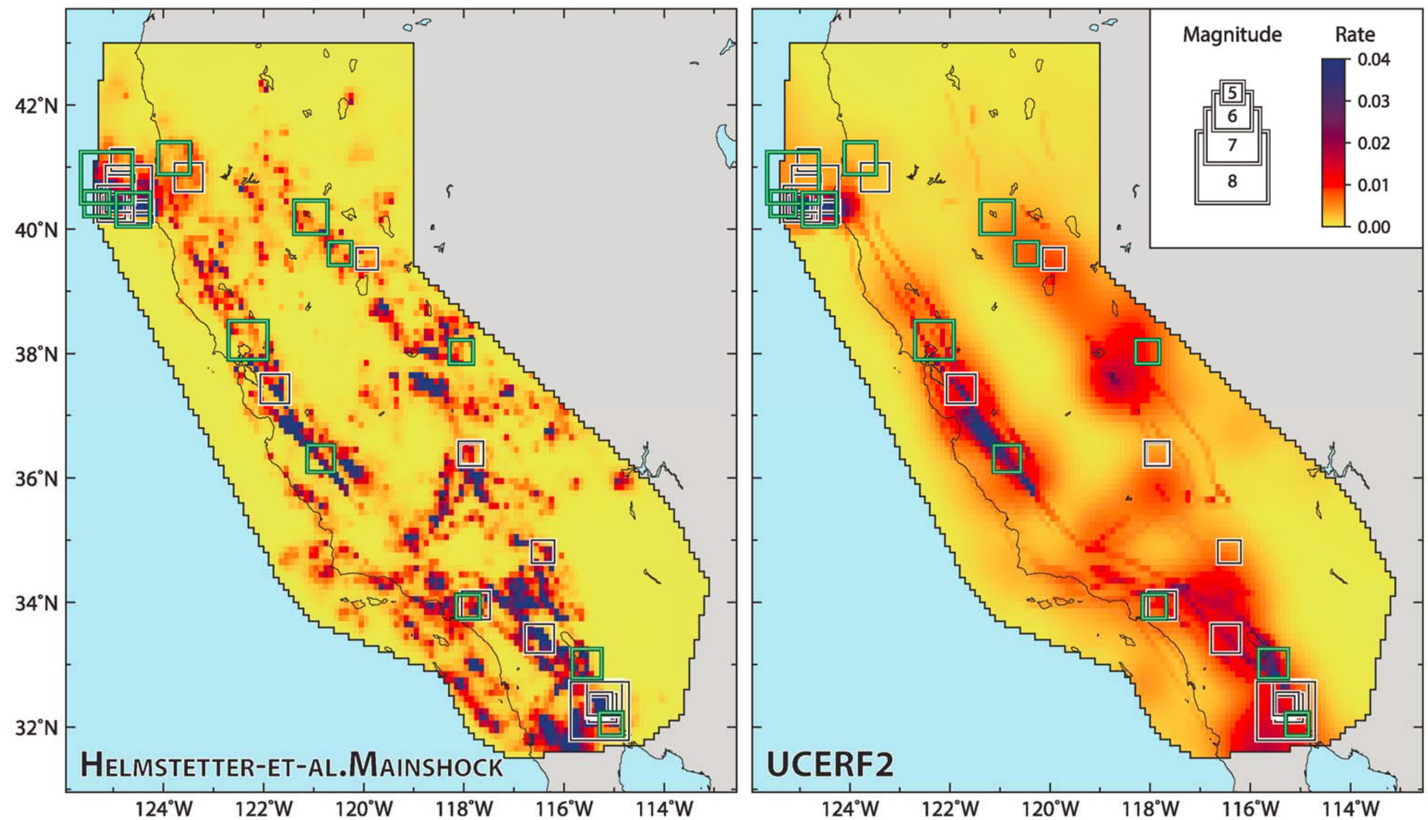
RELM Experiment, Part 2: Prospective and Retrospective Evaluation of Five-Year Earthquake Forecast Models for California



Anne Strader[1], Max Schneider[2,3], Danijel Schorlemmer[1]

1. GFZ-Potsdam, 2. University of Potsdam, 3. University of Washington

SCEC CSEP Workshop 2017: Informing Earthquake Debates with CSEP Results

Outline

- Introduction
  - Brief overview of RELM experiment
  - UCERF2 and NSHMP forecast evaluation
  - New forecasting experiments
- CSEP test results
  - Consistency tests (N, S, M, L)
  - Comparative tests (T, W)
- Where specifically do forecasts perform well/poorly?
  - Log-likelihood scores at target earthquake locations
  - Residual analysis
- Conclusions

RELM Experiment Overview

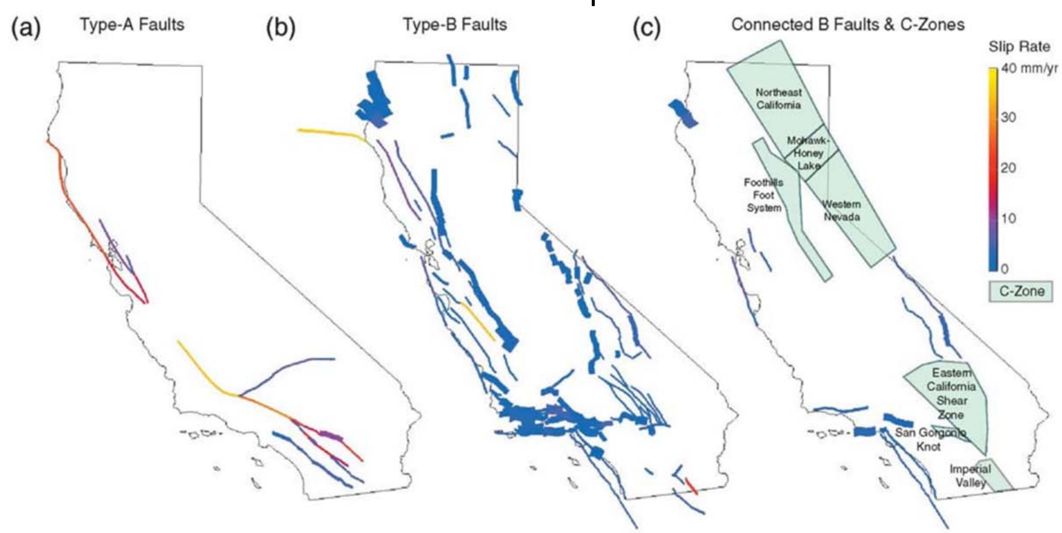
RELM mainshock model name	Regional fit	Input data
EBEL-ET-AL.MAINSHOCK.CORRECTED	Active fault zones	Average rate of $M \geq 5$ declustered earthquakes from the period 1932–2004 (Ebel *et al.* 2007)
HELMSTETTER-ET-AL.MAINSHOCK	Full CA	Smoothed $M \geq 2$ earthquakes since 1981, optimized smoothing kernel, spatially varying magnitude of completeness (Helmstetter *et al.* 2007)
HOLLIDAY-ET-AL.PI	High-seismicity zones	Regions with strongly fluctuating seismicity rates expected to contain large earthquakes (Holliday *et al.* 2007)
KAGAN-ET-AL.MAINSHOCK	Southern CA	Smoothed seismicity since 1800, accounts for large rupture areas (Kagan *et al.* 2007)
SHEN-ET-AL.MAINSHOCK	Southern CA	Earthquake rate is proportional to horizontal maximum shear strain rate (Shen *et al.* 2007)
WARD.COMBO81	Southern CA	Average of WARD.GEODETIC81, WARD.GEOLOGIC81, and WARD.SIMULATION forecasts (Ward 2007)
WARD.GEODETIC81	Southern CA	Seismicity rates derived from strain rates, magnitudes forecasted with truncated Gutenberg-Richter distribution ($M = 8.1$) (Ward 2007)
WARD.GEODETIC85	Southern CA	Same as WARD.GEODETIC81 forecast, with $M = 8.5$ (Ward 2007)
WARD.GEOLOGIC81	Southern CA	Smoothed geological moment rate density from mapped fault slip rates (Ward 2007)
WARD.SEISMIC81	Southern CA	Smoothed seismicity since 1850 (Ward 2007)
WARD.SIMULATION	Southern CA	Simulations of velocity-weakening friction on fixed fault network (Ward 2007)
WIEMER-SCHORLEMMER.ALM	Full CA	Spatially varying a- and b-values influence rate of larger earthquakes (Wiemer & Schorlemmer 2007)

(Strader et al., 2017)

- The RELM Working Group developed nineteen time-invariant seismicity models, including thirteen mainshock models
- RELM experiment, first phase: five-year forecasts for all RELM models were tested from 2006-2011
- The smoothed-seismicity forecast Helmstetter-et-al.Mainshock performed best, passing every CSEP consistency test

USGS Forecasts: UCERF2, NSHMP

- The UCERF2 and NSHMP seismicity models are based on a combination of geophysical (strain rate) and historical seismicity data
- Ruptures on faults with sufficient paleoseismic rupture constraints and slip-rate data are hypothesized to occur within segments of those faults, each of which is assigned a stress-renewal recurrence model
- Regions with well-constrained slip rates but inadequate spatiotemporal seismicity data to assign stress-renewal probabilities are modelled as characteristic full-fault ruptures
- Rupture magnitudes are generated from a Gaussian frequency-magnitude distribution and allow for multiple faults to rupture simultaneously in one large event.
- Where slip-rate data are incomplete or unable to be assigned to specific faults, seismicity rates are based on strain rates where geodetic data are available (otherwise, rates are derived from smoothed historical seismicity)
- For the NSHMP model, a Poisson earthquake distribution over time is assumed; for UCERF2, earthquake probabilities are conditioned to the stress state at the time of the last rupture



(Field et al., 2009)

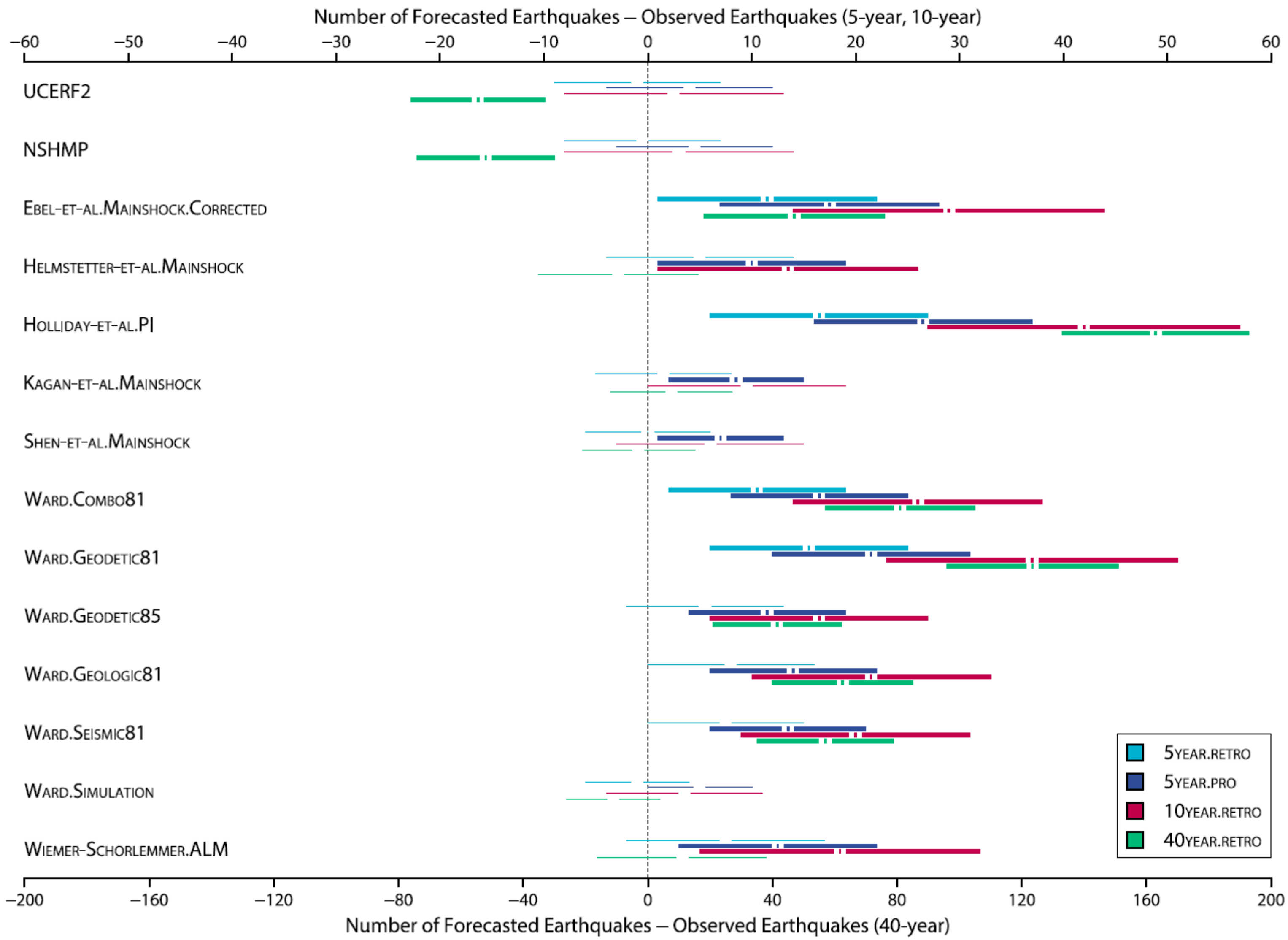
RELM Forecasting Experiments

Experiment name	Experiment period	RELM forecasts	USGS forecasts
5YEAR.RETRO	2006–2011	Prospective	Retrospective
5YEAR.PRO	2011–2016	Prospective	Prospective
10YEAR.RETRO	2006–2016	Prospective	Retrospective
40YEAR.RETRO	1967–2007	Retrospective	Retrospective

(Strader et al., 2017)

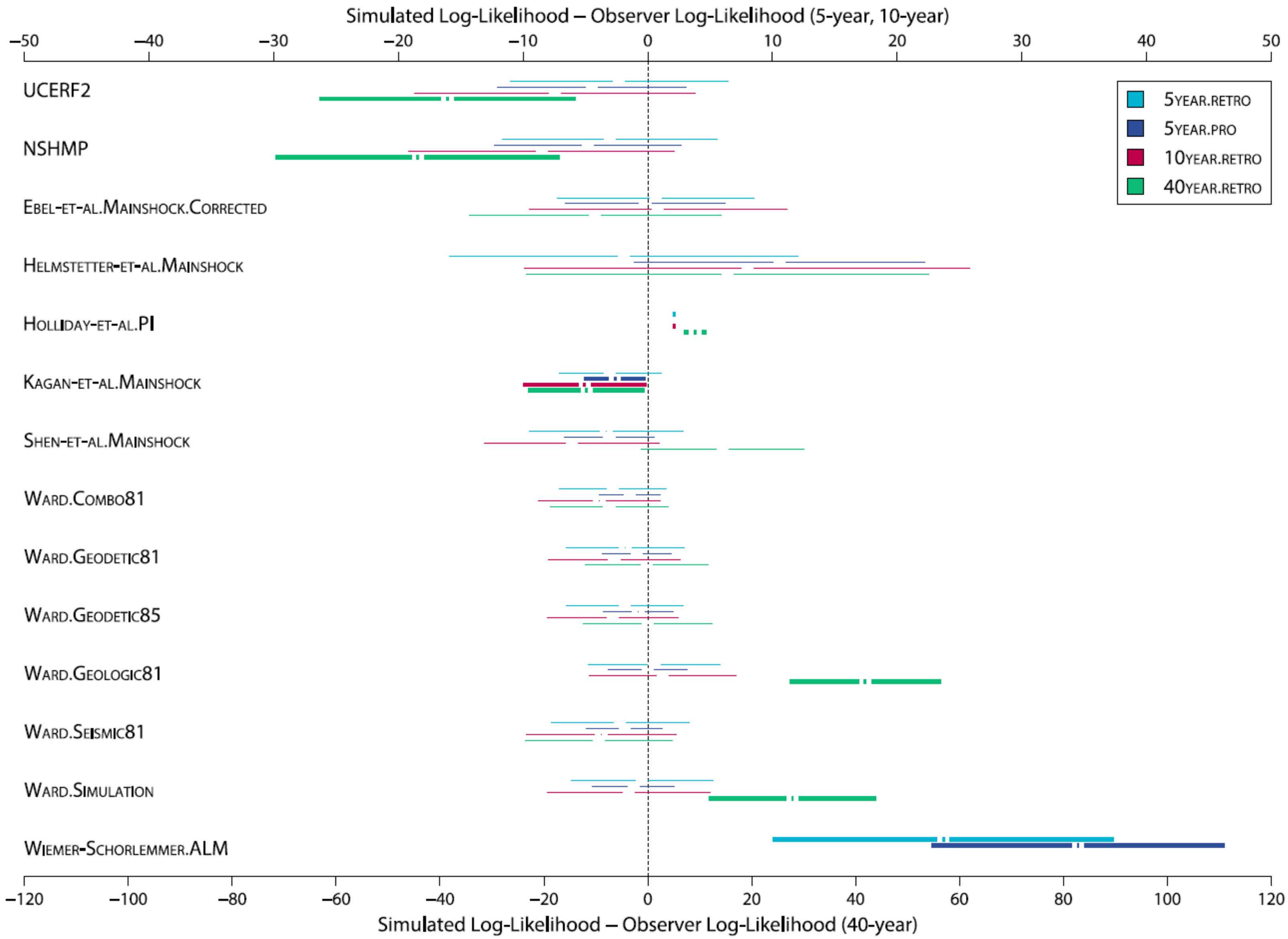
- Second five-year phase (prospective): all RELM and USGS forecasts evaluated from 2011-2016
- First five-year phase (retrospective): USGS and RELM forecasts evaluated from 2006-2011 (for the RELM forecasts, same time as first phase of RELM experiment)
- Testing long-term stability of results (retrospective): all forecasts evaluated for the ten-year duration of both five-year periods
- “Sanity check” (retrospective): all forecasts evaluated from 1967-2007 (data during this time interval were used to calibrate many of the seismicity models)

CSEP Consistency Test Results: N-Test



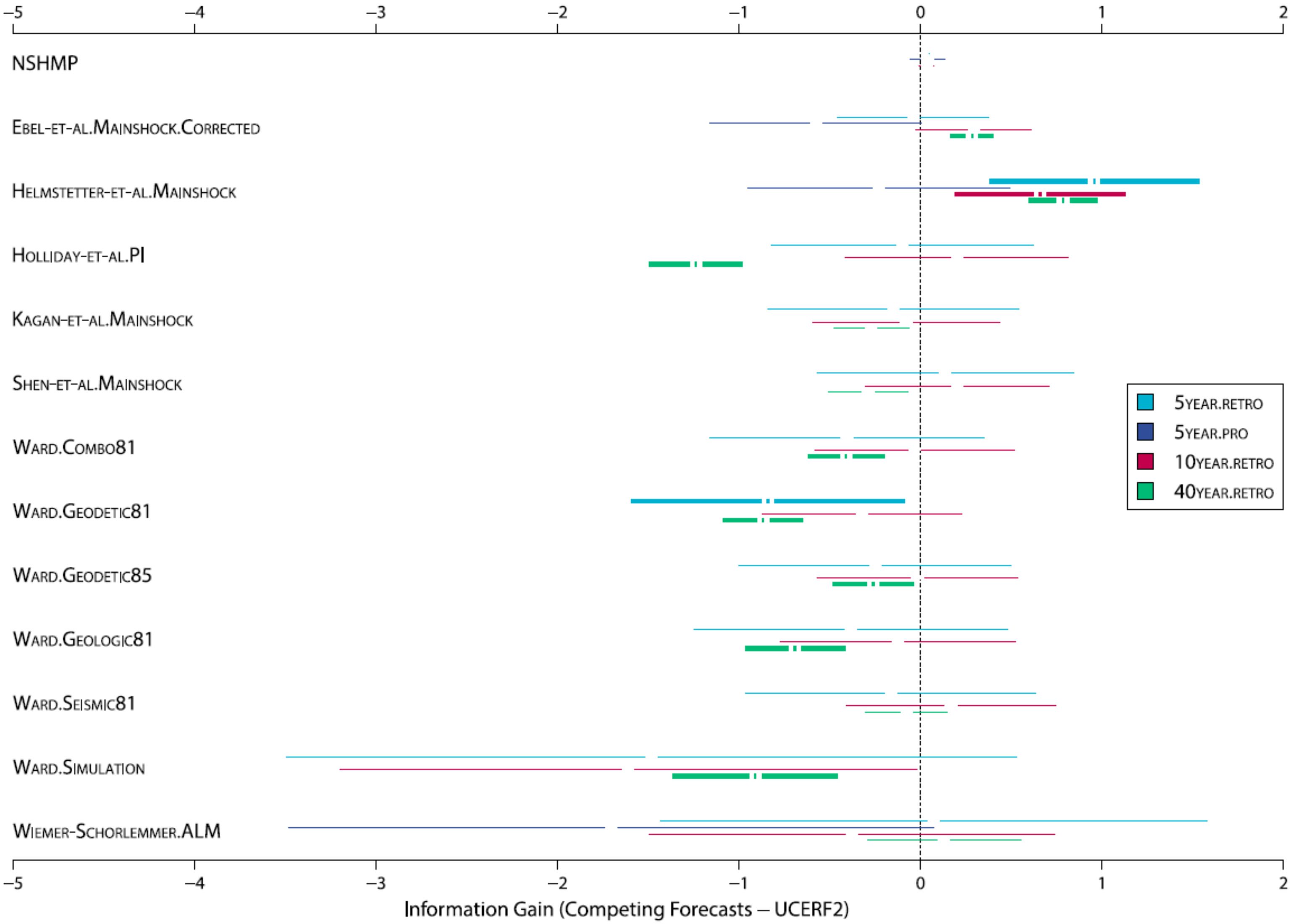
(Strader et al., 2017)

CSEP Consistency Test Results: S-Test



(Strader et al., 2017)

CSEP Comparative Test Results (T, W-Tests)



(Strader et al., 2017)

Log-Likelihood Scores at Target Earthquake Locations

Table 4. Log-likelihood scores at observed earthquake locations during the 10YEAR.RETRO experiment. Cells with light grey shading indicate the forecasts with the highest log-likelihood; cells with dark grey shading indicate the forecasts with the lowest scores. The numbers 1–14 along the top row correspond to the forecast models: (1) UCERF2, (2) NSHMP, (3) EBEL-ET-AL.MAINSHOCK.CORRECTED, (4) HELMSTETTER-ET-AL.MAINSHOCK, (5) HOLLIDAY-ET-AL.PI, (6) KAGAN-ET-AL.MAINSHOCK, (7) SHEN-ET-AL.MAINSHOCK, (8) WARD.COMBO81, (9) WARD.GEODETIC81, (10) WARD.GEODETIC85, (11) WARD.GEOLOGIC81, (12) WARD.SEISMIC81, (13) WARD.SIMULATION, and (14) WIEMER-SCHORLEMMER.ALM.

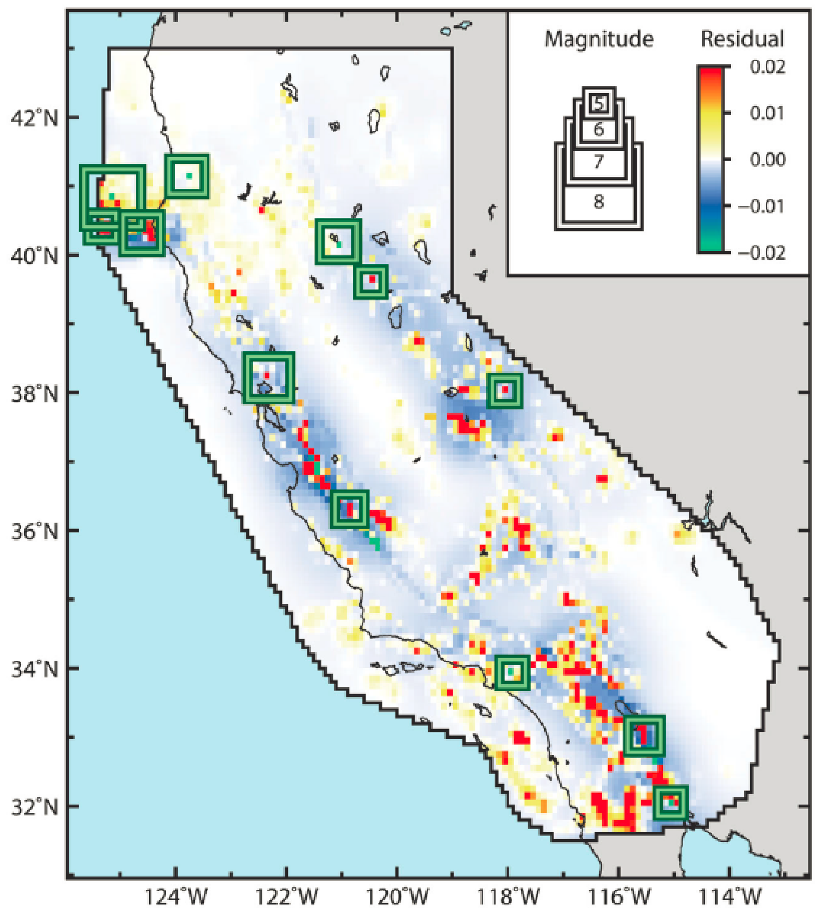
Experiment	Date	Magnitude	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	24.05.2006	5.37	-6.85	-6.85	-5.40	-4.02	-4.91	-6.55	-5.85	-5.42	-5.24	-5.79	-5.55	-5.49	-7.20	-3.85
	19.07.2006	5.00	-4.89	-4.89	-4.27	-3.68	-4.00									-3.90
	25.06.2007	5.00	-7.50	-7.37	-7.69	-7.11										-16.65
	31.10.2007	5.45	-7.09	-7.09	-5.32	-5.54	-5.14									-5.03
	09.02.2008	5.10	-6.29	-6.29	-4.88	-3.42	-4.23	-5.86	-5.16	-4.80	-4.62	-5.17	-4.93	-4.87	-9.64	-3.25
	30.04.2008	5.40	-8.72	-8.50	-8.40	-7.46										-6.36
	29.07.2008	5.39	-7.33	-7.33	-6.32	-6.35	-4.91	-6.87	-7.33	-6.25	-6.15	-6.71	-6.05	-6.63	-6.27	-6.22
	20.11.2008	4.98	-6.06	-6.06	-4.70	-4.45	-4.00	-5.43	-4.90	-4.56	-4.51	-5.06	-4.83	-4.40	-8.24	-3.78
5YEAR.RETRO	06.12.2008	5.06	-7.25	-7.25	-6.26	-6.21		-6.59	-6.12	-6.15	-5.47	-6.02	-7.63	-6.38	-12.09	-6.90
	19.09.2009	5.08	-13.28	-13.28	-10.44	-7.49	-9.14	-12.42	-11.01	-10.28	-9.93	-11.03	-10.55	-10.42	-19.97	-7.16
	01.10.2009	5.00	-7.11	-7.11	-6.99	-6.18	-4.00	-6.40	-7.04							-8.18
	03.10.2009	5.19	-7.48	-7.48	-7.35	-6.59	-4.46	-6.86	-7.50							-8.73
	30.12.2009	5.80	-7.73	-7.73	-7.31	-6.88	-5.83	-7.56	-7.14	-6.37	-6.11	-6.66	-6.49	-6.56	-5.68	-7.61
	10.01.2010	6.50	-10.03	-9.90	-7.78	-8.78	-7.44									-7.95
	04.02.2010	5.88	-6.56	-6.54	-5.88	-6.49	-6.06									-7.83
	04.04.2010	7.20	-7.69	-7.69	-8.59	-9.16	-9.05	-10.57	-10.05	-9.26	-8.95	-9.50	-9.50	-9.43	-10.89	-8.11
	07.07.2010	5.43	-6.75	-6.75	-5.07	-4.14		-6.36	-7.04	-5.56	-6.09	-6.64	-5.35	-5.40	-4.67	-4.71
	18.02.2011	5.07	-6.42	-6.42	-5.23	-5.48		-5.35	-4.85	-4.55	-5.10	-5.40	-4.78	-11.29	-5.33	
	27.10.2011	5.06	-6.85	-6.85	-6.77	-7.72										-7.79
	13.02.2012	5.60	-8.98	-8.74	-8.06	-8.57										-8.44
	21.07.2012	5.19	-5.15	-5.13	-4.68	-2.82										-3.34
	26.08.2012	5.44	-6.01	-6.01	-5.63	-6.27		-6.17	-5.85	-5.40	-5.17	-5.72	-6.29	-5.13	-5.86	-7.36
5YEAR.PRO	21.10.2012	5.29	-6.06	-6.06	-6.83	-6.84	-4.68	-6.86	-5.91							-7.02
	13.02.2013	5.10	-6.61	-6.61	-4.78	-7.41										-9.18
	24.05.2013	5.69	-8.61	-8.61	-7.83	-8.22										-8.81
	10.03.2014	6.80	-11.62	-11.13	-9.09	-10.18										-20.06
	29.03.2014	5.10	-6.91	-6.91	-6.07	-6.56	-4.23	-6.10	-6.80	-5.84	-5.92	-6.47	-5.67	-5.95	-8.18	-7.91
	24.08.2014	6.02	-8.87	-8.87		-10.40										-11.35
	28.01.2015	5.72	-6.01	-6.00	-5.35	-4.83	-5.60									-3.81

(Strader et al., 2017)

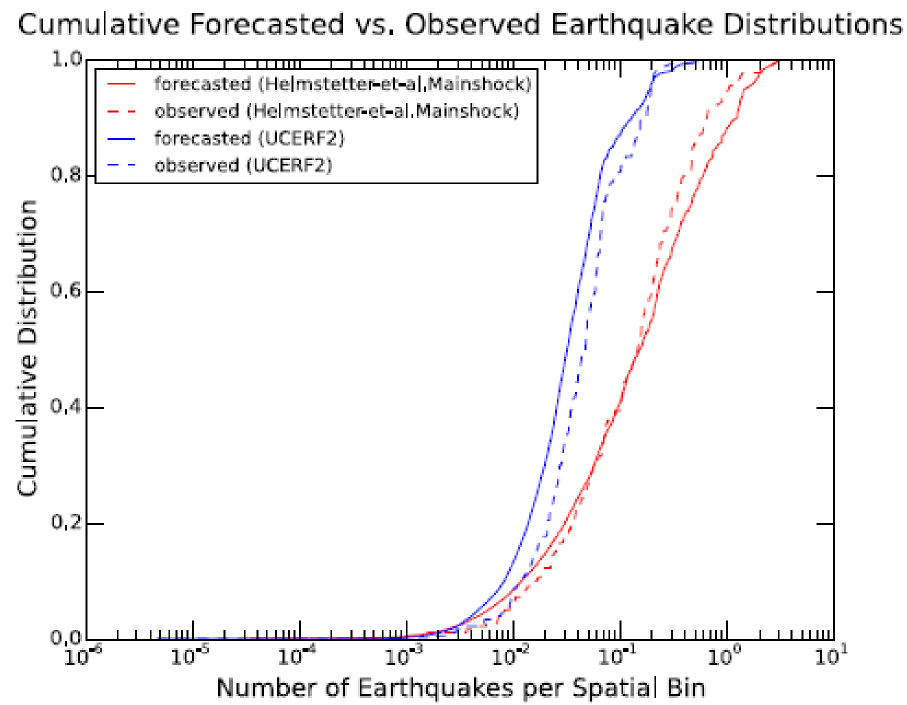
- UCERF2 has the lowest log-likelihoods for nine earthquakes, due to lower forecasted earthquake numbers compared to the RELM forecasts
- UCERF2 and NSHMP forecasts contain the highest log-likelihood at the location of the El Mayor Cucapah earthquake
- Helmstetter-et-al.Mainshock possesses the highest log-likelihoods for five events

Residual Analysis and Impact of Forecast Smoothness

Deviance Residuals (UCERF2-Helmstetter)



Concentration Plots



(Strader et al., 2017)

Conclusions

- USGS seismicity models passed all tests during five-year period; however, there is evidence of long-term underprediction from 40-year experiment results
  - UCERF3 addresses UCERF2's underestimated seismicity rates through implementation of elastic-rebound models and multi-fault ruptures, which increase the probability of large earthquakes along major known faults
- Five years is an insufficient amount of time to adequately assess long-term forecast performance in the RELM testing region
  - Temporal seismicity variations better fit by negative binomial distribution compared to Poisson; this could have contributed to unstable five-year test results
- Forecasts rejected in favor of UCERF2 during 40-year period only included southern California: are incorrect USGS model seismicity rates confined to central/northern California?
- Helmstetter-et-al.Mainshock model still (mostly) successful indicator of future earthquakes, but test results unstable over five-year intervals
- USGS, Helmstetter-et-al.Mainshock models each have advantages/disadvantages (geophysical vs. earthquake-catalog input data)