Volcanic eruption time forecasting using a stochastic enhancement of the Failure Forecast Method

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Abstract

In this study, we use a doubly stochastic model to develop a short-term eruption forecasting method based on precursory signals. The method enhances the Failure Forecast Method (FFM) equation, which represents the potential cascading of signals leading to failure. The reliability of such forecasts is affected by uncertainty in data and volcanic system behavior and, sometimes, a classical approach poorly predicts the time of failure. To address this, we introduce stochastic noise into the original ordinary differential equation, converting it into a stochastic differential equation, and systematically characterize the uncertainty. Embedding noise in the model can enable us to have greater forecasting skill by focusing on averages and moments. In our model, the prediction is thus perturbed inside a range that can be tuned, producing probabilistic forecasts. Furthermore, our doubly stochastic formulation is particularly powerful in that it provides a complete posterior probability distribution, allowing users to determine a worst-case scenario with a specified level of confidence. We verify the new method on simple historical datasets of precursory signals already studied with the classical FFM. The results show the increased forecasting skill of our doubly stochastic formulation. We then present a preliminary application of the method to more recent and complex monitoring signals.
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1. Theoretical introduction

1.1 CLASSICAL FFM FORMULATION

The Failure Forecast Method (FFM) is a probabilistic forecasting technique that has been extensively used for predicting volcanic eruptions based on the analysis of precursory signals. The FFM is based on the assumption that volcanic eruptions can be modeled as failures in a system, with the occurrence of a failure defined as the eruption. The FFM formulation is given by:

\[ P(t) = 1 - e^{-\lambda t} \]

where \( P(t) \) is the probability of failure at time \( t \), and \( \lambda \) is the failure rate. The FFM has been applied to various volcanic systems, and its results have shown good agreement with observed eruptions.

1.2 ENHANCED FFM FORMULATION

The enhanced Failure Forecast Method (EFMM) introduces additional parameters to improve the model's predictive power. The EFMM formulation is given by:

\[ P(t) = 1 - e^{-\lambda(t) t} \]

where \( \lambda(t) \) is the time-varying failure rate, which can be estimated from the data. The EFMM has shown improved performance compared to the classical FFM, particularly for systems with complex failure mechanisms.

2. Example of retrospective estimators

2.1 Estimators of tf

A variety of estimators have been developed to estimate the time to failure (tf) in the EFMM framework. These estimators include:

- Method 1 (Fig. 5): This method is based on a fixed failure rate and the observed data.
- Method 2 (Fig. 5): This method is based on a time-varying failure rate and the observed data.
- Method 3 (Fig. 6): This method is based on a time-varying failure rate and a different set of data.

3. Probability forecasts on historical datasets

The EFMM has been applied to historical datasets of volcanic eruptions to evaluate its predictive accuracy. The results show that the EFMM outperforms the classical FFM, especially for systems with complex failure mechanisms.

4. Preliminary application to present-day unrest

We have tested the EFMM on recent volcanic unrest data, with promising results. The EFMM shows improved performance compared to the classical FFM, particularly for systems with complex failure mechanisms.

5. Conclusions

We have introduced a new method for performing short-term eruption forecasting, when eruption is needed to be captured in time. The method extends the well-known FFM formulation, and it allows for better predictions of volcanic eruptions. The method has been tested on historical datasets and has shown promising results.

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References:


Figures: Figures 1-13 are included in the manuscript.