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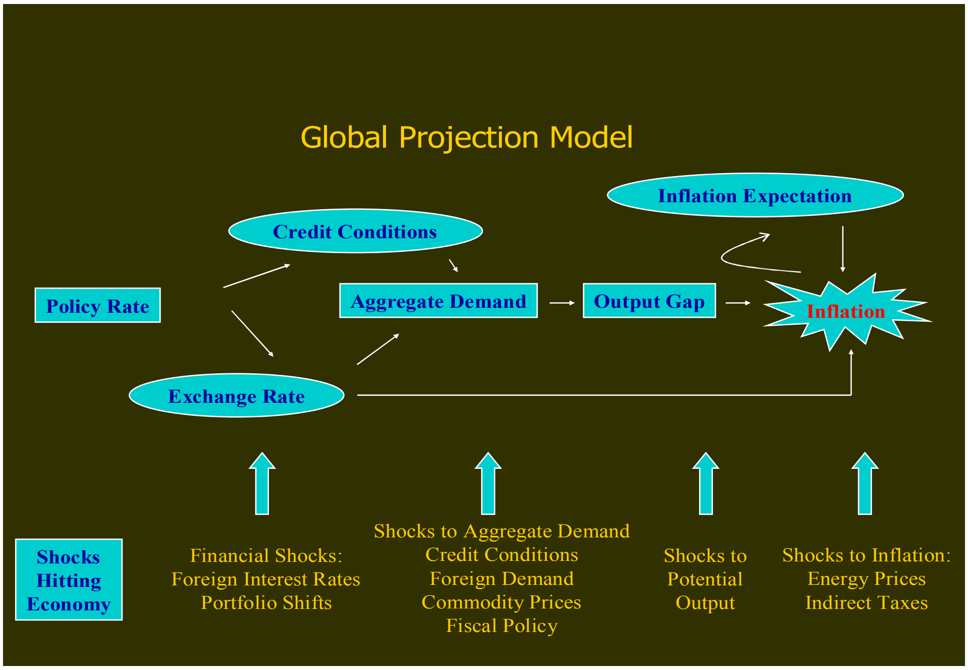
Appendix I. Global Projection Model (GPM)



GPM is well suited to analysis of the practical problem at hand. We employ a Bayesian system estimation technique. This efficiently combines information in the current data set with prior information about coefficients, based on economic theory and existing empirical knowledge, and on properties implied by the model as whole. In contrast, pure a priori calibration may lack empirical plausibility, while data-driven estimation procedures may yield anomalous results, especially when the relevant data series are short.

GPM builds from the standard modern monetary policy model, with equations determining:

- the output gap;
- the inflation rate (an inflation-expectations augmented Phillips curve);
- the exchange rate, and
- the interest rate (a monetary policy rule).

The model adds several features to earlier versions of the standard model. Thus, expectations are based on both lags and leads, representing backward- and forward-looking elements. And it includes important nonlinearities, including the zero bound on interest rates. Moreover, GPM offers various options for monetary policy rules, which may be estimated from the data, or determined by an optimization process, or set to represent counterfactual options.

Output is represented by real GDP; the output gap is the difference between actual and potential.[24] The inflation rate is modeled as the annualized quarterly change in the CPI, but for reporting purposes we follow the normal year-over-year convention. The US exchange rate is euro or yen per dollar (an increase corresponding to US dollar appreciation); the real

[24]All variables except interest rates are in natural logarithms. For all intents and purposes, this means that, e.g., the output gap is measured as a proportion of potential GDP.

exchange rate adjusts for differential changes in CPIs (an increase implying an increase in the relative price of US goods). It is convenient to express all variables as deviations from long-run equilibrium, i.e. in gap form.

The United States sector includes endogenous credit conditions. We construct an index of bank lending tightening (BLT) in the United States from the Federal Reserve Board's Senior Loan Officer Survey. The index subtracts the percentage of "eased" responses against the percentage of "tightened." A BLT in excess of 50 percent means an unusually sharp tightening. This index predicts the US business cycle over the last decade with high precision.[25]

The policy rule for the short-term interest rate is based on a forward-looking Taylor rule in which the policy rate depends on the central bank's forecast of inflation (3 quarters ahead), on the output gap, and on the lagged policy rate.

The Bayesian method provides an estimate of the posterior distribution of the variance-covariance matrix of disturbance terms, as well as of the system parameters. We work with the mode of the posterior distribution and condition all the remaining experiments on this point estimate. Unobservable historical variables, such as potential output, are estimated using a linear Kalman filter, conditioned on the posterior mode.

Simulations to construct the confidence intervals in the baseline forecast, and to derive the results for the policy rule experiments, are done on the assumption that shocks are unanticipated. In each period, the solution is derived on the assumption that all the future shocks will be zero. Thus, in the model simulations, we suppose that the shocks that we simulate surprise economic agents, and we neglect the potential behavioral implications of uncertainty about the future.

Variable definitions for country j

$\overline{Y}_{j,t}$: potential output

$i_{j,t}$: nominal interest rate

$R_{j,t}$: real interest rate

$\overline{R}_{j,t}$: equilibrium real interest rate

$\pi_{j,t}$: annualized quarterly inflation

$\pi 4_{j,t}$: year-on-year inflation

$Z_{j,t}$: real exchange rate

$\overline{Z}_{j,t}$: equilibrium real exchange rate

$Z^{e}_{j,t}$: expected exchange rate of next period

$BLT_{US,t}$: credit tightness

$RPOIL_{US,t}$: log of the real equilibrium price of oil

[25]See Carabenciov and others (2008). In 2008Q4 the index reached an unprecedented 80 percent.

$RPOIL_{US,t}$: log of the real price of oil

Behavioral Equations

Output gap equation of country j:

$$y_{j,t} = \beta_{j,1} y_{j,t-1} + \beta_{j,2} y_{j,t+1} - \beta_{j,3} r_{j,t-1} + \beta_{j,4} \sum_k \omega_{j,k,4} z_{j,k,t-1}$$
$$+ \beta_{j,5} \sum_k \omega_{j,k,5} y_{k,t-1+} \theta_j \eta_{j,t} + \varepsilon^y_{j,t}$$

This equation determines the output gap as a function of

- its own lead and lagged values,
- the real interest rate gap
- bank lending tightening (BLT, US equation only)
- output gaps in its trading partners
- the real exchange rate gap, and
- a disturbance term

The lag from the output gap itself captures both intrinsic delays due to adjustment costs, and the adaptive component of expectations, or habit persistence. The lead corresponds to forward-looking investment and consumption behavior, in anticipation of expected future output and income. Normal cyclical variations in the availability of credit are accounted for implicitly by the interest rate and other variables in the equation. However, shocks to lending practices will have an independent impact, which is not so captured. Their effect is represented by the term $\eta_{US,t}$, which is defined to be a distributed lag of the non-systematic component of the variable BLT. We measure these shocks as the residuals of a simple estimated equation where BLT depends on the expected value of the output gap 4 quarters in the future.

Inflation equation for country j:

$$\pi_{j,t} = \lambda_{j,1} \pi 4_{j,t+4} + (1 - \lambda_{j,1}) \pi 4_{j,t-1} + \lambda_{j,2} y_{j,t-1} + \lambda_{j,3} \sum_k \omega_{j,k,3} \Delta Z_{j,k,t}$$
$$+ \upsilon_{j,1} \pi^{RPOIL}_{j,t} + \upsilon_{j,2} \pi^{RPOIL}_{j,t-1} - \varepsilon^{\pi}_{j,t}$$

This augmented Phillips curve has inflation as a function of

- inflation expectations—a weighted average of past and model-consistent future inflation rates
- the lagged output gap
- the change in the real exchange rate
- the current and lagged increase in the real price of oil, and
- a disturbance term

The model-consistent aspect relates to price setting based on predictions of future inflation.

When monetary policy adheres to a stable policy rule, expectations eventually converge on the inflation path targeted by the central bank.

The greater the weight on the forward-looking component ($\lambda_{j,1}$), the more rapid is the convergence to the policy target. The backward-looking component, in contrast, reflects adaptive behavior, which slows the adjustment.

The coefficient on the lagged output gap embodies the familiar short-run output-inflation tradeoff. This is the crucial link between the real sector of the economy and the price level.

The coefficients on the changes in the real exchange rate and in the real price of oil reflect the pass-through to the CPI of changes in import and oil prices.

The parameter estimates for the inflation equation are reported in Table A1. They suggest that there has a been a significant decline in the weight on lagged inflation relative to earlier sample periods where monetary policy was less successful in providing an anchor for inflation and inflation expectations.

Table A1. Inflation Equation Estimated Coefficients

Output gap

	US	euro area	Japan
Future Inflation ($\lambda_{j,1}$)	0.73	0.69	0.65
Past Inflation (1-$\lambda_{j,1}$)	0.27	0.31	0.35
Lagged Output gap ($\lambda_{j,2}$)	0.17	0.21	0.17
Real Exchange Rate Changes ($\lambda_{j,3}$)	0.06	0.10	0.08

Policy interest rate equation for country j:

$$i_{j,t} = \gamma_{j,1} i_{j,t-1} + (1-\gamma_{j,1})[\bar{r}_{j,t} + \pi 4_{j,t+3}] + \gamma_{j,2}[\pi 4_{j,t+3} - \pi_j^*] + \gamma_{j,3} y_{j,t} + \varepsilon_{j,t}^i$$

This Taylor-type rule determines a key, policy-determined, short-term interest rate (Federal Funds rate for the United States, 30-day interbank rates for the euro area and Japan). The own lag provides smoothed policy responses, in line with the incremental movements typical of central bank decisions.[26] In a steady state, with inflation on target, and the price level on track, the central bank sets the actual nominal interest rate, $i_{j,t}$ at the long-run equilibrium level (equal to the equilibrium real rate plus the rate of inflation). Otherwise, it opens a corrective interest rate gap. A key difference relative to the Taylor rule is that expected Y-o-

[26]Woodford (2003) provides a theoretical rationale for the smoothed interest rate response. In essence, smoothing increases the impact of changes in short-term rates on longer-term rates, because it gives the changes some persistence.

Y inflation rate 3 quarters ahead enters the equatiuon instead of a contemporaneous measure of Y-o-Y inflation. As is the case with the Taylor rule the policy rule also responds to output gaps, which can have important effects on the path of future inflation and reducing variability in the real economy. A disturbance term allows for interest rate actions (possible policy errors) not indicated by the equation. The equation is constrained to respect the zero lower bound to the interest rate.

Exchange rate equation:

$$4\left(Z^{e}_{j,t+1} - Z_{j,t}\right) = \left(R_{j,t} - R_{us,t}\right) - \left(\overline{R}_{j,t} - \overline{R}_{us,t}\right) + \varepsilon^{Z^{e}-Z}_{j,t}$$

This equation embodies a modified uncovered interest parity (UIP) condition. But whereas simple UIP would imply equality of all exchange-rate adjusted short-term interest rates, this equation allows cross-country differences in equilibrium real interest rates ($\overline{R}_{j,t} - \overline{R}_{us,t}$), even in the long-run. That is, each currency has a risk premium, which may be positive or negative—or zero in the case that simple UIP does hold. The expectations process for the real exchange rate has lagged and model-consistent (forward-looking) components—see Carabenciov and others (2008).

Variance and covariance of disturbances

Shocks to the variables are not independent. The present version of GPM contains 3 cross-equation correlations, between:

- potential output and inflation disturbances—negative covariance representing supply shocks—e.g. a positive shock to potential output reduces the current inflation rate;

- potential output growth and output gap disturbances—positive covariance representing the expected income effect of a change in growth, which has an immediate effect on spending and output, implying excess demand in the short run;

- potential output growth and BLT disturbances in the United States—a negative covariance representing asset market/output market interactions—e.g. higher growth of potential eases bank credit (because higher growth implies higher asset values and returns); in the short run an anticipatory increase in spending would produce a positive output gap.

Underlying Equilibrium Values and Stochastic Processes

Underlying real equilibrium values, which determine the long-run paths of real variables, are not directly observable, but within the context of the model, the Bayesian technique allows us to estimate these values, given the stochastic process for each variable.

Potential output

Potential output follows a stochastic trend with disturbances which may affect its level permanently, and its growth rate over a finite period. In addition, increases in the international price of oil have a negative effect on potential output. Disturbances may affect the level of potential output, but its growth rate over time will eventually return to its steady-state growth rate.

Real equilibrium interest rate and exchange rate:

Shocks may cause both short- and long-run changes in the equilibrium values of the interest rate and the exchange rate. The equilibrium real exchange rate follows a random walk.

Oil price:

The log of the real equilibrium price of oil (in inflation-adjusted US dollars), is modeled as a stochastic trend where the current price gradually adjusts to a long-term equilibrium that contains a unit root. In model simulations, the nominal price of oil in the United States rises with the US inflation rate, and in other countries with the rate of exchange against the US dollar. Changes in the price of oil will have two effects in the model. First, permanent increases in the real price of oil will result in a permanent decline in potential output. Second, higher oil prices raise inflation and require an increase in real interest rates, which will result in weaker demand conditions.