BDA Project: Hurricane forecasting in Stan

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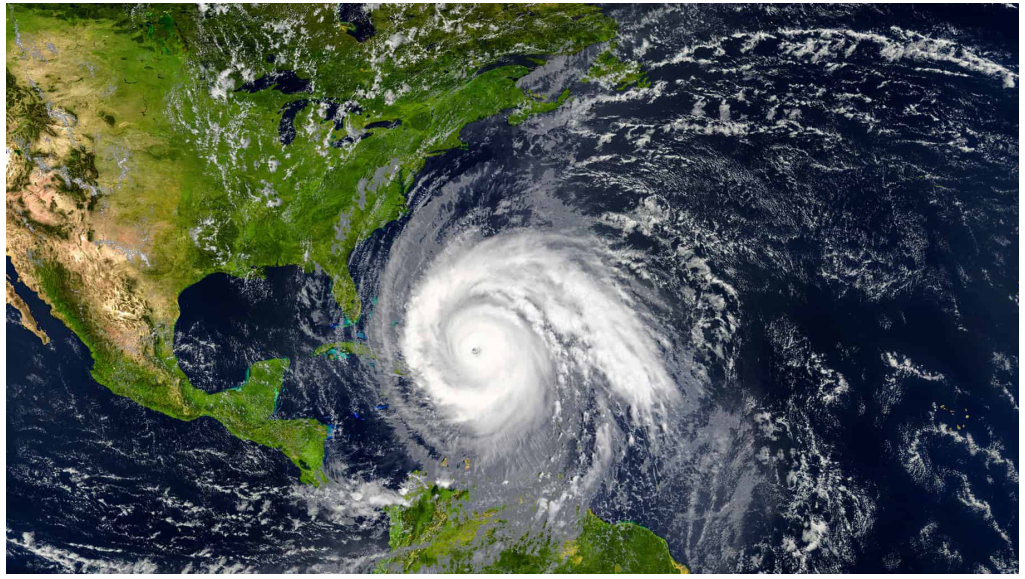
Aalto University

Hurricane introduction

- Destructive storms occuring in the late summer and fall in the northern hemisphere's tropical region.



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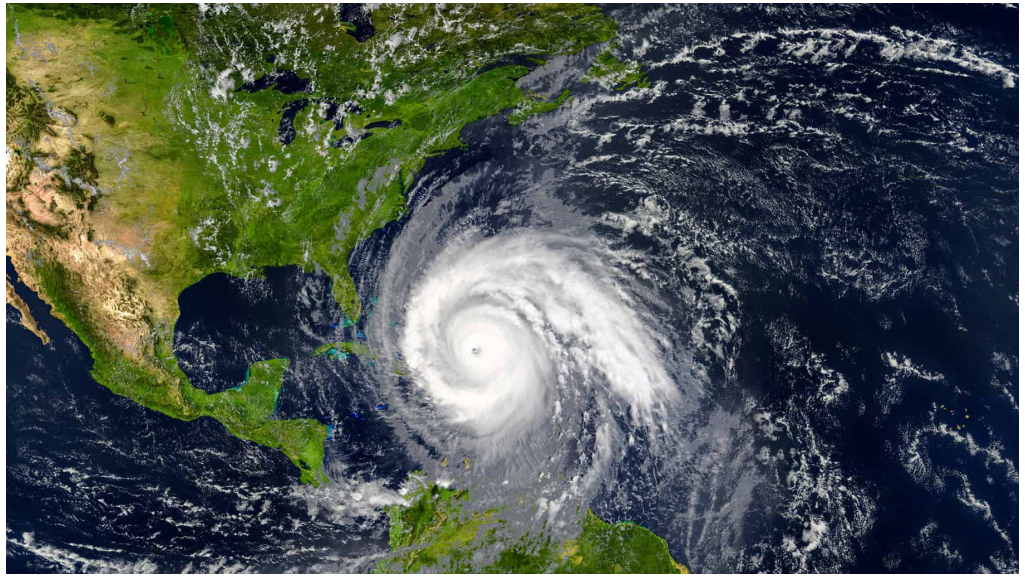

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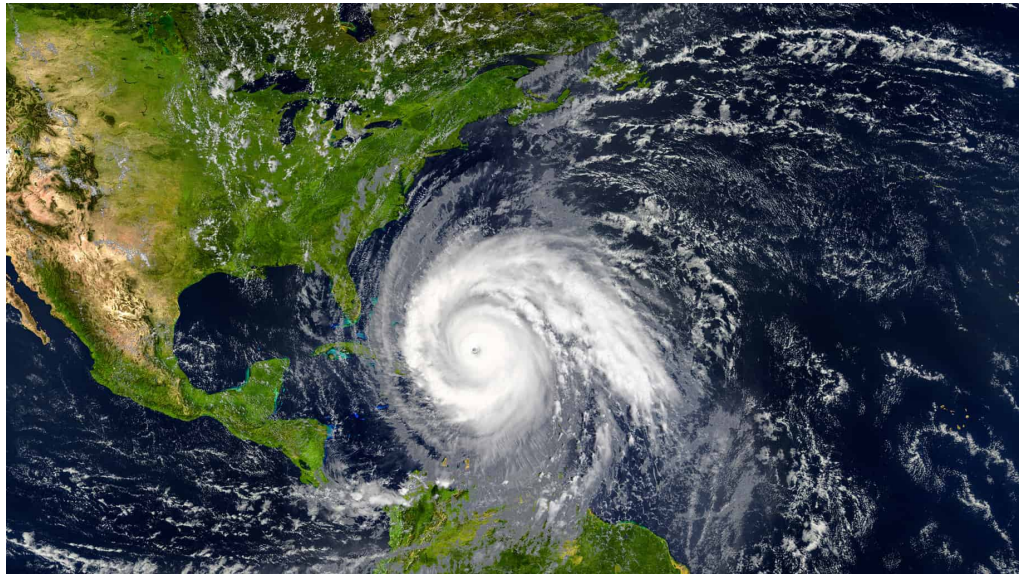

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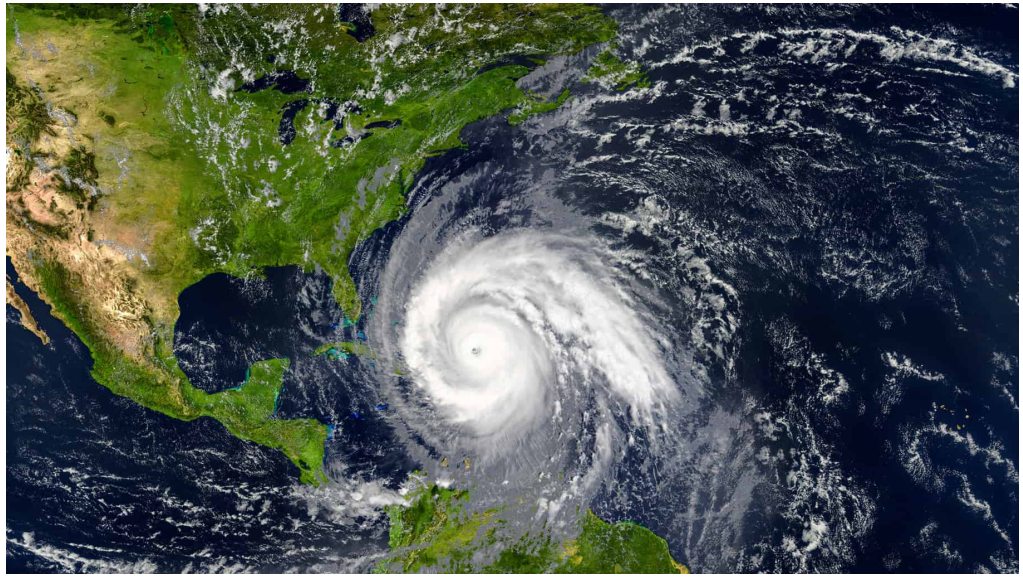
- Monetary damages and loss of lives increase with an almost exponential character as a function of storm intensity.



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- *Rapid intensification*: forecasted better by dynamical models
- This project: a *statistical* model for *intensity*

Hurricane forecasting basics: the SHIPS data

The US government forecasting agency, the National Hurricane Center (NHC), uses a large number of models operationally. The models (together: the *model ensemble*) are used together with experienced meteorologists' judgment to provide the official forecast.

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- SHIPS: only a point estimate; our project: a predictive distribution

Hurricane forecasting basics: the SHIPS data

The SHIPS developmental data is confusing!

```
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```

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T = 0

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		84	79	81	83	83	77	79	82	85	78	80	83	85	76	77	79	81	9999	9999	9999	9999	R000	
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		207	218	217	227	232	239	242	248	249	250	249	251	248	248	251	251	263	9999	9999	9999	9999	TLAT	
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T = 0

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9999	9999	280	280	278	276	274	270	269	272	274	272	271	271	270	269	268	267	266	9999	9999	9999	9999	RSST	0
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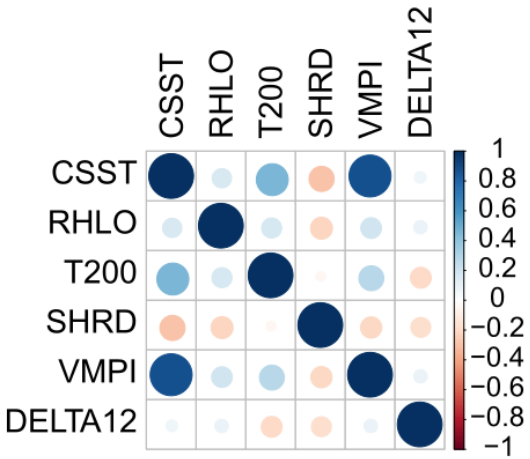
9999	9999	271	278	279	272	267	268	270	272	270	272	272	272	271	271	272	272	274	9999	9999	9999	9999	DSTA	1
		224	187	169	179	209	221	234	236	221	202	229	204	178	182	195	165	172	9999	9999	9999	9999	U200	
		238	162	153	143	139	170	206	158	108	94	125	102	132	149	159	120	212	9999	9999	9999	9999	U20C	
		99	96	163	101	134	164	126	-29	-39	3	-19	-68	-88	-54	-77	-149	-189	9999	9999	9999	9999	V20C	
		3528	3528	3535	3523	3488	3506	3513	3509	3512	3525	3524	3515	3505	3514	3523	3483	3477	9999	9999	9999	9999	E000	
		113	114	114	107	86	104	109	109	118	125	118	116	120	130	141	111	115	9999	9999	9999	9999	EPOS	
		8	9	8	9	11	10	10	10	10	10	9	10	11	11	10	14	14	9999	9999	9999	9999	ENEG	
		51	48	52	48	22	42	42	42	50	55	46	46	48	47	53	22	26	9999	9999	9999	9999	EPSS	
		16	20	18	18	21	23	21	19	18	22	20	19	19	25	23	28	26	9999	9999	9999	9999	ENSS	
		70	68	70	70	66	69	67	67	68	68	69	70	68	62	59	56	55	9999	9999	9999	9999	RHLO	
		57	53	56	59	53	55	51	51	48	48	46	46	43	37	34	33	32	9999	9999	9999	9999	RHMD	
		50	51	54	59	54	49	48	43	35	35	34	31	26	23	24	25	24	9999	9999	9999	9999	RHHI	
		548	31	23	24	13	28	16	40	23	64	82	77	89	92	85	208	200	79	9999	9999	9999	PSLV	
		7	17	0	-14	-8	14	-9	-37	-60	-47	-32	-52	-29	-30	0	-4	-20	9999	9999	9999	9999	Z850	
		64	65	84	70	51	114	42	27	-7	8	-17	-37	-48	-52	-25	-32	-41	9999	9999	9999	9999	D200	
		4	6	3	6	12	4	10	0	-16	-9	-3	-3	-2	2	7	0	-17	9999	9999	9999	9999	REFC	
		-1	0	-1	-1	-2	-1	0	1	1	1	1	2	3	2	3	4	6	9999	9999	9999	9999	PEFC	
		259	267	266	261	253	265	264	258	255	268	265	258	254	269	269	257	252	9999	9999	9999	9999	T000	
		84	79	81	83	83	77	79	82	85	78	80	83	85	76	77	79	81	9999	9999	9999	9999	R000	
		-27	-24	-31	-20	-20	-8	-16	-10	-8	-2	-18	-8	-8	-3	-7	4	8	9999	9999	9999	9999	Z000	
		207	218	217	227	232	239	242	248	249	250	249	251	248	248	251	251	263	9999	9999	9999	9999	TLAT	
		873	867	862	849	840	844	839	839	843	840	839	839	841	840	837	835	839	9999	9999	9999	9999	TLON	
		67	76	69	63	70	83	67	60	65	62	60	51	41	32	22	18	16	9999	9999	9999	9999	TWAC	
		100	104	106	110	110	138	114	102	109	101	98	84	73	62	42	32	34	9999	9999	9999	9999	TWXC	
		-5	-4	-1	-1	-1	0	0	0	0	0	-1	-2	-4	-3	-1	-1	-2	9999	9999	9999	9999	G150	
		3	4	11	12	8	7	9	10	5	3	1	0	-5	-6	-1	-1	2	9999	9999	9999	9999	G200	
		13	12	12	14	11	7	9	10	7	5	4	4	1	0	0	1	3	9999	9999	9999	9999	G250	
		44	38	33	23	18	27	21	18	18	25	14	10	15	13	2	3	13	9999	9999	9999	9999	V000	
		64	77	63	47	58	62	41	39	44	48	47	34	21	12	9	12	17	9999	9999	9999	9999	V850	
		67	63	84	70	62	78	79	52	32	22	18	-25	-22	-17	-24	-19	-34	9999	9999	9999	9999	V500	

Hurricane forecasting basics: our selection

We have not done statistical variable selection. Choice of variable subset is based on theory.

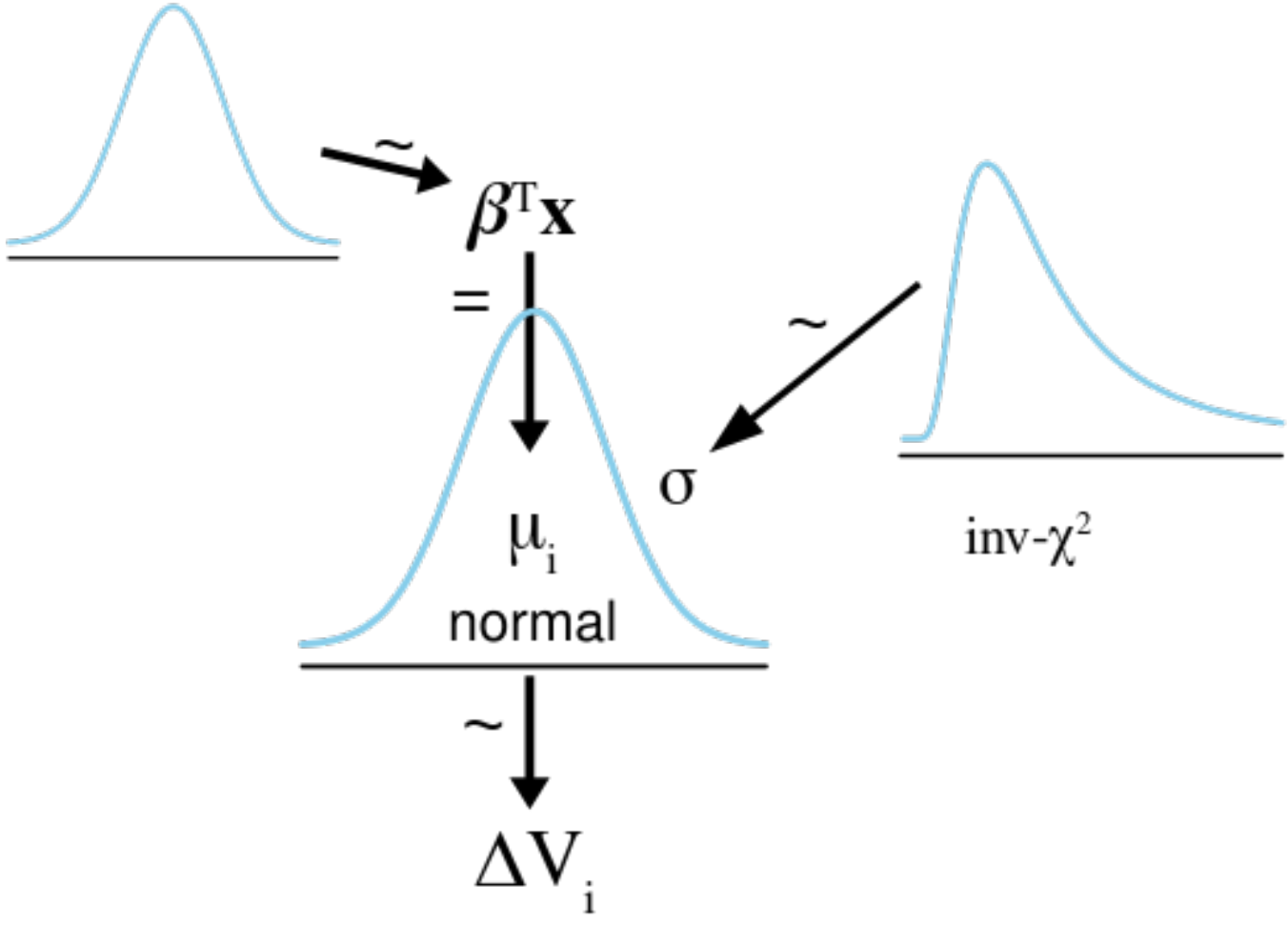
- **CSST**: (climatological) sea surface temperature
- **RHLO**: low-altitude relative humidity
- **T200**: air temperature at 200 mb (very high altitude)
- **SHRD**: wind shear between 850 and 200 mb
- **VMPI**: maximum potential intensity



- for testing, we have variable sets *A*, *B*, *C*
- *A*: LAT/LON, VMAX, CSST, SHRD
- *B*: LAT/LON, VMAX, CSST, SHRD, VMPI
- *C*: LAT/LON, VMAX, CSST, SHRD, VMPI, RHLO, T200

Intensity change predictive model

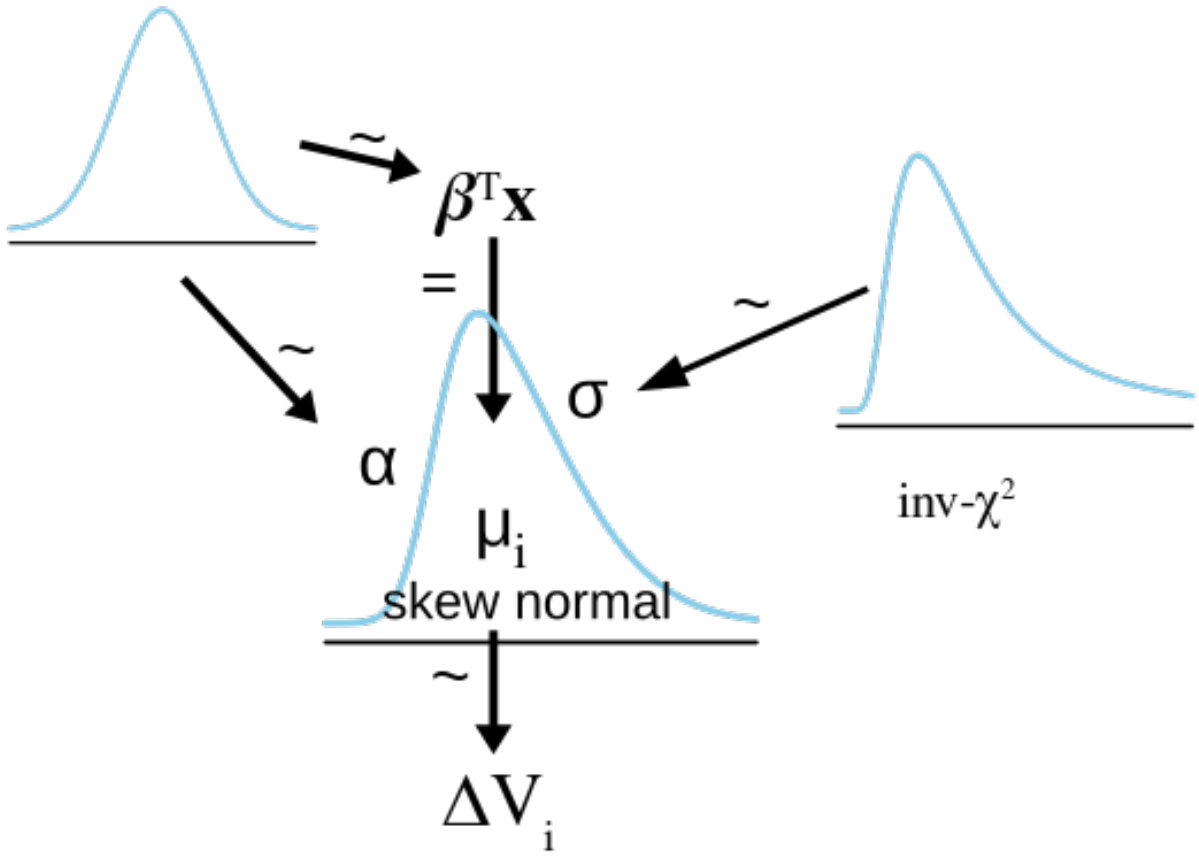
The SHIPS Blunder: a simple linear regression



Intensity change predictive model

Model 2: regression with skewness

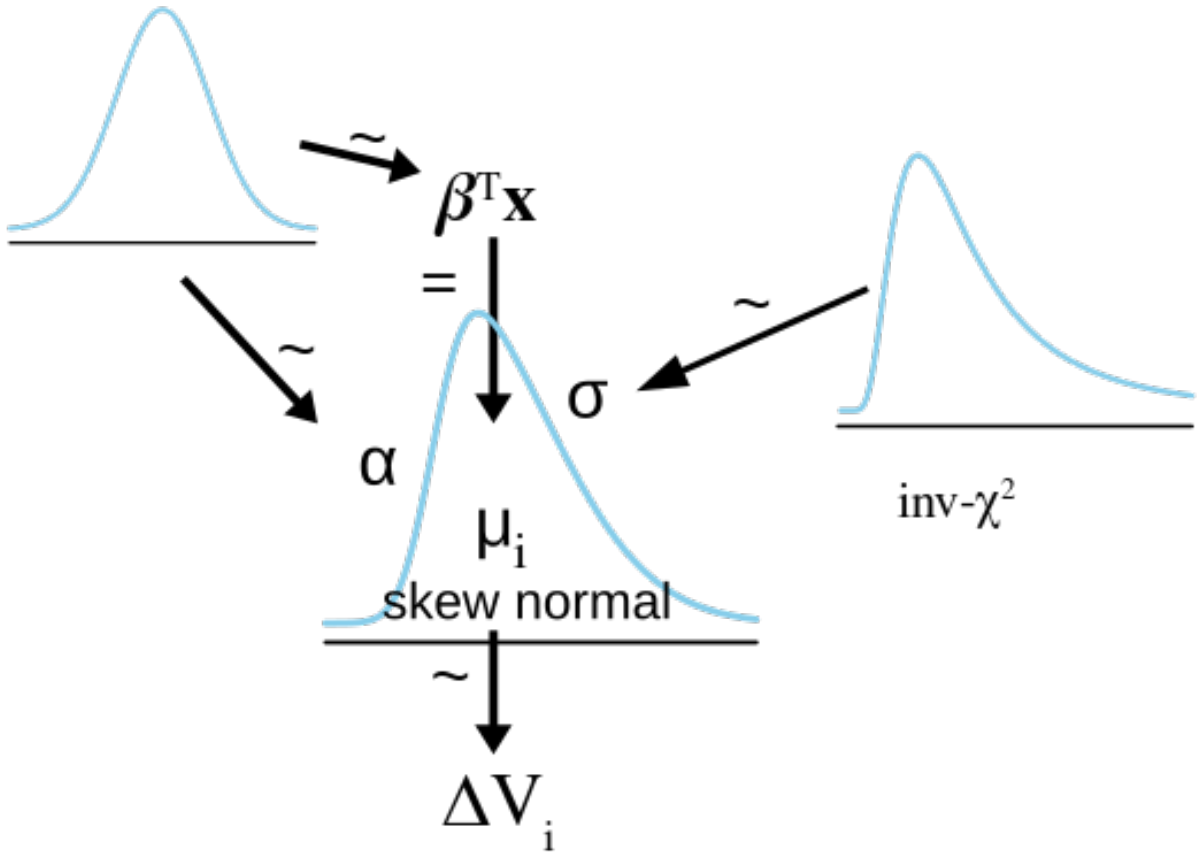
- errors not symmetric around the mean prediction!



Intensity change predictive model

Model 2: regression with skewness

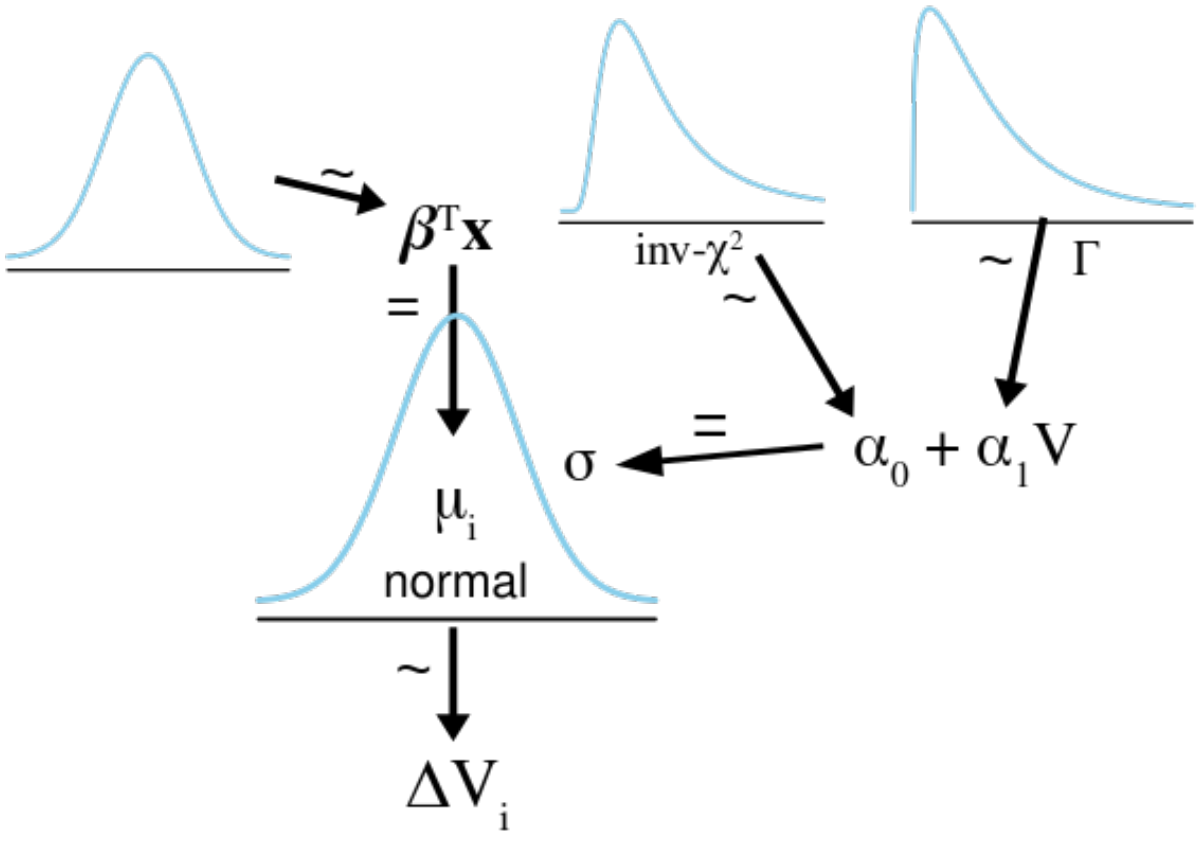
- errors not symmetric around the mean prediction!
- rapid intensification!



Intensity change predictive model

Model 3: regression with a linear model for standard deviation

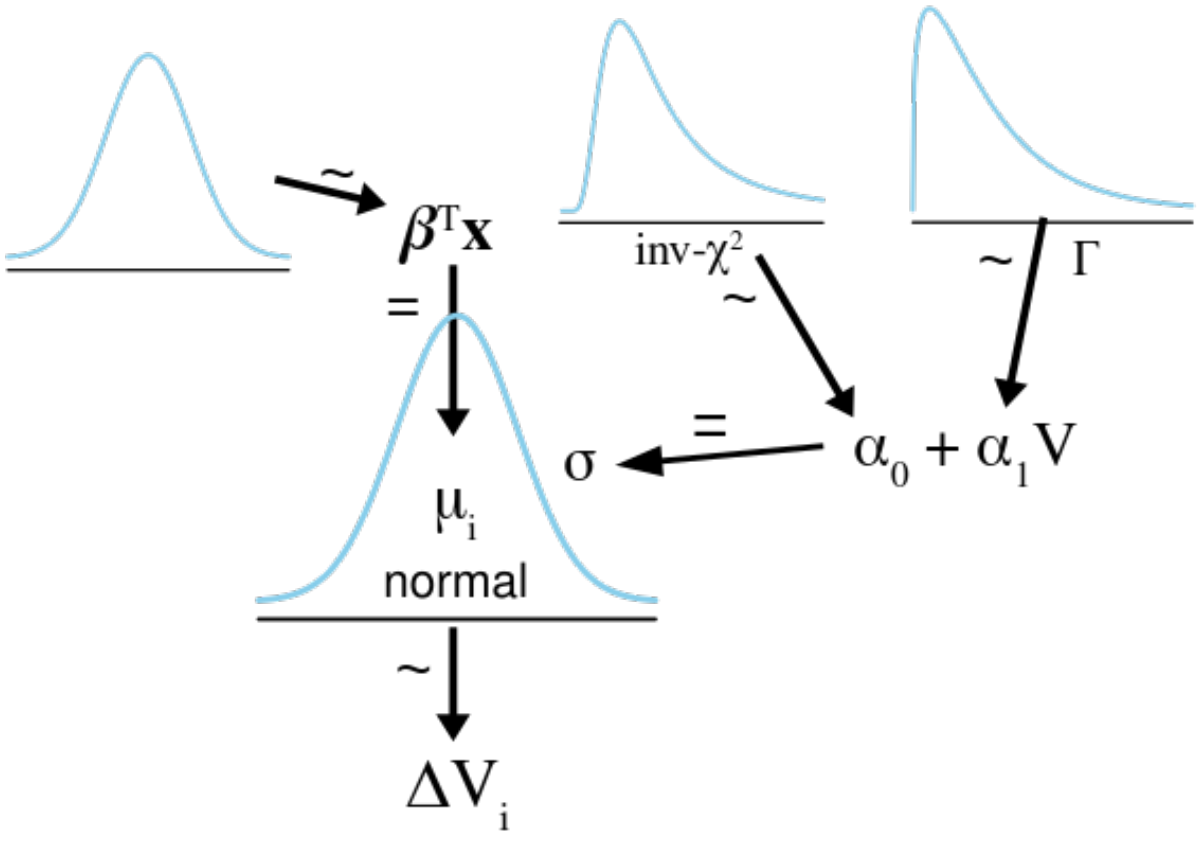
- fewer storms reach higher values of `VMAX`



Intensity change predictive model

Model 3: regression with a linear model for standard deviation

- fewer storms reach higher values of `VMAX`
- allow for higher variance to account for larger historical uncertainty



Models: some remarks

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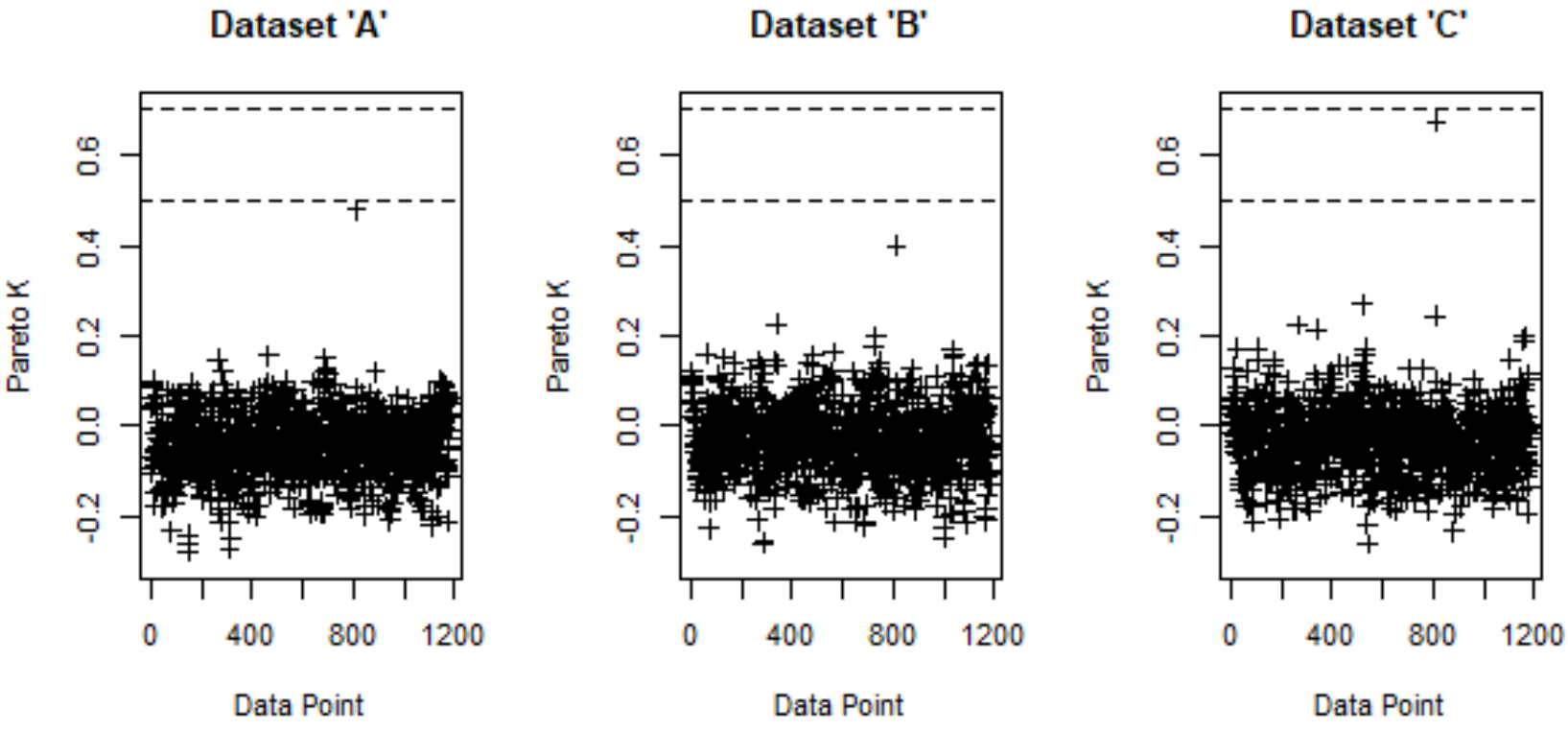
- poor problem setup! True model is the laws of physics, but we are fitting a regression
- models were programmed in Stan; sampling with `rstan` resulted in no divergences or issues except for the skew model and the issue was solved by increasing max tree depth to 15

Forecasting: Model Comparison (1)

Dataset comparison for the **linear regression model** (LOOCV)

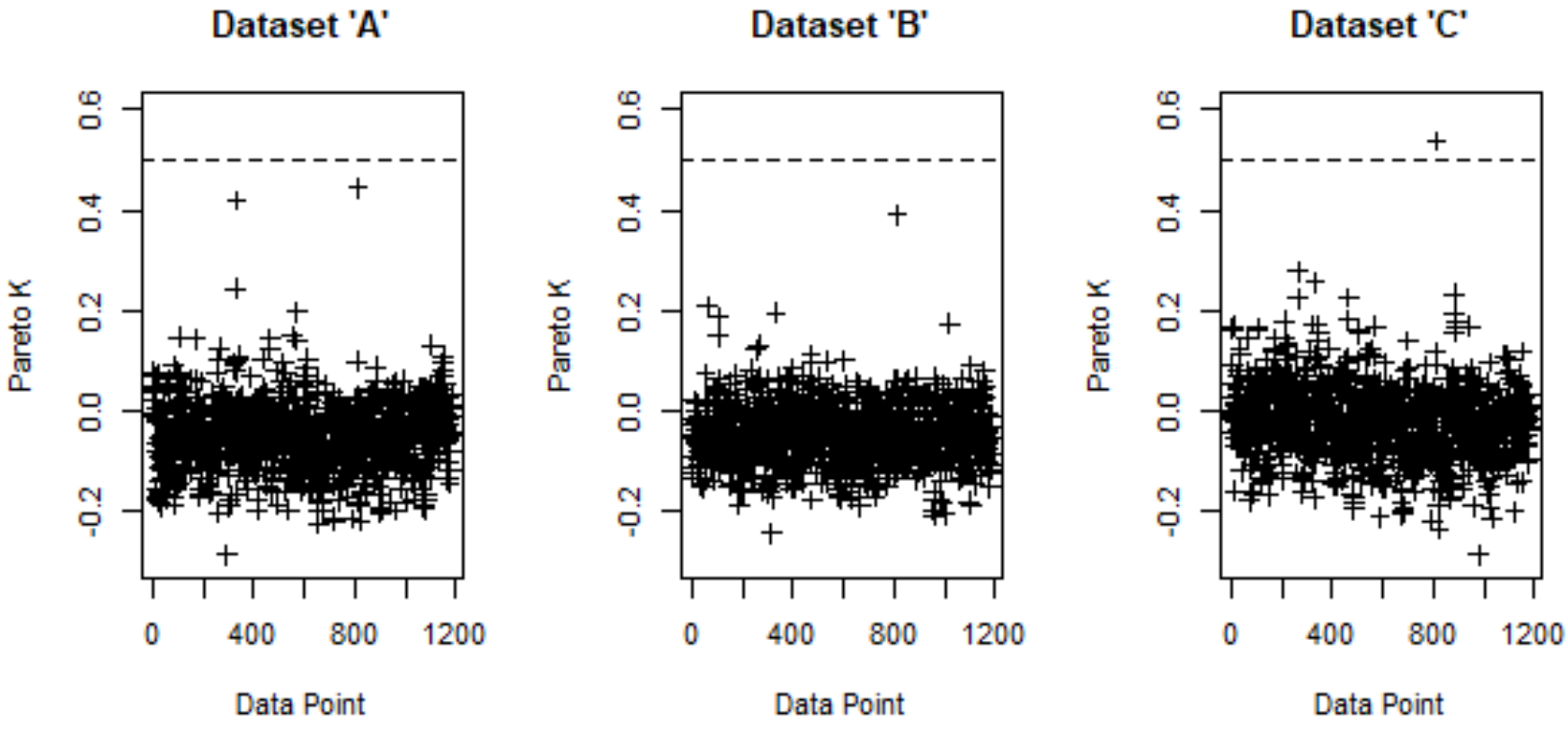
Dataset	**elpd_diff**	**se_diff**
C	0.0	0.0
B	-25.0	6.5
A	-27.4	6.3



Forecasting: Model Comparison (2)

Dataset comparison for the **skewed regression model** (LOOCV)

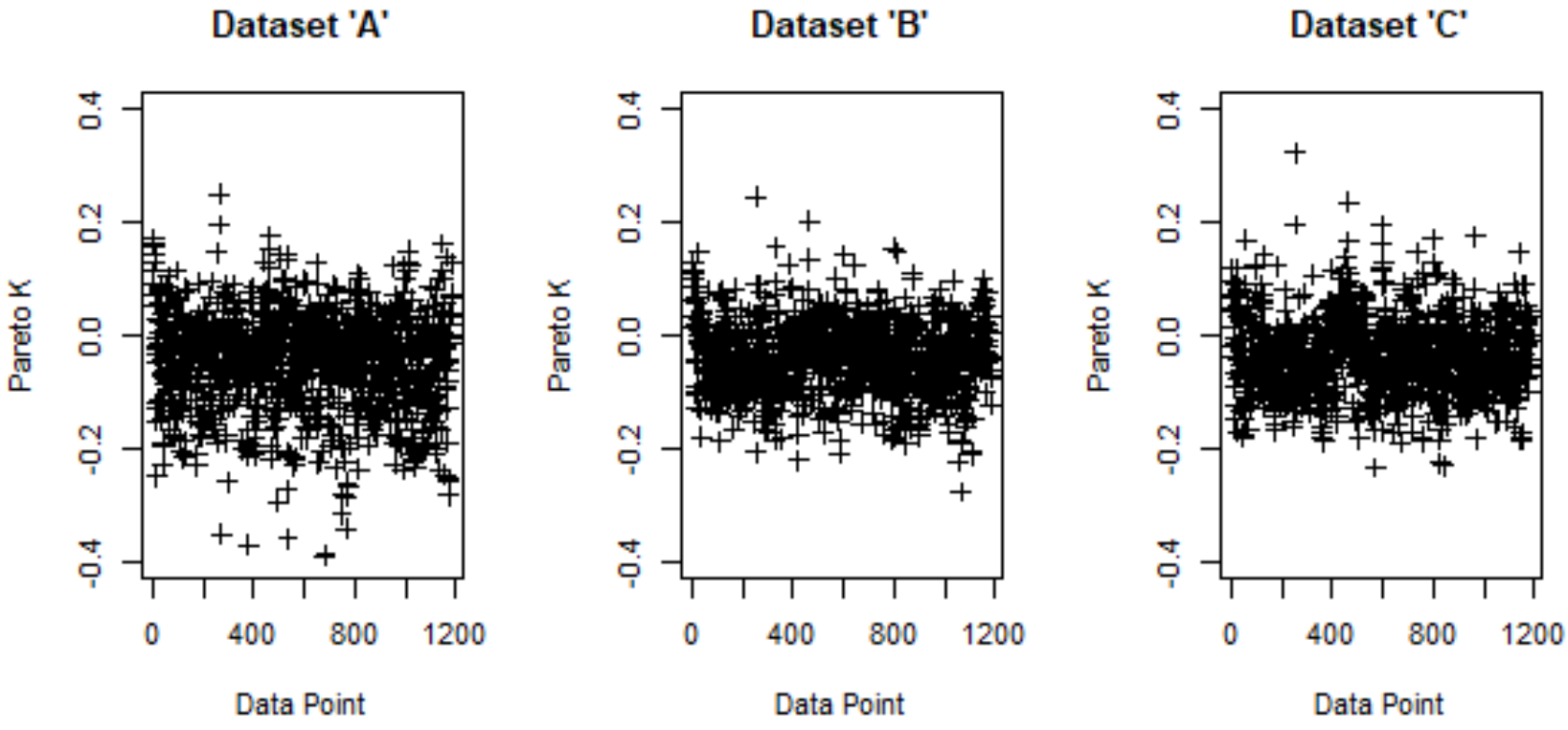
Dataset	**elpd_diff**	**se_diff**
C	0.0	0.0
B	-23.2	6.2
A	-28.7	6.2



Forecasting: Model Comparison (3)

Dataset comparison for the **Changing variance model** (LOOCV)

Dataset	**elpd_diff**	**se_diff**
C	0.0	0.0
B	-32.6	8.2
A	-37.1	8.2



Forecasting: Model Comparison (4)

Model comparison using the Dataset C (LOOCV)

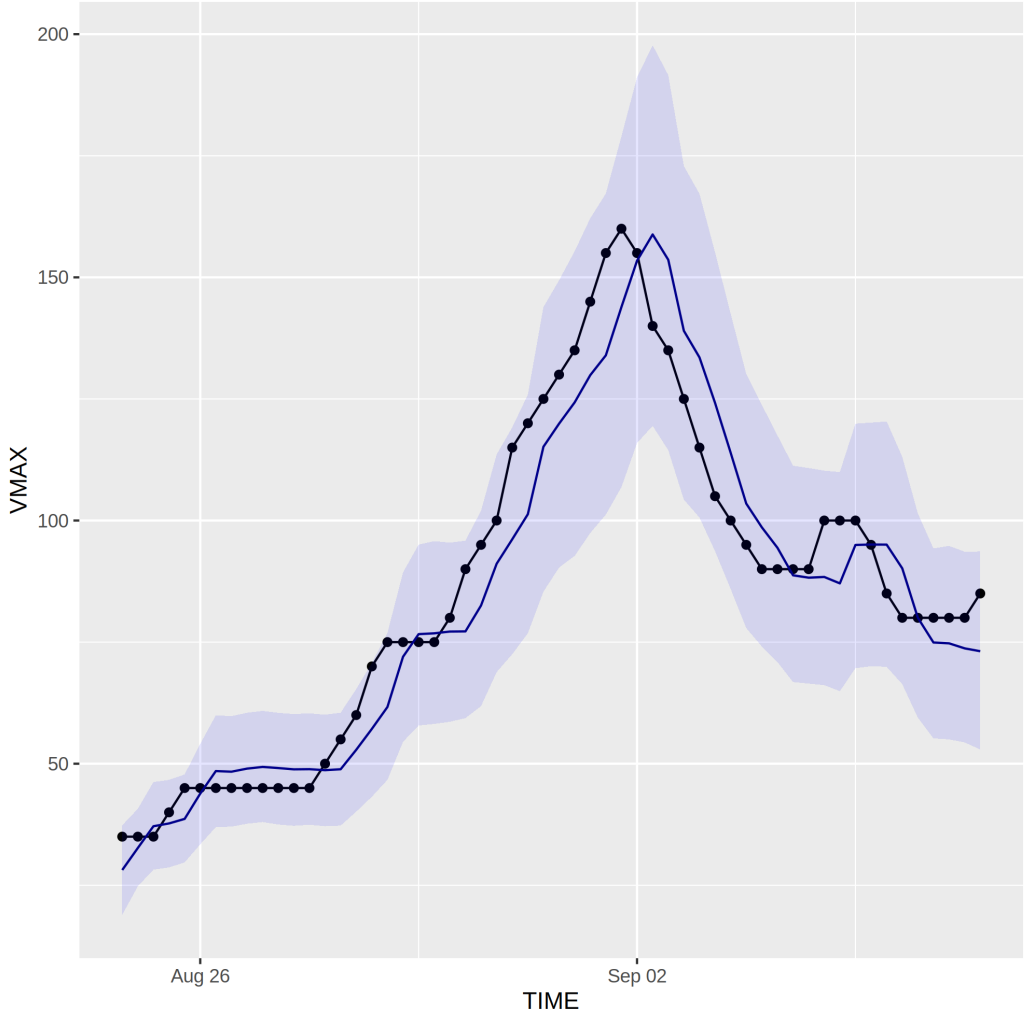
Model	**elpd_diff**	**se_diff**
Variance	0.0	0.0
Skew	-176.3	27.8
Linear	-205.5	34.9

Marginal posteriors

- θ_1: constant term
- θ_2, θ_3: latitude, longitude
- θ_4: sea surface temperature (CSST)
- θ_5: relative humidity (RHLO)
- θ_6: wind shear (SHRD)
- θ_7: maximum potential intensity (VMPI)
- θ_8: air temperature at 200 mb (T200)
- θ_9: intensity at storm core (VMAX)

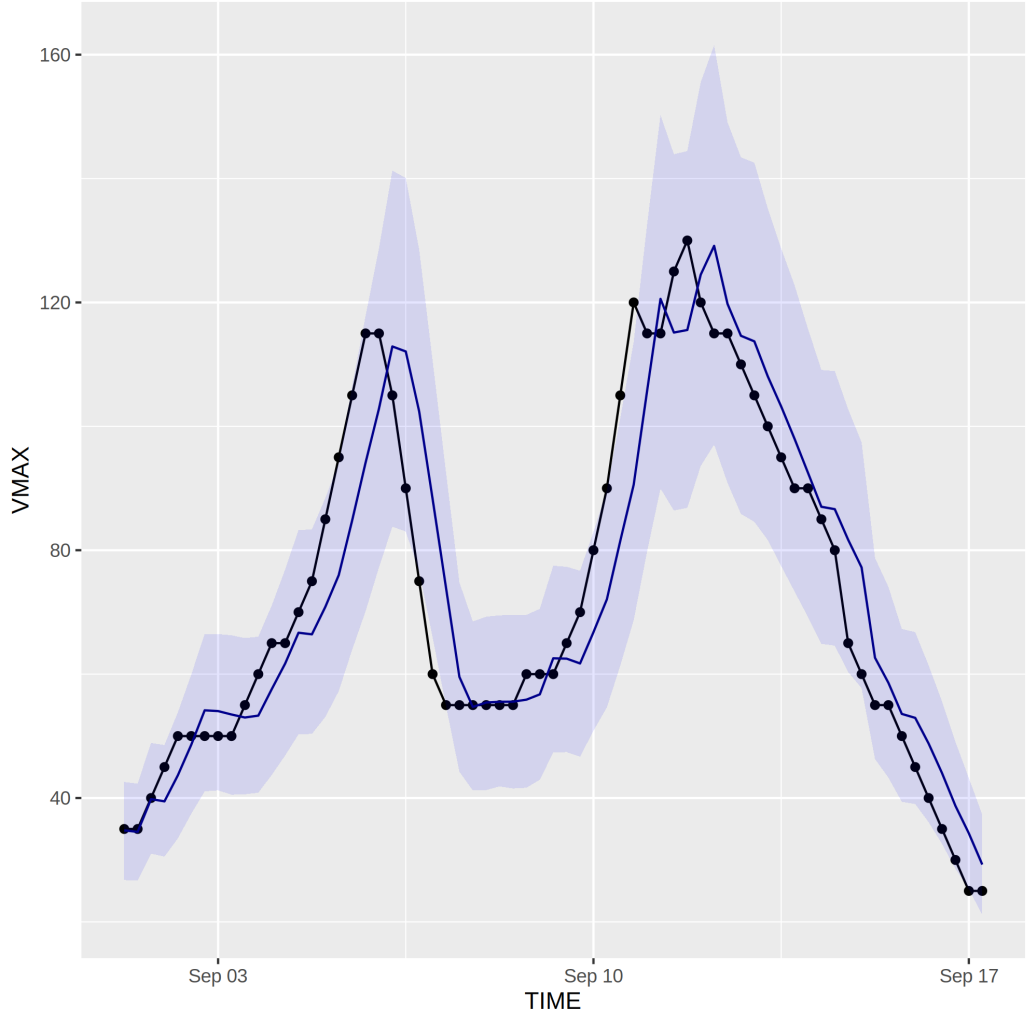
Forecasting: posterior predictive checks

Hurricane Dorian 2019. The image shows a 90% credible interval.
Black dotted line: true VMAX



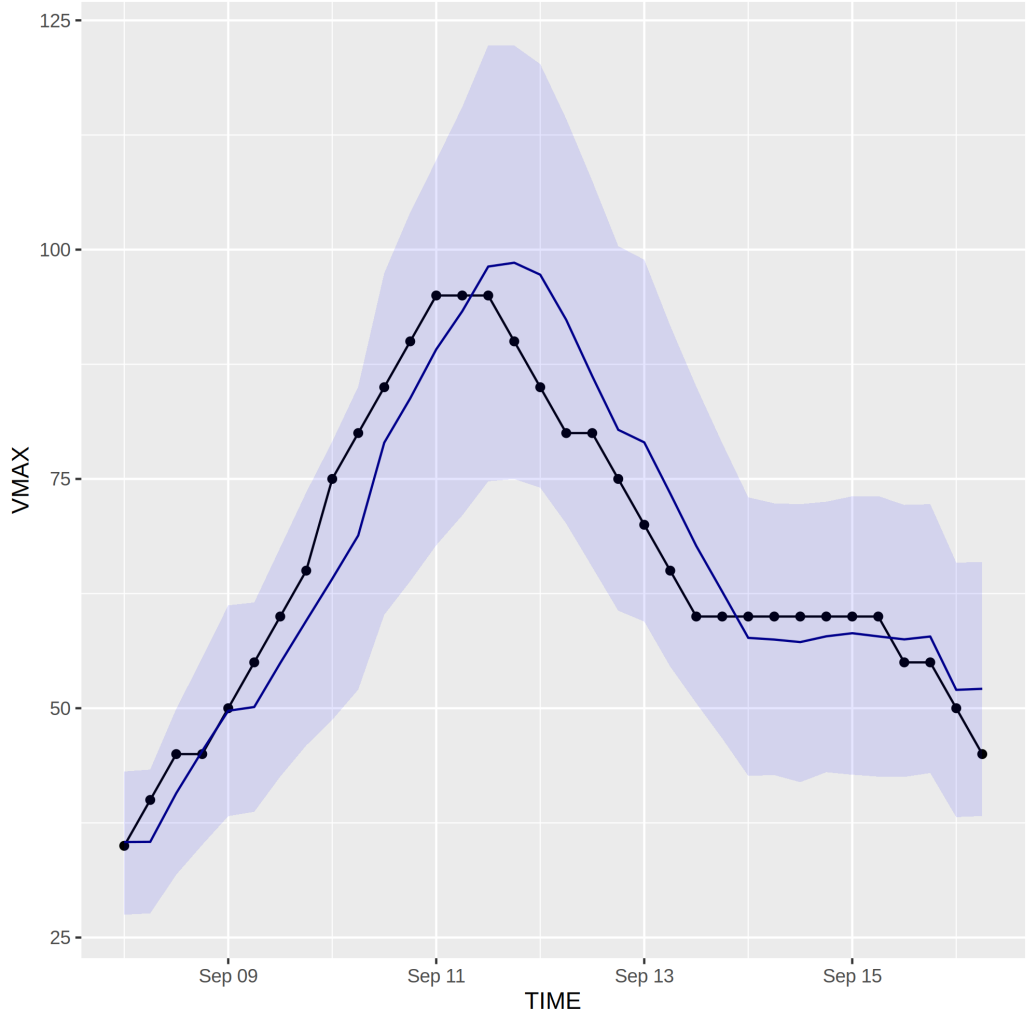
Forecasting: posterior predictive checks

Hurricane Florence 2018. The image shows a 90% credible interval.
Black dotted line: true VMAX



Forecasting: posterior predictive checks

Hurricane Helene 2018. The image shows a 90% credible interval. Black dotted line: true VMAX



Problems to solve & development ideas

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- more time series autoregressive components

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- variable selection in full SHIPS dataset
- more time series autoregressive components
- use LGEM model (will explain)

Conclusions & contact info

Additional information