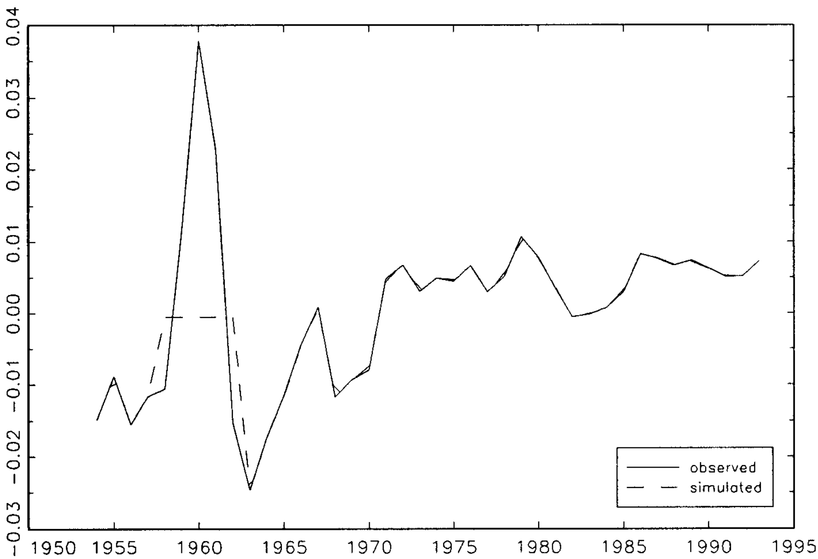

FIG. 2. Observed and simulated residual 2.

TABLE 2

GREAT LEAP FORWARD EFFECT

	Output		Consumption		Capital stock		Log productivity	
Year	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
1952	2.9283	2.9283	2.3011	2.3011	10.676	10.676	0.48132	0.48132
1953	3.2227	3.2227	2.4780	2.4780	11.303	11.303	0.56285	0.56285
1954	3.3276	3.3276	2.4794	2.4794	12.048	12.048	0.57888	0.57888
1955	3.4661	3.4661	2.6715	2.6715	12.896	12.896	0.60262	0.60262
1956	3.7717	3.7717	2.8500	2.8500	13.691	13.691	0.67214	0.67214
1957	3.9038	3.9038	2.9310	2.7747	14.612	14.612	0.69025	0.69025
1958	4.1304	4.1525	2.7289	2.9482	15.585	15.741	0.73053	0.73336
1959	4.7393	4.4162	2.6635	3.1322	16.986	16.946	0.84648	0.77647
1960	4.6947	4.6959	2.8339	3.3274	19.062	18.230	0.80816	0.81959
1961	3.2774	4.9924	2.6465	3.5344	20.923	19.598	0.42542	0.86270
1962	3.0530	5.3069	2.7342	4.2926	21.554	21.056	0.34707	0.90581
1963	3.3543	5.8781	2.7680	4.5729	21.873	22.070	0.43750	0.99625
1964	3.6400	6.4285	2.8314	4.8570	22.459	23.376	0.51262	1.0714
1965	3.9385	7.0076	2.8712	5.1104	23.268	24.947	0.58258	1.1413
1966	4.4182	7.9173	3.0654	5.6422	24.335	26.844	0.68628	1.2450
1967	3.9337	7.0975	3.0963	5.3530	25.688	29.119	0.55660	1.1153
1968	3.6809	6.6849	2.9024	4.9747	26.525	30.864	0.48213	1.0409
1969	4.0273	7.3599	3.0919	5.4272	27.303	32.574	0.56482	1.1236
1970	4.9087	9.0246	3.2916	6.2019	28.239	34.507	0.75429	1.3130
1971	5.0405	9.3203	3.3235	6.2964	29.856	37.329	0.76684	1.3256
1972	5.1180	9.5159	3.5018	6.5478	31.573	40.353	0.76810	1.3268
1973	5.4831	10.249	3.6789	6.9632	33.189	43.321	0.82451	1.3833
1974	5.4627	10.262	3.6958	6.9540	34.993	46.607	0.80751	1.3663
1975	5.8133	10.974	3.8447	7.3186	36.760	49.915	0.85738	1.4161
1976	5.6731	10.759	3.9225	7.3361	38.729	53.570	0.81990	1.3786

TABLE 2—*Continued*

	Output		Consumption		Capital stock		Log productivity	
Year	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
1977	5.8764	11.194	3.9762	7.4969	40.479	56.993	0.84404	1.4028
1978	6.5737	12.576	4.1718	8.0845	42.379	60.690	0.94469	1.5034
1979	6.9773	13.402	4.5635	8.8103	44.781	65.181	0.99046	1.5492
1980	7.1944	13.873	4.9267	9.4212	47.195	69.773	1.0080	1.5667
1981	7.2277	13.990	5.1806	9.8049	49.463	74.225	1.0008	1.5596
1982	7.6748	14.908	5.4636	10.415	51.510	78.410	1.0507	1.6094
1983	8.2453	16.072	5.7936	11.144	53.721	82.903	1.1119	1.6706
1984	9.0219	17.643	6.1797	12.032	56.173	87.831	1.1907	1.7494
1985	10.490	20.579	6.8177	13.562	59.015	93.442	1.3291	1.8878
1986	11.107	21.854	7.2579	14.450	62.687	100.46	1.3711	1.9298
1987	11.438	22.570	7.5423	14.988	66.536	107.86	1.3855	1.9443
1988	12.408	24.554	8.1293	16.238	70.431	115.44	1.4528	2.0115
1989	12.492	24.785	8.2737	16.466	74.710	123.76	1.4447	2.0034
1990	12.409	24.684	8.3370	16.514	78.928	132.08	1.4243	1.9830
1991	12.806	25.536	8.6106	17.069	83.000	140.25	1.4432	2.0019
1992	14.512	29.005	9.5145	19.074	87.196	148.72	1.5559	2.1147
1993	17.491	35.036			92.194	158.65	1.7286	2.2874
Mean	6.7323	12.244	4.4410	7.9904	39.606	57.273	0.90151	1.3469
Std dev	3.6746	8.1727	2.0767	4.7878	22.816	42.633	0.35652	0.47905

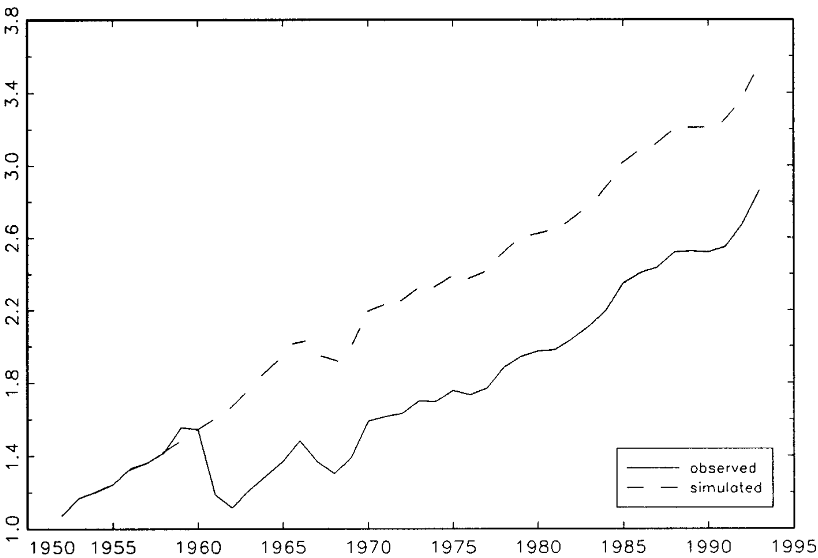

FIG. 3. Observed and simulated output (in log).

by our model if the estimated residuals in the years 1958–1962 are changed to the mean values of the remaining years. The remaining columns of Table 2 are the corresponding actual and simulated series for consumption, capital stock, and log productivity.

From Table 2 and Fig. 3 we observe that simulated output, which would have obtained absent the Great Leap, is about 2 times actual output in 1993. This result is derived from two sources. First, simulated total factor productivity in 1993 is about 0.56 higher than the actual value in logarithm, or about 1.74 times the actual value. Second, simulated capital stock is higher (see Fig. 5), and capital per laborer in 1993 is 1.72 times the actual value, as can be readily computed from the relevant entries in Table 2. According to our model and commonly used models of real business cycles for the United States economy, shifts in productivity due to shocks are permanent. Observe in Table 2 and Fig. 6 that simulated log productivity in 1962 is 0.9058, or 0.5587 higher than actual log productivity. The last figure equals 2.2874 − 1.7286, the difference between simulated and actual log productivity in 1993. Such a parallel shift in log productivity due to the Great Leap is clearly shown in Fig. 6. This is a characteristic of our model as Eq. (4) has a unit root, which implies a permanent shift in total factor productivity when its residual changes. The permanent shift in productivity in turn implies that log output and log consumption (see Fig. 3 and 5) will also undergo a permanent level shift. There is no effect on the steady state growth rate of each variable.

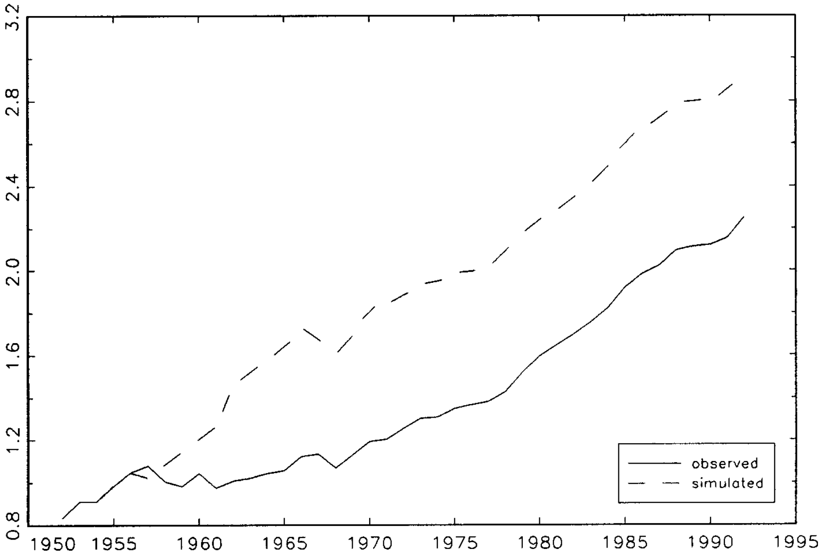

FIG. 4. Observed and simulated consumption (in log).

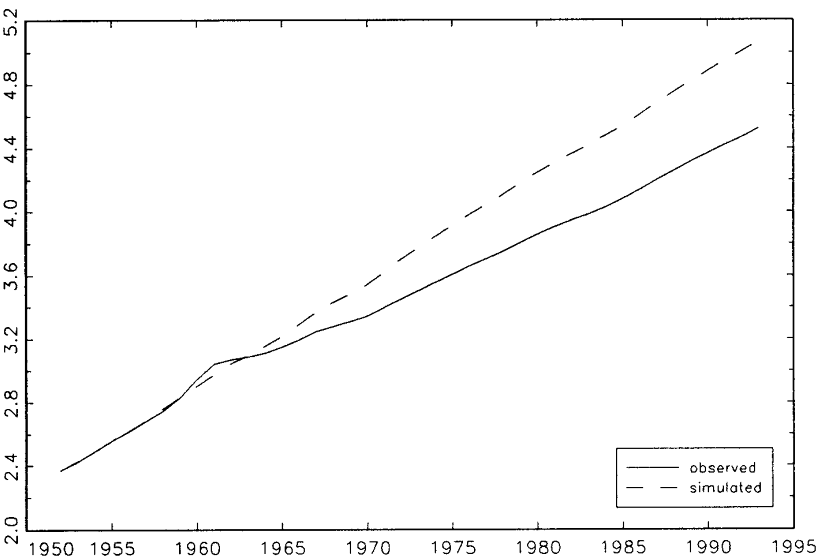

FIG. 5. Observed and simulated capital (in log).

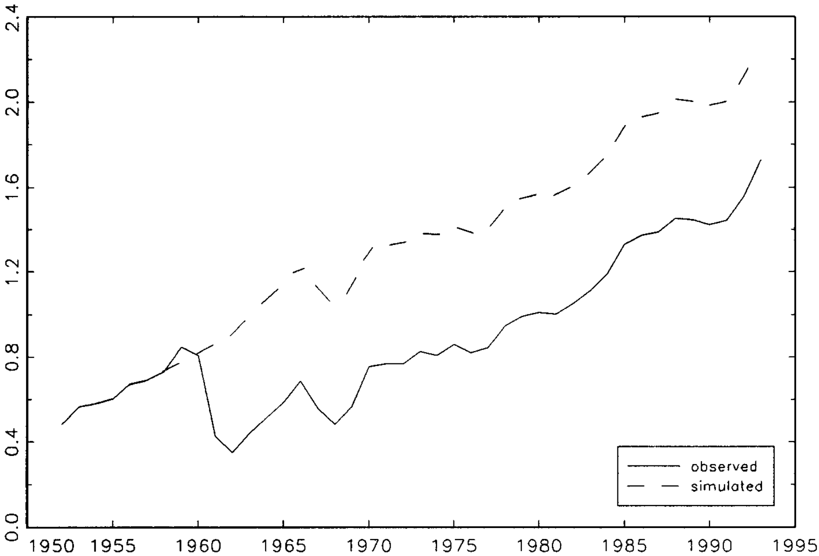

FIG. 6. Observed and simulated Solow residual (in log).

To see the extent of the permanent level shift, we generated 500 residuals of zero mean and covariance matrix given in (15) and appended them to the observed residuals as well as our modified residuals. Output, consumption, and capital were calculated according to these two extended residuals series. Examining the last 100 entries revealed that the steady state had been attained, as evident by the balanced growth of the three variables. Taking the ratio of the two output series gives the permanent level effect which we report in Table 3 in the row labeled as steady state.

To assess the effect of the Cultural Revolution and the combined effect of the two movements, we have performed a similar simulation exercise as that

TABLE 3

SIMULATION/OBSERVED LEVEL IN 1992

	Great leap	Cultural revolution	Both
Output	2.0031	1.2033	2.7130
Consumption	2.0047	1.2022	2.7261
Capital	1.7208	1.1537	2.1687
Steady state	2.1074	1.2204	2.9238

Note. $(\hat{\alpha}, \hat{\beta}, \hat{\gamma}) = (0.7495, 0.9999, 0.0218)$.

TABLE 4

SIMULATION/OBSERVED LEVEL IN 1992

	Great leap	Cultural revolution	Both
Output	2.5446	1.2355	3.6549
Consumption	2.5680	1.2349	3.7277
Capital	1.9708	1.1643	2.5461
Steady state	3.2856	1.3111	5.2465

Note. α fixed at 0.5, $\hat{\beta} = 0.9715$, $\hat{\gamma} = 0.0083$.

described above by removing residuals of the turbulent years. Table 3 provides a short summary for comparison with the Great Leap case; tables similar to Table 2 are available on request. For example, the output level by 1992 would have been 2.7 times higher than otherwise if both political movements had never occurred. To show the degree of sensitivity of our results, Tables 4 and 5 give similar comparisons when other parameter values reported in Section 3 are used.

Absent the Cultural Revolution, output in China in 1992 would have been 1.20 times as large as the actual figure. This estimate might be considered too small. The possibility of under-estimation is mainly due to the omission of the effect on human capital formation in our model. Given that human capital is not considered within the confines of our model, the measured effect appears reasonable. The disruption of the Cultural Revolution in the production of physical output in China is recognized to be much smaller than the disruption of the Great Leap. The relative magnitudes of 1.2 and 2.0 seem quite plausible. The Cultural Revolution is known for its effect on the production of human capital when many schools and universities were closed or ceased to function properly. The estimate of 1.2 can serve as a benchmark for studying the effects of the Cultural Revolution through its effect on the accumulation of human capital.

5. CONCLUSIONS

We have constructed a very simple econometric model to measure the effects of two major political events in China. The model is based on a dynamic optimization framework. It is assumed that an economic planner in China tries to maximize a multiperiod object function in making consumption and investment decisions. The values of the parameters of the optimization model as estimated by maximum likelihood are reasonable. The dynamic optimization framework is useful for studying economic behavior and the effects of political events in China as in other countries.

TABLE 5

SIMULATION/OBSERVED LEVEL IN 1992

	Great leap	Cultural revolution	Both
Output	2.2907	1.2217	3.2082
Consumption	2.3008	1.2207	3.2459
Capital	1.8614	1.1597	2.3796
Steady state	2.6306	1.2648	3.9152

Note. α fixed at 0.6, $\hat{\beta} = 0.9817$, $\hat{\gamma} = 0.0132$.

Concerning the effects of the Great Leap and the Cultural Revolution, our results indicate that absent the former output and consumption per laborer in 1990 would have been 2.0 times as large as the observed, that absent the latter output and consumption would have been 1.2 times as large, and that if neither had occurred output and consumption would have been 2.7 times the actual amounts.

APPENDIX

A standard dynamic optimization problem is to choose a sequence of q by 1 control vectors $\{u_t, t = 0, 1, 2, \ldots\}$ to solve

$$\max E_0 \sum_{t=0}^{\infty} \beta^t r(x_t, u_t) \tag{A1}$$

subject to

$$x_{t+1} = f(x_t, u_t) + \epsilon_{t+1}, \tag{A2}$$

where E_0 is the conditional expectation operator given information at time 0, x_t is a p by 1 vector of state variables, and ϵ_t is an iid random vector with mean zero and covariance matrix Σ. Our problem is to solve

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \ln\{\overline{k}_t^{1-\alpha} z_t^{\alpha-1} - \overline{k}_{t+1} + \overline{k}_t z_t^{-1}\} \tag{A3}$$

subject to

$$\ln z_{t+1} = \mu + \epsilon_{t+1}. \tag{A4}$$

Our problem can be mapped into the standard form by defining the states and control as

$$x_t \equiv (x_{1t}, x_{2t})' = (\ln \bar{z}_t, \ln \bar{k}_t)', \qquad u_t = \ln \bar{k}_{t+1}. \tag{A5}$$

The objective function and the constraint are, respectively,

$$r(x_t, u_t) = \ln\{\exp((1 - \alpha)(x_{2t} - x_{1t})) - \exp(u_t) + \exp(x_{2t} - x_{1t})\} \tag{A6}$$

and

$$f(x_t, u_t) = Ax_t + Cu_t + b, \tag{A7}$$

where A is a 2 by 2 zero matrix, $C = (0, 1)'$, and $b = (\mu, 0)'$. The steady state $(\bar{u}, \bar{x})$ can be found by solving a deterministic, time invariant version of the first order conditions. For our choice of state and control as in (A5), the steady state values are

$$\bar{u} = -\frac{1}{\alpha}\ln[\beta^{-1}\exp(\mu) - 1] + \frac{1}{\alpha}\ln(1 - \alpha) + \mu, \quad \bar{x}_1 = \mu, \quad \bar{x}_2 = \bar{u}. \tag{A8}$$

Only in exceptional cases would one be able to find an analytical solution for the optimal control function. In most applications one has to rely on numerical approximation. One convenient way to do so has been developed in Chow (1992, 1993a). We now describe briefly the solution procedure. Consider the first order conditions

$$r_2(x_t, u_t) + \beta f_2'(x_t, u_t)E_t\lambda_{t+1} = 0, \tag{A9}$$

$$r_1(x_t, u_t) + \beta f_1'(x_t, u_t)E_t\lambda_{t+1} = \lambda_t, \tag{A10}$$

$$x_{t+1} = f(x_t, u_t) + \epsilon_{t+1}, \tag{A11}$$

where the subscripts 1 and 2 of the functions r and f denote derivatives with respect to the first and second arguments, respectively. λ is a vector of random Lagrange multipliers. We proceed by linearizing the non-linear functions in (A9)–(A11) around the steady state $(\bar{x}, \bar{u})$:

$$f = Ax + Cu + b; \qquad r_1 = K_{11}x + K_{12}u + k_1;$$

$$r_2 = K_{21}x + K_{22}u + k_2. \tag{A12}$$

Given the linear functions above, if λ is assumed to be linear, say equal to $Hx + h$, substituting these functions in the first order conditions will yield a linear control function

$$u = Gx + g, \tag{A13}$$

where

$$G = -(K_{22} + \beta C'HC)^{-1}(K_{21} + \beta C'HA) \tag{A14}$$

$$g = -(K_{22} + \beta C'HC)^{-1}(k_2 + \beta C'(Hb + h)), \tag{A15}$$

and the coefficient matrices of the Lagrangean function are, respectively,

$$H = K_{11} + K_{12}G + \beta A'H(A + CG) \tag{A16}$$

$$h = (K_{12} + \beta A'HC)g + k_1 + \beta A'(Hb + h). \tag{A17}$$

Iterating the matrix equation system (A14)–(A17) until convergence gives the required matrices G, g, H, and h. We have accelerated such a direct iteration scheme by incorporating a modified version of the doubling algorithm described in Anderson and Moore (1979, p. 159). A detailed discussion of the algorithm and numerical examples will be reported elsewhere.

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