

Supplemental materials for “A multivariate mixed
hidden Markov model for blue whale behaviour and
responses to sound exposure”

Version Dated: December 5, 2016

1 Time-series plots of the blue whale data

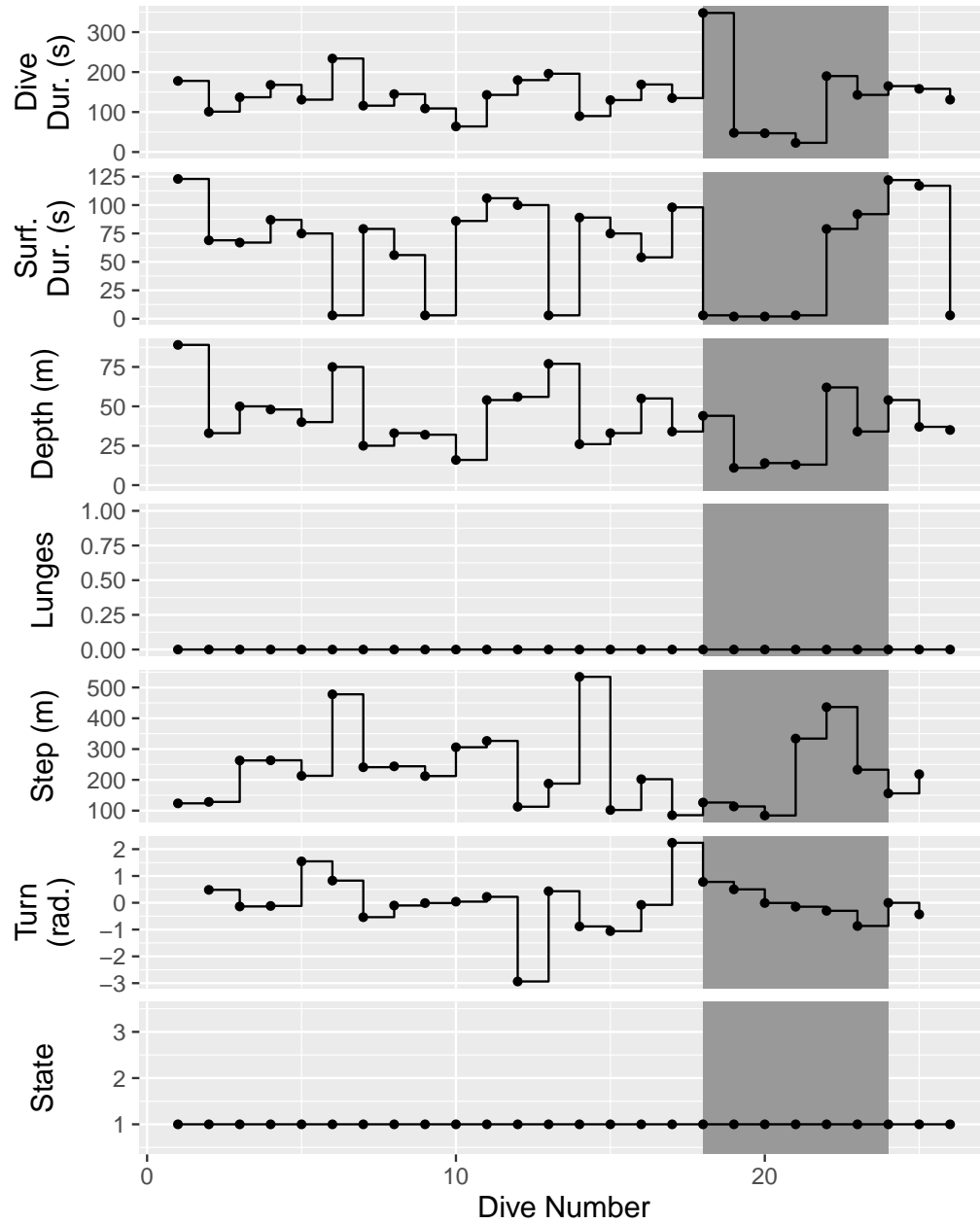


Figure 1: Time-series plot of the input data for whale bw10-235-Bprobe-019. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

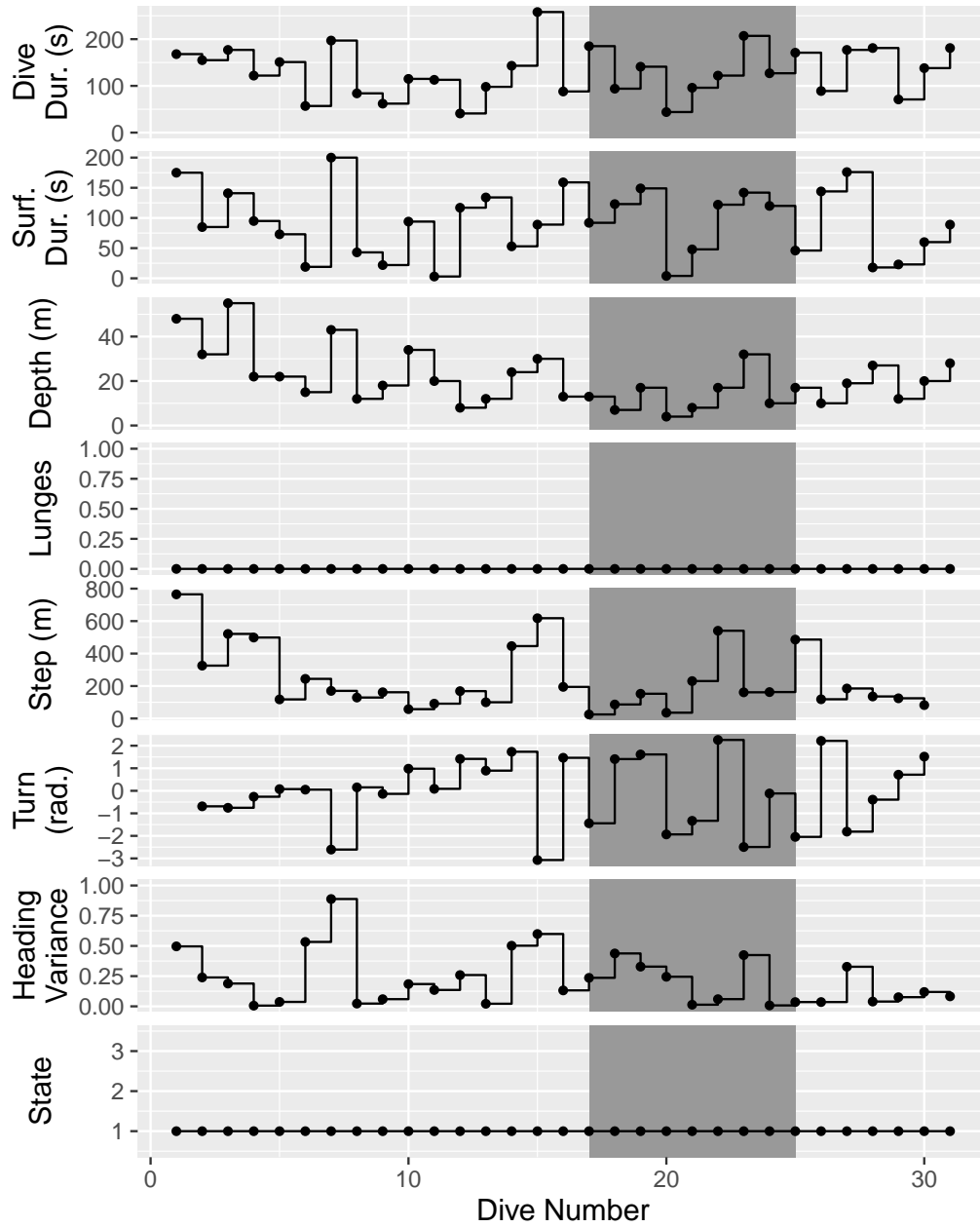


Figure 2: Time-series plot of the input data for whale bw10-235a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

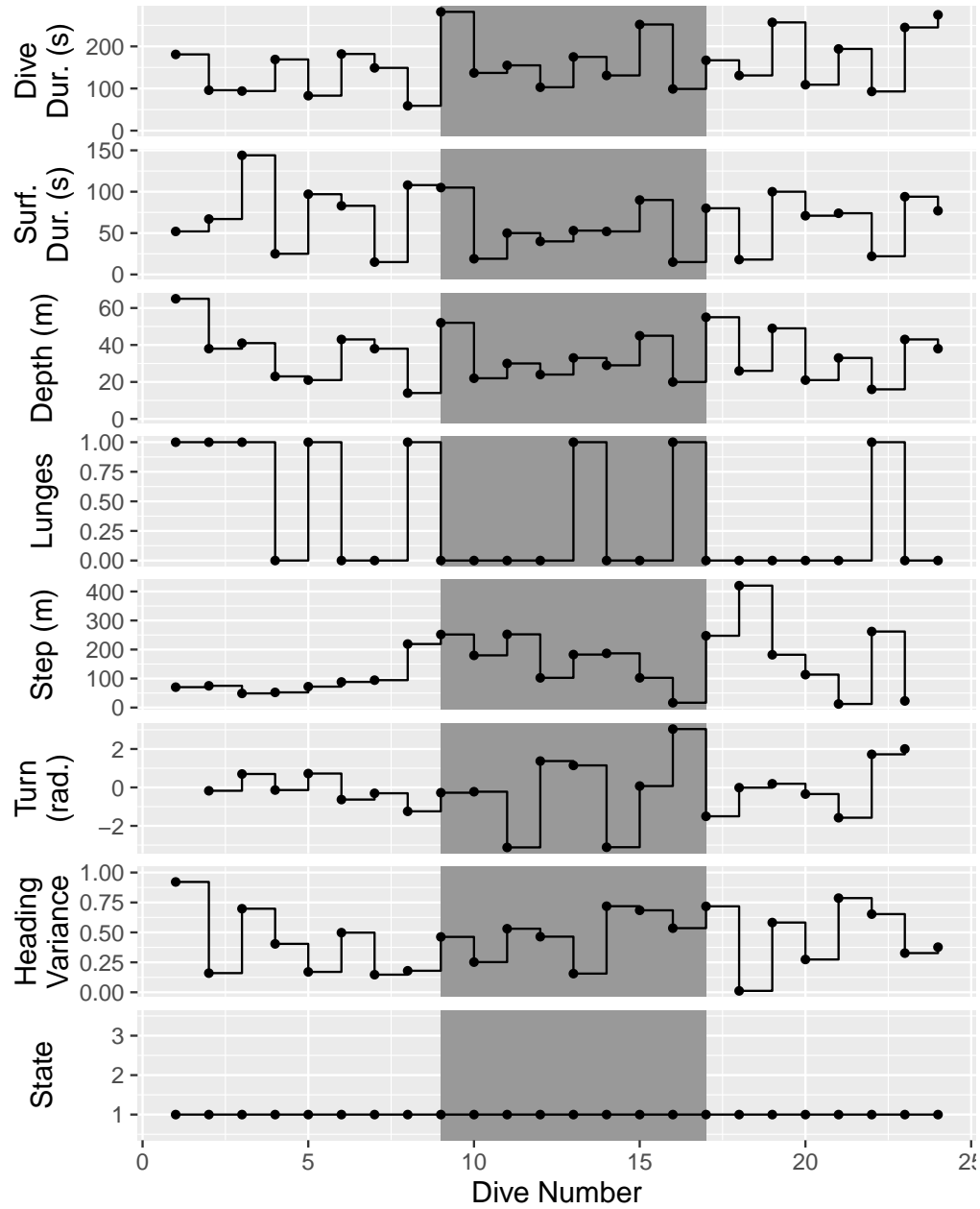


Figure 3: Time-series plot of the input data for whale bw10-235b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

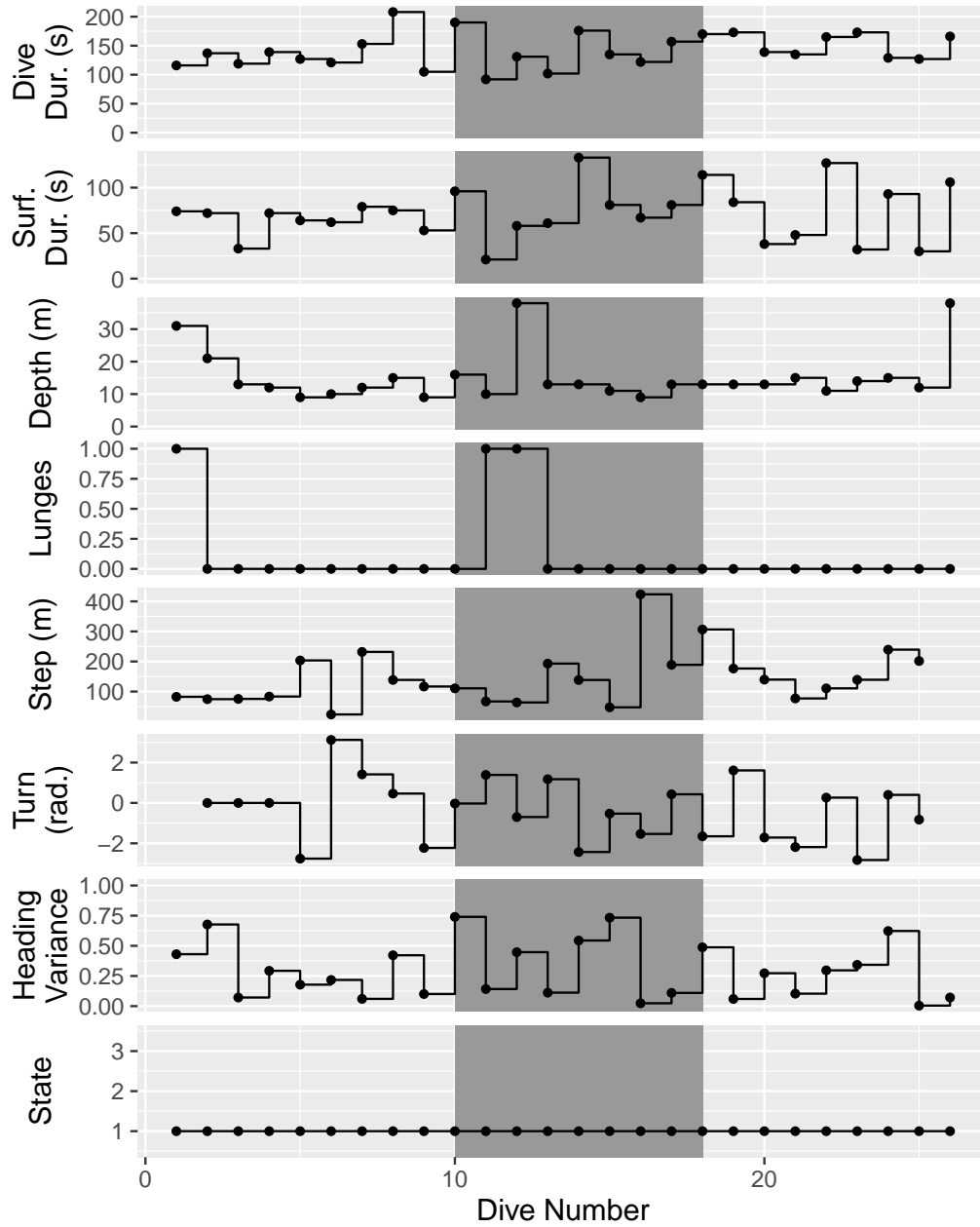


Figure 4: Time-series plot of the input data for whale bw10-238a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

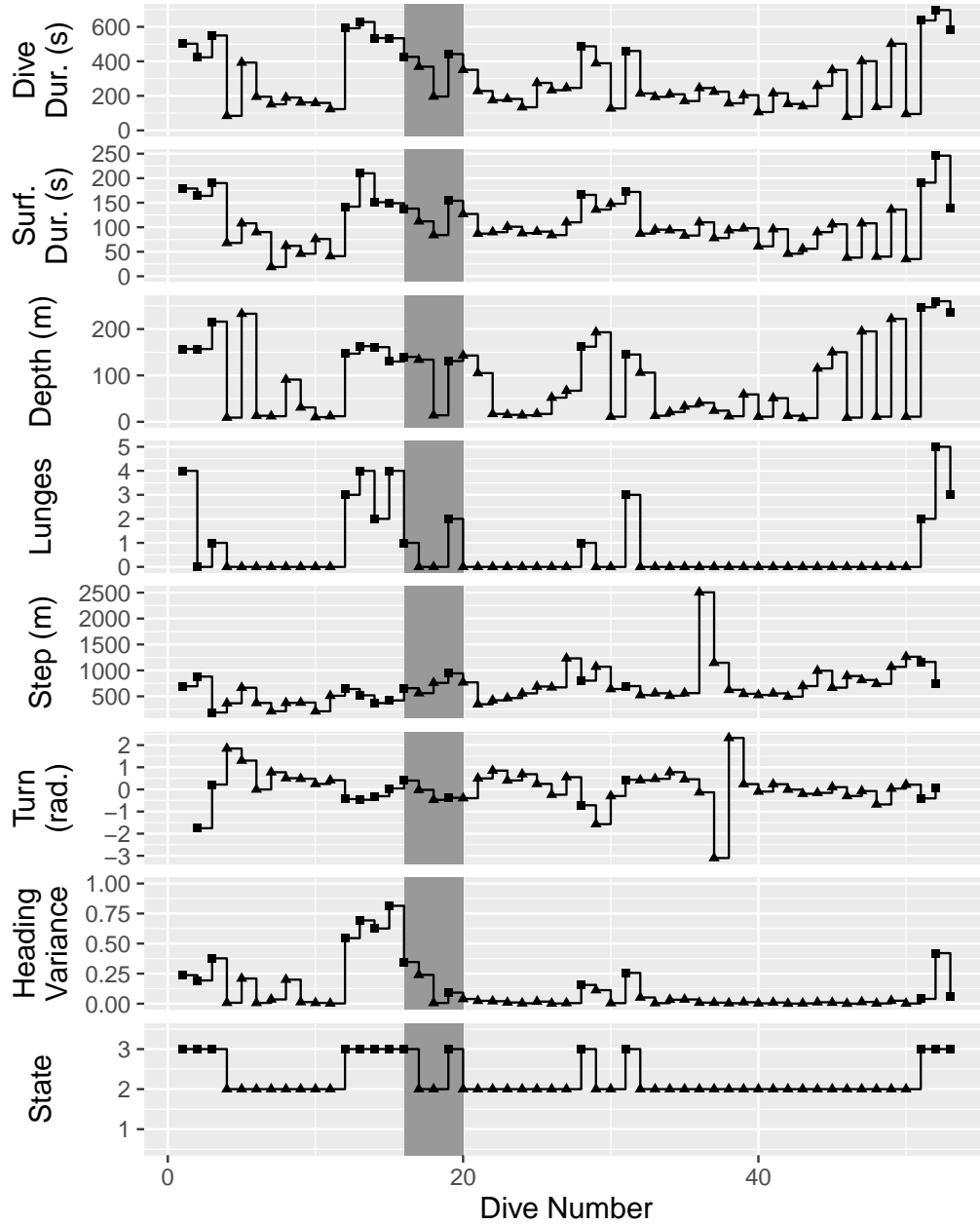


Figure 5: Time-series plot of the input data for whale bw10-239b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

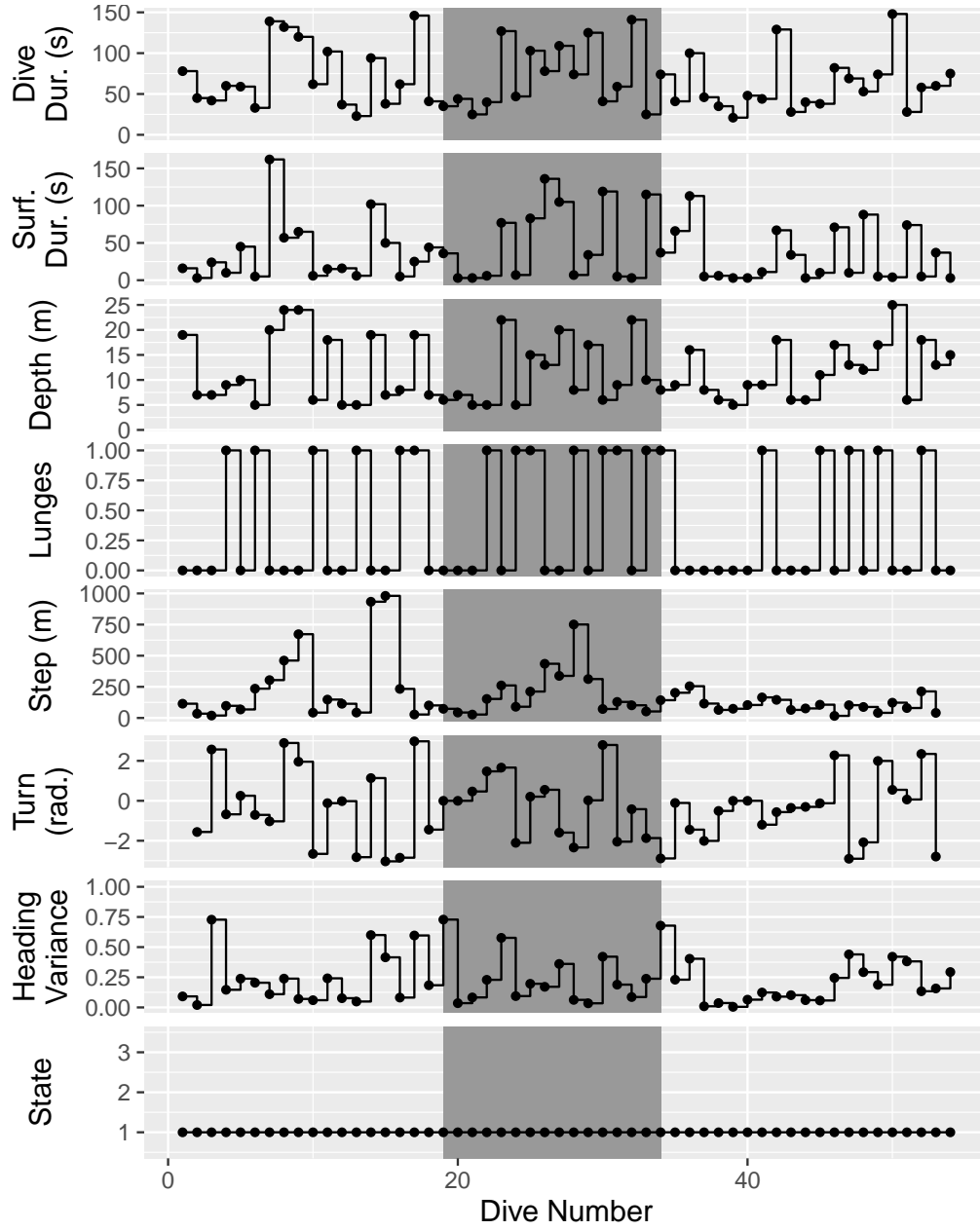


Figure 6: Time-series plot of the input data for whale bw10-240a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

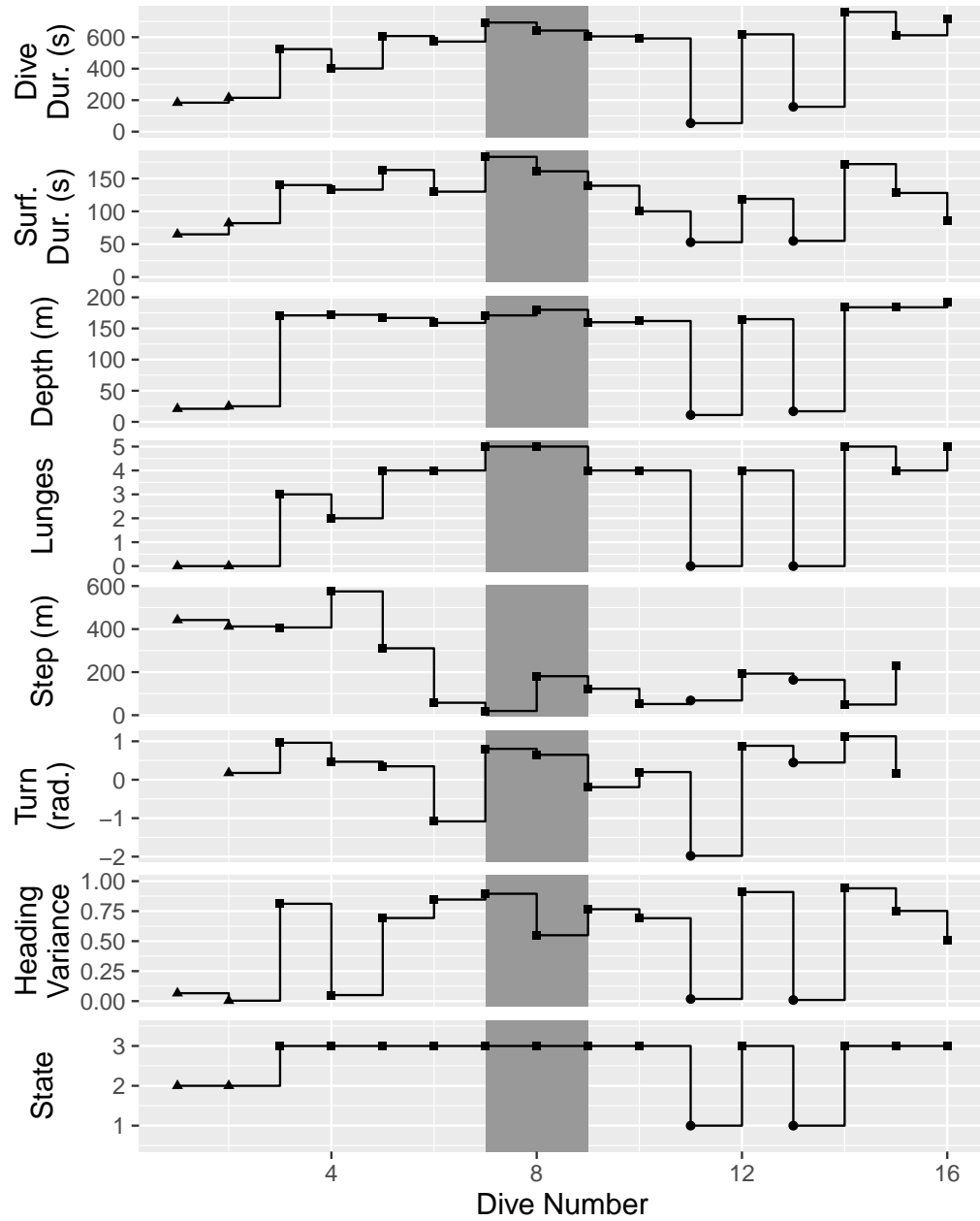


Figure 7: Time-series plot of the input data for whale bw10-240b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

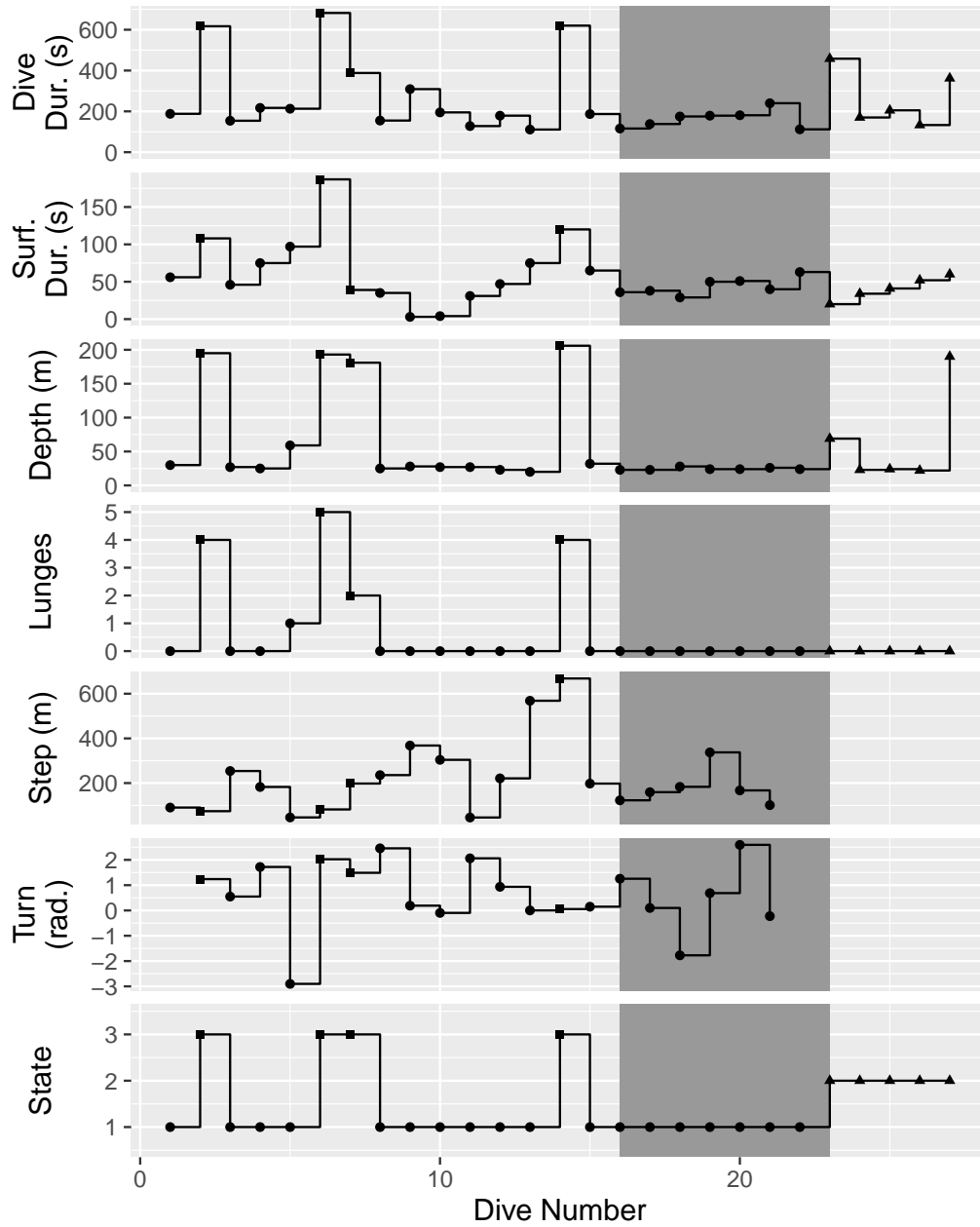


Figure 8: Time-series plot of the input data for whale bw10-241-Bprobe-034. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a silent control CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

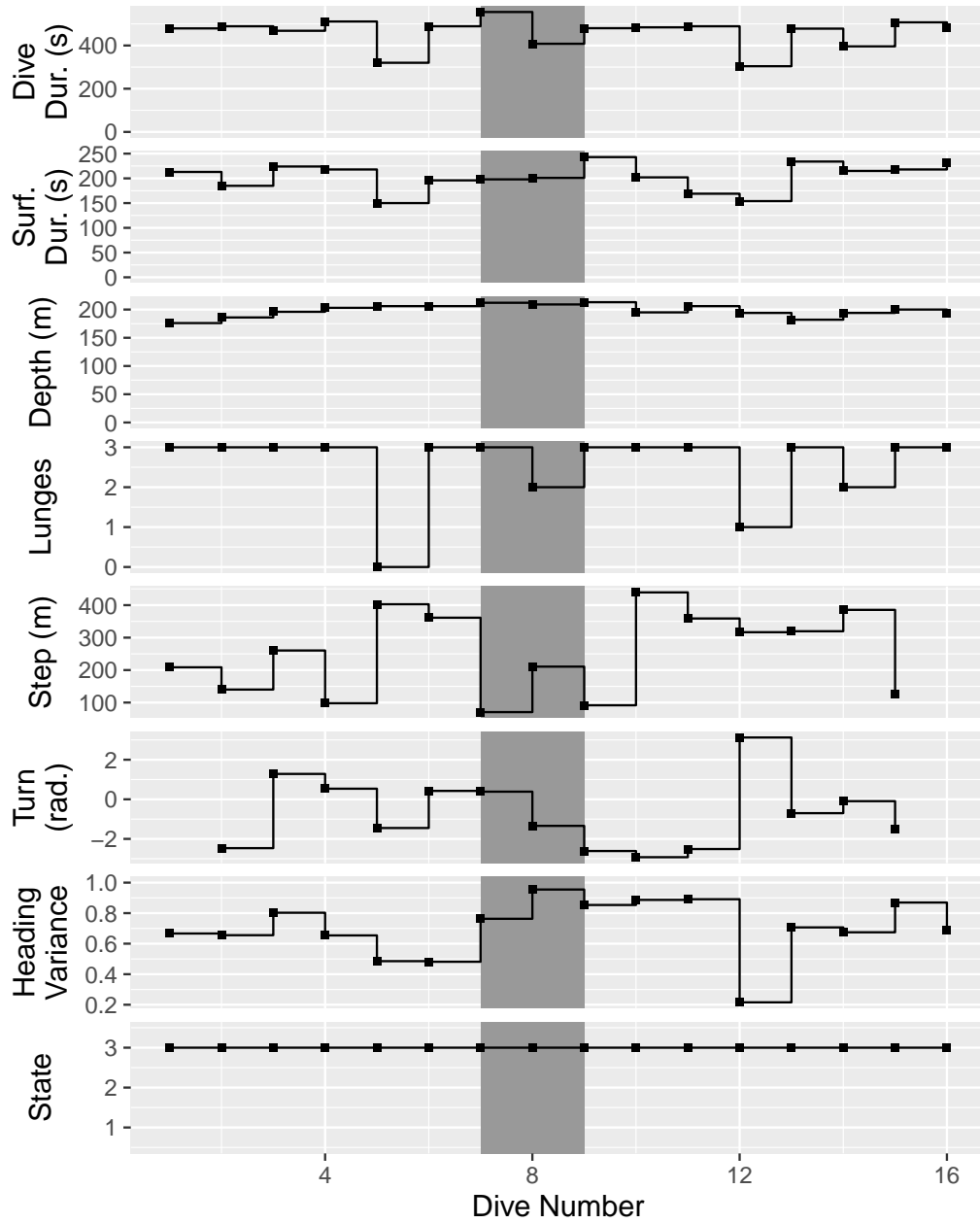


Figure 9: Time-series plot of the input data for whale bw10-241a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a silent control CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

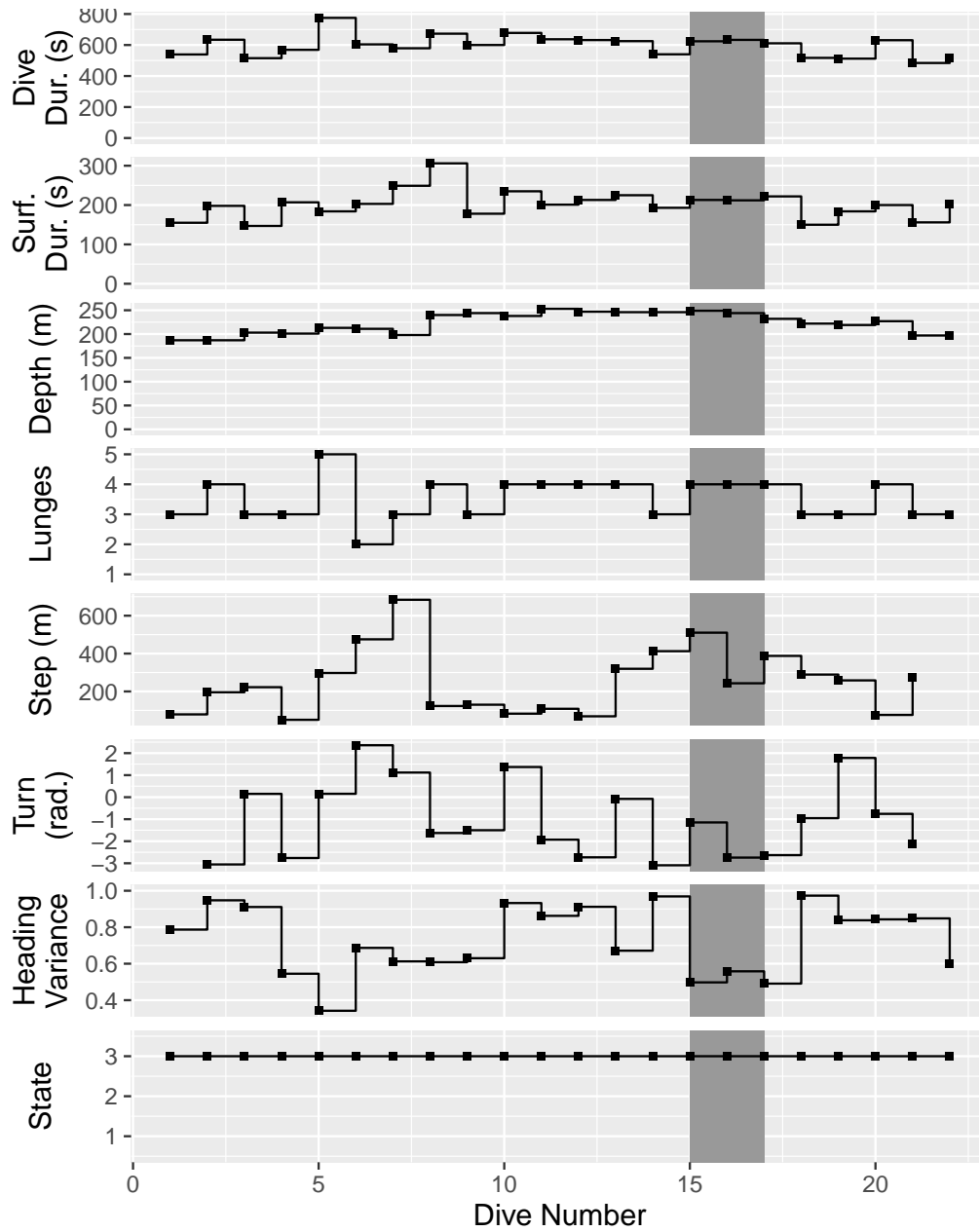


Figure 10: Time-series plot of the input data for whale bw10-243a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

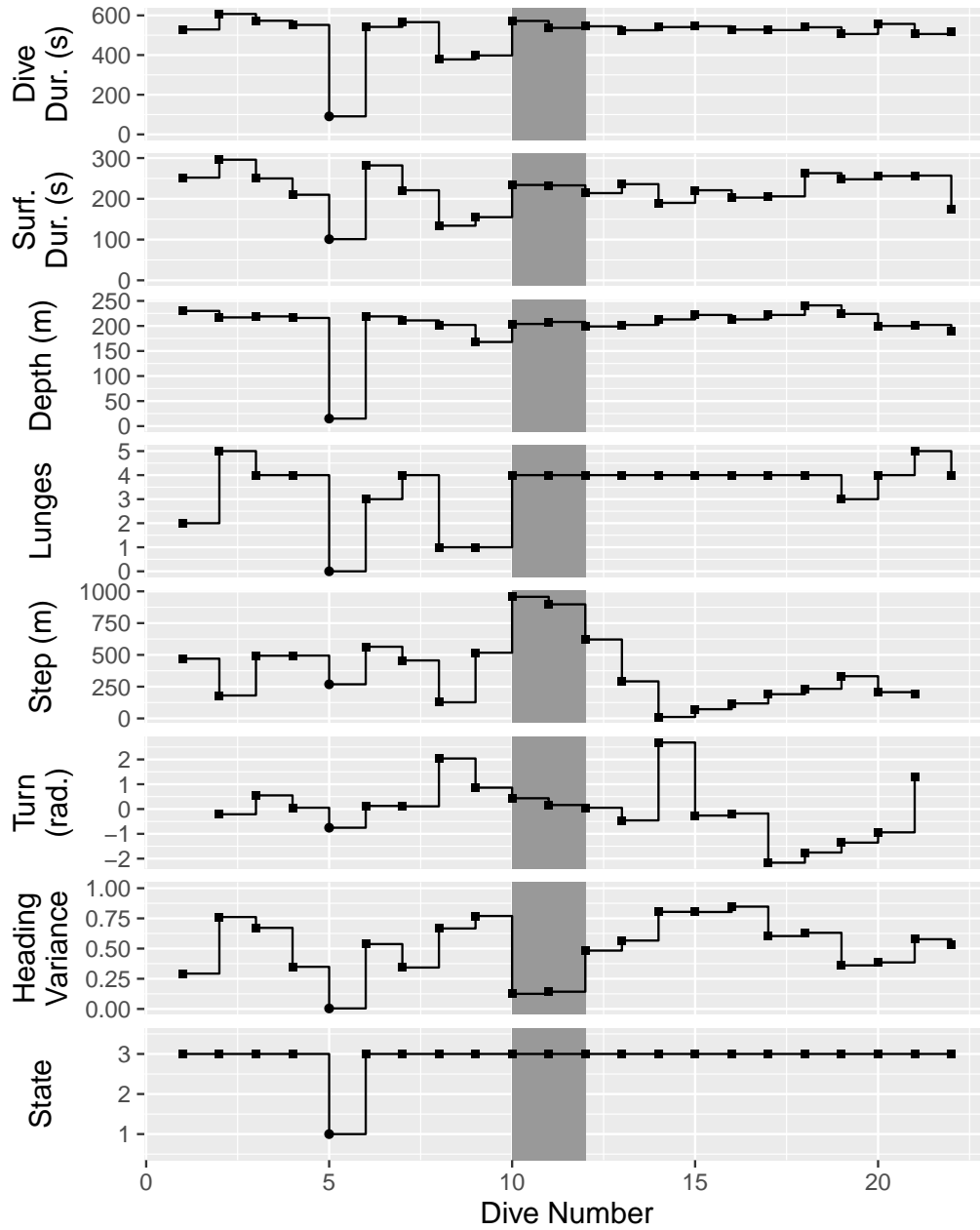


Figure 11: Time-series plot of the input data for whale bw10-243b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

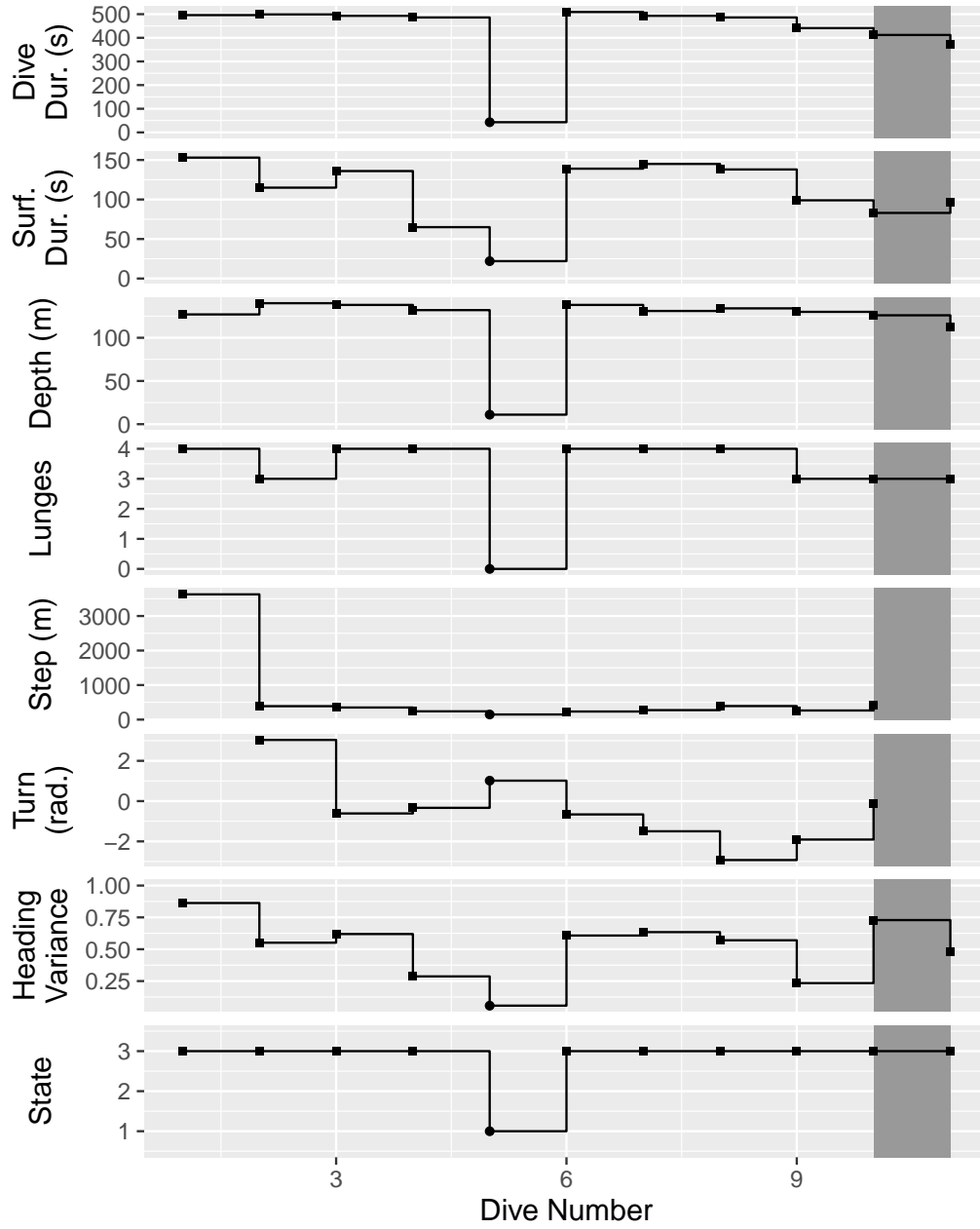


Figure 12: Time-series plot of the input data for whale bw10-244b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

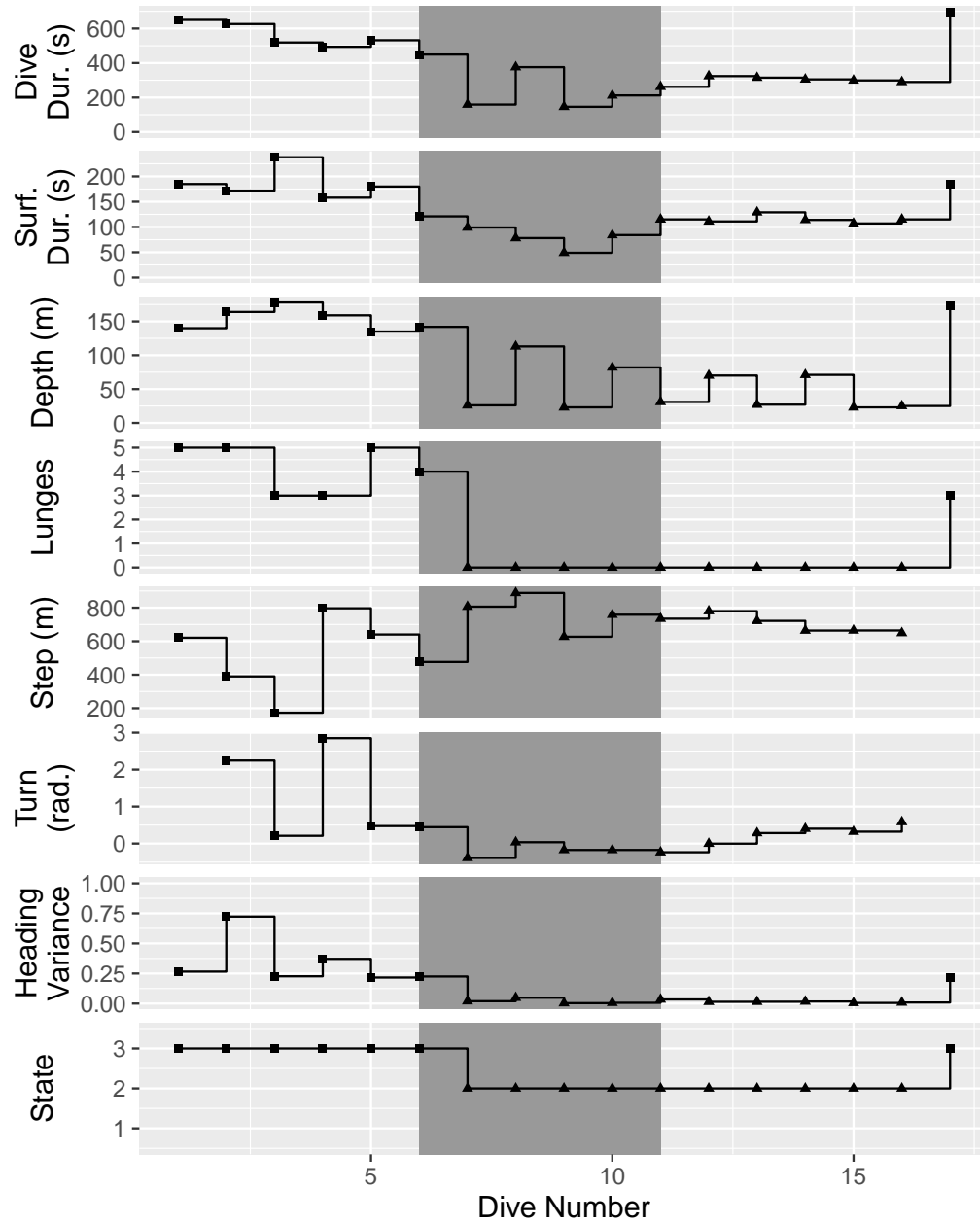


Figure 13: Time-series plot of the input data for whale bw10-244c. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

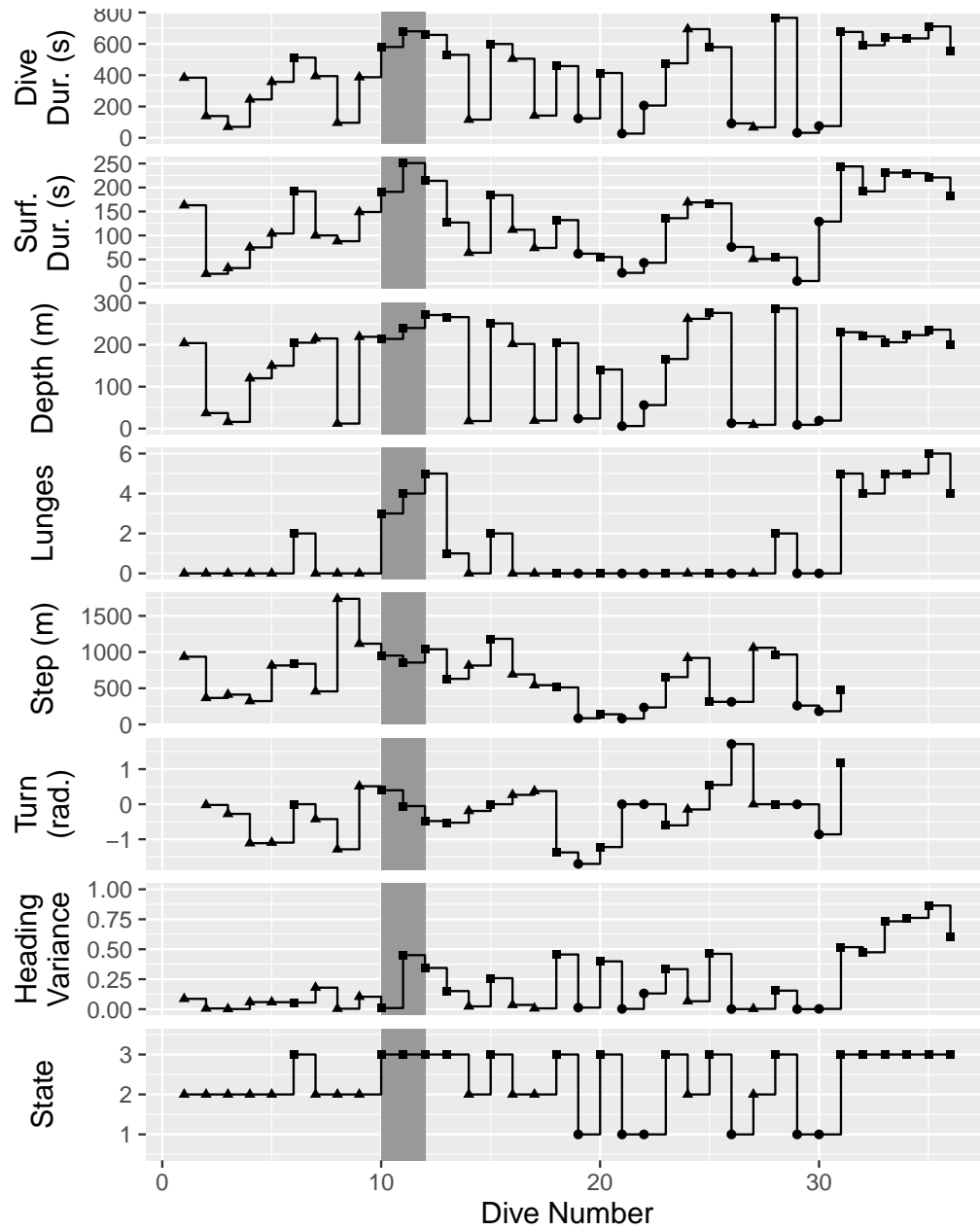


Figure 14: Time-series plot of the input data for whale bw10-245a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

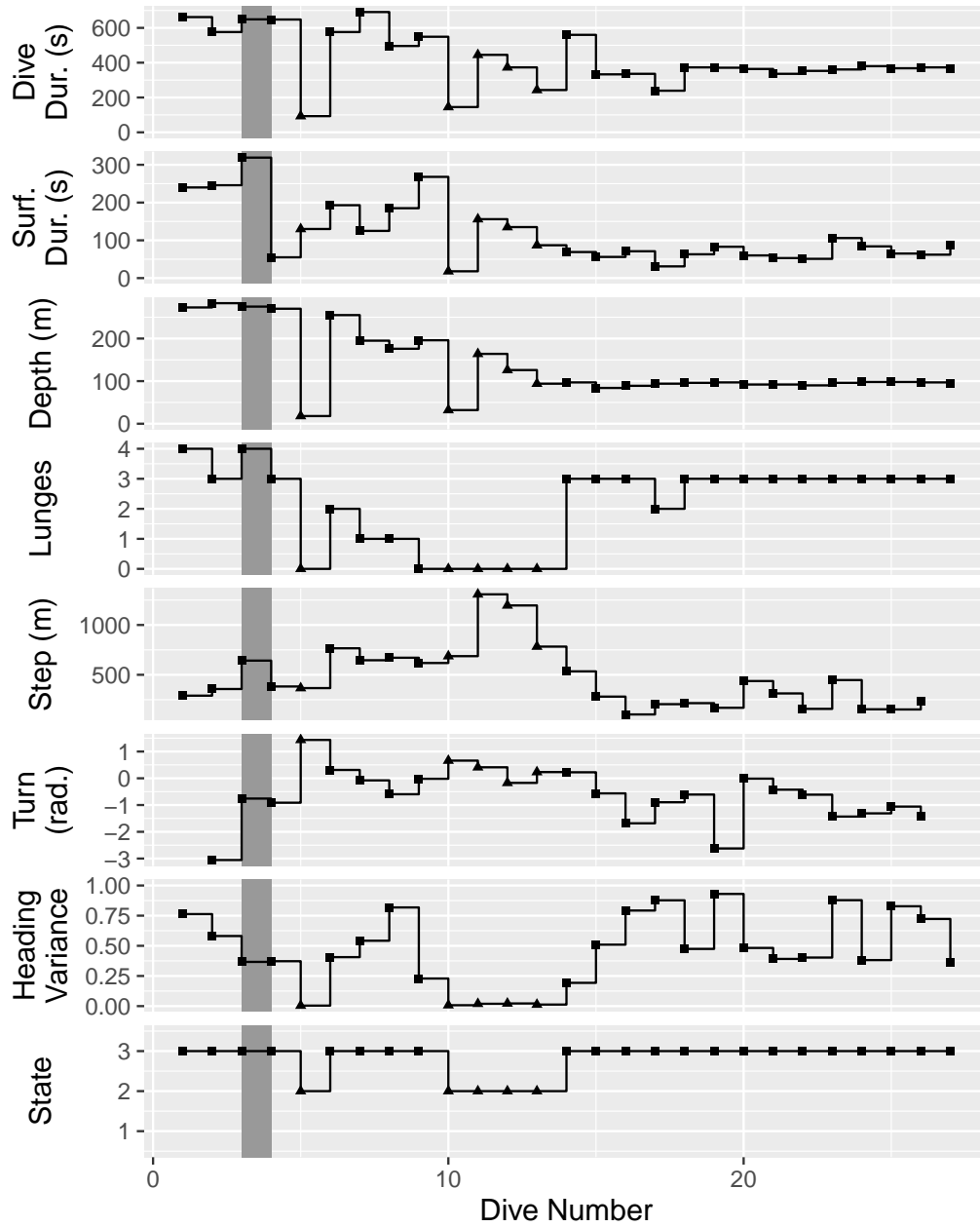


Figure 15: Time-series plot of the input data for whale bw10-246a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

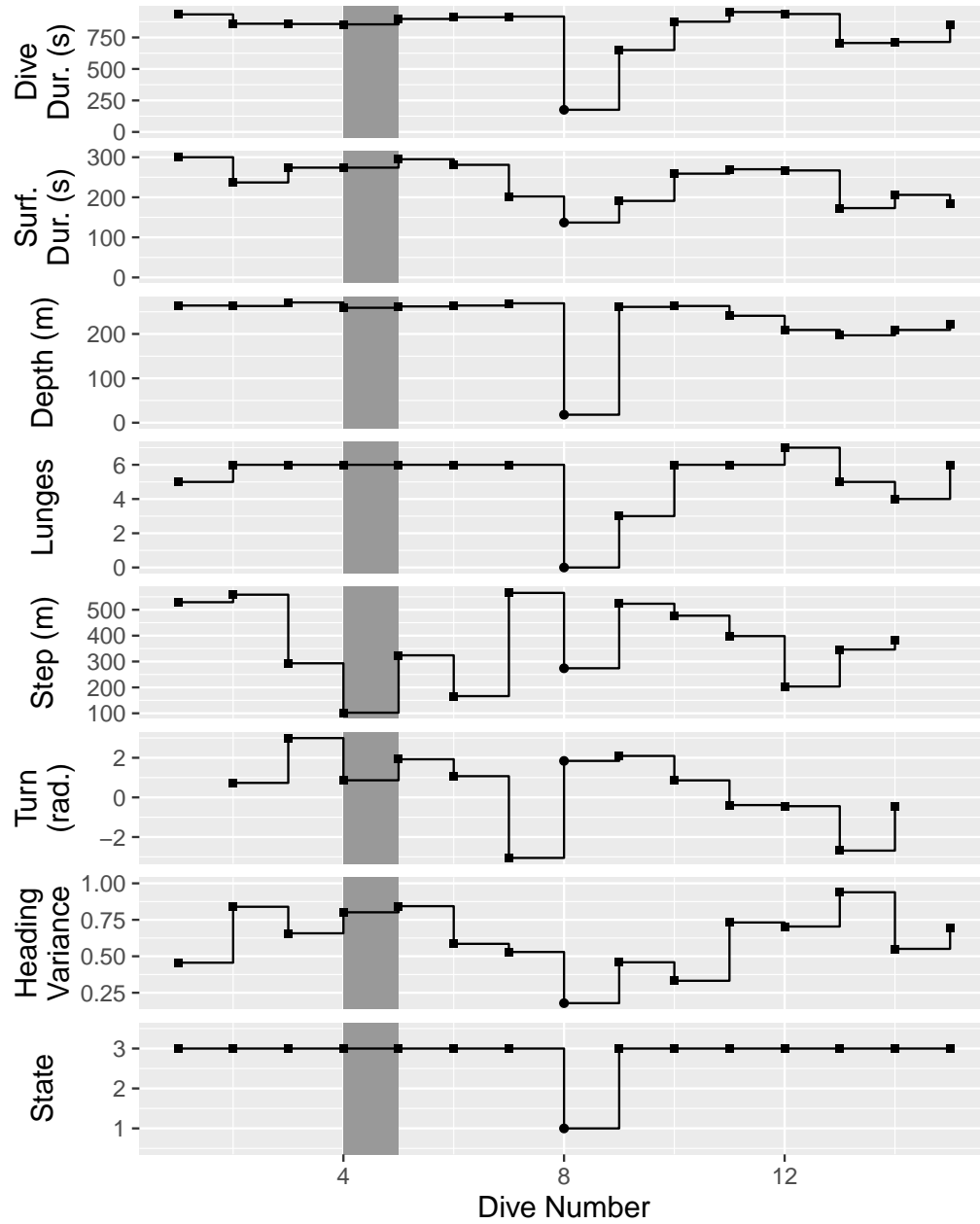


Figure 16: Time-series plot of the input data for whale bw10-246b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

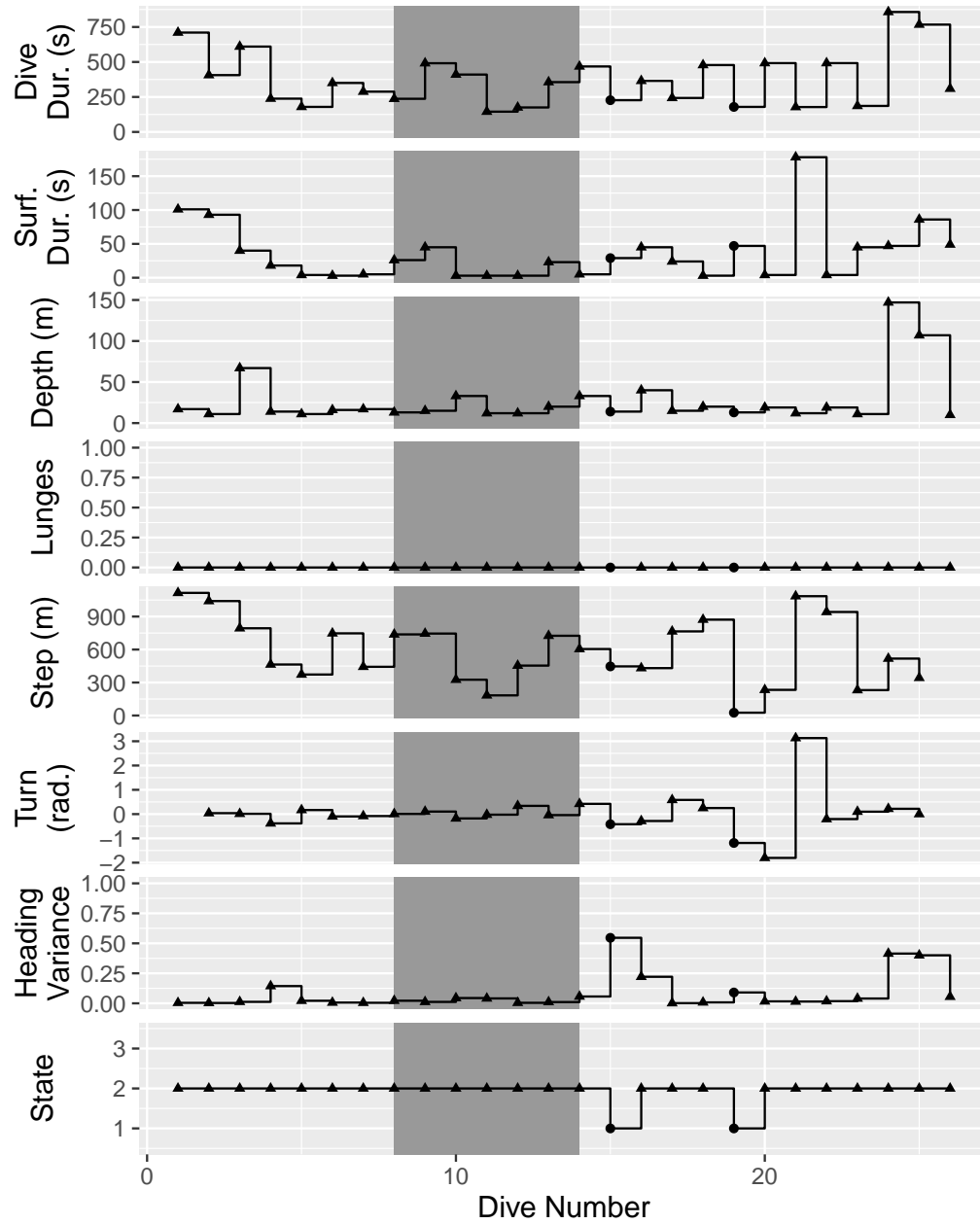


Figure 17: Time-series plot of the input data for whale bw10-251a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

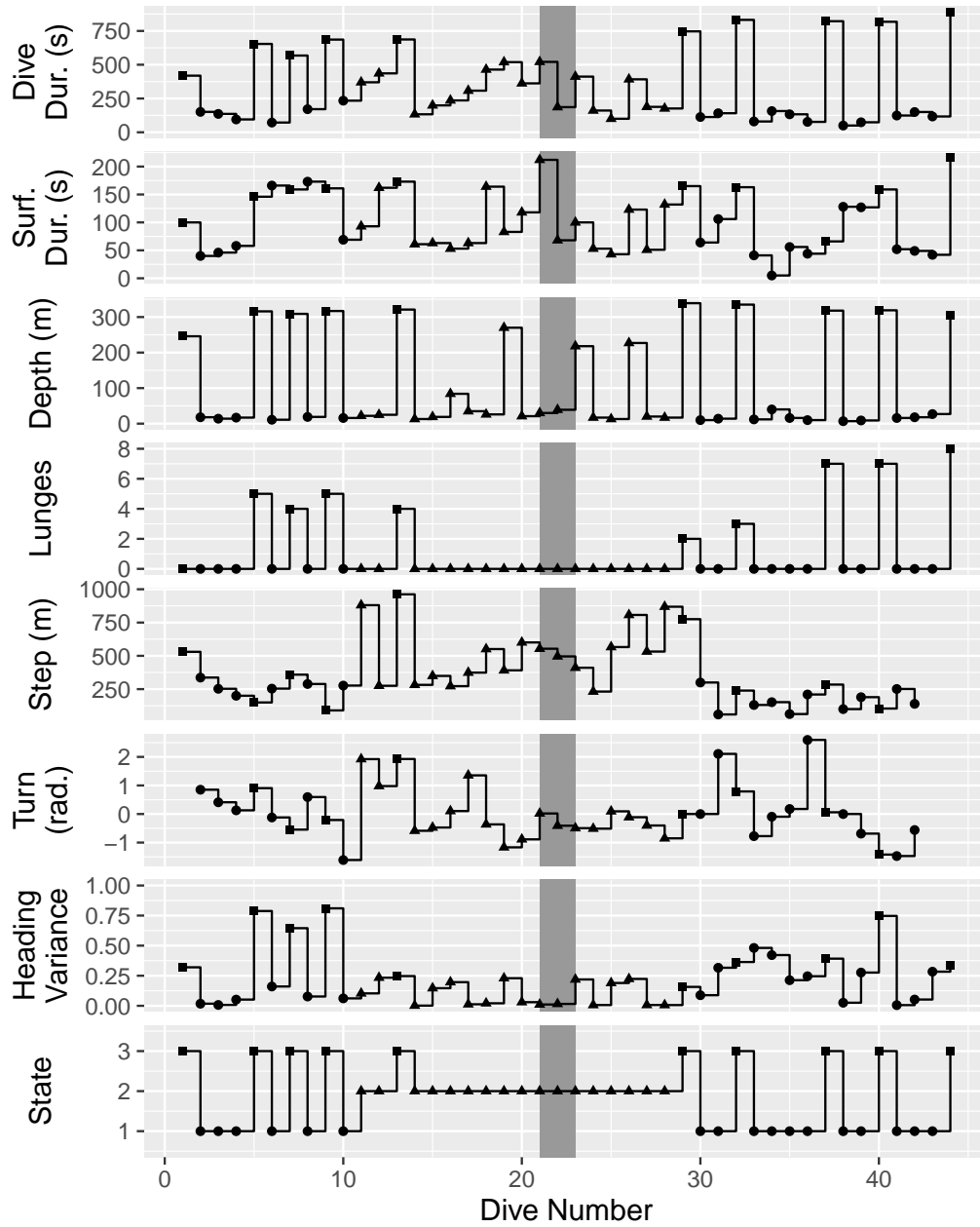


Figure 18: Time-series plot of the input data for whale bw10-265a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

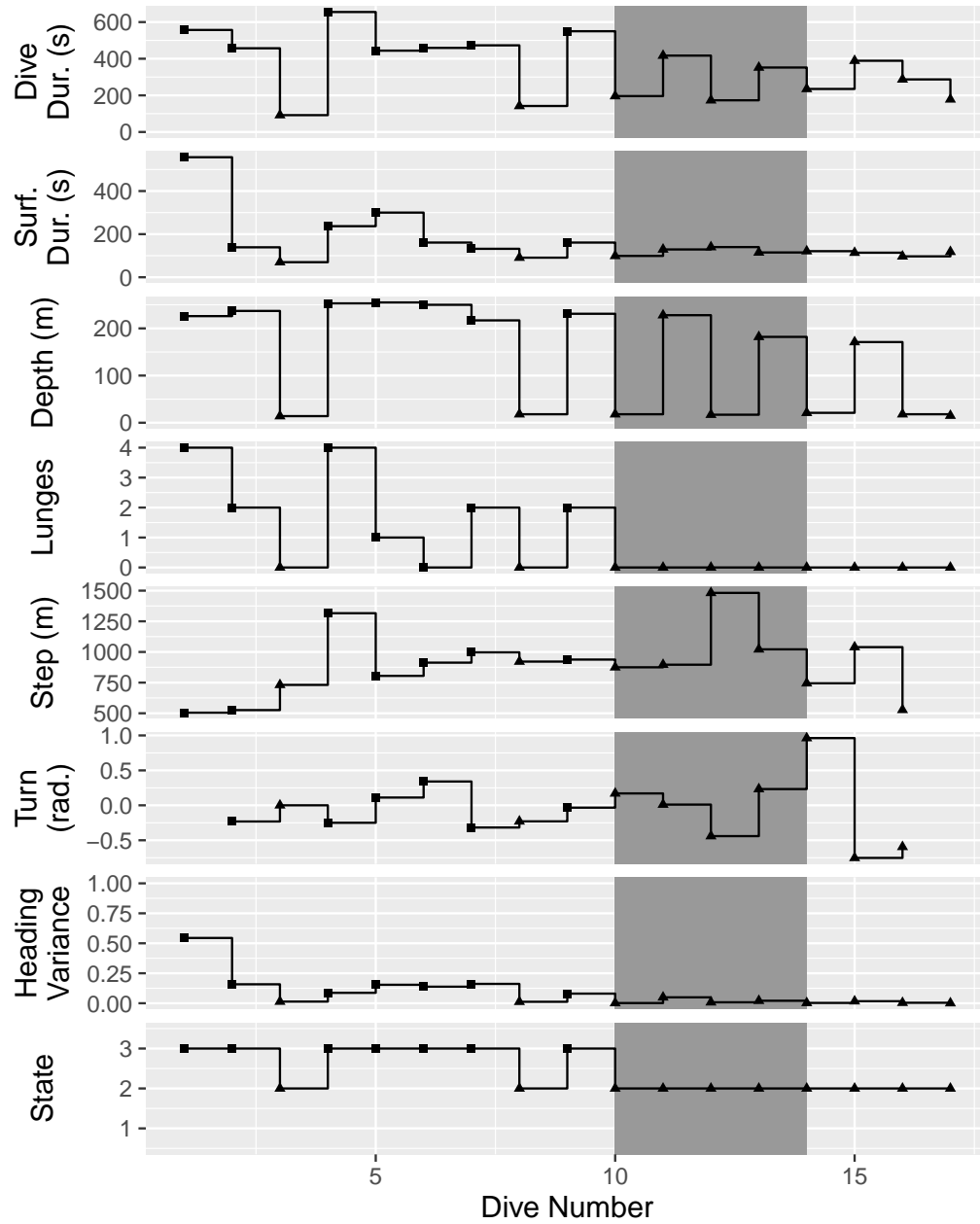


Figure 19: Time-series plot of the input data for whale bw10-266a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

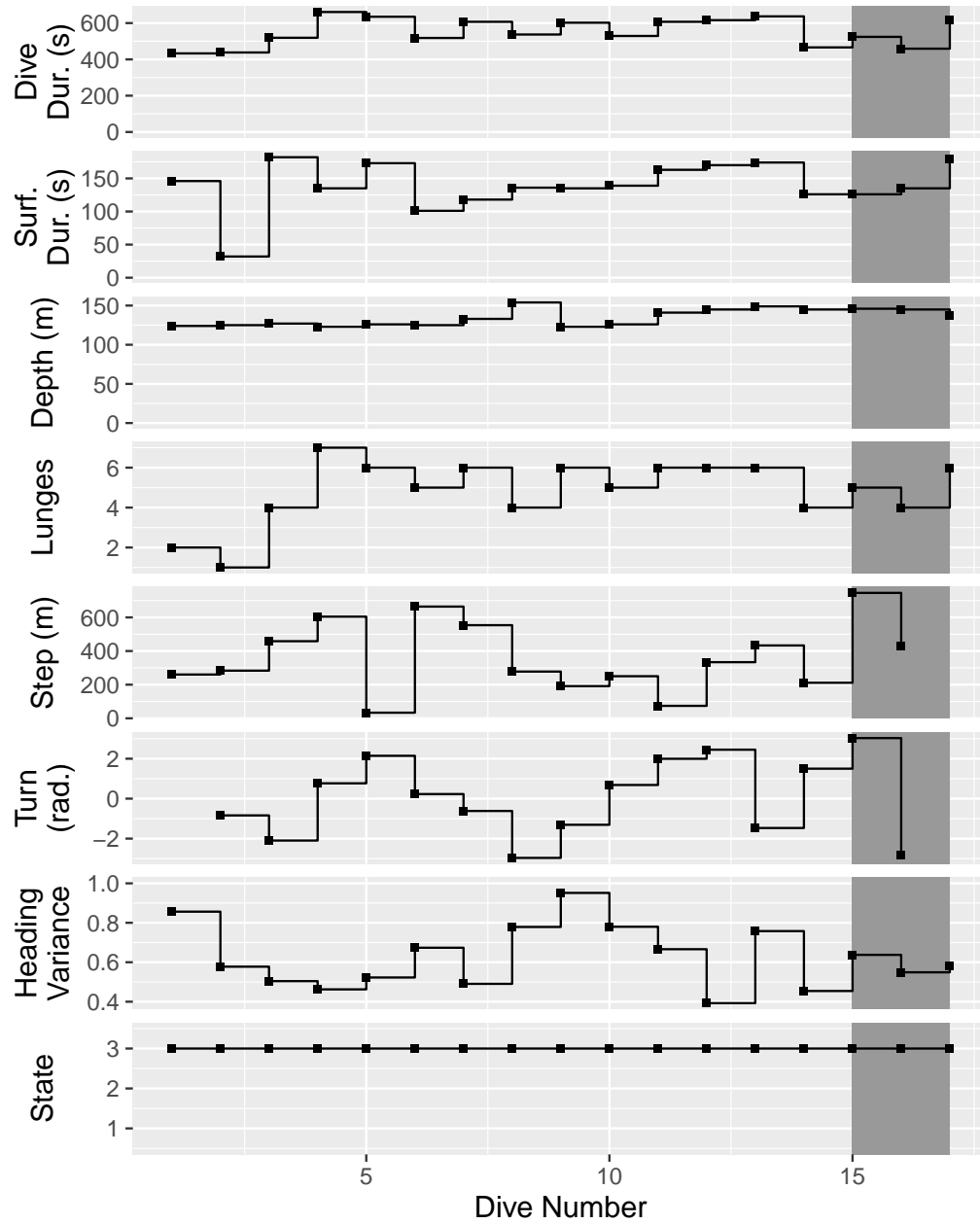


Figure 20: Time-series plot of the input data for whale bw11-210a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

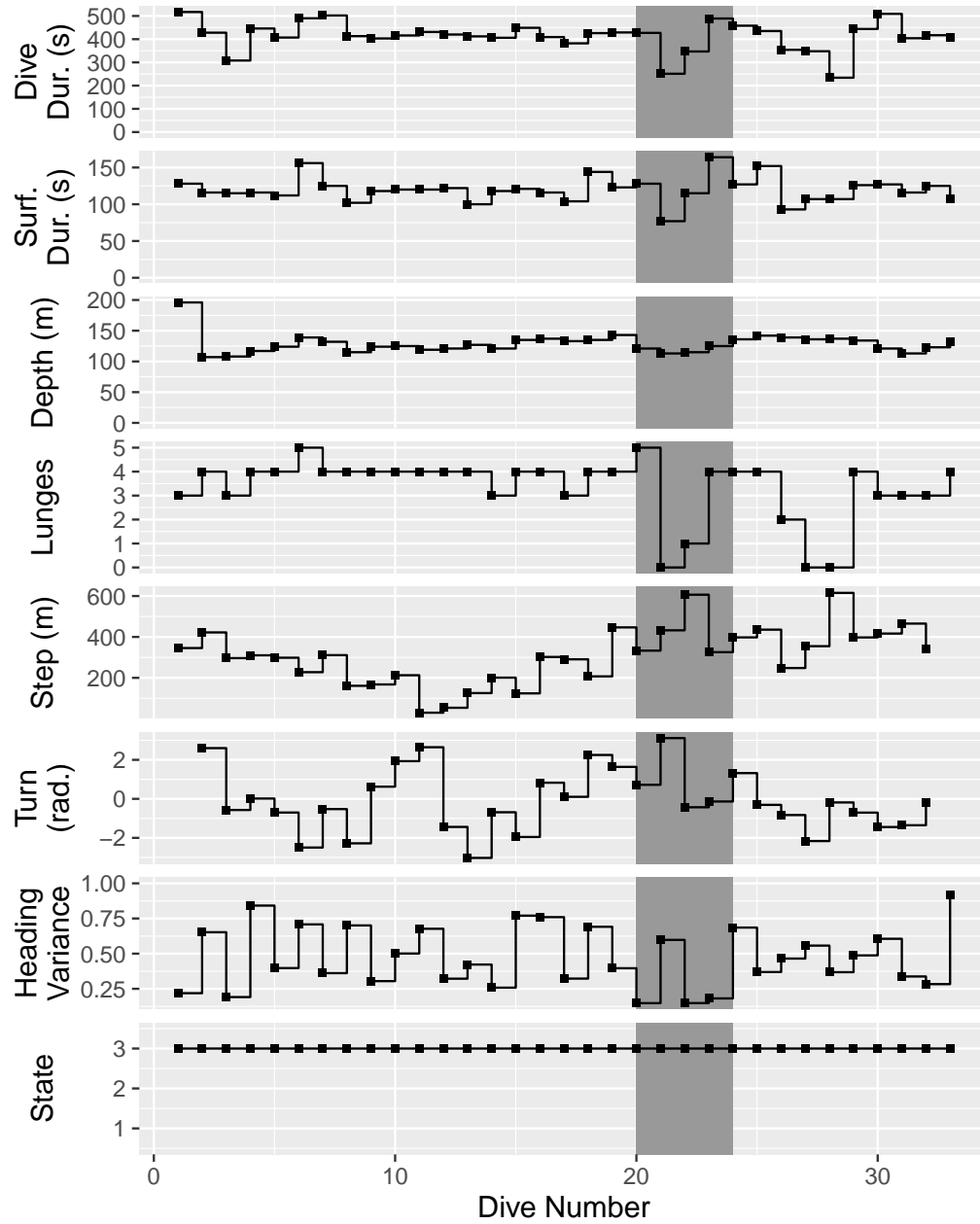


Figure 21: Time-series plot of the input data for whale bw11-210b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

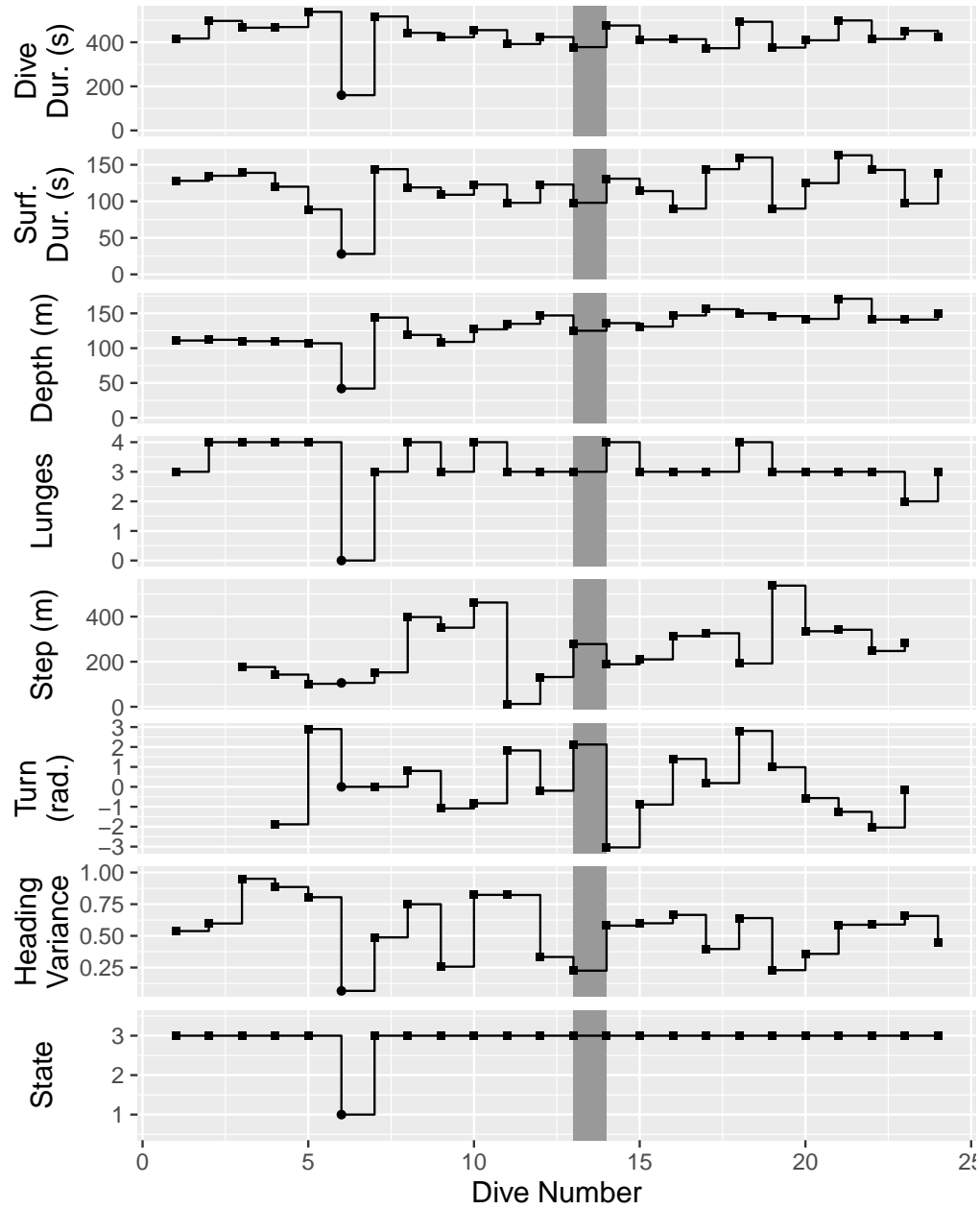


Figure 22: Time-series plot of the input data for whale bw11-211a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

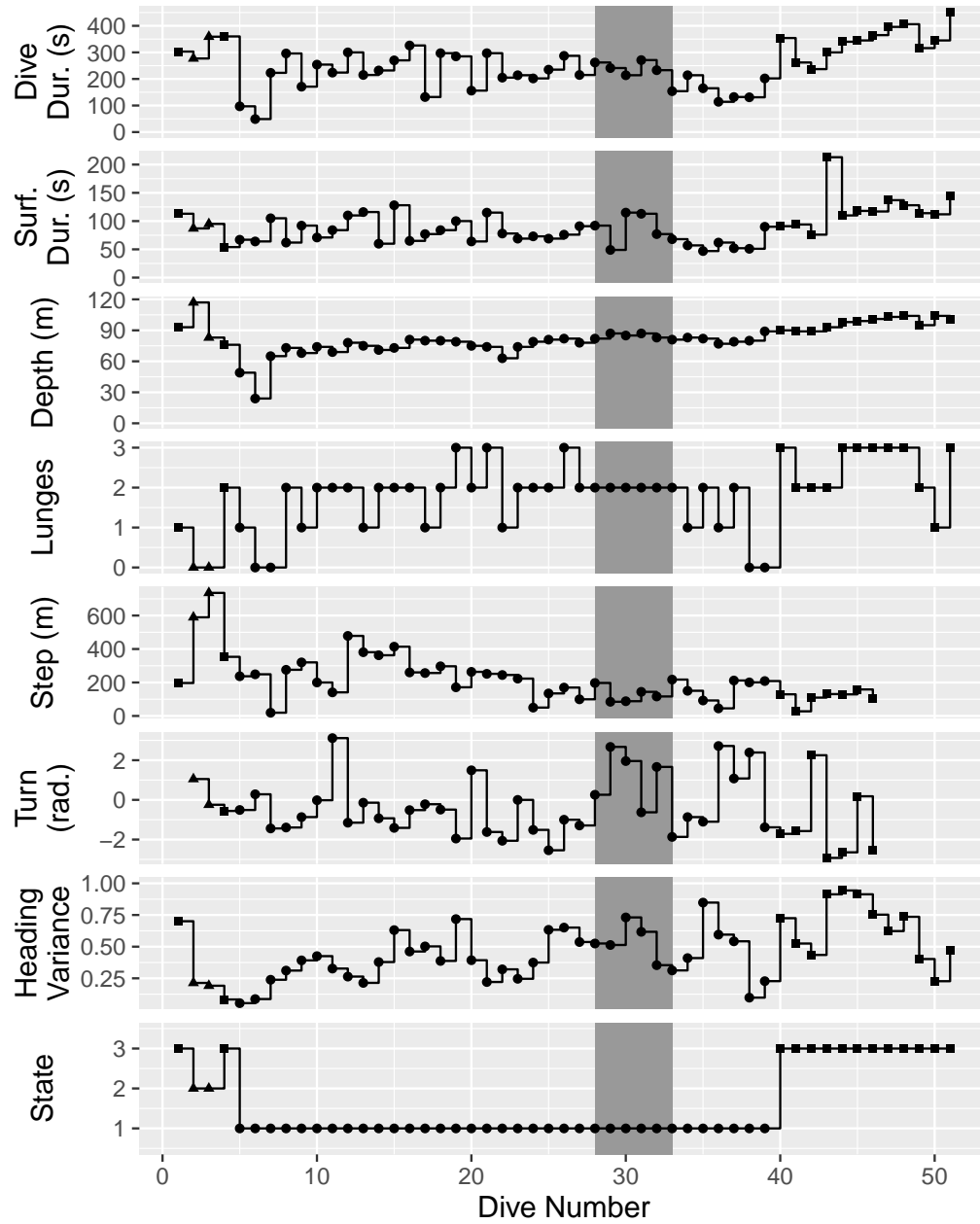


Figure 23: Time-series plot of the input data for whale bw11-213b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

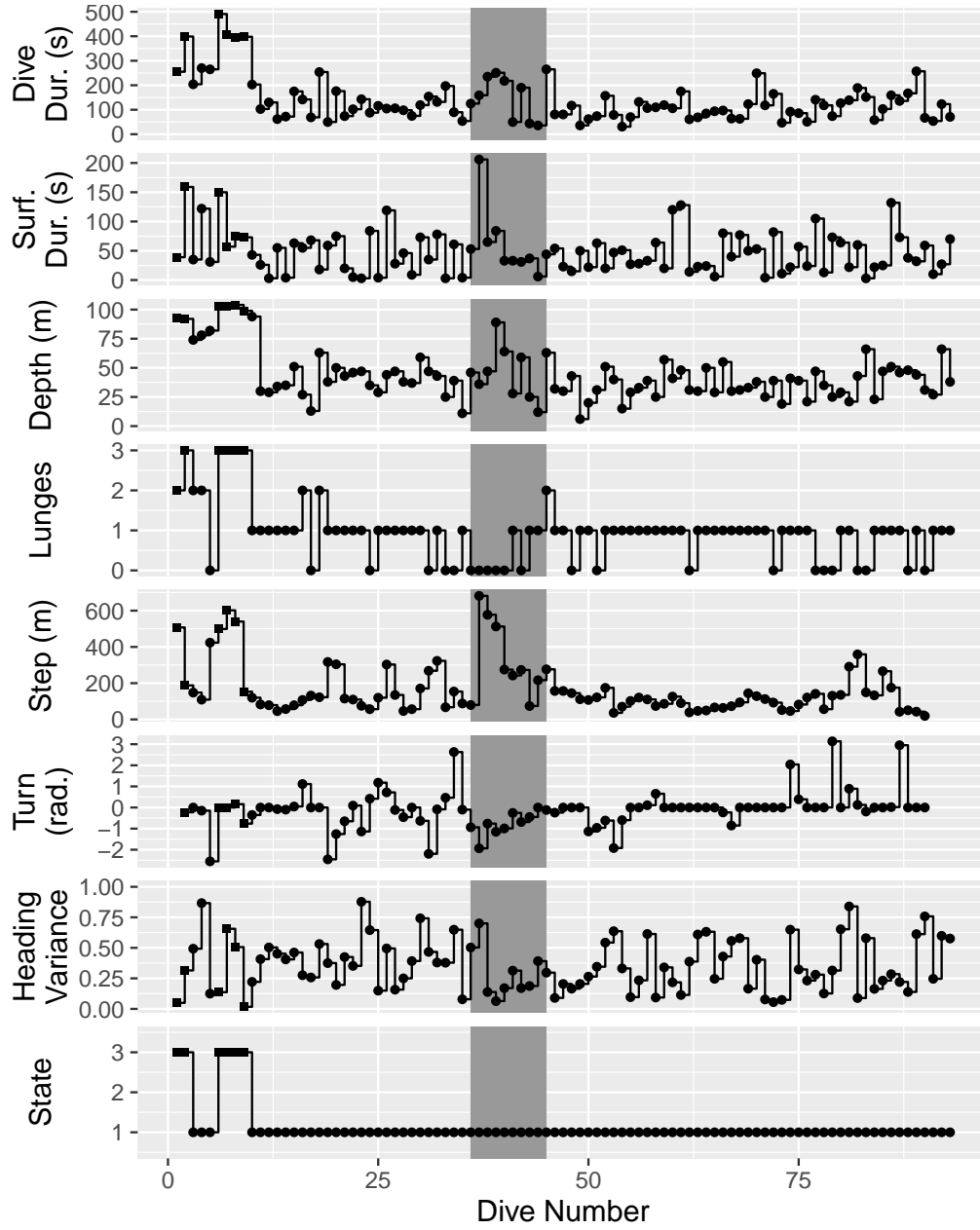


Figure 24: Time-series plot of the input data for whale bw11-214b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

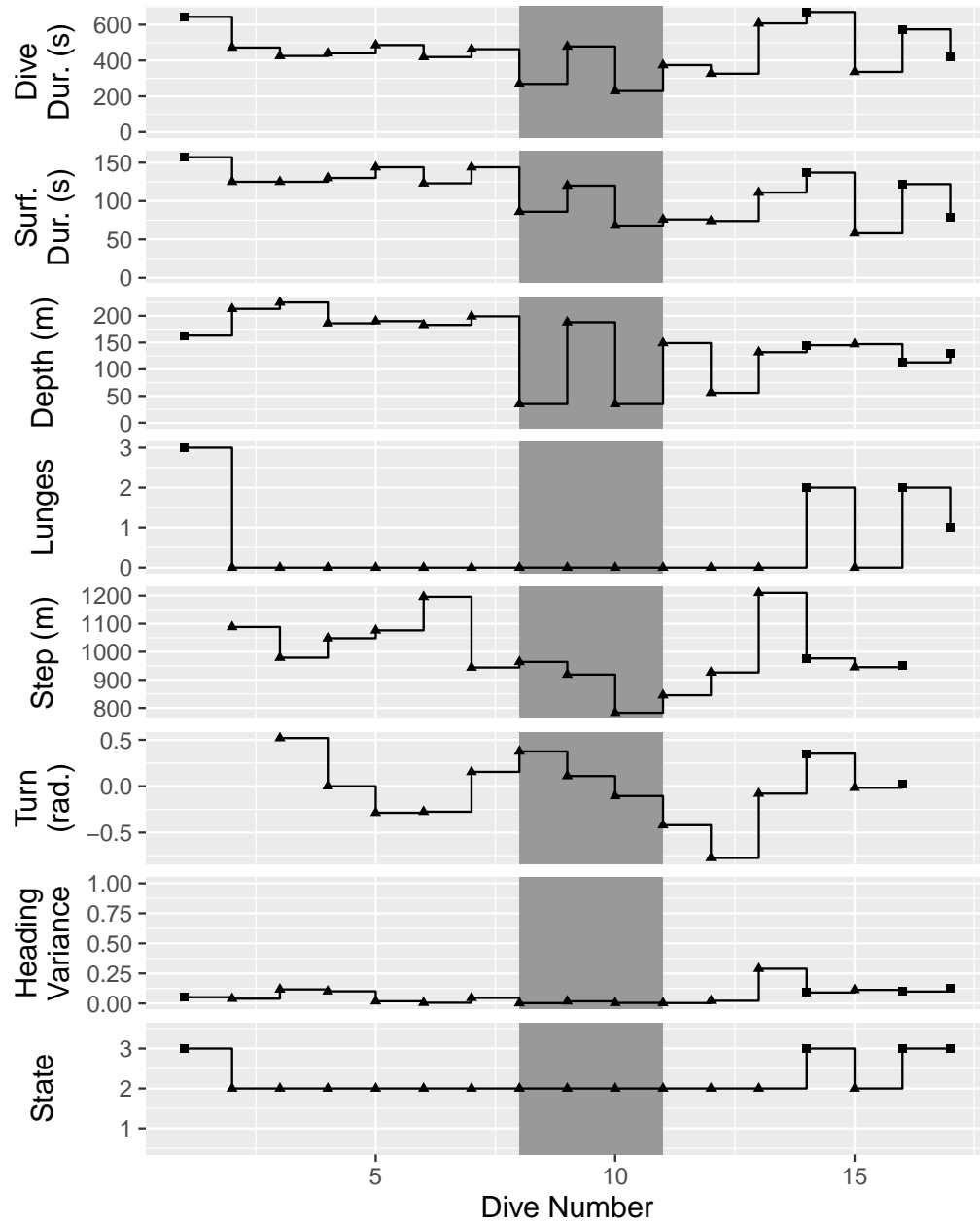


Figure 25: Time-series plot of the input data for whale bw11-218a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

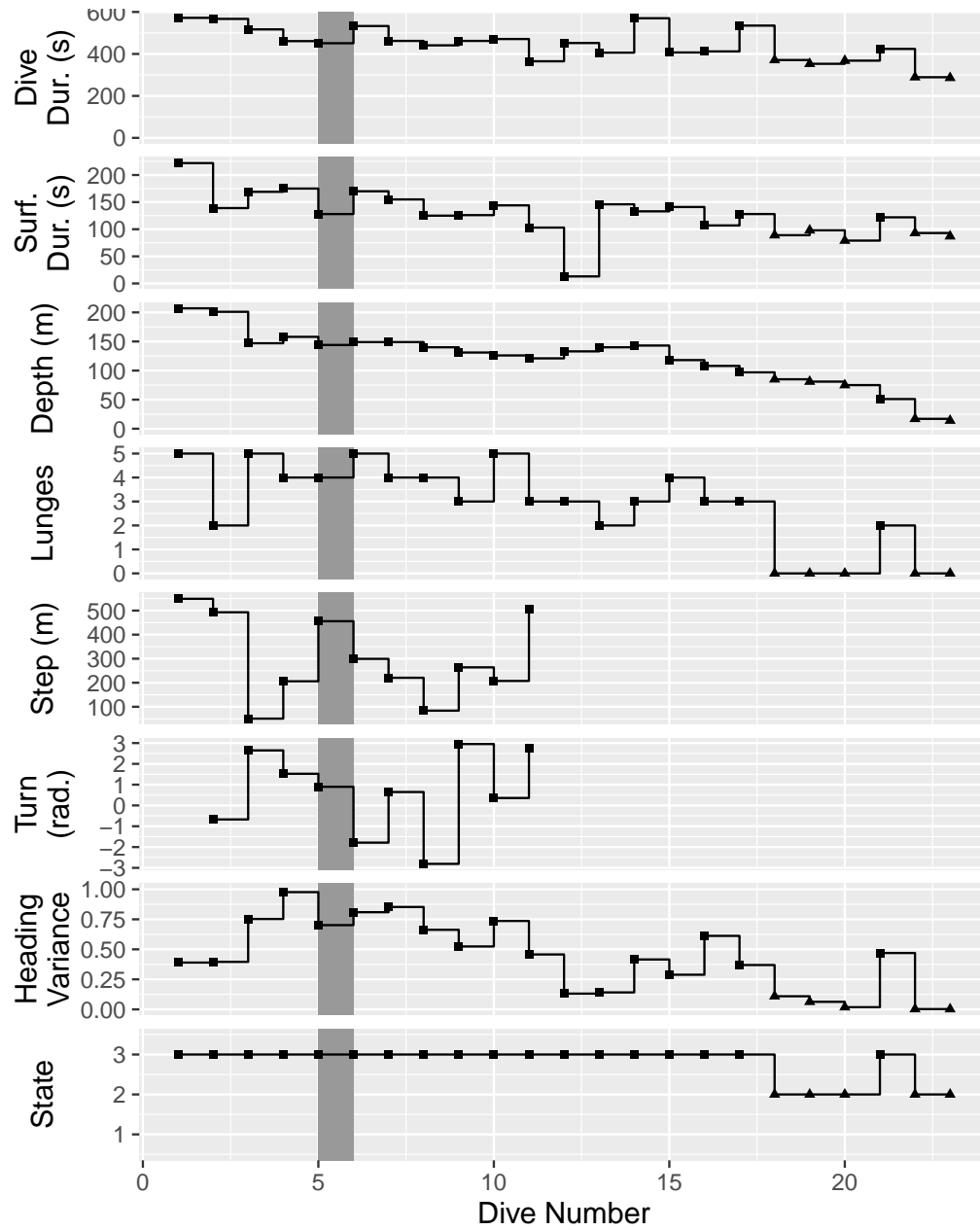


Figure 26: Time-series plot of the input data for whale bw11-218b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

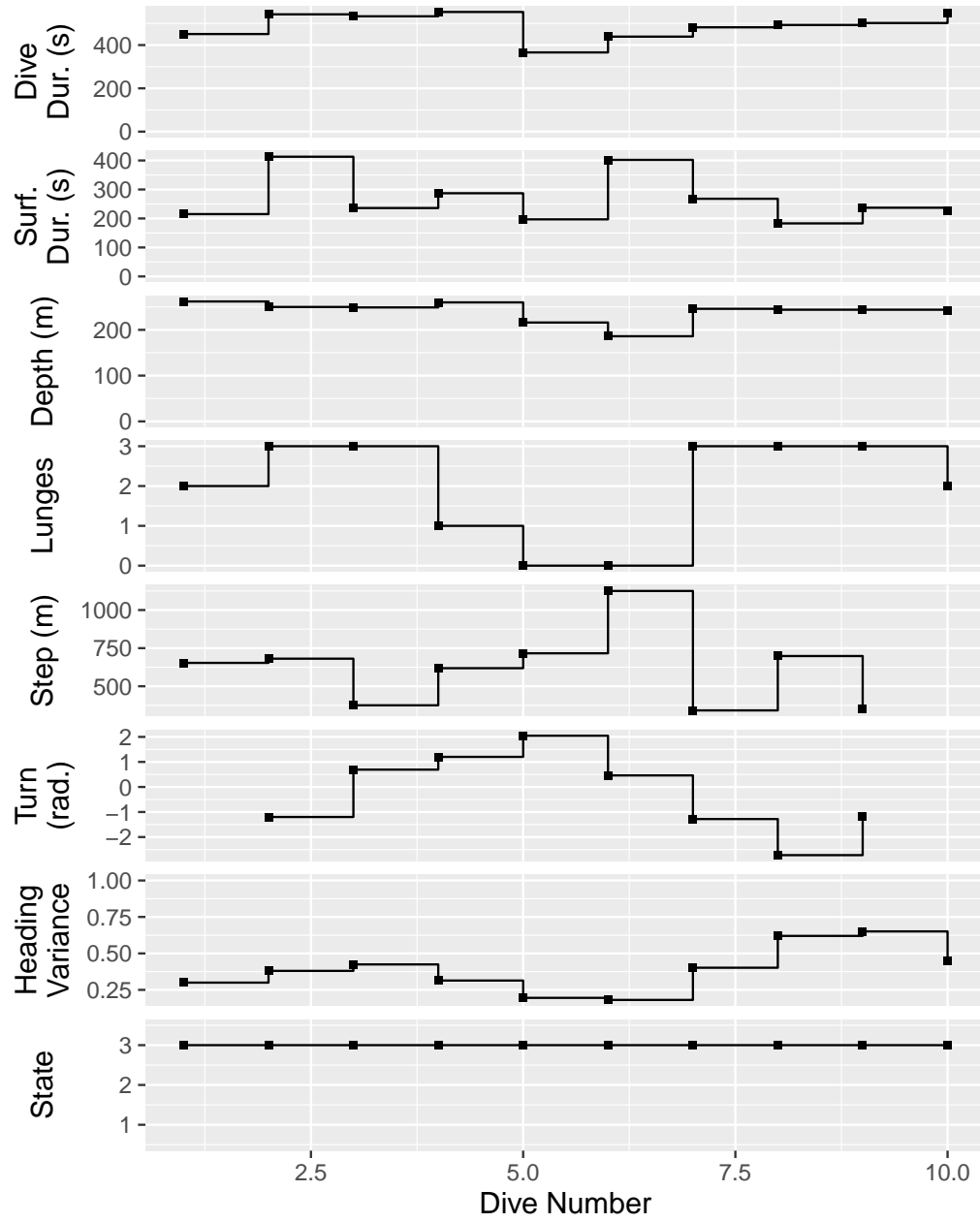


Figure 27: Time-series plot of the input data for whale bw11-219b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to no CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

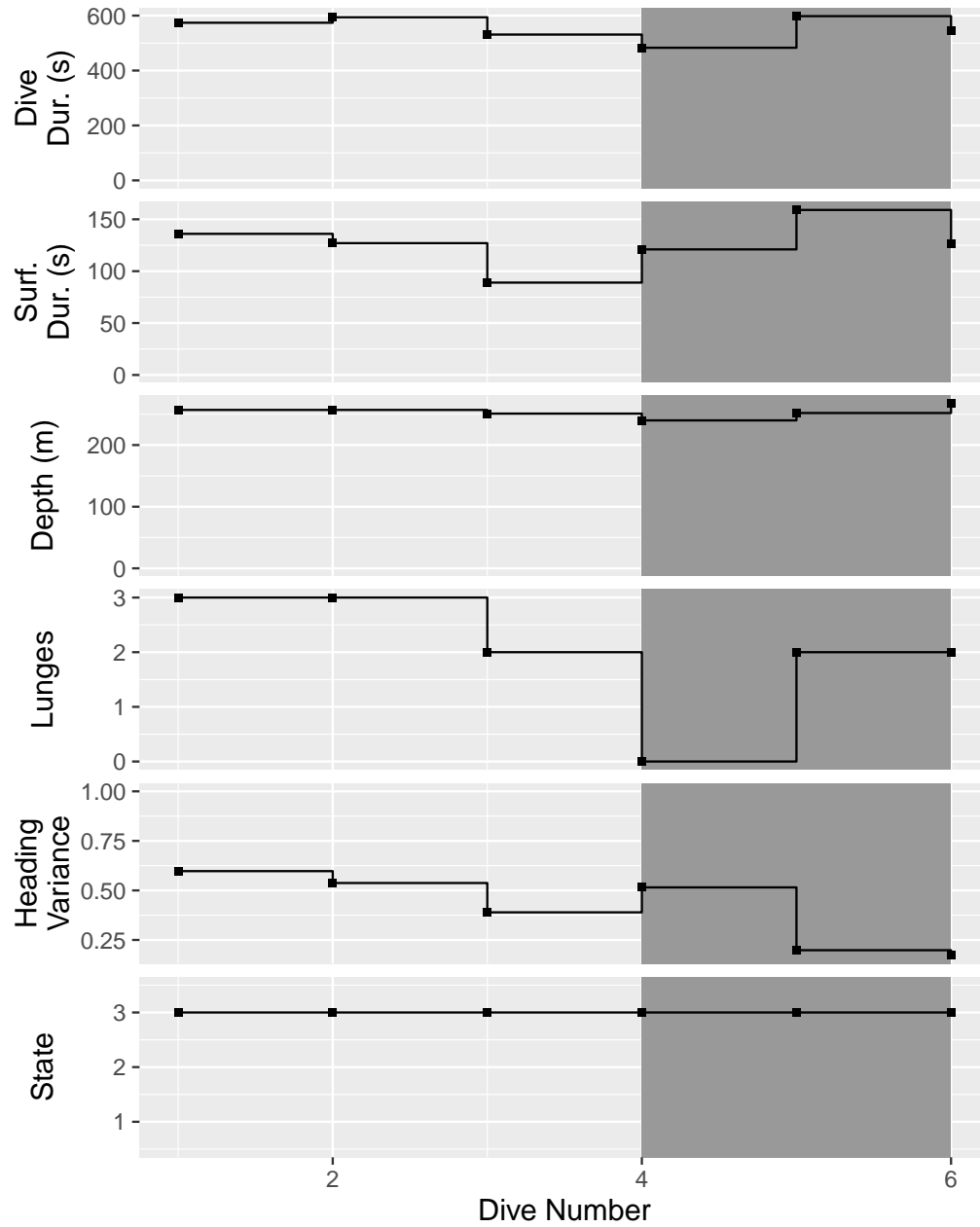


Figure 28: Time-series plot of the input data for whale bw11-220a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

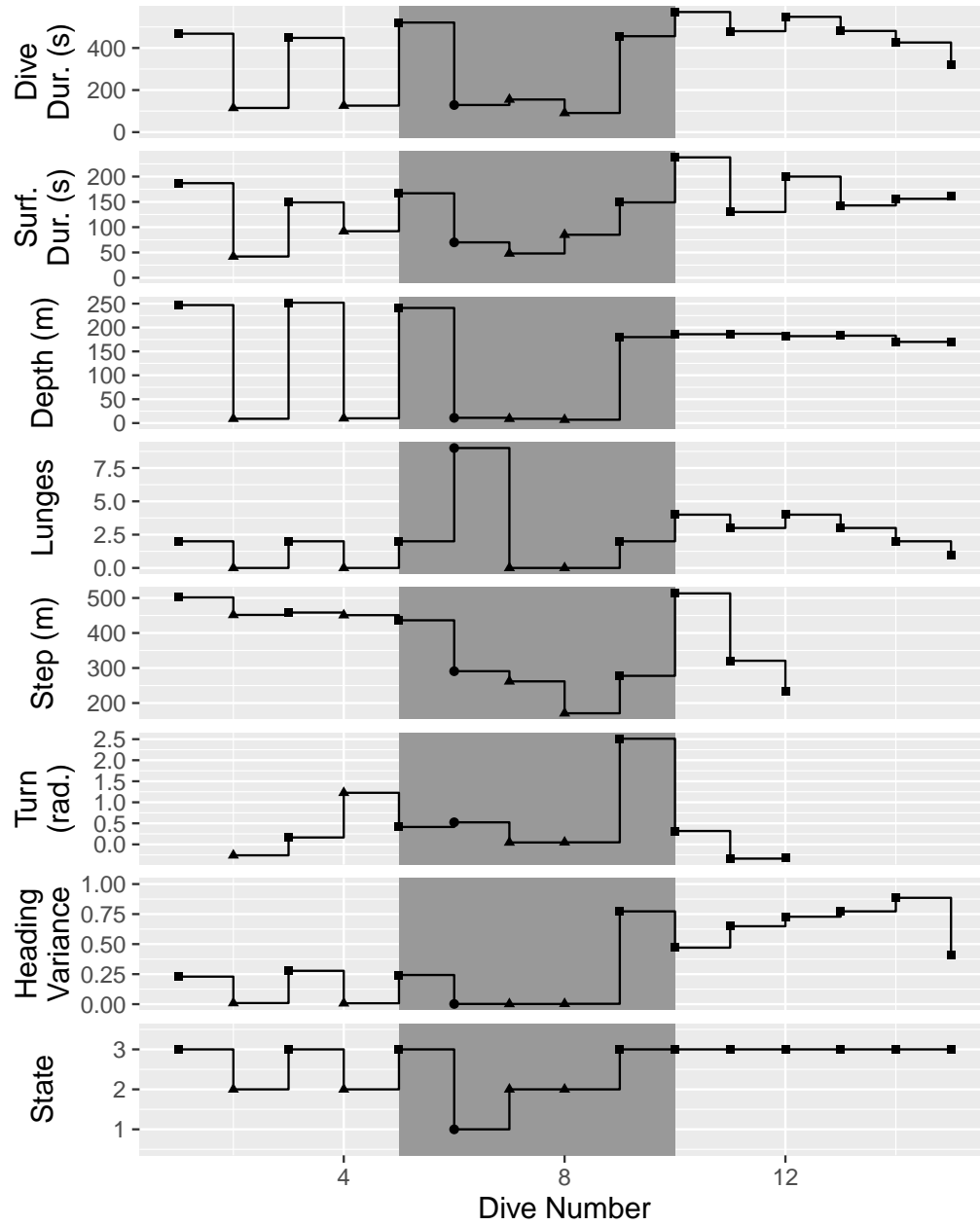


Figure 29: Time-series plot of the input data for whale bw11-220b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

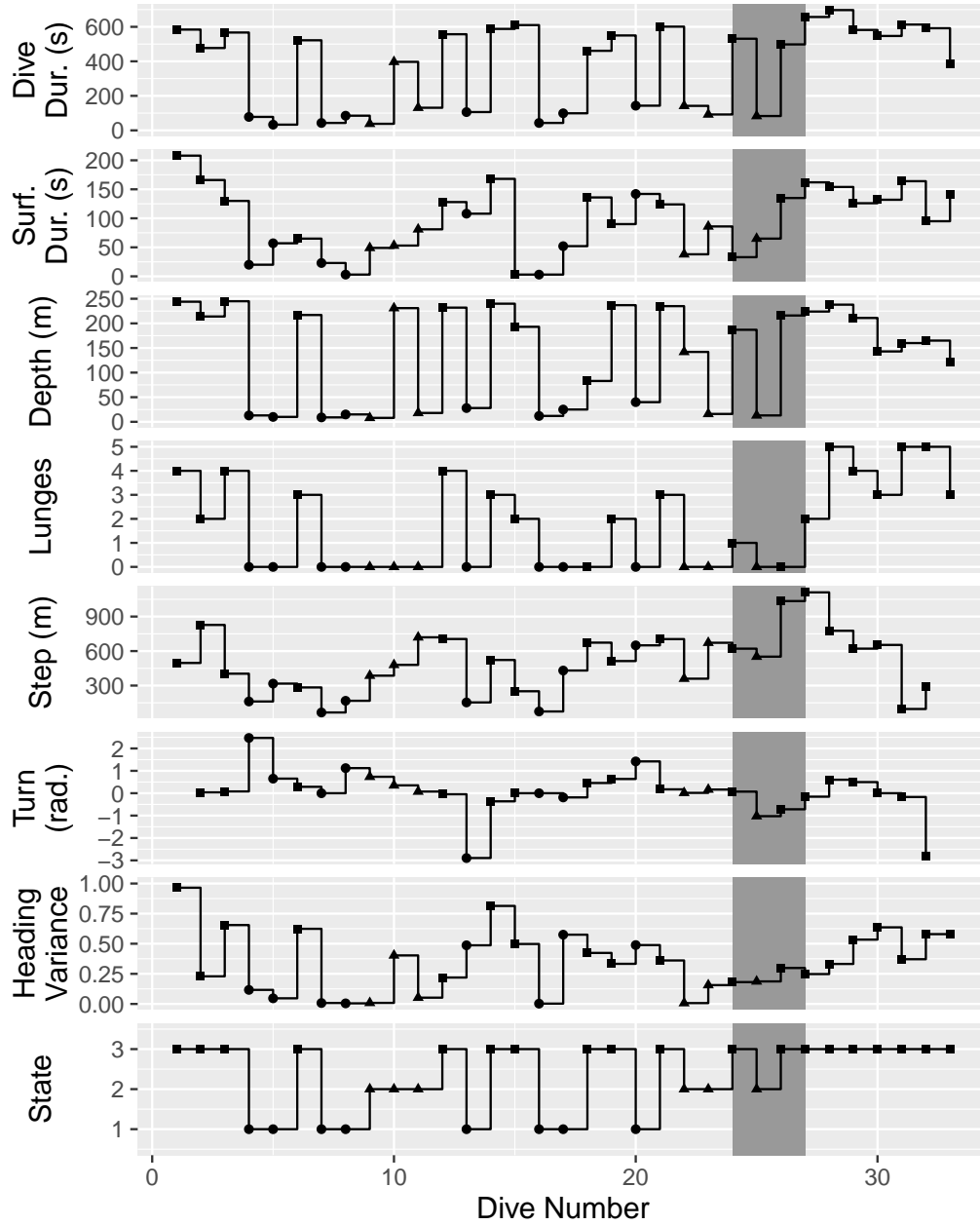


Figure 30: Time-series plot of the input data for whale bw11-221a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

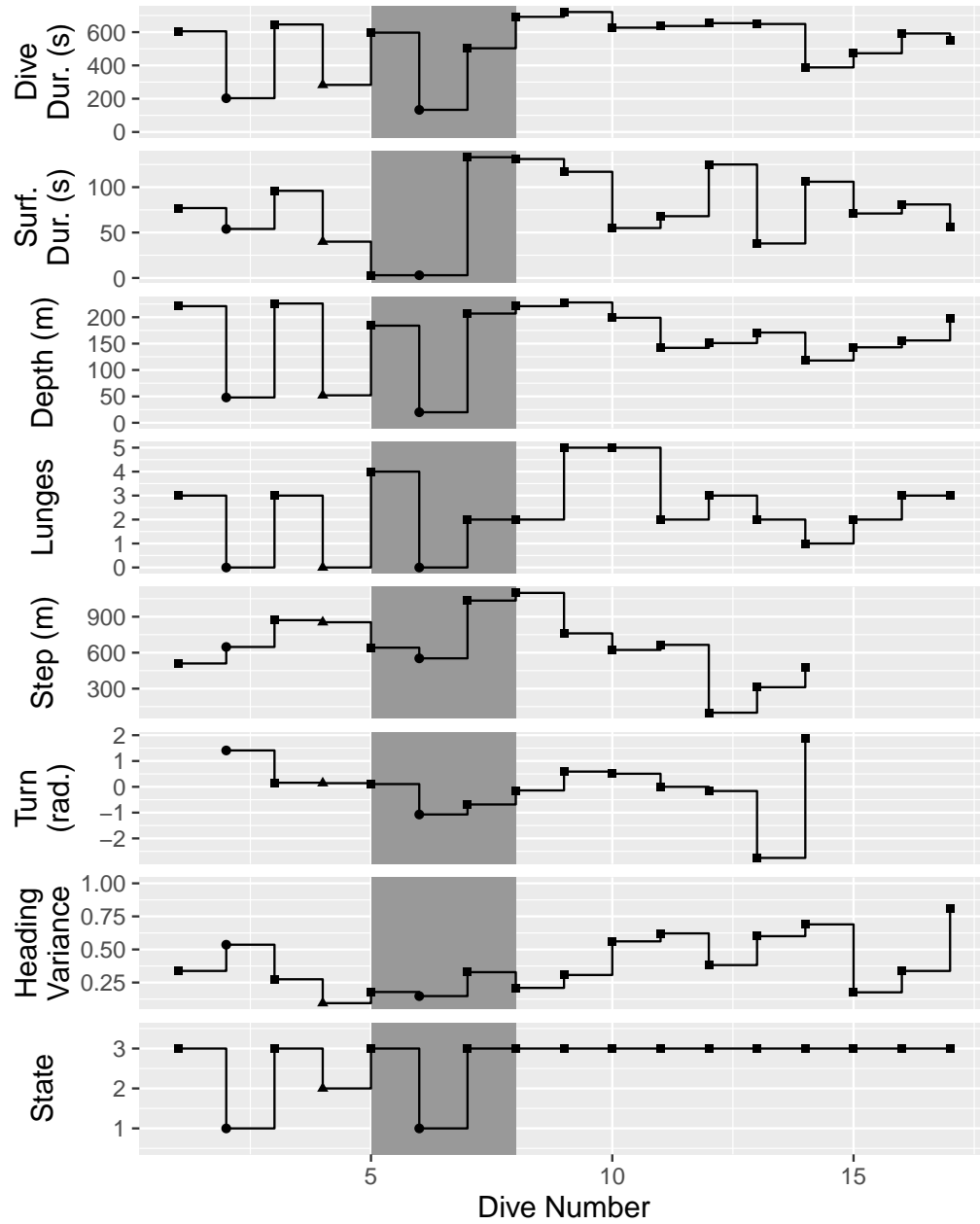


Figure 31: Time-series plot of the input data for whale bw11-221b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

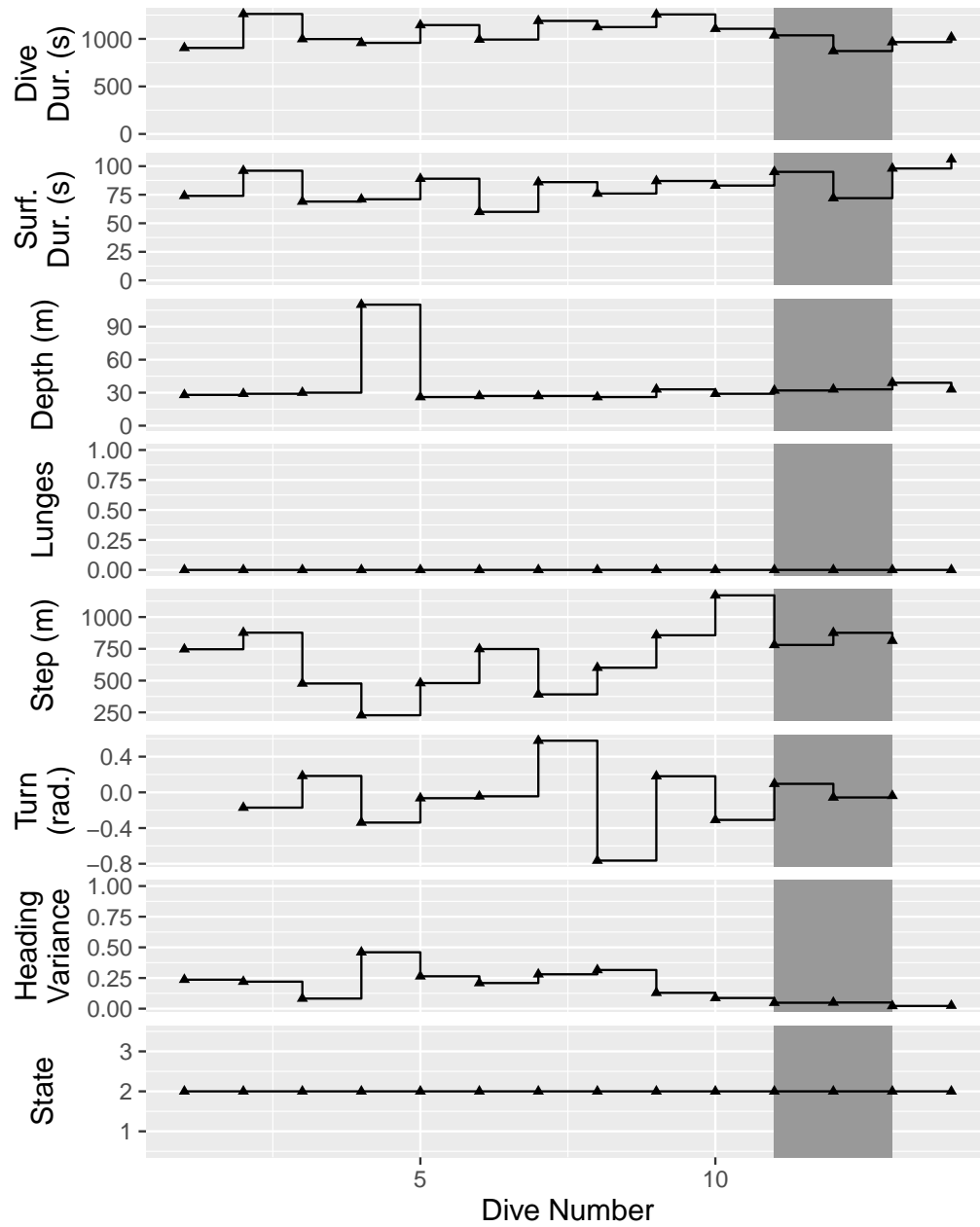


Figure 32: Time-series plot of the input data for whale bw12-292a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a PRN CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

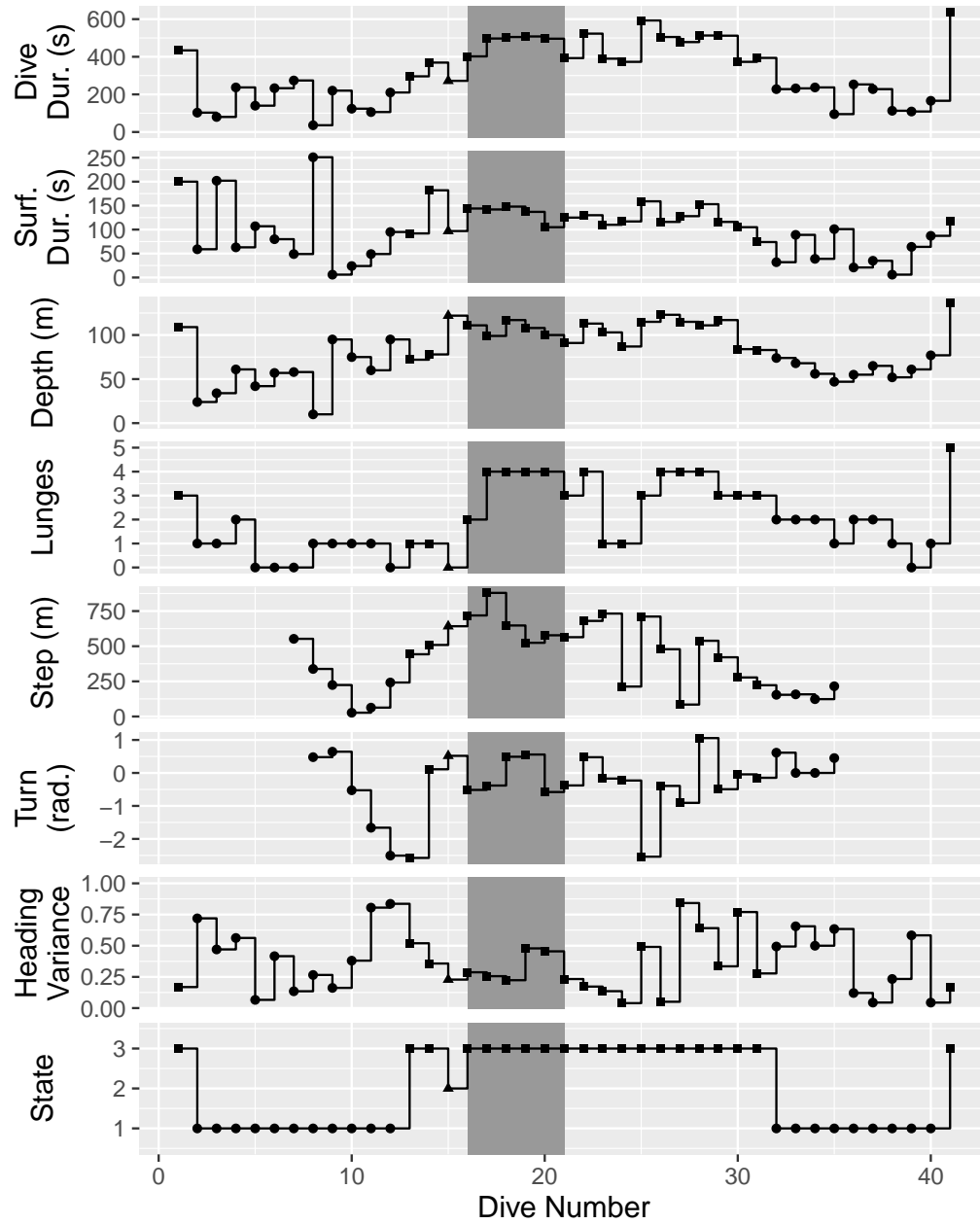


Figure 33: Time-series plot of the input data for whale bw13-191a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a real MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

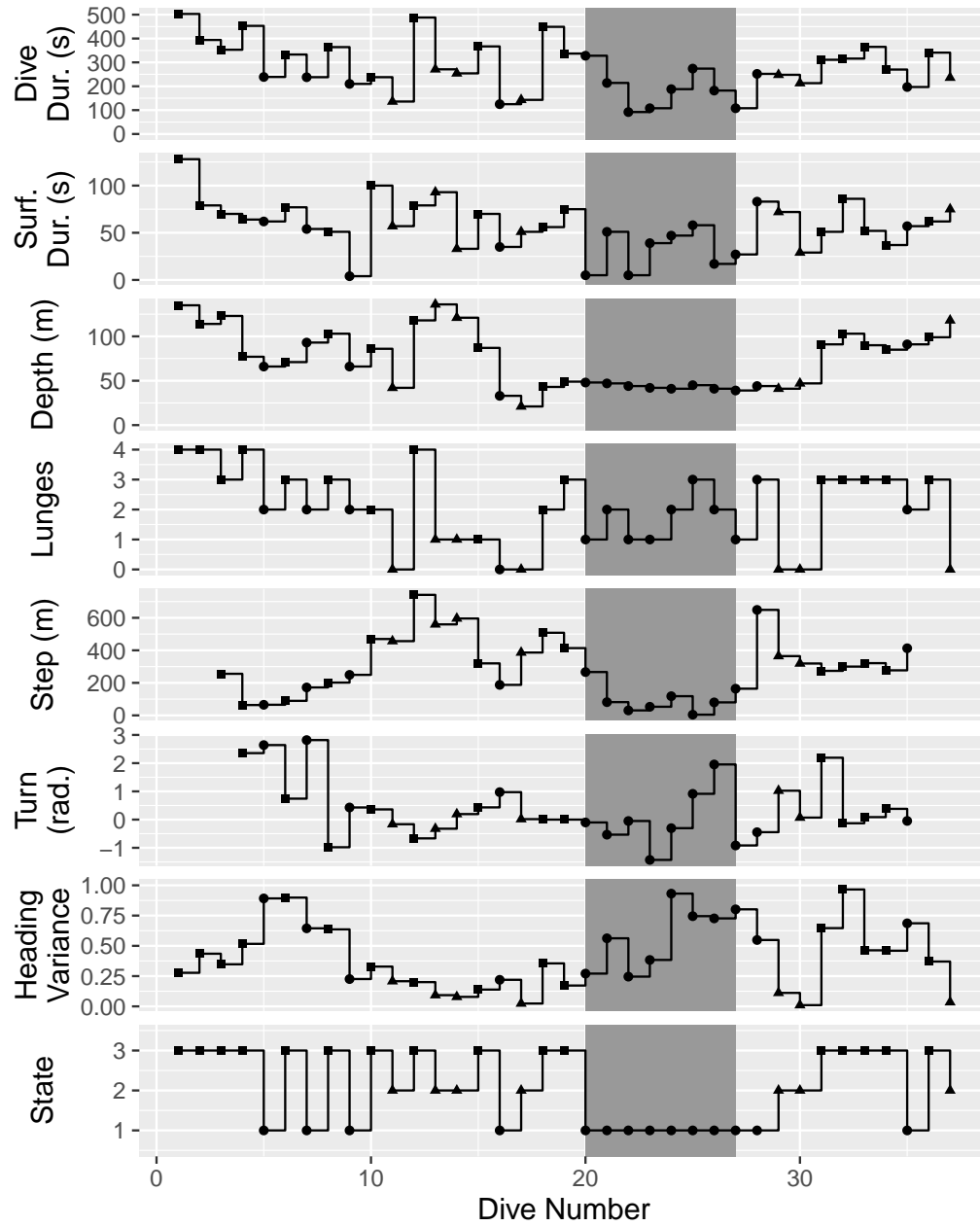


Figure 34: Time-series plot of the input data for whale bw13-207a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a silent control CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

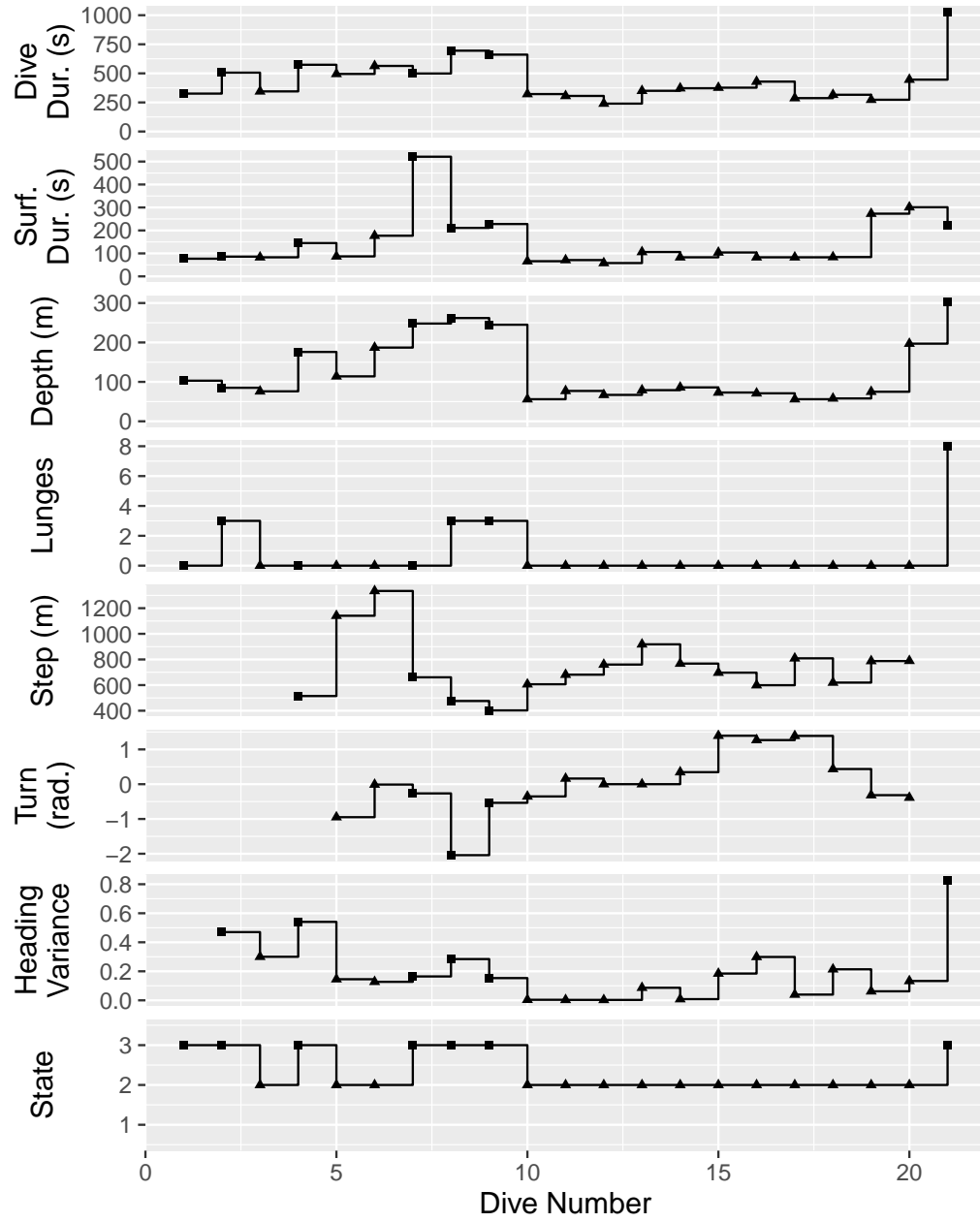


Figure 35: Time-series plot of the input data for whale bw13-214b. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to no CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

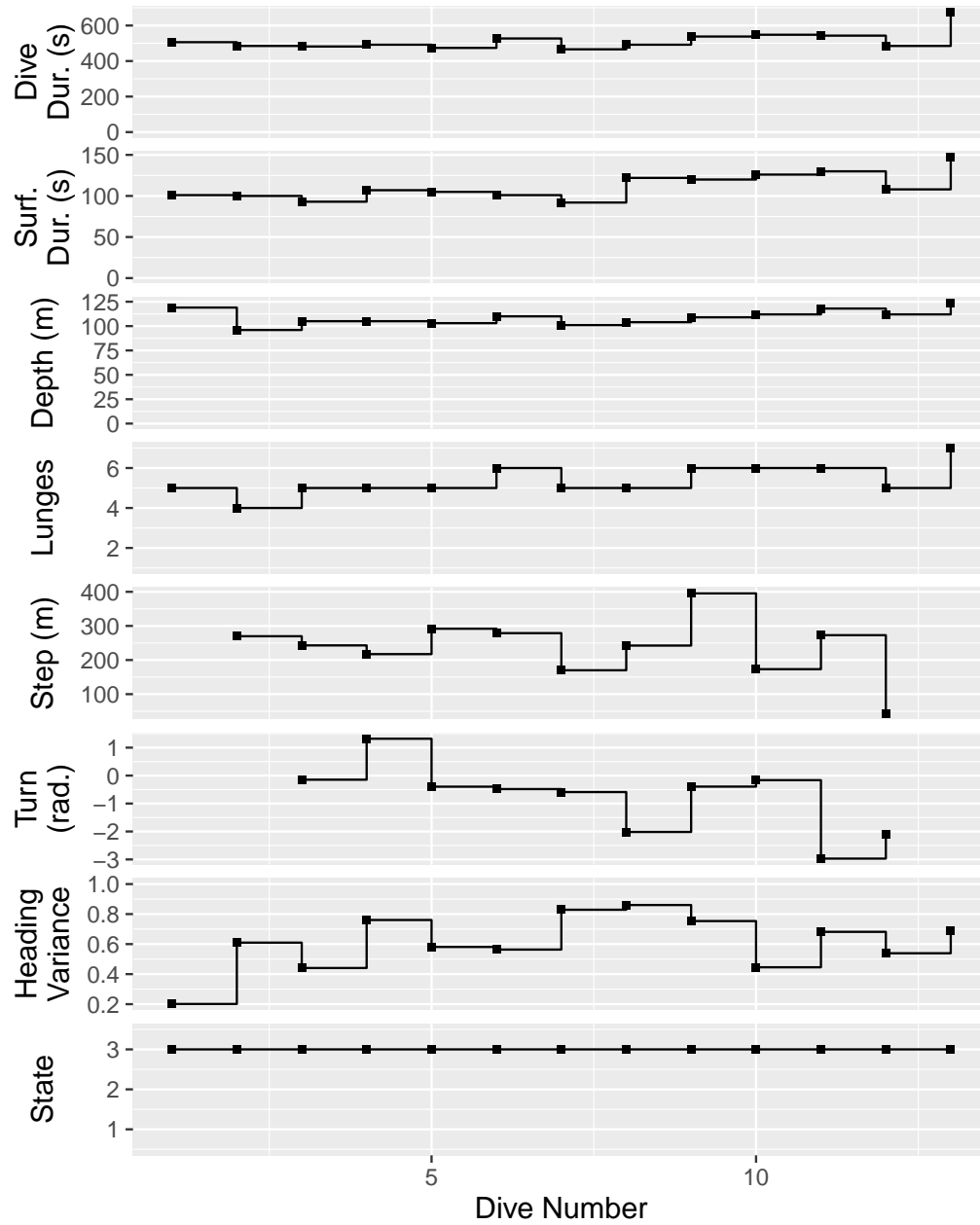


Figure 36: Time-series plot of the input data for whale bw13-217a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to no CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

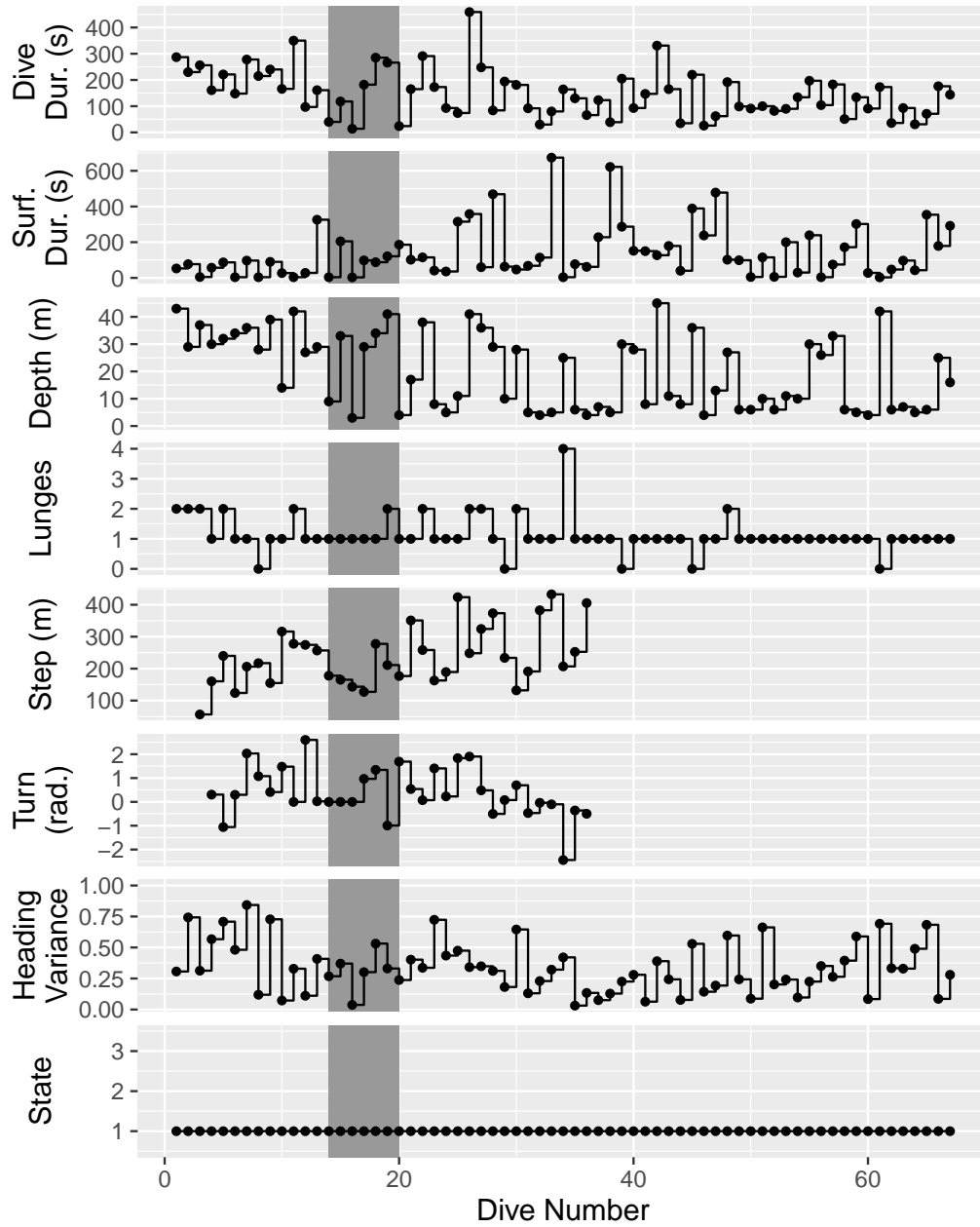


Figure 37: Time-series plot of the input data for whale bw13-259a. The CEE exposure period (if any) is shaded in darker grey; this whale was exposed to a simulated MFA sonar CEE. The bottom panel shows the most probable state for each dive, according to the best model (with 3 states, 4 contexts, and a common effect of acoustic disturbance). These states are also indicated in the other panels by symbols: circles for state 1, triangles for state 2, and squares for state 3.

2 Plots of state-dependent distributions for baseline HMMs

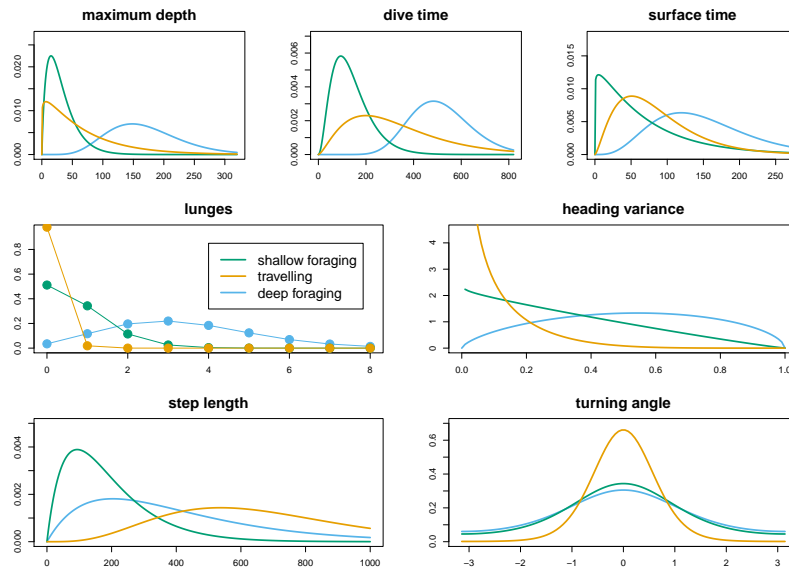


Figure 38: State-dependent distributions, for each of the seven variables considered, obtained when fitting the 3-state baseline model.

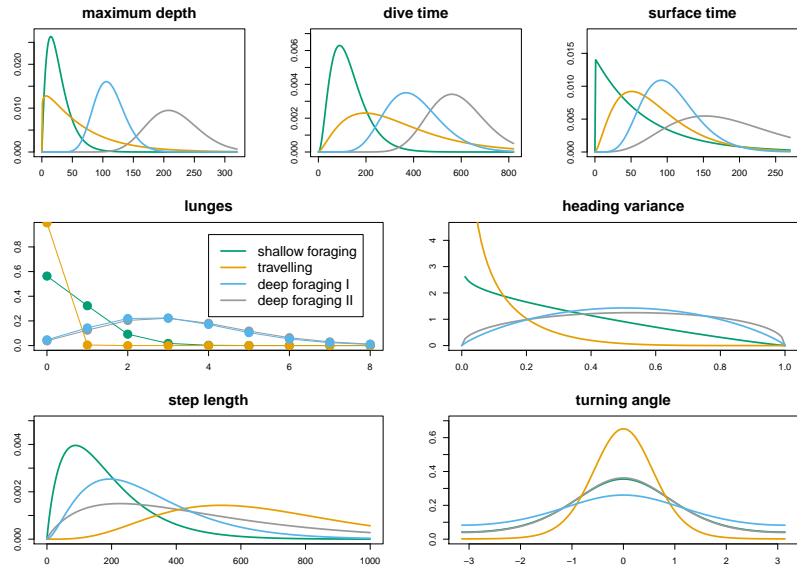


Figure 39: State-dependent distributions, for each of the seven variables considered, obtained when fitting the 4-state baseline model.

3 Checking contemporaneous conditional independence

The HMMs fitted to the blue whale data assume contemporaneous conditional independence of the input time-series data. This assumption can be assessed for example by comparing the empirical correlations between the (seven) different data streams with the model-implied correlation between the data streams (which can most conveniently be obtained using simulations from the fitted model). We did this for the baseline 3-state HMM reported in the paper, and found the following correlation matrices.

Empirical correlations:

	DIVE.TIME	MAX.DEPTH	LUNGES	SUR.TIME	steps	turns	var.head
DIVE.TIME	1.00	0.76	0.62	0.47	0.33	-0.03	0.31
MAX.DEPTH	0.76	1.00	0.62	0.55	0.26	-0.05	0.37
LUNGES	0.62	0.62	1.00	0.42	-0.08	-0.04	0.57
SURFACE.TIME	0.47	0.55	0.42	1.00	0.24	-0.02	0.27
steps	0.33	0.26	-0.08	0.24	1.00	0.02	-0.32
turns	-0.03	-0.05	-0.04	-0.02	0.02	1.00	-0.09
var.head	0.31	0.37	0.57	0.27	-0.32	-0.09	1.00

Model-implied correlations:

	DIVE.TIME	MAX.DEPTH	LUNGES	SUR.TIME	steps	turns	var.head
DIVE.TIME	1.00	0.58	0.48	0.39	0.23	-0.01	0.28
MAX.DEPTH	0.58	1.00	0.52	0.38	0.13	0.00	0.34
LUNGES	0.48	0.52	1.00	0.34	-0.06	0.02	0.40
SURFACE.TIME	0.39	0.38	0.34	1.00	0.08	0.01	0.29
steps	0.23	0.13	-0.06	0.08	1.00	-0.01	-0.17
turns	-0.01	0.00	0.02	0.01	-0.01	1.00	0.02
var.head	0.28	0.34	0.40	0.29	-0.17	0.02	1.00

We see that the model captures most, though not all correlation between the different data streams. Notable deviations are found for example for the correlations between ‘maximum depth’ and ‘dive time’ and between ‘maximum depth’ and ‘surface time’. This is neither surprising (given the expected strong correlation between those variables) nor is it expected to affect the inference on the state-switching dynamics, which is the ultimate aim of the analysis. The goodness-of-fit in this respect would improve if

we would use the 4-state model, which, however, we do not want to use for other, more important reasons (as detailed in the main text). In general, we have found that the contemporaneous conditional independence assumption is usually adequate, except perhaps in cases when interest centers precisely on the correlation between the data streams. Note also that often there is no practical alternative to contemporaneous conditional independence: unless a multivariate normal distribution can be assumed (which rarely is the case), there is usually no simple multivariate distribution available to specify the correlation structure between variables within states.