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# Eastern Bering Sea Pollock Trawl Fisheries: Variation in Salmon Bycatch over Time and Space

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*Abstract.*—The Magnuson-Stevens Act emphasizes the importance of minimizing bycatch, to the extent practicable, as part of the goal to achieve sustainable fisheries. Measures to reduce Pacific salmon (*Oncorhynchus* spp.) bycatch for the eastern Bering Sea walleye pollock *Theragra chalcogramma* trawl fisheries have been developed and implemented, resulting in specific closed (no-fishing) areas when established bycatch limits for Pacific salmon are exceeded. These closure areas were designed based on analyses of groundfish observer data collected from 1990–1995, yet in recent years Pacific salmon bycatch in the pollock fishery has consistently exceeded the limits. As a result, large areas were closed to the fishery, and the spatial pattern of fishing by the pollock fleet was altered. An analysis of the effectiveness of the closed-area management system was reviewed by the North Pacific Fishery Management Council (Council) in 2005, and indicated that when areas were closed, salmon bycatch rates were often higher than observed earlier inside the closure areas. Thus, as an interim measure, the Council adopted a program in October 2005 to exempt vessels from the existing closed-area regulations so that near-real time inseason information could be used to establish dynamic closed areas where salmon bycatch levels are high. In this paper, we review information on the previous closed area management system and qualitatively characterize historical bycatch patterns using fishery observer data. Our results show that the spatial and temporal salmon bycatch patterns are highly variable between years. Variability in size and sex composition of the salmon bycatch adds to the complexity of developing effective management options aimed at minimizing the bycatch of the eastern Bering Sea pollock fishery. These results should assist managers in devising alternative approaches for managing salmon bycatch in the pollock trawl fisheries.

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## Introduction

The walleye pollock *Theragra chalcogramma* fishery is one of the largest fisheries in the world and represents a major component of all commercial Alaskan fisheries (Hiatt et al. 2006). Compared to most fisheries, the relative bycatch of all other species is low representing only about 1.2% of the total removals by weight due to the pollock fishery, 24% of which is attributed to jellyfish while 63% of the bycatch consisted of other quota-managed target groundfish species (Ianelli et al. 2006). This bycatch compares with nation-wide bycatch estimates of about 22% (Harrington et al. 2005). Harrington et al. (2005) estimated bycatch in all Alaskan fisheries as approximately 11% by weight. However, because the pollock fishery catch is large (average 1.464 million t 2001–2005), the absolute magnitude of bycatch needs to be closely monitored, especially of Pacific salmon *Oncorhynchus* spp. Salmon represent an extremely important resource to Alaska and to the countries surrounding the North Pacific. The stock of origin of salmon species in pollock trawl bycatch in the eastern Bering Sea (EBS) has been shown to have a high proportion originating from western Alaska (Myers et al. 2004; Myers and Rogers 1988; Wilmot et al. 1998; Patton et al. 1998; Myers et al. 2009, this volume). Salmon support large and critically important commercial, recreational, and subsistence fisheries, and are the basis of a cultural tradition in many parts of the state. Witherell et al. (2002) characterized the bycatch from groundfish fisheries in the Bering Sea Aleutian Islands (BSAI) for chum *O. keta* and Chinook *O. tshawytscha* salmon. Their results indicated that while chum salmon bycatch from these fisheries may not have substantial effect on western Alaskan runs, the impact of groundfish fisheries on Chinook salmon stocks may be larger (Witherell et al. 2002). The bycatch of both chum and Chinook salmon in the EBS pollock fishery have reached historic highs since the Witherell et al. (2002) analysis was completed, thus the relative impact of bycatch on those stocks may be greater than previously estimated. Consequently, the bycatch mortality of Pacific salmon stocks due to the fishery requires careful evaluation.

Salmon bycatch in the EBS pollock fishery occurs in both the “A” and “B” seasons. The A-season commences on January 20th and extends until late March or early April, until about 40% of the available pollock quota is reached. This early fishery is focused on the southeast portion of the EBS and targets prespawning pollock. The valuable roe from these fish are the main product form with the flesh used for fillets or surimi. The B-season opens in June and continues generally until mid-October for the remaining 60% of the quota. This fishery is typically spread over the outer shelf edge of the Bering Sea extending to the Russian border. Chinook salmon are commonly taken incidentally by pollock trawl gear during both A- and B-seasons. Chum salmon are primarily taken during the B-season. The pollock fleet is composed of three sectors: catcher-vessels that deliver catches to shore-side processing plants, catcher-vessels that deliver to at-sea processing motherships, and vessels that catch and process their fish on board (catcher-processors). By regulation, catcher-processors are restricted from some near-shore areas because shore-based catcher vessels have more limitations on the locations they can fish.

The inseason salmon bycatch management uses scientific observer data and Chinook salmon bycatch annual limits are currently set at 29,000 fish. If inseason catch estimates exceed this value, a closed area is invoked (Figure 1; top panel; NMFS 1999). The Bering Sea “Chinook Salmon Savings Area” was developed based on an analysis of available observer data from 1990 through 1994 (ADF&G 1995a). The Chinook salmon limit, and the time of year that

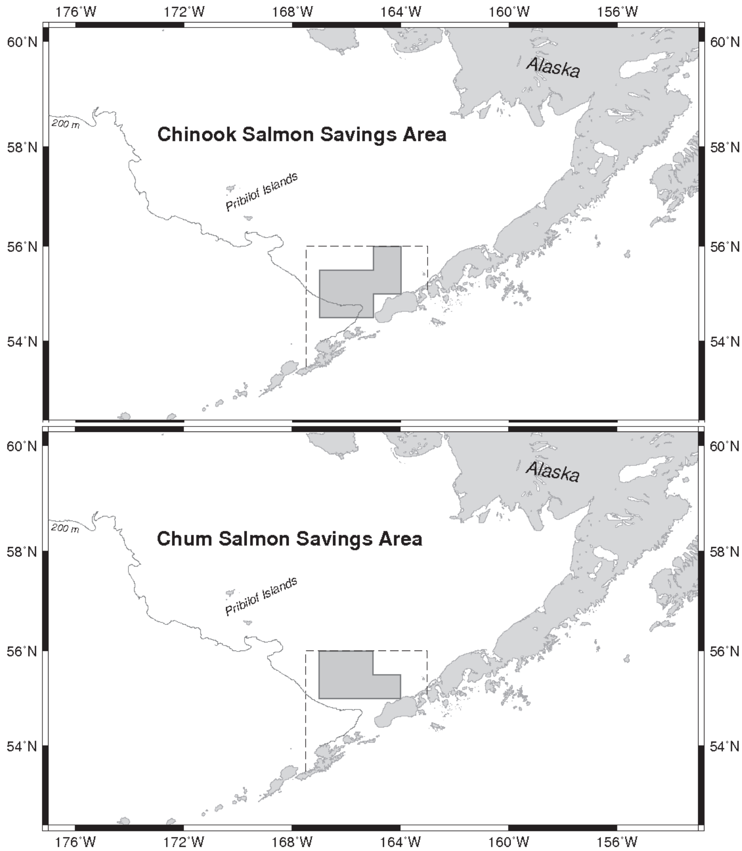


FIGURE 1. NMFS regulatory areas for Chinook salmon (top) and chum salmon (bottom) established in 1996. The dashed outline represents the catcher-vessel operational area (CVOA) management area.

the limit is exceeded, affect how the closure occurs. If the trigger limit is exceeded before April 15, the area closes from that day through the end of the winter-spring fishery (typically late October or early November). In this case, the B-season fishery would be open in all areas from June–September 1st, after which the areas would close for the rest of the year. If the limit is reached after April 15, but before September 1, the areas would close on September 1 through the end of the year. If the limit is reached after September 1, the areas close on that date through the end of the year. Since their establishment, the pollock fishery has been excluded from the Chinook Salmon Savings Areas in each year from 2003–2006 whereas prior to 2003, the levels of Chinook salmon bycatch were below the limit and closures did not occur. Over this time period, the Chinook salmon bycatch was highest in 2006. During this year, the winter fishery caused the Chinook Salmon Savings Area to close on February 14th. This was the first time the closure occurred during the winter fishery.

For chum salmon, a "Chum Salmon Savings Area" (Figure 1; bottom panel) was established in 1994 by emergency rule, and then formalized in the groundfish Fishery Management Plan in 1995 (ADF&G 1995b). By rule, this area is closed to all trawling from August 1 through August 31. Additionally, if 42,000 "other" salmon (i.e., non-Chinook salmon, 98% of which are chum salmon; NPFMC

2005) are caught in the "catcher vessel operational area" (CVOA) during the period August 14–October 14, an additional closure period will be invoked. This period will begin on September 14 and extend through October 14, unless the limit is reached within this period, in which case it will close on the date the limit is exceeded. Catcher processors are prohibited from fishing in the CVOA during the second half of the year (except for operations associated with community development quotas). Since the establishment of the savings area in 1995, the bycatch levels of "other salmon" have resulted in additional closure periods (beyond the automatic August 1–31 period) from 2002 to 2005, but not in 2006.

In this study, salmon bycatch trends in the walleye pollock fishery were described in terms of annual, seasonal, and daily variation. Also, bycatch was compared between sea-and land-based vessels for differences in catch rates between sexes. Additionally, the relationship between the size of salmon and the level of bycatch was evaluated because understanding this relationship may help explain changes due to salmon behavior and the relative size and sources (Asian or North American origin) of salmon runs.

## Methods

The National Marine Fisheries Service (NMFS) trained observers to collect the data used here to evaluate patterns of salmon bycatch. Observers are required to sample all salmon found in the catch. Salmon caught by shore-based "catcher vessels" are sampled at the plant where pollock are delivered. Observers record sex, weight, and total length of salmon by species. Observer sampling protocols are described by NMFS (2007). From the observer collections, two datasets were compiled: haul-specific information and length-frequency information.

The haul-specific dataset included detailed information on pollock catch, total catch of all other groundfish species, haul position, date, time of day, depth of bottom, depth of fishing, vessel type, and numbers of salmon (categorized as either Chinook or non-Chinook salmon). For catch accounting and Pacific Salmon Commission limits, four species of salmon (sockeye, coho, pink, and chum) are aggregated into an 'other salmon' (a non-Chinook salmon species category). Chum salmon comprises over 99.6% of the total catch in this category (NPFMC 2005). Haul-specific data were available from 1990 to 2006 and included only at-sea observations (Table 1). For the purposes of this analysis, the at-sea sampling was considered representative of the salmon bycatch. Fishing operations that were clearly targeting pollock were isolated by including only trawl-haul observations in which pollock catch represented more than 80% (by weight). The actual observed salmon bycatch represents about 82% and 71% of the estimated total catch of Chinook and chum salmon, respectively (during 2003–2006). This estimate suggests that due to the high level of observer coverage, a large fraction of the bycatch was directly observed. The detailed haul information was used to evaluate geographically stratified seasonal and inter-annual bycatch patterns and variability.

The length-frequency dataset included salmon species-specific data from 1998 to 2006. These data included information on large-scale area, date, sex, and length. The salmon sampled for lengths by season and area over years are summarized in Table 2. Fish measured were selected systematically to avoid potential biases. The salmon bycatch length frequency data were examined for seasonal and sex-specific patterns in addition to trends in time. This type of information is important for inferring the age-composition of the bycatch and the potential effects on different spawning groups (i.e., whether the

Table 1. Raw observer-data totals of pollock catch ($t$) and salmon (numbers) by seasons. Note that official totals will differ due to expansions to unobserved operations.

| | A Season (Jan–May) | | | B Season (Jun–Dec) | | | Total | Total | Total |
|---|---|---|---|---|---|---|---|---|---|
| Year | Pollock | Chinook | Chum | Pollock | Chinook | Chum | Pollock | Chinook | Chum |
| 1990 | 405,672 | 3,847 | 159 | 583,119 | 3,039 | 9,924 | 988,791 | 6,886 | 10,083 |
| 1991 | 328,831 | 12,078 | 295 | 435,318 | 2,226 | 12,250 | 764,149 | 14,304 | 12,545 |
| 1992 | 308,989 | 14,985 | 645 | 487,893 | 7,595 | 25,762 | 796,882 | 22,581 | 26,407 |
| 1993 | 358,098 | 12,456 | 201 | 474,089 | 7,898 | 133,073 | 832,188 | 20,354 | 133,274 |
| 1994 | 392,624 | 15,179 | 383 | 514,568 | 3,562 | 67,759 | 907,192 | 18,741 | 68,141 |
| 1995 | 447,995 | 6,978 | 377 | 482,919 | 2,347 | 29,912 | 930,914 | 9,325 | 30,289 |
| 1996 | 367,290 | 24,346 | 147 | 421,396 | 13,328 | 51,825 | 788,686 | 37,673 | 51,971 |
| 1997 | 343,402 | 8,100 | 1,263 | 398,346 | 23,192 | 43,529 | 741,748 | 31,292 | 44,791 |
| 1998 | 384,397 | 11,527 | 3,784 | 413,731 | 27,492 | 30,758 | 798,129 | 39,019 | 34,543 |
| 1999 | 331,664 | 8,441 | 111 | 478,312 | 8,595 | 30,067 | 809,976 | 17,036 | 30,178 |
| 2000 | 371,911 | 5,272 | 238 | 567,065 | 4,437 | 44,617 | 938,976 | 9,709 | 44,855 |
| 2001 | 469,254 | 17,402 | 2,291 | 682,142 | 13,205 | 45,621 | 1,151,396 | 30,607 | 47,912 |
| 2002 | 499,437 | 18,502 | 1,033 | 744,601 | 11,336 | 64,376 | 1,244,039 | 29,838 | 65,409 |
| 2003 | 519,043 | 28,721 | 3,408 | 755,783 | 12,940 | 134,160 | 1,274,826 | 41,661 | 137,568 |
| 2004 | 510,953 | 21,301 | 391 | 732,256 | 23,994 | 345,032 | 1,243,208 | 45,295 | 345,423 |
| 2005 | 511,460 | 27,006 | 519 | 747,335 | 32,423 | 496,726 | 1,258,795 | 59,429 | 497,245 |
| 2006 | 534,293 | 54,450 | 2,308 | 765,460 | 23,703 | 222,115 | 1,299,753 | 78,153 | 224,423 |

bycatch mortality consists of salmon that are likely to be maturing and returning to rivers within the next several months versus the next couple of years).

## Results

Overall, salmon bycatch levels have increased considerably in recent years (Table 3). The catch data for the three species separated by season and latitudinal bands (S = south of 56°N, M = 56° to 58°N, N = north of 58°N) show that inter-annual variability was lowest for pollock, whereas chum salmon was the highest (Table 4). Also, the observed Chinook salmon mean catch level was slightly higher during the A-season than during the B-season, whereas the vast majority of chum salmon were taken during the B-season (Table 4). In addition, the inter-annual variability in the northern region was slightly higher during the B-season than during the A-season for all three species (Table 4).

The catch per hour of fishing for pollock was higher in the A- than the B-season, but has been relatively stable over time, whereas the catch per observed hour fishing has increased dramatically for Chinook salmon during the A-season and for chum salmon during the B-season (Figure 2). Based on cumulative catch over the years, considerable seasonal and inter-annual variability are apparent for Chinook and chum salmon (Figure 3).

The bycatch levels of salmon generally tend to be higher in shore-based catcher vessels than for at-sea catcher processors. The percent of tows with salmon present has increased over time for both shore-based catcher vessels (mean of 42%) and at-sea catcher processors (mean of 17%; Figure 4). Note that the drop in Chinook incidence in tows by the shore-based catcher-vessel fleet in 2000 was due to the closure of the CVOA in the B-season of that year due to conservation concerns over the western stock of Steller sea lion *Eumetopias jubatus*.

TABLE 2. Numbers of Chinook and chum salmon sampled by A (January–May) and B (June–December) seasons and by regions (S = south of 56°, M = 56° - 58°, N = north of 58°).

| | | A season | | | | B season | | | Annual |
|---|---|---|---|---|---|---|---|---|---|
| Chinook | S | M | N | Total | S | M | N | sub-total | Total |
| 1998 | 2,008 | 91 | 39 | 2,138 | 3,550 | 519 | 171 | 4,240 | 6,378 |
| 1999 | 736 | 368 | 16 | 1,120 | 394 | 225 | 615 | 1,234 | 2,354 |
| 2000 | 979 | 501 | 2 | 1,482 | 5 | 188 | 141 | 334 | 1,816 |
| 2001 | 2,041 | 1,776 | 7 | 3,824 | 1,123 | 2,443 | 226 | 3,792 | 7,616 |
| 2002 | 7,326 | 2,144 | | 9,470 | 5,873 | 403 | 52 | 6,328 | 15,798 |
| 2003 | 11,551 | 4,405 | 85 | 16,041 | 4,078 | 2,652 | 1,007 | 7,737 | 23,778 |
| 2004 | 6,996 | 4,257 | 13 | 11,266 | 8,454 | 2,577 | 1,748 | 12,779 | 24,045 |
| 2005 | 10,678 | 3,258 | 41 | 13,977 | 8,901 | 4,960 | 2,596 | 16,457 | 30,434 |
| 2006 | 14,313 | 10,440 | 28 | 24,781 | 11,804 | 1,107 | 922 | 13,833 | 38,614 |

| | | A season | | | | B season | | | Annual |
|---|---|---|---|---|---|---|---|---|---|
| Chum | S | M | N | Total | S | M | N | sub-total | Total |
| 1998 | 471 | 2 | 1 | 474 | 2,062 | 524 | 181 | 2,767 | 3,241 |
| 1999 | 15 | 72 | | 87 | 160 | 566 | 420 | 1,146 | 1,233 |
| 2000 | 110 | 11 | | 121 | 111 | 1,727 | 754 | 2,592 | 2,713 |
| 2001 | 529 | 128 | | 657 | 2,836 | 5,553 | 892 | 9,281 | 9,938 |
| 2002 | 152 | 31 | 1 | 184 | 22,836 | 2,756 | 971 | 26,563 | 26,747 |
| 2003 | 1,157 | 430 | 2 | 1,589 | 47,491 | 9,475 | 4,291 | 61,257 | 62,846 |
| 2004 | 99 | 104 | | 203 | 32,369 | 22,256 | 10,239 | 64,864 | 65,067 |
| 2005 | 76 | 220 | 1 | 297 | 30,919 | 18,218 | 24,534 | 73,671 | 73,968 |
| 2006 | 477 | 196 | 3 | 676 | 26,303 | 14,584 | 5,800 | 46,687 | 47,363 |

TABLE 3. Bycatch of salmon (numbers) by Bering Sea Aleutian Islands trawl fisheries 2002–2006 compared to the average bycatch from 1990–2001. Source: NMFS Alaska Regional Office Catch Accounting database.

| Year | Chinook | Chum |
|---|---|---|
| 1990–2001 (average) | 37,819 | 69,332 |
| 2002 | 36,385 | 81,470 |
| 2003 | 54,911 | 197,091 |
| 2004 | 62,493 | 465,650 |
| 2005 | 67,856 | 703,131 |
| 2006 | 87,524 | 327,690 |

TABLE 4. Summary statistics from observer-data annual catch totals from 1990–2006 by A (Jan–May) and B (June–Dec) seasons and by regions (South = south of 56°, Middle = 56°–58°, North = north of 58°) for walleye pollock *Theragra chalcogramma*, Chinook salmon *Oncorhynchus tshawytscha*, and chum salmon *O. keta*. CV represents the coefficient of variation (over years) computed as the standard deviation divided by the mean. Units are given in the first column.

| | | A season | | | | B Season | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | South | Middle | North | All areas | South | Middle | North | All areas | All areas seasons |
| Pollock (*t*) | Min | 152,243 | 5,170 | 471 | 308,989 | 32,720 | 31,421 | 12,420 | 398,346 | 741,748 |
| | Max | 424,979 | 306,641 | 20,968 | 534,293 | 366,526 | 391,267 | 539,949 | 765,460 | 1,299,753 |
| | Median | 256,186 | 151,221 | 2,302 | 392,624 | 233,448 | 169,122 | 151,384 | 514,568 | 930,914 |
| | Mean | 258,791 | 153,152 | 4,839 | 416,783 | 214,918 | 165,414 | 189,335 | 569,667 | 986,450 |
| | CV | 30% | 62% | 110% | 18% | 41% | 50% | 75% | 24% | 21% |
| Chinook (numbers) | Min | 2,187 | 380 | 74 | 3,847 | 163 | 615 | 62 | 2,226 | 6,886 |
| | Max | 31,276 | 22,757 | 1,785 | 54,450 | 21,879 | 9,828 | 5,018 | 32,423 | 78,153 |
| | Median | 10,926 | 3,372 | 238 | 14,985 | 5,950 | 1,854 | 584 | 11,336 | 29,838 |
| | Mean | 11,712 | 4,959 | 422 | 17,094 | 8,055 | 3,421 | 1,542 | 13,018 | 30,112 |
| | CV | 64% | 116% | 111% | 71% | 86% | 81% | 111% | 74% | 63% |
| Chum (numbers) | Min | 49 | 1 | 0 | 111 | 5,365 | 357 | 27 | 9,924 | 10,083 |
| | Max | 3,764 | 1,170 | 147 | 3,784 | 313,119 | 109,331 | 100,117 | 496,726 | 497,245 |
| | Median | 373 | 24 | 0 | 391 | 28,850 | 14,520 | 2,501 | 45,621 | 47,912 |
| | Mean | 818 | 202 | 13 | 1,033 | 67,345 | 25,395 | 12,407 | 105,147 | 106,180 |
| | CV | 124% | 174% | 279% | 115% | 124% | 128% | 195% | 127% | 125% |

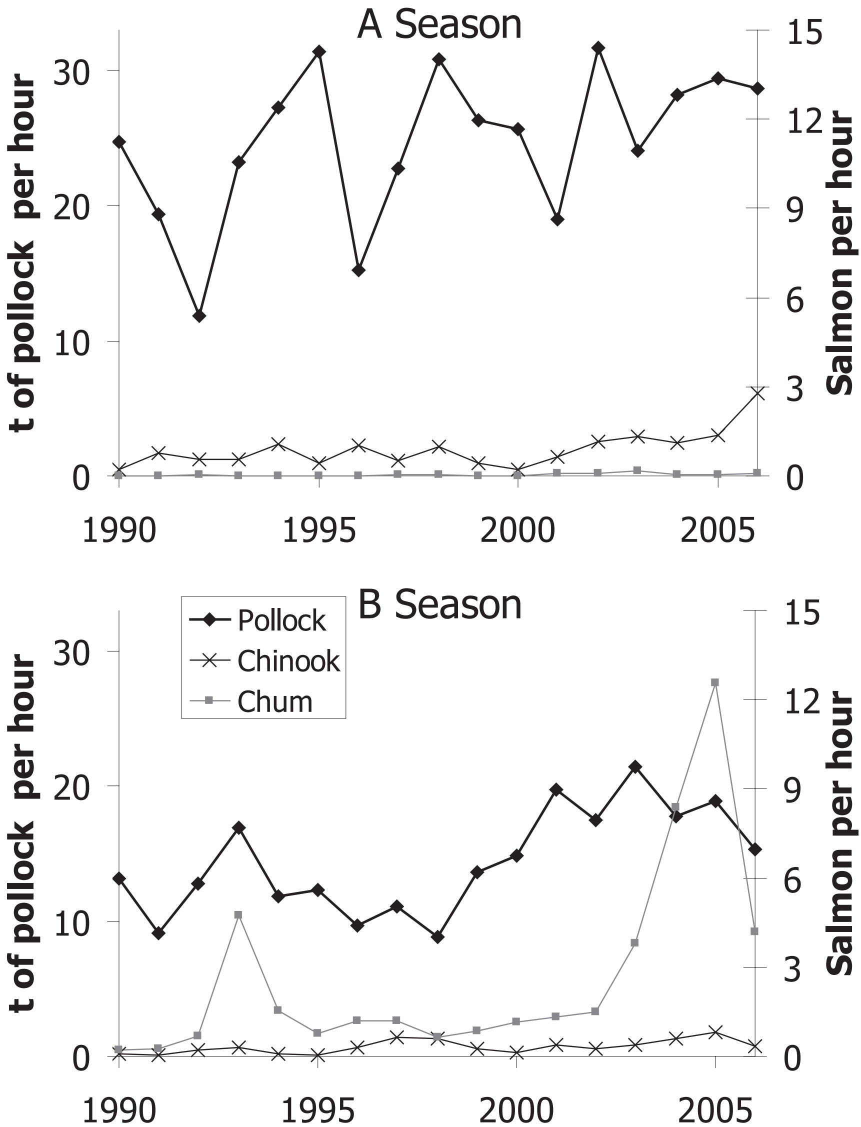


FIGURE 2. Catch rate (t per hour) of pollock and salmon (number per hour) by A (January–April) and B (June–October) seasons, 1990–2006 based on NMFS observer data.

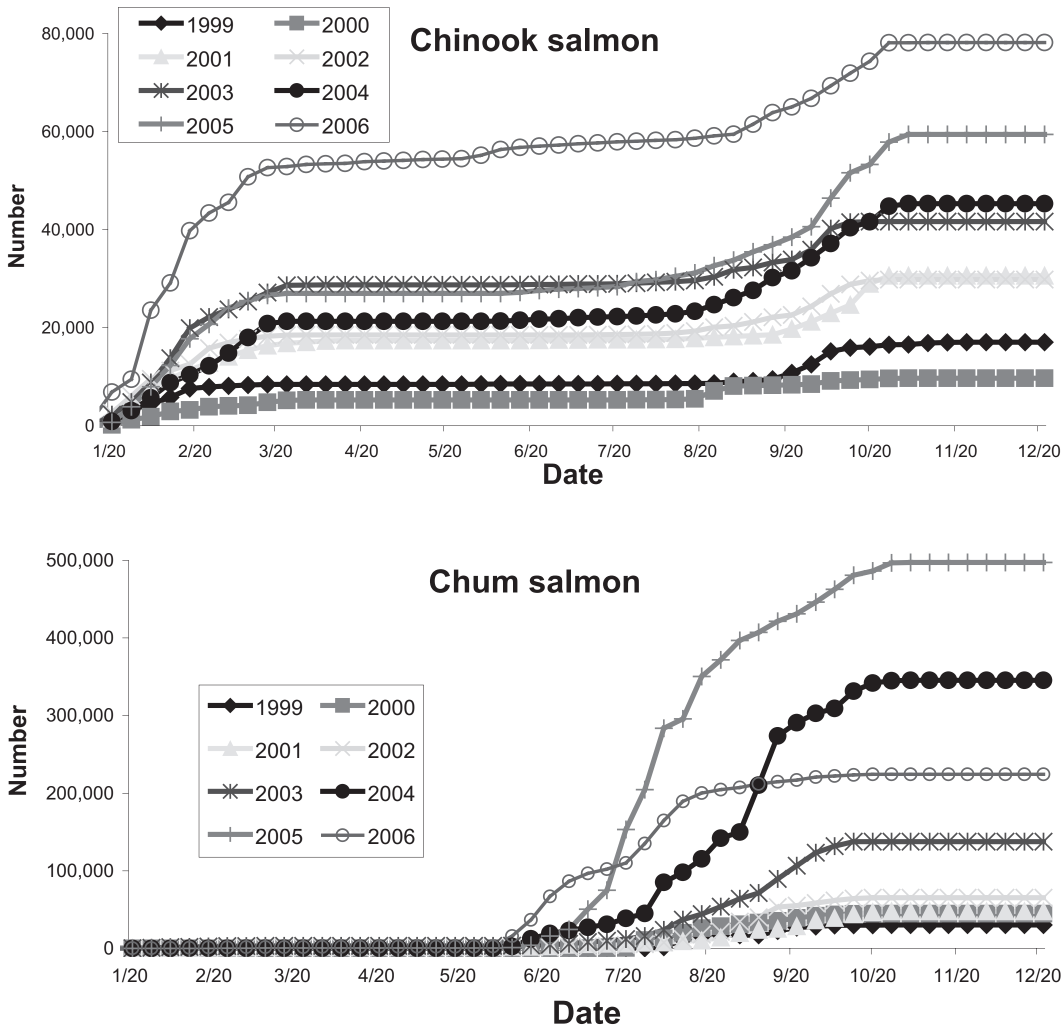


FIGURE 3. Cumulative catch of Chinook and chum salmon over date, 1999–2006 based on NMFS observer data.

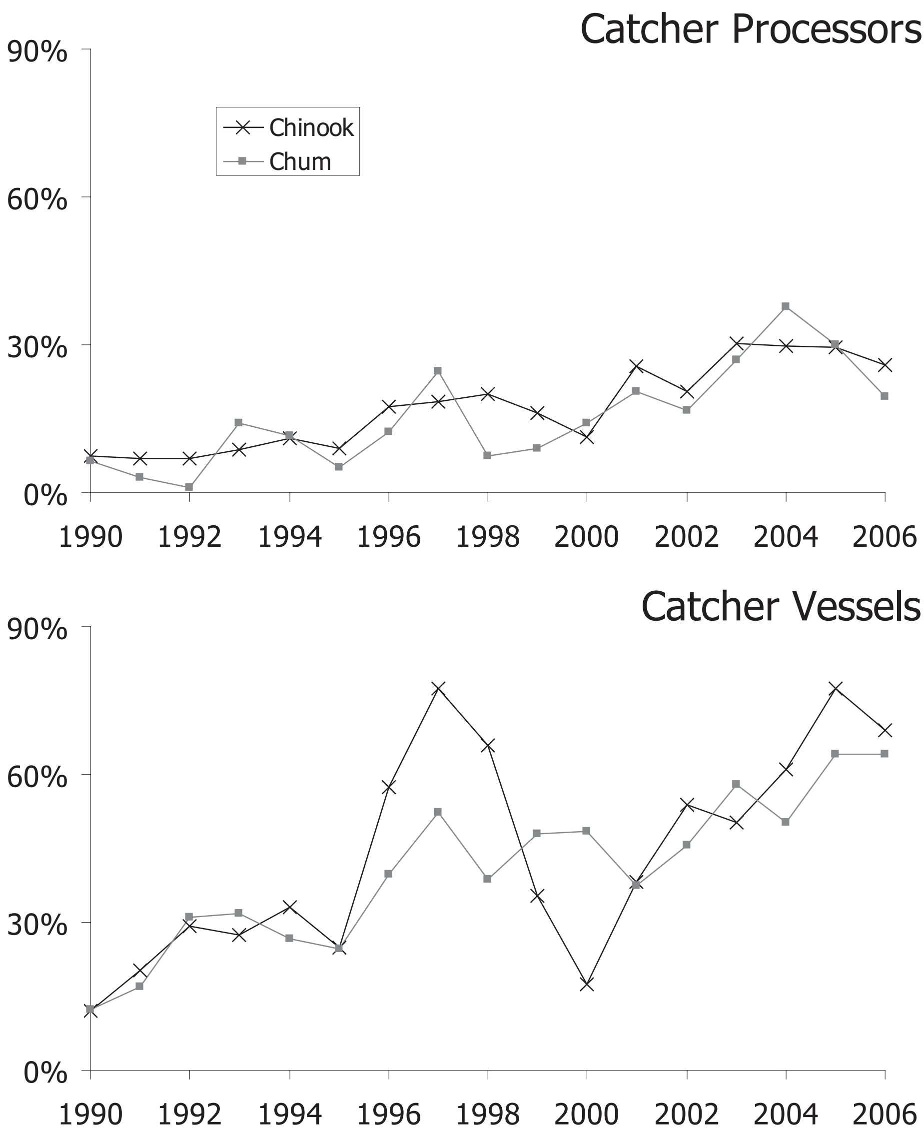


FIGURE 4. Incidents of salmon in pollock tows for at-sea catcher-processors (top panel) and shore-based catcher vessels (bottom panel) based on NMFS observer data, 1990–2006.

Pollock and salmon catch and catch-per-minute were higher during mid-day than during night-time hours (Figure 5). This pattern was consistent with trawl effort, which was highest at mid-day, whereas tows occurring at night represented about 75% of the peak mid-day effort (NMFS unpublished data). While both pollock and salmon have somewhat higher catch rates during mid-day, the catch rate for salmon dropped (relatively speaking) more during night-time hours. The diel changes in catch rate implies that bycatch rates of salmon might be reduced if fishing became more concentrated during night-time hours.

The Chinook salmon bycatch during the A-season came from areas smaller than the area where pollock were caught. This difference indicated that Chinook salmon were not uniformly distributed relative to pollock (Figure 6). During the B-season, bycatch of Chinook salmon tended to occur along the fringes of the areas where pollock catches were concentrated. Chum salmon (for the B-season fishery when the majority of the bycatch occurred) spatial distribution in the pollock fishery was concentrated south of the Pribilof Islands, even though the pollock fishery was concentrated more northerly (Figure 6). Inter-annual spatial variability of these patterns highlight the difficulty in selecting fixed-areas for possible regulatory closures.

The seasonal size composition of Chinook salmon in the pollock fishery during the winter months shows two modes, one at about 52 cm and the other at about 66 cm, with some indication that size increases between June–August (Figure 7). From July–September, the first mode at about 52 cm was not apparent but appeared again in October at about 49 cm, likely representing a new year-class recruiting to the bycatch.

For chum salmon, the seasonal size composition in the pollock fishery was unimodal, with growth occurring from a mode at about 60 cm length in July to 66 cm length by October (Figure 8). Length frequencies from other times of year are based on relatively fewer samples, and more fish tend to be less than 40 cm. Interestingly, chum salmon caught in June have a modal value of about 68 cm, substantially larger than the mode of ~60 cm observed in July and subsequent months. These large fish may have been maturing AYK chum salmon, as tagging experiments indicated that they were distributed in the EBS fishery area in June (see Figures 11–13 in Myers et al. 2009, this volume).

The pollock fishery caught more female than male Chinook salmon, particularly when total lengths were greater than 55 cm (Figure 9). This pattern may have occurred because more age classes of female Chinook were vulnerable to the fishery as they tend to mature at older ages than male Chinook salmon (Healey 1991). Bycatch of Chinook salmon less than 55 cm total length tended to be males more than females, particularly during the summer and fall (B-season). Chum salmon have an opposite pattern with more males overall and with females being smaller than males (Figure 10). Over time, the trends in these observed sex ratios have remained fairly consistent (Figure 11).

Annually, the bimodality of the Chinook salmon length frequencies in the bycatch was apparent and consistent over time (Figure 12). This consistency suggests that the stock composition of Chinook salmon may not vary much in bycatch from year-to-year. For chum salmon, the inter-annual variability was greater than Chinook salmon, with higher proportions of larger chum salmon in some years than in others (e.g., 2002 and 2006 versus 2005; Figure 13). This variation suggests that different chum salmon stocks may be in the bycatch in different years.

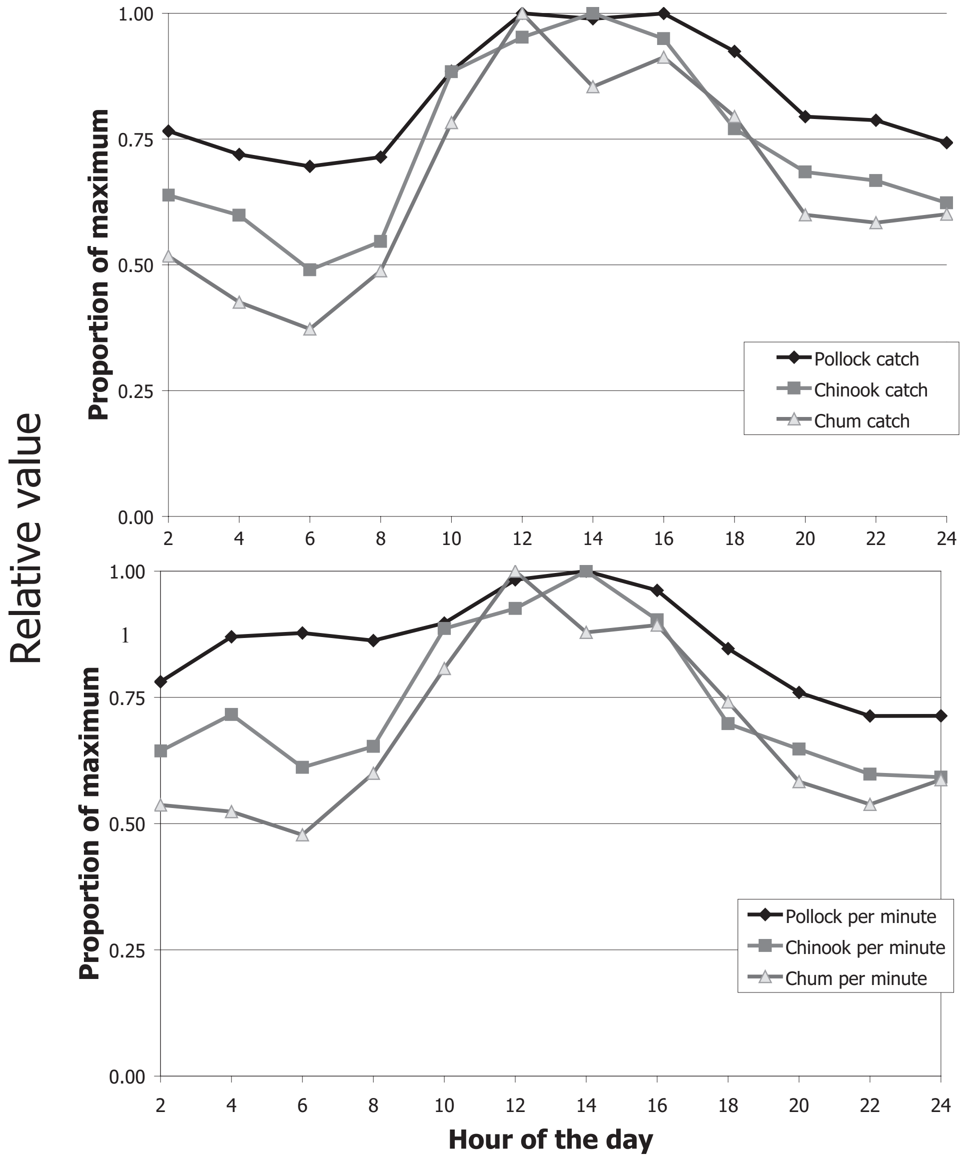


FIGURE 5. The patterns of pollock and salmon catch (top) and catch per minute (bottom) relative to their daily maxima based on NMFS observer data (1990–2006).

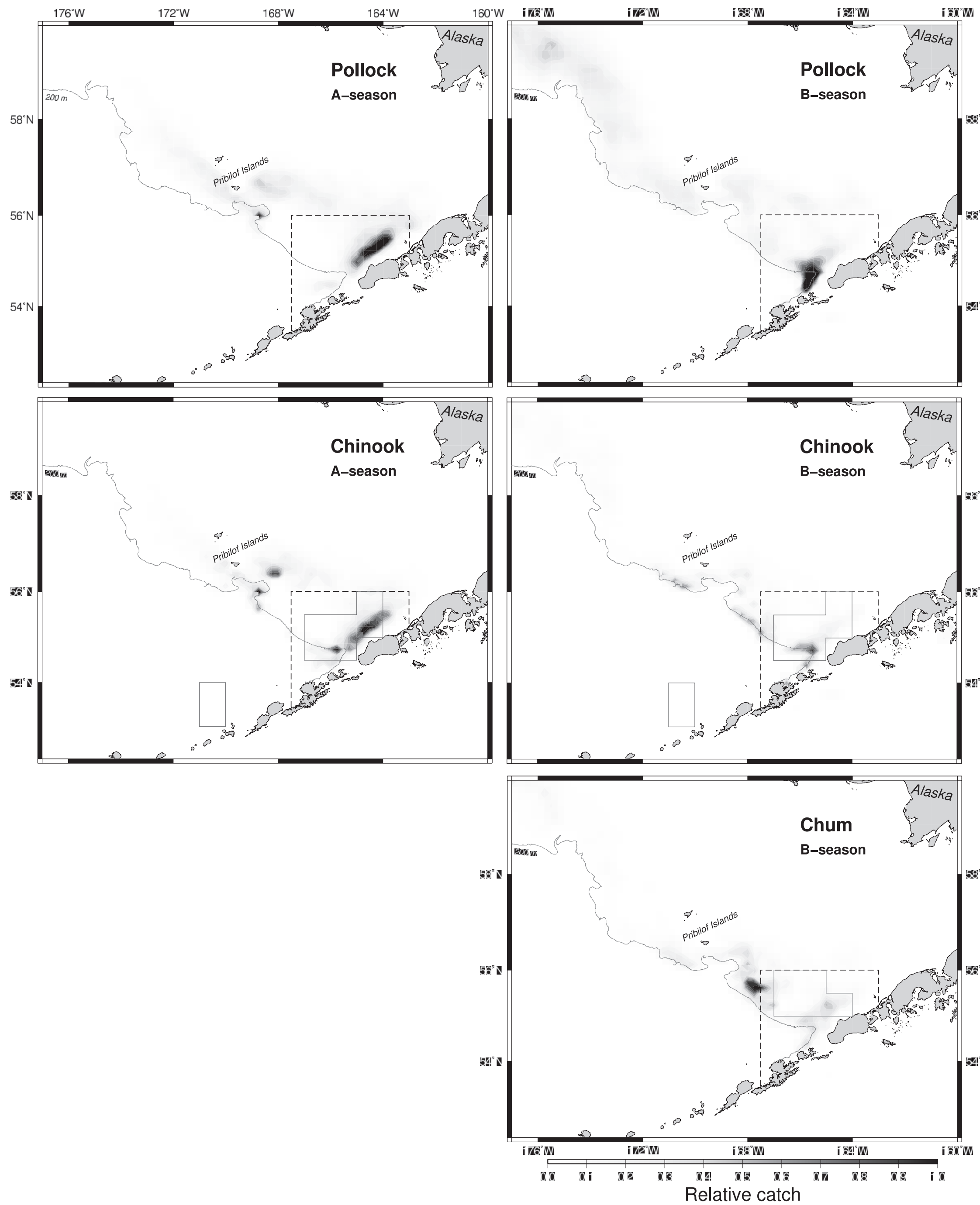


FIGURE 6. The average spatial patterns of pollock, Chinook, and chum salmon catch during the A-season (January–May; left panels), and B-season (June–December) from 2000–2006 NMFS observer data. Note that A-season chum salmon was omitted since catch levels during this period are quite low.

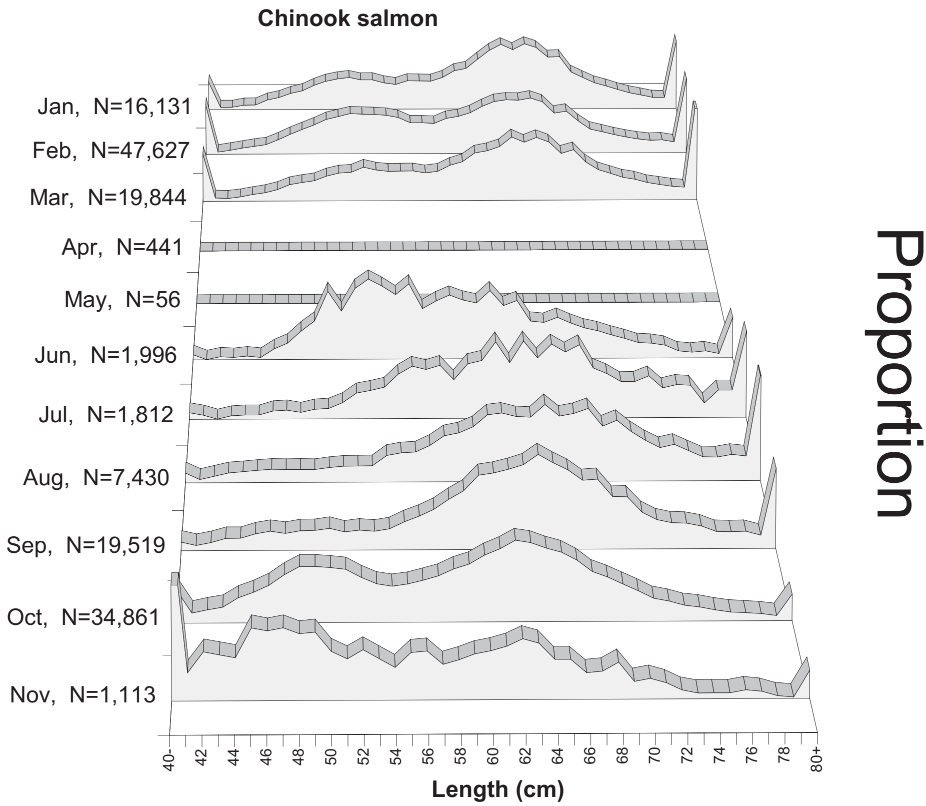


FIGURE 7. Chinook salmon proportions at length by month as taken in the pollock fishery, 1998–2006 combined. Month and sample sizes are shown in the left axis labels.

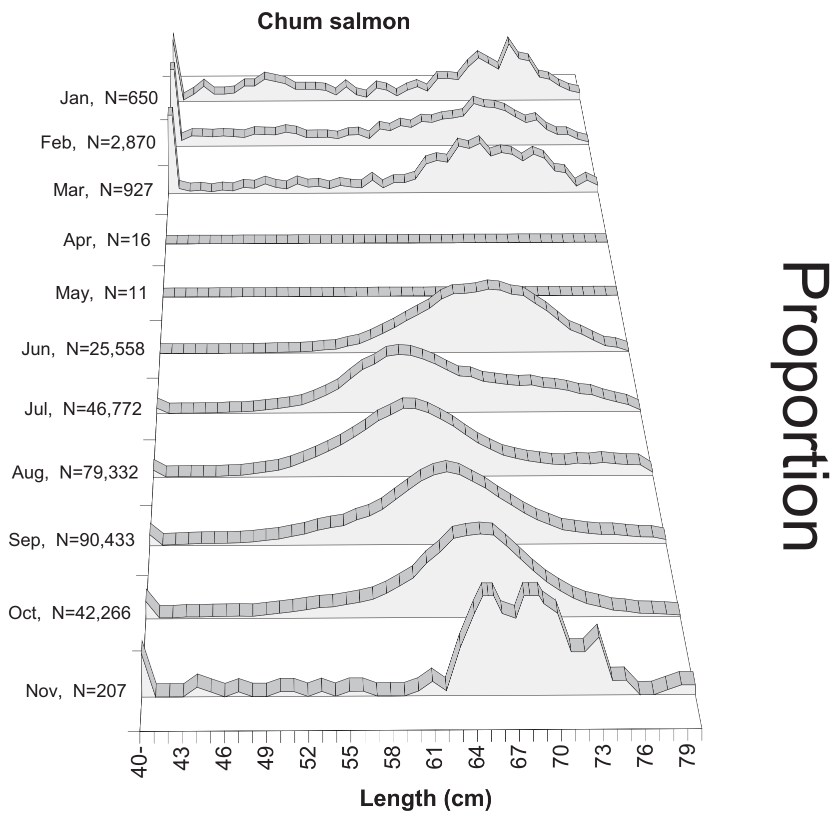


FIGURE 8. Chum salmon proportions at length by month as taken in the pollock fishery, 1998–2006 combined. Month and sample sizes are shown in the left axis labels.

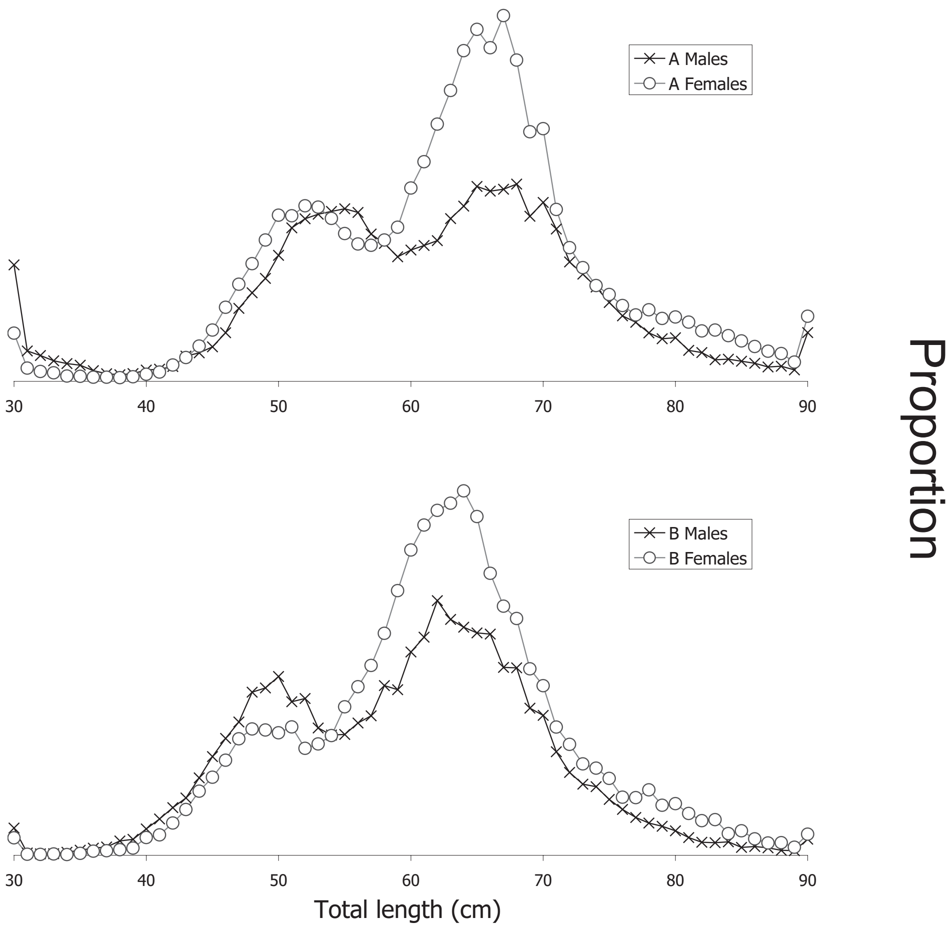


FIGURE 9. Chinook salmon proportions at length by sex for the A-season (January–May, 57% females from 84,099 samples; top panel) and B-season (June–December, 55% females from 66,361 samples; bottom panel) as taken in the pollock fishery, 1998–2006 combined.

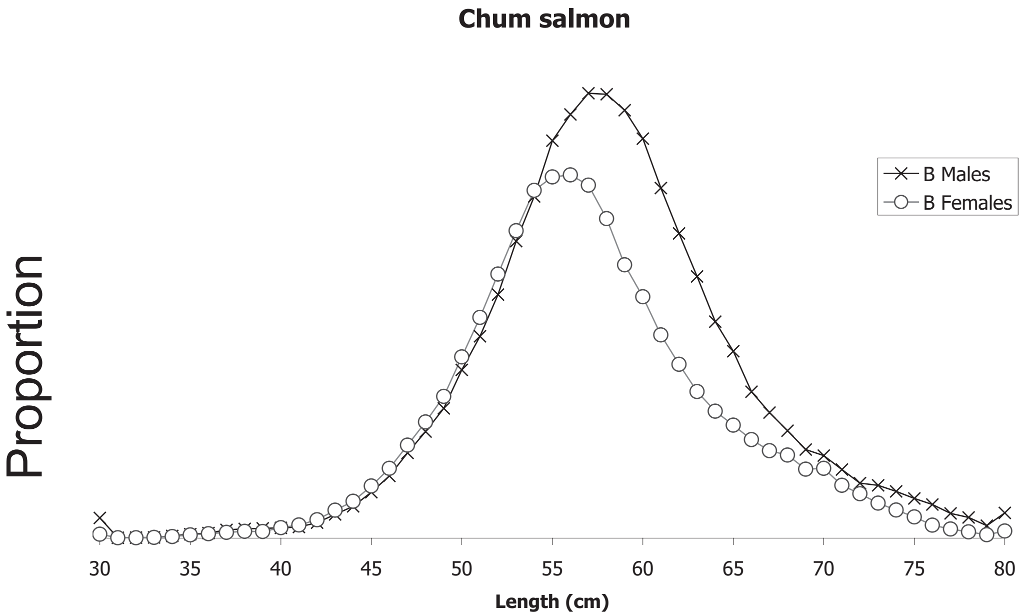


FIGURE 10. Chum salmon proportions at length by sex for the B-season (June–December, 44% females from 287,933 samples) as taken in the pollock fishery, 1998–2006 combined. Chum salmon are much less prevalent (~1% of total chum catch) in A- season hence length frequency samples from those months are omitted.

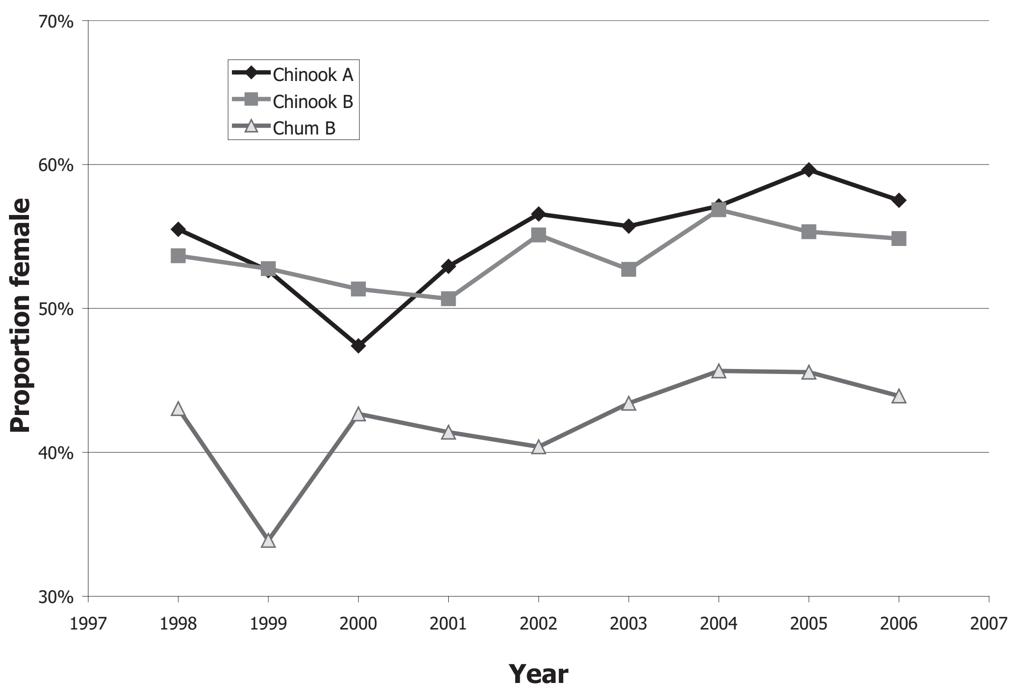


FIGURE 11. Sex ratios for Chinook and chum salmon over time. A- and B-seasons are shown for Chinook since there are significant catches in each of these seasons, chum salmon are primarily taken incidentally during the summer-fall (B) season.

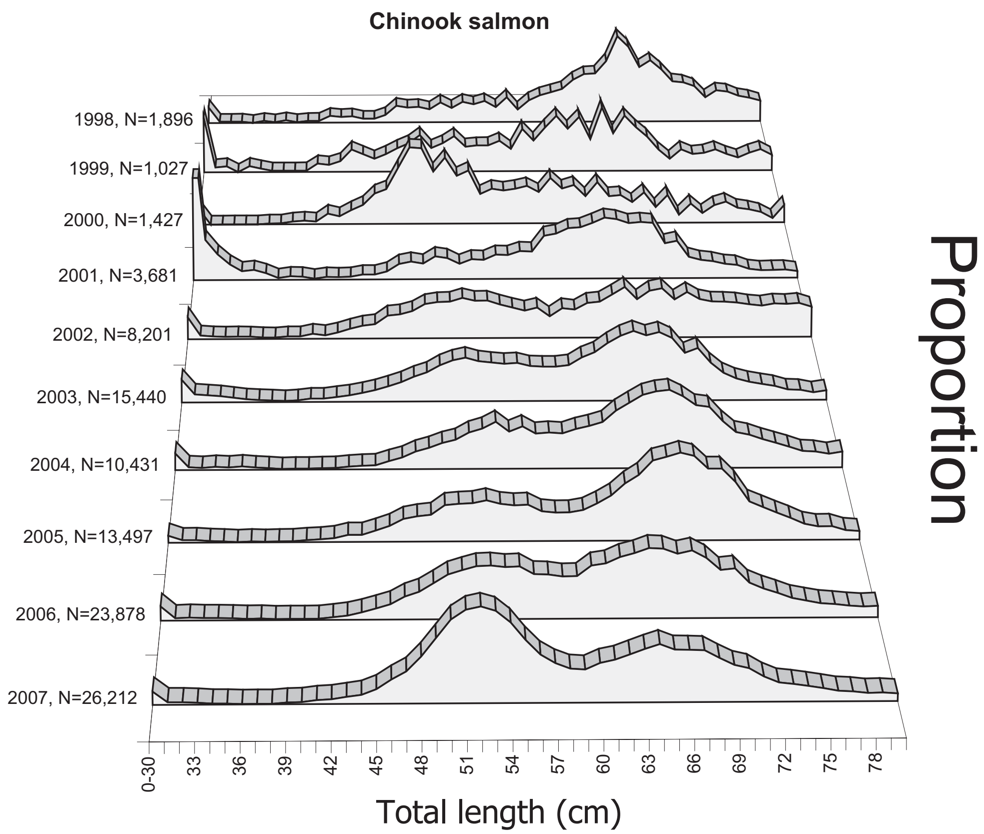


FIGURE 12. Chinook salmon proportions at length by year as taken in the pollock fishery, 1998–2006. Year and sample sizes are shown in the left axis labels.

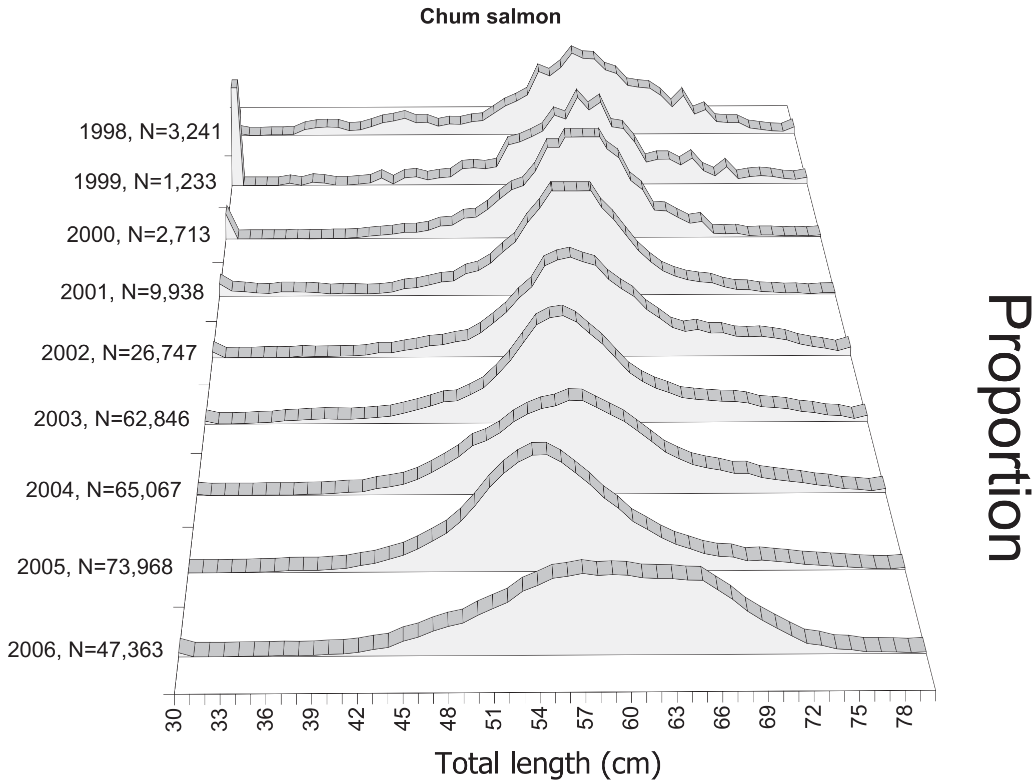


FIGURE 13. Chum salmon proportions at length by year as taken in the pollock fishery, 1998–2006.

## Discussion

The patterns of variability in Pacific salmon bycatch in the Bering Sea pollock fishery occurred at spatial and temporal scales that were incompatible with present fixed "Salmon Savings Area" regulations. Hence, in October 2005, the Council adopted an amendment which exempted vessels that participated in an incentive-based program managed by a third-party (non-regulatory) that establishes dynamic in-season area-time closures based on in-season bycatch data (Gisclair 2009, this volume). Thr results confirmed that the variability between years and areas was high and hence supported the development of alternative management measures. The effects of size and age distribution of salmon in the bycatch should be taken into account when establishing these area-time closures. Additionally, if environmental conditions such as sea surface temperatures were shown to affect the distribution of salmon relative to the pollock fishery, then measures to improve environmental monitoring would be warranted and these variables also could be used to define area closures.

Extensive salmon surveys corroborate the relative abundance patterns reported here in our study. Our results suggested that chum salmon catch per unit effort variability was higher than that for Chinook salmon (Figure 2). Observations from inter-annual surveys by the Bering-Aleutian Salmon International Survey (BASIS) program have also shown recent increases in chum salmon in their survey area and similar relative rates when compared to Chinook. Age-specific differences in the distribution between oldest and youngest groups of salmon indicated that the abundance of small immature chum salmon was high in deep-water areas while large immature and maturing chum were distributed in shallow shelf zones and shelf break areas (NPAFC 2004), consistent with our observations presented here. The overall catch in all areas of the Bering Sea and adjacent North Pacific waters in 2003 showed the highest biomass of salmon since the survey began (2001) and were dominated (75% of total catch) by chum salmon (NPAFC 2004).

Trawl bycatch of chum salmon has continued to increase over this time period (1990–2006; Table 1). While not all of the chum salmon caught were bound for western Alaska, it provides an indicator that ecological conditions favorable to chum salmon survival in the Bering Sea have improved considerably in recent years and that chum salmon productivity might have increased significantly (Bue and Lingnau 2005). Information from the 2002 summer BASIS survey indicated that immature chum salmon in the Bering Sea were of Asian origin (NPAFC 2004). Variation in the observed abundance of Asian-origin chum salmon may be related to variability of migrations of Asian hatchery salmon (Seeb et al. 2004) and related changes in oceanographic temperature patterns affecting chum salmon migration routes (Friedland et al. 2001). Recent BASIS surveys in the eastern and western Bering Sea have provided survey abundance estimates and an overview of the distribution of some size classes of Chinook salmon, and indicated that abundance of juvenile Chinook salmon in 2004 appeared much higher than in either of the previous two years (NPAFC 2004), which was consistent with our findings.

In the 1990s, some studies evaluated the stock composition of the chum salmon bycatch in EBS pollock trawl fisheries (Wilmot et al. 1998; Patton et al. 1998). Wilmot et al. (1998) evaluated bycatch samples of chum salmon from the 1994–1995 pollock trawl fishery in the eastern Bering Sea and employed genetic stock identification (GSI) methodology to evaluate the stock composition of these fish (Wilmot et al. 1998). Results from this study indicated that in 1994 between 39 and 55% of bycatch samples were of Asian origin, 20–35% were western Alaskan stocks, and 21–29% were a combination of southeastern Alaska, British Columbia, and Washington stocks. (Wilmot et al. 1998). The 1995 samples indicated a range of 13–51% Asian, 33–53% western Alaska, and 9–46% southeastern Alaska, British Columbia, or Washington stocks (Wilmot et al. 1998). Estimates of the ratio between immature and maturing fish differed regionally; however, the contribution of maturing fish originating from British Columbia was consistently high both years (Wilmot et al. 1998). Differences in relative stock composition also varied temporally throughout the B-season and by region (Wilmot et al. 1998).

Mixed stock analysis using variation at allozyme loci was used to determine the stock origin of chum salmon caught by a trawl research vessel operating in the central Bering Sea from late August to mid-September 2002 (Urawa et al. 2004). Results indicated that the estimated stock composition for maturing chum salmon was 70% Japanese, 10% Russian, and 20% North American stocks, while immature fish were estimated as 54% Japanese, 33% Russian, and 13% North American (Urawa et al. 2004). The stocks of North American fish were identified as from northwest Alaska, Yukon, Alaskan Peninsula/Kodiak, Susitna River, Prince William Sound, southeast Alaska/northern British Columbia, and southern British Columbia/Washington State. Of these the majority of mature chum salmon for North America stocks came from southern British Columbia/Washington State and Alaska Peninsula/Kodiak (Urawa et al. 2004). For immature chum salmon, the largest contribution for North American stocks came from southeast Alaska/northern British Columbia, followed by Alaska Peninsula/Kodiak and southern British Columbia/Washington State.

A study of Chinook salmon completed in 2003 estimated age and stock composition in the 1997–1999 BSAI groundfish fishery bycatch samples from the NOAA Fisheries observer program database (Myers et al. 2004). Results indicated that bycatch samples of Chinook salmon were dominated by young (age 1.2) fish in summer and older (age 1.3 and 1.4) fish in winter (Myers et al. 2004). The stock structure was dominated by western Alaskan stocks, with the estimated stock composition of 56% western Alaska, 31% central Alaska, 8% southeast Alaska–British Columbia, and 5% Russia.

As indicated in Myers et al. (2004), the origin of salmon differed by season of catch. In the winter, age 1.4 western Alaskan Chinook salmon caught were primarily from the subregions of the Yukon and Kuskokwim river drainages. In the fall, results indicated that age 1.2 western Alaskan Chinook salmon caught were from subregions of the Kuskokwim River and Bristol Bay with a large component of Cook Inlet Chinook salmon stocks as well. The proportions of western Alaskan subregional stocks (Yukon River, Kuskokwim River, and Bristol Bay) appeared to vary considerably with factors such as brood year, time, and area (Myers et al. 2004). Yukon River Chinook salmon were often the dominant stock in winter while Bristol Bay, Cook Inlet and other Gulf of Alaska stocks were often the dominant stocks in the eastern BSAI in the fall (Myers et al. 2004).

Given information indicating that the closed area system of management was ineffective (NPFMC 2005), the North Pacific Fishery Management Council (Council) exempted vessels from these closures provided they participated in a rolling hot spot (RHS) bycatch management system as an interim measure. This RHS system uses information provided from the fleet to an independent contractor to establish small scale, short-term area closures on a more real-time basis (Gisclair 2009; Haflinger and Gruver 2009, this volume). The Council, however, is continuing to consider alternative measures for managing bycatch. To understand the impact of different management measures for bycatch in the pollock fishery on salmon returns to river systems, spatial and temporal information is required on the origins of salmon taken as bycatch. Additional information on pollock fishery characteristics and patterns in relation to salmon bycatch such as presented here can be used in conjunction with stock of origin information to better inform fishery managers on potential alternative management measures. The Council is currently evaluating an analysis which estimates the relative impact of different levels of bycatch on individual streams, with a particular focus on the river systems in western Alaska. This analysis is designed to assist the Council in comparing the trade-offs of choosing different bycatch cap levels as management measures, and is included as part of an Environmental Impact Statement prepared jointly by the Council and NMFS staff (to be finalized in late 2009).

Two measures of limiting incidental catch are being evaluated in conjunction with revised closure areas. The first measure under consideration is a total limit on the number of salmon allowed in the bycatch. When that limit is exceeded, the pollock fishery would be closed. The second measure under consideration is a "trigger" limit on the number of salmon caught whereby some specified area or series of areas of known high bycatch would close when the limit was reached. These limits would ideally be linked to the abundance levels of salmon stocks so that the bycatch could be managed proportionally to salmon abundance. However, this type of information is unavailable and further complicated by variable conditions of salmon stocks within the same year. Salmon run-size forecasting continues to improve (Hilsinger et al. 2009, this volume), and this information would help understand the magnitude of variability in run size and long-term trends. On-going projects such as surveys from the BASIS program may also eventually allow for some projections to be made of future returns to Alaskan rivers. Additional research projects are combining genetic marker results with in-river abundance estimates to evaluate projected returns to rivers (J. Seeb, University of Washington, personal communication). Scientists continue to improve upon the identification of incidentally caught salmon to stock of origin using a variety of genetic markers (Utter et al. 2009, this volume). However, many current estimates of stock origin are from trawl bycatch samples from the late 1990s, and recent preliminary studies indicated that bycatch patterns and stock of origin results vary by season as well as annually (Myers et al. 2004).

Our results show that the catch rates of salmon and pollock catch varied by the time of day. On average, fewer salmon per ton of pollock were caught at night than during the day. This could be due to different patterns in nocturnal behavior of salmon, combined with the pollock fishing practices. Distinct diurnal patterns in salmon depth preferences were reported by Walker et al. (2007, 2000) and Ishida et al. (2001). For example, Ishida et al. (2001) notes that chum salmon spent 48% of the day and 85% of the night in the upper 10 m of the water column. This observation was consistent with the catch data presented here from trawls operated in waters typically from 40 to 200 m depth in the eastern Bering Sea.

Given run-size information and vulnerability to the pollock fishery, an annually varying cap could be used to more accurately reflect changes in salmon abundance. This type of management would fit well within the current multispecies groundfish management practices that restrict fisheries according to the individual species and species-groups quotas. However, specification of an annual cap would require clear specification of acceptable risks to salmon stocks and clear information on the relative abundance of different salmon stocks occurring in the bycatch (i.e., stock composition). Neither of these requirements is likely to be met in the near future.

In the absence of information on abundance levels, some form of precautionary (low-risk) cap will likely be implemented by the Council. Such a cap would be negotiated among interested parties and could be used as an interim measure which could conceivably be replaced with a biomass-based cap when sufficient information exists. Information from our study provides additional insight on patterns of bycatch by age, region, and season. These results, combined with improved information on stock of origin and predictions of salmon abundance will provide managers with improved scientific advice for developing and evaluating management measures to reduce salmon bycatch in BSAI trawl fisheries.

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## References

Alaska Department of Fish and Game (ADF&G). 1995a. Environmental Assessment/Regulatory Impact Review/Initial Regulatory Flexibility Assessment for Proposed Alternatives to Limit Chinook Salmon Bycatch in the Bering Sea Trawl Fisheries: Amendment 21b. Alaska Department of Fish and Game and the Alaska Commercial Fisheries Entry Commission, Juneau.

Alaska Department of Fish and Game (ADF&G). 1995b. Environmental Assessment/Regulatory Impact Review/Initial Regulatory Flexibility Assessment for Proposed Alternatives to Reduce Chum Salmon Bycatch in the Bering Sea Trawl Fisheries: Amendment 35. Alaska Department of Fish and Game, National Marine Fisheries Service and the North Pacific Fishery Management Council, Juneau.

Bue, F. J., and T. L. Lingnau. 2005. 2005 Yukon area subsistence, personal use, and commercial salmon fisheries outlook and management strategies. Alaska Department of Fish and Game, Fishery Management Report NO. 05–31, Anchorage.

Friedland, K. D., R. V. Walker, N. D. Davis, K. W. Myers, G. W. Boehlert, S. Urawa, and Y. Ueno. 2001. Open-ocean orientation and return migration routes of chum salmon based on temperature data from data storage tags. Marine Ecology Progress Series 216:235–252.

Gisclair, B. R. 2009. Salmon bycatch management in the Bering Sea walleye pollock fishery: threats and opportunities for western Alaska. Pages 799–816 *in* C. C. Krueger and C. E. Zimmerman, editors. Pacific salmon: ecology and management of western Alaska's populations. American Fisheries Society, Symposium 70, Bethesda, Maryland.

Haflinger, K., and J. Gruver. 2009. Rolling hot spot closure areas in the Bering Sea walleye pollock fishery: estimated reduction of salmon bycatch during the 2006 season. Pages 817–826 *in* C. C. Krueger and C. E. Zimmerman, editors. Pacific salmon: ecology and management of western Alaska's populations. American Fisheries Society, Symposium 70, Bethesda, Maryland.

Harrington, J. M., R. A. Myers, and A. A. Rosenberg. 2005. Wasted fishery resources: discarded bycatch in the USA. Fish and Fisheries 6:350–361.

Healey, M.C. 1991. Life history of Chinook salmon. Pages 313–393 *in* C. Groot, and L. Margolis, editors. Pacific salmon: life histories. University of British Columbia Press, Vancouver.

Hiatt, T. R. Felthoven, H. Geier, A. Haynie, D. Layton, D. Lew, A. Poole, R. Rowe, J. Sepez, C. Seung, E. Springer, and E. Waters. 2006. Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands area: economic status of the groundfish fisheries off Alaska, 2005. North Pacific Fishery Management Council, Anchorage.

Hilsinger, J. R., E. Volk, G. Sandone, and R. Cannon. 2009. Salmon management in the Arctic-Yukon-Kuskokwim Region of Alaska: past, present, and future. Pages 495–519 *in* C. C. Krueger and C. E. Zimmerman, editors. Pacific salmon: ecology and management of western Alaska's populations. American Fisheries Society, Symposium 70, Bethesda, Maryland.

Ianelli, J. N., S. Barbeaux, S. Kotwicki, K. Aydin, T. Honkalehto, and N. Williamson. 2006. Assessment of Alaska Pollock Stock in the Eastern Bering Sea. Pages 35–138 *in* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage.

Ishida, Y., A. Yano, M. Ban, and M. Ogura. 2001. Vertical movement of a chum salmon *Oncorhynchus keta* in the western North Pacific Ocean as determined by a depth-recording archival tag. Fisheries Science 67:1030–1035.

Myers, K. W., and D. E. Rogers. 1988. Stock Origins of Chinook Salmon in Incidental Catches by Groundfish Fisheries in the Eastern Bering Sea. North American Journal of Fisheries Management 8:162–171.

Myers, K., R. V. Walker, N. D. Davis, and J. L. Armstrong. 2004. High Seas Salmon Research Program, 2003. SAFS-UW-0402, School of Aquatic and Fishery Sciences, University of Washington, Seattle.

Myers, K. D, R. V. Walker, N. D. Davis, J. L. Armstrong, and M. Kaeriyama. 2009. High seas distribution, biology, and ecology of Arctic-Yukon-Kuskokwim salmon: direct information from high seas tagging experiments, 1954–2006. Pages 201–239 *in* C. C. Krueger and C. E. Zimmerman, editors. Pacific salmon: ecology and management of western Alaska's populations. American Fisheries Society, Symposium 70, Bethesda, Maryland.

National Marine Fisheries Service (NMFS). 1999. Environmental Assessment/Regulatory Impact Review/Initial Regulatory Flexibility Assessment for An Amendment to Further Reduce Chinook Salmon Bycatch in Groundfish Trawl Fisheries of the Bering Sea and Aleutian Islands Area. National Marine Fisheries Service, Juneau, Alaska

National Marine Fisheries Service (NMFS). 2007. 2008 Observer Sampling Manual. North Pacific Groundfish Observer Program, Alaska Fisheries Science Center, NMFS/NOAA. Available: http://www.afsc.noaa.gov/FMA/Manual_pages/MANUAL_pdfs/manual2008.pdf. (November 2007).

North Pacific Anadromous Fish Commission (NPAFC). 2004. Annual Report of the Bering-Aleutian Salmon International Survey, 2003. North Pacific Anadromous Fish Commission, Document 769, Vancouver, B.C.

North Pacific Fishery Management Council (NPFMC). 2005. Environmental Assessment/Regulatory Impact Review/Initial Regulatory Flexibility Assessment for Modifying Existing Chum and Chinook Salmon Savings Areas: Amendment 84, Secretarial Review Draft. North Pacific Fishery Management Council, Anchorage.

Patton, William S., Katherine W. Myers, and Robert V. Walker. 1998. Origins of chum salmon caught incidentally in the eastern Bering Sea walleye pollock trawl fishery as estimated from scale pattern analysis. North American Journal of Fisheries Management 18:704–712.

Seeb, L., P. Crane, C. Kondzela, R. Wilmot, S. Urawa, N. Varnavskaya, J. Seeb. 2004. Migration of Pacific Rim chum salmon on the high seas: insights from genetic data. Environmental Biology of Fishes 69:21–36.

Urawa, S., T. Azumaya, P. Crane, and L. Seeb. 2004. Origin and distribution of chum salmon in the Bering Sea during the early fall of 2002: estimates by allozyme analysis. North Pacific Anadromous Fish Commission Document 794. Toyohira-ku, Sapporo, Japan.

Utter, F. M., M. V. McPhee, and F. W. Allendorf. 2009. Population genetics and the management of Arctic-Yukon-Kuskokwim salmon populations. Pages 97–123 *in* C. C. Krueger and C. E. Zimmerman, editors. Pacific salmon: ecology and management of western Alaska's populations. American Fisheries Society, Symposium 70, Bethesda, Maryland.

Walker, R. J., V. V. Sviridov, S. Urawa, and T. Azumaya. 2007. Spatio-temporal variation in vertical distributions of Pacific salmon in the ocean. North Pacific Anadromous Fish Commission Bulletin 4:193–201.

Walker, R. V., K. W. Myers, N. D. Davis, K. Y. Aydin, K. D. Friedland, H. R. Carlson, G. W. Boehlert, S. Urawa, Y. Ueno, and G. Anma. 2000. 2000. Diurnal variation in thermal environment experienced by salmonids in the North Pacific as indicated by data storage tags. Fisheries Oceanography 9:2171–186.

Wilmot, R. L., C. Kondzela, M. Guthrie and M. M. Masuda. 1998. Genetic stock identification of chum salmon harvested incidentally in the 1994 and 1995 Bering Sea trawl fishery. North Pacific Anadromous Fish Commission Bulletin 1:285–299.

Witherell, D. W., D. Ackley, and C. Coon. 2002. An overview of salmon bycatch in Alaska groundfish fisheries. Alaska Fishery Research Bulletin 9:53–64.