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Using indicators of ENSO, IOD, and SAM to improve lead time and accuracy of tropical cyclone outlooks for Australia

Andrew D. Magee* and Anthony S. Kiem

Centre for Water, Climate and Land (CWCL), University of Newcastle, Callaghan, NSW, 2308, Australia

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Supplemental material

* Corresponding author details: Andrew D. Magee, G106-A, Earth Science Building, The University of Newcastle, University Drive, Callaghan, NSW, 2308, Australia (andrew.magee@newcastle.edu.au)

Table S1. Summary statistics for AR (Australian region) pre-season outlook models initiated each month between April-October for the November-April TC season and in-season outlook models initiated each month between November, December and January for the remaining December-April, January-April and February-April TC season, respectively. Note: statistics reported for October are the same as in Table 3, but are included here for comparison with other pre-season forecast months. Model statistics are reported for three periods: (i) the full 1970-2019 training/calibration period, (ii) the shorter 1970-2009 training/calibration period, and (iii) the 2010-2019 validation period. For the 2010-2019 validation period, only Strike rate: exact (SR-E; %) and Strike rate: ± 1 (SR ± 1 ; %) are reported as n=10 is too small to report other statistics. Pearsons correlation coefficient (r), R square, Root Mean Square Error (RMSE), Skill Score (%), Strike rate: exact (SR-E; %), Strike rate: ± 1 (SR ± 1 ; %) and Finite Corrected AIC (AICc) summarise the performance of the derived models. For AICc, model performance (top value) is compared with the intercept only model (bottom value). Superior models are defined using Method A (see Section 3.1.1; the highest SS for the 1970-2019 training/calibration period). * correlation significant at 99% level.

| | | Pre-Season | | | | | | | In-Season | | |
|---------------------------------------------|--------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| | | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan |
| | Model Number | 4 | 1 | 7 | 6 | 8 | 10 | 1 | 7 | 10 | 10 |
| 1970-2019 training/calibration period | Correlation | 0.78* | 0.60* | 0.78* | 0.84* | 0.80* | 0.80* | 0.80* | 0.81* | 0.76* | 0.66* |
| | R-square | 0.60 | 0.31 | 0.60 | 0.70 | 0.64 | 0.65 | 0.65 | 0.65 | 0.58 | 0.43 |
| | RMSE | 2.29 | 2.92 | 2.30 | 1.99 | 2.18 | 2.17 | 2.16 | 1.99 | 1.72 | 1.57 |
| | Skill Score (%) | 60.45 | 36.09 | 60.25 | 70.15 | 64.18 | 64.71 | 64.82 | 65.08 | 58.33 | 43.25 |
| | Strike Rate: exact (%) | 16 | 18 | 26 | 18 | 20 | 12 | 18 | 18 | 36 | 22 |
| | Strike Rate: ± 1 (%) | 44 | 48 | 58 | 60 | 56 | 58 | 54 | 56 | 64 | 62 |
| | AICc | 229.38 271.38 | 253.37 271.38 | 229.59 271.38 | 215.27 271.38 | 224.42 271.38 | 223.62 271.38 | 223.52 271.38 | 215.16 262.89 | 200.66 241.08 | 191.46 218.02 |
| AICc difference (intercept only-model) | 42.00 | 18.00 | 41.79 | 56.10 | 46.95 | 47.75 | 47.86 | 47.73 | 40.42 | 26.56 | |
| 1970-2009 training/calibration period | Correlation | 0.78* | 0.59* | 0.76* | 0.85* | 0.83* | 0.79* | 0.83* | 0.79* | 0.71* | 0.61* |
| | R-square | 0.60 | 0.34 | 0.57 | 0.71 | 0.69 | 0.63 | 0.69 | 0.62 | 0.50 | 0.38 |
| | RMSE | 2.35 | 3.03 | 2.44 | 2.00 | 2.07 | 2.29 | 2.06 | 2.14 | 1.86 | 1.64 |
| | Skill Score (%) | 58.29 | 33.02 | 59.82 | 69.11 | 62.74 | 63.87 | 62.81 | 65.12 | 57.92 | 41.94 |
| | Strike Rate: exact (%) | 15 | 17.5 | 30 | 20 | 30 | 15 | 22.5 | 17.5 | 22.5 | 22.5 |
| | Strike Rate: ± 1 (%) | 42.5 | 50 | 52.5 | 55 | 57.5 | 55 | 57.5 | 50 | 62.5 | 62.5 |
| | AICc | 186.46 219.35 | 206.68 219.35 | 189.51 219.35 | 173.48 219.35 | 176.35 219.35 | 184.25 219.35 | 176.08 219.35 | 178.99 212.77 | 167.83 193.51 | 157.59 175.52 |
| AICc difference (intercept only-model) | 32.88 | 12.66 | 29.84 | 45.86 | 42.99 | 35.10 | 43.26 | 33.78 | 25.68 | 17.93 | |
| 2010-2019 validation period | Strike Rate: exact (%) | 20 | 20 | 20 | 20 | 10 | 10 | 10 | 30 | 40 | 30 |
| | Strike Rate: ± 1 (%) | 60 | 20 | 40 | 60 | 10 | 60 | 50 | 80 | 90 | 60 |

Table S2. As in Table S1 but for AR-E (Eastern region).

| | | Pre-Season | | | | | | | In-Season | | |
|---------------------------------------------|-------------------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| | | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan |
| | Model Number | 4 | 3 | 8 | 6 | 4 | 1 | 2 | 5 | 4 | 8 |
| 1970-2019 training/calibration period | Correlation | 0.72* | 0.64* | 0.66* | 0.76* | 0.71* | 0.76* | 0.71* | 0.80* | 0.74* | 0.72* |
| | R-square | 0.52 | 0.41 | 0.43 | 0.57 | 0.50 | 0.58 | 0.51 | 0.63 | 0.55 | 0.52 |
| | RMSE | 1.31 | 1.45 | 1.43 | 1.24 | 1.34 | 1.23 | 1.33 | 1.18 | 1.16 | 0.96 |
| | Skill Score (%) | 52.11 | 41.23 | 43.32 | 57.39 | 50.32 | 57.74 | 50.34 | 63.13 | 55.01 | 51.73 |
| | Strike Rate: exact (%) | 36 | 24 | 20 | 32 | 26 | 28 | 40 | 34 | 34 | 44 |
| | Strike Rate: ± 1 (%) | 68 | 68 | 76 | 78 | 74 | 78 | 70 | 82 | 82 | 86 |
| | AICc | 173.50 200.86 | 183.74 200.86 | 181.94 200.86 | 167.66 200.56 | 175.30 200.86 | 167.22 200.76 | 175.10 200.56 | 162.84 203.89 | 161.62 194.05 | 142.22 172.56 |
| | AICc difference (intercept only-model) | 27.35 | 17.12 | 18.92 | 33.20 | 25.55 | 33.63 | 25.76 | 41.06 | 32.43 | 30.34 |
| 1970-2009 training/calibration period | Correlation | 0.74* | 0.66* | 0.68* | 0.76* | 0.74* | 0.77* | 0.75* | 0.82* | 0.75* | 0.73* |
| | R-square | 0.55 | 0.43 | 0.46 | 0.58 | 0.55 | 0.59 | 0.57 | 0.68 | 0.56 | 0.53 |
| | RMSE | 1.34 | 1.51 | 1.47 | 1.30 | 1.34 | 1.28 | 1.31 | 1.17 | 1.22 | 1.00 |
| | Skill Score (%) | 45.80 | 37.80 | 42.47 | 56.30 | 49.98 | 55.57 | 50.64 | 61.51 | 54.52 | 51.18 |
| | Strike Rate: exact (%) | 37.5 | 17.5 | 25 | 35 | 15 | 27.5 | 30 | 32.5 | 30 | 47.5 |
| | Strike Rate: ± 1 (%) | 72.5 | 70 | 67.5 | 77.5 | 82.5 | 75 | 77.5 | 82.5 | 80 | 87.5 |
| | AICc | 141.32 164.79 | 150.91 164.79 | 148.86 164.79 | 138.98 164.79 | 141.32 164.79 | 137.93 164.79 | 139.80 164.79 | 130.88 168.06 | 133.90 159.63 | 177.97 142.44 |
| | AICc difference (intercept only-model) | 23.47 | 13.88 | 15.92 | 25.80 | 23.47 | 26.85 | 24.98 | 37.18 | 25.73 | 24.48 |
| 2010-2019 validation period | Strike Rate: exact (%) | 30 | 20 | 20 | 50 | 20 | 30 | 50 | 30 | 30 | 40 |
| | Strike Rate: ± 1 (%) | 70 | 70 | 80 | 80 | 70 | 70 | 80 | 60 | 90 | 100 |

Table S3. As in Table S1 but for the AR-N (Northern region).

| | | Pre-Season | | | | | | | In-Season | | |
|---------------------------------------------|--------------------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| | | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan |
| | Model Number | 7 | 9 | 7 | 4 | 8 | 8 | 1 | 6 | 8 | 4 |
| 1970-2019 training/calibration period | Correlation | 0.59* | 0.59* | 0.58* | 0.60* | 0.76* | 0.76* | 0.63* | 0.63* | 0.72* | 0.63* |
| | R-square | 0.35 | 0.35 | 0.33 | 0.36 | 0.58 | 0.58 | 0.39 | 0.40 | 0.52 | 0.40 |
| | RMSE | 1.27 | 1.27 | 1.28 | 1.26 | 1.02 | 1.02 | 1.22 | 1.22 | 1.02 | 0.98 |
| | Skill Score (%) | 34.92 | 34.50 | 33.40 | 36.08 | 57.91 | 57.92 | 39.44 | 39.99 | 52.26 | 40.15 |
| | Strike Rate: exact (%) | 36 | 30 | 38 | 36 | 38 | 38 | 32 | 34 | 28 | 42 |
| | Strike Rate: ± 1 (%) | 74 | 76 | 78 | 76 | 84 | 84 | 80 | 80 | 94 | 82 |
| | AICc | 170.12 192.56 | 170.36 192.26 | 171.27 192.26 | 169.11 192.26 | 148.20 192.26 | 148.20 192.26 | 166.51 192.56 | 166.28 192.14 | 148.01 184.10 | 144.48 168.04 |
| | AICc difference (intercept only- model) | 22.14 | 21.90 | 20.99 | 23.15 | 44.06 | 44.06 | 25.75 | 25.86 | 36.09 | 23.56 |
| 1970-2009 training/calibration period | Correlation | 0.62* | 0.61* | 0.56* | 0.58* | 0.78* | 0.78* | 0.60* | 0.61* | 0.75* | 0.70* |
| | R-square | 0.39 | 0.37 | 0.32 | 0.33 | 0.60 | 0.60 | 0.36 | 0.37 | 0.56 | 0.48 |
| | RMSE | 1.27 | 1.29 | 1.35 | 1.33 | 1.03 | 1.03 | 1.30 | 1.30 | 1.01 | 0.97 |
| | Skill Score (%) | 33.61 | 32.89 | 31.35 | 35.86 | 56.72 | 56.72 | 38.35 | 38.94 | 50.44 | 34.06 |
| | Strike Rate: exact (%) | 35 | 32.5 | 35 | 40 | 42.5 | 42.35 | 32.5 | 35 | 45 | 40 |
| | Strike Rate: ± 1 (%) | 72.5 | 77.5 | 77.5 | 75 | 85 | 85 | 77.5 | 77.5 | 90 | 85 |
| | AICc | 137.40 156.63 | 138.45 156.63 | 142.00 156.63 | 141.08 156.63 | 120.11 156.63 | 120.11 156.63 | 139.19 156.63 | 139.05 156.58 | 119.09 149.80 | 116.02 138.85 |
| | AICc difference (intercept only-model) | 19.22 | 18.17 | 14.63 | 15.54 | 36.52 | 36.52 | 17.44 | 17.53 | 30.70 | 22.83 |
| 2010-2019 validation period | Strike Rate: exact (%) | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 30 | 30 |
| | Strike Rate: ± 1 (%) | 60 | 80 | 90 | 90 | 90 | 90 | 80 | 80 | 70 | 80 |

Table S4. As in Table S1 but for the AR-NW (NW sub-region).

| | | Pre-Season | | | | | | | In-Season | | |
|---------------------------------------------|-------------------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| | | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan |
| | Model Number | 1 | 9 | 7 | 2 | 8 | 5 | 4 | 6 | 3 | 1 |
| 1970-2019 training/calibration period | Correlation | 0.59* | 0.58* | 0.74* | 0.59* | 0.67* | 0.55* | 0.59* | 0.64* | 0.72* | 0.58* |
| | R-square | 0.35 | 0.34 | 0.55 | 0.35 | 0.44 | 0.30 | 0.34 | 0.41 | 0.52 | 0.34 |
| | RMSE | 1.79 | 1.80 | 1.49 | 1.80 | 1.66 | 1.86 | 1.80 | 1.69 | 1.26 | 1.18 |
| | Skill Score (%) | 34.91 | 33.86 | 54.90 | 34.55 | 44.15 | 29.88 | 34.33 | 40.84 | 51.74 | 33.65 |
| | Strike Rate: exact (%) | 20 | 20 | 26 | 26 | 18 | 22 | 18 | 24 | 36 | 38 |
| | Strike Rate: ± 1 (%) | 66 | 50 | 70 | 56 | 66 | 60 | 48 | 62 | 76 | 78 |
| | AICc | 204.86 221.29 | 205.69 221.29 | 186.51 221.89 | 205.17 221.29 | 197.12 221.29 | 208.61 221.89 | 205.32 221.29 | 198.88 219.62 | 169.67 201.33 | 162.95 182.28 |
| | AICc difference (intercept only-model) | 16.43 | 15.60 | 34.78 | 16.12 | 24.17 | 12.68 | 15.97 | 20.73 | 31.66 | 19.33 |
| 1970-2009 training/calibration period | Correlation | 0.63* | 0.63* | 0.77* | 0.57* | 0.68* | 0.52* | 0.59* | 0.61* | 0.73* | 0.69* |
| | R-square | 0.39 | 0.40 | 0.60 | 0.32 | 0.47 | 0.27 | 0.34 | 0.37 | 0.54 | 0.47 |
| | RMSE | 1.80 | 1.79 | 1.47 | 1.90 | 1.69 | 1.98 | 1.87 | 1.80 | 1.26 | 1.03 |
| | Skill Score (%) | 30.81 | 31.36 | 39.44 | 28.47 | 40.71 | 29.97 | 32.13 | 33.37 | 42.35 | 19.50 |
| | Strike Rate: exact (%) | 17.5 | 22.5 | 25 | 15 | 17.5 | 17.5 | 25 | 15 | 37.5 | 30 |
| | Strike Rate: ± 1 (%) | 60 | 57.5 | 75 | 55 | 67.5 | 55 | 52.5 | 55 | 80 | 85 |
| | AICc | 165.33 180.69 | 164.61 180.69 | 148.98 180.69 | 169.66 180.69 | 160.11 180.69 | 172.74 180.69 | 168.35 180.69 | 164.95 178.81 | 136.40 163.90 | 120.51 146.07 |
| | AICc difference (intercept only-model) | 15.35 | 16.08 | 31.70 | 11.03 | 20.57 | 7.94 | 12.34 | 13.86 | 27.50 | 25.56 |
| 2010-2019 validation period | Strike Rate: exact (%) | 30 | 10 | 20 | 50 | 10 | 40 | 30 | 50 | 20 | 40 |
| | Strike Rate: ± 1 (%) | 70 | 40 | 60 | 80 | 80 | 70 | 50 | 70 | 70 | 60 |

Table S5. As in Table S1 but for AR-W (Western region).

| | | Pre-Season | | | | | | | In-Season | | |
|---------------------------------------------|-------------------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| | | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan |
| | Model Number | 8 | 8 | 8 | 8 | 8 | 6 | 3 | 4 | 8 | 1 |
| 1970-2019 training/calibration period | Correlation | 0.72* | 0.68* | 0.72* | 0.78* | 0.75* | 0.72* | 0.72* | 0.72* | 0.56* | 0.49* |
| | R-square | 0.53 | 0.46 | 0.52 | 0.61 | 0.57 | 0.51 | 0.52 | 0.52 | 0.31 | 0.24 |
| | RMSE | 1.65 | 1.74 | 1.65 | 1.49 | 1.56 | 1.67 | 1.65 | 1.51 | 1.41 | 1.36 |
| | Skill Score (%) | 52.09 | 46.48 | 51.78 | 60.98 | 56.91 | 51.12 | 51.83 | 51.73 | 31.24 | 24.18 |
| | Strike Rate: exact (%) | 34 | 22 | 20 | 30 | 28 | 24 | 30 | 14 | 24 | 34 |
| | Strike Rate: ± 1 (%) | 56 | 60 | 62 | 70 | 64 | 54 | 58 | 64 | 68 | 74 |
| | AICc | 196.38 228.65 | 201.92 228.65 | 196.71 228.65 | 186.10 228.65 | 191.08 228.65 | 197.38 228.65 | 196.64 228.65 | 187.80 220.74 | 180.79 201.87 | 176.90 190.66 |
| | AICc difference (intercept only-model) | 32.27 | 26.73 | 31.95 | 42.55 | 37.57 | 31.27 | 32.01 | 32.95 | 21.08 | 13.76 |
| 1970-2009 training/calibration period | Correlation | 0.79 | 0.73 | 0.74 | 0.79 | 0.77 | 0.69 | 0.71* | 0.77 | 0.47 | 0.52 |
| | R-square | 0.62* | 0.54* | 0.55* | 0.62* | 0.59* | 0.48* | 0.51 | 0.59* | 0.22* | 0.27* |
| | RMSE | 1.49 | 1.65 | 1.63 | 1.50 | 1.54 | 1.75 | 1.70 | 1.44 | 1.50 | 1.34 |
| | Skill Score (%) | 47.59 | 43.93 | 48.18 | 58.96 | 55.43 | 46.17 | 47.44 | 39.29 | 27.42 | 16.29 |
| | Strike Rate: exact (%) | 30 | 27.5 | 20 | 27.5 | 22.5 | 17.5 | 25 | 25 | 20 | 27.5 |
| | Strike Rate: ± 1 (%) | 60 | 60 | 65 | 75 | 67.5 | 52.5 | 55 | 60 | 57.5 | 77.5 |
| | AICc | 150.24 185.21 | 158.02 185.21 | 157.30 185.21 | 150.65 185.20 | 152.93 185.21 | 162.81 185.21 | 160.52 185.20 | 147.28 179.44 | 150.87 163.58 | 141.28 154.50 |
| | AICc difference (intercept only-model) | 34.96 | 27.18 | 27.90 | 34.56 | 32.28 | 22.40 | 24.68 | 32.16 | 120.71 | 13.22 |
| 2010-2019 validation period | Strike Rate: exact (%) | 0 | 0 | 0 | 10 | 30 | 30 | 0 | 40 | 20 | 0 |
| | Strike Rate: ± 1 (%) | 50 | 40 | 50 | 60 | 60 | 70 | 70 | 70 | 90 | 60 |

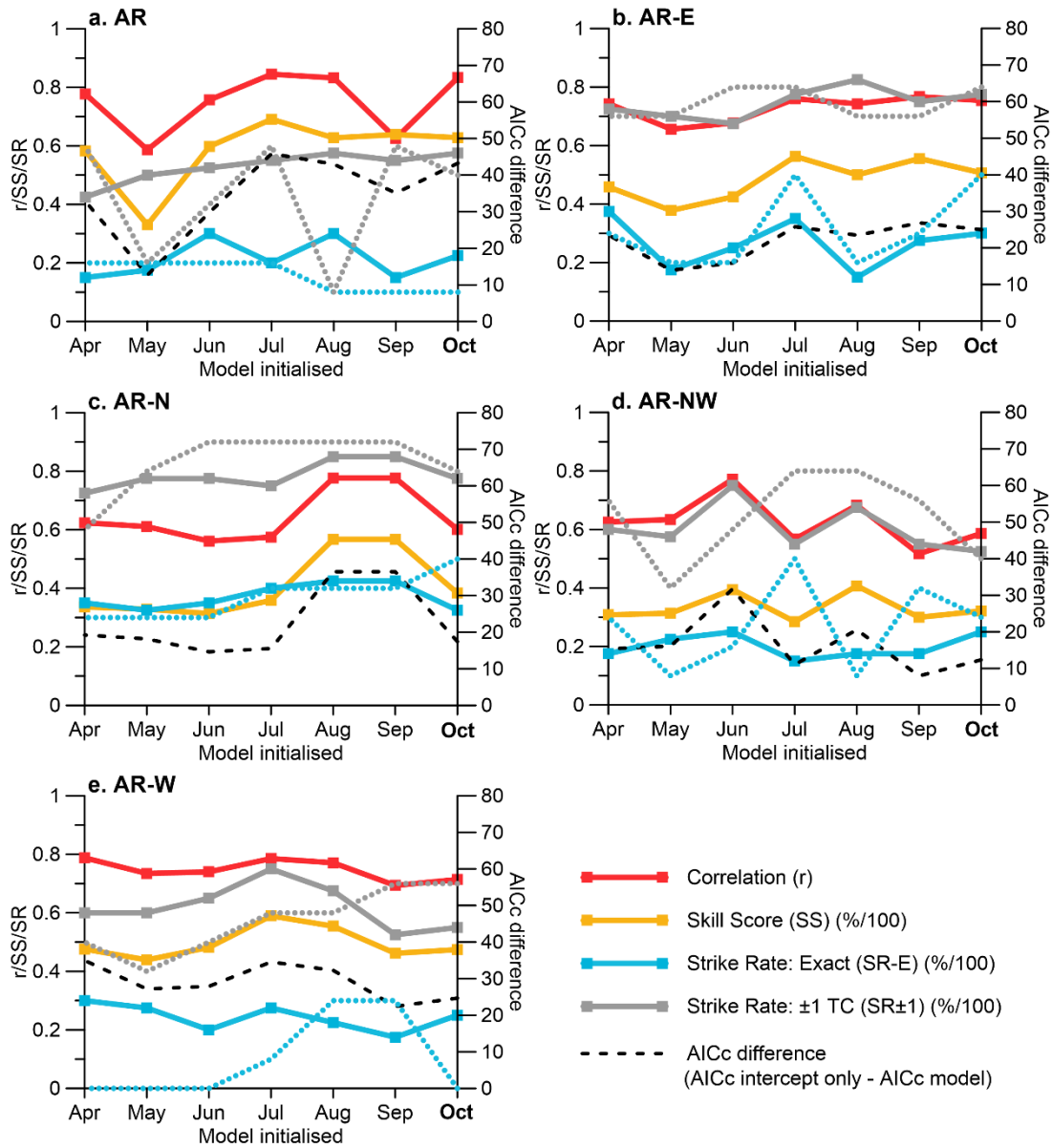


Figure S1. Cross-validation statistics to support Figure 6. Evaluation of superior predictor model performance for pre-season model initialisation runs between April and October for November-April TC forecasts. Statistics are based on the 1970-2009 training period (solid lines) and 2010-2019 validation period (dashed lines). Only SR-E and SR ± 1 are calculated for the validation period due insufficient sample size ($n=10$) to calculate other skill metrics.

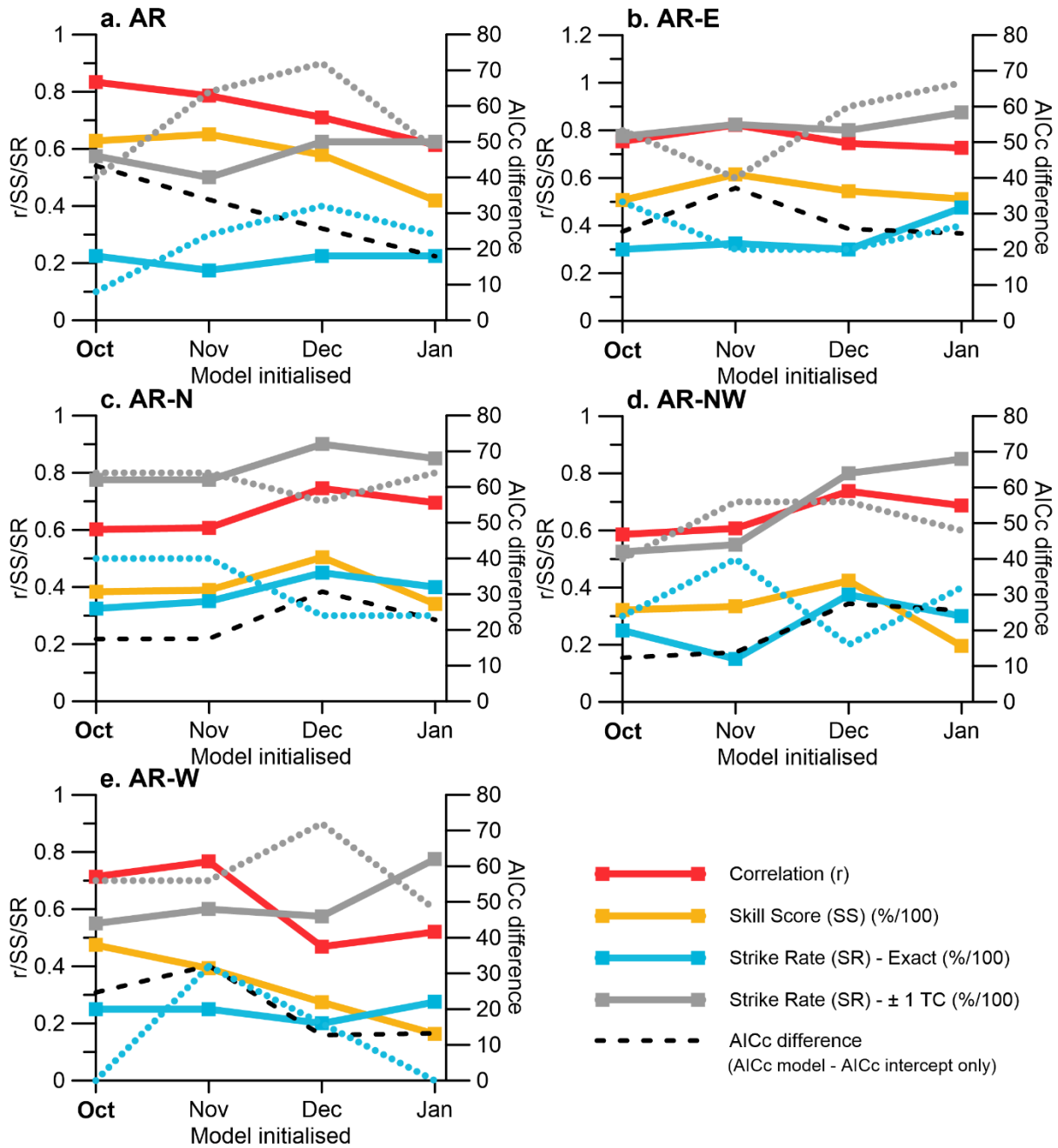


Figure S2. Cross-validation statistics to support Figure 9. Evaluation of superior predictor model performance for in-season model initialisation runs for October and November-January (in-season forecast model runs). Models run in October predict the entire November-April TC season. In-season forecasts run in November, December and January predict TCs for the remaining TC season; December-April, January-April and February-April, respectively. Statistics compare the 1970-2009 training period (solid lines) and the 2010-2019 validation period (dashed lines). Only SR-E and SR ± 1 are calculated for the validation period due insufficient sample size ($n=10$) to calculate other skill metrics. Refer to Tables S1-S5 for further information relating to selected predictor models and cross-validation statistics.