

BDA Project: Hurricane forecasting in Stan

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Hurricane introduction

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- Classified by their wind intensity at the eye wall.
- They can cause extreme levels of flooding and destroy many buildings.
- 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

The SHIPS developmental data is confusing!

[illegible]

[illegible]

Hurricane forecasting basics: the SHIPS data

We are making *synoptic* models and choosing variables.

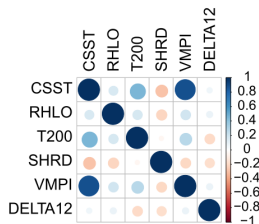
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9999	9999	297	218	217	227	232	239	242	248	249	250	249	251	248	248	251	251	263	9999	9999	9999	9999	9999	TLAT	
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Hurricane forecasting basics: our selection

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

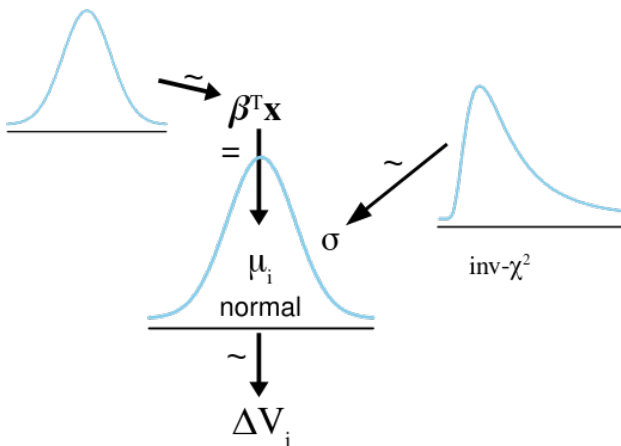


- for testing, we have variable sets *A*, *B*, *C*
- *A*: LAT/LON, VMAX, CSST, SHRD
- *B*: LAT/LON, VMAX, CSST, SHRD, VMPI
- *C*: LAT/LON, VMAX, CSST, SHRD, VMPI, RHLO, T200

Intensity change predictive model

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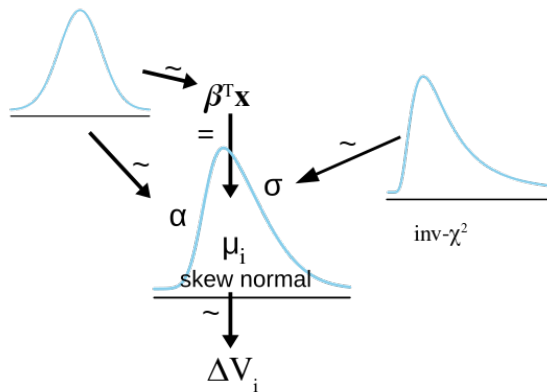
The SHIPS model: a simple linear regression



Intensity change predictive model

Model 2: regression with skewness

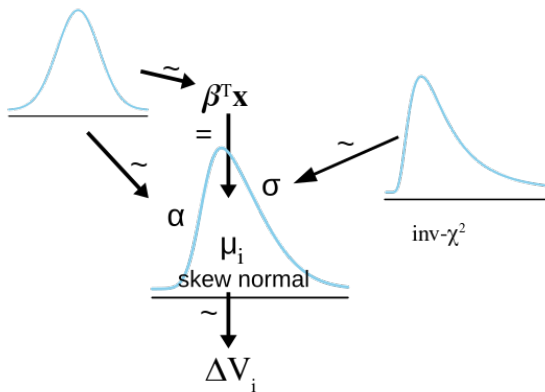
- errors not symmetric around the mean prediction!



Intensity change predictive model

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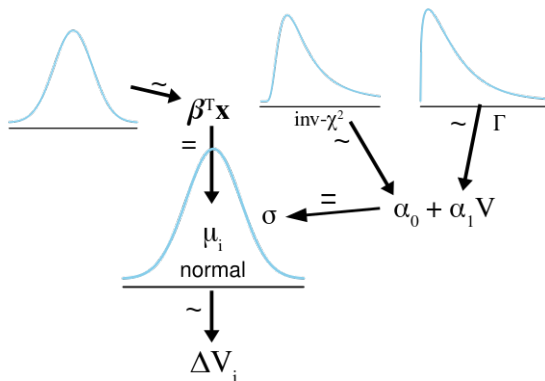
- errors not symmetric around the mean prediction!
- rapid intensification!



Intensity change predictive model

Model 3: regression with a linear model for standard deviation

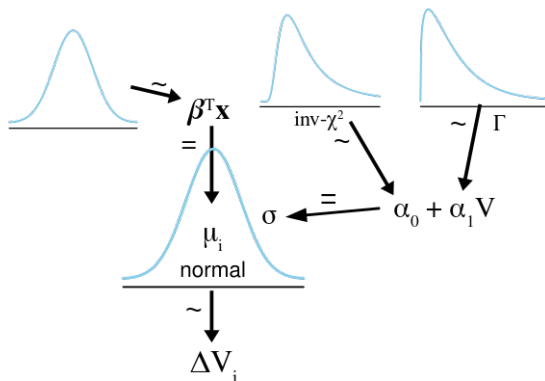
- fewer storms reach higher values of VMAX



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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Models: some remarks

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- SHIPS data: 1982-2019; our restriction: 2017-2019
- poor problem setup! True model is the laws of physics, but we are fitting a regression
- models were programmed in Stan; sampling with `rstan` using default parameters; resulted in no divergences or issues except for the skew model and it was solved by increasing max tree depth to 15

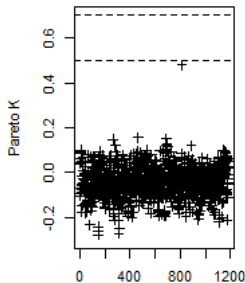
Forecasting: Model Comparison

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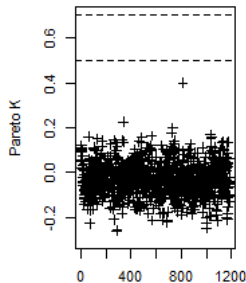
Dataset comparison for the **linear regression model** (LOOCV)

Dataset	elpd_diff	se_diff
<i>C</i>	0.0	0.0
<i>B</i>	-25.0	6.5
<i>A</i>	-27.4	6.3

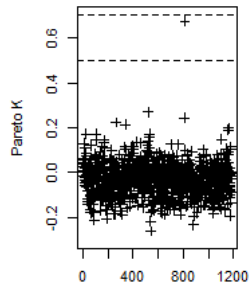
Dataset 'A'



Dataset 'B'



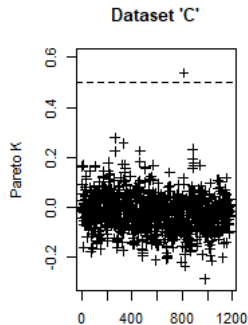
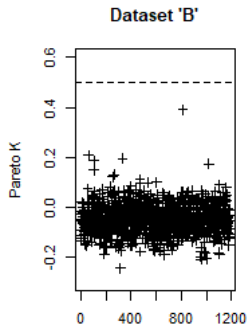
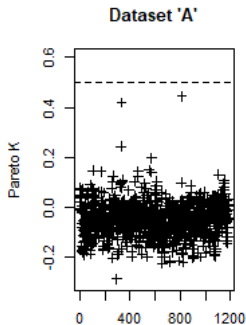
Dataset 'C'



Forecasting: Model Comparison (2)

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

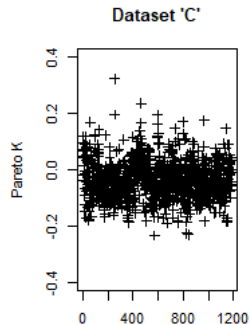
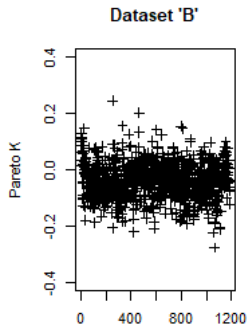
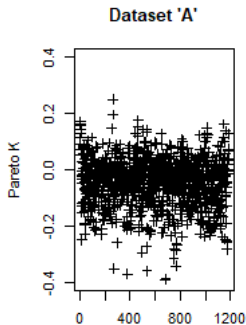
Dataset	elpd_diff	se_diff
C	0.0	0.0
<i>B</i>	-23.2	6.2
<i>A</i>	-28.7	6.2



Forecasting: Model Comparison (3)

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

Dataset	elpd_diff	se_diff
C	0.0	0.0
<i>B</i>	-32.6	8.2
<i>A</i>	-37.1	8.2

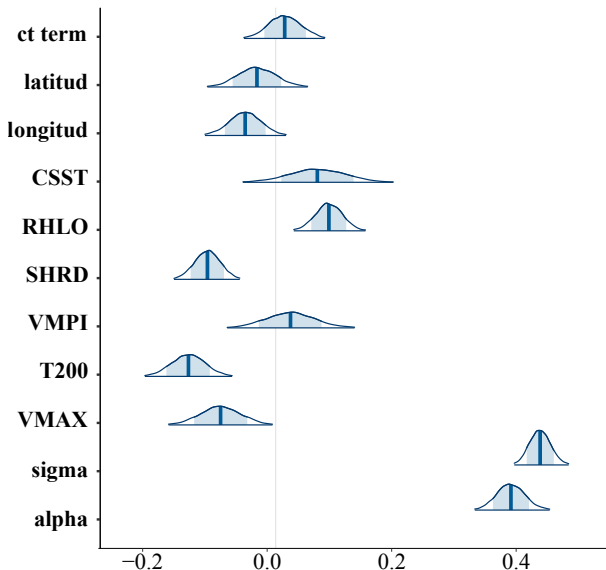


Forecasting: Model Comparison (4)

Model comparison using the Dataset C (LOOCV)

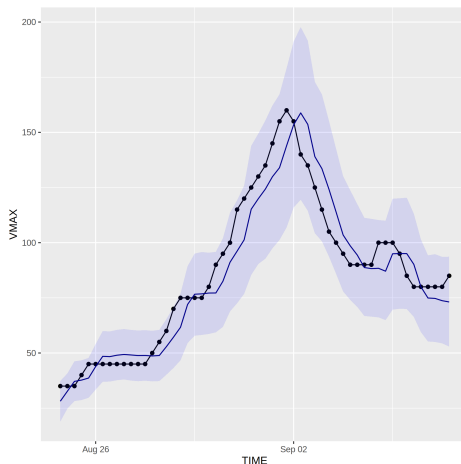
Model	elpd_diff	se_diff
Variance	0.0	0.0
Skew	-176.3	27.8
Linear	-205.5	34.9

Marginal posteriors



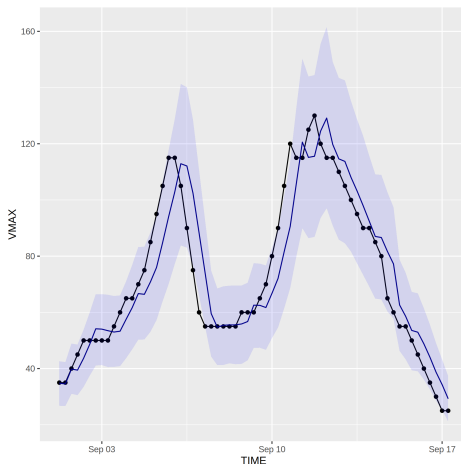
Forecasting: checking predictions

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



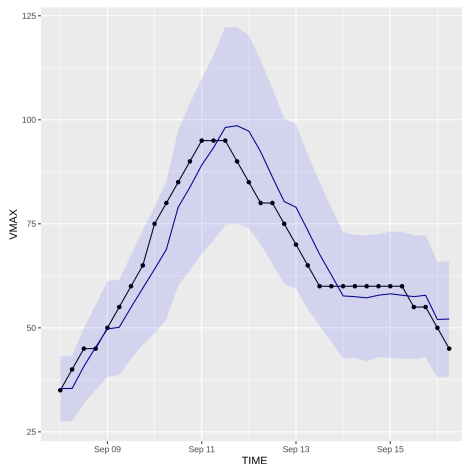
Forecasting: checking predictions

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



Forecasting: checking predictions

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



Concluding section

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Further development ideas:

- variable selection in full SHIPS dataset

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- more time series autoregressive components

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Further development ideas:

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

A final takeaway

Talking about the 2017 category 5 hurricane Irma:

“The hurricane will be moving through an environment of low vertical wind shear, a moist mid-level atmosphere, and increasing upper-ocean heat content, and this is ideal for some additional intensification. However, given that the SHIPS models do not show any significant change in the intensity, the NHC forecast keeps Irma a powerful hurricane through five days.” — NHC 5AM advisory Sep. 5th

While the NHC published the advisory, Irma was undergoing rapid intensification from 130 to 175 knots over a span of only a few hours.

Conclusions & contact info

- Takeaway: the SHIPS model is terrible!
- Simple changes to the predictive distribution can improve the model
- Further development using Bayesian methods seems promising and there are several possible directions

More at our Github repo:

<https://github.com/jnlb/bda-hurricane-modeling>

The SHIPS website: http://rammb.cira.colostate.edu/research/tropical_cyclones/ships/index.asp

Contact info:

José Miguel Ramírez

- rocket-chat: @jose

Jonas Lindblad

- rocket-chat: @jnlb

Additional information

The SHIPS model:

$$y_i \sim \mathcal{N}(\alpha + X_i \cdot \beta_{N-1}, \sigma), \quad i = 1, \dots, r,$$

where we let X_i denote the i :th row of the data, β_{N-1} is an $N - 1$ -dimensional parameter vector, and r is the number of observations (rows) in the data. Its priors were

$$\begin{bmatrix} \alpha_0 \\ \beta_{N-1,0} \end{bmatrix} \sim \mathcal{N}(\mathbf{0}_N, 10 \cdot \mathbf{I}_N), \sigma_0 \sim \text{Inv-}\chi^2\left(\frac{1}{10}\right).$$

The skew-normal regression model:

$$y_i \sim \text{SkewNormal}(\alpha + X_i \cdot \beta_{N-1}, \sigma, \psi), \quad i = 1, \dots, r,$$

with priors

$$\begin{bmatrix} \alpha_0 \\ \beta_{N-1,0} \end{bmatrix} \sim \mathcal{N}(\mathbf{0}_N, 10 \cdot \mathbf{I}_N), \sigma_0 \sim \text{Inv-}\chi^2\left(\frac{1}{10}\right), \psi_0 \sim \mathcal{N}(0, 1).$$

Additional information

The variance model:

$$y_i \sim \mathcal{N}(\alpha + X_i \cdot \beta_{N-1}, \sigma + \gamma |V_{\max,i}|), \quad i = 1, \dots, r,$$

where, again, we use the same notation as before and let $V_{\max,i}$ denote the V_{\max} -value of the i :th row. The priors that were fed into Stan were

$$\begin{bmatrix} \alpha_0 \\ \beta_{N-1,0} \end{bmatrix} \sim \mathcal{N}(\mathbf{0}_N, 10 \cdot \mathbf{I}_N), \quad \sigma_0 \sim \text{Inv-}\chi^2\left(\frac{1}{10}\right), \quad \gamma_0 \sim \Gamma(1, 1).$$

Additional information

The variance regression was run in rstan with the following options

```
variance_m <- rstan::stan_model(file = file.path(mod_path,  
  "minimal3.stan"))  
variance_model <- rstan::sampling(variance_m,  
  data = stan_data,  
  control = list(max_treedepth = 10),  
  iter=4000, seed = SEED)
```

LGEM model

The Logistic Growth Equation Model models the intensity as

$$V_t = V_0 \left[1 + \alpha \beta t \left(\frac{V_0}{V_{mpi}} \right)^\beta \right]^{(-1/\beta)},$$

where α, β are parameters to be fitted.

Reference: *A Simplified Dynamical System for Tropical Cyclone Intensity Prediction*, M. DeMaria, *Monthly Weather Review, 2009.

Additional information

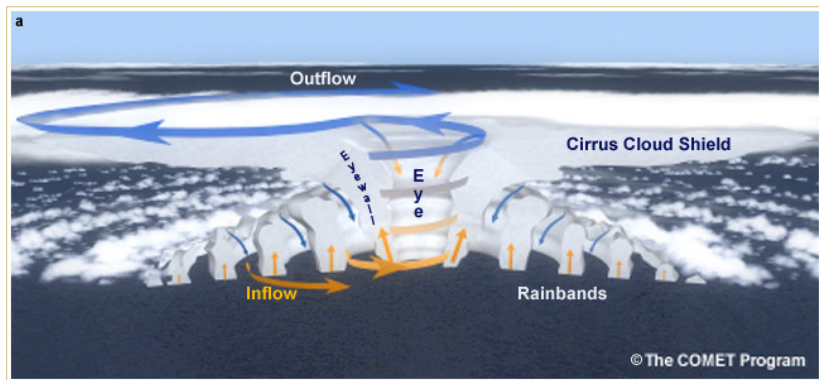


Image from *Introduction to Tropical Meteorology, 2nd Ed.*, 2011, by A. Laing & J-L Evans.

Additional information

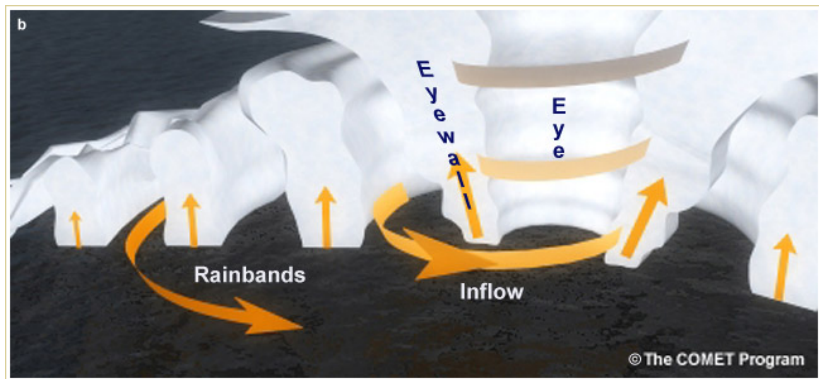


Image from *Introduction to Tropical Meteorology, 2nd Ed.*, 2011, by A. Laing & J-L Evans.