

Model checking – overview

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- External validation
 - compare predictions to completely new observations
 - cf. relativity theory predictions
- Internal validation
 - posterior predictive checking
 - cross-validation predictive checking

Chapter 6

- 6.1 The place of model checking in applied Bayesian statistics
- 6.2 Do the inferences from the model make sense?
- 6.3 Posterior predictive checking
- 6.4 Graphical posterior predictive checks
 - this can be skimmed, see instead the paper
Gabry et al. (2019). *Visualization in Bayesian workflow*
<https://doi.org/10.1111/rssa.12378>
- 6.5 Model checking for the educational testing example

Model checking

- demo6_1: Posterior predictive checking - light speed
- demo6_2: Posterior predictive checking - sequential dependence
- demo6_3: Posterior predictive checking - poor test statistic
- https://avehtari.github.io/BDA_R_demos/demos_rstan/brms_demo.html

Simon Newcomb's light of speed experiment in 1882

Newcomb measured ($n = 66$) the time required for light to travel from his laboratory on the Potomac River to a mirror at the base of the Washington Monument and back, a total distance of 7422 meters.

Posterior predictive checking – example

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 - model $y \sim \text{normal}(\mu, \sigma)$ with prior $(\mu, \log \sigma) \propto 1$

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 - draw $\mu^{(s)}, \sigma^{(s)}$ from the posterior $p(\mu, \sigma|y)$

Posterior predictive checking – example

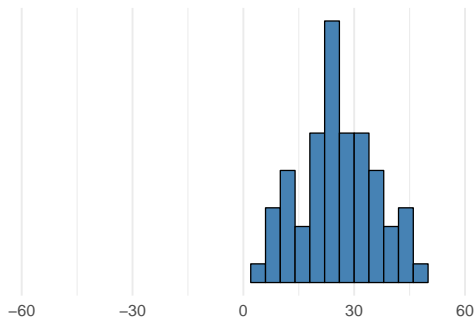
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Replicates vs. future observation

- Predictive \tilde{y} is the next not yet observed possible observation.
 y^{rep} refers to replicating the whole experiment (potentially with same values of x) and obtaining as many replicated observations as in the original data.

Posterior predictive checking – example

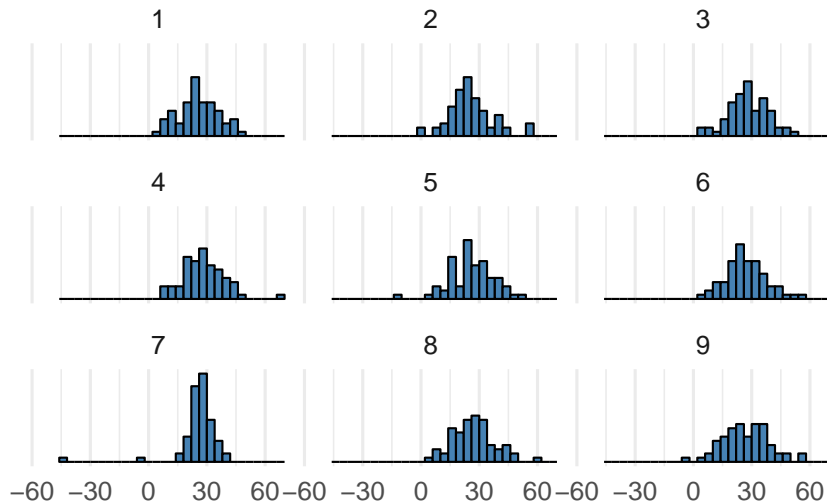
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Posterior predictive checking – example

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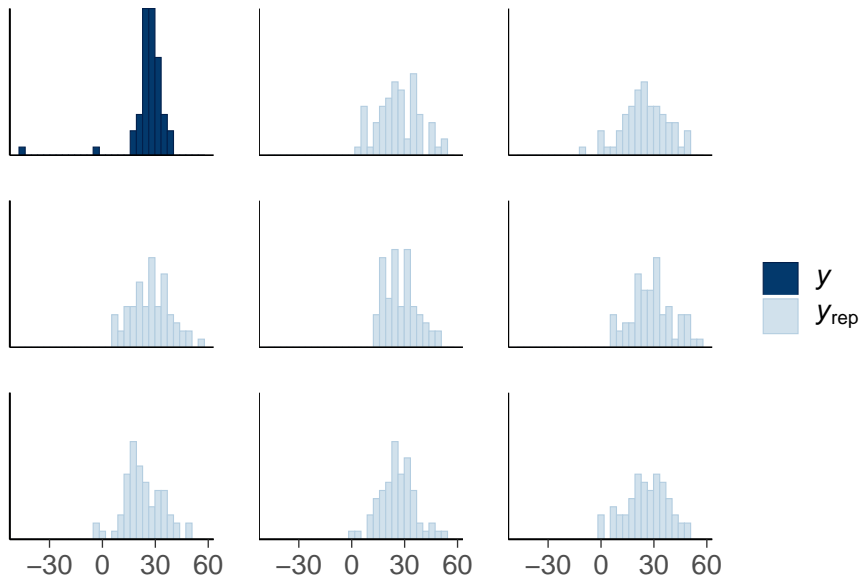
Posterior predictive checking – example

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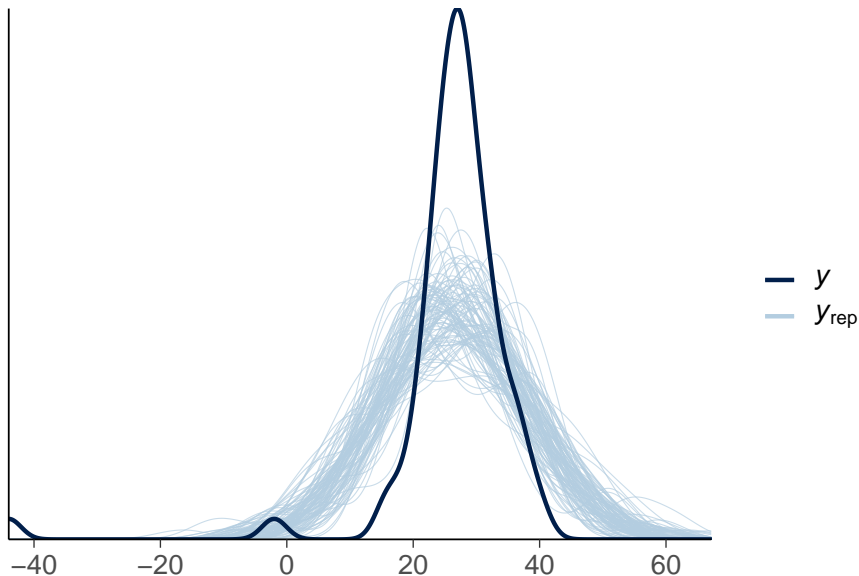
Posterior predictive checking – bayesplot

`ppc_hist(y, yrep[1:8,])`



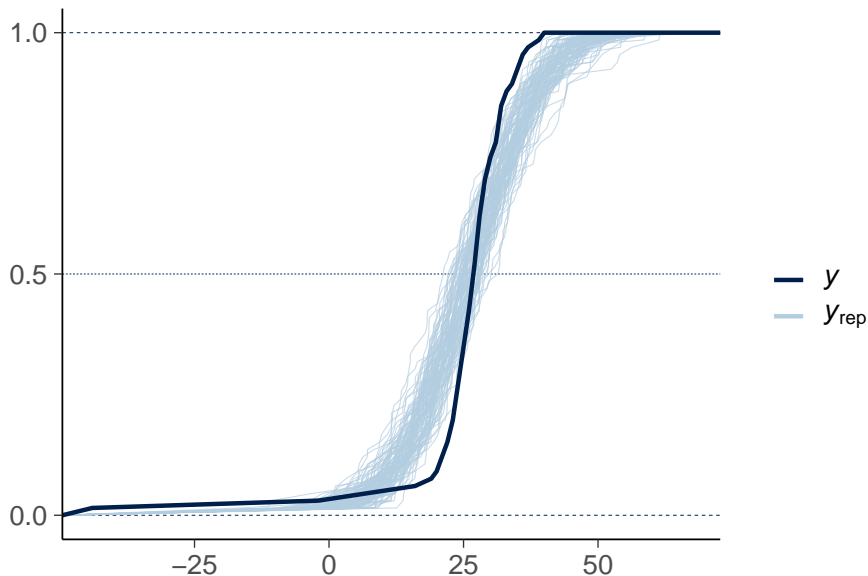
Posterior predictive checking – bayesplot

`ppc_dens_overlay(y, yrep[1:100,])`



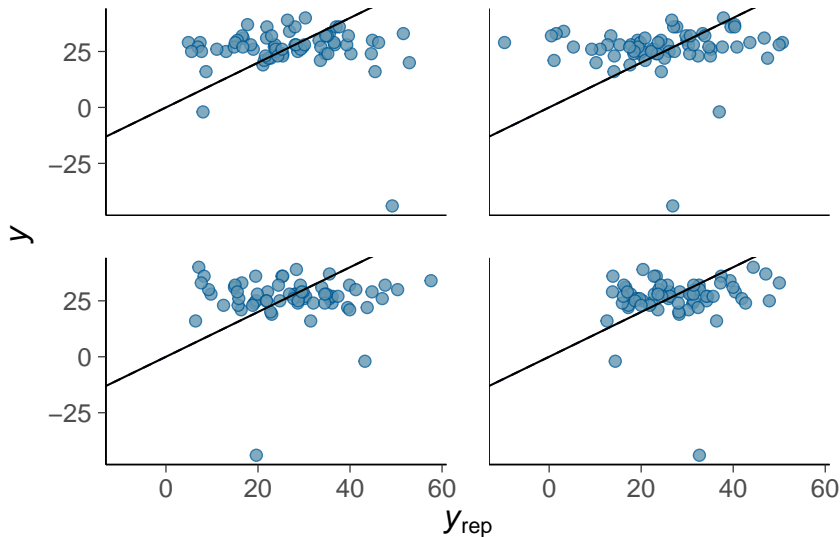
Posterior predictive checking – bayesplot

`ppc_ecdf_overlay(y, yrep[1:100,])`



Posterior predictive checking – bayesplot

`ppc_scatter(y, yrep[1:4,]) + geom_abline()`



Posterior predictive checking with test statistic

- Replicated data sets y^{rep}
- Test quantity (or discrepancy measure) $T(y, \theta)$
 - summary quantity for the observed data $T(y, \theta)$
 - summary quantity for a replicated data $T(y^{\text{rep}}, \theta)$
 - can be easier to compare summary quantities than data sets

Posterior predictive checking – example

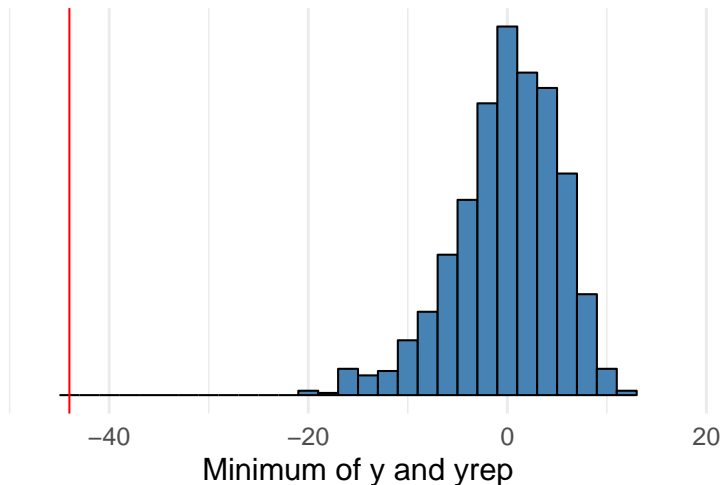
- Compute test statistic for data $T(y, \theta) = \min(y)$

Posterior predictive checking – example

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Posterior predictive checking – example

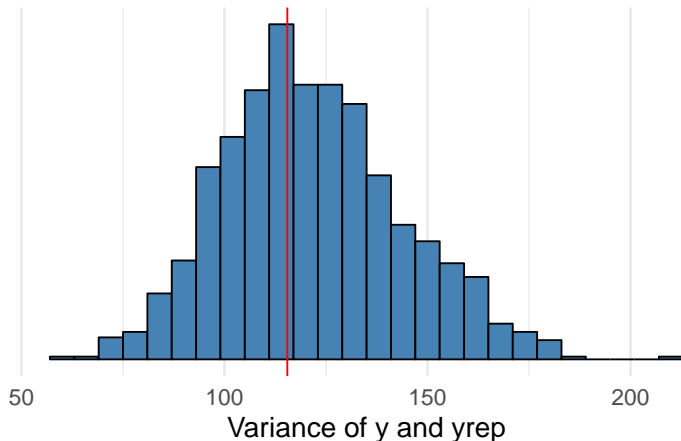
- Good test statistic is (almost) *ancillary* (fi: *aputunnusluku*)
 - ancillary if it depends only on observed data and if its distribution is independent of the parameters of the model

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 - e.g. variance for normal model

Posterior predictive checking – example

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 - ancillary if it depends only on observed data and if its distribution is independent of the parameters of the model
- Bad test statistic is highly dependent of the parameters
 - e.g. variance for normal model



Posterior predictive checking

- *Posterior predictive p-value*

$$\begin{aligned} p &= \Pr(T(y^{\text{rep}}, \theta) \geq T(y, \theta) | y) \\ &= \int \int I_{T(y^{\text{rep}}, \theta) \geq T(y, \theta)} p(y^{\text{rep}} | \theta) p(\theta | y) dy^{\text{rep}} d\theta \end{aligned}$$

where I is an indicator function

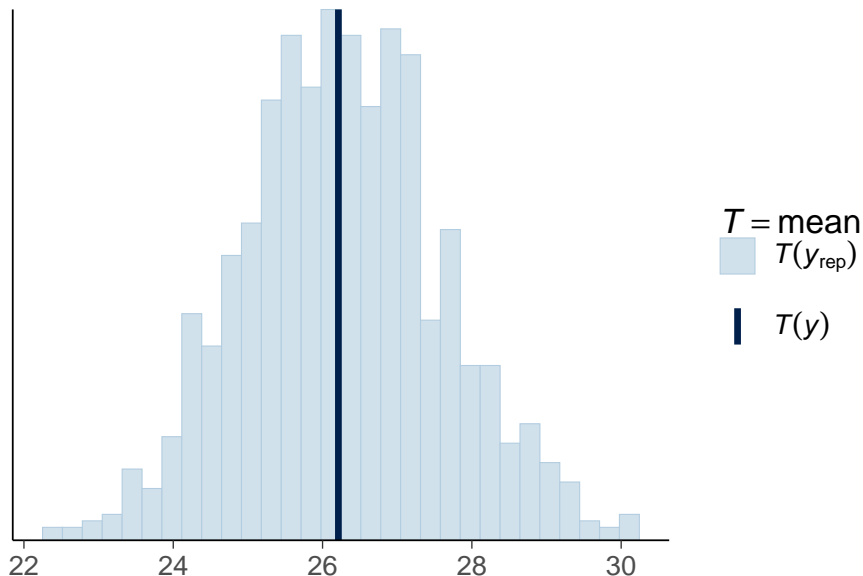
- having $(y^{\text{rep}(s)}, \theta^{(s)})$ from the posterior predictive distribution, easy to compute

$$T(y^{\text{rep}(s)}, \theta^{(s)}) \geq T(y, \theta^{(s)}), \quad s = 1, \dots, S$$

- Posterior predictive p -value (ppp-value) estimates whether difference between the model and data could arise by chance
- Not commonly used, as
 - not calibrated in case of non-ancillary statistic
 - the distribution of test statistic has more information

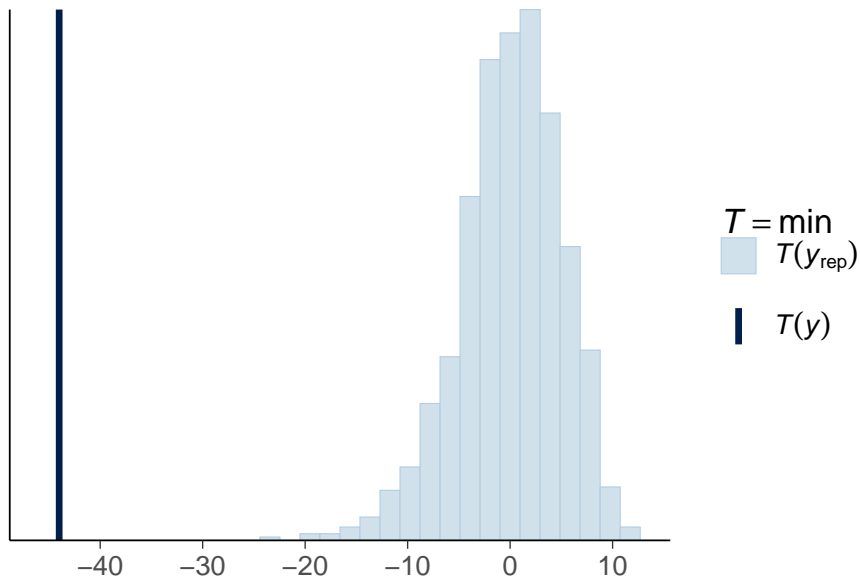
Posterior predictive checking – bayesplot

`ppc_stat`(y , y_{rep}), the default statistic "mean" is usually bad



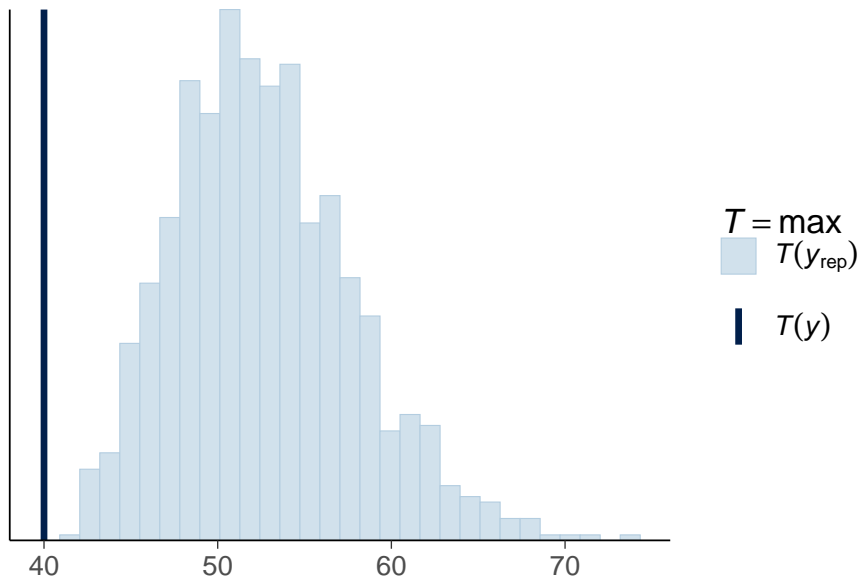
Posterior predictive checking – bayesplot

```
ppc_stat(y, yrep, stat="min")
```



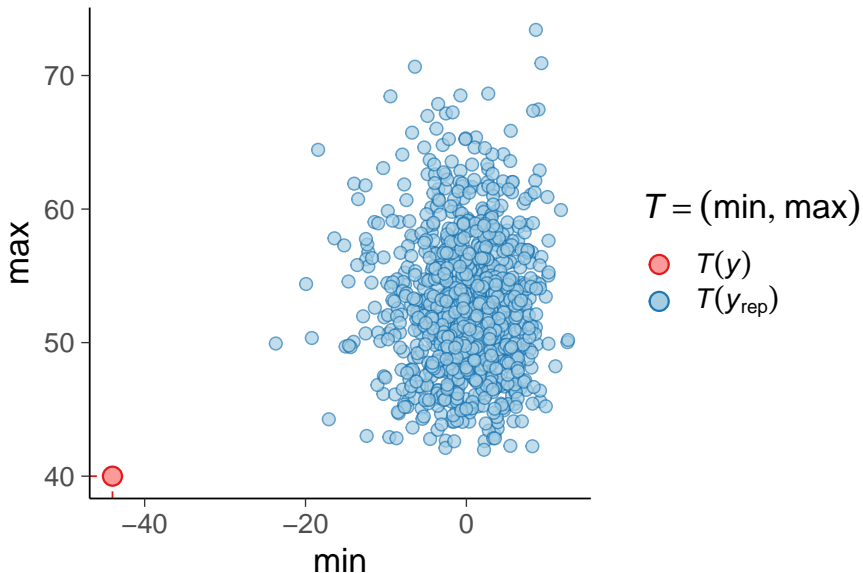
Posterior predictive checking – bayesplot

```
ppc_stat(y, yrep, stat="max")
```



Posterior predictive checking – bayesplot

```
ppc_stat2d(y, yrep, stat=c("min", "max"))
```



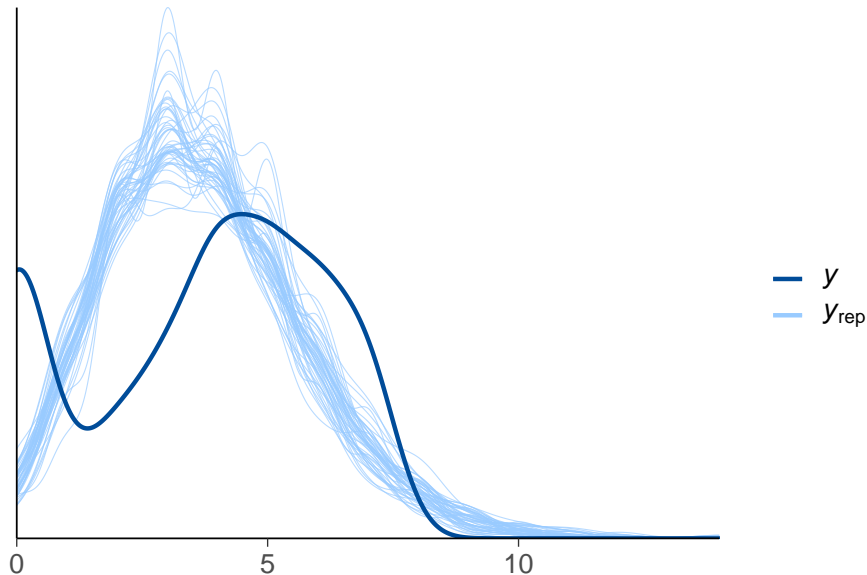
Posterior predictive checking – Stan code

- demo demos_rstan/ppc/poisson-ppc.Rmd

```
data {  
  int<lower=1> N;  
  array[N] int<lower=0> y;  
}  
parameters {  
  real<lower=0> lambda;  
}  
model {  
  lambda ~ exponential(0.2);  
  y ~ poisson(lambda);  
}  
generated quantities {  
  real log_lik[N];  
  array[N] int y_rep;  
  for (n in 1:N) {  
    y_rep[n] = poisson_rng(lambda);  
    log_lik[n] = poisson_lpmf(y[n] | lambda);  
  }  
}
```

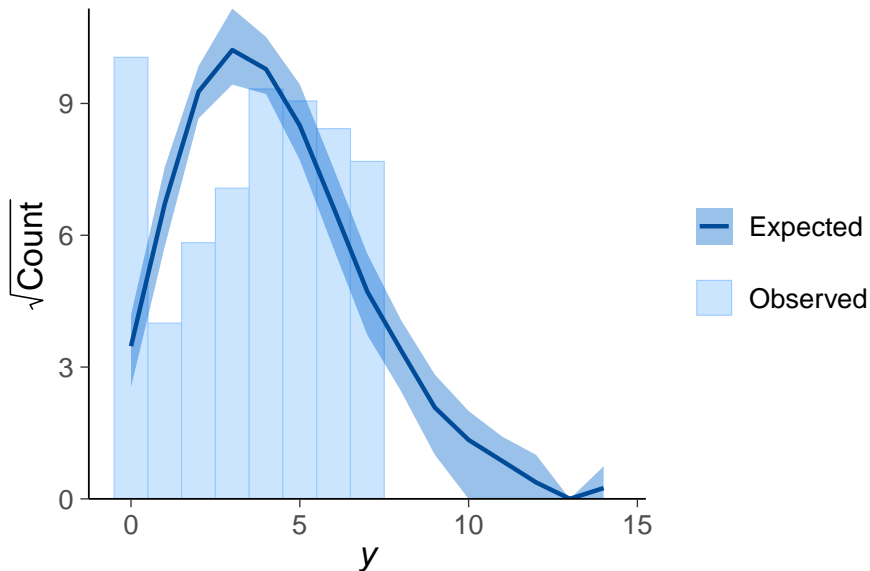
PPC for count data – Poisson model

```
ppc_dens_overlay(y, yrep[1:50,])
```



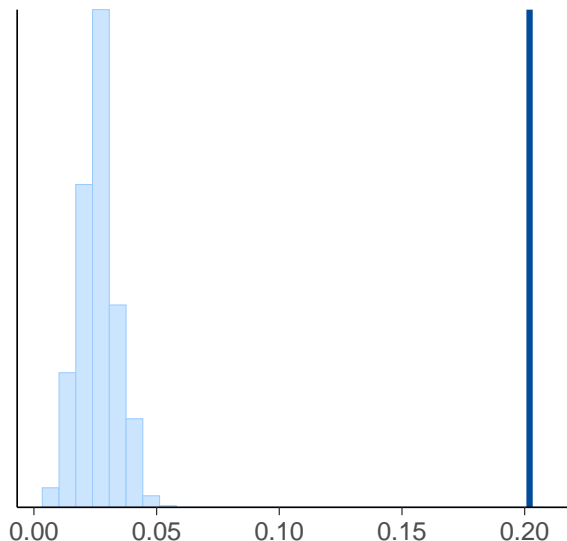
PPC for count data – Poisson model

`ppc_rootogram(y, yrep)`



PPC for count data – Poisson model

```
prop_zero <- function(x) mean(x == 0)  
ppc_stat(y, yrep, stat = "prop_zero")
```



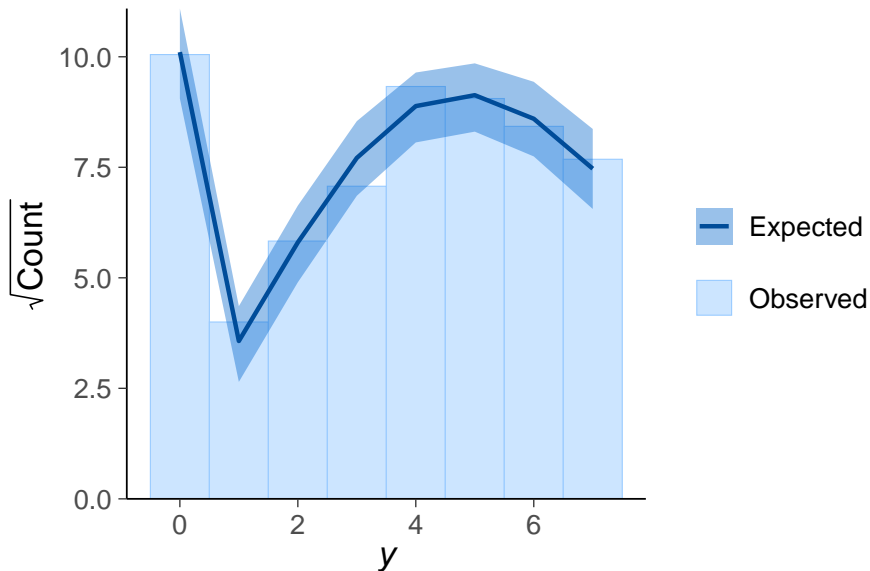
$T = \text{prop_zero}$

$T(y_{\text{rep}})$

$T(y)$

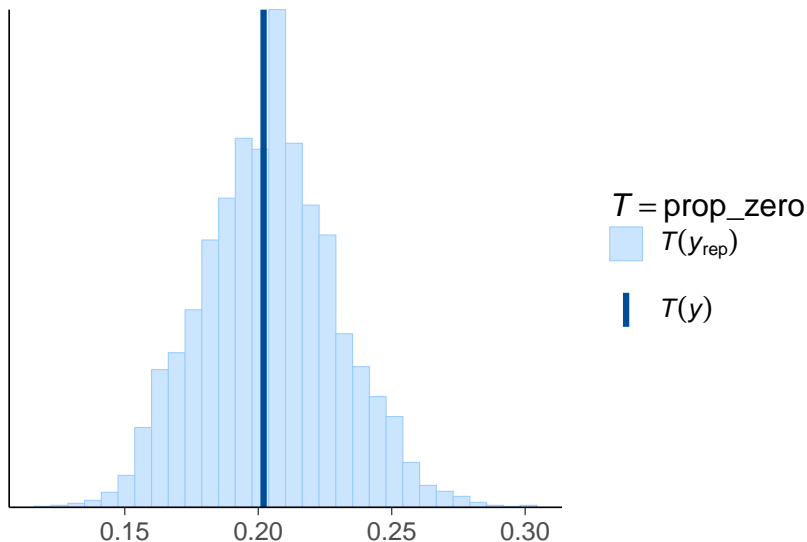
PPC for count data – hurdle truncated Poisson model

`ppc_rootogram(y, yrep2)`



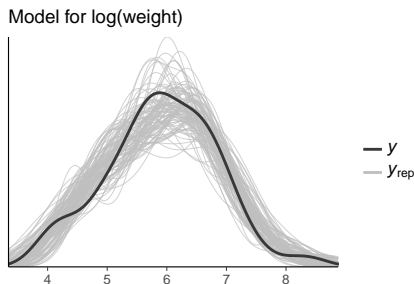
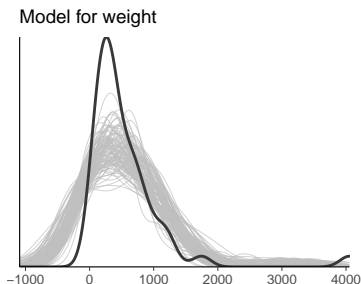
PPC for count data – hurdle truncated Poisson model

```
prop_zero <- function(x) mean(x == 0)  
ppc_stat(y, yrep2, stat = "prop_zero")
```



Posterior predictive checking: Mesquite bushes

Positive target: normal vs log-normal model

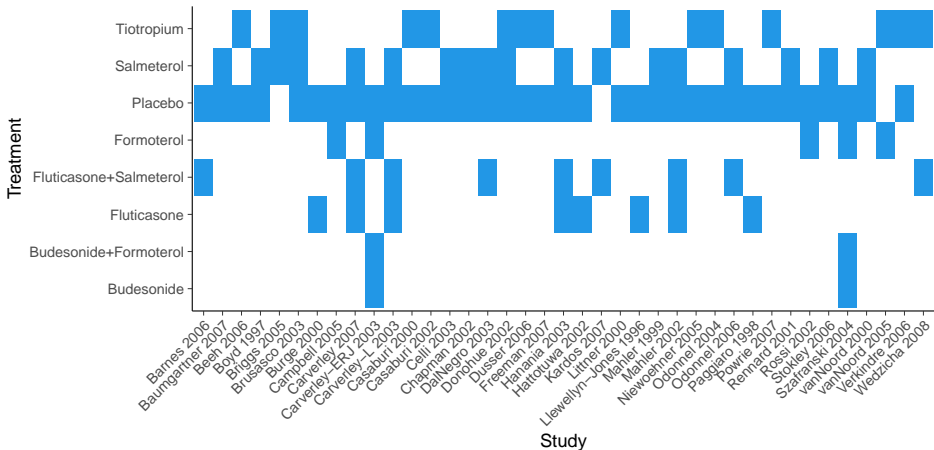


Predicting the yields of mesquite bushes.

Gelman, Hill & Vehtari (2020): Regression and Other Stories, Chapter 11.

Meta-analysis

Pharmacologic treatments for chronic obstructive pulmonary disease

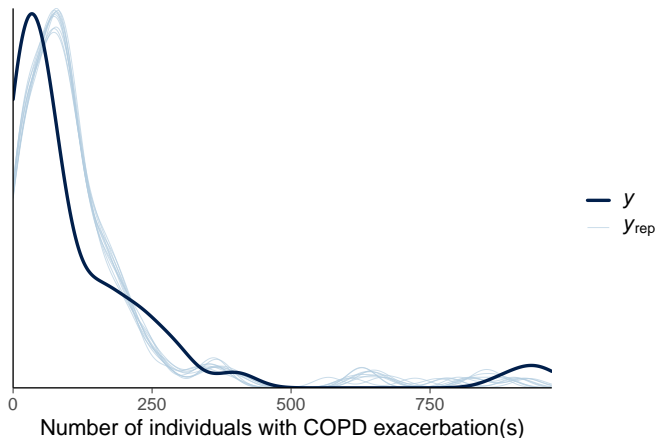


Posterior predictive checking

Pharmacologic treatments for chronic obstructive pulmonary disease

Pooled over studies, separate for treatments

```
fit_pooled <- brm(exac | trials(total) ~ 0 + treatment,  
  prior = prior(student_t(7, 0, 1.5), class='b'),  
  family=binomial(), data=dat.baker2009)
```

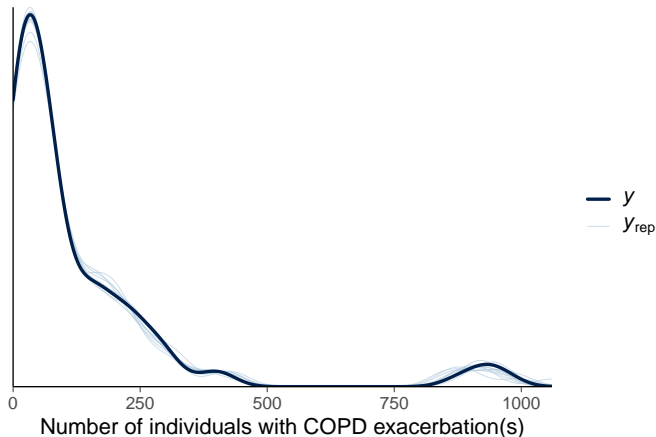


Posterior predictive checking

Pharmacologic treatments for chronic obstructive pulmonary disease

Hierarchical for studies, hierarchical for treatments

```
fit_hier <- brm(exac | trials(total) ~ (1 | treatment) + (1 | study),  
               family=binomial(), data=dat.baker2009)
```

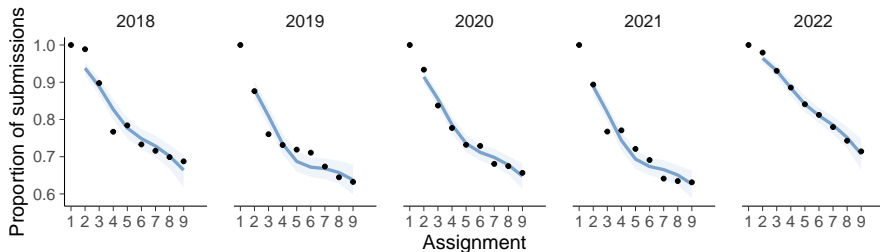


Student retention

Latent hierarchical linear + spline

```
nstudents | trials(nstudents1) ~  
  s(assignment, k=4) + (assignment | year),  
  family=binomial()
```

Latent functions + posterior uncertainty

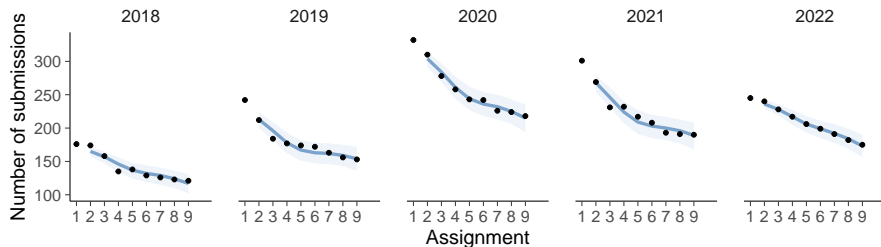


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Student retention

1. Latent hierarchical linear model

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nstudents | trials(nstudents1) ~  
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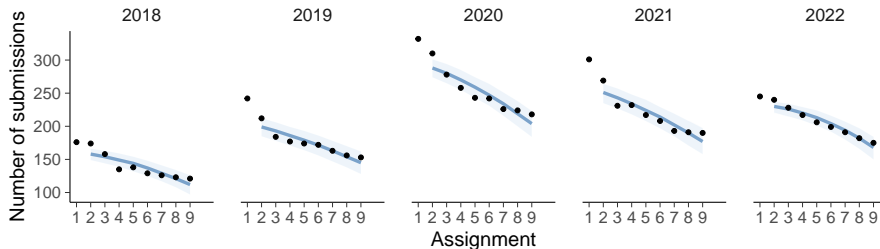
2. Latent spline + hierarchical linear model

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```

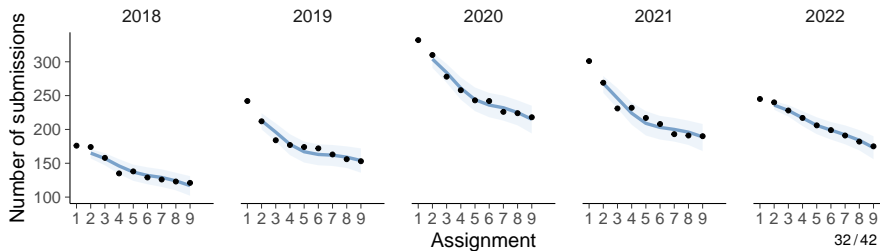
Student retention – Posterior predictive distributions

with tidybayes

Latent hierarchical linear model



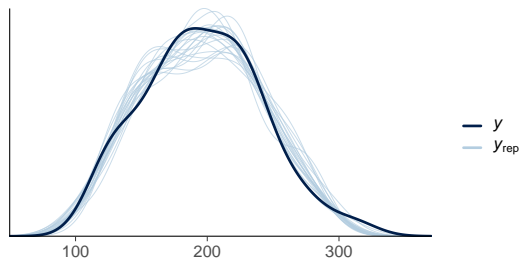
Latent hierarchical linear model + spline



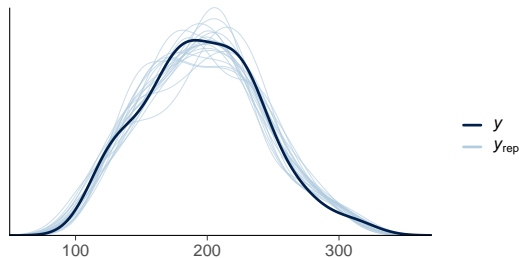
Student retention – Marginal PPC (brms)

```
pp_check(fit, ndraws=100)
```

Latent hierarchical linear model



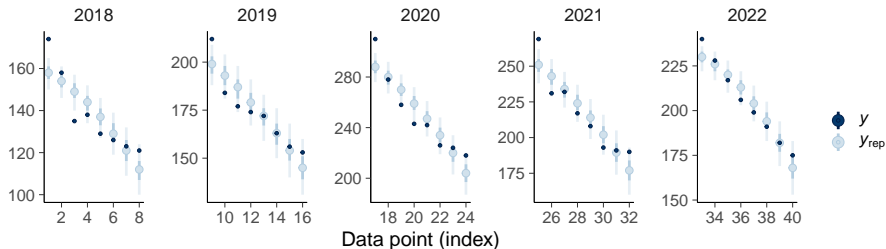
Latent hierarchical linear model + spline



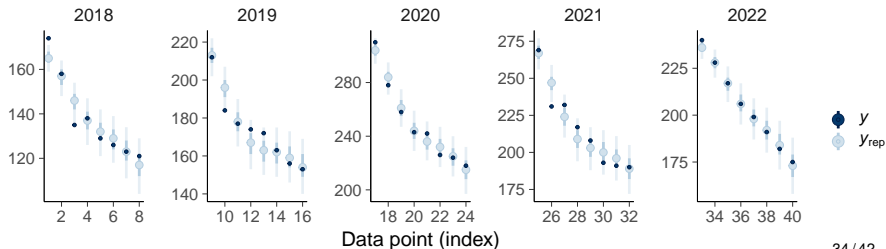
Student retention – Posterior predictive intervals (brms)

```
pp_check(fit, type = "intervals_grouped", group="year")
```

Latent hierarchical linear model



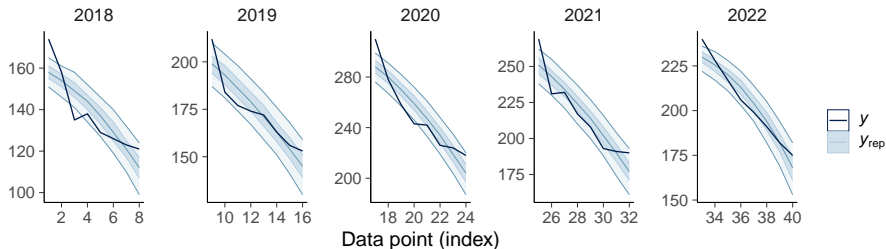
Latent hierarchical linear model + spline



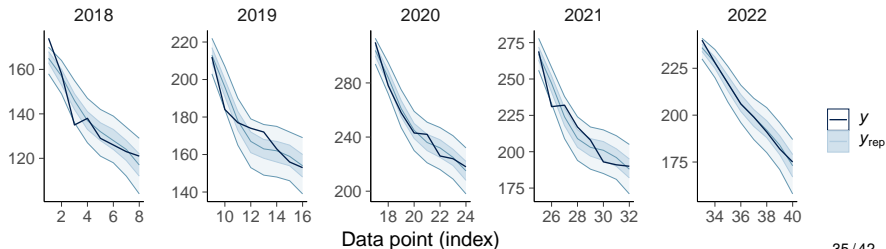
Student retention – Posterior predictive ribbon (brms)

```
pp_check(fit, type = "ribbon_grouped", group="year")
```

Latent hierarchical linear model

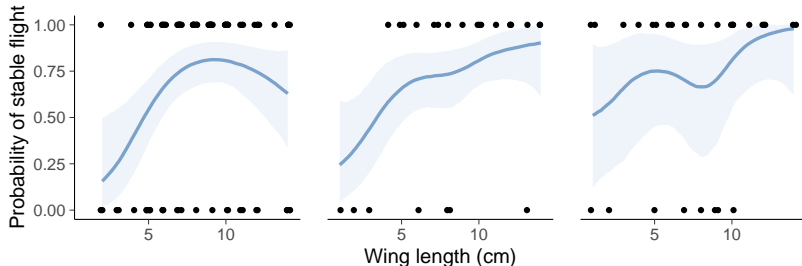


Latent hierarchical linear model + spline



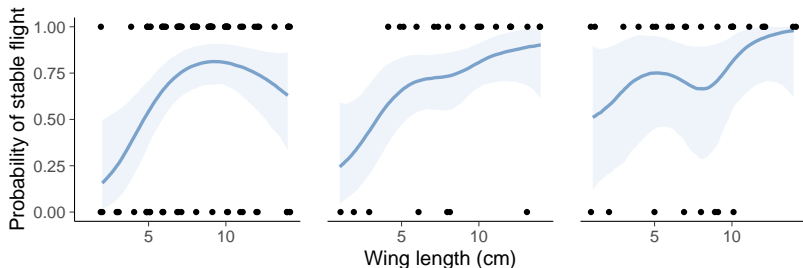
PPC for binary target – Helicopters (brms)

```
stable_flight ~ s(wing_length) + s(wing_length, by = nclips),  
family = bernoulli()
```

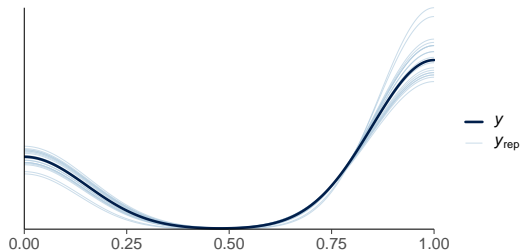


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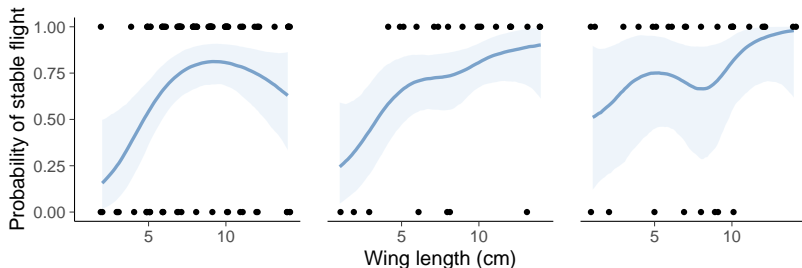


```
pp_check(fit, ndraws=20)
```

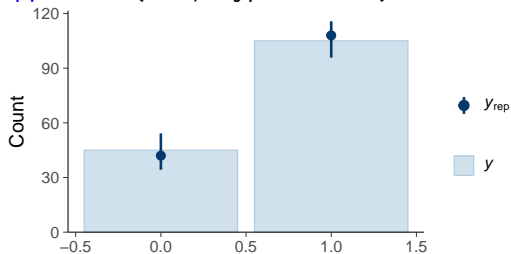


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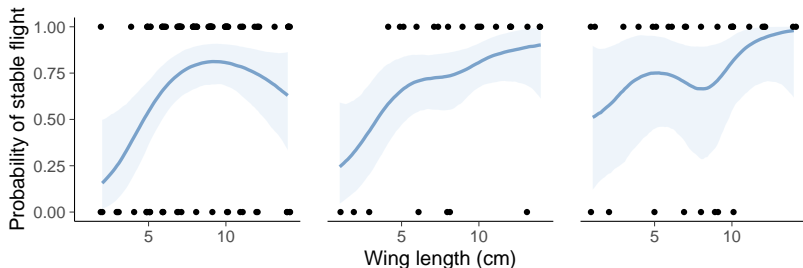


```
pp_check(fit, type="bars")
```

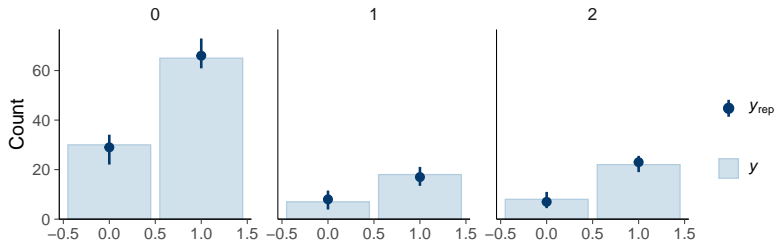


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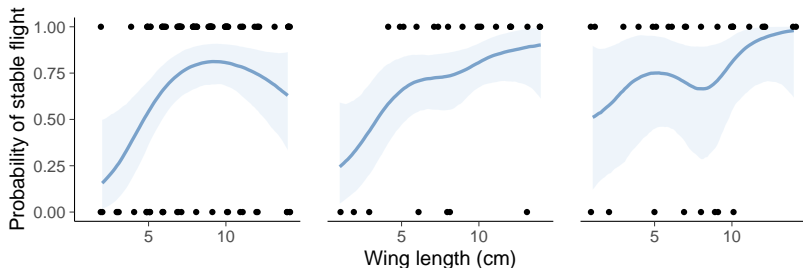


```
pp_check(fit, type="bars_grouped")
```

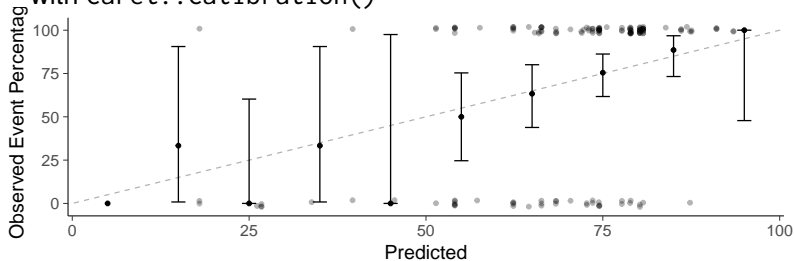


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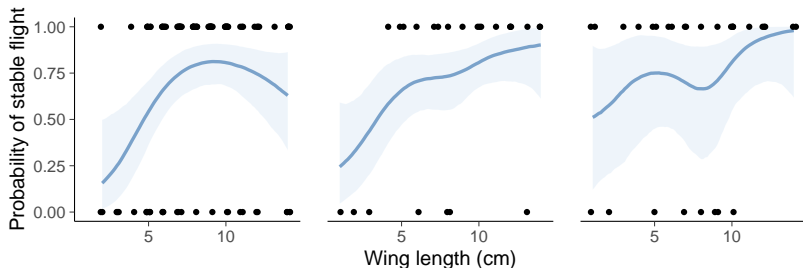


with `caret::calibration()`

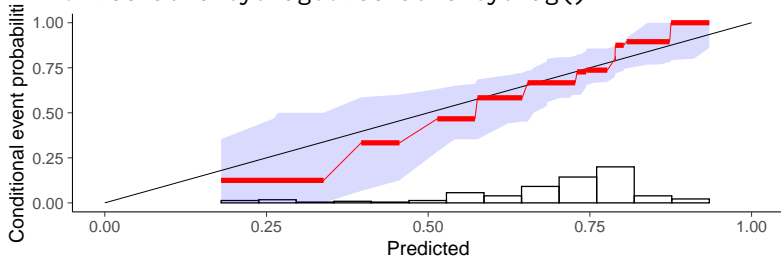


PPC for binary target – Helicopters (brms)

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```



with `reliabilitydiag::reliabilitydiag()`

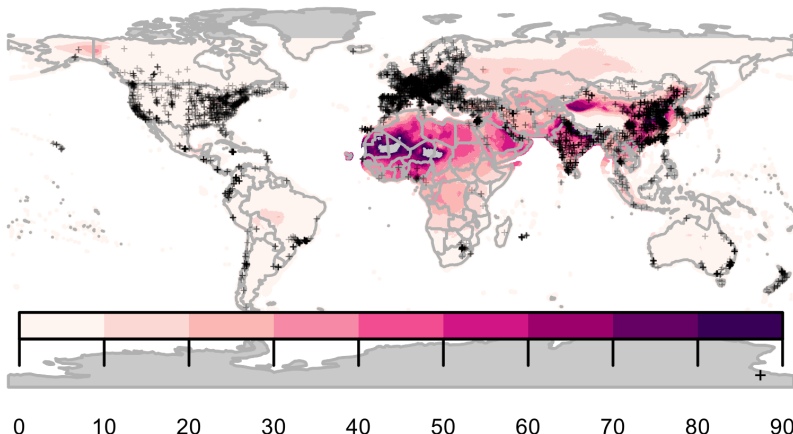


Prior predictive checking: Exposure to air pollution

- Example from Gabry, Simpson, Vehtari, Betancourt, and Gelman (2019). Visualization in Bayesian workflow.
<https://doi.org/10.1111/rssa.12378>
- Estimation of human exposure to air pollution from particulate matter measuring less than 2.5 microns in diameter ($PM_{2.5}$)
 - Exposure to $PM_{2.5}$ is linked to a number of poor health outcomes and a recent report estimated that $PM_{2.5}$ is responsible for three million deaths worldwide each year (Shaddick et al., 2017)
 - In order to estimate the public health effect of ambient $PM_{2.5}$, we need a good estimate of the $PM_{2.5}$ concentration at the same spatial resolution as our population estimates.

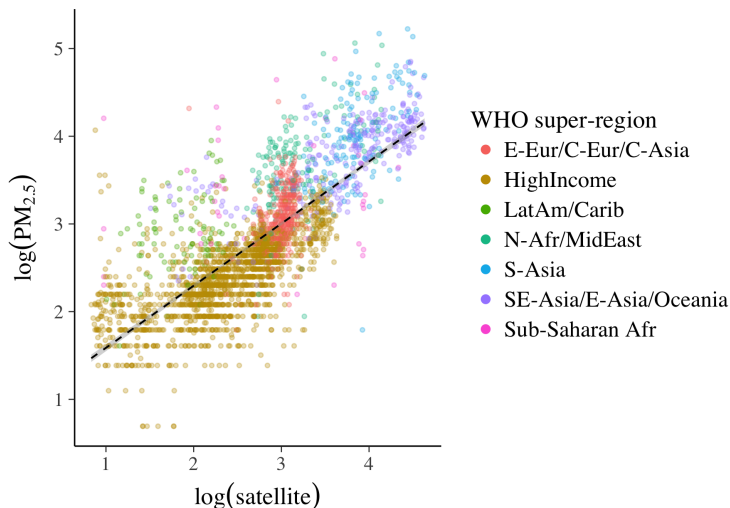
Prior predictive checking: Exposure to air pollution

- Direct measurements of PM 2.5 from ground monitors at 2980 locations
- High-resolution satellite data of aerosol optical depth



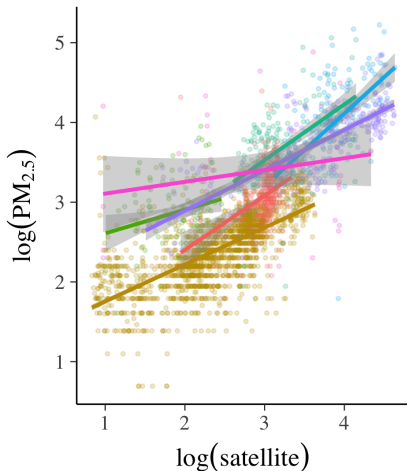
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Prior predictive checking: Exposure to air pollution

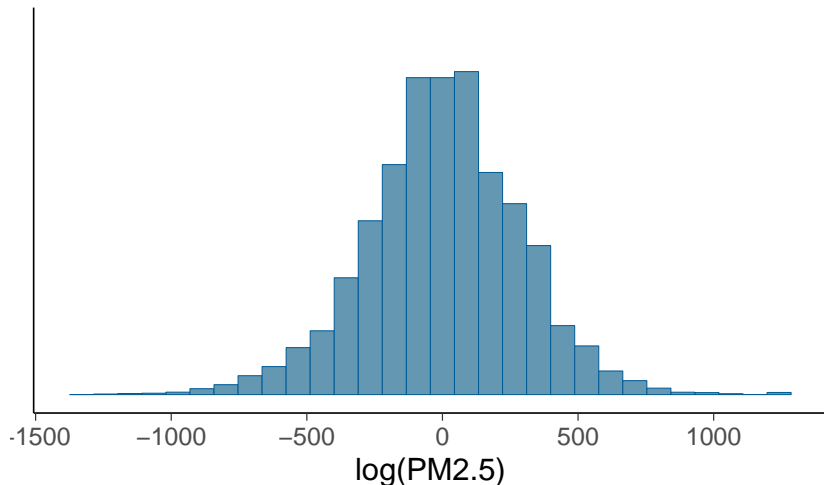
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Prior predictive checking: Exposure to air pollution

Prior predictive checking

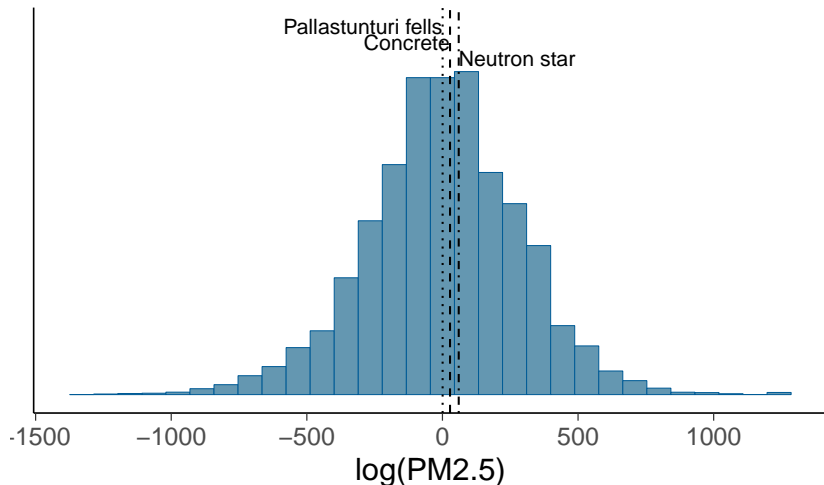
Prior predictive distribution with vague prior



Prior predictive checking: Exposure to air pollution

Prior predictive checking

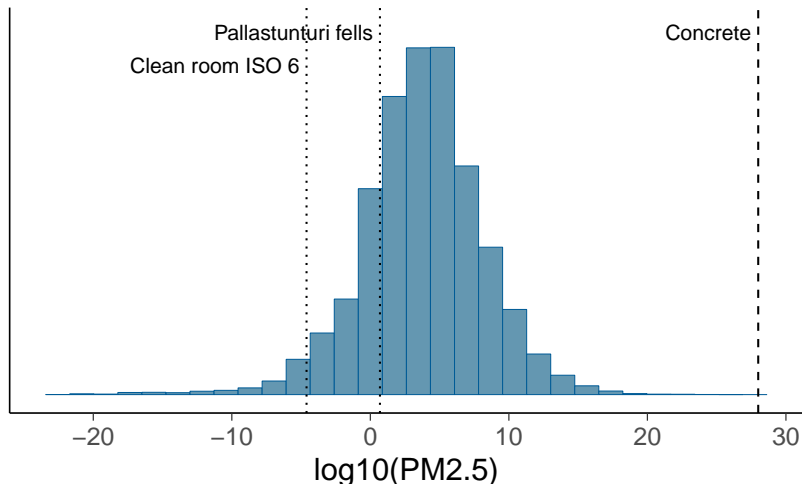
Prior predictive distribution with vague prior



Prior predictive checking: Exposure to air pollution

Prior predictive checking

Prior predictive distribution with weakly informative



Further reading and examples

- Gabry, Simpson, Vehtari, Betancourt, and Gelman (2019). Visualization in Bayesian workflow.
<https://doi.org/10.1111/rssa.12378>.
- Graphical posterior predictive checks using the bayesplot package
<http://mc-stan.org/bayesplot/articles/graphical-ppcs.html>
- brms demos https://avehtari.github.io/BDA_R_demos/demos_rstan/brms_demo.html

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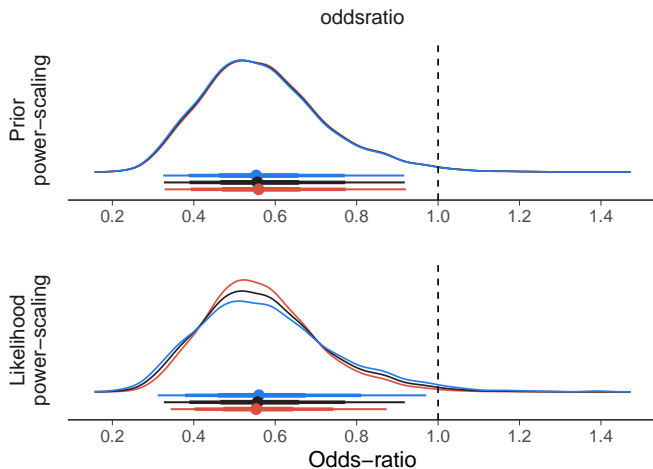
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- Compare sensitivity of essential inference quantities
 - extreme quantiles are more sensitive than means and medians
 - extrapolation is more sensitive than interpolation

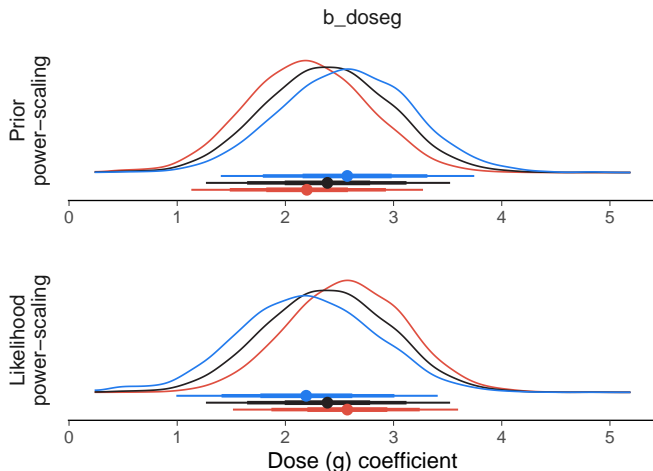
priorsense — prior and likelihood sensitivity analysis

- Power-scale prior and likelihood separately as $p(\theta)^\alpha$ and $p(y|\theta)^\alpha$
- Beta blockers — randomized control-treatment experiment
 - no prior sensitivity
 - likelihood is informative



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 - due to accidentally too narrow prior

