Improving Earthquake Forecasts During Swarms

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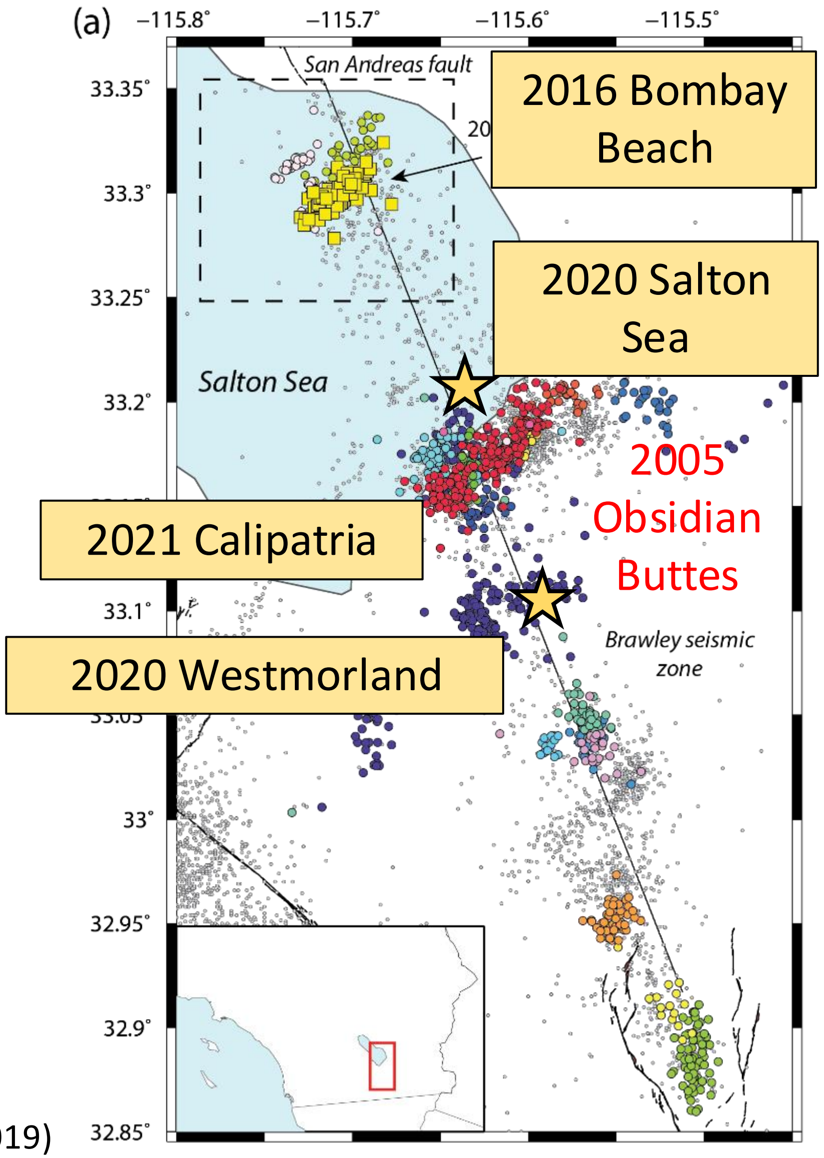
With thanks to: Andrew Michael, Nicholas van der Elst, Morgan Page, Sara McBride, Max Schneider

California Earthquake Prediction Evaluation Council Meeting

16 July 2026

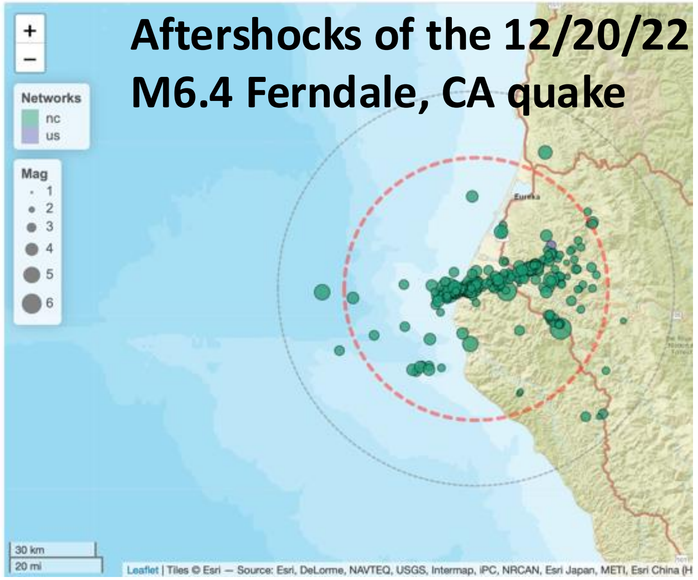
Outline

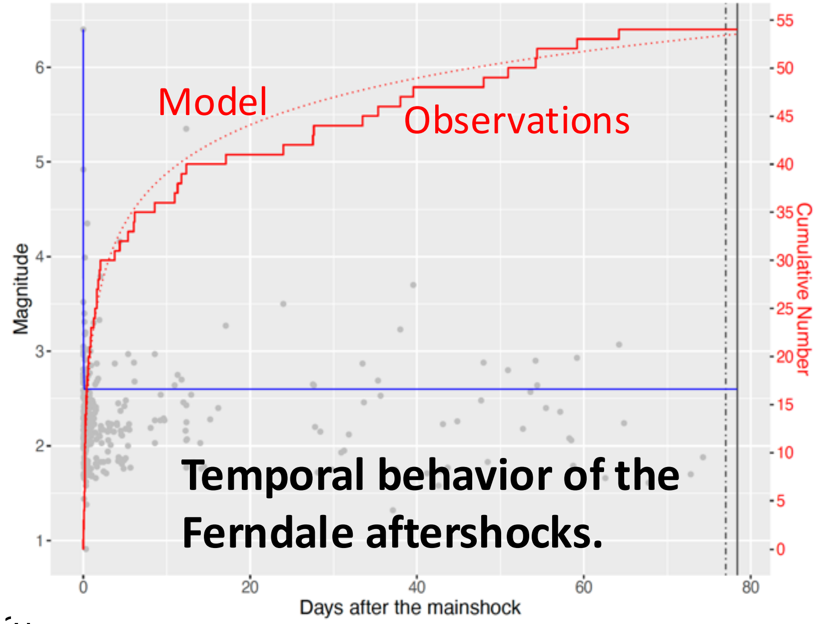
- Introduction
  - USGS Operational Aftershock Forecasting
  - (Tectonic) Swarm forecasting
- Current building blocks for swarm forecasting
  - The ETAS model
  - Actuarial swarm duration model (now implemented in USGS swarm forecasts)
- Ongoing work
  - Modeling time-varying background rates within swarms
  - Ensemble forecasts
  - Improved methods of defining and identifying swarms
- Summary



Llenos & van der Elst (BSSA, 2019)

USGS Operational Aftershock Forecasting



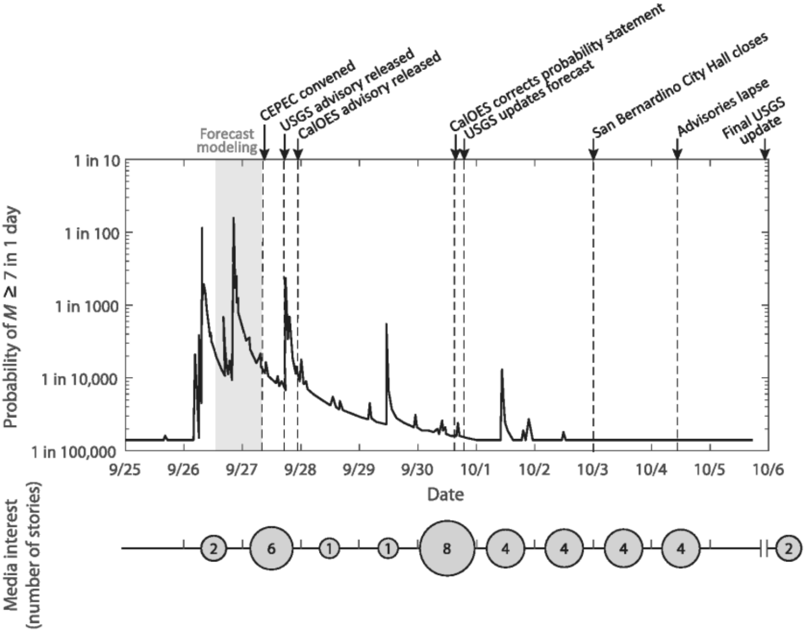


https://earthquake.usgs.gov/data/oaf (July 2023)

- USGS Operational Aftershock Forecasts (OAFs) are made automatically after M4+ events in the U.S. and its territories.
- Empirical models are used to forecast likely numbers and probabilities of M3+ through M7+ aftershocks for the next day, week, month, and year.
  - Reasenberg & Jones (1989, 1994) for automatic domestic forecasts
  - Epidemic-Type Aftershock Sequence (ETAS) model (Ogata, 1988) for international forecasts

Some recent USGS swarm forecasts

The USGS releases earthquake advisories and aftershock forecasts during some swarms, particularly in the Salton Trough in southern California.



McBride et al. (SRL, 2020)

2016 Bombay Beach

U.S. Geological Survey (USGS)
September 27, 2016 ·

Earthquake Swarm Activity Near Bombay Beach

An earthquake swarm near Bombay Beach, California, started on 2016 Sept. 26 at 4:03 am (PDT) in the Brawley Seismic Zone, which lies near the southern terminus of the San Andreas Fault.

The swarm includes 142 events so far (as of 26 Sep 2016, 11:31PM PDT) in the magnitude range M1.4 to M4.3. Relocations of these events show that they are occurring in the depth range 4 to 9 km.

The earthquakes are occurring near a set of north-northeast trending cross-faults in the Salton Sea. The cross-faults are part of a fault network that connect the southernmost end of the San Andreas fault with the Imperial fault. Some of the cross-faults are oriented such that they add stress to the San Andreas fault and the San Jacinto fault system when they rupture in small earthquakes like those in the ongoing swarm.

Earthquake Swarms & Probabilities

Swarm-like activity in this region has occurred in the past, so this week's activity, in and of itself, is not necessarily cause for alarm.

Preliminary calculations indicate that, as of 10:00 am (PDT) Sept. 27, 2016, there is a 0.03%-1% chance (1 in 3000 to 1 in 100) of a magnitude 7 or greater earthquake being triggered on the Southern San Andreas fault within the next next seven days through October 4, with the likelihood decreasing over time. This probability range is estimated using several models developed in California to assess foreshock/aftershock probabilities.

Learn more at: http://earthquake.usgs.gov/

2020 Salton Sea

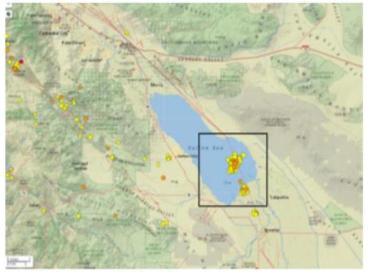
Earthquake Forecast for the Salton Sea Swarm of August 2020

08/13/2020:

Over the past 3 days, we have been carefully monitoring the Salton Sea for ongoing earthquake activity. The earthquake swarm that began on August 10th continues to quiet down, producing only 1 earthquake of magnitude 2 and larger in the last 24 hours (as of noon August 13th). This is compared to a peak of 54 earthquakes on August 10th, the day of the M4.6 mainshock, which remains the largest earthquake so far. Our updated probabilities for the following three scenarios reflect this reduction in activity; however, the risk of a large earthquake remains elevated due to the swarm when compared to background levels.

The southernmost section of the San Andreas Fault is capable of rupturing in large magnitude earthquakes (magnitude 7+), the last of which occurred more than 300 years ago. In a typical week, there is approximately a 1 in 10,000 chance of a magnitude 7+ earthquake on the southernmost San Andreas Fault. For the next week, we estimate an elevated chance of such an earthquake to be less than 1 in 1,000.

Historically, this area has seen swarms before – most recently in 2001, 2009, and 2016. During the last swarm in 2016, there were three bursts of activity



Map showing the Salton Sea, CA earthquake swarm of August 2020 (as of August 13, 2020 12pm Pacific). Circles are earthquake locations, red indicates an earthquake in the past hour, orange the past 24 hours, and yellow the past 7 days. (Public domain.)

2020 Westmorland

Earthquake Forecast for the Westmorland Swarm beginning Sept. 30, 2020

Release Date: SEPTEMBER 30, 2020

A swarm of earthquakes southeast of the Salton Sea, in the Brawley seismic zone, began on Sept. 30, 2020.

Forecast last updated October 7, 2020 at 8:00am PDT.

October 7, 2020

We have been carefully monitoring a swarm of earthquakes southeast of the Salton Sea in the Brawley seismic zone that began on Sept. 30, 2020. The swarm activity has stabilized at a low rate, with only two magnitude 3 or larger earthquakes recorded since the morning of Oct. 3rd. There have been over 60 magnitude 3 and larger earthquakes since the beginning of this swarm, most of which (46) occurred in the first burst of activity on the evening of Sept. 30th. The largest earthquake that has occurred, as of this release, is a magnitude 4.9 at 5:31 PM PDT on Sept. 30th. This earthquake swarm is located in an area of diffuse seismic activity between the San Andreas fault to the north and the Imperial fault to the south. This area has seen swarms in the past – notably the 1981 Westmorland swarm, which included a M5.8 earthquake, and the 2012 Brawley swarm, which included a M5.4 earthquake. Past swarms have remained active for 1 to 20 days, with an average duration of about a week.

Since the swarm activity has stabilized, we will no longer be updating this forecast on a daily basis. However, this does not mean that the risk of a larger earthquake is gone. Both the San Andreas Fault to the north, and the Imperial Fault to the south are capable of rupturing in large magnitude

Screenshot of Latest Earthquakes (as of October 7, 8:00am PDT) showing the Westmoreland Earthquake Swarm that began on the afternoon of Sep 30, 2020.

Contacts

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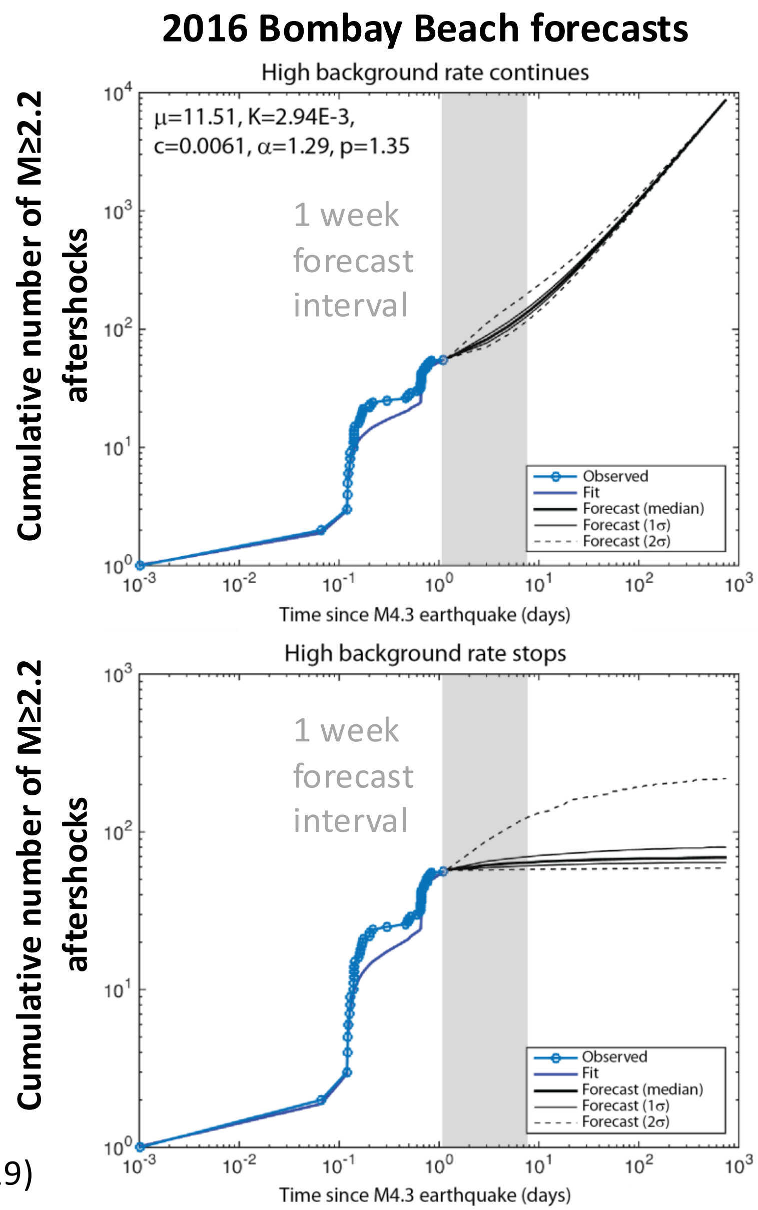
How do we know we need a swarm forecast?

- What is a swarm?
  - Lack of obvious mainshock/violation of Båth's law of aftershock behavior (e.g., Mogi, 1963; Båth, 1965)
  - Changes in Gutenberg-Richter *b*-values
  - Spatio-temporal characteristics (e.g., timing of largest event, spatial migration, cluster branching structure) (e.g., Vidale and Shearer, 2006; Zaliapin and Ben-Zion, 2013)
  - Transient increases in background rate (e.g., Hainzl and Ogata, 2005; Llenos et al., 2009)
  - Detection of seismogenic processes (e.g., fluid migration, slow slip, volcanic processes)
- Our proposed operational definition: **A sequence of earthquakes where changes in rates are driven by processes beyond typical mainshock-aftershock triggering**
  - Allows us to model a swarm by adding a time-varying background rate term to aftershock models
  - Encompasses all the different driving processes that can trigger swarms
  - Relatively simple and actionable

Swarm forecasting

- Swarms present unique challenges to forecasting.
  - Unlike aftershocks, swarms are driven by external time-varying processes such as fluid flow.
  - Lack of knowledge of the driving process makes it difficult to predict how long swarms last, but forecasts depend heavily on this.
  - Swarms require manual intervention to produce forecasts using a more appropriate model.
- Some building blocks for swarm forecasting
  - Background rate variations (ETAS model)
  - Actuarial swarm duration model (now implemented in USGS swarm forecasts in the Salton Trough)



Llenos and van der Elst (BSSA, 2019)

The ETAS Model

- The ETAS model (Ogata, 1988) is a statistical model already used to produce aftershock forecasts in many regions.

Background seismicity rate

Aftershock productivity

Magnitude scaling

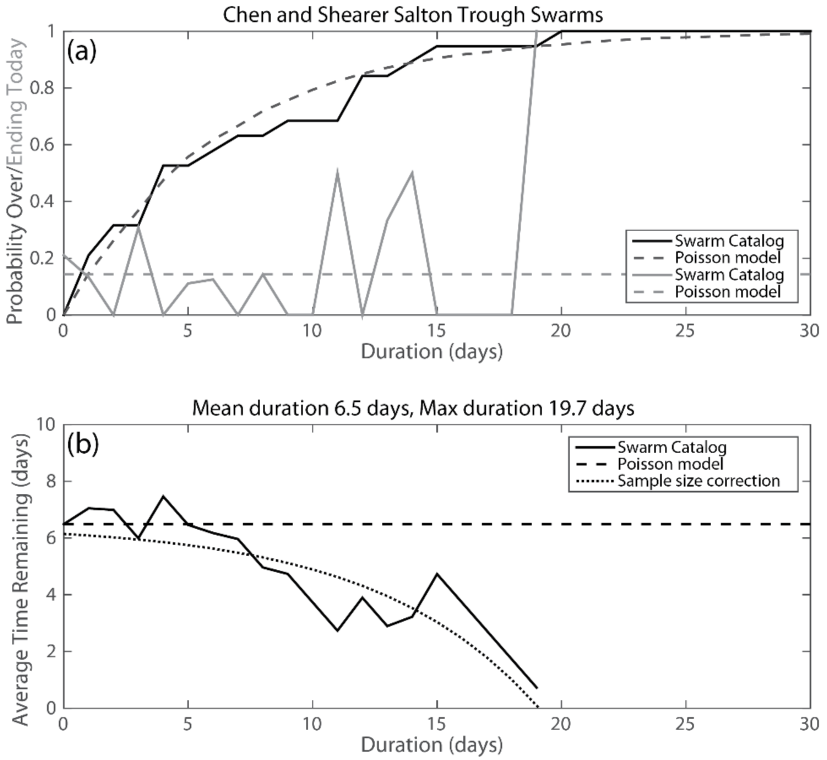
$$\lambda(t) = \mu + \sum_{t_i \le t} \frac{K e^{\alpha(M_i - M_c)}}{(t - t_i + c)^p}$$

Omori decay

- Model parameters are optimized to fit previously occurring seismicity and forecasts are made by simulating catalogs with these parameters.
- Swarms can be represented by adding a time-varying background rate μ.
- But how long does this increase in μ last?

Modeling swarm durations with actuarial statistics

- Actuarial statistics (life expectancy) can be used to characterize swarm durations in regions with many swarms.
- Swarm durations in the Salton Trough are exponentially distributed, implying a Poisson probability of terminating on any given day.



Llenos and van der Elst (BSSA, 2019)

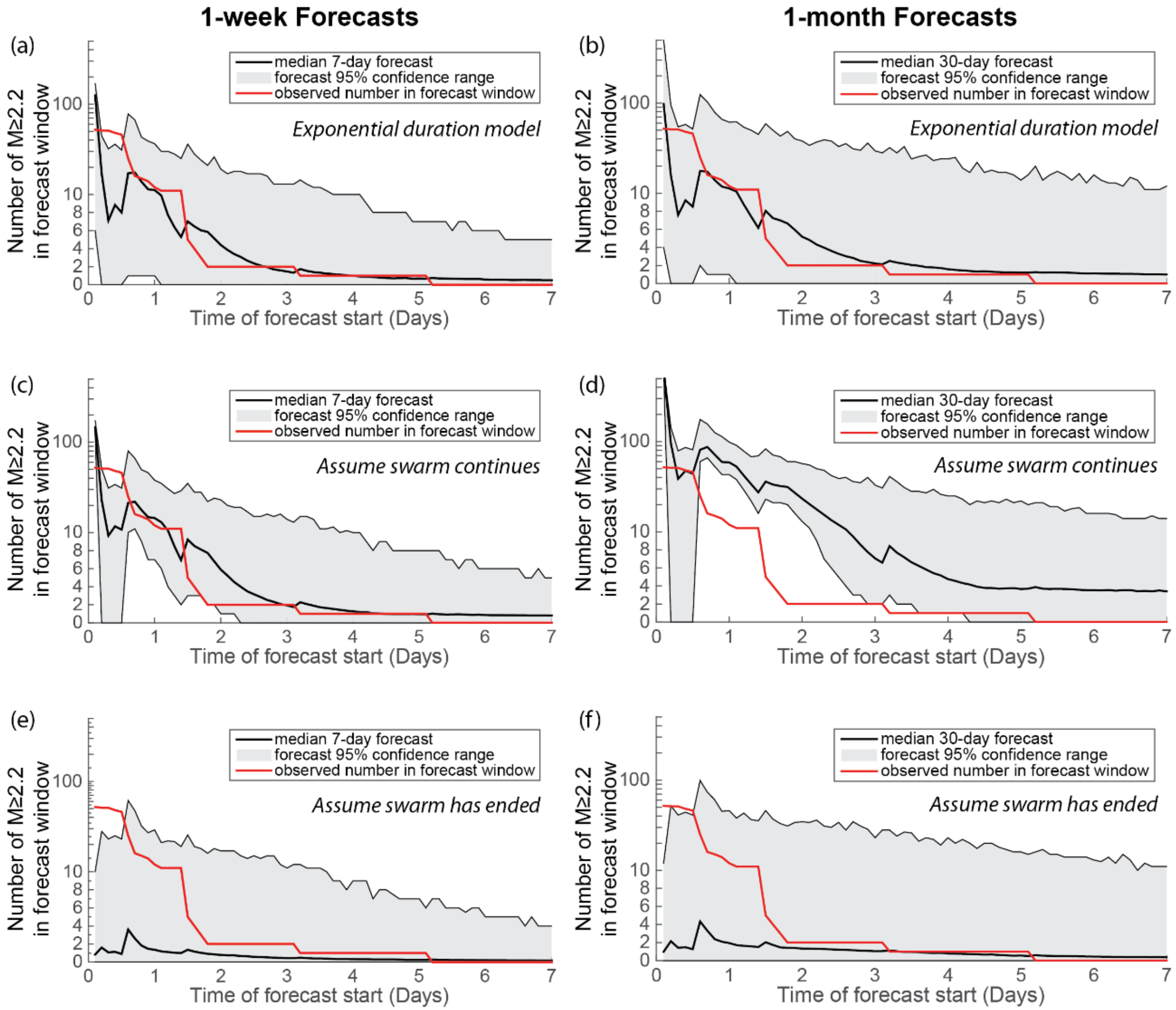
Table 1
Salton Trough Swarm Life Table

Swarm Age (Days)	Number of Swarms Lasting to Swarm Age	Probability the Swarm Ends in the Next 24 Hr	Expected Time Remaining in the Swarm (Days)
0	19	0.211	6.485
1	15	0.133	7.045
2	13	0.000	6.990
3	13	0.308	5.990
4	9	0.000	7.461
5	9	0.111	6.461
6	8	0.125	6.174
7	7	0.000	5.962
8	7	0.143	4.962
9	6	0.000	4.732
10	6	0.000	3.732
11	6	0.500	2.732
12	3	0.000	3.894
13	3	0.333	2.894
14	2	0.500	3.221
15	1	0.000	4.726
16	1	0.000	3.726
17	1	0.000	2.726
18	1	0.000	1.726
19	1	1.000	0.726

Based on swarms identified in Chen and Shearer (2011).

Forecasts are improved with a duration model

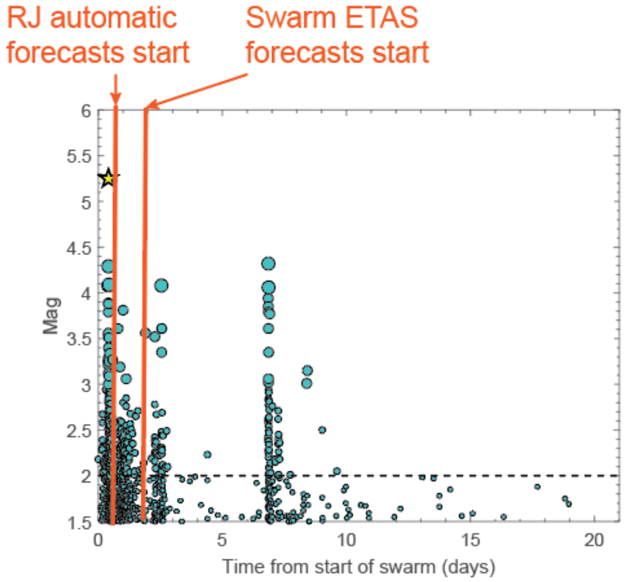
Forecasts of number of events during the 2016 Bombay Beach swarm

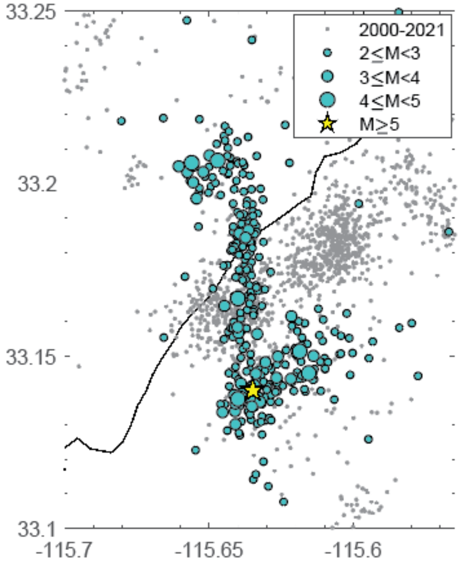


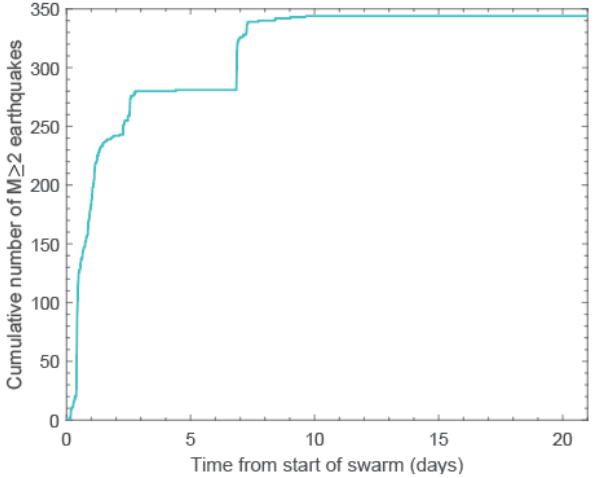
Llenos and van der Elst (BSSA, 2019)

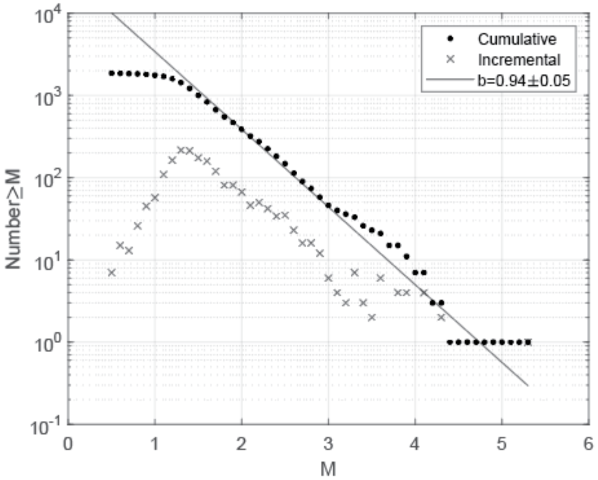
2021 Calipatria swarm

- Sequence began on June 5, 2021, with the largest earthquake (M5.3) occurring 10 hrs later, preceded minutes before by a M4.1.
- Seismicity migrated over next several days and included three M4+ earthquakes.
- After quieting down, another burst occurred 4 days later, including a M4.3.
- Was this a swarm?
  - Lack of obvious mainshock/violation of Båth's law of aftershock behavior -> **clear mainshock (M5.3)**
  - Higher Gutenberg-Richter b-values -> **b=0.94**
  - Spatio-temporal characteristics (e.g., timing of largest event, spatial migration, cluster branching structure) -> **some migration**
  - **Increase in background rate**
- After the M5.3, automatic aftershock forecasts were made using the Reasenberg & Jones model.
- ETAS+swarm duration model was used.
  - Probability of an M5+ in the next week rose from 8% to 30% then fell to 15% the following day.





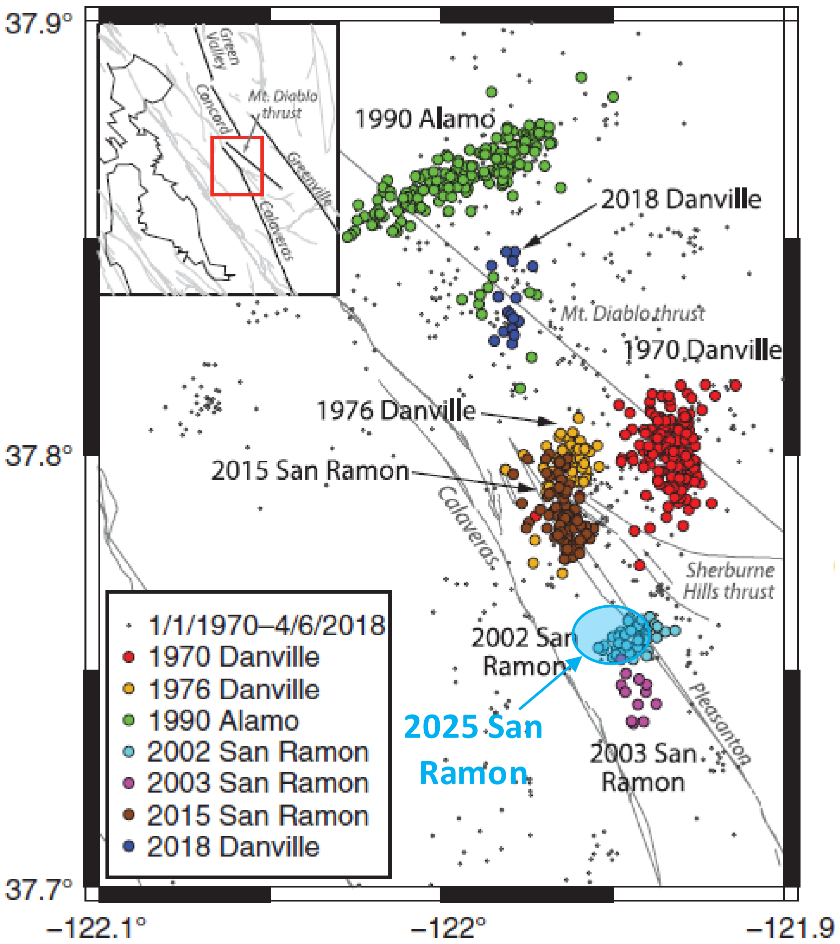




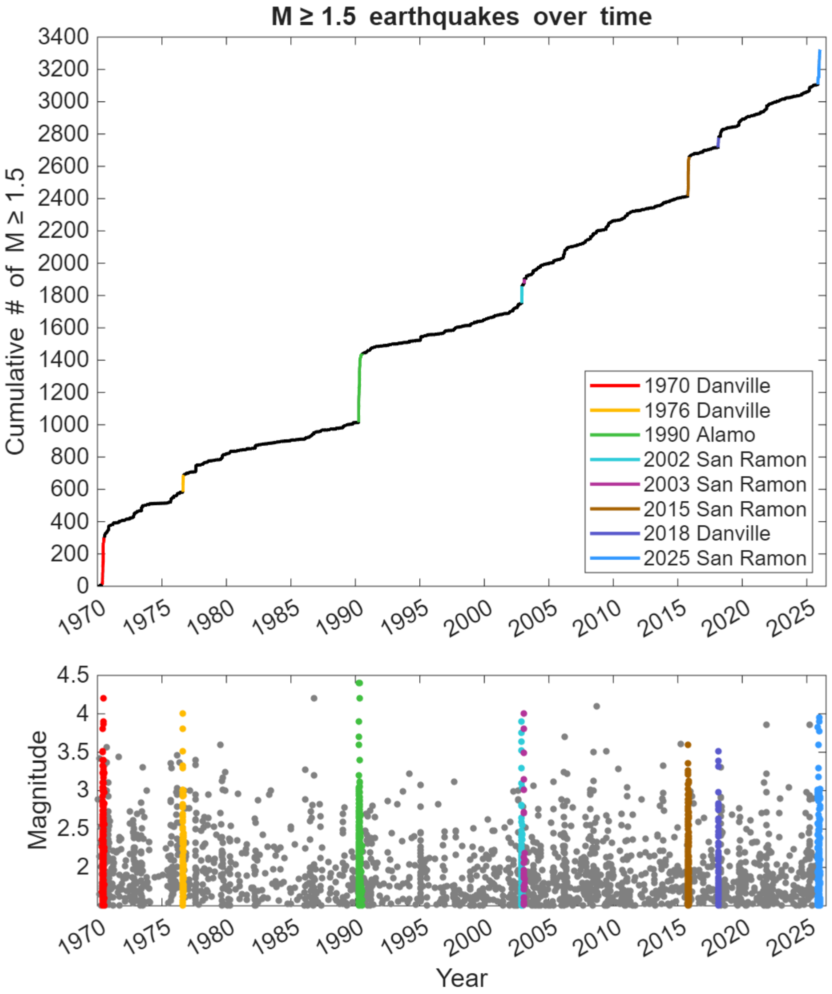
Current status of USGS swarm forecasting

- Our working definition of a swarm: **A sequence of earthquakes where changes in rates are driven by processes beyond typical mainshock-aftershock triggering**
- Is the sequence occurring in a location with known swarm activity? How well do standard aftershock models fit the sequence? Is there enough information available to constrain a swarm forecast model?
  - 2025-2026 San Ramon swarm(s): No swarm forecast produced (no duration model available)
  - 2026 Brawley swarm: No swarm forecast produced (sequence fit well enough by RJ model)
- Currently expert judgment is needed to determine when including the background rate term improves the forecast.
- Work can still be done to:
  - Objectively determine that a swarm is occurring
  - Account for time-varying rates throughout an entire swarm
  - Forecast swarm duration in areas that do not have an extensive swarm history
  - Improve communication of swarm-specific forecasts
- Current ongoing case study: San Ramon Valley swarms

San Ramon swarms



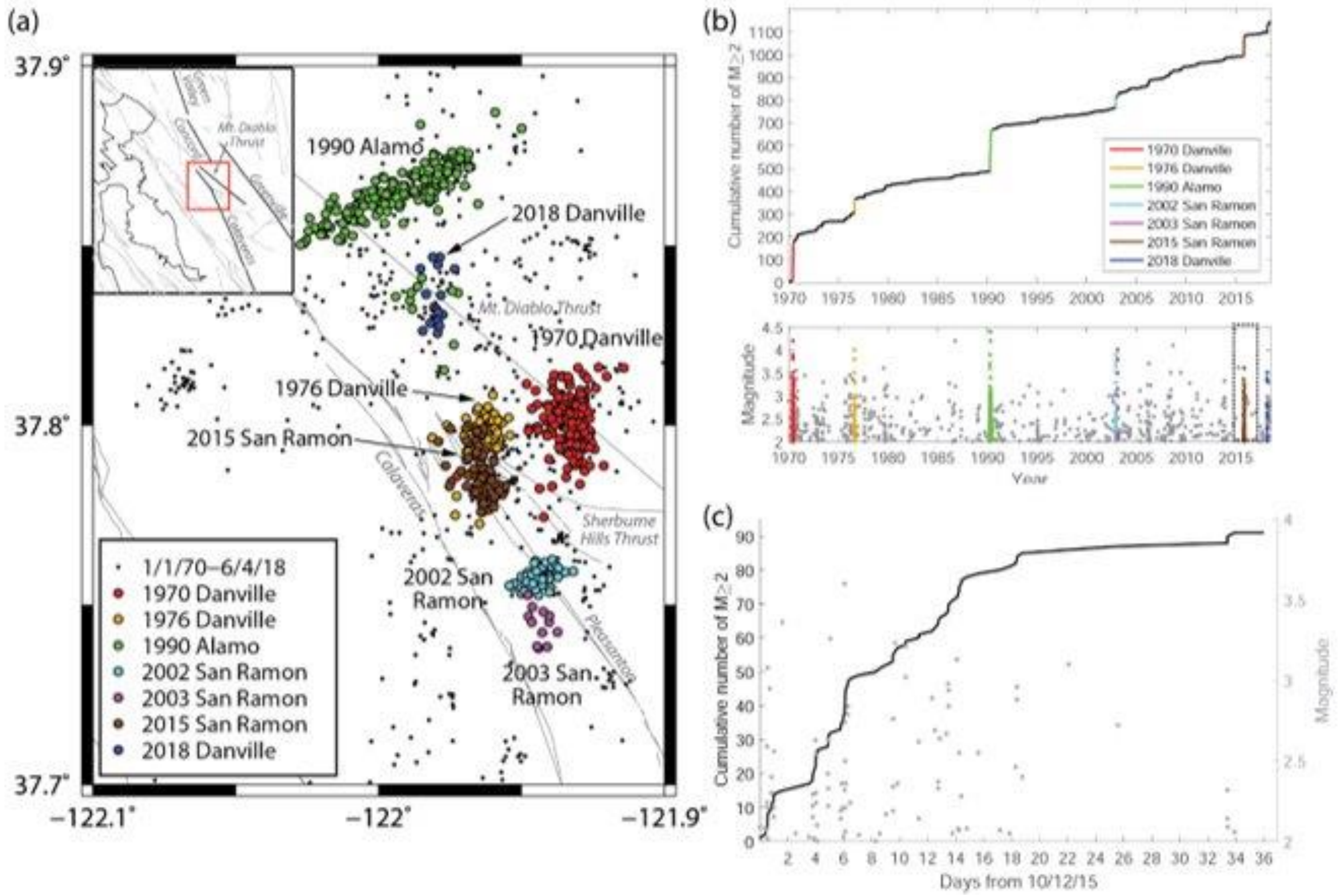
Modified from Llenos & Michael (2019)



- The San Ramon Valley has hosted a number of swarms over the past few decades.
- Largest magnitudes M<4.5.
- Durations range from a few days to weeks, if not months, depending on how swarms are defined.

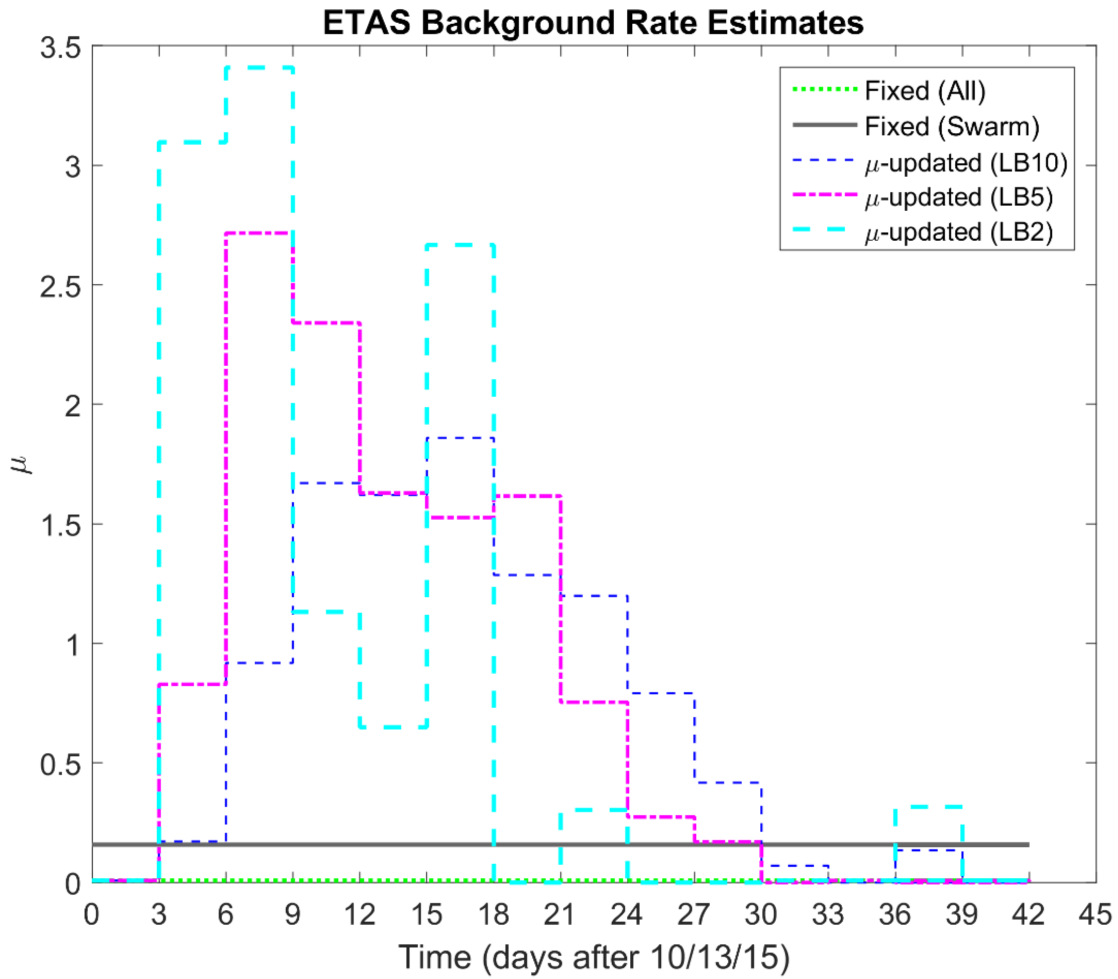
What is the best background rate to use in a forecast?

- Forecasting during swarms requires determining the temporally varying background rate.
- 2015 San Ramon, CA swarm lasted ~1 month, producing almost 100 2<M<3.6 earthquakes



Llenos and Michael (BSSA, 2019)

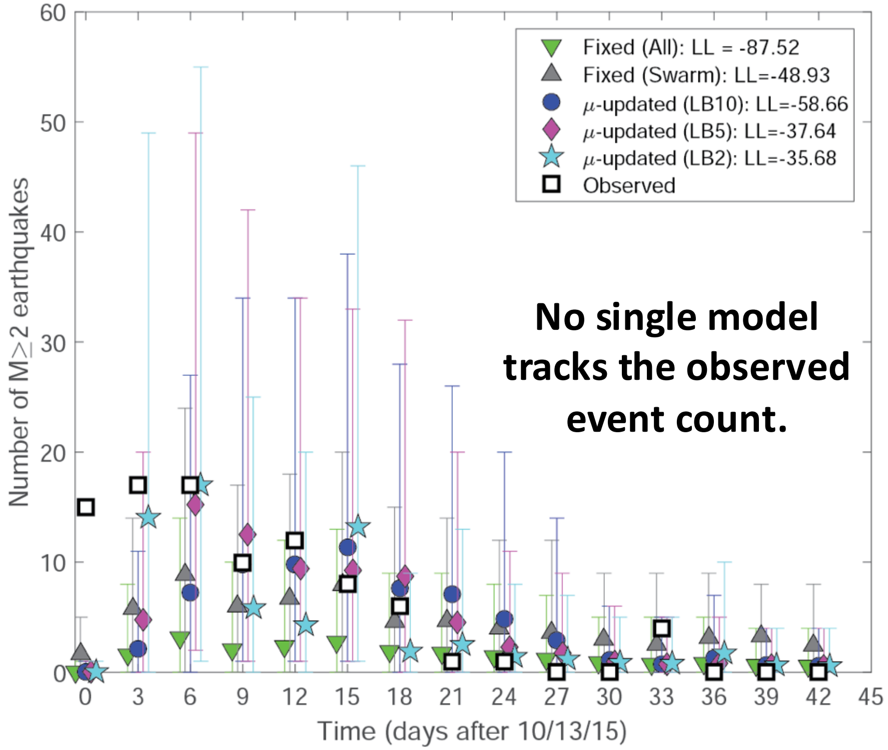
Earthquake forecast models for the 2015 swarm



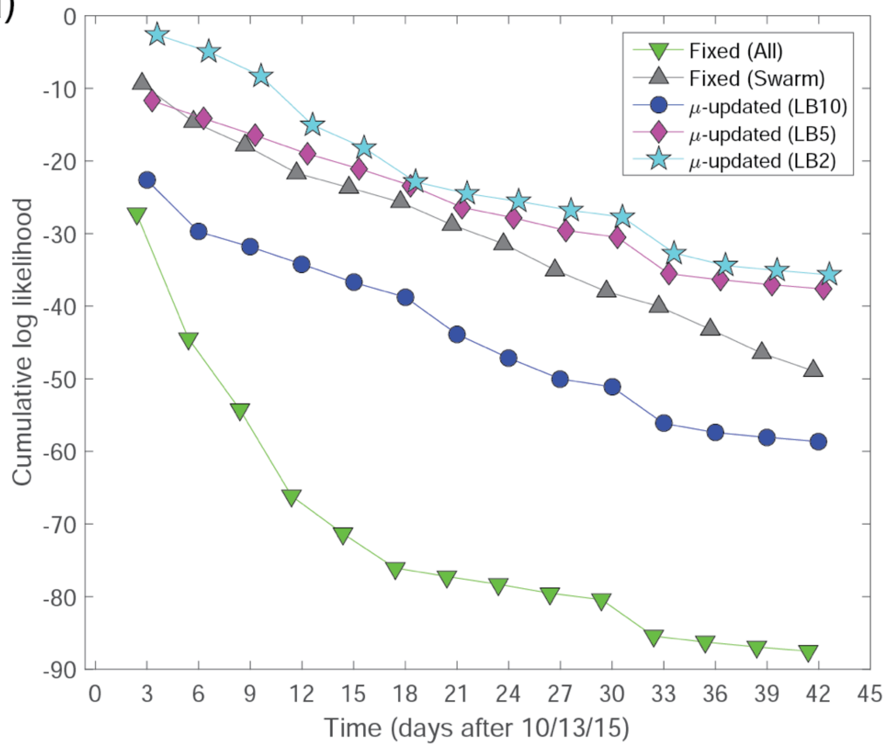
- How well can we forecast the rate of M≥2 earthquakes during the swarm?
- Forecast models to compare
  - **Fixed models**: Parameters constant
    - (1) 1/1/70-10/12/15 (Fixed-All)
    - (2) Prior swarms (Fixed-Swarm)
  - **Updated models**: μ updated every 3 days, using data in different lookback windows
    - (3) Lookback = 10 days (LB10)
    - (4) Lookback = 5 days (LB5)
    - (5) Lookback = 2 days (LB2)
- At start of each 3-day forecast window, seismicity updated, parameters updated, then 100,000 catalogs simulated with the different models to forecast number of earthquakes likely to occur during next 3 days

Forecast results

(a)

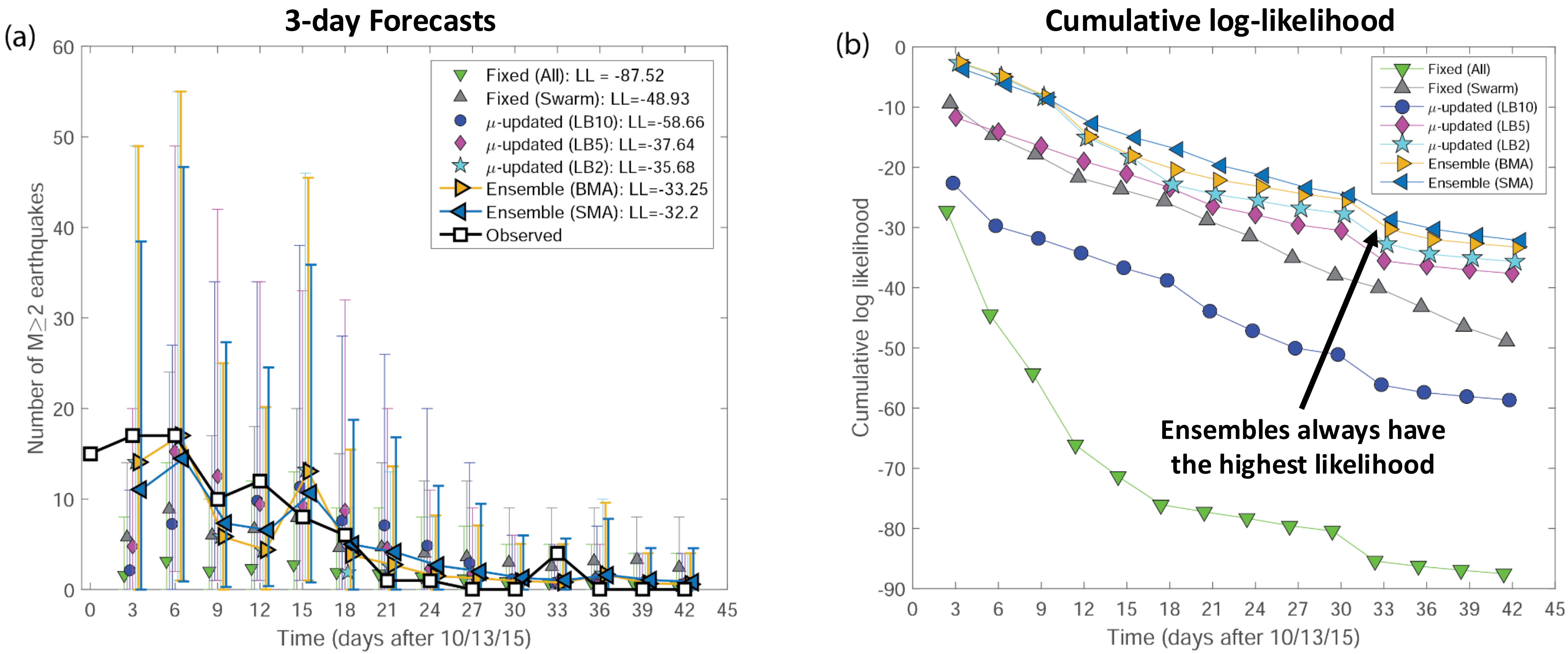


(d)

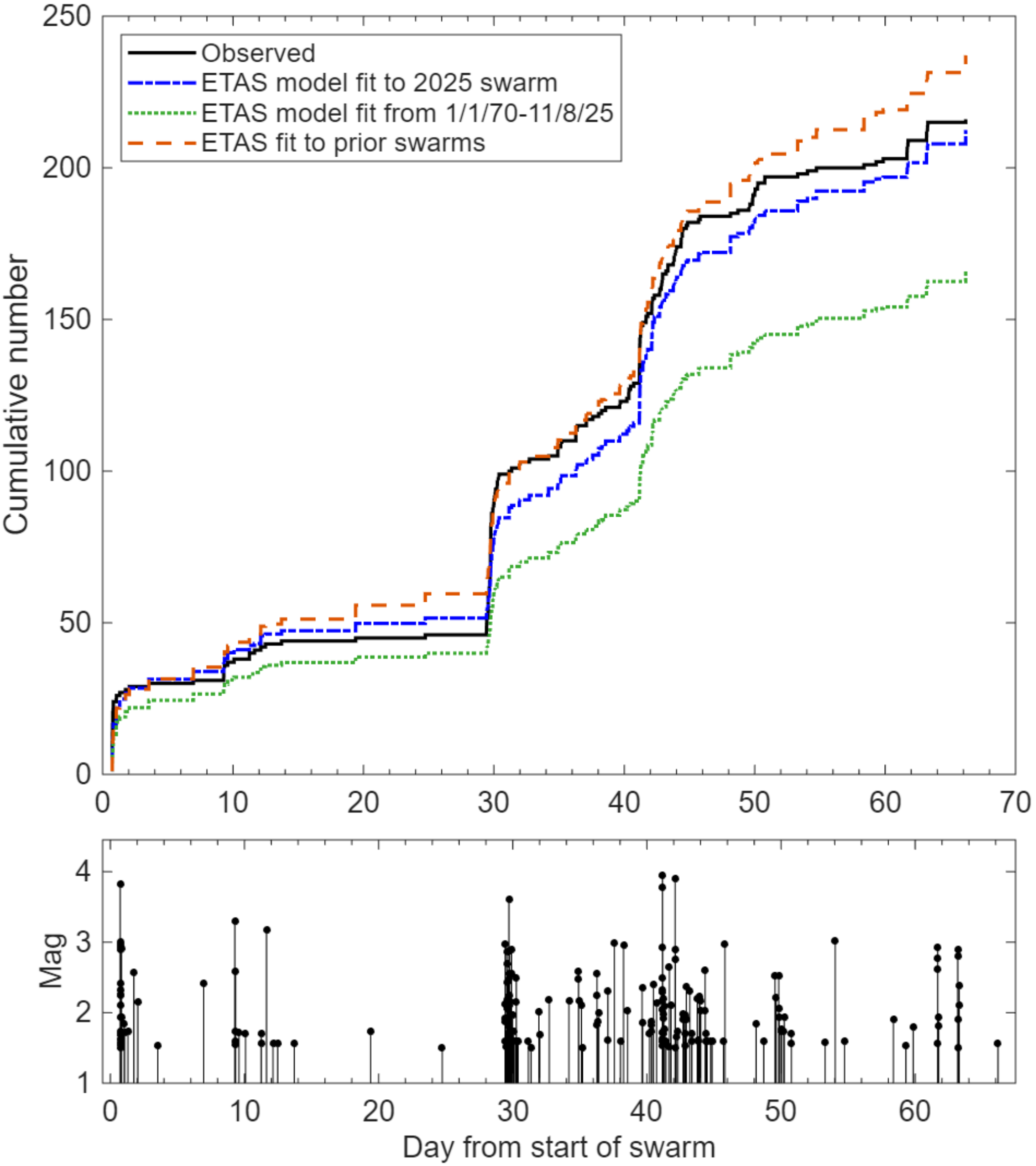


- Of the fixed models, the Fixed-All model almost always underestimates rates. The Fixed-Swarm model performs better though it overpredicts towards the end of the swarm.
- Updated models generally perform better than the fixed models.
- No single model always provides the clearly best forecast. Which to use?

Ensemble models outperform individual models



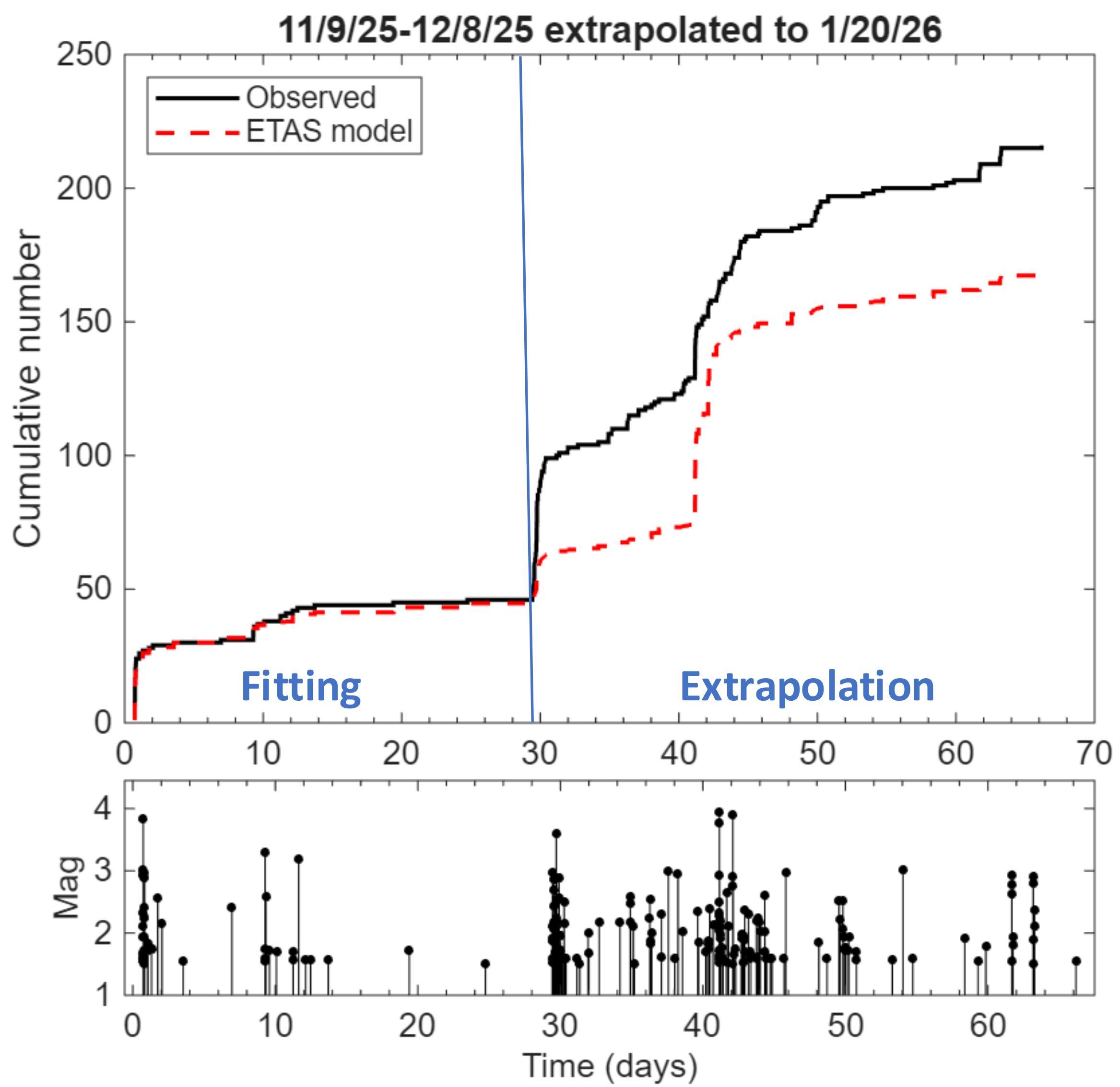
Modeling the 2025 San Ramon swarm(s)

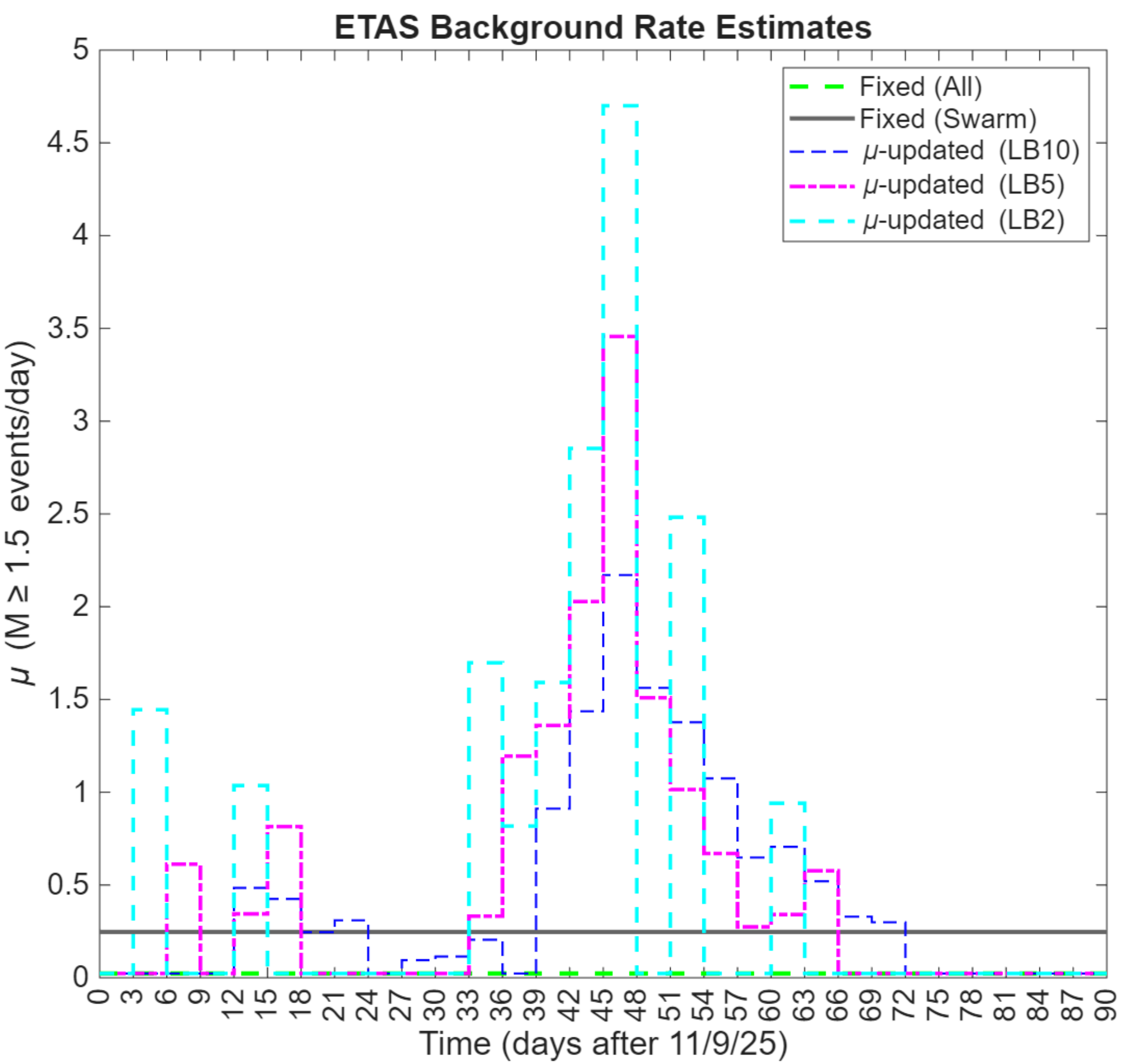


- 2025 swarm not well explained by ETAS model fit to all prior seismicity.
- A larger μ is required to fit the swarm.
- ETAS fit to only prior swarms fits better.
- Second half of the swarm is not as well fit as the first half.

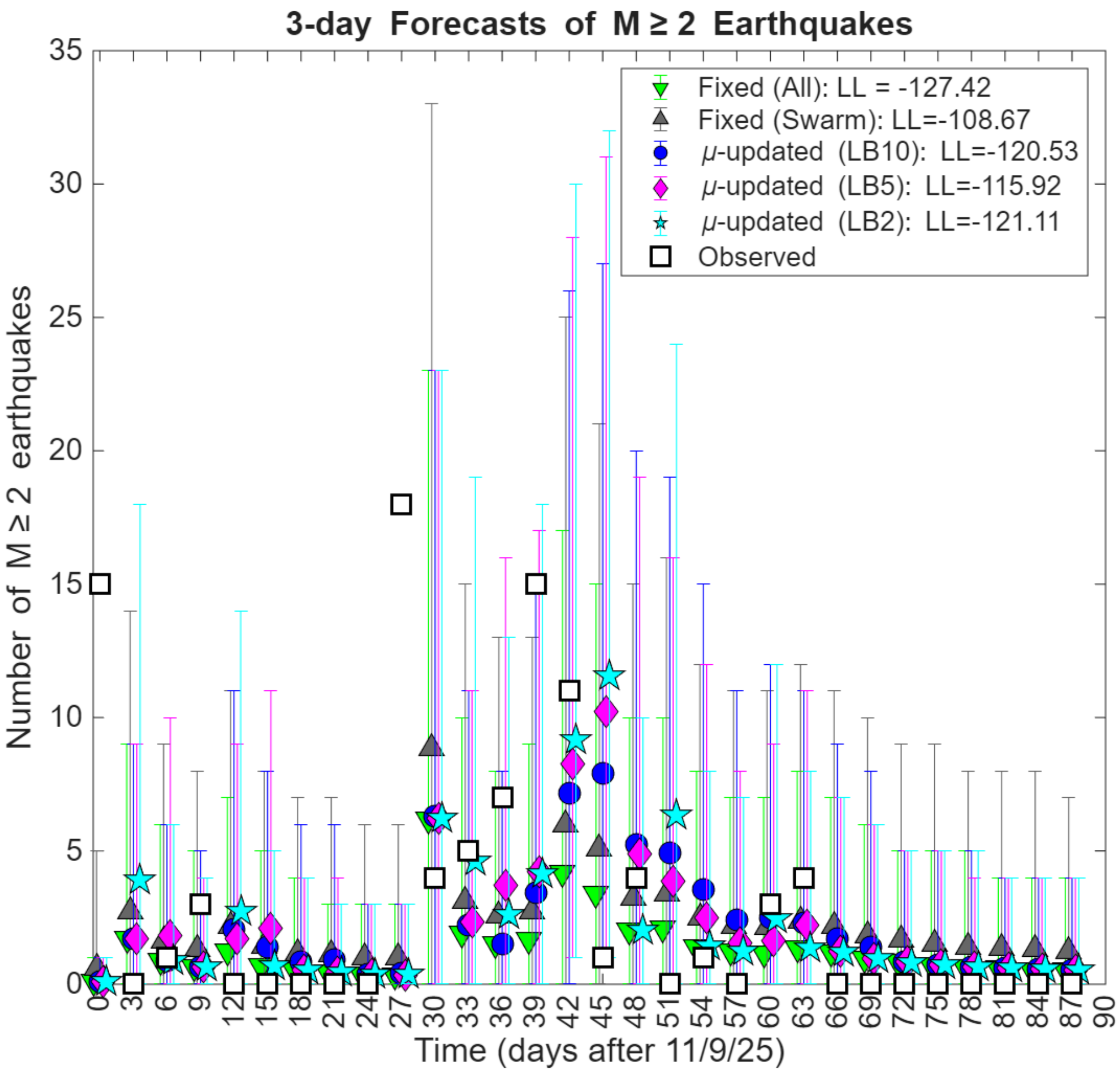
Model	Background rate μ
All prior seismicity	0.0232
Prior swarms	0.247
11/9/25-1/20/26	0.0901

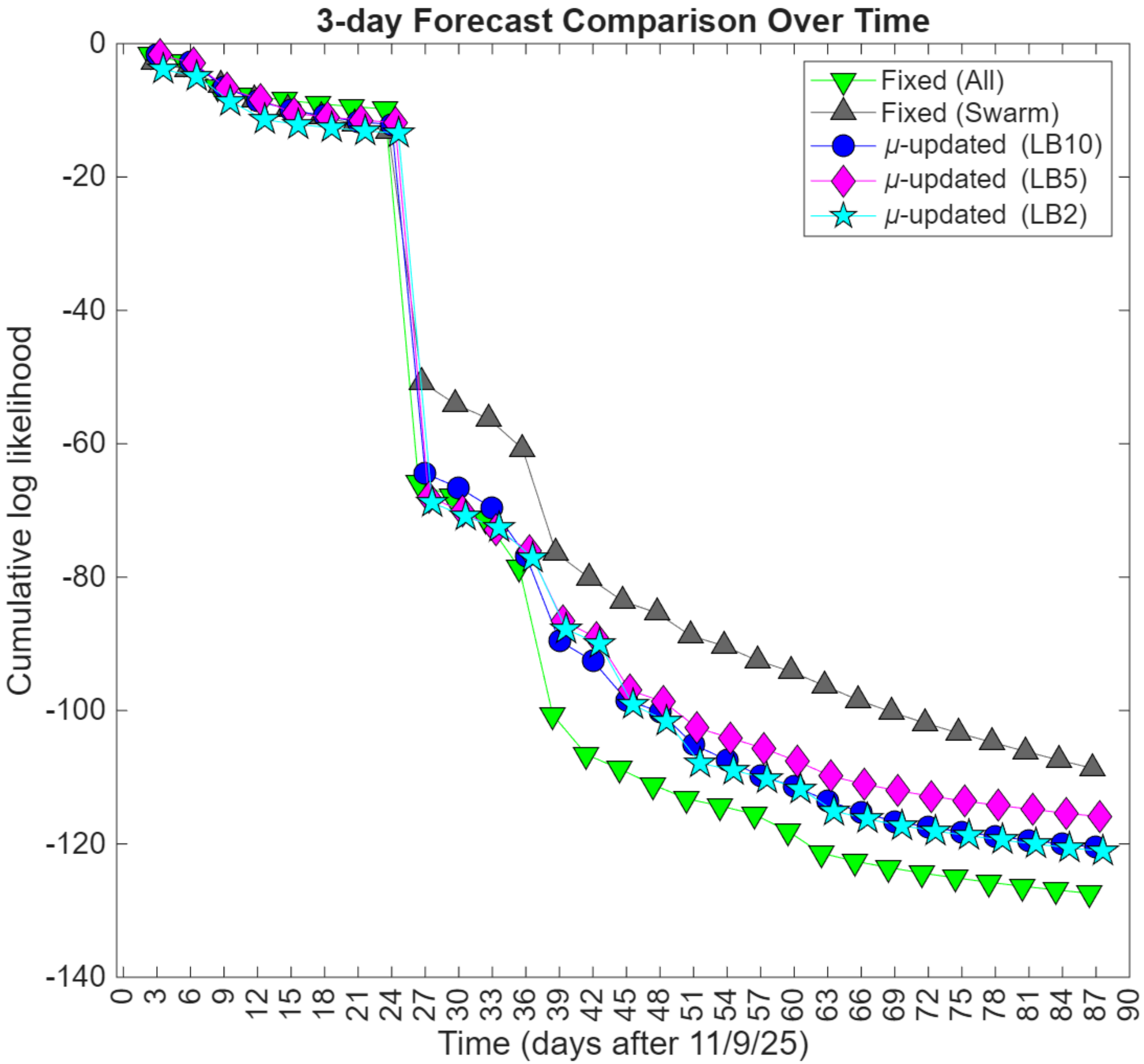
Parameters change in the middle of the swarm





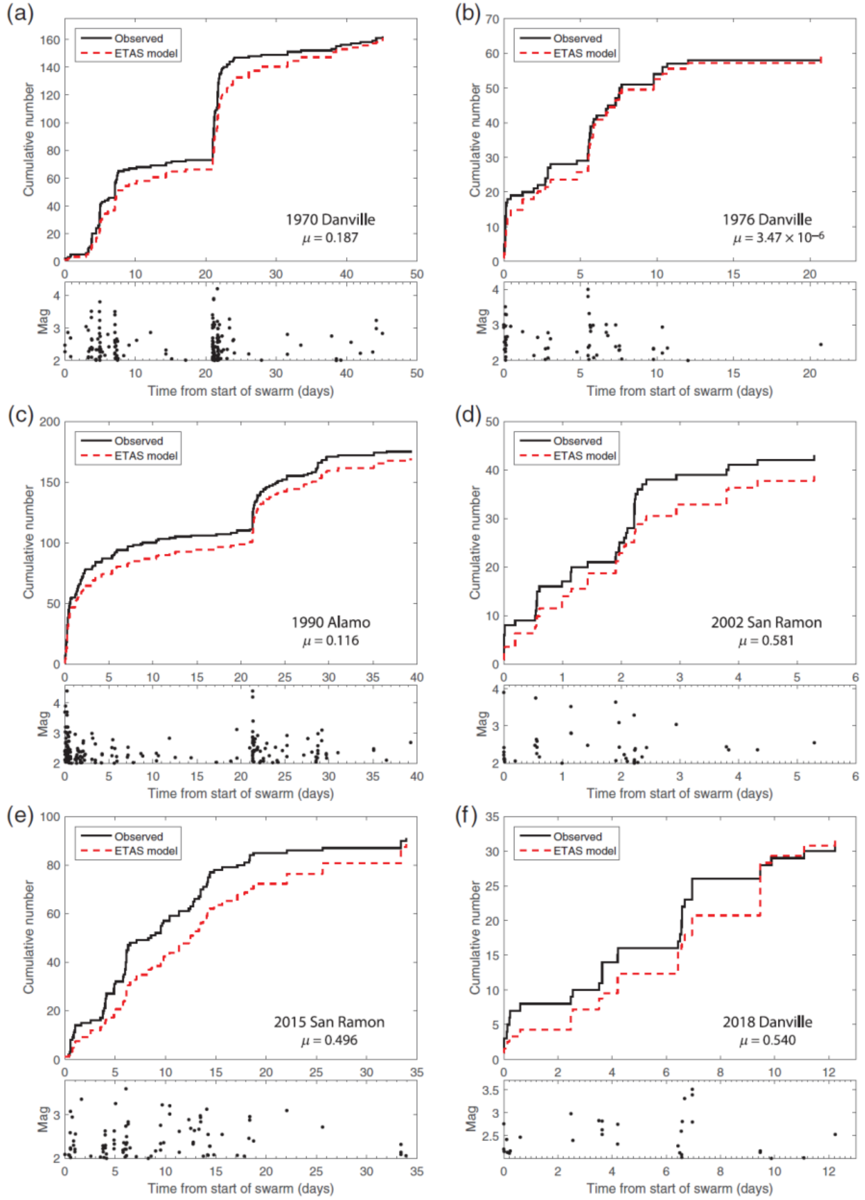
Best forecasts require higher background rates





Ongoing work in San Ramon and beyond

- How/why does model performance vary between swarms?
- Developing a method to consistently identify and characterize swarms over time in the San Ramon region
- Computing meaningful actuarial model inputs if/where possible (e.g., average swarm duration)



Llenos and Michael (BSSA, 2019)

Summary

- Earthquake swarms present challenges to current forecast models. Both causes and effects are different compared to standard mainshock-aftershock sequences that form the basis of many of our forecasting products.
- We have developed some critical building blocks for swarm operational earthquake forecasting:
  - The use of the ETAS model to incorporate high background rates during swarms
  - A swarm duration model based on actuarial statistics
  - Including time-varying background rates into forecasts
  - Ensemble forecasts
- But there is still a lot of work to be done to consider how swarms affect our traditional aftershock and seismic hazard forecasts.

Llenos, A. L. and N. J. van der Elst (2019). Improving earthquake forecasts during swarms with a duration model. doi: 10.1785/0120180332.
Llenos, A. L. and A. J. Michael (2020). Ensembles of ETAS Models Provide Optimal Operational Earthquake Forecasting During Swarms: Insights from the 2015 San Ramon, California Swarm. doi: 10.1785/0120190020.
McBride, S. K. et al. (2020). #EarthquakeAdvisory: Exploring Discourse between Government Officials, News Media, and Social Media during the 2016 Bombay Beach Swarm. doi: 10.1785/0220190082.