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WORKING PAPER

Time Variation in U.S. Wage Dynamics

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Abstract

This paper explores time variation in the dynamic effects of technology shocks on U.S. output, prices, interest rates as well as real and nominal wages. The results indicate considerable time variation in U.S. wage dynamics that can be linked to the monetary policy regime. Before and after the "Great Inflation", nominal wages moved in the same direction as the (required) adjustment of real wages, and in the opposite direction of the price response. During the "Great Inflation", technology shocks in contrast triggered wage-price spirals, moving nominal wages and prices in the same direction at longer horizons, thus counteracting the required adjustment of real wages, amplifying the ultimate repercussions on prices and hence increasing inflation volatility. Using a standard DSGE model, we show that these stylized facts, in particular the estimated magnitudes, can only be explained by assuming a high degree of wage indexation in conjunction with a weak reaction of monetary policy to inflation during the "Great Inflation", and low indexation together with aggressive inflation stabilization of monetary policy before and after this period. This means that the monetary policy regime is not only captured by the parameters of the monetary policy rule, but importantly also by the degree of wage indexation and resultant second round effects in the labor market. Accordingly, the degree of wage indexation is not structural in the sense of Lucas (1976).

JEL classification: C32, E24, E31, E42, E52
Keywords: technology shocks, second-round effects, Great Inflation

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1 Introduction

A growing literature has been investigating the underlying driving forces of the "Great Inflation" of the 1970s and the "Great Moderation" in macroeconomic volatility since the mid 1980s. Several studies, e.g. Clarida, Gali and Gertler (2000), Gali, López-Salido and Vallés (2003) and Lubik and Schorfheide (2004) argue that a shift in systematic monetary policy can explain these phenomena. More specifically, monetary policy has been found to have overstabilized output at the cost of generating excessive inflation variability in the 1970s, and became more aggressive with respect to inflation when Paul Volcker became Fed chairman. However, a number of other studies conclude that the shift in the systematic component of monetary policy is insufficient or unable to explain the observed changed macroeconomic volatility over time. Primiceri (2005), Sims and Zha (2006) and Canova and Gambetti (2006) conduct counterfactual simulations with alternate monetary policy rules and find limited consequences of changes in the policy rule parameters for the dynamics and variability of output and inflation across the regimes.[1]

The parameters of the policy rule may however not adequately capture the wider macroeconomic implications of a change in the monetary policy regime. Indeed, there is a widely held perception among policymakers that the incidence of so-called second-round effects , i.e. the amplification of supply side shocks via mutually reinforcing feedback effects between wages and prices arising from explicit or implicit indexation, ultimately depend on the monetary policy regime (e.g. Bernanke 2004). More specifically, second round effects are perceived to have been significant as a result of unanchored inflation expectations and widespread indexation during the "Great Inflation" and to have vanished with the firm anchoring of inflation expectations in the subsequent era of price stability. This reasoning essentially reflects the Lucas (1976) critique that a change in the policy regime could have wider effects on empirical macroeconomic regularities, in this case on the prevalence of indexation practices in wage setting. These wider potential effects of a change

[1] Instead, they attribute the reduction in volatility to a changed variance of structural shocks affecting the economy. Also Stock and Watson (2002) and Gambetti, Canova and Pappa (2008) find support for the alternative "Good luck" hypothesis as the main explanation for greater macroeconomic stability in more recent periods. On the other hand, Benati and Surico (2009) demonstrate that the impact of a change in the systematic component of monetary policy may very well be identified as changes in the innovation variances of other variables in these studies.

in the monetary policy regime are obviously not captured by the policy rule parameters alone. While the link between indexation of prices, as reflected in the degree of inflation persistence, and the monetary policy regime has recently been explored and established (Benati 2008), the link between wage indexation and the monetary policy regime and its wider implications for macroeconomic dynamics have so far remained unexplored.[2] This is all the more surprising given the important role of wage indexation in the contemporary literature on the causes of the "Great Inflation" (e.g. Fischer 1983; Bruno and Sachs 1985).

There is in fact institutional evidence supporting the conjecture that wage indexation has not been constant over time and could be linked to the inflation regime. Consider Figure 1, which shows the coverage of private sector workers by cost-of-living adjustment (COLA) clauses.[3] The chart reveals that, from the late 1960s onwards, COLA coverage steadily increased to levels around 60% in the mid 1980s, after which there was again a decline towards 20% in the mid 1990s, when the reporting of COLA coverage has been discontinued. Interestingly, as also shown in the figure, we observe a substantial increase in inflation volatility and the correlation between price and wage inflation during the same period, suggesting that there is an interplay between the inflation regime, wage indexation and possibly second-round effects. A significant positive impact of inflation and inflation uncertainty on the prevalence of COLA clauses included in major collective wage bargaining agreements has also been found by Holland (1986, 1995) and Ragan and Bratsberg (2000).[4] However, while these studies can establish a link between the inflation

[2] Blanchard and Gali (2008) show that improved monetary policy credibility could have contributed to more muted output and inflationary effects of oil shocks since the mid 1980s, but do not provide evidence for this hypothesis. Peersman and Van Robays (2009) find no second-round effects in the U.S. after oil shocks, but focus only on the post-1985 period. A notably exception is a recent study by Blanchard and Riggi (2009) who document vanishing wage indexation and an improvement in the credibility of monetary policy as a source for the lower impact of oil price shocks over time. Kilian (2009) and Baumeister and Peersman (2008), however, show that oil price shocks cannot be compared over time due to structural changes in the oil market.

[3] COLA coverage obviously only measures explicit wage indexation in major wage agreements for unionized workers and does therefore not capture explicit wage indexation in other wage agreements or implicit wage indexation. However, Holland (1988) shows that COLA coverage is positively related to the responsiveness of union, non-union and economy-wide wage aggregates to price level shocks and suggests, based on this finding, that COLA coverage is a suitable proxy for the overall prevalence of explicit and implicit wage indexation in the U.S. economy.

[4] Ehrenberg, Danziger and San (1984) show in an efficient contract model with risk averse workers that

regime and explicit indexation in collective bargaining agreements, they do not asses the implications of this link for macroeconomic dynamics and volatility.

This paper aims to fill this gap by inspecting time variation in U.S. wage dynamics in response to technology shocks and its interrelation with the prevailing monetary policy regime as well as with the dynamic responses of other key macro variables over the period 1957-2008. To this end we start by estimating an otherwise standard time-varying parameters bayesian structural vector autoregression (TVP-BVAR) model including, besides the usual set of macro variables, aggregate nominal wages. The results reveal some striking and new stylized facts. First, the estimation of the reduced form VAR already supports the idea of time variation in wage indexation. Whereas lagged price inflation had a significant impact on wage inflation until the early 1980s, we do not find a significant effect afterwards. Second, when we consider the dynamic effects of technology shocks over time, we find that before and after the high inflation regime of the 1970s, nominal wages adjust in a way that supports the required adjustment of real wages (i.e. both variables increase after a positive technology shock, while the price level declines and output rises permanently) and that the long-run effect of the shock on the price level is relatively mild. In contrast, whereas the immediate response of nominal wages to a technology shock during the "Great Inflation" is not very different from the two other historical episodes, i.e. inversely related to the price response, nominal wages move in the same direction as prices at longer horizons after the shock, thus counteracting the required adjustment of real wages (i.e. nominal wages fall after a positive technology shock) and considerably amplifying the ultimate repercussions of the shock on inflation. This pattern of time variation in the nominal wage response across the three inflation regimes covered by our analysis hence supports the notion that the incidence of second-round effects and, as a consequence, the occurrence of wage-price spirals in response to supply side shocks and accompanying inflation variability can be linked to the monetary policy regime. This hypothesis is further supported by examining real wage adjustment over time. The incidence of second-round effects and strong wage indexation should also result in more real wage rigidity after a technology shock, which is exactly what we find for the "Great Inflation" period.

the higher inflation uncertainty is, the greater is the likelihood of indexation.

We then continue our analysis by investigating the role of the monetary policy rule and the degree of wage indexation in explaining the above-described stylized facts using a standard dynamic stochastic general equilibrium (DSGE) model. The results of model-based simulations suggest that variations over time in both the policy rule parameters and the degree of wage indexation simultaneously are needed in order to match the stylized facts established by the empirical analysis. To be more specific, the simulations reveal that a policy rule with an aggressive response to inflation together with a very low degree of wage indexation can reproduce the reaction patterns of nominal wages and prices to a technology shock found for the episodes before and after the "Great Inflation", i.e. an increase of nominal wages supporting the required increase in real wages, while prices fall. Altering the policy rule towards very poor inflation stabilization can reproduce a positive co-movement of the long-run response of nominal wages and prices to a technology shock, but totally fails to generate the magnitudes of the effects in the 1970s. These magnitudes can only be matched with a combination of a weakly inflation stabilizing monetary policy rule and considerable wage indexation. On the other hand, when we consider a model with only a high degree of wage indexation, together with a strongly inflation stabilizing policy rule, the simulations can reproduce neither the magnitudes of the impulse responses in the 1970s, nor those in the preceding and subsequent periods. This finding supports a point made by Fischer (1983), who shows in a simple macroeconomic model that the association between all aspects of indexation and inflation depends on the monetary and fiscal policies being followed by the government.

Accordingly, only the combination of changes in both the policy rule and wage indexation *simultaneously* can explain the variation of the conditional volatility of price and wage inflation after technology shocks over time, suggesting that time variation in the parameters of a central bank reaction function and the degree of wage indexation in the U.S. were two sides of the same coin, i.e. the monetary policy regime. A weakly inflation stabilizing policy rule is conducive to high and volatile inflation. This fosters the use of wage indexation clauses as protection against inflation uncertainty, which in turn contributes to inflation uncertainty by amplifying the effects of inflationary shocks. On the other hand, a regime of price stability requires a strong inflation stabilizing policy rule and reduces the need for protection against inflation uncertainty, thus mitigating wage indexation. A lower degree of wage indexation in turn reduces the effect of inflationary shocks, thus further contributing to price stability. Hence, counterfactual experiments in the context of the "Great Inflation" and "Great Moderation" literature should take both features of the monetary policy regime into account. Furthermore, our finding that labor market dynamics and particularly the existence of second-round effects via wages are likely to be dependent on the policy regime also implies that hard-wiring a certain degree of wage indexation in macro models like the ones of Christiano, Eichenbaum and Evans (2005) or Smets and Wouters (2007) is potentially misleading when changes in the monetary policy regime are analyzed. In particular, the degree of wage indexation is not structural in the sense of Lucas (1976), a point which is also made and shown by Benati (2008) for inflation persistence.

The remainder of the paper is structured as follows. In the next section, we present the empirical evidence on time variation in U.S. wage dynamics. We first discuss the methodology and some reduced form evidence on possible wage indexation, before we report the results of the estimated effects of technology shocks over time. In section 3, we propose a standard DSGE model to evaluate the role of the monetary policy rule and the degree of indexation in explaining the estimated time variation. Finally, section 4 concludes.

2 Time variation in wage dynamics - empirical evidence

2.1 A Bayesian VAR with time-varying parameters

To estimate the impact of technology shocks on wage and inflation dynamics, we use a VAR*(p)* model with time-varying parameters and stochastic volatility in the spirit of Cogley and Sargent (2002, 2005), Primiceri (2005) and Benati and Mumtaz (2007). We consider the following reduced form representation:

$$y_t = c_t + B_{1,t} y_{t-1} + ... + B_{p,t} y_{t-p} + u_t \equiv X_t' \theta_t + u_t \tag{1}$$

where y_t is a vector of observed endogenous variables, i.e. output (real GDP), prices (GDP deflator), nominal wages (hourly compensation in the non-farm business sector) and the interest rate (three-months Treasury bill rate).[5] All variables are transformed to non-annualized quarter-on-quarter growth rates by taking the first difference of the natural logarithm, except the interest rate which remains in levels. The overall sample covers the period 1947Q1-2008Q1, but the first ten years of data are used as a training sample to generate the priors for the actual sample period. The lag length of the VAR is set to $p = 2$ which is sufficient to capture the dynamics in the system. The time-varying intercepts and lagged coefficients are stacked in θ_t to obtain the state-space representation of the model. The u_t of the observation equation are heteroskedastic disturbance terms with zero mean and a time-varying covariance matrix Ω_t which can be decomposed in the following way: $\Omega_t = A_t^{-1} H_t \left(A_t^{-1}\right)'$. A_t is a lower triangular matrix that models the contemporaneous interactions among the endogenous variables and H_t is a diagonal matrix which contains the stochastic volatilities:

$$A_t = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \alpha_{21,t} & 1 & 0 & 0 \\ \alpha_{31,t} & \alpha_{32,t} & 1 & 0 \\ \alpha_{41,t} & \alpha_{42,t} & \alpha_{43,t} & 1 \end{bmatrix} \qquad H_t = \begin{bmatrix} h_{1,t} & 0 & 0 & 0 \\ 0 & h_{2,t} & 0 & 0 \\ 0 & 0 & h_{3,t} & 0 \\ 0 & 0 & 0 & h_{4,t} \end{bmatrix} \tag{2}$$

Let α_t be the vector of non-zero and non-one elements of the matrix A_t (stacked by rows) and h_t be the vector containing the diagonal elements of H_t. Following Primiceri (2005), the three driving processes of the system are postulated to evolve as follows:

$$\theta_t = \theta_{t-1} + \nu_t \qquad \nu_t \sim N(0, Q) \tag{3}$$

$$\alpha_t = \alpha_{t-1} + \zeta_t \qquad \zeta_t \sim N(0, S) \tag{4}$$

$$\ln h_{i,t} = \ln h_{i,t-1} + \sigma_i \eta_{i,t} \qquad \eta_{i,t} \sim N(0, 1) \tag{5}$$

The time-varying parameters θ_t and α_t are modeled as driftless random walks. The elements of the vector of volatilities $h_t = [h_{1,t}, h_{2,t}, h_{3,t}, h_{4,t}]'$ are assumed to evolve as geometric random walks independent of each other. The error terms of the three transition

[5] The data series were taken from the St. Louis FRED database.

equations are independent of each other and of the innovations of the observation equation. In addition, we impose a block-diagonal structure for S of the following form:

$$S \equiv Var(\zeta_t) = \begin{bmatrix} S_1 & 0_{1x2} & 0_{1x3} \\ 0_{2x1} & S_2 & 0_{2x3} \\ 0_{3x1} & 0_{3x2} & S_3 \end{bmatrix} \tag{6}$$

which implies independence also across the blocks of S with $S_1 \equiv Var(\zeta_{21,t})$, $S_2 \equiv Var\left([\zeta_{31,t}, \zeta_{32,t}]'\right)$, and $S_3 \equiv Var\left([\zeta_{41,t}, \zeta_{42,t}, \zeta_{43,t}]'\right)$ so that the covariance states can be estimated equation by equation.

We estimate the above model using Bayesian methods (Markov Chain Monte Carlo algorithm). The priors for the initial states of the regression coefficients, the covariances and the log volatilities are assumed to be normally distributed, independent of each other and independent of the hyperparameters. Particularly, the priors are calibrated on the point estimates of a constant-coefficient VAR estimated over the training sample period. The posterior distribution is simulated by sequentially drawing from the conditional posterior of four blocks of parameters: the coefficients, the simultaneous relations, the variances and the hyperparameters. For further details of the implementation and MCMC algorithm, we refer to Primiceri (2005), Benati and Mumtaz (2007) and Baumeister and Peersman (2008). We perform 50,000 iterations of the Bayesian Gibbs sampler but keep only every 10^{th} draw in order to mitigate the autocorrelation among the draws. After a "burn-in" period of 50,000 iterations, the sequence of draws of the four blocks from their respective conditional posteriors converges to a sample from the joint posterior distribution. We ascertain that our chain has converged to the ergodic distribution by performing the usual set of convergence tests (see Primiceri 2005; Benati and Mumtaz 2007). In total, we collect 5000 simulated values from the Gibbs chain on which we base our structural analysis.

2.2 Wage indexation over time - some reduced form evidence

To have a first impression about time variation in wage indexation, Figure 2 reports at each point in time the median, 16th and 84th percentiles of the long-run multiplier effect of lagged price inflation on wage inflation, obtained from the posterior of the reduced form

VAR. Some caution is required when interpreting the results since these figures do not capture indexation within the quarter, that is only lagged indexation effects are captured. However, given the fact that wages are mostly adjusted with some lag, the figures should give at least some indication of possible time variation in wage indexation to past inflation rates.[6] They can also be interpreted as a causality test. From the next subsection onwards, when we identify structural innovations, also immediate effects will be taken into account.

The charts illustrate already a lot of time variation that is consistent with the conjecture that wage indexation could be linked to the monetary policy regime. Specifically, Figure 2 shows that the impact of lagged price inflation on wage inflation was relatively high at the beginning of our sample period, after which we observe a decline to an insignificant impact in the mid 1960s. From the mid 1960s onwards, however, we find an increased and significant impact of lagged inflation until the early 1980s, after which the sum of the coefficients became again insignificant up until today. This pattern matches more or less the time variation in COLA coverage shown in Figure 1. The estimates also confirm a causal effect from prices on wages during the "Great Inflation", which is a precondition for triggering wage-price spirals.

2.3 Impact of technology shocks - stylized facts

We next analyze wage and price dynamics in a more structural manner by focusing on the dynamic effects of technological innovations. Technological disturbances are particularly interesting for the examination of time variation of possible second-round effects since they should move prices and wages in opposite directions, unless this is prevented by strong wage indexation. More specifically, in contrast to monetary policy or other demand-side shocks, labor supply or wage mark-up shocks, a favorable technology shock is expected to generate a positive effect on (real) wages, while prices should decline. In section 2.3.1, we briefly discuss the identification strategy which we borrow from Peersman and Straub (2009), and the estimation results are presented in section 2.3.2.

[6] Note that in standard DSGE models, wages are always indexed to past inflation rates. Notice also that prices can predict wages due to the structure of the economy, which is not necessarily via indexation.

2.3.1 Identification

For the identification of technology shocks in a structural VAR, Peersman and Straub (2009) derive a set of sign restrictions that are consistent with a large class of DSGE models and robust for parameter uncertainty. Peersman and Straub (2009) use this sign restrictions model-based identification strategy to estimate the impact of technology shocks on hours worked and employment. We impose the same restrictions in the above described VAR with time-varying parameters.[7] Specifically, positive technology shocks are identified as shocks with a non-negative effect on output and real wages and non-positive effects on prices. These restrictions, which are imposed the first four quarters after the shock, are sufficient to uniquely disentangle the innovations from monetary policy, aggregate demand and labor market disturbances. In particular, expansionary monetary policy and other aggregate demand shocks are expected to have a positive effect on prices, while expansionary labor market innovations such as labor supply or wage mark-up shocks are typically characterized by a fall in real wages.[8] Notice that the nominal wage response to a technology shock is left unconstrained at all horizons. Note also that, while the shock is labelled as a technology shock, it could still comprise other supply-side shocks such as commodity price or price mark-up shocks. In the context of our analysis, however, a further decomposition is not required.

2.3.2 Results

Figure 3 displays the median impulse responses of real GDP, the GDP deflator, the nominal interest rate, real and nominal wages to a one standard deviation technology shock for

[7] Peersman and Straub (2009) propose this identification strategy with sign restrictions as an alternative to Gali's (1999) long-run restrictions. The latter, however, cannot be implemented in our time-varying SVAR. To keep the number of variables manageable, we do not have hours worked or labor productivity as one of the variables in the model. The approach of Peersman and Straub (2009) does instead not need these variables for identification purposes. Imposing long-run neutrality of non-technological disturbances in a model where the underlying structure and dynamics change over time is also something difficult to implement without making additional assumptions. See also Dedola and Neri (2007) for a similar sign restrictions approach.

[8] As a robustness check we reestimated the VAR with the full set of shocks identified simultaneously (i.e. monetary policy, aggregate demand, labour market as well as technology shocks) and found that the results for the technology shocks were not affected. Hence, we only report the results for the single-shock identification scheme. The results of the estimation with the full set of shocks identified are available upon request.

horizons up to 28 quarters at each point in time spanning the period 1957Q1 to 2008Q1. The estimated responses have been accumulated and are shown in levels.[9] The responses reveal that there is considerable time variation in the dynamic effects of technology shocks. This is demonstrated even more clearly in Figure 4, where the time-varying median responses of output, real wages, prices and nominal wages are plotted respectively 0 and 28 quarters after the shock, together with the 16th and 84th percentiles of the posterior distribution. Since it is not possible to uniquely identify the innovation variances of the structural shocks, it is also not possible to exactly pin-down to which extent the time variation is due to changes in the sizes of the shocks or in the way they are transmitted to the economy.[10] However, by carefully examining how the trends and correlations between impulse responses have evolved over time, it is still possible to come up with some meaningful interpretations.

A first result that emerges from the inspection of the impulse responses is a weaker impact of an average technology shock on economic activity since the early 1980s, a break date which coincides with the start of the "Great Moderation". In contrast to this, there is no evidence of a reduced effect of technology shocks on real wages. The short-run effect is even found to have slightly increased over time, while the long-run effect has remained at the elevated levels reached in the early 1970s. This result is in line with recent micro evidence reported by Davis and Kahn (2008), who document that the "Great Moderation" was not associated with a reduction in household income volatility. The most striking time-

[9] Impulse response functions are computed as the difference between two conditional expectations with and without the exogenous shock:

$$IRF_{t+k} = E\left[y_{t+k} \mid \varepsilon_t, \omega_t\right] - E\left[y_{t+k} \mid \omega_t\right]$$

where y_{t+k} contains the forecasts of the endogenous variables at horizon k, ω_t represents the current information set and ε_t is the current disturbance term. At each point in time the information set we condition upon contains the actual values of the lagged endogenous variables and a random draw of the model parameters and hyperparameters. In the figures, we show the median impulse responses for each quarter based on 500 draws. The impulse response function of the real wage for each draw is obtained via the response of the nominal wage rate and the GDP deflator.

[10] This is a well-known problem when VAR results are compared across different samples. Only the impact of an "average" shock on a number of variables can be measured. Consequently, it is not possible to know exactly whether the magnitude of an average shock has changed or the reaction of the economy (economic structure) to this shock, unless an arbitrary normalization on one of the variables is done (e.g. Gambetti, Pappa and Canova 2006 normalize on output or prices). See also Baumeister and Peersman (2008) on this problem in the context of oil supply shocks.

variation however is a substantial stronger long-run impact of an average technology shock on prices and nominal wages between the end of the 1960s and the early 1980s, i.e. during the "Great Inflation" period, compared to the preceding and subsequent periods.

Gali, López-Salido and Vallés (2003) already detected a much stronger impact of a technology shock on inflation in the pre-Volcker period (54Q1-79Q2) relative to the Volcker-Greenspan era (82Q3-98Q3). Given the more muted inflationary consequences we also find for the period before the start of the "Great Inflation", our results indicate that the first period they consider actually also covers two different regimes.

The sign switch in the response of nominal wages to a technology shock at the start and at the end of the "Great Inflation" is a stylized fact which has not been documented before. As a matter of fact, the few studies that do analyze the impact of technology shocks on wages using SVARs assuming constant parameters over the whole sample period, e.g. Basu, Fernald and Kimball (2006) or Liu and Phaneuf (2007), conclude that there is only a very weak negative or insignificant response of nominal wage inflation accompanying a significant rise in real wages. The present analysis suggests that these findings are misleading since they are ignoring considerable time variation in the reaction pattern of wages. Before and after the high inflation regime of the 1970s, nominal wages adjusted to technology shocks in a way that supported the required adjustment of real wages. During the "Great Inflation", in contrast, nominal wages moved in the same direction as prices after the supply-side shock, thus even counteracting the required adjustment of real wages. Interestingly, this is not the case for the contemporaneous impact. As can be seen from Figure 4, the immediate response of nominal wages has always been positive after a favorable technology shock, and even of a similar magnitude. Only after a few quarters, there is a sign switch in the nominal wage reaction. The latter is more clearly visible in Figure 5, which shows the pass-through of a technology shock to output, prices, interest rates as well as real and nominal wages at three points in time: before (1960Q1), during (1974Q1) and after (2000Q1) the "Great Inflation".

Another interesting result of the analysis is the time variation in the adjustment speed of prices, real and nominal wages. As illustrated in Figure 5, adjustment patterns of these variables look very similar for the periods before and after the "Great Inflation", where we find an immediate adjustment of prices, nominal and especially real wages to their new equilibrium values. In contrast, the adjustment of real wages is very sluggish in the 1970s. This result points to a high degree of real wage rigidity following permanent technology shocks in this period, with an estimated half-life of the overall real wage adjustment of approximately one year (and even more).[11]

3 Explaining the stylized facts

3.1 Interpretation of the evidence

It appears implausible that only changes in the size of technology shocks are driving the pattern of the responses of prices and nominal wages over time. If this were the case, then we should see the same pattern of time variation in the impulse responses of the other variables, which is not the case. Although we cannot pin-down the exact magnitude of the shocks, the long-run (permanent) effects on output suggest that technology shocks could have been bigger in the 1970s (see Figure 4).[12] However, when we consider the long-run effects on real wages, a variable which is also expected to be closely related to productivity changes, the impact was not even stronger in the 1970s relative to more recent periods. The time variation of the output effects is also much more subdued than the time variation of the impact on nominal wages and prices. Furthermore, a different size of the underlying shocks over time cannot explain why the contemporaneous impact on nominal wages has always been positive (and of a similar magnitude), whereas the long-run effects became negative at the start of the "Great Inflation" and changed back to positive at the end of this episode in the early 1980s. This sign switch in the reaction of nominal wages clearly points to a structural change in the labor market.

A plausible explanation for the changing pattern in the responses of prices and nominal wages is that second-round effects via wage indexation played an important role during the "Great Inflation" so that technology disturbances during that period simultaneously

[11] The conclusions are not altered if we select alternative quarters in each period. The half life is calculated for each draw of the posterior independently.

[12] Note that this finding is not at odds with the "bad luck" hypothesis contributing to the "Great Inflation".

triggered wage-price spirals giving rise to larger long-run effects of such shocks on wages and prices, and hence increased inflation variability.[13] This hypothesis can also perfectly explain the sign switch in the nominal wage response during the 1970s. Consider an unfavorable technology shock. Whereas this shock has a downward impact on real wages, also nominal wages tend to decline in the very short-run. The accompanying rise in prices, however, generates a positive effect on nominal wages due to the second-round effects, triggering a wage-price spiral resulting in a sign switch of the nominal wage response and a positive long-run co-movement between prices and wages. Furthermore, a high level of wage indexation is also consistent with the sluggish adjustment of real wages following a technology shock that we found for the 1970s. In particular, a strong link between price and wage dynamics due to explicit or implicit wage indexation hinders a fast adjustment of the real wage, which is the ratio of the two, to its new equilibrium.

The existence of second-round effects via rising wages could be the consequence of explicit or implicit wage indexation schemes. As we have shown in Figure 1, the prevalence of cost-of-living adjustment clauses in collective bargaining agreements increased considerably during the 1970s, peaked in the late 1970s, and declined again afterwards. This pattern fits very well with the estimated time variation in wage dynamics. A detailed analysis of the determinants of wage indexation is beyond the scope of this paper, but the existing literature refers particularly to the role of inflation uncertainty as the most important determinant.[14] The latter, however, corroborates very well with the "bad monetary policy" hypothesis of the "Great Inflation". In particular, Gali, López-Salido and Vallés (2003) find the Fed's response to a technology shock in the Volcker-Greenspan period to be consistent with an optimal monetary policy rule. For the Pre-Volcker period, in contrast, the Fed tended to overstabilize output at the cost of generating excessive inflation volatility. An insufficient unconditional interest rate response to inflation before Volcker became the Fed's chairman has also been brought forward by Judd and Rudebusch (1999), Clarida, Gali and Gertler (2000) and Cogley and Sargent (2002, 2005) among others.[15]

[13] Note that when we identify additional shocks using the sign restrictions proposed by Peersman (2005), a similar strong wage-price spiral in the 1970s shows up. These results are available upon request.

[14] E.g. Holland (1986, 1995), Weiner (1986) or Ragan and Bratsberg (2000). Alternative reasons put forward in this literature are changes in regulation, power of unions or competition.

[15] Francis, Owyang and Theodorou (2005) find that the type of monetary policy rule also contributes

By conducting counterfactual simulations, a number of studies (e.g. Primiceri 2005; Sims and Zha 2006; Canova and Gambetti 2006) conclude that this shift in the monetary policy rule is unable to explain the changed macroeconomic dynamics and volatility over time, hence questioning the monetary policy hypothesis. To the extent that improved monetary policy has also provided a clear anchor for inflation expectations, contributing to reduced inflation uncertainty, our analysis indicates that the additional effects via lower wage indexation and contained second-round effects should also be taken into account. What is striking, is that our results suggest that increased wage indexation itself in turn leads to additional inflation variability via second-round effects, thus further strengthening the incentive to include cost-of-living adjustments in collective bargaining agreements. The relevance of both features characterizing the monetary policy regime in explaining the time variation in the reactions to a technology shock uncovered by our empirical analysis, and in particular their interplay, is analyzed in more detail in the next subsection.

3.2 Dynamic effects of technology shocks in a DSGE model

To explore the sources of time variation more carefully, we use a standard DSGE model with Calvo sticky prices and wages, price and wage indexation, habit formation, and a conventional Taylor rule. The model can be considered as a simplified version of Smets and Wouters (2007) or Christiano, Eichenbaum and Evans (2005). Details of the model can be found in the appendix. Since we focus on the role of changes in the monetary policy rule and changes in wage indexation, we simulate the dynamics of a technology shock within the model by varying the inflation reaction parameter in the monetary policy rule and the degree of wage indexation. For all simulations, the other parameters of the model are set at the following baseline values: the discount factor $\beta = 0.99$; the preference parameter $\zeta = 3$; habit persistence $b = 0.9$; degree of monopolistic competition in respectively the goods and labor market $\lambda_p = 6$, $\lambda_w = 10$; Calvo price and wage parameters $\theta_p = 0.85$, $\theta_w = 0.85$; degree of price indexation $\gamma_p = 0.6$; coefficient on output in the monetary

to cross-country differences in the effects of technology shocks. Bilbiie and Straub (2006) argue that limited asset market participation before 1980 in the US (and the change thereof) is crucial in explaining macroeconomic performance and monetary policy conduct.

policy rule $\phi^y = 0.5$; and interest rate smoothing $\rho^r = 0.65$.[16] To match the empirical set-up, we simulate the dynamic effects of a permanent technology shock in the model by imposing $\rho^a = 1$.

All results are reported in Figure 6. The first column reports the simulated dynamic effects of a technology shock assuming a policy rule with a very weak reaction to inflation and no wage indexation by setting $\phi^\pi = 1.01$ and $\gamma_w = 0.0$.[17] As a benchmark to match the stylized facts of the "Great Inflation", the graphs also show the estimated median impulse responses for 1974Q1, together with 16th and 84 percentiles of the posterior. To match the magnitude of a technology shock in the DSGE model, the VAR responses are normalized to a 1 percent long-run increase of the output level. The similarity of the simulations and the estimated output and real wage responses is high. The contemporaneous reaction of the interest rate is also the same as in the data, and we do find a negative long-run response of nominal wages. However, the simulated magnitudes of the effects on prices and wages are much smaller than in the data. Hence, a policy rule with weak inflation stabilization alone cannot explain the stylized facts of technology shocks in the 1970s, particularly not the wage dynamics and accompanying inflation variability.

In the second column of Figure 6, we augment the model with wage indexation by setting $\gamma_w = 0.65$. A relative high degree of wage indexation is clearly crucial to explain the estimated magnitudes of the effects of technological innovations during the "Great Inflation". More specifically, we now find a substantial decline of nominal wages in the long-run, counteracting the required adjustment of real wages and amplifying the ultimate repercussions on prices. The inflationary effects are almost double compared to a

[16] The choices of the parameter values, e.g. Calvo parameters or habit persistence, are mainly determined to capture the 'shapes' of the estimated impulse responses. We also experimented with possible time variation of price indexation or alternative parameters for output and interest rate smoothing in the policy rule, but the results of these experiments do not affect the conclusions, i.e. the consequences of varying these parameters for price and wage dynamics are very limited. Accordingly, we can focus on the inflation parameter in the policy rule and the degree of wage indexation. These other simulations are available upon request.

[17] We impose an inflation reaction parameter which is larger than 1 in order to avoid model indeterminacy. We also simulated the model under indeterminacy using the mimum state variable approach (see Lubik and Schorfheide 2004). The results of this exercise suggested that allowing for indeterminacy in this way does not alter the conclusion of our analysis that a change in the inflation reaction parameter in the policy rule alone cannot explain the time variation in U.S. wage and price inflation dynamics documented in section 2.

situation without wage indexation. The initial nominal wage response in the model is even positive,consistent with what we found in the data. Hence, second-round effects via wage indexation must have been important in the 1970s, contributing to higher inflation variability.

Interestingly, wage indexation alone can also not explain the stylized facts. In column 3, we report the results of a simulation assuming a policy rule with a strong reaction to inflation ($\phi^{\pi} = 2.8$) combined with a high degree of wage indexation. Again, it is impossible to match the estimated magnitudes from section 2, i.e. a weak inflation stabilizing monetary policy rule is also needed to explain the stylized facts of the 1970s.

Why is the interaction of weak monetary policy response and wage indexation crucial for reproducing the results? Note that in our model the parameter γ_w partially indexes nominal wages to lagged price inflation for all those households that are not able to re-optimize wages. Now if prices decline, as is the case following a permanent technology shock, average wages decline more substantially with wage indexation than without. At the same time a weak monetary policy response is amplifying the described effect. Weak monetary policy inflation reaction to inflation implies, ceteris paribus, that interest rates fall less notably following a permanent technology shock. This results in a stronger decline in inflation rates than under a rule that reacts aggressively to price developments. That is, the interaction of high wage indexation and weak monetary response to inflation pushes up the volatility of nominal variables in the model; a feature that is in line with the data for the 'Great Inflation' period.

That the interaction between policy rule parameter and wage indexation is crucial to get the substantial inflationary repercussions of technology shocks can be illustrated with a simple back-of-the-envelope calculation. Whereas the long-run impact of a technology shock in the DSGE model on prices increases by 63% when the inflation reaction coefficient in the policy rule is reduced to a low level, and by 52% when only wage indexation is high, combining both raises the ultimate effects by 197%. This finding is consistent with Fischer (1983) who shows in a simple theoretical model that the inflationary effects of all aspects of indexation depends on the monetary and fiscal policy followed by the government.

Is it possible to get the positive long-run response of nominal wages from the period before and after the "Great Inflation"? A shift in the monetary policy rule towards aggressive inflation stabilization, while still assuming the presence of a relatively high level of wage indexation, clearly cannot. The long-run impact on nominal wages is still negative. Furthermore, such a shift in the policy rule alone can also not explain the magnitude of the inflationary effects of technological innovations in more recent periods. This is illustrated for 2000Q1 in the fourth column of Figure 6.[18] The simulated effect on inflation is now too strong. To get the positive response of nominal wages and more plausible values for the magnitudes, the assumption of high wage indexation also has to be abandoned. As can be seen from the last column of Figure 6, a policy rule with a strong reaction to inflation together with low or no wage indexation is able to generate magnitudes of impulse responses that are in line with the stylized facts.

In sum, only the combination of a policy rule with a low inflation reaction coefficient and a high degree of wage indexation can explain U.S. wage dynamics and inflation fluctuations following technology shocks during the "Great Inflation". On the other hand, an aggressive policy rate response to inflation combined with very low wage indexation is needed to explain wage dynamics and inflationary effects before and after this period. As we have argued, however, the degree of wage indexation and the existence of second-round effects is likely to be dependent on the monetary policy regime, and improved monetary policy over time involves much more than only the monetary policy rule of the central bank. In particular, both characteristics can be considered as two sides of the same coin, namely monetary policy credibility, a feature which should be taken into account when examining the implications of changes in the monetary policy regime.

4 Conclusions

In this paper, we examine the time-varying dynamic effects of technology shocks on a set of key U.S. macroeconomic variables using data spanning the period 1947 till 2008. The focus of the analysis is on time variation in wage dynamics, which has so far remained unexplored in the literature. We find considerable time variation that can be linked to

[18] Which is also the case for other quarters before and after the "Great Inflation".

the monetary policy regime. More specifically, during the "Great Inflation", technology shocks triggered second-round effects via mutually reinforcing feedback effects between wages and prices, amplifying the ultimate effects on prices and hence increasing inflation variability. In contrast, before and after this period, nominal wages are found to move in the same direction as the required adjustment of real wages and in the opposite direction of the price response after technological innovations, contributing to a subdued impact on inflation and inflation volatility.

Based on a standard DSGE model, we explore the explanations for these new stylized facts. Model-based simulations suggest that variations over time in both the policy rule parameters and the degree of wage indexation are needed in order to match the stylized facts established by the empirical analysis. What is needed is the combination of a low inflation reaction parameter in the policy rule and a high degree of wage indexation in the "Great Inflation" period and the combination of a high inflation reaction parameters and low wage indexation in the preceding and subsequent period. This implied simultaneous time variation of the inflation reaction parameter in the policy rule and the degree of wage indexation are two sides of the same coin, the monetary policy regime. A weakly inflation stabilizing policy rule is conducive to high and volatile inflation. This fosters the use of wage indexation clauses as protection against inflation uncertainty, which in turn contributes to inflation uncertainty by amplifying the effects of inflationary shocks. On the other hand, a regime of price stability requires a strong inflation stabilizing policy rule and reduces the need for protection against inflation uncertainty, thus mitigating wage indexation. A lower degree of wage indexation in turn reduces the effects of inflationary shocks, thus further contributing to price stability.

The fact that the monetary policy regime is not only characterized by the parameters of the monetary policy rule, but also by the wage setting behavior in the labor market, has two important implications for policy analysis. First, counterfactual experiments by altering solely the monetary policy rule, often done in the context of the "Great Moderation" literature, do not adequately capture the wider consequences of a change in the policy regime that are shown to be very important. Second, a certain degree of wage indexation is typically embedded in micro-founded macroeconomic models, which could also be misleading when optimal monetary policy or significant regime changes in policy are analyzed. As pointed out by Benati (2008) in the context of inflation persistence, the degree of wage indexation is also not structural in the sense of Lucas (1976).

A Appendix - the DSGE model

A.1 Households

In the first step we present the optimization problem of a representative household denoted by h. The household maximizes lifetime utility by choosing consumption $C_{h,t}$ and financial wealth in form of bonds $B_{h,t+1}$.

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log\left(C_t - H_t\right) - \frac{N_{h,t}^{1+\zeta}}{1+\zeta} \right\} \tag{7}$$

where β is the discount factor and ζ is the inverse of the elasticity of work effort with respect to the real wage. The external habit variable H_t is assumed to be proportional to aggregate past consumption:

$$H_t = bC_{t-1} \tag{8}$$

Household's utility depends positively on the change in $C_{h,t}$, and negatively on hours worked, $N_{h,t}$. The intertemporal budget constraint of the representative household is given by:

$$\begin{aligned} & C_{h,t} + R_t^{-1}\frac{B_{h,t+1}}{P_t} \\ = \; & \frac{W_{h,t}}{P_t}N_{h,t} + D_{h,t} + T_{h,t} + \frac{B_{h,t}}{P_t} \end{aligned} \tag{9}$$

Here, R_t is the nominal interest rate, $W_{h,t}$ is the nominal wage, $T_{h,t}$ are lump-sum taxes paid to the fiscal authority, P_t is the price level and $D_{h,t}$ is the dividend income. In the following we will assume the existence of state-contingent securities that are traded amongst households in order to insure households against variations in household-specific wage income. As a result where possible, we neglect the indexation of individual households.

The maximization of the objective function with respect to consumption, bond holding and next period capital stock can be summarized by the following standard Euler equations:

$$\beta R_t \mathrm{E}_t \left[\frac{(C_t - H_t)}{E_t\,(C_{t+1} - H_{t+1})} \frac{P_t}{P_{t+1}} \right] = 1 \tag{10}$$

A.2 Firms

There are two types of firms. A continuum of monopolistically competitive firms indexed by $f \in [\,0,1\,]$, each of which produces a single differentiated intermediate good, $Y_{f,t}$, and a distinct set of perfectly competitive firms, which combine all the intermediate goods into a single final good, Y_t.

A.2.1 Final-Good Firms

The final-good producing firms combine the differentiated intermediate goods $Y_{f,t}$ using a standard Dixit-Stiglitz aggregator:

$$Y_t = \left(\int_0^1 Y_{f,t}^{\frac{1}{1+\lambda_{p,t}}}\, df \right)^{1+\lambda_{p,t}} \tag{11}$$

where $\lambda_{p,t}$ is a variable determining the degree of imperfect competition in the goods market. Minimizing the cost of production subject to the aggregation constraint (11) results in demand for the differentiated intermediate goods as a function of their price $P_{f,t}$ relative to the price of the final good P_t,

$$Y_{f,t} = \left(\frac{P_{f,t}}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t \tag{12}$$

where the price of the final good P_t is determined by the following index:

$$P_t = \left(\int_0^1 P_{f,t}^{-\frac{1}{\lambda_{p,t}}}\, df \right)^{-\lambda_{p,t}}$$

A.2.2 Intermediate-Goods Firms

Each intermediate-goods firm f produces its differentiated output using a production function of a standard Cobb Douglas form:

$$Y_{f,t} = A_t N_{f,t} \tag{13}$$

where A_t is a technology shock and real marginal cost MC_t follows:

$$MC_t = \frac{W_t}{A_t P_t}$$

A.2.3 Price Setting

Following Calvo (1983), intermediate-goods producing firms receive permission to optimally reset their price in a given period t with probability $1 - \theta_p$. All firms that receive permission to reset their price choose the same price $P^*_{f,t}$. Each firm f receiving permission to optimally reset its price in period t maximizes the discounted sum of expected nominal profits,

$$\mathrm{E}_t \left[\sum_{k=0}^{\infty} \theta_p^k \, \chi_{t,t+k} \, D_{f,t+k} \right]$$

subject to the demand for its output (12) where $\chi_{t,t+k}$ is the stochastic discount factor of the households owing the firm and

$$D_{f,t} = P_{f,t} \, Y_{f,t} - MC_t Y_{f,t}$$

are period-t nominal profits which are distributed as dividends to the households.

Hence, we obtain the following first-order condition for the firm's optimal price-setting decision in period t:

$$P^*_{f,t} \, Y_{f,t} - (1+\lambda_p) \, MC_t Y_{f,t} + \mathrm{E}_t \left[\sum_{k=1}^{\infty} \theta_p^k \, \chi_{t,t+k} \, Y_{f,t+k} \left(P^*_{f,t} \left(\frac{P_{t+k}}{P_{t+k-1}} \right)^{\gamma_p} - (1+\lambda_p) \, MC_{t+k} \right) \right] = 0 \tag{14}$$

With the intermediate-goods prices $P_{f,t}$ set according to equation (14), the evolution of the aggregate price index is then determined by the following expression:

$$P_t = \left((1-\theta_p)(P^*_{f,t})^{-\frac{1}{\lambda_p}} + \theta_p \left(P_{f,t-1} \left(\frac{P_{t-1}}{P_{t-2}} \right)^{\gamma_p} \right)^{-\frac{1}{\lambda_p}} \right)^{-\lambda_{p,t}}$$

A.3 Wage Setting

There is a continuum of monopolistically competitive unions indexed over the same range as the households, $h \in [0,1]$, which act as wage setters for the differentiated labor services supplied by the households taking the aggregate nominal wage rate W_t and aggregate labor demand N_t as given. Following Calvo (1983), unions receive permission to optimally reset their nominal wage rate in a given period t with probability $1-\theta_w$. All unions that receive permission to reset their wage rate choose the same wage rate $W^*_{h,t}$. Each union h that receives permission to optimally reset its wage rate in period t maximizes the household's lifetime utility function (7) subject to its intertemporal budget constraint (9) and the demand for labor services of variety h, the latter being given by

$$N_{h,t} = \left(\frac{W_{h,t}}{W_t} \right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} N_t$$

where $\lambda_{w,t}$ is a variable determining the degree of imperfect competition in the labor market. As a result, we obtain the following first-order condition for the union's optimal wage-setting decision in period t:

$$\frac{W^*_{h,t}}{P_t} - (1+\lambda_w)\ MRS_t + \mathrm{E}_t \sum_{k=1}^{\infty} \theta_w^k\, \beta^k \left[\frac{W^*_{h,t}}{P_{t+k}} \left(\frac{P_{t+k}}{P_{t+k-1}} \right)^{\gamma_w} - (1+\lambda_w)\ MRS_{t+k} \right] = 0 \quad (15)$$

where $MRS_t = N^{\zeta}_{h,t}(C_t - H_t)$ stands for the marginal rate of substitution, and γ_w determines the degree of wage indexation. Aggregate labor demand, N_t, and the aggregate nominal wage rate, W_t, are determined by the following Dixit-Stiglitz indices:

$$N_t = \left(\int_0^1 (N_{h,t})^{\frac{1}{1+\lambda_w}}\, dh \right)^{1+\lambda_w}$$

$$W_t = \left(\int_0^1 (W_{h,t})^{-\frac{1}{\lambda_w}} \, dh \right)^{-\lambda_w}$$

With the labor-specific wage rates $W_{h,t}$ set according to (15), the evolution of the aggregate nominal wage rate is then determined by the following expression:

$$W_t = \left((1-\theta_w)(W^*_{h,t})^{-\frac{1}{\lambda_w}} + \theta_w \left(W_{h,t-1} \left(\frac{P_{t-1}}{P_{t-2}} \right)^{\gamma_p} \right)^{-\frac{1}{\lambda_w}} \right)^{-\lambda_w}$$

A.4 Market Clearing and Shock Process

The labor market is in equilibrium when the demand for the index of labor services by the intermediate-goods firms equals the differentiated labor services supplied by households at the wage rates set by unions. Furthermore, the final-good market is in equilibrium when the supply by the final-good firms equals the demand by households:

$$Y_t = C_t$$

The model is simulated in its log-linearized form, i.e. small letters will characterize in the following percentage deviations form the steady state. The exogenous shock process follows an AR(1) described by the following equations:

$$a_t = \rho^a a_{t-1} + \eta_t^a \tag{16}$$

whereby we set $\rho^a = 1$, implying a random walk productivity shock which induces permanent effects. Finally, monetary policy follows a standard log-linearized Taylor rule:

$$r_t = \rho^r r_{t-1} + (1-\rho^r)\left(\phi^y \Delta y_t + \phi^\pi \pi_t\right) \tag{17}$$

where ρ^r is a parameter determining the degree of interest rate smoothing, while ϕ^y and ϕ^π represent the elasticity of the interest rate to output and inflation respectively.

A.5 Equilibrium dynamics

The log-linearized equilibrium of the model consist of the following equations:

$$\pi_t = \frac{\beta}{\left(1+\beta\gamma_p\right)}\pi_{t+1} + \frac{\gamma_p}{\left(1+\beta\gamma_p\right)}\pi_{t-1} + \frac{(1-\beta\theta_p)(1-\theta_p)}{\left(1+\beta\gamma_p\right)\theta_p}\left(w_t - a_t\right) \tag{18}$$

$$\pi_t^w = \beta E_t \pi_{t+1}^w - \gamma_w \beta \pi_t + \gamma_w \beta \pi_{t-1} + \frac{1}{(1+\beta)} \frac{(1-\beta\theta_w)(1-\theta_w)}{(\theta_w(1+\frac{1+\lambda_w}{\lambda_w}\zeta))} \begin{pmatrix} \zeta n_t - w_t \\ +\frac{1}{1-b}\left(c_t - bc_{t-1}\right) \end{pmatrix} \tag{19}$$

$$w_t = w_{t-1} + \pi_{w,t} - \pi_t \tag{20}$$

$$r_t - E_t\pi_{t+1} = \frac{1}{1-b}\left(E_t c_{t+1} - (1-b)c_t + bc_{t-1}\right) \tag{21}$$

$$r_t = \rho^r r_{t-1} + (1-\rho^r)\left(\phi^y \Delta y_t + \phi^\pi \pi_t\right) \tag{22}$$

A.6 Stationary equilibrium of the model

In this section, we present the stationary equilibrium of our model. To induce stationarity, we divide consumption, output, real wage by the level of the permanent supply shock A_t. We denote transformed variables consumption and real wages by $\widetilde{C}_t = \frac{C_t}{A_t}$ and $\widetilde{W}_t = \frac{W_t}{P_t A_t}$. Furthermore, we label log-deviations of a stationary variable $\widetilde{X}_t$ from its steady-state value by $\widetilde{x}_t = \log(\widetilde{X}_t/\widetilde{X})$. The equilibrium dynamics can by summarized by the following equations.

$$\pi_t = \frac{\beta}{\left(1+\beta\gamma_p\right)}\pi_{t+1} + \frac{\gamma_p}{\left(1+\beta\gamma_p\right)}\pi_{t-1} + \frac{(1-\beta\theta_p)(1-\theta_p)}{\left(1+\beta\gamma_p\right)\theta_p}\widetilde{w}_t \tag{23}$$

$$\pi_t^w = \beta E_t \pi_{t+1}^w - \gamma_w \beta \pi_t + \gamma_w \beta \pi_{t-1} + \frac{1}{(1+\beta)} \frac{(1-\beta\theta_w)(1-\theta_w)}{(\theta_w(1+\frac{1+\lambda_w}{\lambda_w}\zeta))} \left(\begin{array}{c} \left(\frac{1}{1-b}+\zeta\right)\widetilde{c}_t \\ -\widetilde{w}_t - \frac{b}{1-b}\left(\widetilde{c}_{t-1}-\Delta a_t\right) \end{array} \right) \quad (24)$$

$$\widetilde{w}_t = \widetilde{w}_{t-1} + \pi_{w,t} - \pi_t - \Delta a_t \quad (25)$$

$$r_t - E_t \pi_{t+1} = \frac{1}{1-b}\left(E_t \widetilde{c}_{t+1} - (1-b)\widetilde{c}_t + b\widetilde{c}_{t-1} - b\Delta a_t\right) \quad (26)$$

$$r_t = \rho^r r_{t-1} + (1-\rho^r)\left(\phi^y\left(\Delta\widetilde{c}_t - \Delta a_t\right) - +\phi^\pi \pi_t\right) \quad (27)$$

Note that due to market clearing $\widetilde{c}_t = \widetilde{y}_t$.

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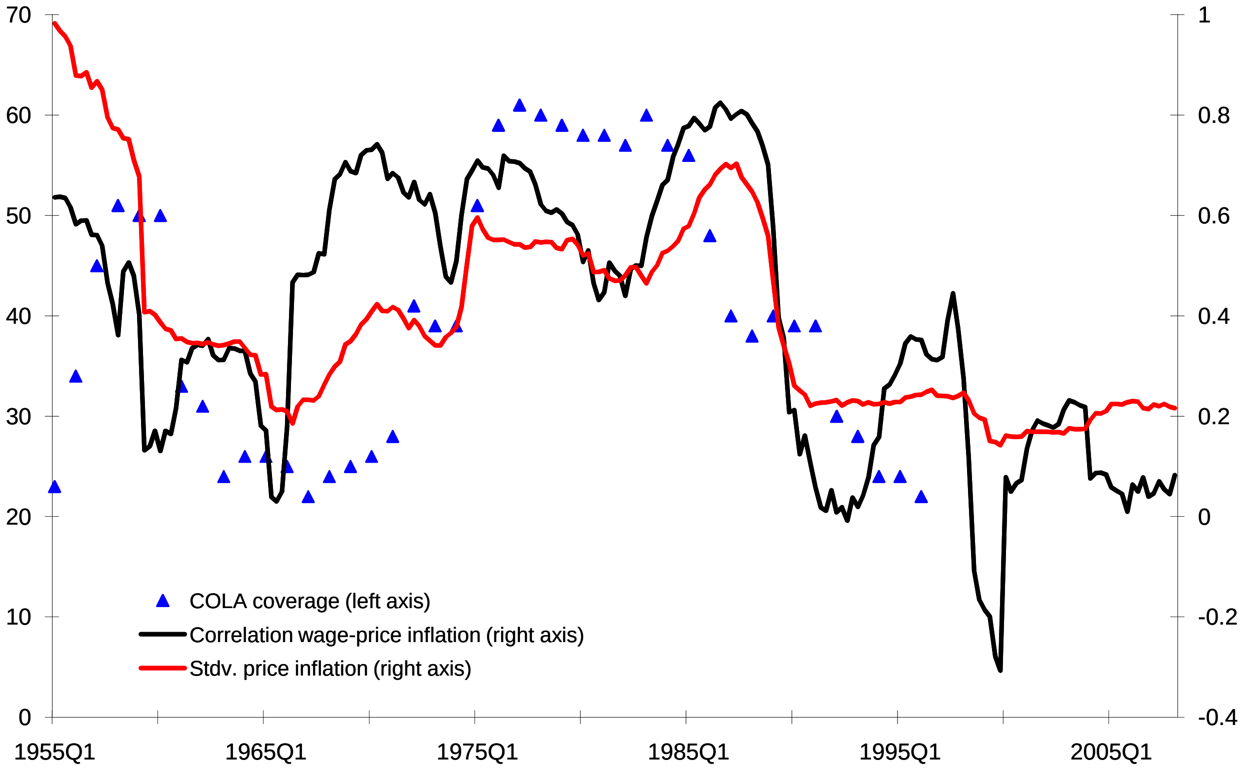
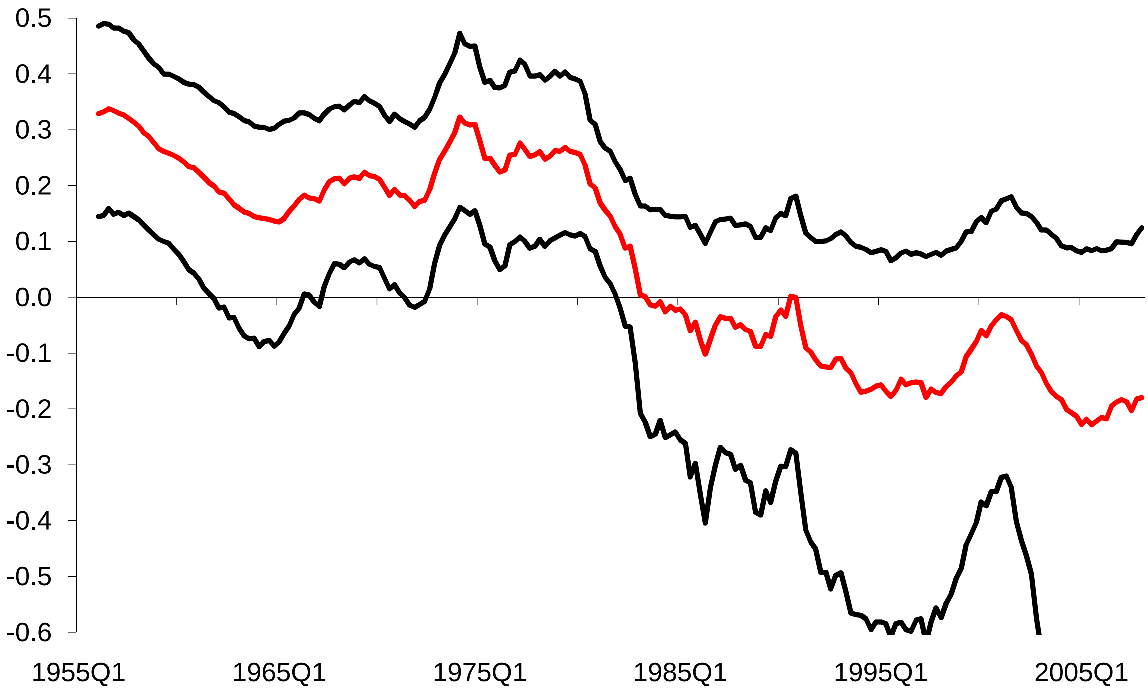
Figure 1 - COLA coverage, correlation wage-price inflation and inflation variability



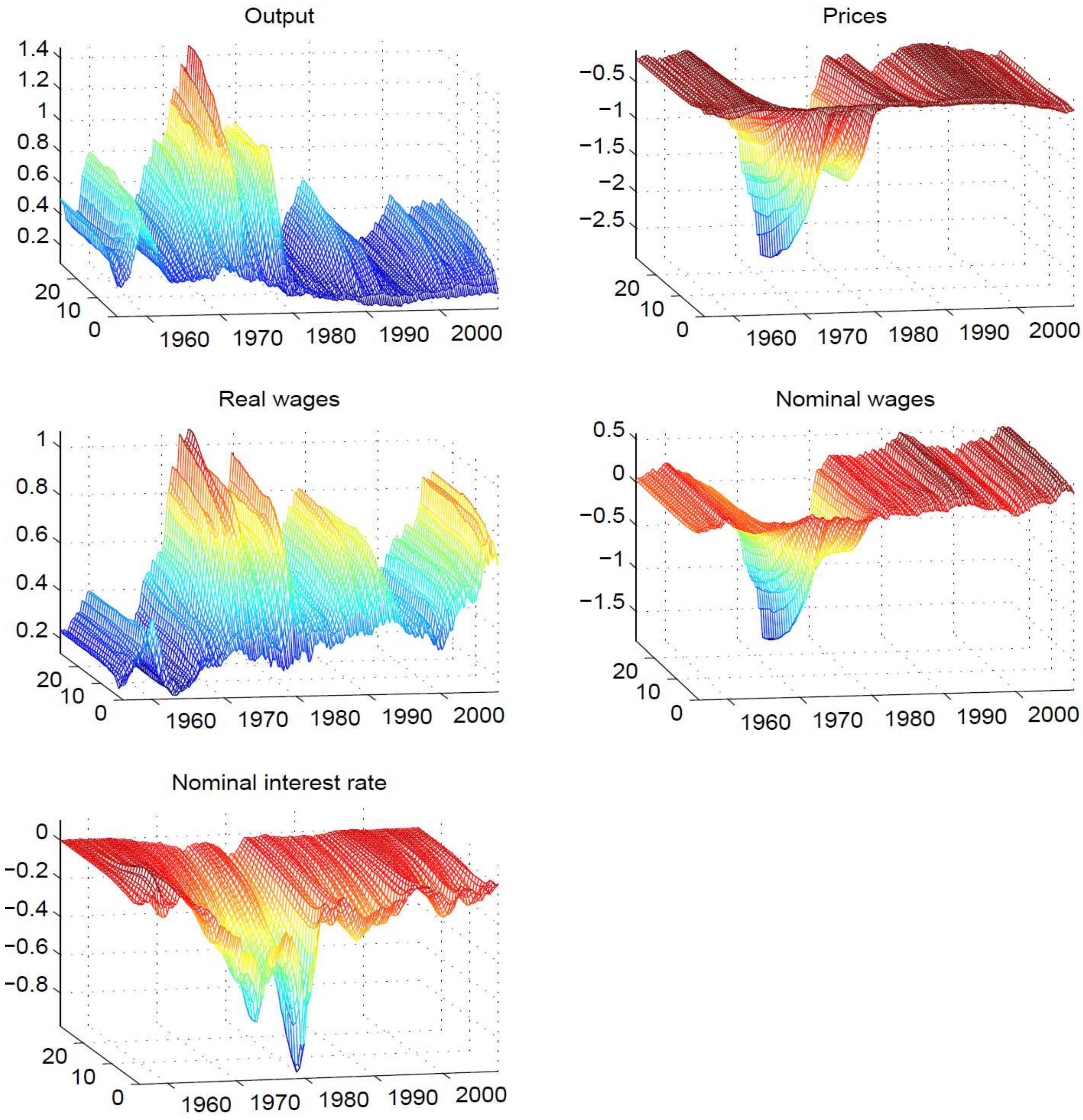
Note: COLA = cost-of-living adjustment clauses included in major collective bargaining agreements (i.e. contracts covering more than 1,000 workers). Figures refer to end of preceding year. Source: Hendricks and Kahn (1985), Weiner (1986) and Bureau of Labor Statistics. The observation for 1956 is interpolated, and the series has been discontinued in 1996. Correlation of wage-price inflation and standard deviation of price inflation is calculated as an 8-year moving window.

Figure 2 - Impact lagged price inflation on wage inflation



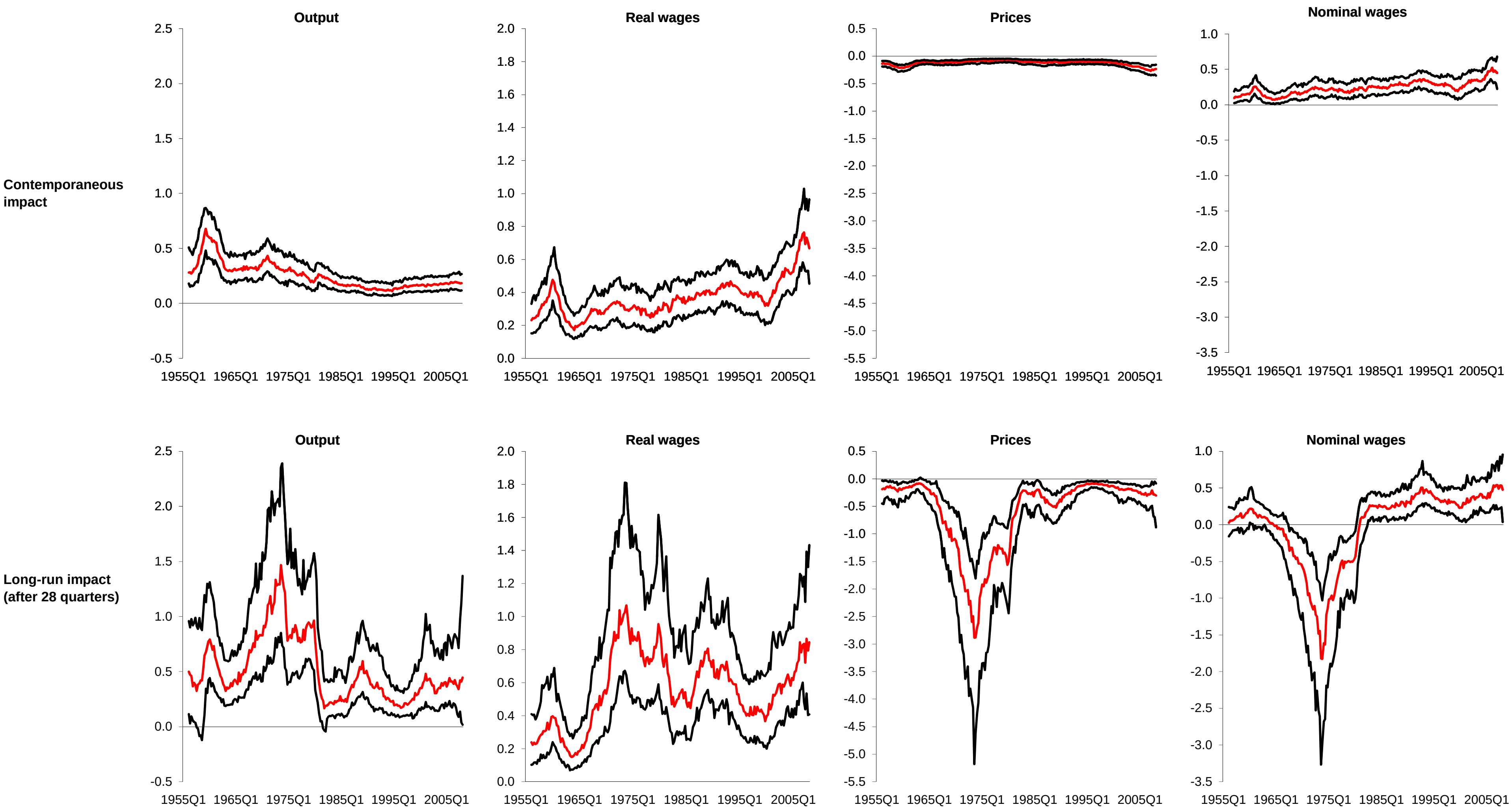
Note: Figures are time-varying medians of the posterior distribution together with 16th and 84th percentiles, and show (sum coefficients dp at t-1 and t-2 on dw at t) / [1 - (sum coefficients dw at t-1 and t-2 on dw at t)]

Figure 3 - Time-varying impulse response functions to a technology shock



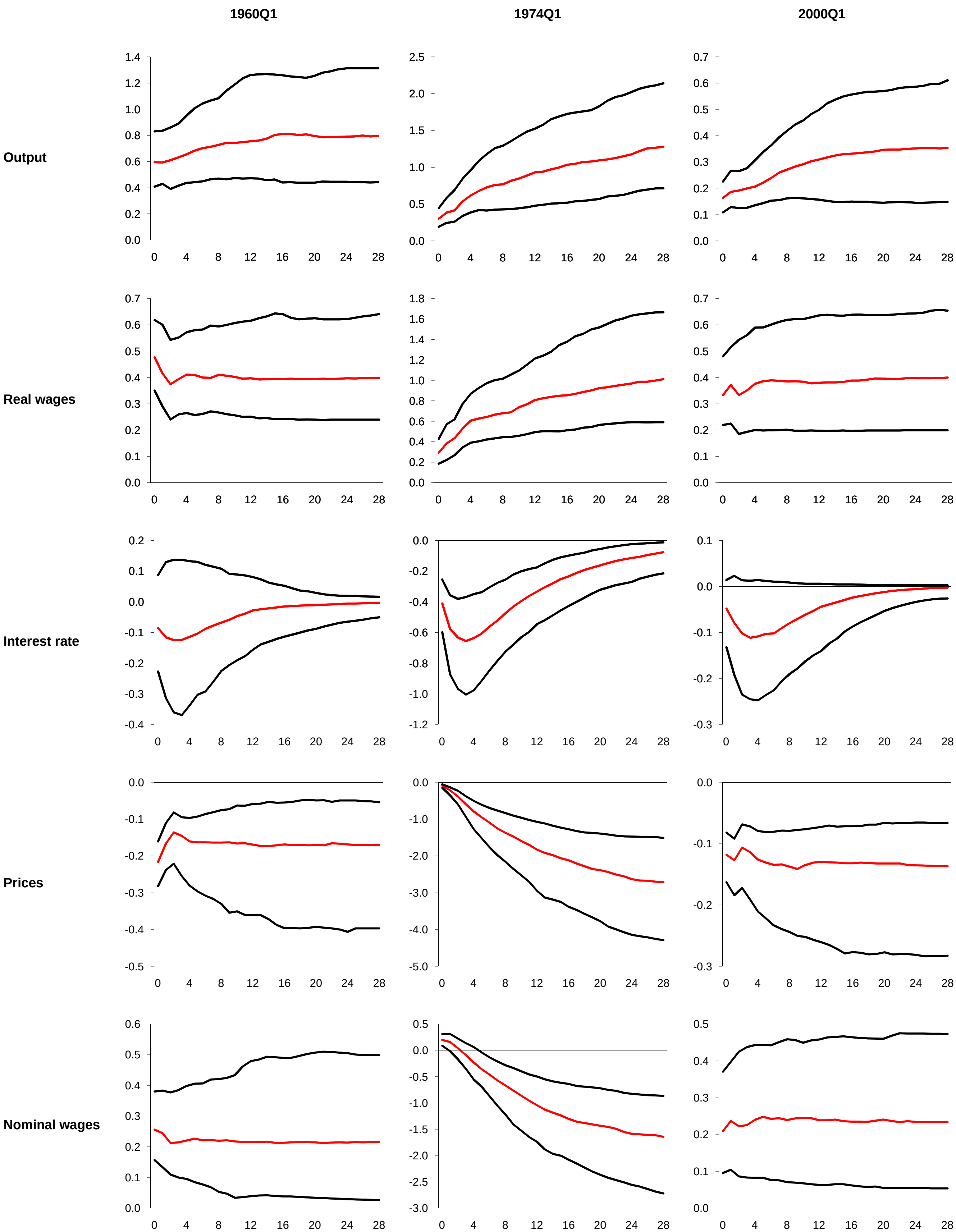
Note: Median impulse response function obtained from the posterior distributions.

Figure 4 - Contemporaneous and long-run impact of a technology shock



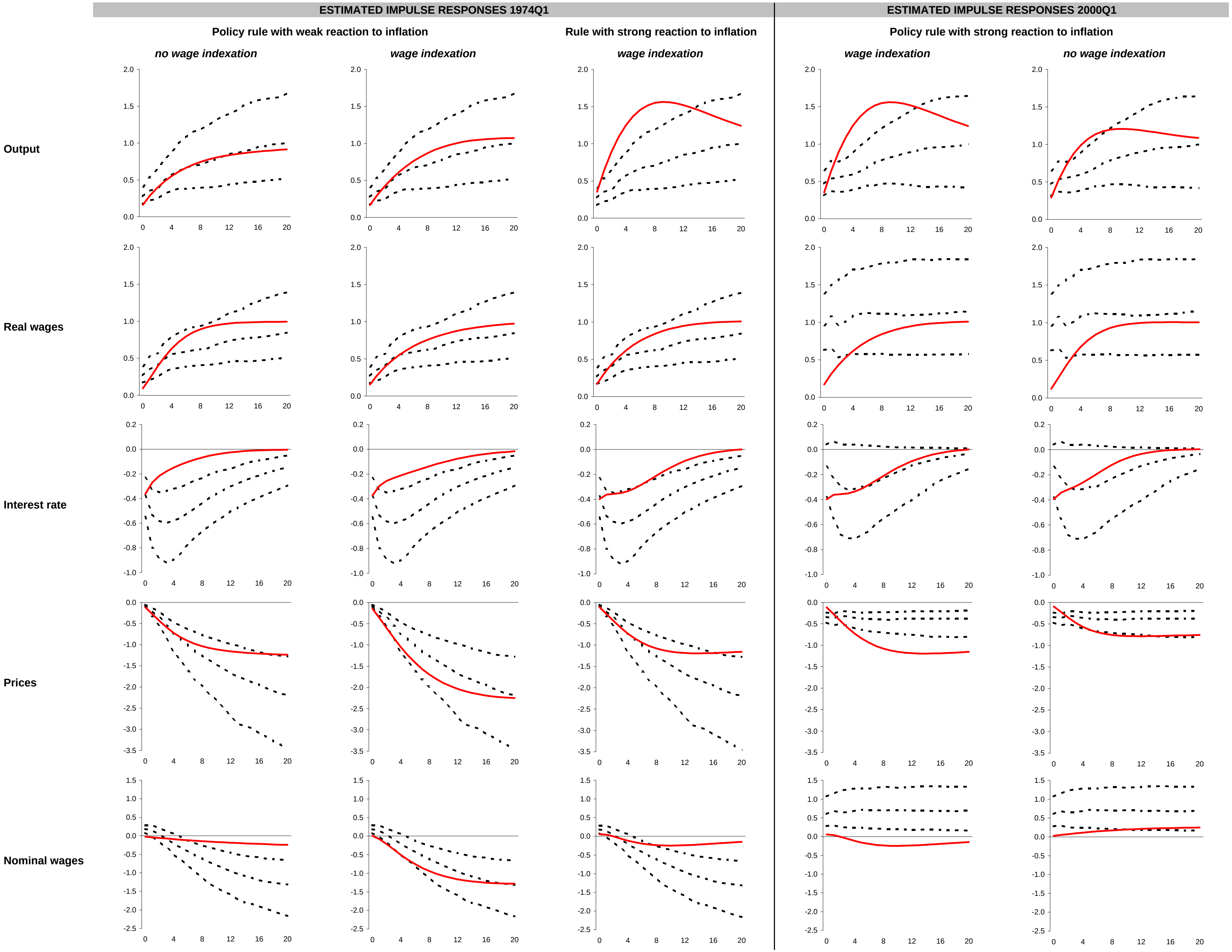
Note: Figures are median of the posterior, together with 16th and 84th percentiles.

Figure 5 - Impulse responses to a technology shock at selected dates



Note: Median impulse responses of the posterior distribution, together with 16th and 84 percentiles

Figure 6 - Impact of a technology shock for different versions of a DSGE model



Note: black dotted lines are estimated median impulse responses, together with 16th and 84th percentiles for respectively 1974Q1 and 2000Q1. Responses normalized to have a 1 percent long-run impact on output.
Full red lines are DSGE impulse responses for a permanent technology shock