Abstract. In this paper, we examine the timing of emergency meetings. Meetings are critical to the success of organizations, allowing them to coordinate information, discuss strategies, and realign policies to meet their objectives. We treat emergency meetings between scheduled meetings as real options. The optimal strategy involves time-varying threshold values that, when exceeded, trigger an emergency meeting. The model explains why organizations need both scheduled and emergency meetings. The model also predicts more frequent emergency meetings during periods of high volatility and a hump-shaped distribution for the timing of emergency meetings. We find empirical support for these predictions using data from the Organization of Petroleum Exporting Countries (OPEC) and the Federal Open Market Committee (FOMC) of the U.S. Federal Reserve system.

JEL Codes: C44, C61, C63

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1. **Introduction**

Meetings are critical to the success of organizations. Meetings allow organizations to coordinate information, discuss strategies, and realign policies to meet their objectives. For example, firms schedule regular meetings to assess whether current pricing is in line with changing market demand. International organizations such as the United Nations schedule regular meetings to discuss worldwide political conditions and assess the need for military or humanitarian support. Meetings can also be interpreted more loosely to represent any situation where individuals get together and share information toward a common purpose, such as the financial audit of a firm. In fact, it is difficult to think of a single organization that does not require some form of meetings to make decisions and set policy.

Organizations typically set meeting schedules in advance. The frequency of these scheduled meetings tends to be based on institutional factors, and in many instances, does not change over time. Predetermined meeting schedules can improve efficiency by allowing for the collection and processing of information prior to the meeting, as well as the coordination of individual schedules. However, conditions often change unexpectedly between scheduled meetings and policies set at a previous meeting are no longer optimal. This may necessitate the need for organizations to schedule an emergency meeting. While emergency meetings allow the flexibility to handle unscheduled deviations from the optimal policy set at the last scheduled meeting, they are less efficient than scheduled meetings because they do not allow for an in-depth and thorough analysis of the situation. Statements from former Federal Reserve Chairman Alan Greenspan allude to the fact that meetings planned in advance are preferable to emergency meetings. Chairman Greenspan stated during an emergency meeting of the FOMC, “I think we
should be prepared, if it turns out to be the consensus of the Committee, … to wait until we can have a full-scale FOMC deliberation and then make decisions” (FOMC, 2003).

We develop a real options model of emergency meetings. In our model, unanticipated changes to the economy occur randomly. When it appears that there have been sufficiently large deviations to the economy since the last meeting, it is worth paying the cost of an emergency meeting. The emergency meeting is not as thorough as a regular meeting. However, when there are large deviations it is worthwhile to pay the cost of an emergency meeting and optimize policy based on the incomplete analysis of the emergency meeting rather than wait until the next regular meeting.

We apply our model of emergency meetings to two organizations that rely heavily on meetings to set policy: the Federal Open Market Committee (FOMC) of the U.S. Federal Reserve system and the Organization of the Petroleum Exporting Countries (OPEC). The FOMC schedules eight regular meetings a year to assess national economic conditions and determine the appropriate direction of U.S. monetary policy. These regularly scheduled meetings involve a thorough analysis and discussion of the state of the macroeconomy and policy direction. Similarly, OPEC depends on regular meetings to set policy. Since its inception in 1960, OPEC has scheduled two regular meetings each year in March and September to discuss and set policy.

Although the variables that make up the relevant economic or financial conditions may be difficult to measure, we have precise data on the number and timing of regular and emergency meetings. This allows us to test the theory even if we do not observe all the variables driving the
decision to call an emergency meeting. OPEC has called 60 such emergency meetings since 1960, while the FOMC has called 123 emergency meetings since 1978.\(^1\)

The rest of the paper is organized as follows. Section 2 presents a review of the related literature, while section 3 presents our model. Section 4 investigates the case of emergency meetings with a fixed schedule of meetings. Section 5 explores the relationship between crude oil prices and the timing of OPEC emergency meetings. Section 6 tests whether the distribution of FOMC emergency meetings are consistent with our theory. Section 7 concludes.

2. Related Literature

The problem of when to schedule an emergency meeting is related to the inventory models of Miller and Orr (1966) and Huberman (1988). In Miller and Orr (1966), a firm has cash balances in a checking account that is not earning interest. The balance fluctuates randomly from inflows and outflows. When the balance gets too large there is an incentive to move funds out of the account, and if it becomes zero, there is a need to move funds into the account. This is an \((S,s)\) type model. In a different inventory problem, Huberman (1988) considers a firm which accumulates random projects. The projects arrive in continuous time according to a Poisson arrival process. To begin earning a return the projects must be activated. There is a fixed cost of acting on the projects, which is independent of the number accumulated. Huberman discusses a planned schedule for acting on accumulated projects, which is similar to a regular meeting. Only

\(^1\) The websites for OPEC (www.opec.org/opec_web/en/index.htm) and the FOMC (www.federalreserve.gov/monetarypolicy/fomc.htm) present the entire history of regular and emergency meetings. For OPEC, the regular meetings are listed as “ordinary” meetings while the emergency meetings are listed as “extraordinary” meetings. After 2000, some of OPEC’s extraordinary meetings were scheduled in advance. We discuss this issue in more detail later in the paper.
when there is an unplanned accumulation of projects is an emergency action worthwhile. The optimal strategy for emergency action is to wait until the number of projects builds up to a desired level and then pay to have them processed. Unprocessed projects do not earn interest so the interest rate plays a central role in the decision of when to act.

Our analysis of emergency meetings shares similarities to the models of Miller and Orr (1966) and Huberman (1988). In both of these models, the accumulation of random events may eventually trigger the need for action. The interest rate drives the need for action in their models. In our model, the accumulation of discrete-time fluctuations instead creates distortions from the optimal policy set at the last meeting. The random events in our model can be either positive or negative, so the events may self-correct and reduce the need for emergency action. Our optimal strategy is a pair of thresholds with equal magnitude – one positive and one negative – which depend upon the time remaining until the scheduled meeting. As in Huberman (1988), the threshold level for emergency action rises as we approach the date of the next regularly scheduled meeting.

The decision to call an emergency meeting shares features with several other problems in economics, finance, and management. The literature on the timing of internal audits looks at how frequently firms should schedule an audit to resolve accounting errors or inefficiencies in their internal control system (Hughes, 1977; Morey and Dittman, 1986). Errors in financial accounts or distortions in the efficiency of the production process accumulate over time until an audit is necessary to fix the problem. The objective is to determine the optimal frequency of audits to balance auditing costs with the value of the firm. Similarly, the literature on external audits considers the decision of when a regulator should pay a cost and perform an audit of a firm that may have more information than the regulator (e.g., Baron and Besako, 1984). The
corporate governance literature considers the timing of board meetings and how this influences the value of the firm. Vafeas (1999) investigates whether more frequent board meetings increases the value of the firm or whether it is symptomatic of declines in share prices. Vafeas finds evidence of the latter, a negative correlation between the frequency of corporate board meetings and the value of the firm.

Another related problem is the refinancing of mortgages which is analyzed in Stanton (1995). As time goes by, interest rates fluctuate randomly. If the interest rate declines then it may be beneficial for the homeowner to incur some fixed costs in order to refinance at the lower interest rate. However, the potential benefit of refinancing declines as an increasing amount of the balance is paid off and the time remaining on the mortgage declines. The optimal strategy depends upon how much the interest rate declines and how much time is left on the mortgage. Finally, the state-dependent pricing (SDP) literature in macroeconomics employs an \((S,s)\) framework to model the pricing decision of firms. Menu costs (Mankiw, 1985) encourage firms to keep prices fixed unless changing economic conditions warrant a new price. The SDP literature treats this pricing decision as dependent on the state of the macroeconomy and resulting distortions in relative prices (Caplin and Leahy, 1991; Dotsey and King, 2005).

All of the studies mentioned in the previous two paragraphs share a common underlying problem – when should an organization take a costly action that has the potential to increase the stream of future payoffs? The primary difference between our paper and the majority of these studies is the existence of a fixed upcoming decision date. As the scheduled meeting

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2 Emergency meetings are also related to the real options literature. The real options literature examines the decision to undertake an investment project when the return on the project is uncertain and it is costly to reverse the investment (Brennan and Schwartz, 1985; Dixit and Pindyck, 1995). Real options methodology improves the traditional net present value (NPV) rule by explicitly accounting for the value in waiting to invest when returns are uncertain and it is costly to reverse the decision.
approaches, conditions must be increasingly less desirable to prompt the need for an emergency meeting. A key feature of our model is that the value of an optional emergency meeting is reduced if a regularly scheduled meeting is about to occur.

3. Model

Regularly scheduled meetings are set at discrete points in time. An organization may choose to schedule regular meetings each period \( T = 1 \), every other period \( T = 2 \), every third period \( T = 3 \), etc., or schedule no meetings \( T = \infty \). The entire schedule of regular meetings can therefore be represented by the set \{0, T, 2T, 3T, \ldots\} such that there are \( T - 1 \) possible emergency meetings between any two adjacent scheduled meetings. Regular meetings are more efficient than emergency meetings because they allow for the processing of information prior to the meeting and the coordination of individual schedules. Organizations therefore consider regular meetings to be better than emergency meetings. The disadvantage of regular meetings is that they are scheduled well in advance and their timing is inflexible. As such, the costs of the scheduled meeting can be treated as sunk costs. We now present a model that captures the essential features of scheduled and emergency meetings.

Let \( Z_t \) be a vector of state variables which are of interest. If the organization is a firm, then \( Z_t \) might be a vector of variables influencing the demand for their product. For OPEC, \( Z_t \) might include a wide array of variables such as the world demand for oil, global macroeconomic conditions, new discoveries of oil deposits, technological advances in oil extraction, etc. As the elements of \( Z_t \) fluctuate the optimal policy changes. OPEC uses the information in \( Z_t \) to set
production quotas for crude oil. By scheduling a meeting, the organization is able to share information and make changes to policy in response to fluctuations in $Z_t$.

For simplicity, we let $Z_t = (Z_{1,t}, Z_{2,t})'$ be a $2 \times 1$ vector. The two elements of $Z_t$ are based on different types of information. The first element $Z_{1,t}$ includes information which is difficult for the organization to process, while the second element $Z_{2,t}$ is easier to process. For OPEC, $Z_{1,t}$ is based on variables that affect oil markets in complex ways. Some examples are financial crises, speed of market adjustment to a previous quota change, and changes in demand resulting from new environmental regulations. $Z_{2,t}$ might be related to variables that are more transparent such as oil prices, oil inventories, and storage costs. The two components $Z_{1,t}$ and $Z_{2,t}$ are added together to form total distortions. Because they are added together a single policy instrument may be used to make corrections for these distortions.

Assume that $Z_t$ follows a random walk so that

$$Z_t = Z_{t-1} + e_t$$

(1)

where $e_t = (e_{1,t}, e_{2,t})'$ is a $2 \times 1$ vector of mutually independent random elements with zero means and variances $\sigma_1^2$ and $\sigma_2^2$, respectively. Policy can only be changed at meetings. If the meeting was scheduled in advance, the optimal policy is chosen knowing both elements of $Z_t$. If the meeting is an emergency meeting, then $Z_{2,t}$ and the value of $Z_1$ identified at the previous regular meeting are both known.

Equation (1) implies that $Z_{1,t}$ and $Z_{2,t}$ are independent of one another. A set of variables $Z_{1,t}^*$ and $Z_{2,t}^*$ which are correlated can be transformed into uncorrelated components $Z_{1,t}$ and $Z_{2,t}$. Consider a set of complex variables related to $Z_{1,t}^*$ such as financial crises and environmental regulations and more transparent variables related to $Z_{2,t}^*$ such as oil price changes. $Z_{1,t}^*$ and $Z_{2,t}^*$
are likely to be correlated but can be transformed into independent components. The predicted value of $Z_{1,t}^*$ based on $Z_{2,t}^*$ is $E(Z_{1,t}^* | Z_{2,t}^*) = \hat{a} + \hat{b}Z_{2,t}^*$ where $\hat{a}$ and $\hat{b}$ are coefficients. This prediction can be used to form two new uncorrelated variables:

$$Z_{1,t} = Z_{1,t}^* - E(Z_{1,t}^* | Z_{2,t}^*)$$ and
$$Z_{2,t} = Z_{2,t}^* + E(Z_{1,t}^* | Z_{2,t}^*)$$

that satisfy the assumptions of equation (1).

To illustrate $Z_{1,t}$ and $Z_{2,t}$, consider the onset of a financial crisis. This is an event that OPEC has considered in an actual meeting. A financial crisis might influence $Z_{1,t}^*$ and will impact oil markets in a complex way. A more transparent variable is oil price changes which influences $Z_{2,t}^*$. If $Z_{1,t}^*$ is not observable, any change in the quota for OPEC should incorporate both $Z_{2,t}^*$ and $E(Z_{1,t}^* | Z_{2,t}^*)$. At emergency meetings, $Z_{1,t}^*$ is not observable but optimal policy is set based on transparent variables such as changes in oil prices and oil inventories. A regular meeting presents the opportunity to undertake a more detailed analysis of how financial crises interact with oil markets.

The model is set in discrete time; however, it is consistent with a Brownian motion process which is only observed at discrete points in time. Over time both elements of $Z_t$ wander and create a distortion from the last time policy was set. We define $Y_t = (Y_{1,t}, Y_{2,t})'$ as the vector of changes in $Z_t$ since the last time policy was reset. The first element in $Y_t$ is the change in $Z_1$ since the last regular meeting because $Z_1$ is not observed at emergency meetings. The second element of $Y_t$ is the change in $Z_2$ since the last meeting, which could be either a regular or an emergency meeting.

We assume a quadratic loss from suboptimal policy, such as when OPEC sets production quotas. OPEC is an international cartel that acts as a monopolist, responding to changing supply and demand conditions by varying the quantity of oil supplied. Suppose that OPEC faces a
linear demand curve, \( l_t - bP_t \), where the intercept \( l_t = Z_{1,t} + Z_{2,t} \) follows a random walk.

Without discounting, the firm sets quantity \( q_t \) to maximize expected profits between regular meetings:

\[
\sum_{n=0}^{T-1} E_t \pi_{t+n} = \pi_t + E_t \pi_{t+1} + \cdots + E_t \pi_{t+T-1},
\]

(2)

where \( \pi_t = q_t (P_t - c) = q_t \left( \frac{l_t - a_t}{b} - c \right) \). The first-order condition is

\[
\frac{\partial \pi_t}{\partial q_t} = \left( \frac{l_t - a_t}{b} - c \right) - \frac{a_t}{b} = 0
\]

(3)

with optimal quantity

\[
q_t^* = \frac{l_t - bc}{2}.
\]

(4)

Assume the firm last optimized quantity at \( t - s \). If the firm resets \( q_t \) at time \( t \), then profits for period \( t \) are

\[
q_t^* \left( \frac{l_t - q_t^*}{b} - c \right).
\]

If the firm does not reset quantity so quantity remains at \( q_{t-s}^* \), profits for period \( t \) are

\[
q_{t-s}^* \left( \frac{l_t - q_{t-s}^*}{b} - c \right).
\]

The difference is a quadratic loss of \((l_t - l_{t-s})^2/4b\), which is equal to \((Y_t'Y_t)/4b\).

More generally, we assume a loss function given by \( \varphi Y_t'Y_t \) where \( \varphi > 0 \), so that the current-period loss involves both components of \( Y_t \). Emergency meetings can be scheduled at a cost of \( \beta \) at any time based on observing \( Z_{2,t} \). The opportunity cost of participants’ time may be one of the major components of \( \beta \).
Clearly, the current-period loss can be equivalently expressed as \( Y_t' Y_t \) through an appropriate re-scaling of \( e_{1,t} \) and \( e_{2,t} \). Without loss of generality, we therefore set \( \varphi = 1 \). Proportional increases in \( \sigma_1^2 \), \( \sigma_2^2 \) and \( \beta \) increases the costs but have no effect on the optimal thresholds or the decision to hold an emergency meeting. We therefore set \( \sigma_2^2 = 1 \) so that \( \beta \) and \( \sigma_1^2 \) are the free parameters. Alternatively, we can interpret \( \beta \) as the cost of an emergency meeting in \( Y_t' Y_t \) units. We do not allow for any drift in \( Z_t \). In the case of OPEC, there might be a small upward drift for oil demand through population and economic growth, however in six months the drift would be small. In the case of the FOMC, the nominal drift from inflation may be larger but the intermeeting periods are much shorter.\(^3\) If we allowed for a drift in our model, the thresholds would not be symmetric and policymakers would overshoot the values of the policy variables that would be optimal for the current period.

4. Optimal Timing of Emergency Meetings

In this section we examine the properties of the optimal threshold for emergency meetings in the presence of regular meetings.\(^4\) To illustrate the problem, we start by looking at current-period losses. Recall that the period-\( t \) loss function is based on \( Y_{1,t} \) and \( Y_{2,t} \) and is given by the quadratic form \( Y_t' Y_t \). The component \( Y_{2,t} \) is observed every period while \( Y_{1,t} \) is only observed at regular meetings. When deciding whether to hold an emergency meeting, the organization will need to consider the expected value \( E(Y_t' Y_t | Y_{2,t}^2) \). Since \( Y_{1,t} \) and \( Y_{2,t} \) are assumed to be

\(^3\) A related issue is monetary “gradualism”, where there is a short-run drift in the policy variable (Bernanke, 2004).

\(^4\) If the first component of \( Z_t \) is always zero, then there is no need for regular meetings and it is most efficient for organizations to hold emergency meetings only. A separate document (available upon request) considers the case of emergency meetings only and establishes the relationship between the optimal thresholds when \( Z_{1,t} = 0 \) and when \( Z_{1,t} \neq 0 \).
independent, \( E(Y_t'Y_t|Y_{2,t}^2) \) is equal to \( Y_{2,t}^2 + E(Y_{1,t}^2) \). This result decomposes the expected costs into two additively separable parts, the second of which is not influenced by holding an emergency meeting. Similarly, the optimal threshold for an emergency meeting is based solely on \( Y_{2,t}^2 \) and not \( E(Y_{1,t}^2) \).

Consider our previous example of a monopolist choosing an optimal quantity subject to a linear demand curve. In that example, the intercept of the demand curve is given by \( I_t = Z_{1,t} + Z_{2,t} \). If the value of \( Z_{1,t} \) is known, we can apply equation (4) to write the value of the optimal policy instrument as

\[
q_t^* = \frac{Z_{1,t} + Z_{2,t} - bc}{2}.
\]  

By choosing \( q_t^* \) with full knowledge of \( Z_{1,t} \), an organization such as OPEC is resetting \( Y_{1,t} \) and \( Y_{2,t} \) to zero so that the current-period loss function \( Y_t'Y_t \) is equal to zero.

If the organization instead does not know \( Z_{1,t} \), then the best policy is based on the expected value of \( I_t \). The expected value of \( I_t \) is \( E(I_t) = E(Z_{1,t}) + Z_{2,t} \). Since \( Z_{1,t} \) is a random walk, the value of \( E(Z_{1,t}) \) is the value observed at the last regular meeting. If the last regular meeting occurred \( s \) periods ago, the optimal value of the policy instrument is

\[
q_t^*(s) = \frac{Z_{1,t-s} + Z_{2,t} - bc}{2}.
\]  

This optimal value of the policy instrument resets \( Y_{2,t} \) to zero, but \( Y_{1,t} \) cannot be reset to zero because the current value of \( Z_{1,t} \) is unknown and has not been observed since the last regular meeting. This implies that at an emergency meeting the optimal strategy is to base policy on the last known value of \( Z_{1,t} \) and on the recently observed value of \( Z_{2,t} \).
Now consider the current and future costs of not knowing $Z_{1,t}$. These costs are independent of the decision of when to hold an emergency meeting. The expected losses up to the next regular meeting are given by

$$
\sum_{n=t}^{T-1} E(Y_{1,n}^2).
$$

Assume that the last regular meeting occurred $s$ periods ago and $Y_1$ was reset to zero. Since $Y_1$ follows a random walk, the variance of this unobserved component at time $t$ is $s\sigma_1^2$. In period $t + 1$, the variance of this component grows by $\sigma_1^2$ and becomes $(s + 1)\sigma_1^2$. Continuing to period $T - 1$, this sequence of unobserved costs sums to

$$
\sum_{n=t}^{T-1} E(Y_{1,n}^2) = \sum_{n=s}^{T-1-t+s} n \sigma_1^2.
$$

Therefore without regular meetings, the cost of ignoring changes in $Z_1$ increases without bound. This explains why there are both regular and emergency meetings because this uncertainty can only be resolved by holding a scheduled meeting. Therefore, it is critical that there be occasional scheduled meetings since this is the only way to resolve uncertainty regarding $Z_1$. Interestingly, it also explains why the next regular meeting is not canceled after an emergency meeting because this uncertainty cannot be resolved at an emergency meeting. The two organizations we consider, OPEC and FOMC, do not cancel the upcoming regular meeting when they have an emergency meeting.

Next we turn our focus to the dynamic problem of when to hold an emergency meeting.

Toward that end, consider the total expected costs looking forward from period $t$. As we showed above, the costs can be decomposed into the part coming from $Y_{1,t}$ and the part coming from $Y_{2,t}$. Therefore, the total expected costs are:
\[
J_t(Y_{2,t}^2) + \sum_{n=t}^{T-1} E(Y_{1,n}^2),
\]

where the second component is given in equation (7) and independent of the decision of when to hold an emergency meeting. Thus, we now focus exclusively on the first component of expected costs, which is given by

\[
J_t(Y_{2,t}^2) = \min\{Y_{2,t}^2 + E(J_{t+1}(Y_{2,t+1}^2)|Y_{2,t}^2), \beta + E(J_{t+1}(Y_{2,t+1}^2)|Y_{2,t} = 0)\}
\]

for \( t = 1, \ldots, T-1 \) and \( J_T(Y_{2,T}^2) = 0 \). This is a Bellman type equation where we assume an optimal strategy conditional on \( Z_{1,t-s} \) is followed in all future periods up to the next meeting.

\( J_t(Y_{2,t}^2) \) is the current plus expected future costs assuming optimal strategies are used. The value of \( J_t(Y_{2,t}^2) \) is non-negative because \( Y_{2,t}^2 \geq 0 \) and \( \beta > 0 \). If the costs of continuing with the current policy, \( Y_{2,t}^2 + E(J_{t+1}(Y_{2,t+1}^2)|Y_{2,t}^2) \), become too large, it may be optimal to schedule an emergency meeting and pay \( \beta \). There are two advantages to an emergency meeting: 1) the cost in the current period is reduced from \( Y_{2,t}^2 \) to zero, and 2) future periods will begin from \( Y_{2,t}^2 = 0 \) rather than \( Y_{2,t}^2 \) ’s current value. The total expected future benefit of an emergency meeting is \( E(J_{t+1}(Y_{2,t+1}^2)|Y_{2,t}^2) - E(J_{t+1}(Y_{2,t+1}^2)|Y_{2,t} = 0) \), which we denote as \( \Delta_t(Y_{2,t}^2) \). Consequently, the total benefit of an emergency meeting is \( Y_{2,t}^2 + \Delta_t(Y_{2,t}^2) \).

Future values included in \( J_{t+1} \) are often discounted. We simplify the analysis by assuming a zero discount rate. This can be justified by either noting that discounting will have a small effect over short periods of time between scheduled meetings or by assuming that all values of \( Y_{2,t}^2 \) are in present-value terms. Our model relies on removing distortions as the motivation for action rather than on interest rates. This is different from the inventory models such as Miller and Orr (1966) and Huberman (1988) where interest rates play a central role.
The optimal strategy for calling emergency meetings is based on a pair of symmetrical thresholds. Since the magnitude of the threshold for positive $Y_{2,t}$ and negative $Y_{2,t}$ are the same, we express the threshold as a function of $Y_{2,t}^2$. This is justified by the symmetry assumption for the probability density function of the disturbances in equation (1); see the Appendix for more details. Expressing the problem in terms of $Y_{2,t}^2$ is convenient because we do not need to refer to positive and negative values of the threshold. This is different from Huberman (1988) where the threshold is one-sided and different from Miller and Orr (1966) where the thresholds are not symmetrical.

The optimal thresholds for $Y_{2,t}^2$, which we denote as $\theta_t^+$, can be obtained through dynamic programming. Although analytical expressions are not always available, we can obtain insights into the solution via backward induction. Merton (1973) points out that for an American put option the threshold is time varying and there may not be a closed-form solution. Since our problem also involves a time-varying threshold we solve for it numerically. However it is useful to consider dynamic programming to better understand the properties of the solution.

Consider one period prior to the scheduled meeting. The benefit of calling an emergency meeting and resetting is $Y_{2,T-1}^2$, while the cost is $\beta$. There is no future benefit of resetting because there is a scheduled meeting next period, so that $\Delta_{T-1} = 0$. The optimal threshold for $Y_{2,T-1}^2$ is found by equating benefits and costs, which gives the threshold value $\theta_{T-1}^+ = \beta$. Moving back one period, the optimal decision must now consider the possibility that an emergency meeting will be called at $T-1$. If an emergency meeting is called at $T-2$, the total expected cost is

$$A = \beta + (1 - p_{T-1}|Y_{2,T-2}=0)E[y_{2,T-1}^2|Y_{2,T-2}=0 \text{ and } Y_{2,T-1}^2 < \theta_{T-1}^-] + p_{T-1}|Y_{2,T-2}=0] \beta. \quad (9)$$
where \( p_{T-1|Y_{2,T-2}=0} \) is the probability that \( Y_{2,T-1}^2 > \theta_{T-1} \) given that \( Y_{2,T-2} = 0 \). The total expected cost without an emergency meeting is

\[
B = Y_{2,T-2}^2 + (1 - p_{T-1|Y_{2,T-2}})E[Y_{2,T-1}^2 | (Y_{2,T-2}^2 \text{ and } Y_{2,T-1}^2 < \theta_{T-1})] + p_{T-1|Y_{2,T-2}} \beta, \tag{10}
\]

where \( p_{T-1|Y_{2,T-2}} \) is the probability that \( Y_{2,T-1}^2 > \theta_{T-1} \) conditional on the value of \( Y_{2,T-2} \).

Subtracting \( B \) from \( A \) produces the net benefit of calling an emergency meeting at \( T-2 \). The first terms on the right side of (9) and (10) are the immediate costs, while the remaining parts are the expected future costs. Setting \( A = B \) and solving produces the threshold value \( \theta_{T-2}^* \).

Continuing with this procedure and working backwards gives the entire set of threshold values \( \{\theta_1^*, \theta_2^*, \ldots, \theta_{T-1}^*\} \). This set of thresholds characterizes the optimal strategy for calling emergency meetings.\(^5\)

At each point in time, an organization has the option of calling an emergency meeting at cost \( \beta \). The total benefit of an emergency meeting is \( Y_{2,t}^2 + \Delta_t(Y_{2,t}^2) \). The optimal strategy involves a threshold value for \( Y_{2,t}^2, \theta_t^* \), which is defined by the following equation:

\[
\theta_t^* + \Delta_t(\theta_t^*) = \beta. \tag{11}
\]

When \( Y_{2,t}^2 \) is below \( \theta_t^* \), benefits are less than \( \beta \) and it pays to wait – no emergency meeting will be held. When \( Y_{2,t}^2 \) is equal \( \theta_t^* \), the organization is indifferent between holding an emergency meeting.
meeting and proceeding without one. Since the benefit of an emergency meeting is increasing in $Y_{2,t}^2$, if $Y_{2,t}^2$ exceeds $\theta_t^*$, benefits will be greater than $\beta$ and an emergency meeting will be held.

To further understand the thresholds, consider the expected future benefits of an emergency meeting, $\Delta_t(Y_{2,t}^2)$. When there is only one period until the scheduled meeting $\Delta_{T-1} = 0$. When there is more than one period before the scheduled meeting, $\Delta_t$ is greater or equal to zero and (weakly) increasing in $Y_{2,t}^2$ (see Proposition #1 in the Appendix). The function $\Delta_t(Y_{2,t}^2)$ depends on the number of periods remaining until the next meeting, $T - t$. The total benefit of calling an emergency meeting now is $Y_{2,t}^2 + \Delta_t(Y_{2,t}^2)$. Since both of these are increasing functions of $Y_{2,t}^2$, the benefit increases as $Y_{2,t}^2$ increases. If it exceeds $\beta$, then calling an emergency meeting is optimal.

Figure 1 depicts the total benefits, $Y_{2,t}^2 + \Delta_t(Y_{2,t}^2)$, as a function of $Y_{2,t}^2$ given a particular value of the time remaining $T - t$. Note that the first component of total benefits is $Y_{2,t}^2$ and the second component is nonlinear in $Y_{2,t}^2$. If $Y_{2,t} = 0$, the total benefit is zero for all values of $T - t$ so all curves come out of the origin. The horizontal line is the cost of the emergency meeting, $\beta$. When the total benefit curve crosses the $\beta$ line, the organization is indifferent between calling an emergency meeting and not calling a meeting. This is the threshold value $\theta_t^*$, which is defined by equation (11). As the scheduled meeting approaches and $T - t$ declines, the optimal thresholds increase. Figure 1 shows the $Y_{2,t}^2 + \Delta_t(Y_{2,t}^2)$ curves for four different values of $T - t$. The intersections of all the total benefit curves and the $\beta$ line define the entire set of threshold values, $\{\theta_1^*, \theta_2^*, ..., \theta_{T-1}^*\}$.

[Insert Figure 1]

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6 In the Appendix, we prove that the optimal strategy involves a threshold value.
Huberman (1988) also finds upper and lower bounds for the thresholds in his model. The upper and lower bounds for our model, along with the shaded region for the optimal thresholds, are shown in Figure 2 and graphed as a function of $t$. The dashed line shows a stylized set of optimal thresholds. The threshold value starts at $\beta$ and asymptotes to the optimal threshold without regular meetings, $\theta^E$, as $T - t$ grows large.\footnote{A separate document describing the derivation of the emergency-only threshold, $\theta^E$, is available upon request.}

Next, we discuss a procedure to calculate the optimal thresholds. Numerical simulation methods are useful because analytical solutions may not be not feasible. The simulations can also be used to provide confidence intervals for the predicted distribution of emergency meetings.

The optimal thresholds depend upon $\beta$ and the time to the next regular meeting. For a given $\beta$ and time to maturity, we can find the entire set of thresholds using the following methodology. We start with a grid search to calculate the emergency-only optimal threshold, $\theta^E$. The grid range $[0, \beta]$ is divided into 100 evenly spaced nodes. At each potential value for $\theta^E$, we use the normal distribution to simulate a time series of 20,000 periods and calculate the average cost using $\theta^E$ as the threshold. Of the 100 possibilities, the optimal $\theta^E$ is the one that minimizes average costs over the 20,000 periods. The optimal thresholds with scheduled meetings are then calculated. Because $\theta^*_{T-1}$ is known, we work backwards starting at $T - 2$ and bound the value of $\theta^*_{T-2}$ in the region $[\theta^E, \theta^*_{T-1}]$. Since benefits of a meeting are increasing in $Y_{2,t}$, we use a bisection algorithm to find $\theta^*_{T-2}$. The search region is split in half at $(\theta^*_{T-1} + \theta^E)/2$, which becomes the first candidate value for $\theta^*_{T-2}$. We then calculate the average costs over 10,000
replications starting at $Y_{2,T-2}^2 = (\theta_{T-1}^* + \theta^E)/2$ under the two possible strategies: (i) no emergency meeting and accept distortion cost $Y_{2,T-2}^2$ or (ii) call an emergency meeting, pay $\beta$, and reset to $Y_{2,T-2} = 0$. If costs are greater by calling an emergency meeting, the new search region becomes $[(\theta_{T-1}^* + \theta^E)/2, \theta_{T-1}^*]$. If costs are lower by calling an emergency meeting, the new search region becomes $[\theta^E, (\theta_{T-1}^* + \theta^E)/2]$. The procedure is then repeated 20 times using increasingly smaller search regions until we have narrowed-in on the optimal $\theta_{T-2}^*$. The process is then repeated moving backwards until the entire set of thresholds $\{\theta_1^*, \theta_2^*, ..., \theta_{T-1}^*\}$ is found. The number of replications increases at the rate $\sqrt{t}$ as we move backwards in time, reflecting the fact that there are more decisions to make the farther we are from $T$.

5. Oil Prices and OPEC Emergency Meetings

In this section, we investigate whether reactions to changes in the price of crude oil are able to explain the timing of OPEC emergency meetings. There are many potential factors such as the state of the global economy, crises in financial markets, new environmental regulations, discoveries of oil supplies, changes in storage capacity, and political uprisings that may determine whether OPEC decides to call an emergency meeting. A complete understanding of market conditions certainly involves more than just the price of crude oil. For example, markets are often affected when the U.S. Department of Energy makes announcements of inventory levels. Seasonal effects might exist as well. Here we explore the extent to which changes in the price of crude oil reflect these potential factors and are capable of explaining the timing of OPEC emergency meetings.
Crude oil prices are measured by daily spot prices in Cushing, Oklahoma, USA over the sample period June 1986 through December 2010. The approximate six-month interval between OPEC regular meetings is then divided into ten equally spaced periods. Each of these deciles corresponds to approximately 18 days but this varies slightly over the sample period because OPEC regular meetings are not held on the same calendar day each year. The measured crude oil price in each decile is the average daily oil price over the decile deflated by the corresponding monthly U.S. consumer price index. Figure 3 shows a time series plot of real crude oil prices measured at the decile frequency.

[Insert Figure 3]

The model in Section 3 assumes a constant variance $\sigma^2$. However, Figure 3 suggests that the latter part of the sample period may be subject to a higher variance for the innovations in crude oil prices. To test this, we regress squared changes in real crude oil prices $(\Delta p_t)^2$ on the first three lags of the same variable and plot the predicted values in Figure 4. Only predicted values greater than 1.5 are shown to highlight periods of high volatility. The graph shows clear evidence of higher volatility in crude oil prices during the first Gulf War (1990-1991) and after the year 2000. Therefore, we split the sample according to the periods of low and high volatility in oil prices.

[Insert Figure 4]

As noted in Section 3, increasing $\sigma_2$ and $\beta$ by the same proportion increases the thresholds by the same proportional amount and does not change the frequency of emergency meetings.

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8 Spot crude oil prices are available from the U.S. Energy Information Administration: http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm.

Increasing $\sigma_2$ and leaving $\beta$ the same will increase the thresholds less than proportionally but will also increase the frequency of emergency meetings. The effect on the frequency is like leaving $\sigma_2$ the same and reducing $\beta$. Therefore if our sample is comprised of two regions – one with low volatility and another with high volatility – then our model predicts that the high-volatility region will have more frequent meetings than the low-volatility region.

To calculate the predicted number of emergency meetings, we follow the methodology laid out in Section 4 and calculate the thresholds, $\{\theta_1^*, \theta_2^*, ..., \theta_{T-1}^*\}$, across low- and high-volatility periods. We start by calibrating the cost of emergency meetings, $\beta$, to match the frequency of actual OPEC emergency meetings over the sample period. Approximately 43 percent of the intervals between OPEC regular meetings contain an emergency meeting. This calibration process resulted in a cost of emergency meetings equal to $\beta = 20.5$. Given the estimated ratio of high-to-low volatility, $\sigma_{2,H}^2/\sigma_{2,L}^2 = 4.3$, we then normalize the average variance of oil price innovations to equal one across the low- and high-volatility periods. As derived earlier, the value of $\theta_{T-1}^*$ is set equal to $\beta$ in both the low- and high-volatility periods, but the high-volatility thresholds are greater than the low-volatility thresholds in all other deciles. While the thresholds are higher during the high-volatility period, the higher volatility increases the likelihood of exceeding the threshold and results in more predicted emergency meetings during the high-volatility period.

We compare the (squared) accumulated changes in real crude oil prices since the last meeting (the equivalent of $Y_{2t}^2$) to the thresholds. Whenever $Y_{2t}^2$ crosses the threshold for the first time, we predict an emergency meeting. We then see whether we can predict the relative frequency of emergency meetings across the low- and high-volatility periods.
Table 1 summarizes the predicted (emergency) and actual (extraordinary) occurrences of first meetings during the sample period. There are 21 actual OPEC first extraordinary meetings during the entire sample period; 18 occurring in the high-volatility period and 3 occurring during the low-volatility period. Using crude oil prices and our model, we predict 25 first emergency meetings with 17 occurring during the high-volatility period and 8 during the low-volatility period. Although we predict too many emergency meetings during the low-volatility period, our model is successful in matching the fact that relatively more emergency meetings happened during the high-volatility period. This prediction is consistent with our theoretical model in Section 3 that for a constant cost of emergency meetings ($\beta$), an increase in volatility ($\sigma^2$) will lead to higher thresholds and an increase frequency of emergency meetings.

When faced with a period of high volatility, an organization such as OPEC has the choice to call more frequent emergency meetings or increase the number of scheduled meetings. After the increase in oil price volatility after 2000, OPEC chose to increase the number of meetings scheduled in advance.\textsuperscript{10} Although these meetings were labeled extraordinary meetings, the fact that they were scheduled in advance suggests they should be treated more like regular meetings. However, they do not include all the reports that a regular meeting has so they might regarded as another type of meeting which is more flexible than a regular meeting but not as complete. Huberman (1988) has a model where advance planning lowers costs. Applying his model to meetings would suggest increasing the number of meetings when the volatility increases. Our model, on the other hand, assumes that the number of scheduled meetings is fixed and OPEC should instead increase the frequency of emergency meetings in response to an increase in volatility. Despite this difference, the choice to schedule more meetings – regular or emergency – in response to higher volatility is consistent with our general theory. Our results show that if

OPEC had instead used a threshold strategy focusing on crude oil prices, they would have called a similar number of emergency meetings during the high-volatility period.

6. The FOMC and the Distribution of Emergency Meetings

In this section we test whether the simulated distribution of first emergency meetings from our model match those of the FOMC. We start by calibrating our model to the FOMC. The value of $\beta$ determines both the frequency of emergency meetings and the shape of the distribution for first emergency meetings. Although $\beta$ is not directly observable, we observe both the frequency of emergency meetings and the timing of the emergency meetings in the interval between scheduled meetings. We use this fact to calibrate $\beta$ to fit the frequency of emergency meetings. Then as a way of analyzing how well the model works, we compare the timing of the actual emergency meetings with the theoretical distribution of first emergency meeting times from the model.

When the FOMC decides whether or not to call an emergency meeting, they may also consider the signal it sends to the public. The announcement of an emergency meeting might send a signal to some market participants that there is a problem in financial markets and cause a sense of hysteria. In this case, the emergency meeting has an undesirable effect and the costs of the meeting could be thought to be greater than $\beta$. The cost of an emergency meeting might be $\beta + \gamma$, where $\gamma > 0$. Alternatively, the announcement might have a calming effect when investors realize that the central bank is concerned about the problem and taking action. This would be an added benefit of the meeting. In this case, the cost of an emergency meeting might
be $\beta - \gamma$. While the signaling effect is different than $\beta$, a simple adjustment for signaling would consider an additive increase or decrease in the costs of an emergency meeting.

A more complex possibility is that as a crisis builds, such as the risk of a sovereign default in foreign country, the concern by the public grows. The losses associated with this concern might grow in a quadratic function and may fluctuate randomly. An emergency meeting would reassure the public and reduce the hysteria. This can be thought of as another component of $Y_{Z,t}^2$. Losses build in a random fashion and a meeting reassures the public and reduces both components of $Y_{Z,t}^2$ to zero. First, it shows the public that the Fed is taking action, reducing one component to zero. Second, it changes $Z_{Z,t}$ to the new optimal value reducing the other component of $Y_{Z,t}^2$ to zero. The reassurance does not necessarily mean that the default will be avoided, but rather that the appropriate actions have been taken to minimize the impact on the domestic country.

Neither of these two possible ways to incorporate signaling changes the structure of our model. In the first possibility, signaling leads to a different cost of an emergency meeting, $\beta + \gamma$ if an emergency meeting sends a negative signal to the public or $\beta - \gamma$ if an emergency meeting sends a positive, calming signal to the public. In the second possibility, the impending crisis causes a growing concern by the public which leads to a different value of $Y_{Z,t}^2$ and a change in its underlying volatility, $\sigma_Z^2$. Assuming the Federal Reserve takes into account the impacts of signaling when choosing to call an emergency meeting, then the calibration of the model and calculation of the thresholds can be done in the same manner with or without signaling.

To calibrate $\beta$, we seek a value such that the fraction of intervals between regular meetings with an emergency meeting matches the FOMC data. FOMC data covers 271 intervals between
regular meetings with 82 of the intervals containing at least one emergency meeting. We start by choosing a candidate value of $\beta$ and use the procedure described in the preceding paragraph to find the corresponding set of thresholds: $\{\theta_1^*, \theta_2^*, \ldots, \theta_{T-1}^*\}$. For each of the 271 intervals, we then simulate the random fluctuations in $Y_{2,t}$ over the ten periods between regular meetings. If $Y_{2,t}^2$ crosses a threshold, then we record which of the ten deciles would contain the emergency meeting. This produces a distribution of first emergency meetings across 271 intervals, with each interval containing ten sub periods. We then repeat this historical simulation 1000 times. We average the number of intervals with an emergency meeting and compare to 82, the number of FOMC emergency meetings over the sample period. If the average result of the 1000 trials is above 82, we choose a higher $\beta$ which will lead to fewer emergency meetings. If the average result is below 82, we choose a lower value of $\beta$. When the new $\beta$ is selected, we recalculate the thresholds and try another 1000 simulations of the 271 period histories. When $\beta = 42.5$, we found approximately 82 meetings so this becomes our calibrated value for the FOMC.

Now consider the distribution of emergency meetings for FOMC. We hypothesize that few meetings will be called in the days after a regular scheduled meeting because it takes time for economic distortions to build up. Similarly, few meetings should be called in the days before the next regularly scheduled meeting because the organization can simply wait a short time until the scheduled meeting to resolve the distortion. This reasoning suggests some sort of hump-shaped distribution for the timing of emergency meetings.11

Figure 5 shows the distribution of first emergency meetings for the FOMC. Only first emergency meetings are shown so the time interval between the last meeting and the next

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11 The hump-shaped distribution depends on the cost of emergency meetings not being too low. For example, if the cost of emergency meetings were near zero, the organization may choose to hold a meeting almost every period.
scheduled meeting are of similar length across the sample period.\textsuperscript{12} Although the sample sizes are relatively small, the empirical distribution clearly shows that most emergency meetings were called in the center portion of the interval, not right after or right before schedule meetings.\textsuperscript{13}

[Insert Figure 5]

To more carefully test whether the FOMC distribution of first emergency meetings match those predicted from our model, we superimpose in Figure 5 the median (dashed lines) and 95\% confidence intervals (solid lines) from 1000 replications. The actual distribution of first emergency meetings falls between the confidence intervals for all periods except for the first and last. There were four emergency meetings in the period (each period represents 5 days) after a regular meeting and two emergency meetings in the period before a scheduled meeting. The model predicts there should be no more than one emergency meeting in the period immediately after or before a scheduled meeting. Therefore, the predicted timing of emergency meetings is not perfectly consistent with the experience of the FOMC. However, since 1978 there have been several changes in the way monetary policy is conducted. For example, there was a period in the late 1970s and early 1980s where non-borrowed reserves were targeted. These regime changes in monetary policy may partially explain the lesser fit for the FOMC. However, we note that the number of regular FOMC meetings has remained constant and that the distribution for times of

\begin{footnotesize}
\begin{itemize}
  \item Our focus on first emergency meetings also follows Huberman (1988), who states that “the distribution of [first meetings] \ldots is a good approximation to the distribution of emergency adoptions [meetings] in \((0, T)\)”.
  \item OPEC’s distribution of first emergency (extraordinary) meetings also appears to be hump shaped. However, once you exclude the pre-scheduled extraordinary meetings during the high-volatility period after 2000, the sample includes only 26 first emergency meetings. We feel this sample is too small to draw any definitive conclusions about the shape of the distribution. Results are available upon request.
\end{itemize}
\end{footnotesize}
first emergency meetings has been fairly robust. This evidence supports the idea that the FOMC uses a time-varying threshold strategy to determine the timing of emergency meetings.\(^{14}\)

In our model, fluctuations accumulate until there is either a scheduled meeting or an emergency meeting. An alternative model would be that crises arise according to a Poisson arrival process and a crisis requires a meeting. If this is the case, then the distribution of first meeting times would be an exponential distribution. To apply this to our ten intervals we note that the probability of zero events occurring in a time interval is \(e^{-\lambda t}\), where \(t\) is the length of the interval and the probability of one or more events occurring is \(1 - e^{-\lambda t}\). We then calibrate \(\lambda\) based on the number of intervals where there were no emergency meetings. For the FOMC, 189 of the 271 intervals did not contain an emergency meeting so that \(e^{-\lambda t} = \frac{189}{271}\). Setting \(t = 1\) for the entire period between regular meetings and solving gives \(\lambda = 0.3604\).\(^{15}\)

To analyze the distribution of first arrival times we start with the probability of no meetings during the first decile between regular meetings. The probability of no meetings during the first decile is \(e^{-\lambda(0.1)}\) and the probability of one or more meetings occurring in this decile is \(1 - e^{-\lambda(0.1)}\). Thus the probability of a first meeting occurring in the first decile is \(1 - e^{-\lambda(0.1)}\). In order for a first meeting to occur in any other decile it is necessary that no meetings occur in earlier deciles in the interval and at least one meeting occurs in the given decile. For decile \(i\) the probability of no meetings in earlier intervals is \(e^{-(i-1)\lambda(0.1)}\) and the probability of at least one meeting in decile \(i\) is the same as other deciles: \(1 - e^{-\lambda(0.1)}\). The probability of a first meeting occurring in decile \(i\) is then given as

\(^{14}\) In the Appendix, we investigate the statistical power of the distributional test by selecting a range of values for \(\beta\).

\(^{15}\) We have focused exclusively on first meetings. An alternative method is to use all emergency meetings in the interval to calibrate \(\lambda\). For the FOMC, this produces an almost identical value for \(\lambda\).
\[ \text{Prob(a first meeting in decile } i) = e^{-(i-1)\lambda(0.1)}(1 - e^{-\lambda(0.1)}). \]  

(12)

These probabilities decline geometrically and sum to considerably less than one because the interval between regular meetings may not contain an emergency meeting.

The data do not show the declining exponential pattern predicted by the Poisson arrival process. Instead, they show a hump-shaped distribution consistent with our model. We can formally test the statistical significance of the Poisson arrival process. The number of times a first meeting occurs in a given decile follows a binomial distribution. The probability of a first meeting in decile \( i \) is given by equation (12) and the number of trials is one less than the number of scheduled meetings. Since the probability of a first meeting occurring in a given decile is different across deciles, the binomial distribution is not uniform across deciles. In Table 2, the number of first meetings in each decile is given as \( x \). Then using the appropriate binomial distribution for that decile, we calculate \( \text{Prob}(X \leq x) \) and \( \text{Prob}(X \geq x) \). Since the distribution is discrete, the sum of these probabilities is one plus the \( \text{Prob}(X = x) \). We use one-tailed tests since our model predicts low values of \( x \) in the first (and last) deciles and high values of \( x \) in the middle deciles.

[Insert Table 2]

Table 2 shows that we reject the Poisson arrival process for emergency meetings in favor of our model of accumulated fluctuations and a threshold strategy. The first, second, fourth, sixth and tenth deciles are all inconsistent with the number of first emergency meetings predicted by the Poisson arrival process. We reject the null hypothesis for these deciles at the 5% significance level. We also reject the same null hypothesis at the 10% significance level for the seventh decile.
7. Conclusions

We construct a simple theoretical model of meetings that involves the random arrival of two types of changes. The first type of change to the economy is opaque and requires significant deliberation and analysis before setting policy, while the second type of change is readily observable and easier to interpret. The two types of changes imply the need for both scheduled and emergency meetings. Meetings scheduled in advance allow organizations to assess the more complicated changes through careful analysis and deliberation before reaching a consensus about the direction of policy. The need to occasionally assess more complicated changes also explains why regular meetings are not canceled after an emergency meeting. Emergency meetings are more flexible and are called when the more transparent type of changes occurs before the next scheduled meeting.

The main focus of the paper is the timing of emergency meetings based on real options. The decision to have an emergency meeting depends upon how much change there has been since the last meeting and the time to the next regular meeting. An emergency meeting allows the institution to make corrections to policy that are beneficial when circumstances have appreciably changed. Without the emergency meeting, it is necessary to wait until the next regular meeting. Consequently, the value of an emergency meeting in part depends upon the time to the next regular meeting. The longer the time until the next meeting the more important it is to hold an emergency meeting to correct the current policy. Our model combines these two effects and the emergency meetings become a real option where the exercise strategy and its associated value
depend upon the time until the next regular meeting. We then solve for the optimal thresholds that define the exercise strategy and simulate the predicted pattern of emergency meetings.

We apply the theory to OPEC and the FOMC, two organizations with complex decisions. The decision process of OPEC depends upon factors that influence the market for crude oil. Using the price of crude oil, we confirm a prediction from our model that the frequency of meetings will increase in response to higher volatility in oil markets. The decision process for the FOMC is likely to include numerous variables that impact the U.S. economy, including many that may be difficult to quantify. However, we are able to observe exactly when emergency meetings occur. We match this observed pattern of emergency meetings for the FOMC with those predicted from our model of accumulated fluctuations and those from a Poisson arrival process. The Poisson arrival process could be thought to represent a model of sudden and unanticipated crises. The data clearly reject the crises model in favor of a humped-shaped distribution of emergency meetings. In sum, we interpret this as evidence that OPEC’s and the FOMC’s decisions of when to call emergency meetings can be characterized as a real options problem that depends on the cumulative distortion since the last policy decision and the time to the next regular meeting.
References


Table 1. Actual and Predicted Frequency of OPEC First Emergency Meetings

<table>
<thead>
<tr>
<th>First Emergency Meetings</th>
<th>Sample Period</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-Volatility</td>
<td>High-Volatility</td>
<td>Overall</td>
<td></td>
</tr>
<tr>
<td>Actual</td>
<td>3</td>
<td>18</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>Predicted</td>
<td>8</td>
<td>17</td>
<td></td>
<td>25</td>
</tr>
</tbody>
</table>

**Notes.** The sample period covers June 1986 through December 2010 and contains a total of 101 intervals that are candidates for an emergency meeting. The high-volatility period covers the Gulf War (1990-1991) and after the year 2000. The remaining years are considered low-volatility periods.
Table 2. Testing the Poisson Arrival Process for FOMC Emergency Meetings

<table>
<thead>
<tr>
<th>Decile</th>
<th>No. of Meetings (x)</th>
<th>Prob((X \leq x))</th>
<th>Prob((X \geq x))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>0.0356**</td>
<td>0.9872</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.0046***</td>
<td>0.9991</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>0.8135</td>
<td>0.2830</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>0.9935</td>
<td>0.0139**</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>0.6796</td>
<td>0.4505</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>0.9841</td>
<td>0.0323**</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>0.9510</td>
<td>0.0902*</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>0.3817</td>
<td>0.7572</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>0.4195</td>
<td>0.7264</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>0.0296**</td>
<td>0.9928</td>
</tr>
</tbody>
</table>

Notes. The number of first meetings in each decile is given as \(x\). Each decile measures one-tenth of the total interval between regular meetings. We use one-tailed test for testing the null hypothesis of a Poisson arrival process versus the model of accumulated distortions. Since the distribution is discrete, the sum of the probabilities in the third and fourth columns is one plus the \(Prob(X = x)\). The accumulated distortion model in the paper predicts low values of \(x\) in the first (and last) deciles and high values of \(x\) in the middle deciles. The columns for \(Prob(X \leq x)\) and \(Prob(X \geq x)\) sum to more than one because both columns share the \(Prob(X = x)\). We reject the null hypothesis of a Poisson arrival process for the first, second, fourth, sixth, seventh and tenth deciles. *, **, and *** refer to significance at the 10, 5 and 1 percent levels, respectively.
Figure 1. Total Benefit and Cost Curves for Emergency Meetings

Notes. The figure is only an illustration and not based on a numerical exercise. For the purpose of presentation, the curves are drawn as a continuous function of time. The solid horizontal line is the cost of an emergency meeting, $\beta$. The dashed lines are the total benefit ($Y^2_2 + \Delta$) of an emergency meeting and decrease as the next scheduled meeting approaches.
Figure 2. Optimal Thresholds

Notes. The figure is only an illustration and not based on a numerical exercise. For the purpose of presentation, the thresholds are drawn as a continuous function of time. Period $T - 1$ is the last period to make a decision of whether or not to call an emergency meeting.
Figure 3. Real Crude Oil Prices

Notes. Crude oil prices are measured by daily spot prices in Cushing, Oklahoma, USA over the sample period June 1986 through December 2010. The approximate six-month interval between OPEC regular meetings is then divided into ten equally spaced periods. Each of these deciles corresponds to approximately 18 days but this varies slightly over the sample period because OPEC regular meetings are not held on the same calendar day each year. The measured crude oil price in each decile is the average daily oil price over the decile deflated by the corresponding monthly U.S. consumer price index with a base period of 1982-1984.
Figure 4. Predicted Volatility of Real Crude Oil Prices

Notes. The volatility of crude oil prices is given by the predicted squared changes in crude oil prices from the estimated model: 

$$(\Delta p)^2_t = 0.937 + 0.157(\Delta p)^2_{t-1} + 0.151(\Delta p)^2_{t-2} + 0.180(\Delta p)^2_{t-3} + e_t,$$

where $t$ indexes deciles between each regular meeting. Only predicted values greater than 1.5 are shown to highlight the periods of high volatility.
Figure 5. Distribution of FOMC Emergency Meetings and 95% Simulated Confidence Bands

Notes. The histogram is the frequency distribution of first emergency meetings for the FOMC over the sample period 1978-2010. There were 82 first emergency meetings during this sample period. The solid lines represent 95% confidence bands for first emergency meetings from 1000 simulations with $\beta = 42.5$. The value for $\beta$ is selected to match the fraction of intervals between the FOMC regular meetings with a first emergency meeting ($82/271 = 30.26\%$). To be comparable to the FOMC, each simulation contains 271 intervals with $T - 1 = 10$. The dashed line is the median for first simulated emergency meetings.
Appendix

A1. Technical Details of the Threshold Strategy

We start by considering two assumptions regarding the stochastic process $e_{2,t}$.

**Assumption #1.** The probability density function for $e_{2,t}$ is symmetric.

**Assumption #2.** For any values $|Y_{2,t-1}^*| > |Y_{2,t-1}^{**}|$, assume the probability density function for $e_{2,t}$ is such that the distribution of $(Y_{2,t-1}^* + e_{2,t})^2$ first-order stochastic dominates the distribution of $(Y_{2,t-1}^{**} + e_{2,t})^2$.

Assumption #1 allows us to cast our analysis in terms of the squared value of $Y_{2,t}$.

Assumption #2 states that first-order stochastic dominance applies to $Y_{2,t}^2$. An example of a distribution with this feature is the normal distribution. Consider a normal random variable $\mu + e_t$ with mean $\mu$ and unit variance. The square of $\mu + e_t$ has a non-central chi-square cumulative distribution function:

$$F(x; \mu) = e^{-0.5\mu^2} \sum_{l=0}^{\infty} \frac{(0.5\mu^2)^l}{l!} \chi^2_{1+2l}(x),$$  \hspace{1cm} (A1)

where $\chi^2_\kappa$ is the central chi-square cumulative distribution function with $\kappa$ degrees of freedom and $x \geq 0$ support. The function $F(x; \mu)$ is a decreasing function of $\mu$ (Johnson and Kotz, 1970, p.135), implying that if we have two random variables, $x_1 = (\mu_1 + e_t)^2$ and $x_2 = (\mu_2 + e_t)^2$, where $\mu_1 > \mu_2$, then the $\Pr(x_1 \leq x) < \Pr(x_2 \leq x)$ for all $x$. This is first-order
stochastic dominance and it will be useful for establishing properties of our thresholds and cost functions.

Consider the binomial distribution. Assumption #2 does not hold for the binomial distribution because of its discrete nature. For example, if \( \mu_1 = 1 \) and \( \mu_2 = 0 \), then the probability that \( x_2 = 0 \) is zero while the probability that \( x_1 = 0 \) is positive. The probability of zero is higher for \( x_1 \) than for \( x_2 \). Therefore, first-order stochastic dominance does not apply and Assumption #2 is not satisfied.

We now introduce two propositions and a lemma regarding the benefits of an emergency meeting:

**Proposition #1.** \( \Delta_t(Y_{2,t}^2) \) and \( J_t(Y_{2,t}^2) \) are weakly increasing in \( Y_{2,t}^2 \). \( \Delta_t(Y_{2,t}^2) \) is non-negative for all \( Y_{2,t} \).

**Lemma #1.** \( J_t(\phi^2) > J_{t+1}(\phi^2) \) for all \( \phi \) and \( t = 1, ..., T - 2 \).

**Proposition #2.** If Assumptions #1 and #2 hold, then the optimal strategy is to schedule an emergency meeting when the value of \( Y_{2,t}^2 \) exceeds threshold \( \theta_{t}^* \). The threshold value one period before the scheduled meeting is \( \beta \). The threshold value in all other periods is less than \( \beta \).

Proofs of Proposition #1 and Lemma #1 are provided below. Proposition #1 implies that the expected benefits of an emergency meeting are lower when \( Y_{2,t}^2 \) is lower; organizations prefer to start from a point of less distortion. Lemma #1 shows that expected total costs are decreasing as we approach the scheduled meeting. Proposition #1 is used below as we develop optimal
strategies for the decision to hold an emergency meeting. Proposition #2 summarizes some of the properties of the optimal threshold strategy.

Proof of Proposition #1. We start by showing that $J_t(Y_{2,t}^2)$ is an increasing function. The proof is by backward induction. For the base step we know that $J_{T-1}(Y_{2,t}^2) = \min\{Y_{2,t}^2, \beta\}$, which is a weakly increasing function of $Y_{2,t}^2$. For the inductive step we start by assuming $J_{t+1}(Y_{2,t+1}^2)$ is weakly increasing in $Y_{2,t+1}^2$ and show that $J_t(Y_{2,t}^2)$ is weakly increasing in $Y_{2,t}^2$. If $E(J_{t+1}(Y_{2,t+1}^2)|Y_{2,t}^2)$ is weakly increasing in $Y_{2,t}^2$, then it follows from equation (11) that $J_t(Y_{2,t}^2)$ is weakly increasing in $Y_{2,t}^2$.

The expected value can be written as

$$\int_{-\infty}^{\infty} J_{t+1} \left( (Y_{2,t} + e_{2,t+1})^2 \right) f(e_{2,t+1}) de_{2,t+1},$$

where $f(e_{2,t+1})$ is the probability density function for $e_{2,t+1}$. Given Assumption #2 is satisfied, we know that the distribution of $(Y_{2,t}^* + e_{2,t+1})^2$ first-order stochastic dominates the distribution of $(Y_{2,t}^{**} + e_{2,t+1})^2$, where $|Y_{2,t}^*| > |Y_{2,t}^{**}|$. Also $J_{t+1} \left( (Y_{2,t} + e_{2,t+1})^2 \right)$ is weakly increasing in $(Y_{2,t} + e_{2,t+1})^2$ therefore if $|Y_{2,t}^*| > |Y_{2,t}^{**}|$, then

$$\int_{-\infty}^{\infty} J_{t+1} \left( (Y_{2,t} + e_{2,t+1})^2 \right) f(e_{2,t+1}) de_{2,t+1} \geq \int_{-\infty}^{\infty} J_{t+1} \left( (Y_{2,t}^{**} + e_{2,t+1})^2 \right) f(e_{2,t+1}) de_{2,t+1}. \quad (A2)$$

This shows that $E(J_{t+1}(Y_{2,t+1}^2)|Y_{2,t}^2)$ is weakly increasing in $Y_{2,t}^2$. It then follows that $J_t(Y_{2,t}^2)$ is weakly increasing in $Y_{2,t}^2$. 

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Next, note that $\Delta_t(Y_{2,t}^2) = E(J_{t+1}(Y_{2,t+1}^2|Y_{2,t}^2) - E(J_{t+1}(Y_{2,t+1}^2|Y_{2,t}^2 = 0)$. We have shown that $J_{t+1}(Y_{2,t+1}^2)$ is an increasing function. Using Assumption #2 and $|Y_{2,t}^*| > |Y_{2,t}^*|$, we find that (A2) holds and $E(J_{t+1}(Y_{2,t+1}^2|Y_{2,t}^2)$ is an increasing function in $Y_{2,t}^2$. Therefore, $\Delta_t(Y_{2,t}^2)$ is increasing in $Y_{2,t}^2$.

Finally, since $\Delta_t(0) = 0$ and $\Delta_t(Y_{2,t}^2)$ is increasing in $Y_{2,t}^2$, it must be non-negative for all $Y_{2,t}$. ■

Proof of Lemma #1. To show this we use mathematical induction. The base step involves the two periods prior to the regular meeting, $t = T − 1$ and $t = T − 2$. We know $J_{T−1}(\phi^2) = \min\{\phi^2, \beta\}$ and $J_{T−2}(\phi^2) = \min\{\phi^2 + \Delta_{T−2}(\phi^2), \beta\} + EJ_{T−1}(e_{2,T−1}^2)$. Since $\Delta_t(\cdot)$ and $J_t(\cdot)$ are positive for all $t$, we know that $J_{T−2}(\phi^2) > J_{T−1}(\phi^2)$, which establishes the base step for mathematical induction.

The inductive step then shows that if $J_{t+1}(\phi^2) > J_{t+2}(\phi^2)$, then $J_t(\phi^2) > J_{t+1}(\phi^2)$ for all $t = 1, ..., T − 3$. Start by using equation (11) to write

$$J_t(\phi^2) = \min\{\phi^2 + E (J_{t+1}(( \phi + e_{2,t+1})^2)), \beta + E (J_{t+1}(e_{2,t+1}^2))\} \quad (A3)$$

$$J_{t+1}(\phi^2) = \min\{\phi^2 + E (J_{t+2}(( \phi + e_{2,t+2})^2)), \beta + E (J_{t+2}(e_{2,t+2}^2))\}. \quad (A4)$$

Comparing (A4) to (A3) and given that $J_{t+1}(\phi^2) > J_{t+2}(\phi^2)$ for any $\phi$, it follows that $J_t(\phi^2) > J_{t+1}(\phi^2)$. This completes the mathematical induction. ■
A2. Assessing the Statistical Power of the Distributional Test for First Emergency Meetings

In this section, we investigate the statistical power of the test for the hump-shaped distribution of first emergency meetings. In the main text, the cost of an emergency meeting, $\beta$, is calibrated by choosing the value that matches the observed frequency of first FOMC emergency meetings across the sample period 1978-2010. Of the 271 possible intervals for emergency meetings, 82 of the intervals have a first emergency meeting. The observed frequency of 30.3% is then matched in the simulations by selecting the cost of emergency meetings to be $\beta = 42.5$.

In Figure A1, we show the 95% confidence intervals and median frequency of first emergency meetings across a range of different values for $\beta$. For low costs of emergency meetings, most first emergency meetings occur in the early deciles and the overall frequency of emergency meetings is too high. For high costs of emergency meetings, the distribution is still hump-shaped but there are too few meetings. The value of $\beta = 42.5$ is the best estimate in terms of matching the observed frequency of first emergency meetings and maximizing the number of deciles inside the 95% confidence intervals.
Figure A1. FOMC and Simulated 1st Emergency Meeting Distributions

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<table>
<thead>
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<tbody>
<tr>
<td><strong>β = 5</strong></td>
<td><strong>β = 10</strong></td>
<td><strong>β = 25</strong></td>
</tr>
<tr>
<td>Average Frequency: 86.6%</td>
<td>Average Frequency: 70.7%</td>
<td>Average Frequency: 46.1%</td>
</tr>
<tr>
<td>Number of Deciles inside C.I.: 4</td>
<td>Number of Deciles inside C.I.: 5</td>
<td>Number of Deciles inside C.I.: 4</td>
</tr>
<tr>
<td><strong>β = 40</strong></td>
<td><strong>β = 42.5</strong></td>
<td><strong>β = 50</strong></td>
</tr>
<tr>
<td>Average Frequency: 32.2%</td>
<td>Average Frequency: 30.3%</td>
<td>Average Frequency: 26.0%</td>
</tr>
<tr>
<td>Number of Deciles inside C.I.: 7</td>
<td>Number of Deciles inside C.I.: 8</td>
<td>Number of Deciles inside C.I.: 7</td>
</tr>
<tr>
<td><strong>β = 60</strong></td>
<td><strong>β = 100</strong></td>
<td></td>
</tr>
<tr>
<td>Average Frequency: 20.7%</td>
<td>Average Frequency: 9.7%</td>
<td></td>
</tr>
<tr>
<td>Number of Deciles inside C.I.: 5</td>
<td>Number of Deciles inside C.I.: 1</td>
<td></td>
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</table>

**Notes.** The histogram in each panel is the FOMC frequency of first emergency meetings across all possible intervals during the 1978-2010 sample period. The solid lines represent 95% confidence intervals (C.I.s) for first emergency meetings from 1000 simulations for various values of $\beta$. The dashed line is the median for first simulated emergency meetings. When $\beta = 42.5$, the simulated fraction of intervals with a first emergency meeting matches the actual frequency of FOMC first emergency meetings (i.e., 82/271 = 30.3%). To be comparable to the FOMC sample period, each simulation contains 271 intervals with $T - 1 = 10$. 

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