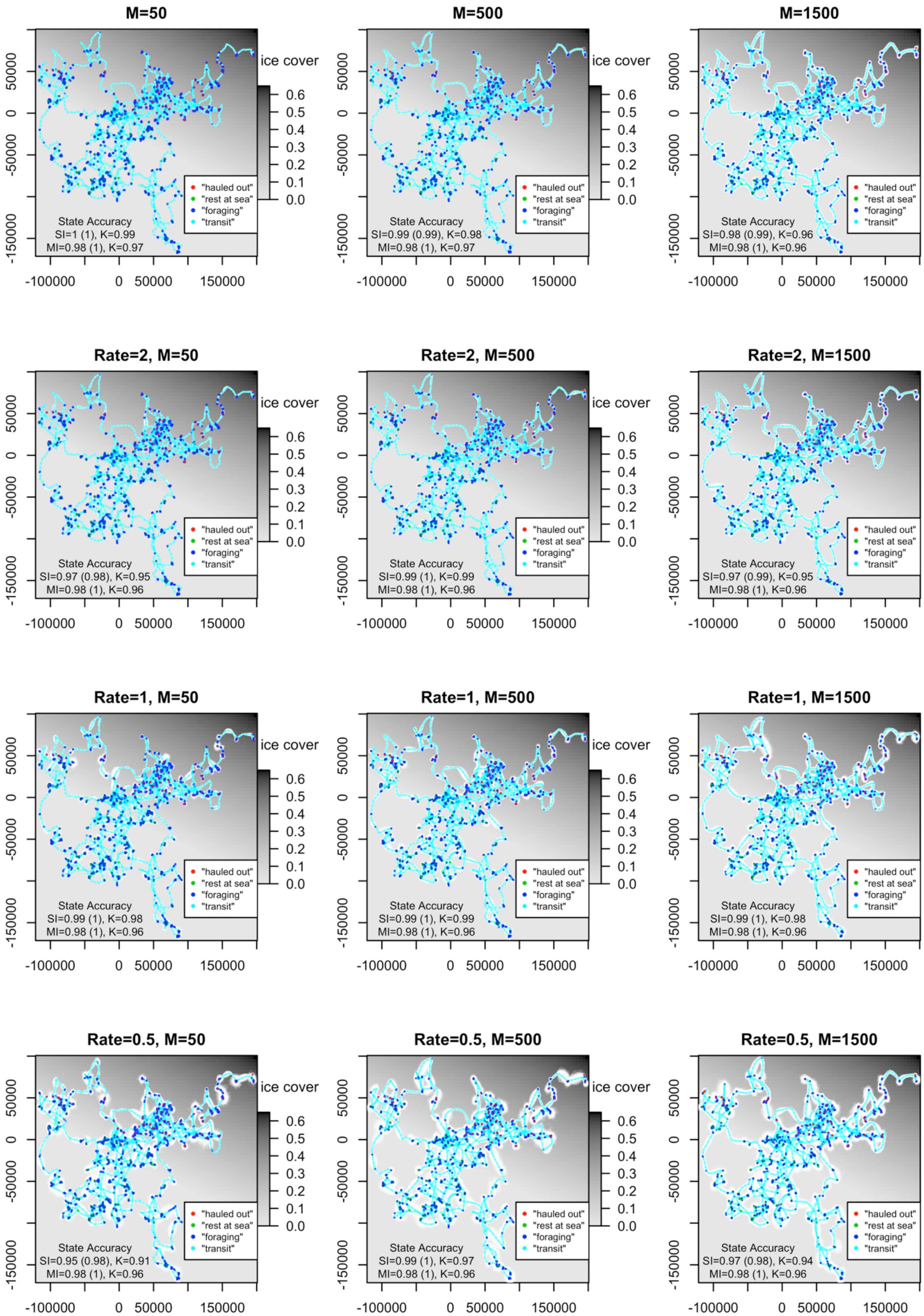
Appendix C. 4-state simulations excluding the dry time data stream

I was somewhat surprised that measurement error and sampling rate did not have a larger impact on identification of the two ice-associated non-diving states ("hauled out on ice" and "resting at sea") in the original set of 4-state simulations. I therefore performed an identical analysis excluding the "dry time" data stream from the fitted HMMs, thereby leaving sea ice concentration as the sole data stream distinguishing these two non-diving states. For this set of simulations, I again found the single and multiple imputation approaches performed well in all scenarios with respect to state and $\boldsymbol{\mu}_t$ estimation. Measurement error and sampling rate had little impact on the accuracy of state and location estimation, including the ice-associated non-diving states (Figure C1). The absence of the dry time data stream resulted in slightly lower state accuracy based on the most likely state sequences when measurement error was high or sampling rates were low, although the estimated state probabilities ($q_{z,t}$) using multiple imputation always included at least 5% probability for the true state at each time step. The estimated probability distributions for the dive time and number of dive data streams were generally unbiased (Figures C2 and C3), but as with all other simulations examined here, the estimated step length (Figure C4) and turning angle (Figure C5) distributions became more biased as measurement error increased and sampling rate decreased. Relative to the simulations including dry time, the estimated probability distributions for step length, turning angle, and sea ice concentration (Figure C6) exhibited some differences, but overall they were still very similar.

Figure C1. Selected simulation results under the 4-state (“hauled out on ice” = red, “resting at sea” = green, “foraging” = blue, and “transit” = light blue) scenarios excluding the dry time data stream. Each panel presents the estimated tracks for $N = 7$ individuals relative to a spatially-correlated sea ice concentration grid (“ice %”) under varying levels of location measurement error ($M \in \{50,500,1500\}$) and missing location data arising from temporally-irregular sampling rates (Rate $\in 2,1,0.5$). The first row pertains to scenarios with temporally-regular sampling that exactly matches the time steps of the simulated tracks. Solid lines indicate the tracks and state sequences using the single imputation (SI) approach, while white lines indicate each realization of the position process using the multiple imputation (MI) approach. Under the data-generating model, both the “hauled out on ice” and “resting at sea” states were associated with short step lengths and high directional persistence, but individuals could only switch to the “hauled out on ice” state if the grid cell of its current position contained >0.05 sea ice concentration. State classification accuracy for each scenario is based on the proportion of time steps for the estimated most likely state sequence that match the true state, the proportion of estimated state probabilities with at least 0.05 probability assigned to the true state (in parentheses), and a measure of agreement between the true and estimated states (K) that takes chance agreement into account and ranges from 0 (no better than chance) to 1 (perfect agreement not attributable to chance).



M=50
ice cover
0.6
0.5
0.4
0.3
0.2
0.1
0.0
"hauled out"
"rest at sea"
"foraging"
"transit"
State Accuracy
SI=1 (1), K=0.99
MI=0.98 (1), K=0.97
50000
0
-50000
-150000
-100000
0
50000
150000
M=500
State Accuracy
SI=0.99 (0.99), K=0.98
MI=0.98 (1), K=0.97
M=1500
State Accuracy
SI=0.98 (0.99), K=0.96
MI=0.98 (1), K=0.96
Rate=2, M=50
State Accuracy
SI=0.97 (0.98), K=0.95
MI=0.98 (1), K=0.96
Rate=2, M=500
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Rate=2, M=1500
State Accuracy
SI=0.97 (0.99), K=0.95
MI=0.98 (1), K=0.96
Rate=1, M=50
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Rate=1, M=500
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Rate=1, M=1500
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Rate=0.5, M=50
State Accuracy
SI=0.95 (0.98), K=0.91
MI=0.98 (1), K=0.96
Rate=0.5, M=500
State Accuracy
SI=0.99 (1), K=0.97
MI=0.98 (1), K=0.96
Rate=0.5, M=1500
State Accuracy
SI=0.97 (0.98), K=0.94
MI=0.98 (1), K=0.96

Figure C2. Selected simulation results under the 4-state ("hauled out on ice" = black, "resting at sea" = dark gray, "foraging" = gray, and "transit" = light gray) excluding the dry time data stream. Each panel presents the true and estimated probability densities for dive time based on the single (SI) and multiple (MI) imputation approaches with varying levels of location measurement error ($M \in \{50,500,1500\}$) and missing location data arising from temporally-irregular sampling rates ($\text{Rate} \in 2,1,0.5$). The first column pertains to scenarios with temporally-regular sampling that exactly matches the time steps of the simulated tracks. State classification accuracy for each scenario is based on the proportion of time steps for the estimated most likely state sequence that match the true state, the proportion of estimated state probabilities with at least 0.05 probability assigned to the true state (in parentheses), and a measure of agreement between the true and estimated states (K) that takes chance agreement into account and ranges from 0 (no better than chance) to 1 (perfect agreement not attributable to chance). Location accuracy for each scenario is based on the proportion of true locations that fall within their respective estimated 95% confidence bands using the multiple imputation approach.

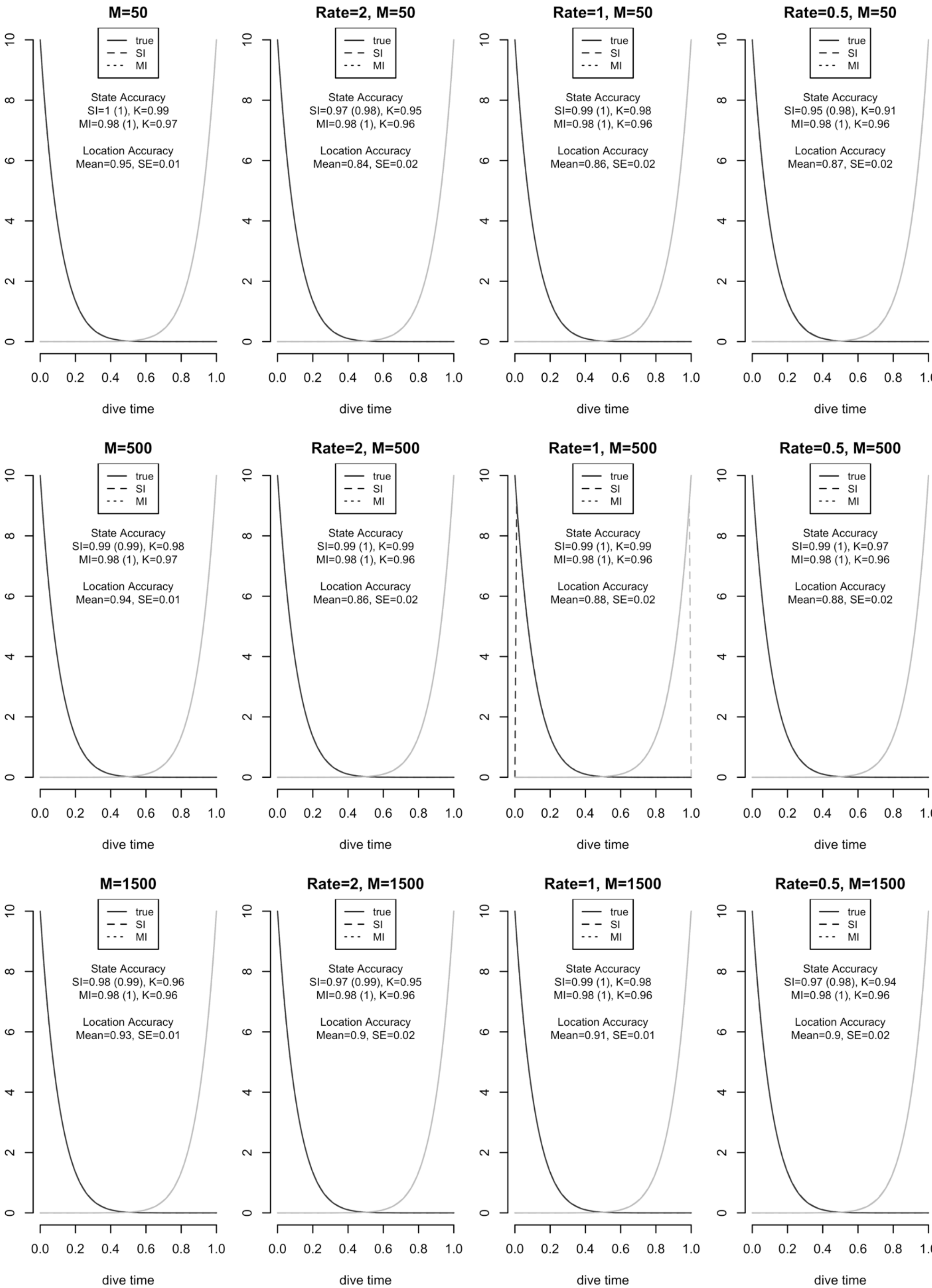

M=50
true
SI
MI
State Accuracy
SI=1 (1), K=0.99
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.95, SE=0.01
dive time
Rate=2, M=50
true
SI
MI
State Accuracy
SI=0.97 (0.98), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.84, SE=0.02
dive time
Rate=1, M=50
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
dive time
Rate=0.5, M=50
true
SI
MI
State Accuracy
SI=0.95 (0.98), K=0.91
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.87, SE=0.02
dive time
M=500
true
SI
MI
State Accuracy
SI=0.99 (0.99), K=0.98
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.94, SE=0.01
dive time
Rate=2, M=500
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
dive time
Rate=1, M=500
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
dive time
Rate=0.5, M=500
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.97
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
dive time
M=1500
true
SI
MI
State Accuracy
SI=0.98 (0.99), K=0.96
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.93, SE=0.01
dive time
Rate=2, M=1500
true
SI
MI
State Accuracy
SI=0.97 (0.99), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
dive time
Rate=1, M=1500
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.91, SE=0.01
dive time
Rate=0.5, M=1500
true
SI
MI
State Accuracy
SI=0.97 (0.98), K=0.94
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
dive time

Figure C3. Selected simulation results under the 4-state ("hauled out on ice" = black, "resting at sea" = dark gray, "foraging" = gray, and "transit" = light gray) excluding the dry time data stream. Each panel presents the true and estimated probability densities for number of dives based on the single (SI) and multiple (MI) imputation approaches with varying levels of location measurement error ($M \in \{50,500,1500\}$) and missing location data arising from temporally-irregular sampling rates (Rate $\in 2,1,0.5$). The first column pertains to scenarios with temporally-regular sampling that exactly matches the time steps of the simulated tracks. State classification accuracy for each scenario is based on the proportion of time steps for the estimated most likely state sequence that match the true state, the proportion of estimated state probabilities with at least 0.05 probability assigned to the true state (in parentheses), and a measure of agreement between the true and estimated states (K) that takes chance agreement into account and ranges from 0 (no better than chance) to 1 (perfect agreement not attributable to chance). Location accuracy for each scenario is based on the proportion of true locations that fall within their respective estimated 95% confidence bands using the multiple imputation approach.

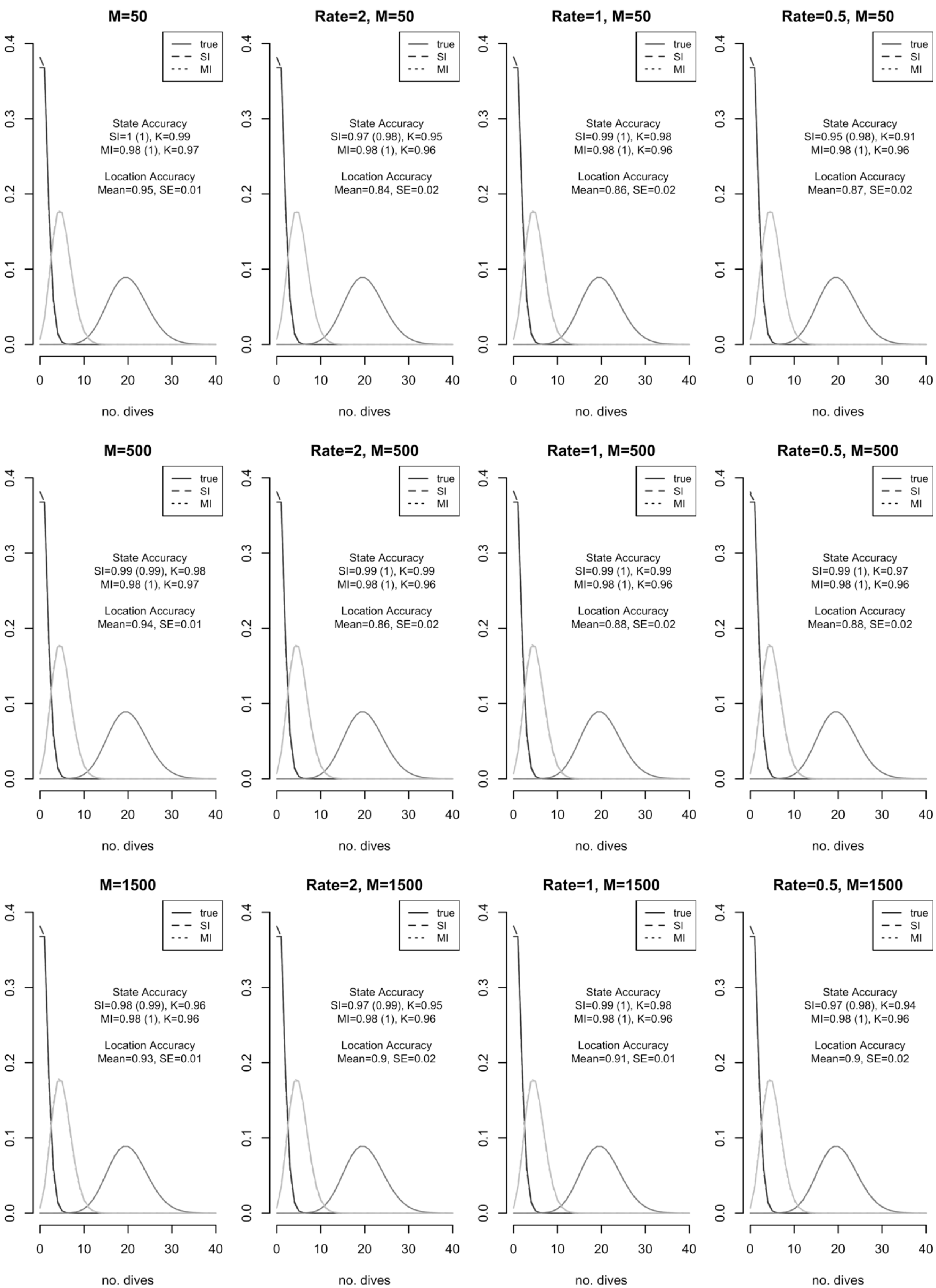

M=50
true
SI
MI
State Accuracy
SI=1 (1), K=0.99
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.95, SE=0.01
no. dives
Rate=2, M=50
State Accuracy
SI=0.97 (0.98), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.84, SE=0.02
Rate=1, M=50
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
Rate=0.5, M=50
State Accuracy
SI=0.95 (0.98), K=0.91
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.87, SE=0.02
M=500
State Accuracy
SI=0.99 (0.99), K=0.98
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.94, SE=0.01
Rate=2, M=500
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
Rate=1, M=500
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
Rate=0.5, M=500
State Accuracy
SI=0.99 (1), K=0.97
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
M=1500
State Accuracy
SI=0.98 (0.99), K=0.96
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.93, SE=0.01
Rate=2, M=1500
State Accuracy
SI=0.97 (0.99), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
Rate=1, M=1500
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.91, SE=0.01
Rate=0.5, M=1500
State Accuracy
SI=0.97 (0.98), K=0.94
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02

Figure C4. Selected simulation results under the 4-state ("hauled out on ice" = black, "resting at sea" = dark gray, "foraging" = gray, and "transit" = light gray) excluding the dry time data stream. Each panel presents the true and estimated probability densities for step length based on the single (SI) and multiple (MI) imputation approaches with varying levels of location measurement error ($M \in \{50,500,1500\}$) and missing location data arising from temporally-irregular sampling rates ($\text{Rate} \in 2,1,0.5$). The first column pertains to scenarios with temporally-regular sampling that exactly matches the time steps of the simulated tracks. State classification accuracy for each scenario is based on the proportion of time steps for the estimated most likely state sequence that match the true state, the proportion of estimated state probabilities with at least 0.05 probability assigned to the true state (in parentheses), and a measure of agreement between the true and estimated states (K) that takes chance agreement into account and ranges from 0 (no better than chance) to 1 (perfect agreement not attributable to chance). Location accuracy for each scenario is based on the proportion of true locations that fall within their respective estimated 95% confidence bands using the multiple imputation approach.

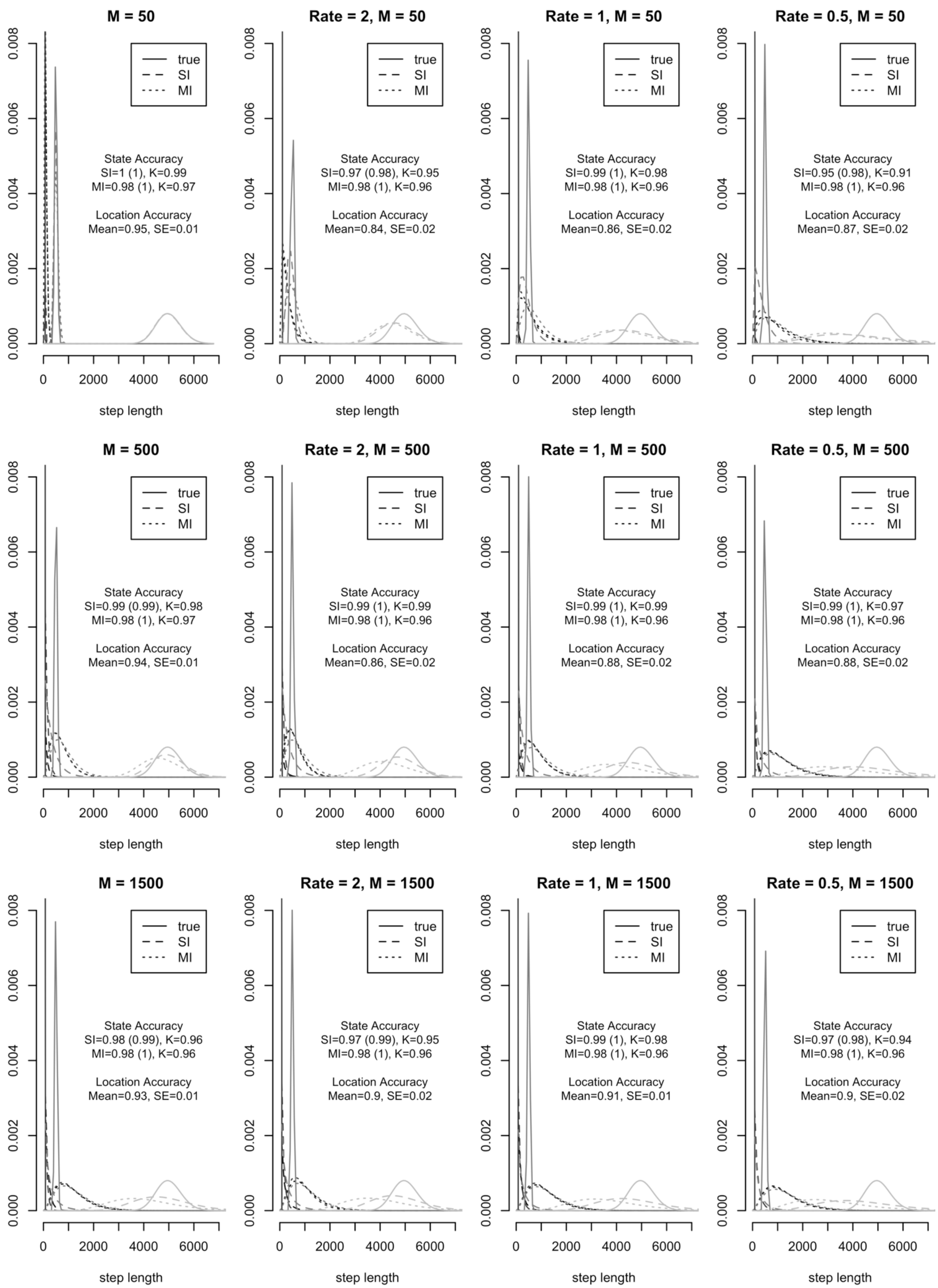

M = 50
true
SI
MI
State Accuracy
SI=1 (1), K=0.99
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.95, SE=0.01
Rate = 2, M = 50
State Accuracy
SI=0.97 (0.98), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.84, SE=0.02
Rate = 1, M = 50
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
Rate = 0.5, M = 50
State Accuracy
SI=0.95 (0.98), K=0.91
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.87, SE=0.02
M = 500
State Accuracy
SI=0.99 (0.99), K=0.98
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.94, SE=0.01
Rate = 2, M = 500
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
Rate = 1, M = 500
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
Rate = 0.5, M = 500
State Accuracy
SI=0.99 (1), K=0.97
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
M = 1500
State Accuracy
SI=0.98 (0.99), K=0.96
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.93, SE=0.01
Rate = 2, M = 1500
State Accuracy
SI=0.97 (0.99), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
Rate = 1, M = 1500
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.91, SE=0.01
Rate = 0.5, M = 1500
State Accuracy
SI=0.97 (0.98), K=0.94
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
step length
0.000 0.002 0.004 0.006 0.008
0 2000 4000 6000

Figure C5. Selected simulation results under the 4-state ("hauled out on ice" = black, "resting at sea" = dark gray, "foraging" = gray, and "transit" = light gray) excluding the dry time data stream. Each panel presents the true and estimated probability densities for turning angle based on the single (SI) and multiple (MI) imputation approaches with varying levels of location measurement error ($M \in \{50,500,1500\}$) and missing location data arising from temporally-irregular sampling rates (Rate $\in$ 2,1,0.5). The first column pertains to scenarios with temporally-regular sampling that exactly matches the time steps of the simulated tracks. State classification accuracy for each scenario is based on the proportion of time steps for the estimated most likely state sequence that match the true state, the proportion of estimated state probabilities with at least 0.05 probability assigned to the true state (in parentheses), and a measure of agreement between the true and estimated states (K) that takes chance agreement into account and ranges from 0 (no better than chance) to 1 (perfect agreement not attributable to chance). Location accuracy for each scenario is based on the proportion of true locations that fall within their respective estimated 95% confidence bands using the multiple imputation approach.

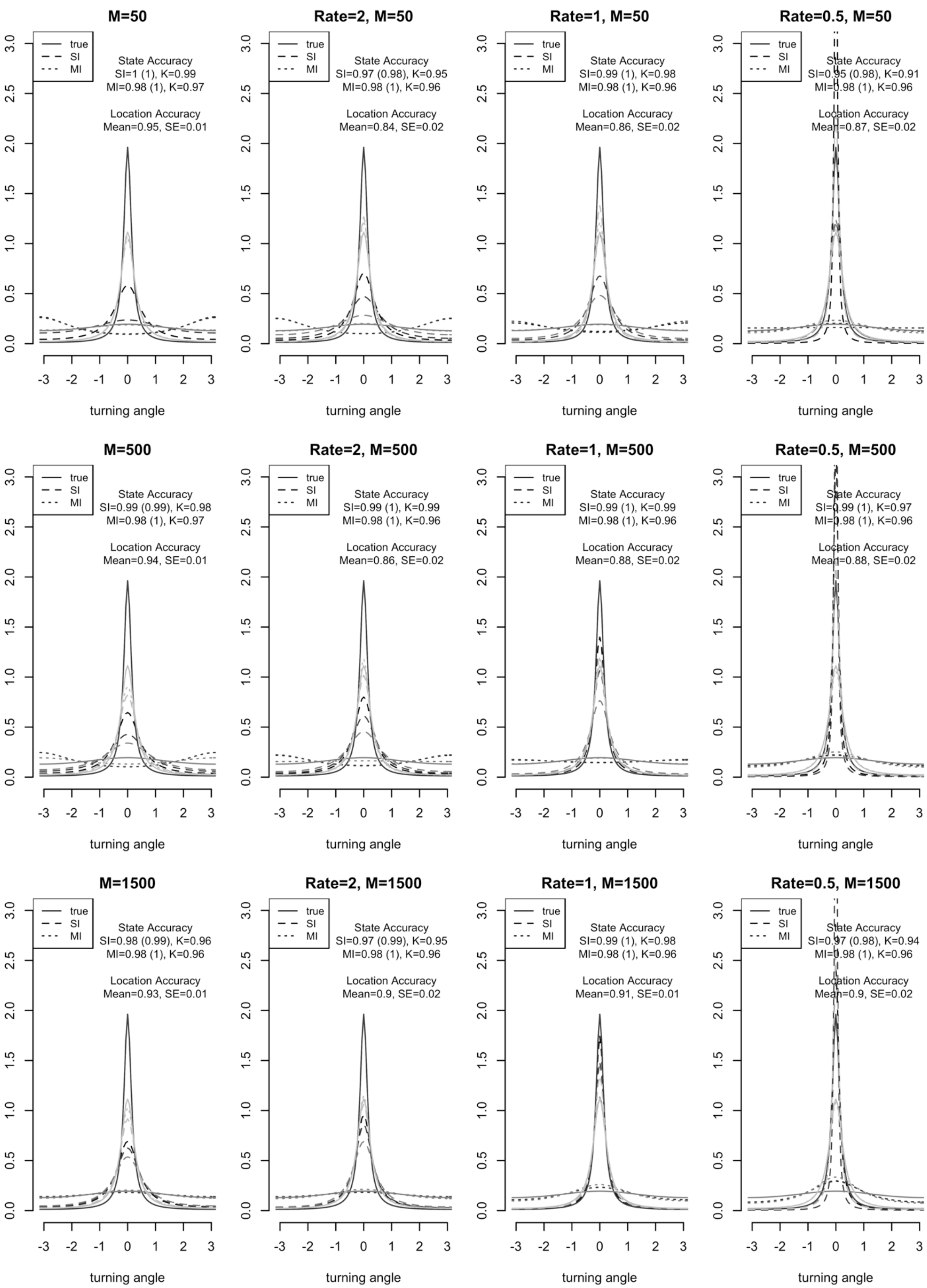
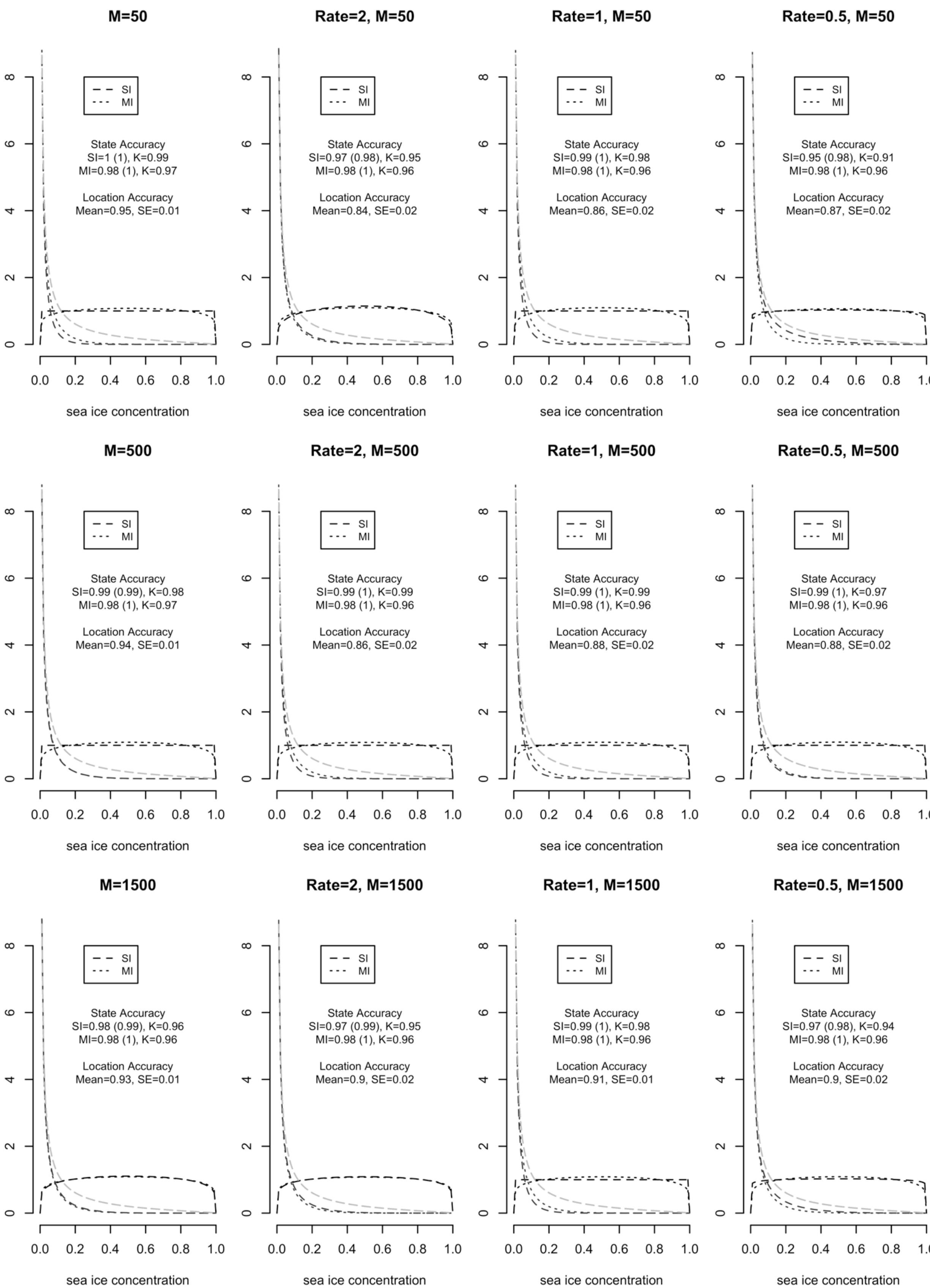

M=50
true
SI
MI
State Accuracy
SI=1 (1), K=0.99
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.95, SE=0.01
turning angle
Rate=2, M=50
true
SI
MI
State Accuracy
SI=0.97 (0.98), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.84, SE=0.02
turning angle
Rate=1, M=50
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
turning angle
Rate=0.5, M=50
true
SI
MI
State Accuracy
SI=0.95 (0.98), K=0.91
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.87, SE=0.02
turning angle
M=500
true
SI
MI
State Accuracy
SI=0.99 (0.99), K=0.98
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.94, SE=0.01
turning angle
Rate=2, M=500
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
turning angle
Rate=1, M=500
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
turning angle
Rate=0.5, M=500
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.97
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
turning angle
M=1500
true
SI
MI
State Accuracy
SI=0.98 (0.99), K=0.96
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.93, SE=0.01
turning angle
Rate=2, M=1500
true
SI
MI
State Accuracy
SI=0.97 (0.99), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
turning angle
Rate=1, M=1500
true
SI
MI
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.91, SE=0.01
turning angle
Rate=0.5, M=1500
true
SI
MI
State Accuracy
SI=0.97 (0.98), K=0.94
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
turning angle

Figure C6. Selected simulation results under the 4-state ("hauled out on ice" = black, "resting at sea" = dark gray, "foraging" = gray, and "transit" = light gray) excluding the dry time data stream. Each panel presents the estimated probability densities for sea ice concentration based on the single (SI) and multiple (MI) imputation approaches with varying levels of location measurement error ($M \in \{50,500,1500\}$) and missing location data arising from temporally-irregular sampling rates ($\text{Rate} \in 2,1,0.5$). The first column pertains to scenarios with temporally-regular sampling that exactly matches the time steps of the simulated tracks. State classification accuracy for each scenario is based on the proportion of time steps for the estimated most likely state sequence that match the true state, the proportion of estimated state probabilities with at least 0.05 probability assigned to the true state (in parentheses), and a measure of agreement between the true and estimated states (K) that takes chance agreement into account and ranges from 0 (no better than chance) to 1 (perfect agreement not attributable to chance). Location accuracy for each scenario is based on the proportion of true locations that fall within their respective estimated 95% confidence bands using the multiple imputation approach.


M=50
SI
MI
State Accuracy
SI=1 (1), K=0.99
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.95, SE=0.01
sea ice concentration
Rate=2, M=50
SI
MI
State Accuracy
SI=0.97 (0.98), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.84, SE=0.02
sea ice concentration
Rate=1, M=50
SI
MI
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
sea ice concentration
Rate=0.5, M=50
SI
MI
State Accuracy
SI=0.95 (0.98), K=0.91
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.87, SE=0.02
sea ice concentration
M=500
SI
MI
State Accuracy
SI=0.99 (0.99), K=0.98
MI=0.98 (1), K=0.97
Location Accuracy
Mean=0.94, SE=0.01
sea ice concentration
Rate=2, M=500
SI
MI
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.86, SE=0.02
sea ice concentration
Rate=1, M=500
SI
MI
State Accuracy
SI=0.99 (1), K=0.99
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
sea ice concentration
Rate=0.5, M=500
SI
MI
State Accuracy
SI=0.99 (1), K=0.97
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.88, SE=0.02
sea ice concentration
M=1500
SI
MI
State Accuracy
SI=0.98 (0.99), K=0.96
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.93, SE=0.01
sea ice concentration
Rate=2, M=1500
SI
MI
State Accuracy
SI=0.97 (0.99), K=0.95
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
sea ice concentration
Rate=1, M=1500
SI
MI
State Accuracy
SI=0.99 (1), K=0.98
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.91, SE=0.01
sea ice concentration
Rate=0.5, M=1500
SI
MI
State Accuracy
SI=0.97 (0.98), K=0.94
MI=0.98 (1), K=0.96
Location Accuracy
Mean=0.9, SE=0.02
sea ice concentration