Table 1. Notation used in the operating model.

| Symbol | Description |
| --- | --- |
| *T*0 | Starting year of initialisation period |
| *T*1 | Year in which the management procedure begins |
| *T*2 | Year in which the simulation ends |
| *A* | Number of age-classes |
| *t* | Time step |
| *a* | Age-class in years |
| *B*0 | Unfished spawning biomass (units determined by units of weight-at-age) |
| *h* | Recruitment function steepness |
| *Mt* | Instantaneous natural mortality rate in year *t* |
| *L∞* | Asymptotic length (cm) |
| *L*1 | Mean length-at-age-1 (cm) |
| *k* | von Bertalanffy growth constant (/yr) |
|  | Age-at-50% maturity |
|  | Age-at-95% maturity |
|  | Age-at-50% selectivity by survey (X=S) and fishery (X=F) |
|  | Age-at-95% selectivity by survey (X=S) and fishery (X=F) |
| *q* | Spawn survey scaling parameter |
| *R*0 | Unfished recruitment |
| *ma* | Proportion mature-at-age |
|  | Proportion selected-at-age by survey (X=S) and fishery (X=F) |
| *wa* | Individual weight-at-age |
| x | Equilibrium yield (x=y) or spawning biomass (x=ssb) per recruit |
| *Na,t* | Number of age *a* fish in year *t* |
| *Ba,t* | Biomass of age *a* fish in year *t* |
|  | Spawning biomass in year *t* |
|  | Exploitable biomass in year *t* |
| *Ca,t* | Number of age *a* fish in year *t* catch |
| *Ct* | Fishery catch numbers |
|  | True proportion-at-age *a* in time *t* catch |
| *Qt* | Fishery catch biomass |
| *It* | Survey biomass estimate |
|  | Standard error of the random walk in recruitment |
|  | Standard error of the random walk in natural mortality rate |
|  | Standard error of the random walk in Walford intercept (growth rate) |
|  | Lag-1 autocorrelation in log-natural mortality rate (*X = M*), log-recruitment (*X = R*), and the growth parameter (). |
|  | Auto-correlated error in log-natural mortality rate (*X = M*), log-recruitment (*X = R*), and the growth parameter ( ) |
|  | *Normal*(0,1) error component in log-natural mortality rate (*X = M*), log-recruitment (*X = R*), and the growth parameter ( |
|  | Survey coefficient of variation in year *t* |
|  | Standard error of proportions-at-age in fishery catch (*X = F*) and surveys (*X = S*) |
|  | Uncorrelated *Normal*(0,1) error in log-survey |
|  | Uncorrelated *Normal*(0,1) error in logistic-transformed proportions-at-age |
|  | Zero-centred log-residual of proportion-at-age |
|  | Observed proportion-at-age *a* in year *t* catch |

Table 2. Operating model parameter values used to specify simulation scenarios. Equilibrium values in the final three columns are computed using M1983 and the historical values for . Biomass columns B0, BMSY and MSY are in units of Kt.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | B0 | avgR | M1983 | M2016 | M2036 |  |  |  |  | FMSY | BMSY | MSY |
| ConM\_.5R | 915.27 | 505.51 | 0.39 | 0.36 | 0.28 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM40\_.5R | 915.27 | 505.51 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM20\_.5R | 915.27 | 505.51 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM20lim\_.5R | 915.27 | 505.51 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| ConM\_1.5R | 915.27 | 1516.55 | 0.39 | 0.36 | 0.28 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM40\_1.5R | 915.27 | 1516.55 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM20\_1.5R | 915.27 | 1516.55 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |
| pM20lim\_1.5R | 915.27 | 1516.55 | 0.39 | 0.36 | 0.31 | 0.24 | 0.01 | 0.2 | 0.2 | 0.289 | 1200 | 242.94 |

Table 3. General age-structured, continuous fishery operating model used in closed loop simulations of 23JKL Cod. The generic superscript "X" is used wherever a function is identical for the fishery (X=F) and survey (X=S).

|  |  |
| --- | --- |
| **Parameters** | |
| OM2.1 |  |
| **Fixed life history schedules** | |
| OM2.2 |  |
| OM2.3 |  |
| **Stock-recruitment parameters and equilibrium population** | |
| OM2.4 |  |
| OM2.5 |  |
| OM2.6 |  |
| OM2.7 |  |
| OM2.8 |  |
| OM2.9 |  |
| **State dynamics** | |
| OM2.10 |  |
| OM2.11 |  |
|  |  |
|  |  |
| OM2.12 |  |
| OM2.13 |  |
| OM2.14 |  |
| OM2.15 |  |
| OM2.16 |  |
| OM2.17 |  |
| OM2.18 |  |
| OM2.19 |  |
| OM2.20 |  |
| **Survey and proportion-at-age observations** | |
| OM2.21 |  |
| OM2.22 |  |
| OM2.23 |  |
| OM2.24 |  |

Table 4. Equilibrium solutions for spawning biomass, , exploitable biomass, , and yield, , given a fishing mortality rate,. Top set of parameters, , is used to calculate operating model reference points. Elements of the parameter set,  are estimates updated to time T by the assessment model – these are substituted for their operating model counterparts to compute equilibrium quantities B0 and FMSY as required by the harvest control rules. Values for FMSY are obtained by numerically maximizing  with respect to .

|  |  |
| --- | --- |
| Eq. | Formula |
| EQ3.1 |  |
| EQ3.2 |  |
| EQ3.3 |  |
| EQ3.4 |  |
| EQ3.5 |  |
| EQ3.6 |  |
| EQ3.7 |  |
| EQ3.8 |  |
|  |  |

Table 5. Catch-at-age assessment model (AM) quantities that differ from operating model values. The generic superscript "X" is used for selectivity because fishery F and survey S selectivity functions only differ in the parameters given in AM.1.

|  |  |
| --- | --- |
| AM.1 |  |
| AM.2 |  |
| AM.3 |  |
| AM.4 |  |
| AM.5 |  |
| AM.6 |  |
| AM.7 |  |
| AM.8 |  |

Table 6. Components of the total negative log-posterior density function (G) given data up to time T. Negative log-likelihood functions for biomass index and recruitment () and age-proportion data (), prior distributions for stock-recruitment steepness () and natural mortality ( including M1 and deviations in the random walk).

|  |  |
| --- | --- |
| L.1 |  |
| L.2 |  |
| L.3 |  |
| L.4 |  |
| L.5 |  |
| L.6 |  |
| L.7 |  |
| L.8 |  |
| L.9 |  |
| L.10 |  |

Table 7. Estimates of important parameters from the 2016 stock assessment model NCAM (Cadigan, 2016), the assessment model (section 2.2.2) fit to the data for 23JKL cod and the operating model (section 2.1) initialized on NCAM outputs. Estimates are shown of Blim (average SSB for ), SSB2015, SSB2015/Blim, average M2015.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Model | Blim | SSB2015 | SSB2015/Blim | M2015 |
| NCAM | 839 | 294 | 0.35 | 0.289 |
| AMdata | 833 | 190 | 0.23 | 0.186 |
| OM | 788 | 255 | 0.32 | 0.342 |

Table 8. Management procedure (MP) performance for the scenarios with average age 1 recruitment half of the 1980s average age 1 recruitment. Performance metrics from left to right are: average catch (Kt) for 3, 5 and 10 year time periods, median probabilities of being in the critical zone for 3, 5 and 10 year time periods; the first time that Blim is reached with 50%, 75% and 90% probability; the first time that the upper stoc reference is reached with 50%, 75% and 90% probability; and average annual variation for the 10 year period. Taking median probabilities leads to probabilities that do not sum to 1 in some scenarios. Times marked NA in the and columns show that the operating model SSB did not reach those levels with the given probability in the projection period (20 years). Emboldened entries indicate the best performing management procedure in each metric for each scenario (except for no fishing procedures)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **0.5R Recruitment Proj** |  |  |  | **Simulation outcome** | | |  |  | **Performance Metrics** | | | |  |  |  |
| **Operating Model Scenario** | **MP** |  |  |  |  |  |  |  |  |  |  |  | |  | **AAV** |
| Constant M | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .58 | .06 | 37 | 37 | 39 | NA | NA | | NA | 0.0 |
|  | conF | 10.42 | 26.01 | 46.31 | 1.0 | .67 | .19 | 37 | 38 | NA | NA | NA | | NA | 25.23 |
|  | maxTAC | 8.33 | 17.5 | **87.64** | 1.0 | .66 | .21 | 37 | 38 | NA | NA | NA | | NA | 63.33 |
|  | noMaxTAC | 3.93 | 21.05 | 79.74 | 1.0 | .62 | .21 | 37 | 38 | NA | NA | NA | | NA | 63.24 |
|  | F\_SAR | **24.02** | **56.13** | 94.35 | 1.0 | .80 | .40 | 38 | NA | NA | NA | NA | | NA | **25.20** |
| Pulse M every 40 years | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .60 | .23 | 37 | 37 | NA | NA | NA | | NA | 0.0 |
|  | conF | 10.34 | 25.95 | 40.70 | 1.0 | .73 | .32 | 37 | NA | NA | NA | NA | | NA | 31.41 |
|  | maxTAC | 8.33 | 21.75 | **67.18** | 1.0 | .71 | .35 | 37 | NA | NA | NA | NA | | NA | 37.85 |
|  | noMaxTAC | 3.76 | 21.45 | 66.82 | 1.0 | .68 | .36 | 37 | NA | NA | NA | NA | | NA | 97.07 |
|  | F\_SAR | **24.48** | **58.06** | 84.37 | 1.0 | .83 | .47 | 38 | NA | NA | NA | NA | | NA | **29.32** |
| Pulse M every 20 years | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .65 | .40 | 37 | NA | NA | NA | NA | | NA | 0.0 |
|  | conF | 10.38 | 24.69 | 34.71 | 1.0 | .75 | .49 | 38 | NA | NA | NA | NA | | NA | **30.88** |
|  | maxTAC | 8.33 | 17.5 | 48.57 | 1.0 | .74 | .51 | 37 | NA | NA | NA | NA | | NA | 60.34 |
|  | noMaxTAC | 3.65 | 19.98 | **55.47** | 1.0 | .72 | .52 | 37 | NA | NA | NA | NA | | NA | 69.62 |
|  | F\_SAR | **23.43** | **56.84** | 71.10 | 1.0 | .85 | .61 | NA | NA | NA | NA | NA | | NA | 31.63 |
| Pulse M 20 when | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .65 | .31 | 37 | 44 | NA | NA | NA | | NA | 0.0 |
|  | conF | 10.38 | 24.69 | 40.61 | 1.0 | .75 | .42 | 38 | NA | NA | NA | NA | | NA | **27.64** |
|  | maxTAC | 8.33 | 17.5 | 52.96 | 1.0 | .74 | .45 | 37 | NA | NA | NA | NA | | NA | 58.61 |
|  | noMaxTAC | 3.65 | 19.98 | **59.39** | 1.0 | .72 | .46 | 37 | NA | NA | NA | NA | | NA | 67.61 |
|  | F\_SAR | **23.43** | **56.84** | 76.79 | 1.0 | .85 | .56 | 49 | NA | NA | NA | NA | | NA | 30.36 |

Table 9. Management procedure (MP) performance for the scenarios projected with an average age 1 recruitment as 150% of the 1980s average age 1 recruitment. Performance metrics from left to right are: average catch (Kt) for 3, 5 and 10 year time periods, median probabilities of being in the critical zone for 3, 5 and 10 year time periods; the first time that Blim is reached with 50%, 75% and 90% probability; the first time that the upper stoc reference is reached with 50%, 75% and 90% probability; and average annual variation for the 10 year period. Taking median probabilities leads to probabilities that do not sum to 1 in some scenarios. Times marked NA in the and columns show that the operating model SSB did not reach those levels with the given probability in the projection period (20 years). Emboldened entries indicate the best performing management procedure in each metric for each scenario (except for no fishing procedures).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **1.5R Recruitment Proj** |  |  |  | **Simulation outcome** | | |  |  | **Performance Metrics** | | | |  |  |  |
| **Operating Model Scenario** | **MP** |  |  |  |  |  |  |  |  |  |  |  | |  | **AAV** |
| Constant M | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .25 | .0 | 37 | 37 | 37 | 38 | 39 | | 40 | 0.0 |
|  | conF | 10.10 | 22.27 | 92.66 | 1.0 | .30 | .0 | 36 | 37 | 37 | 38 | 40 | | 42 | **29.90** |
|  | maxTAC | 8.33 | 15.0 | **265.57** | 1.0 | .29 | .0 | 37 | 37 | 37 | 38 | 40 | | NA | 45.01 |
|  | noMaxTAC | 3.59 | 19.5 | 258.05 | 1.0 | .33 | .0 | 37 | 37 | 37 | 38 | 40 | | NA | 43.72 |
|  | F\_SAR | **23.0** | **51.10** | 193.65 | 1.0 | .38 | .0 | 37 | 37 | 37 | 39 | 40 | | NA | 31.86 |
| Pulse M every 40 years | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .35 | .13 | 37 | 37 | 52 | 39 | 40 | | NA | 0.0 |
|  | conF | 7.48 | 22.2 | 72.67 | 1.0 | .38 | .14 | 37 | 37 | NA | 39 | 43 | | NA | 34.87 |
|  | maxTAC | 8.33 | 15.0 | **204.23** | 1.0 | .38 | .15 | 37 | 37 | NA | 39 | NA | | NA | 43.0 |
|  | noMaxTAC | 3.41 | 16.16 | 200.24 | 1.0 | .36 | .15 | 37 | 37 | NA | 39 | NA | | NA | 46.81 |
|  | F\_SAR | **23.0** | **48.81** | 165.38 | 1.0 | .44 | .15 | 37 | 37 | NA | 39 | 53 | | NA | **33.78** |
| Pulse M every 20 years | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .40 | .22 | 37 | 38 | NA | 39 | NA | | NA | 0.0 |
|  | conF | 9.62 | 22.48 | 66.0 | 1.0 | .46 | .24 | 37 | 39 | NA | 40 | NA | | NA | **34.12** |
|  | maxTAC | 8.33 | 17.5 | **170.82** | 1.0 | .45 | .25 | 37 | 40 | NA | 40 | NA | | NA | 50.34 |
|  | noMaxTAC | 3.29 | 17.5 | 167.87 | 1.0 | .42 | .26 | 37 | 40 | NA | 40 | NA | | NA | 53.22 |
|  | F\_SAR | **22.57** | **49.66** | 133.02 | 1.0 | .52 | .25 | 37 | 40 | NA | 40 | NA | | NA | 35.87 |
| Pulse M 20 when | NoFish | 0.0 | 0.0 | 0.0 | 1.0 | .37 | .10 | 37 | 37 | 41 | 39 | 40 | | 45 | 0.0 |
|  | conF | 9.63 | 22.49 | 74.32 | 1.0 | .44 | .12 | 37 | 37 | 43 | 39 | 41 | | 46 | **29.67** |
|  | maxTAC | 8.33 | 17.5 | 188.61 | 1.0 | .43 | .12 | 37 | 37 | 43 | 39 | 42 | | NA | 46.71 |
|  | noMaxTAC | 3.29 | 17.51 | **205.22** | 1.0 | .40 | .11 | 37 | 37 | 43 | 39 | 42 | | NA | 47.72 |
|  | F\_SAR | **22.57** | **49.66** | 149.15 | 1.0 | .51 | .14 | 37 | 38 | 44 | 39 | 42 | | 46 | 31.82 |



Figure 1. The harvest control rule (HCR) defined in section 2.2.3, with a 2 stage increase in target fishing mortality F. In the critical zone (left of the red line) where the first stage increases slowly between F = 0 and F = 0.05, then for the target F increases more rapidly to 0.18, where it levels off in the healthy zone (to the right of the orange line).



Figure 2. Total Allowable Catch estimated by using the HCR defined in section 2.2.3 and shown in Figure 1. The thin blue line shows the TAC as given by the noMaxTAC management procedure, and the thin black stepped lines show the TAC ceilings defined by the maxTAC rule.



Figure 3. Time series plots of outputs from the three models NCAM, AMdata and OM comparing (a) spawning stock biomass, (b) fully selected (maximum) fishing mortality and (c) mean natural mortality across all age classes. The OM is not shown in (b) or (c) as the NCAM values are identical for the years shown.



Figure 4. Natural mortality rate (M) envelopes by scenario. The vertical line represents the first year of the projection period. Simulation envelopes include the median (thick black dashed line) and central 90% of M trajectories over 100 simulations (grey shaded region).



Figure 5. Single simulation replicate of the noMaxTAC management procedure under the Constant M scenario with half of 1980s average recruitment. a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of abundance, b) realized catch and c) realized fishing mortality and d) recruitment numbers. Dashed lines represent MSY (b), and FMSY (c), respectively. Survey indices are consistently above SSB because they represent indices of abundabce for survey exploitable biomass.



Figure 6. Single simulation replicate of the noMaxTAC management procedure under the Pulse M every 40 years scenario with half of 1980s average recruitment. a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of abundance, b) realized catch and c) realized fishing mortality and d) recruitment numbers. Dashed lines represent MSY (b), and FMSY (c), respectively. Survey indices are consistently above SSB because they represent indices of abundabce for survey exploitable biomass.



Figure 7. Single simulation replicate of the noMaxTAC management procedure under the Pulse M every 20 years scenario with half of 1980s average recruitment. a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of abundance, b) realized catch and c) realized fishing mortality and d) recruitment numbers. Dashed lines represent MSY (b), and FMSY (c), respectively. Survey indices are consistently above SSB because they represent indices of abundance for survey exploitable biomass..



Figure 8. Single simulation replicate of the noMaxTAC management procedure under the Pulse M every 20 years while scenario with half of 1980s average recruitment. a) retrospective stock assessment performance, operating model spawning biomass trajectory and survey index of abundance, b) realized catch and c) realized fishing mortality and d) recruitment numbers. Dashed lines represent MSY (b), and FMSY (c), respectively. Survey indices are consistently above SSB because they represent indices of abundabce for survey exploitable biomass.



Figure 9. Simulated spawning biomass depletion compared to (top) and catch (bottom) performance envelopes for the constant M scenario with (a) 50% of average 1980s recruitment and (b) 150 % of average recruitment (bottom) during the projection period. Each pair of Depletion/Catch panels corresponds to the management procedures listed in section 2. Envelopes are for the projection period only (2017 – 2036) and include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shading).



Figure 10. Simulated spawning biomass depletion compared to (top) and catch (bottom) performance envelopes for the Pulse M every 40 years scenario with (a) 50% of average 1980s recruitment and (b) 150 % of average recruitment (bottom) during the projection period. Each pair of Depletion/Catch panels corresponds to the management procedures listed in section 2. Envelopes are for the projection period only (2017 – 2036) and include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shading).



Figure 11. Simulated spawning biomass depletion compared to (top) and catch (bottom) performance envelopes for the Pulse M every 20 years scenario with (a) 50% of average 1980s recruitment and (b) 150 % of average recruitment (bottom) during the projection period. Each pair of Depletion/Catch panels corresponds to the management procedures listed in section 2. Envelopes are for the projection period only (2017 – 2036) and include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shading).



Figure 12. Simulated spawning biomass depletion compared to (top) and catch (bottom) performance envelopes for the Pulse M every 20 years while SSB is less than scenario with (a) 50% of average 1980s recruitment and (b) 150 % of average recruitment (bottom) during the projection period. Each pair of Depletion/Catch panels corresponds to the management procedures listed in section 2. Envelopes are for the projection period only (2017 – 2036) and include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shading).

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Figure 13. Fishing mortality envelope plots for the maxTAC management procedure under all pM20 and conM scenarios. Large spikes in realised fishing mortality in the pM20 scenarios are the result of increased natural mortality, driving biomass down and increasing assessment error. Higher average recruitment means that the peak biomass may reach much higher levels before a decline, leading to higher peaks of envelopes in the lower panels.