Run timing of adult Chinook salmon passing Bonneville dam on the Columbia River

White Paper

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Introduction

The arrival timing of adult Chinook to the Columbia River varies by a month or more and there are currently no good methods to predict when this will occur. Relative stock timing (within-run) has been reconciled to a certain extent with radio-tag observations. Keefer et al. (2004) observed that arrival time of individual stocks is relatively constant compared to the variability in over-all run timing. Spawning success and egg to smolt survival are a function of headwater conditions under strong selective pressure so specific stocks have their own optimal time to arrive relative to the run as a whole. One interpretation is that the run as a whole is more under control of external variables than stock-specific genetic/adaptive differences that account for differences between the stocks.

Traditional enumeration methods at Bonneville divide the runs of Chinook salmon into a spring, summer and fall run based on specific calendar days. While convenient for record-keeping purposes, it ignores the ecological basis for variation in run-timing and therefore prediction of the arrival of Chinook. A late-arriving spring run is seen as smaller and/or appears to have a summer component. The arrival of the spring run is quite dramatic in some years. In recent years, daily counts of spring run arrivals increased by 2-3 orders of magnitude in less than two weeks.

Spring Chinook arrival timing at Bonneville dam could be a result of three different factors. First, their location relative to the mouth of the river at the onset of migration determines the total travel distance. Second, movements of the water in the near-shore environment can accelerate or retard their travel speed as they get close to the mouth of the river. Third, in-stream conditions that are sub-optimal (flow or temperature) are known to delay salmonids.

In this white paper, we examine the arrival timing of the spring Chinook salmon at Bonneville Dam. We determine arrival timing independently of the ACOE calendar dates and examine ocean conditions, river mechanisms and within-run variables that may be related to arrival timing. The passage at Bonneville is described with a closed-form mathematical function which in turn quantifies specific between-year timing signals. These signals are related univariately to environmental measures that identify specific mechanisms related to timing.

Background and Data

Fish timing data. Distinguishing the timing of Chinook populations has to be based on one of three available data sets: PIT-tag passage records, Radio-tag studies, and/or visual counts. PIT-tag passage records are available since 2000. Radio-tag studies extend back to 1996 and daily visual counts have been made at Bonneville Dam since 1938 (CBR 2007).

Radio-tagged fish studies have been useful for confirming that within-year differences in timing of individual stock groups are small. Genetic influences on timing results in sequencing of the stocks (Keefer et al. 2004). PIT-tagged fish offer a slightly different view of arrival timing because the data spans different years (2000-2006), and their origin is known once they have been identified, regardless of their success in migrating. This data is available on-line (CBR 2007). Records of PIT-tagged fish returning to Bonneville Dam are compared across and within years by compiling metrics on the stocks such as median passage and other quantiles for each year.

Daily visual counts of adult Chinook passing Bonneville offer the most extensive time series of return timing data. There are also separate counts of jack Chinook (precocious males that return after a single year at sea). The distinction between jack Chinook and other adult Chinook began in 1977.

Environmental Data. Several environmental indices are potentially pertinent due to their established climatic impacts. Pacific Decadal Oscillation (PDO, Mantua et al. 1997) is an index of sea surface temperatures that is correlated with many ecological variables: winter land-surface temperatures, precipitation, stream flow, and salmon landings (NOAA 2007a). During the cool phase of the PDO (based on an average of the monthly values from May-September), adult returns to Bonneville Dam are generally above average, and warm-phase periods result in below average returns. There is an apparent lag of two years between the apparent phase change and adult returns. Since this particular index is taken between May and September, these conditions can not affect the within-year returns. Thus, at best, this index is correlated with the overall survival for the fish returning in subsequent years and a two year lag suggests a cumulative process that spans winter periods and two growth cycles.

Monthly values of PDO are available from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) at the University of Washington (JISAO 2007) and can be used to create indices for other time spans which for this study are conditions in the year prior to arrival. A related climatic predictor is tracked by the Multivariate El Niño Southern Oscillation which varies on an inter-annual scale (NOAA 2007c). It is treated as for the PDO.

One of the important mechanisms that creates the sea-surface temperatures indexed by PDO is the direction of the prevailing wind. Southwest winds result in warmer waters and more northerly winds result in cooler waters. Two indices related to these conditions, upwelling and along-shore transport, are monitored by the Pacific Fisheries Environmental Laboratory (NOAA 2007b):

> "Coastal upwelling indices are calculated based upon Ekman's theory of mass transport due to wind stress. Assuming homogeneity, uniform wind and steady

state conditions, the mass transport of the surface water due to wind stress is 90° to the right of the wind direction in the Northern Hemisphere. Ekman mass transport is defined as the wind stress divided by the Coriolis parameter (a function of the earth's rotation and latitude). The depth to which an appreciable amount of this offshore transport occurs is termed the surface Ekman layer, and is generally 50 to 100 meters deep. Ekman transports are resolved into components parallel and normal to the local coastline orientation. The magnitude of the offshore component is considered to be an index of the amount of water upwelled from the base of the Ekman layer. Positive values are, in general, the result of equatorward wind stress. Negative values imply downwelling, the onshore advection of surface waters accompanied by a downward displacement of water."

Upwelling and Along-shore transport data are available from PFEL (NOAA 2007b) for 15 oceanic bouys (see Figure 1) that provide wind shear data from which the upwelling and alongshore transport indices are computed. A derivative of these indices is termed the "spring transition" (Logerwell et al. 2003) when the along-shore transport changes from a predominantly northerly flow to a southerly one.

In-river conditions could affect movements prior to passage of the first dam on the Columbia River. Flow and Temperature data from Bonneville Dam (CBR 2007, Streamnet 2007) extend back to 1940. Following the method of Petersen and Kitchell (2001) the historic scroll case water temperatures (Streamnet 2007) were modified by the monthly average difference between the scroll case measurements and the downstream USGS Water Quality Monitoring station measurements at Warrendale, OR (CBR 2007) for overlapping months (not shown). This removed a bias in the scroll case temperatures.

Fish Location. The Pacific Fishery Management Council analyzes coded wire tag data along with catch records to predict the abundance of salmon stocks on the West Coast of the US in each year. The locations of these fish in relation to management plans for harvest and escapement are pertinent. Ocean- and stream-type chinook salmon are recovered differentially in coastal and mid-ocean fisheries, indicating divergent migratory routes (Healey 1983, 1991). Ocean-type chinook salmon tend to migrate along the coast, while stream-type chinook salmon are found farther from the coast in the central North Pacific (Healey 1983, 1991; Myers et al. 1984)."

The PFMC (2007) concludes that:

> "The majority of ocean Chinook harvest north of Cape Falcon is provided by Columbia River salmon stocks," and in turn most of these range as far north as Southeast Alaska. The only Columbia River stock that is acknowledged to migrate farther south is the Snake River fall Chinook that range south to Pigeon Point, CA (south of San Francisco Bay).

Myers et al. (1998) report that:

> "Chinook salmon whose natal stream lies south of Cape Blanco tend to migrate to the south, while those to the north of Cape Blanco tend to migrate in a northerly direction. Transplants of south migrating stocks to release sites north of Cape Blanco do not alter the basic southerly direction of ocean migration (Nicholas and Hankin 1988). Recoveries of CWT-marked fish from ocean fisheries indicate that fish stocks follow predicable ocean migration patterns, and that these are based on "ancestral" feeding routes (Brannon and Setter 1987).

In addition, since oceanic environmental/climatic processes have measurable effects on salmonid survival and marine ecosystems (Logerwell et al. 2003, Barth et al. 2007) any optimization on the part of the fish to enhance their survival by moving to different regions in the North Pacific in response to differing ocean conditions will have consequences for total travel distance which is what makes movement of the fish an important aspect of their timing.

Movement. Timing issues may be related to oceanic environmental conditions that would either retard or accelerate arrivals. Bourque et al. (1999) concluded that tidal currents have a significant effect on return timing of sockeye salmon off the northern coast of British Columbia where tidal current rates are on the order of 0.5 m s^{-1}. Although this oscillates daily, other water movements are not so easily turned around. Prevailing winds along the coast influence the movement of waters along the coast due to Eckman transport processes (PFEL 2007b) and results in the upwelling and along-shore transport mentioned above. The coastal waters of the California current are dominantly either south moving or north moving depending on the season, and as a result can create along-shore movements of coastal waters that are “typically 20-30 km per day” (NOAA 2007). For an adult chinook salmon swimming ~1 $m{\cdot}s^{-1}$ around-the-clock in order to travel ~86 $km{\cdot}d^{-1}$ this represents ± 25% to 30% per day. The distance from the Queen Charlotte Islands, British Columbia, Canada, to the mouth of the Columbia River is over 800 km. A favorable “current” might make the journey take ~ 7-8 days. An unfavorable one might mean twice as long.

Ocean Currents. The switch from a dominantly northward movement of water in the winter to the dominantly southward movement in the spring and summer is called the “Spring Transition” (Logerwell et al. 2003). The long term average day that this occurs is day 96 (April 6) but in the last 40 years has varied by over 100 days. Along-shore movement toward the south is associated with offshore movements of water and upwelling which brings nutrient rich waters to the near-shore surface waters. This in turn provides nutrients for a complex food web and results in high plankton productivity and good survival of chinook salmon (Scheuerell & Williams 2005). On the other hand, strong downwelling, associated with northward movement of water could aid productivity in different ways, by advecting plankton from the California Current (Scheuerell & Williams 2005).

Instream Conditions. Returning salmon are sensitive to flow and temperature when they arrive in freshwater and it is known to affect their travel time under certain conditions (Keefer et al. 2004, Salinger and Anderson 2006). These conditions will be detected by the fish after they arrive at the mouth of the river and could further delay them before they travel the 200+ km to Bonneville Dam where they are observed. Extreme high flows and sub-optimal temperatures can be a significant hindrance to Chinook movements for bioenergetic reasons (Salinger and Anderson 2006) but these are unlikely to influence timing until after the fish have returned to the estuary and temperatures at this time of year are not close to critical.

Within-stock effects. There may be density-dependent effects due to very high or low numbers of migrants, their distribution in time, and run composition because there will be mixtures of stocks of different ages with varying ocean experience. Although there is no way to determine the mixture of Chinook that return, Jacks are separately enumerated and represent a more distinct group, having been in the ocean for a single year.

Methods

Fish timing measures

The PIT-tag records are aggregated by release site, HUC and 6-digit HUC. Histograms of arrival counts help distinguish bi-modal returns and these are omitted so that a fall run and spring run can be distinguished. Arrival timing measures (first, last, mean, median, and quantiles for 10%, 25%, 75%, and 90%) are computed for each group within these aggregations.

If we assume that arrival distributions are specific to any particular stock then we would also expect unimodal arrival distributions and the possibility of simple closed forms to describe these distributions. Keefer et. al (2004) describe the arrivals of fish at Bonneville dam in terms of closed forms such as the mean, median, variance, skew and kurtosis which have specific interpretations pertaining to their distribution in time.

The visual counts are fitted with a non-linear routine as the sum of three normal distributions each with three parameters for the mean passage day, the variance of passage day and the number of fish passed. The three normal distributions correspond to the spring, summer and fall runs, independent of the ACOE's counting seasons that are calendar based. Given the apparent tri-modal arrival pattern of visual counts at Bonneville dam in recent years, we fit the sum of three normal distributions to the visual count data back to 1940. The total count passing on any day is given by:

$$N_i = n_{spr} \bullet N(i, m_{spr}, sd_{spr}) + n_{summer} \bullet N(i, m_{sum}, sd_{sum}) + n_{fall} \bullet N(i, m_{fall}, sd_{fall})$$

Thus, there are nine parameters to estimate in each year. A non-linear least-squares method is used to fit the model. "Seed" values of n_x for the non-linear fitting routine are from the conventional seasonal count of spring and summer and fall fish. E.g. $\hat{n}_{summer}$ = Cumulative passage between June 1 and July 31. Additional quantiles based on the assumed normal distribution are made after the year's arrivals have been parameterized (see Table 3).

Three, summed logistic curves are fitted as well. There is more flexibility in the shape of these distributions, although the parameters are less intuitive.

$$N_i = n_{spr} \bullet L(i, m_{spr}, sd_{spr}) + n_{summer} \bullet L(i, m_{sum}, sd_{sum}) + n_{fall} \bullet L(i, m_{fall}, sd_{fall})$$

Although parameters are estimated for the three runs, only the spring run is considered in this analysis. The 25% quantile date for the spring run is used as the timing signal for cross-year comparisons and correlation with environmental correlates.

The identical procedure is performed with the jack Chinook arrivals. The adult count data includes the jacks prior to 1977. Jack and adult Chinook are separately enumerated from 1977-2006.

Environmental Condition Indices

For univariate regressions of arrival timing on environmental conditions, a predictor variable is required for each year. Either a single annual variable, a specific-month average of a continuously changing variable, or an alternative time-span average of a continuously changing variable are used as indices.

- Corrected in-stream Bonneville Dam water temperature (Streamnet 2007, CBR 2007) averages across a time-frame were used as an index. For example, the average water temperature from March 10-20 was an index.
- In-stream Bonneville Dam water flow (CBR 2007) averages across a time-frame were used as an index. For example, the average flow during 1st two weeks of April was an index.
- The spring transition is a single day in each year. That value (day-of-year) was used as an index.
- PDO and ENSO monthly values were used in two ways. First, a single month average was used as a single index. For example, January PDO in each year was used as an index.
- Second, PDO and ENSO multi-month averages were used to test for more persistent signals. For example, average PDO from November through March was used to create an index.
- Upwelling and Along-shore transport are near-continuous measures from 15 different locations. A single month average of daily values was used as an index at each site, and the indices at each site were compared. However, based on the understood distribution of chinook salmon in the Pacific ocean, conditions at a site proximal to the Columbia River are given more consideration.
- Upwelling and Along-shore transport averages across various time spans were used as indices. For example, average upwelling from November through March at site "p05" was used as an index.

Linear Regressions

Single-variable linear regressions of arrival timing on predictor variables (along-shore transport, upwelling, PDO and instream flow and temperature and within-stock metrics) are used to screen parameters.

Results

Pit Tag Returns

The PIT Tag return information from 2000-2006 allows identification of individual stocks timing. These results are very consistent with the results of Keefer et al. (2004) in that certain stocks arrive close in time to other stocks (Figure 2). There are some notable inconsistencies. The ENTH returns in 2003 (and prior, not shown) were very late compared to 2004 (and subsequent years). It is clear that the fish at ENTH (Entiat Hatchery) changed dramatically between these years and had switched from a summer run to a spring run. Sequencing appears to be the case as Keefer et al. (2004) reported.

Summary of Visual Counts

The visual counts of adult Chinook and jack Chinook were fit with the triple normal and the triple logistic models. The parameters for the adult fits are shown in Table 3 and Table 4 in the Appendix. In Figure 3, for years 2006 and 2005, the fit of three independent normal distributions to the passage observations at Bonneville is shown along with the daily observations as an illustration.

Comparable fits are made for all years. One measure of the success of this method is the error between the fitted numbers and the observed total count. For the triple normal, since 2000, it was at a low of ~ -1% in 2002 and a high of ~ -6% in 2005. Over all years, the average for the triple normal is

-1.04% and for the triple logistic is 0.50%. For a complete list of the parameters see Appendix 1 Fits to visual counts in all years. For a complete list of errors between the fit and the model, see Appendix 2 Comparison of "Triple Normal" Total Run Size fits to Observations.

The spring run median passage day (50% passage) has a mean of 117 and ranges from 105 to 140. The first quartile passage day (25% passage) has a mean of 108 and ranges from 96 to 132. (see Table 1and Figure 4). Summaries of the normal and logistic model fits are in Table 1. The results are very similar, just as they are for the individual years. As a result, the "normal" parameters are used in subsequent analysis.

Table 1 Summaries of fitted counts from the "triple normal" and "triple logistic" model fits to arrival timing data. The most significant numbers in the table (bold) are the means of the 25% and 50% passage days. They are the best indicators of average arrival. Day 106 (115) is April 16 (April 25)

Metrics for Spring Chinook	Normal	Logistic
Years	1940 - 2006	1940 - 2006
Missing years	1965, 1966	1965, 1966
Minimum/Median/Maximum Total Count error (%)	-2.33 / 0.50 / 2.46	-5.10 / -1.15 / 0.82
Median / mean of Mean passage Day	115 / 117	116 / 117
Earliest of Mean passage Day	105	105
Latest of Mean passage Day	140	140
Median/mean of first quartile (25%) passage day	**106** / 108	107 / 108
Earliest first quartile (25%) passage day	96	96
Latest first quartile (25%) passage day	133	132
Median/mean of median (50%) passage day	**115** / 117	116 / 117
Earliest median (50%) passage day	105	106
Latest median (50%) passage day	140	141
Least / Mean / Greatest Standard Deviation (days)	9 / 13 / 19	6 / 8 / 12

Within-stock conditions

Jack arrival at both the 25% and 50% quantiles are comparably delayed by an average of 15 days and are both correlated with the comparable measure for the arrival of the adults. The arrival of the adults in one year is not a predictor of arrival timing in the next year ($p > 0.9$). However, timing of the jacks is a predictor for the adult run in the following year for both the 25% quartile ($p=0.02$ $R^2=0.19$) and even more significantly the median ($p=0.0005$, $R^2=0.38$). This is the best univariate predictor found in this analysis. See Figure 5.

Total run size, the spread of the arrival distribution (standard deviation) and Jack Chinook arrival in the previous year are also correlated with arrival timing. The total run size is marginally significant ($p=0.06$) and the standard deviation of the arrival distribution ($p=0.0015$) are both negatively correlated with arrival timing (Figure 6). These are not useful as predictors however because they are not known in advance.

In-River Conditions

Average temperatures and average flows were computed across time-windows beginning as early as day-of-year 63 and ending on a day between 63 and 120 for each year. These were then correlated with the 25% arrival day and this results in a surface of correlations across various time-span windows (Figure 7).

For temperature, there is a consistent pattern of negative correlation starting on various days and ending on day 83 with a low point corresponding to starting the window on day 70 (Figure 7a). So, the average temperature from day 70 to day 83 (two weeks in mid-March) is best correlated with arrival timing. Arrivals have begun well before day 100 but the earliest 25% quartile occurs on day 96. Regression of the 25% Arrival Day to mid-March temperature is significant ($p=0.0005$, $R^2=0.17$, Figure 8).

For flow, arrival correlations with flow averages continue to improve with later and later windows of time, exceeding 0.5 when day 120 is included (Figure 7b) and exceeding 0.6 near day 150 (not shown), but this is not useful for understanding the mechanisms that lead to arrival timing since the fish are already moving at this point in the year. Correlations of arrivals to conditions after they have begun to migrate do not have mechanisms to control the linkage and are not useful as predictors. Regression of the 25% Arrival Day to early-April flow is significant ($p=0.0009$, $R^2=0.18$, Figure 8).

Another perspective on this is to examine the flow and temperature during the 2 weeks just prior to the 25% arrival day across the years which would correspond to the time when fish are moving and are just beginning to arrive at Bonneville dam. If particular flow and temperature conditions are preferred by the Chinook then these should not have significant correlations, however, the temperatures prior to arrival are positively correlated with arrival date (Figure 8). Some of this temperature increase with time is due to seasonal warming which averages 0.10ºC/day during April at Bonneville. Over the three week window when most arrival has begun, this accounts for ~2ºC of warming over the three weeks. None of the encountered temperatures would be considered detrimental to salmon passage (Salinger and Anderson 2006). Similarly, flow is increasing at this time of year. The average daily increment is 1.76 KCFS/day. Only in a few years (~20% of historic record) has average change in daily flow decreased during the month of April (1960, 1966-1969, 1972, 1975, 1977, 1982, 1983, 1986). Within years, temperature always increases during April and in most years flow does as well.

Over the historical record, there is also a trend across years for temperature just prior to arrival (Figure 9a) It has been increasing for nearly 30 years since the mid-1970's, although the variability in temperature on the day of 25% arrival has increased greatly in the last 5 years from a low of 7.4ºC in 2003 to a high of 11.9 ºC in 2002. See Figure 10 for time series of temperature and flow indices and conditions just prior to arrival.

Oceanic Conditions

The Pacific Decadal Oscillation (PDO) and the El-Niño Southern Oscillation (ENSO) indices are both (separately) poorly correlated with arrival timing. Individual month averages as well as multi-month averages from October through March prior to arrival were significant but weak predictors of arrival timing. The best PDO indicator was the average from November through March ($R^2=0.15$, $p=0.0015$). The ENSO index over the same time period had $R^2=0.1$ ($p=0.008$). See Figure 11.

The spring transition is positively correlated with arrival timing (0.36, $R^2=0.13$ Figure 12) but makes a poor predictor because it varies over 100 days and is often well after the fish begin passing Bonneville. It is probably more useful as in indicator of oceanic conditions in general.

Correlations of the Upwelling and Alongshore indices at 15 sites in the Eastern Pacific Ocean are expected to be positive based on the theory: high equator-ward movements correspond with high offshore movments. This is, however, highly variable along the coast (Figure 13). A screening of monthly upwelling and along-shore indices indicates that arrival timing is correlated with Along-shore transport at “p08” for many months of the year (Figure 14a) but is better correlated with upwelling in January (Figure 14b) at various sites. The strength of the positive correlation with upwelling is fairly consistent from site “p05” south to site “p12”.

To examine in more detail how cumulative along-shore and upwelling conditions are correlated with arrival timing, variable time windows are used within a site. At site “p05” using cumulative conditions that begin as early as October 1 in the previous year and run until as late as April in the year of arrival, the average conditions are correlated with the 25% arrival time of Chinook. The surfaces of correlation (Figure 15) show that upwelling conditions that begin in January are a consistent indicator of arrival timing. Data resulting in the January-only correlation (point “X” in Figure 14 and Figure 15) are shown as a linear regression in Figure 16. The correlation is 0.47 (R^2=0.22).

For jacks, upwelling in February at “p05” is better correlated (0.43) than January to their own arrival time. This was not pursued further in this study.

Summary and Discussion

Numerous correlations are made between various variables and Chinook arrival timing. Oceanic conditions and the distribution of the run have an impact on the timing of arrival at the mouth of the river because more distant fish have to travel a greater distance and because movement of water either accelerates or retards the speed toward the mouth of the Columbia. The correlations of the predictors used in this analysis are summarized in Table 2, but not all of them represent a useful predictor for estimating arrival timing.

Table 2 Summary of significant predictors for spring Chinook arrival timing at Bonneville Dam. Correlation is shown because it includes the trend (+ or -). Some R^2 values are shown for comparison with captions on figures when regressions were completed.

Env. predictor	Qualifier	Correlation (R^2)	Comments
Upwelling (p05)	January	0.47	Best environmental predictor
Upwelling (p06)	January	0.41	
Alongshore Transport (p05)	January	-0.14	
Alongshore Transport (p06)	January	0.36	
Spring Transition		0.36	Poor predictor since spring transition ranges over months and the arrival times are in a window of a few weeks.
Bonneville Dam water temperature average	2 weeks mid-March	-0.41 (R^2 = 0.17)	Temp and flow immediately at beginning of the run are not stable, so these are poor cues.
Bonneville Dam flow average	First 2 weeks April	0.42 (R^2 = 0.18)	
PDO average	Nov-March	- 0.38	
ENSO average	Nov- March	- 0.33	
Total run size		0.25	
Adult arrival time in previous year	25% or 50%	~ 0	
Jack arrival time in previous year	25% quartiles	0.43 (R^2 = 0.19)	
Jack arrival time in previous year	50% (median)	0.62 (R^2 = 0.38)	Best univariate predictor, and earliest available predictor.

Flow and temperature in the Columbia River are related partially to the management of the hydro-system as well as large-scale climate and weather patterns. Rain and snow precipitation in the vast watershed of the Columbia River creates the link between the oceanic/atmospheric conditions and the terrestrial/in-river conditions. The correlations we observe in arrival timing to in-river conditions may in fact be no more than that. Two studies that related arrival timing to in-river conditions focused on correlations rather than possible cues. Hodgson et al (2006) found that Sockeye passage timing in the Columbia River was negatively correlated with average June temperature and positively correlated with average June flow, although Sockeye rarely begin passing before June 1 and are well finished by the end of July. Over the last 10 years, the run has been 80% finished by June 30. Similarly, Keefer et al. (2004) found that radio-tagged Chinook timing was positively correlated with flow but their flow index included values from April through July, which is the entire migrational season for both the spring and summer runs. Most telling is that Hodgson et al. (2006) noted that temperature and flow were poor predictors for the majority of the stocks they studied, and even within the Columbia River run, it had varying success as a predictor for different sub-populations (Keefer et al. 2004).

Even though temperatures at a fixed point in time prior to migration are a significant predictor for arrival timing, there is a lack of stability in conditions at the beginning of migration which means that these are not likely to be cues for movement. For flow or temperature to be a cue for migration, we might expect a threshold but flow or temperature conditions are changing linearly with time and later-arriving fish generally experience increased flows and temperatures.

In the ocean, upwelling generally brings nutrient rich waters to the surface and results in high plankton productivity, however, upwelling in winter may be less useful at high latitudes because day lengths are quite short. Conceivably, strong northward currents that result in downwelling and advect southern species into north Pacific waters could provide alternative foods for salmonids. The least productive conditions for Chinook would then be times with neither strong upwelling nor strong downwelling. The January upwelling index was the best predictor for arrival timing at multiple sites (Figure 14). Also, the upwelling conditions at a point just north of the Columbia River ("p05") from January through the beginning of migration (April) were consistently, positively correlated with the arrival timing (Figure 15). Figure 16 shows a regression for arrival timing on the January upwelling index at "p05" corresponding to the value at "X" in Figure 15. The values during January are almost all negative, implying strong downwelling. The interpretation can be inverted such that "strong downwelling leads to earlier arrival".

Unfortunately, we still do not have a complete understanding of how ocean conditions could lead to arrival timing patterns. The observed variability may be just noise around a general timing signal cued by day-length at latitude. If arrivals began much earlier and were more spread at the beginning of the season, this would be plausible, however, a striking quality of the return timing is the rate at which the fish counts increase once they get started. In a year with a big run, the daily counts can quickly increase by 3+ orders-of-magnitude in less than two weeks. It suggests a certain amount of contagion in the movements of the fish such that the shear numbers contribute to the initiation of the run. This is somewhat reinforced by the fact that both arrival distribution spread and total run size are also related to the arrival timing. Furthermore, although skew and other distribution shapes were not studied here, Keefer et al (2004) noted that arrival patterns of individual stocks are mostly positively skewed (to the right) so that fish continue to arrive for an extended period after the peak has passed. This may be additional evidence that the onset of migration has one or more cues, whereas there is no cue to end the run.

The most interesting and hopeful predictor for the run timing comes from the jack Chinook returns. Jacks represent a special snapshot of the run. They are precocious males that return in small percentages one or two years earlier than their out-migrating cohort. They are already used as an indicator of run size in the following year (R^2 =0.78, for 1983-2006 data, Beer et al. 2007) and probably for similar reasons, they are also predictors of the next year's run timing. One speculative interpretation of this may be that Chinook are relatively stable in their ocean positions once established, and that the jacks are returning from a position in the ocean from which the subsequent year's adults will also return. The jacks and adults may actually be responding to identical cues and their consistent late arrival is due to their slower size-limited swimming speed and/or due to their final feeding prior to migration. This autocorrelation is perhaps a key not only to the location of the fish in the ocean but also to their behavior in the months prior to migration.

Future work on arrival timing could include:

- detailed analysis of the age structure of the PIT-tag groups especially as more and more data become available and rigorous testing of the arrival timing for sufficiently large groups that might help discern whether within-stock arrivals are more or less consistent than the timing of the run overall.
- further develop theory on the mechanisms and physical processes that lead to arrival timing in order to improve prediction potential
- examine auto-correlation of the daily arrivals for evidence of density-dependence in upstream movements because day-to-day difference in counts at Bonneville can vary by a factor of 2
- examine the link between jack returns and oceanic conditions since the optimal month for ocean conditions to correlate with jack 25% arrival is February not January as it is for the adults.
- examine autocorrelation or other syntheses of oceanic conditions since upwelling conditions over many years is associated with survival of Chinook (Scheuerell and Williams 2004).
- obtain daily return patterns of spring-run Chinook from other rivers and examine similarities/differences in timing. Analogous Sockeye salmon predictors varied widely (Hodgson et al. 2006).

Most importantly for our immediate needs, the arrival timing of Jacks has significant advantages over all of the other predictors: it is available an entire year in advance of the run and has the best correlation of all the variables studied here.

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Figures

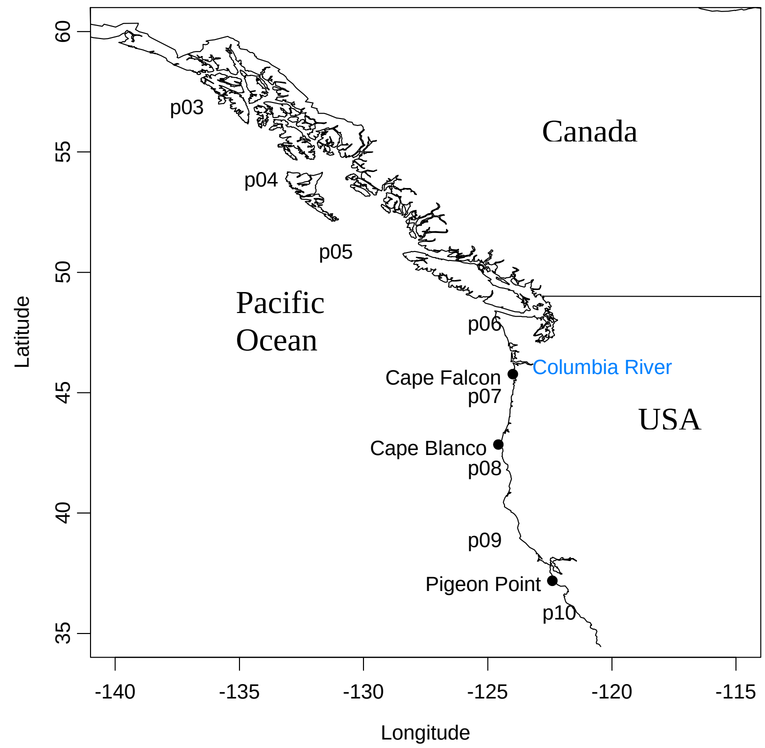


Figure 1 Map of Study Area. "pXX" (where XX is a two digit number) marks show positions of PFEL Upwelling and Transport data collection sites.

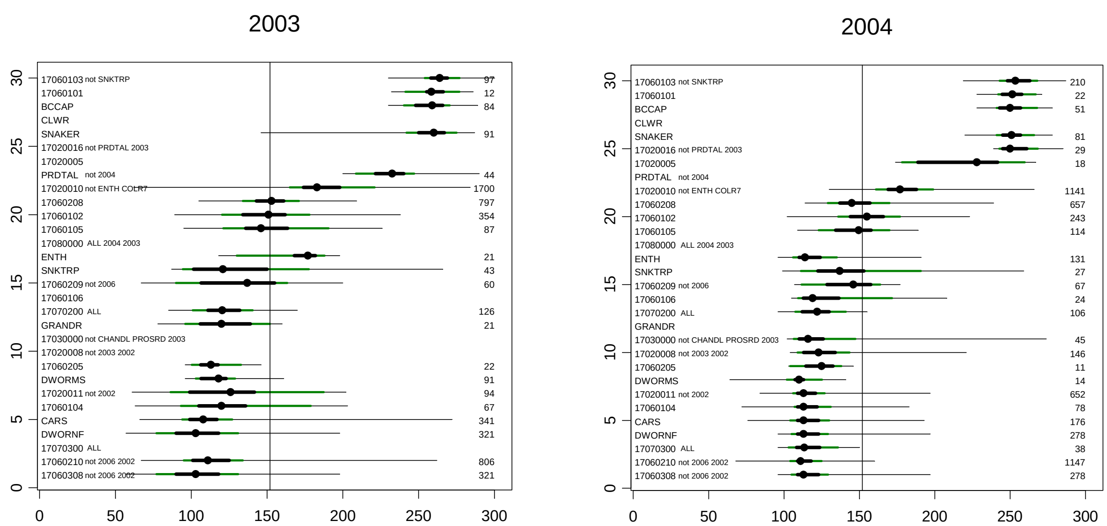


Figure 2 Timing of PIT-tagged fish arrivals in 2003 and 2004. The sites are ordered from bottom to top by the average arrival date over all years (2000-2006). The point is the median, the wide bar depicts the middle 50%, the thinner bar depicts the middle 80% and the whiskers show the range of arrival times. There are 30 groups listed on the left side of the image. The HUC or tagging site is first followed by qualifiers. If fish from multiple sub-watersheds are included then the word "All" follows the HUC number. If there are no records of returns within a particular year then the word "not" is followed by the missing years. In the right-hand column, is the number of

tags from that group. The vertical line depicts the May 31, end of the ACOE spring Chinook counting season.

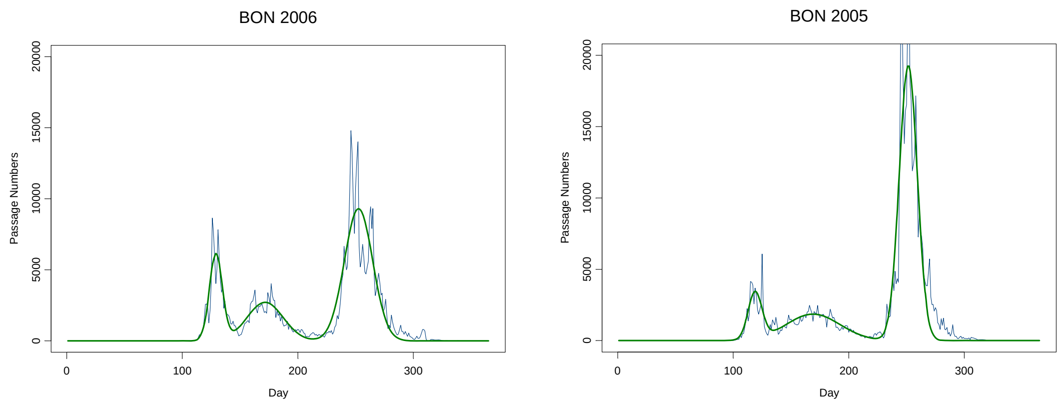


Figure 3 Fitted passage of three runs at Bonneville in 2006 and 2005. The thinner line is the profile of the observed arrivals. The thicker line is the triple normal curve that is fit with a non-linear least-squares routine.

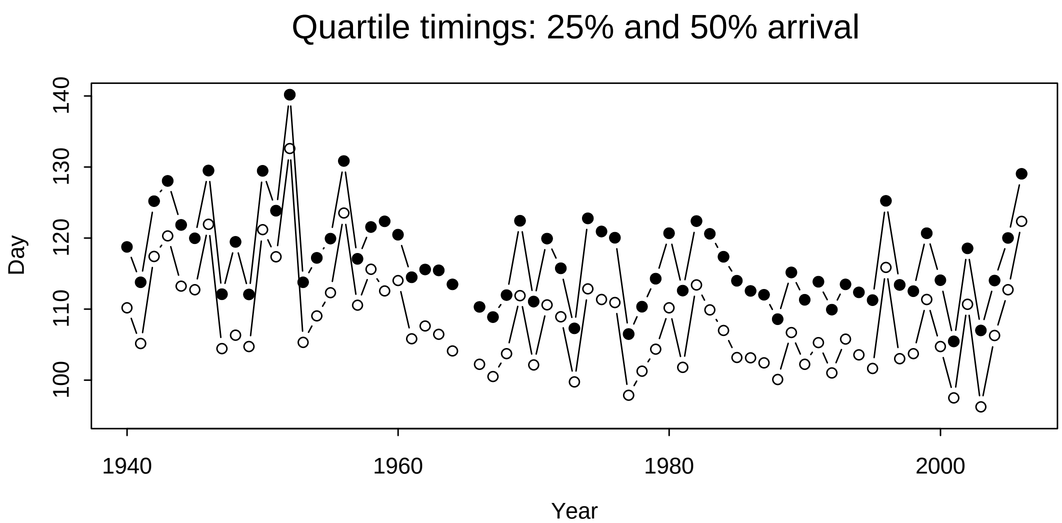


Figure 4 Timings of spring Chinook first quartile (25%, "open points") and median (50%, "solid points") passage day at Bonneville Dam based on fit of triple normal.

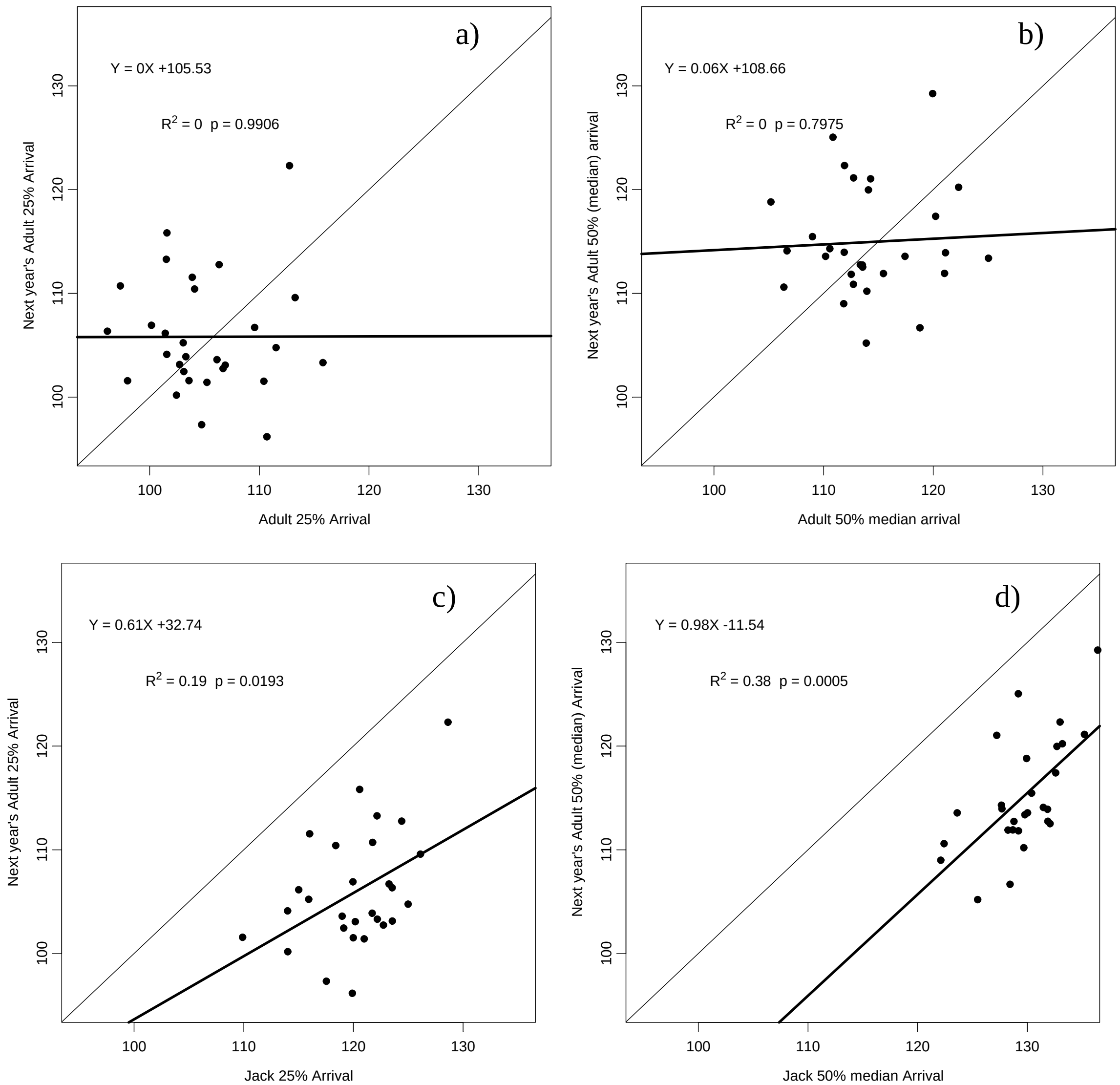


Figure 5 Autocorrelation of arrival timing metrics for spring run Chinook. In all plots the abscissa and ordinate have identical time spans. The heavier line shows the fitted regression and the thinner one is the 1:1 line. Adult arrival timing in one year is not a predictor for the timing in the following year for neither the 25% quartiles (a) nor the medians (b). Jacks consistently arrive later (c) than the adult Chinook (points are well below the 1:1 line), but their timing is a predictor for the adult run in the following year for both the 25% quartile (panel c, p=0.02 R^2=0.19) and the median (panel d, p=0.0005, R^2=0.38). The average difference in the arrival of the 25% quartile of each group is 15 days.

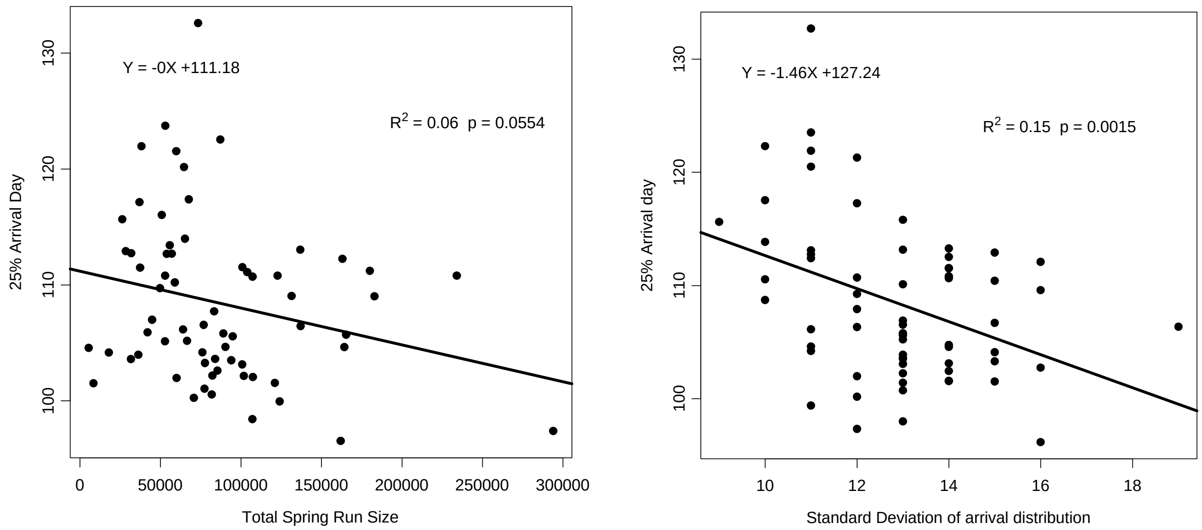


Figure 6 Run distribution metrics' relationship to arrival timing. The total spring run count is a weak predictor for the 25% arrival time. Arrival timing is negatively correlated with the standard deviation of the arrival time distribution. Thus, a larger run that is more spread in time begins earlier, however, the spread of the arrival distribution is not related to the run size (not shown).

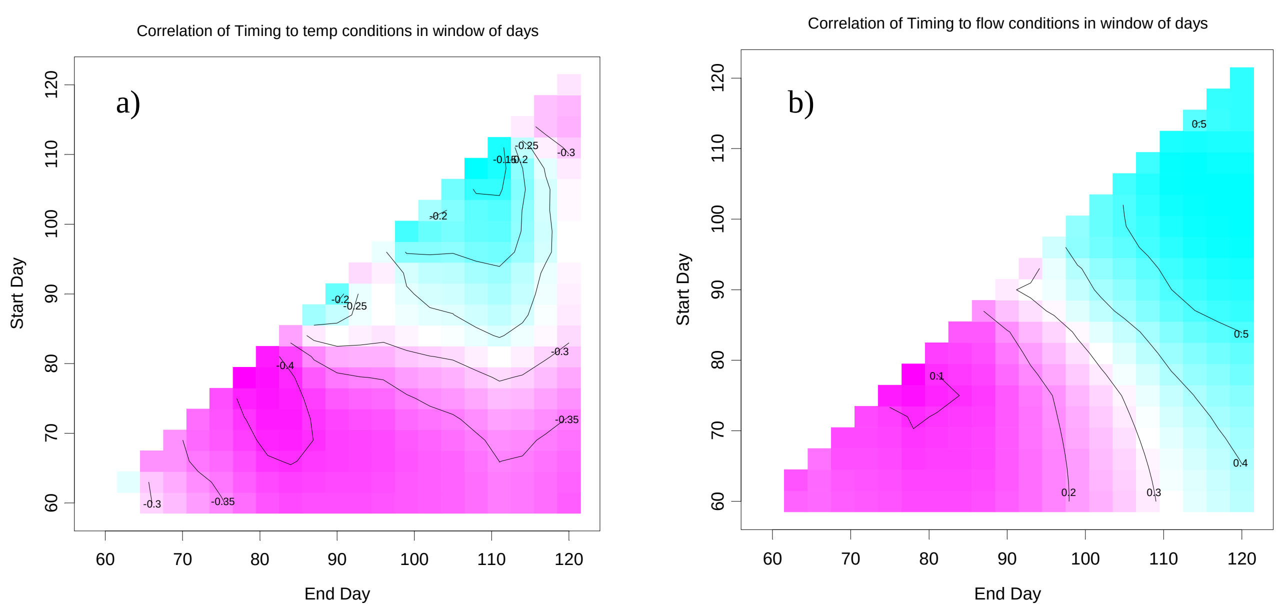


Figure 7 Correlation of 25% Arrival Day to temperatures, a), or flows, b), averaged over a range of days. The earliest measured 25% arrival day is day 96 (Table 1). Temperatures near mid-March are better predictors than at other times. Flows over the short-term, averaged over a few days ending near day 105 or 110 are better predictors than at other times.

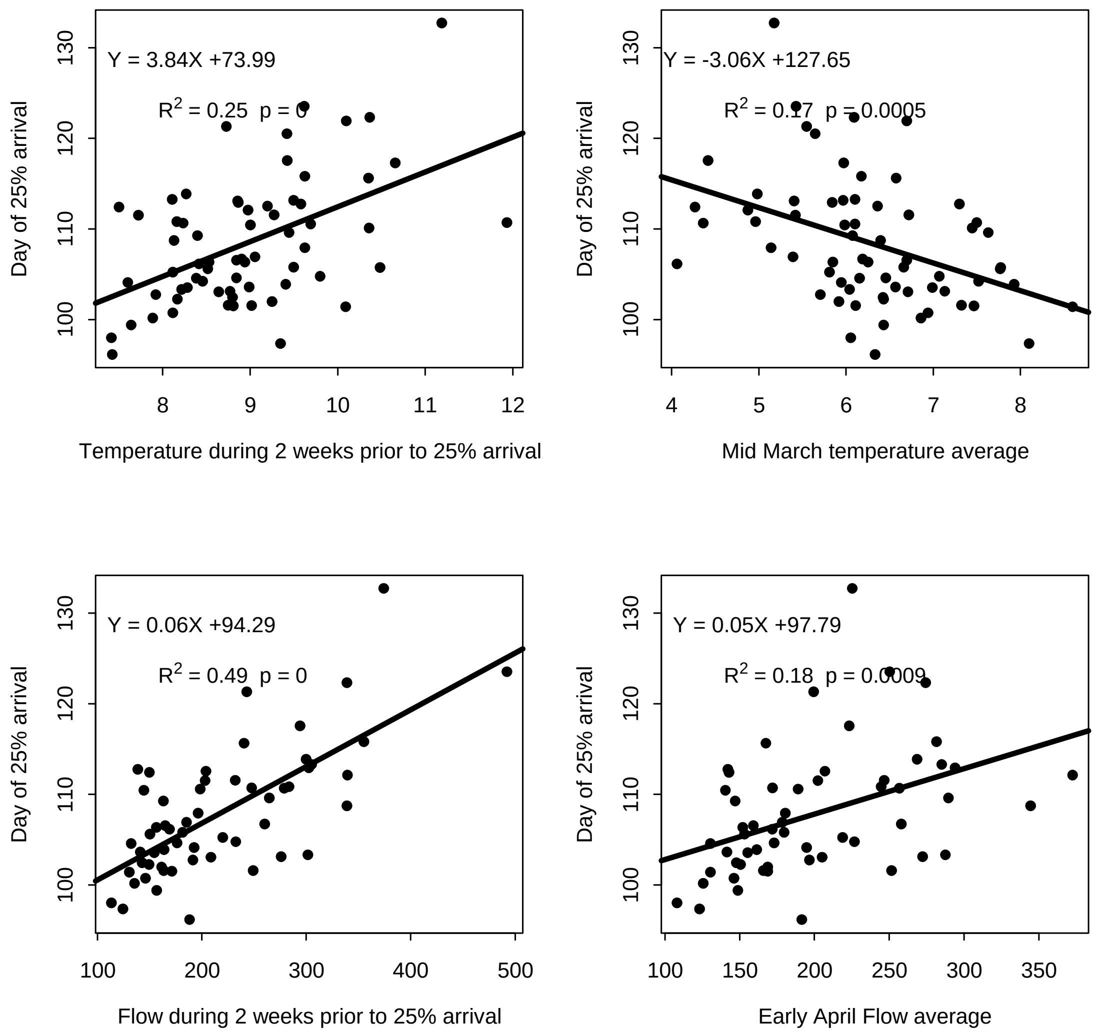


Figure 8 Temperature and Flow Relationships to the 25% arrival day for chinook at Bonneville Dam. In the 2 weeks prior to arrival at Bonneville of the quartile, temperatures vary significantly (7 to 12 °C) but this is not significantly related to the arrival day. Mid-March temperatures are a significant but weak predictor of subsequent arrival. Arrival timing is positively correlated with high flow conditions, however, flows can vary by a factor of 2 or more just prior to arrival even though delay in arrival is also positively correlated with flow.

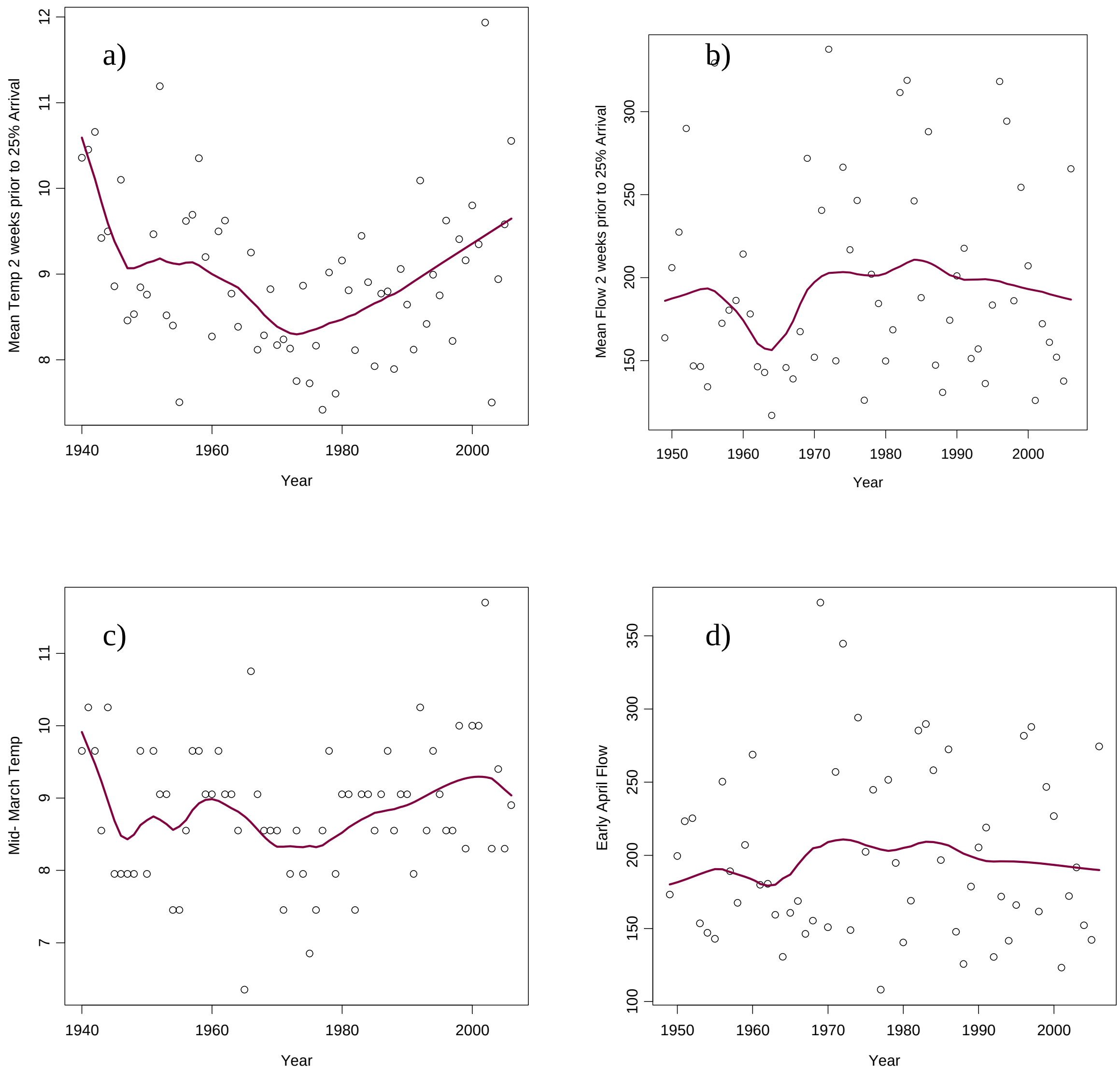


Figure 9 Time-series of temperature and flow in mid-March and during 2 weeks prior to 25% passage of spring Chinook at Bonneville Dam. Line through points shows smoothed trend. Temperatures have been increasing for 20 years. See also Figure 10.

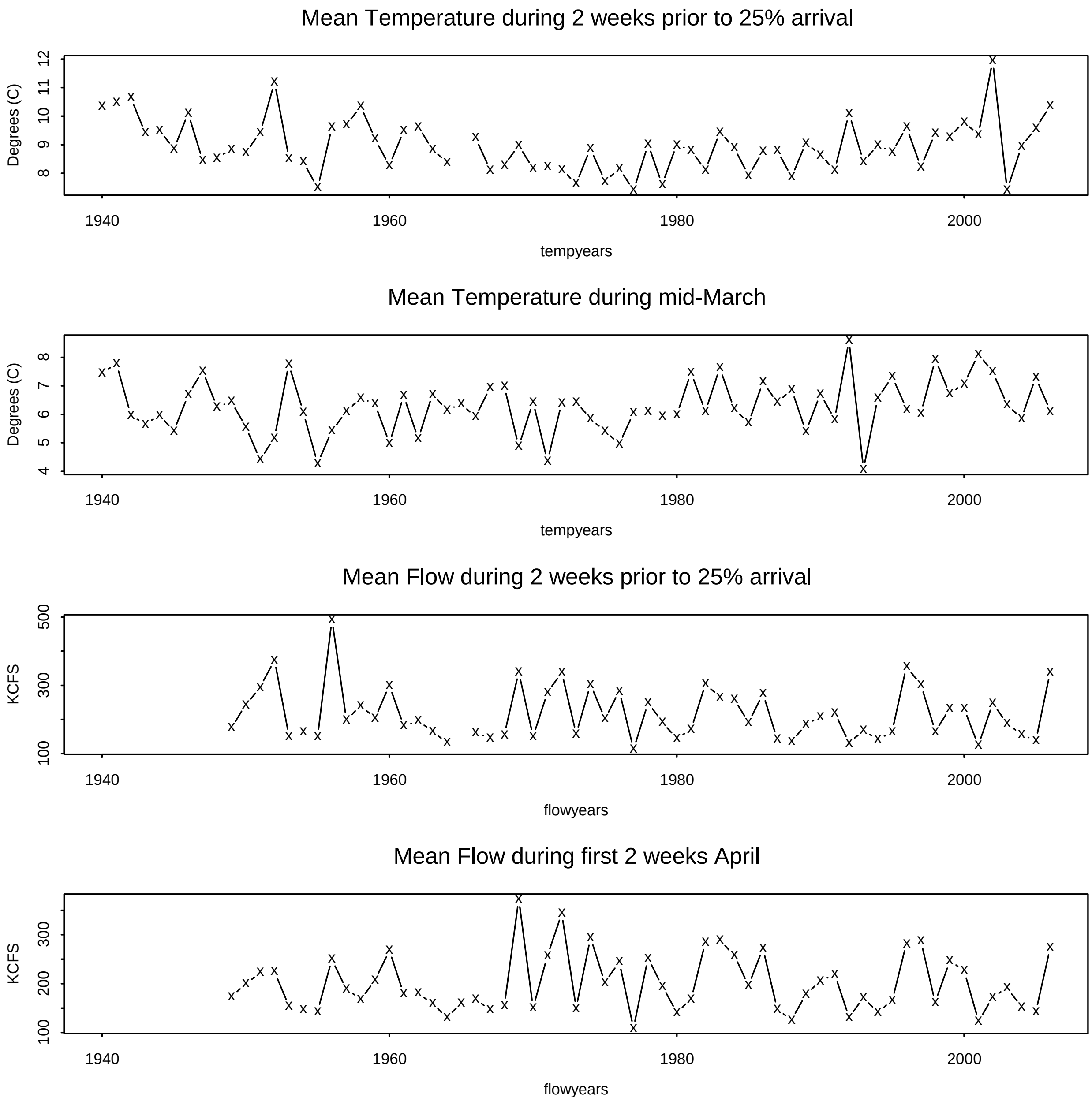


Figure 10 Time-series of temperature in mid-March and flow during first two weeks of April and during 2 weeks prior to 25% passage of spring Chinook at Bonneville Dam. See also Figure 9

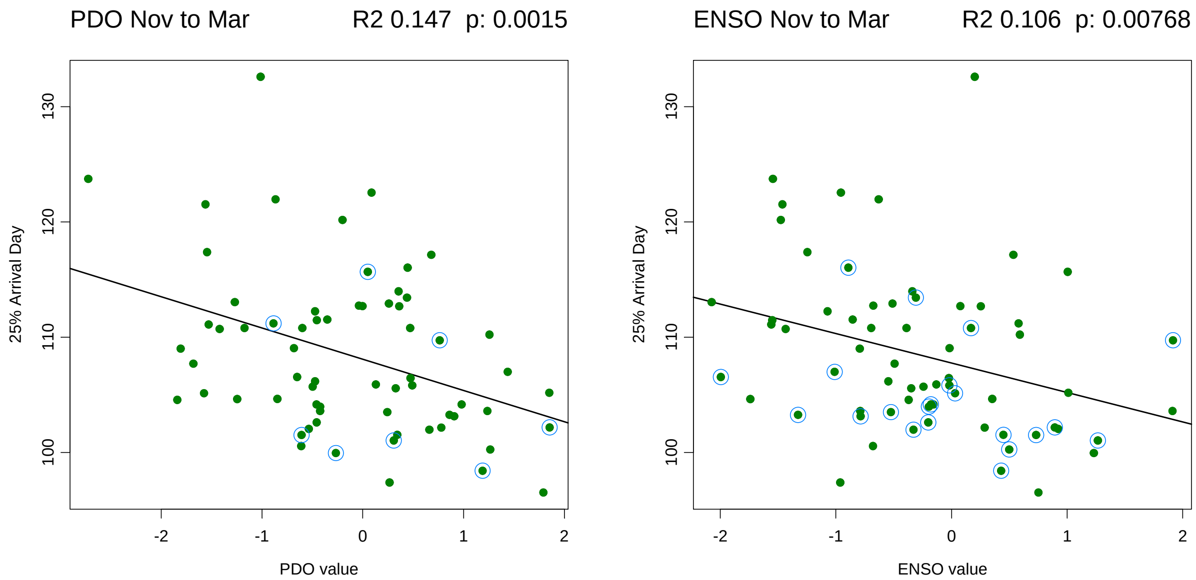


Figure 11 Left: Regression of 25% arrival day on PDO winter average (average of monthly values from November, December, January, February and March). Circled points are the El Nino years: 1958, 1965, 1969, 1973, 1977, 1983, 1987, 1992, and 1995. Right: Regression of 25% arrival day on ENSO winter average (average of monthly values from November, December, January, February and March). Circled points are the warm PDO years, 1977-1997.

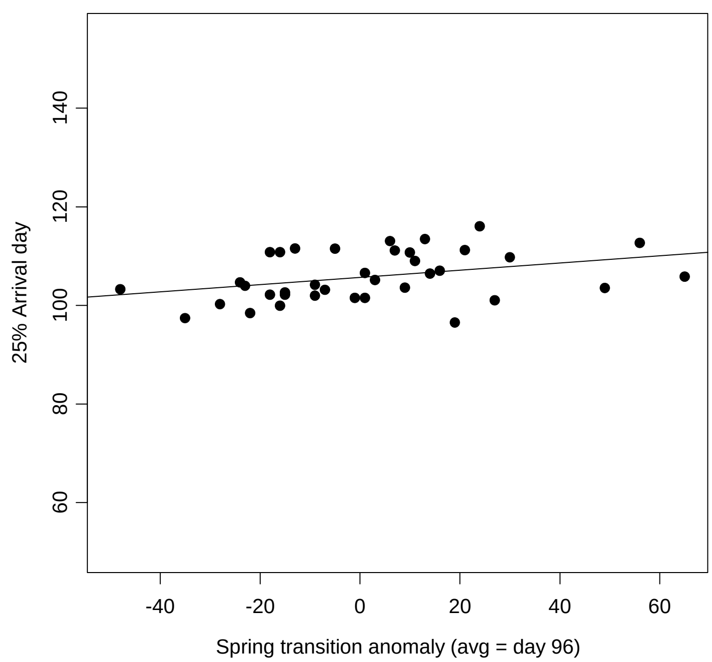


Figure 12 Relationship of spring transition anomaly to 25% Arrival Timing. The range of days (105 days) is the same on both axes. The correlation is 0.36 (R^2=0.13 and p=0.03). Based on the timing, this is a weak predictor. Although the arrival date is generally after the transition, the transition varies by several months compared to the variation in the arrival time on the order of a few weeks.

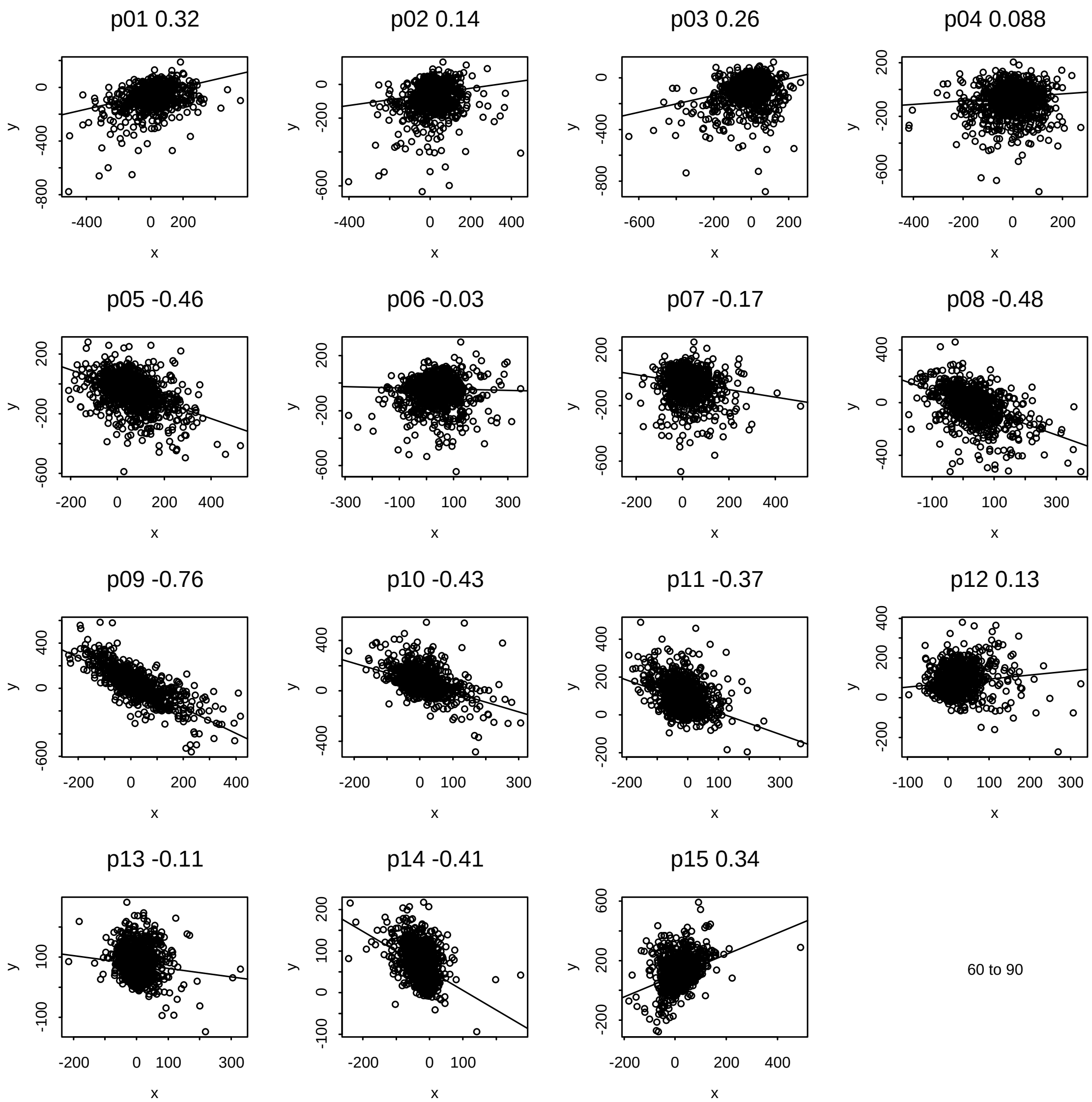


Figure 13 Correlations of Upwelling and Alongshore Transport at 15 sites in the Eastern Pacific between 1967 – 2006 during March (days 60-90). The mouth of the Columbia is between "p06" and "p07". Correlations at "p05" are consistently negative and range from -0.39 in January to -0.73 in August (not shown). Other sites are not so consistent. Site "p09" has even stronger negative relations year-round, but is out of the expected range of Columbia River spring Chinook.

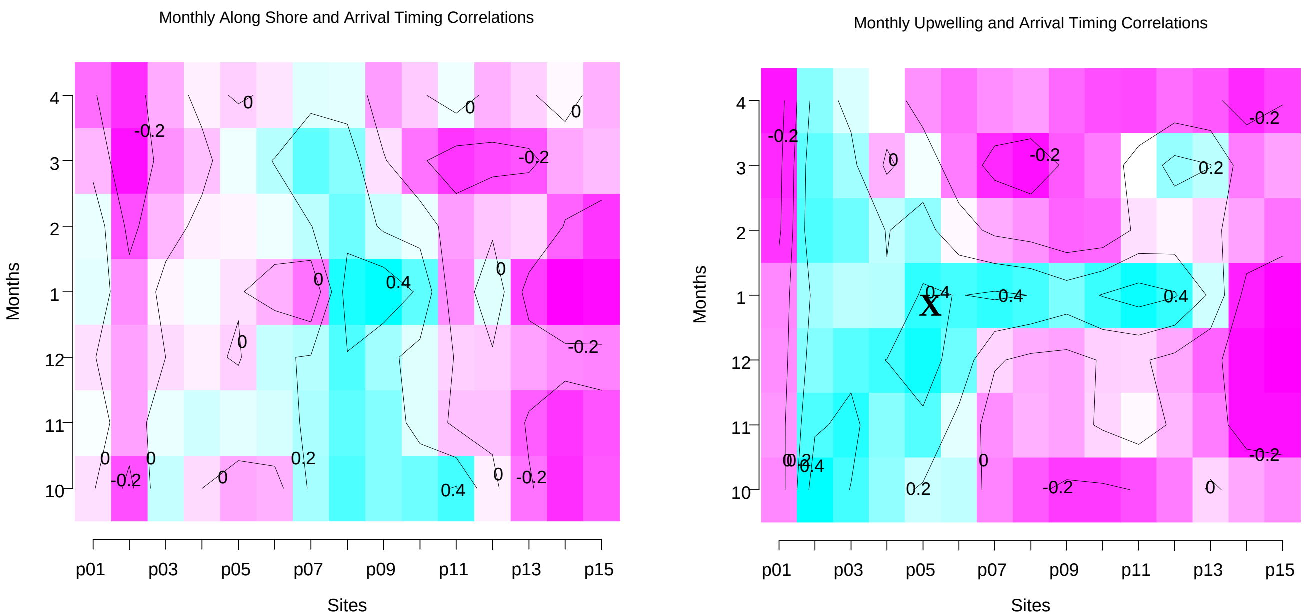


Figure 14 Correlations of the 25% arrival day and monthly averages of daily alongshore transport or upwelling at the 15 PFEL monitoring sites during the months prior to fish arrival at Bonneville Dam. More positive correlations are colored blue and more negative ones are colored pink. Colors are relative to range within the plot. Along Shore transport at site p08 show a consistent signal of positive correlation with arrival timing across many months. Upwelling in January (month 1) at sites p05 – p12 show a consistent signal of positive correlation with arrival timing.

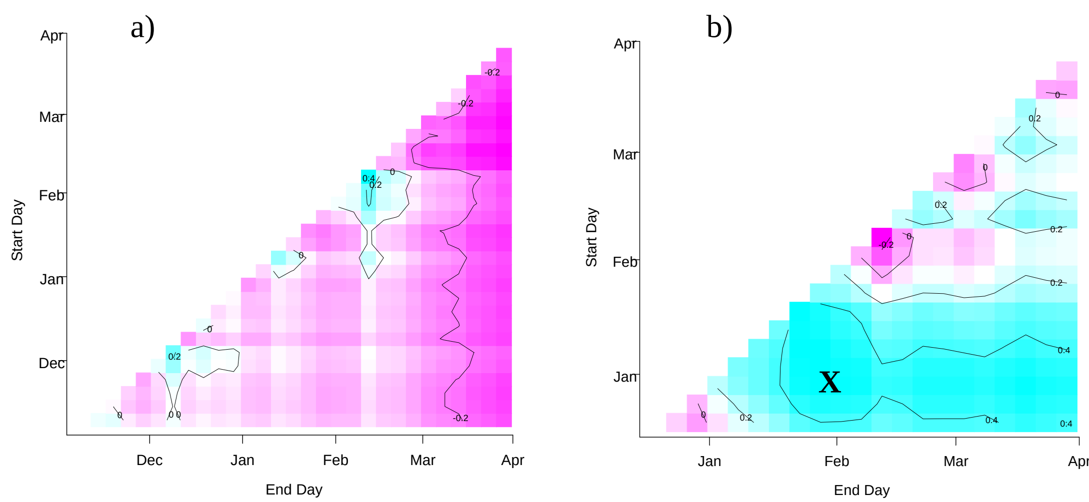


Figure 15 Correlations of 25% quartile arrivals with cumulative daily alongshore transport (a) and upwelling (b) values at p05 in a "window of time" measured between the Start day and End day. More positive correlations are colored blue and more negative ones are colored pink. Colors are relative to range within the plot. Contours of correlation are drawn and labeled on each plot. Range of correlation in Along-shore plot a) is -0.39 to 0.40 and range in Upwelling plot b) is -0.30 to 0.50. Point X represents the entire month of January: start day is at beginning of January and end day is beginning of February.

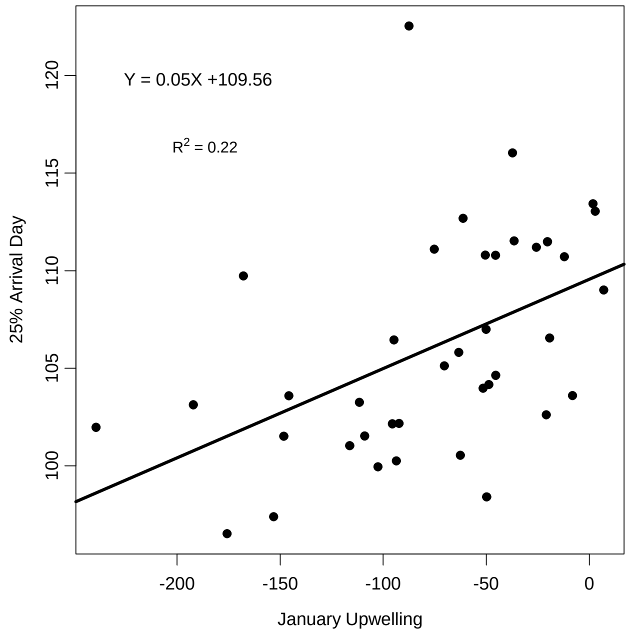


Figure 16 25% arrival day related to Upwelling in January at site "p05" (51N 131W). This corresponds with the "X" in Figure 15b. R^2 = 0.22 with a positive slope corresponds to a correlation of 0.47.

Appendix 1 Fits to visual counts in all years

Table 3 Parameters from fitting normal distributions to Bonneville chinook salmon visual counts.

	Spring Run			Summer Run			Fall Run			Spring Run Quantiles				
Year	N1	mean1	std1	N2	mean2	std2	N3	mean3	Std3	0%	25%	50%	75%	100%
1940	54989	117	9	46190	186	41	290847	250	7	81.94	111.06	117.2	123.09	147.07
1941	52882	115	7	65684	202	88	347232	253	5	83.77	110.64	115.24	119.98	140.06
1942	38374	126	9	214776	250	6	109295	252	1	92.36	120.15	125.96	131.62	158.11
1943	64609	128	8	41839	232	43	207841	250	5	97.66	122.3	127.8	133.22	156.9
1944	25803	121	7	138887	250	-9	46789	247	2	91.31	116.03	120.83	125.8	149.38
1945	29434	121	5	80523	209	53	190050	252	5	98.82	117.03	120.69	124.42	140.69
1946	47249	131	9	137820	206	53	266054	252	4	93.82	125.19	131.43	137.42	162.78
1947	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1948	44836	120	20	57898	177	7	274054	252	5	48.89	107.02	120.21	133.35	193.79
1949	3059	119	1	25006	162	10	132434	250	3	114.1	118.04	118.97	119.89	124.35
1950	41716	129	5	107851	200	48	209769	250	4	112.2	125.7	128.77	131.78	146.45
1951	67950	125	5	182652	174	50	83355	252	4	104.08	122.02	125.33	128.76	141.89
1952	138123	143	11	36949	172	4	205397	247	6	99.76	135.24	142.62	150.47	184.16
1953	89278	113	3	165291	150	53	83576	248	5	99.51	110.5	112.48	114.54	124.53
1954	130169	118	9	86059	180	19	89805	250	5	82.22	111.62	118.01	124.28	156.27
1955	127461	120	5	165268	179	48	67324	248	4	102.47	117.22	120.54	123.82	141.83
1956	59995	133	9	77197	176	7	110457	249	6	97.2	127.33	133.16	139.02	166.26
1957	108323	119	4	93090	170	5	113152	250	6	105.06	116.04	118.69	121.34	132.34
1958	47786	126	4	99950	163	12	240495	253	6	110.87	123.37	126.36	129.42	146.4
1959	58326	122	13	102233	184	20	177216	253	6	60.42	113.14	121.75	130.59	168.34
1960	62531	121	5	65853	168	6	87673	250	6	102.3	117.46	120.91	124.34	140.06
1961	93462	115	10	50896	174	8	96189	252	6	76.52	108.84	115.41	122.03	151.01
1962	88207	116	10	49506	167	4	106395	249	7	77.97	109.42	116.13	122.95	161.17
1963	60555	116	10	85063	178	27	119266	250	6	79.67	108.79	115.6	122.33	152.6
1964	90761	114	11	87963	186	16	145694	252	5	75.61	106.91	114.2	121.89	161.47
1965	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1966	106005	110	9	0	0	0	134795	256	8	75.29	104.53	110.68	116.66	147.09
1967	82850	109	10	112711	186	19	156118	256	5	66.91	102.09	108.82	115.73	149.8
1968	82238	112	10	113734	179	28	134871	250	5	75.21	105.57	111.87	118.36	148.59
1969	178664	123	14	45314	194	11	4991	280	7	62.56	113.93	123.2	132.38	177.87
1970	103454	112	12	142885	207	44	141001	253	4	65.04	103.64	111.78	119.63	154.71
1971	50899	118	4	209647	171	56	147523	252	4	105.05	115.72	118.22	120.78	131.63
1972	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1973	130874	108	8	123735	217	54	148522	252	4	76.15	102.26	107.72	113.18	135.4
1974	135855	122	12	55262	193	20	160120	256	6	76.24	114.03	122.14	130.29	165.23
1975	96315	121	12	95325	208	44	235183	251	5	79.59	113.09	120.99	128.51	166.04
1976	60183	121	6	189824	184	66	265617	252	6	99.81	117.31	121.18	125.03	141.21
1977	107246	106	10	54001	180	35	115313	253	6	68.14	99.77	106.54	113.28	143.06
1978	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1979	44285	115	15	73067	217	47	105806	251	4	59.99	105.42	115.22	125.11	174.06
1980	55225	121	14	93304	256	14	34683	252	2	60.78	111.6	121.29	130.86	180.2
1981	59437	112	13	29698	181	24	140765	251	8	65.84	102.84	111.49	120.37	158.66
1982	54176	123	10	59427	187	70	137255	252	8	88.77	116.24	122.93	129.78	161.01
1983	50746	121	15	45904	208	61	92296	255	11	62.04	110.88	121.21	131.3	193.15
1984	43782	117	14	70091	231	50	105664	251	7	66.84	108.02	117.41	126.6	168.94
1985	74784	114	15	74646	220	65	151921	251	8	60.81	104.43	114.39	123.95	171.23
1986	105484	112	12	93120	219	63	178171	254	7	64.44	103.79	111.56	119.63	157.51
1987	95956	113	13	198080	250	-15	137354	256	2	64.55	103.81	112.69	121.4	165.09
1988	76977	109	10	200408	244	10	80981	255	2	67.51	102	108.54	115.06	148.32
1989	79555	115	10	96982	234	22	180265	250	9	76.35	108.16	115	121.86	154.99
1990	79137	110	10	44533	163	34	169810	249	9	74.73	103.59	110.48	117.15	145.6
1991	53293	114	10	67328	258	6	68621	247	2	77.31	107.25	113.79	120.57	154.6
1992	78505	110	11	28513	160	32	106159	251	8	64.11	102.29	109.85	117.36	150.86
1993	81122	112	7	54203	145	30	120850	250	11	85.45	107.26	112.14	117.01	140.47
1994	14800	112	9	50862	219	58	144694	250	9	75.88	105.27	111.74	117.64	152.15
1995	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1996	50850	126	11	149889	249	12	49014	250	4	83.9	118.77	125.76	133.03	172.33
1997	94941	112	14	53186	155	29	201799	247	8	61.53	103.17	112.28	121.35	163.62
1998	31574	113	11	31146	173	28	183643	251	12	73.11	105.03	112.35	119.7	151.23
1999	36353	120	11	31536	184	22	225308	249	10	75.63	113.22	120.61	128.11	161.2
2000	160955	114	11	51653	166	32	184159	245	11	69.82	106.33	113.89	121.11	154.53
2001	253289	105	7	228318	139	38	365413	250	8	75.37	99.95	104.44	109.01	135.91
2002	129896	119	4	288563	149	39	444642	249	9	104.62	115.93	118.56	121.17	131.72
2003	147173	106	13	177599	170	29	567401	254	8	61.28	97.65	106.09	114.49	153.89
2004	73429	111	3	202295	150	36	546719	253	9	98.24	109.19	111.39	113.6	122.17
2005	48865	119	6	108778	169	23	376425	252	8	94.35	114.88	118.89	122.89	142.13
2006	85016	129	6	106486	172	16	285975	253	12	108.55	125.39	129.03	132.83	151.57

Table 4 Parameters from fitting logistic distributions for Bonneville Chinook salmon visual counts.

	Spring Run			Summer Run			Fall Run			Spring Run Quantiles				
Year	N1	mean1	std1	N2	mean2	std2	N3	mean3	Std3	0%	25%	50%	75%	100%
1940	66981	119	9	23545	190	12	305697	250	7	26.5	109.9	119.2	128.6	200.5
1941	70753	114	8	15803	180	-12	378441	253	6	40.2	105.3	114.3	123.4	180.2
1942	41170	126	8	23419	181	13	341249	251	6	48.5	117.2	125.9	134.6	205
1943	68181	128	7	11016	186	9	237593	250	6	63.6	120.1	128.1	136.3	196.7
1944	29660	122	8	15600	190	18	197440	248	7	22.5	113	121.9	130.7	198.9
1945	39671	121	8	35581	184	15	225038	251	7	49.3	112.8	121	129.3	193.7
1946	59183	130	9	64153	175	17	326694	251	6	33.7	120.6	130.1	139.5	204.7
1947	80778	112	7	92384	150	19	306783	249	7	48.4	103.8	111.6	119.6	192.9
1948	42287	118	12	68132	179	8	298819	251	6	-2.1	104.5	118.4	132	236.7
1949	5235	111	7	25212	163	8	143334	250	6	24.5	104.1	111.1	118.5	170.6
1950	62753	129	8	47250	189	9	249494	249	6	63.1	120.7	129.6	137.9	210.9
1951	83012	124	7	118848	164	16	131568	250	8	66.2	117.3	124.3	131.5	185.6
1952	107349	140	8	93306	169	14	221704	247	7	64.1	132	140.7	149.4	217.9
1953	170020	114	8	65390	185	11	100032	248	7	37.2	104.7	113.6	122.1	188.1
1954	135110	117	8	84203	180	12	103265	249	7	28.2	109	117.6	126	200.2
1955	168162	120	7	90506	181	11	100285	247	7	55.3	112.1	119.7	127.7	232.4
1956	55135	131	7	104959	178	10	136549	248	8	39.2	123.4	131.1	138.6	204.8
1957	124286	117	6	141751	170	9	133934	248	8	38.8	110.5	117.2	123.8	176.2
1958	43445	123	7	129944	163	13	252476	252	6	61.3	115.6	123	130.4	216.4
1959	57957	122	9	99527	184	12	192505	252	7	21.8	112.1	122.1	132.4	210
1960	65555	120	6	82668	170	8	101829	250	7	68.7	113.9	120.6	127.2	182.4
1961	97315	115	8	69016	178	10	114181	251	7	30.5	105.3	114.3	123.5	188.5
1962	86162	116	8	78126	171	10	118339	249	7	46.8	107.2	115.9	124.2	191.8
1963	66502	116	9	77248	177	15	132137	251	7	41.3	106.3	115.8	125	207.9
1964	91848	113	8	86342	187	10	164690	252	7	42.9	104.6	113.5	122.5	202.4
1965	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1966	110734	110	8	0	0	0	134664	256	7	40.3	101.4	110	118.3	185.9
1967	82856	109	8	111731	185	12	174072	256	7	30.4	99.9	108.8	117.2	211.7
1968	86048	112	8	107531	178	17	148433	251	7	38.7	103.6	112.3	121.2	224.1
1969	185118	123	10	41865	195	7	5889	283	8	24.1	111.5	122.8	133.5	218.7
1970	106270	112	9	89225	184	17	191492	252	7	31.8	102	111.4	120.8	196.8
1971	113787	121	9	103589	181	16	188942	252	7	48.3	110.4	120.6	130.7	209.9
1972	187933	116	7	79507	185	11	130408	255	7	43.5	108.7	115.9	122.9	177.1
1973	135959	107	7	63860	180	20	199374	252	7	43.5	99.4	107.4	115.3	170.9
1974	141989	123	9	46048	192	10	177170	256	7	25.3	112	122.3	132.6	235.5
1975	107071	121	9	50379	191	14	272183	251	6	29.7	111.2	121	131.2	194.6
1976	109718	121	9	76504	180	13	318527	252	7	29.4	110.8	120.3	129.9	205.9
1977	112031	107	8	43888	177	17	127352	254	7	40.4	97.7	106.8	115.3	173.5
1978	135592	111	9	59299	168	18	140271	254	7	25.1	101.5	111.1	120.9	196.6
1979	46449	115	10	36155	183	17	138615	250	7	1.9	103.8	115.2	126.6	225
1980	55178	121	10	25932	184	11	128030	254	8	16.9	110.2	121	132.1	205.3
1981	63310	112	10	23834	181	12	148439	251	7	-8.9	101.8	112.5	122.8	211
1982	71645	123	10	18941	178	13	157947	252	8	38.5	112.7	123.2	133.9	255.3
1983	56191	121	11	18768	176	14	112760	255	9	12.6	110.1	121.6	132.9	226.9
1984	47580	118	10	23980	184	12	144885	251	8	11.1	107.5	118	129.2	210
1985	84103	115	11	24434	175	13	187057	251	8	14.4	103.1	114.6	126.2	216
1986	110563	112	9	39882	170	19	221550	254	8	31.3	101.9	111.8	121.5	199.4
1987	84913	112	9	70842	183	30	317066	254	7	32.3	102.3	111.8	121.1	200.6
1988	73759	109	8	60244	177	26	283272	249	8	46.4	99.9	108.6	117.2	166.2
1989	78690	115	8	53360	202	24	245955	249	9	5.2	106.7	115.4	123.9	182.6
1990	92606	112	9	28688	174	14	178527	250	8	38.1	102.4	112	121.4	190.1
1991	56244	114	8	21221	176	13	150336	251	7	37	105.1	114.1	123.2	186.2
1992	85257	111	9	19733	165	14	115790	252	8	30.8	100.7	110.4	119.8	195.2
1993	98131	114	7	37492	157	17	127199	250	9	56.6	105.8	113.6	121.6	177.4
1994	19140	113	9	18427	180	12	170694	250	8	28.6	103.4	113.1	122.6	194.3
1995	9329	112	10	14774	179	12	164799	250	9	-39.5	101.2	112	122.6	206.6
1996	53961	125	9	12393	179	9	205975	250	8	36	115.9	125.6	135.3	211.8
1997	98448	113	10	47214	154	17	215674	248	8	32.1	103	113.4	124.1	203.7
1998	35183	113	9	23751	171	13	192468	251	9	25.6	103.9	113.6	123.5	192.2
1999	39435	121	9	23528	181	10	244522	250	8	20	111.5	121.4	131.1	202
2000	177469	114	9	32172	172	13	195654	245	9	24.6	104	114.3	124.4	193.5
2001	321872	105	8	157827	152	21	394051	250	8	27.7	97.3	105.5	113.8	182.5
2002	249161	119	8	147575	171	13	474799	249	8	47.8	110.7	119	127.3	207
2003	174080	108	11	140988	171	14	608189	253	7	-22.6	96.2	107.9	119.7	201.6
2004	148123	115	8	116948	169	13	583423	254	8	46.9	106.6	114.9	123.1	196.9
2005	58642	121	7	94788	170	13	414932	252	8	60.5	112.9	120.8	128.5	204.5
2006	92385	130	7	100271	172	10	300173	253	9	81.2	122.5	129.6	136.8	196.7

In the graphs that follow, the data and the model fits are depicted. Each frame has the same scale. Images without a thicker line indicate the run could not be easily fit within that year. There were no interventions of the fitting routine to accommodate unusual years. The thinner lines are the observed daily passage.

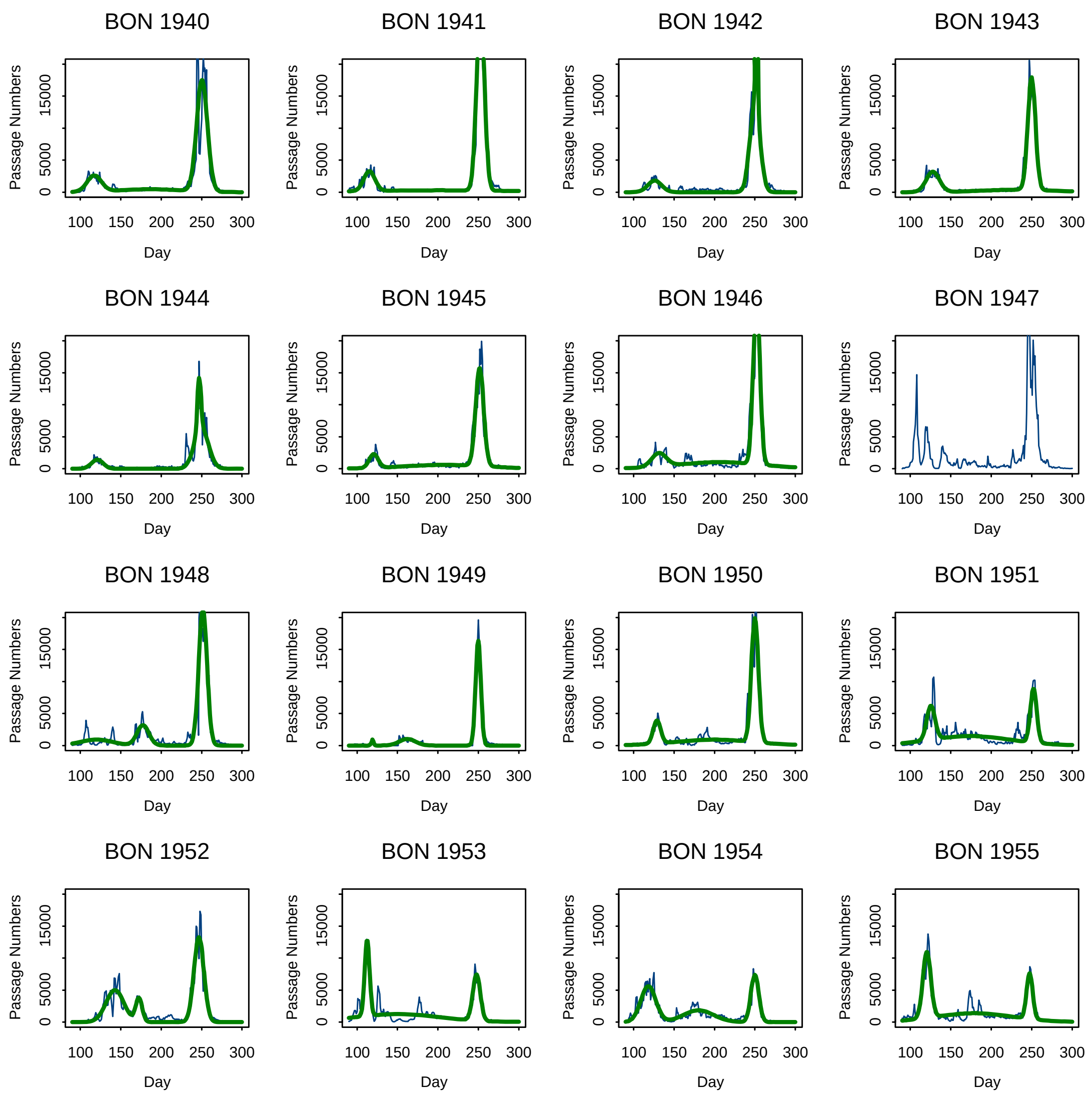


Figure 17 Observations and fits of the triple normal model from 1940 - 2006

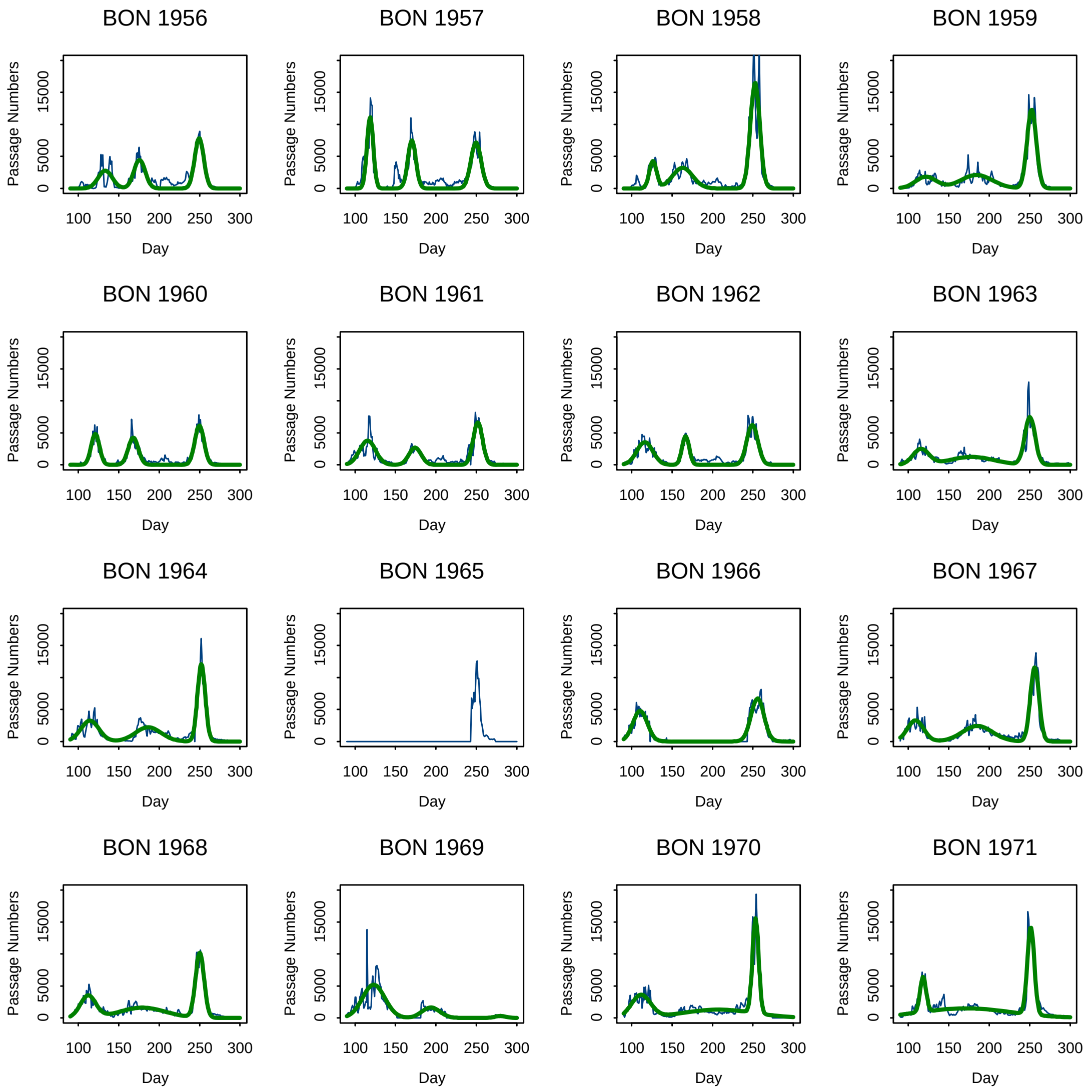


Figure continued

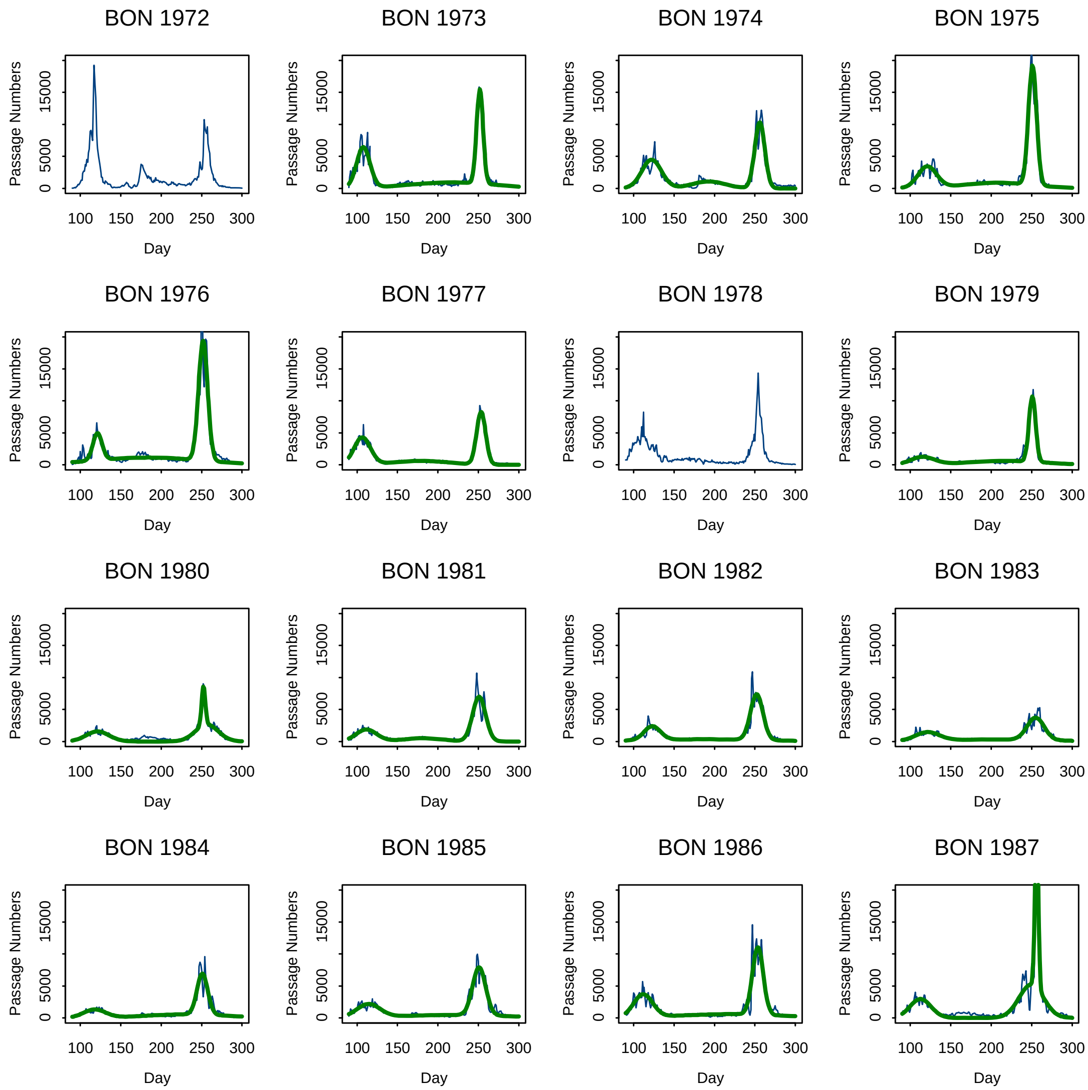
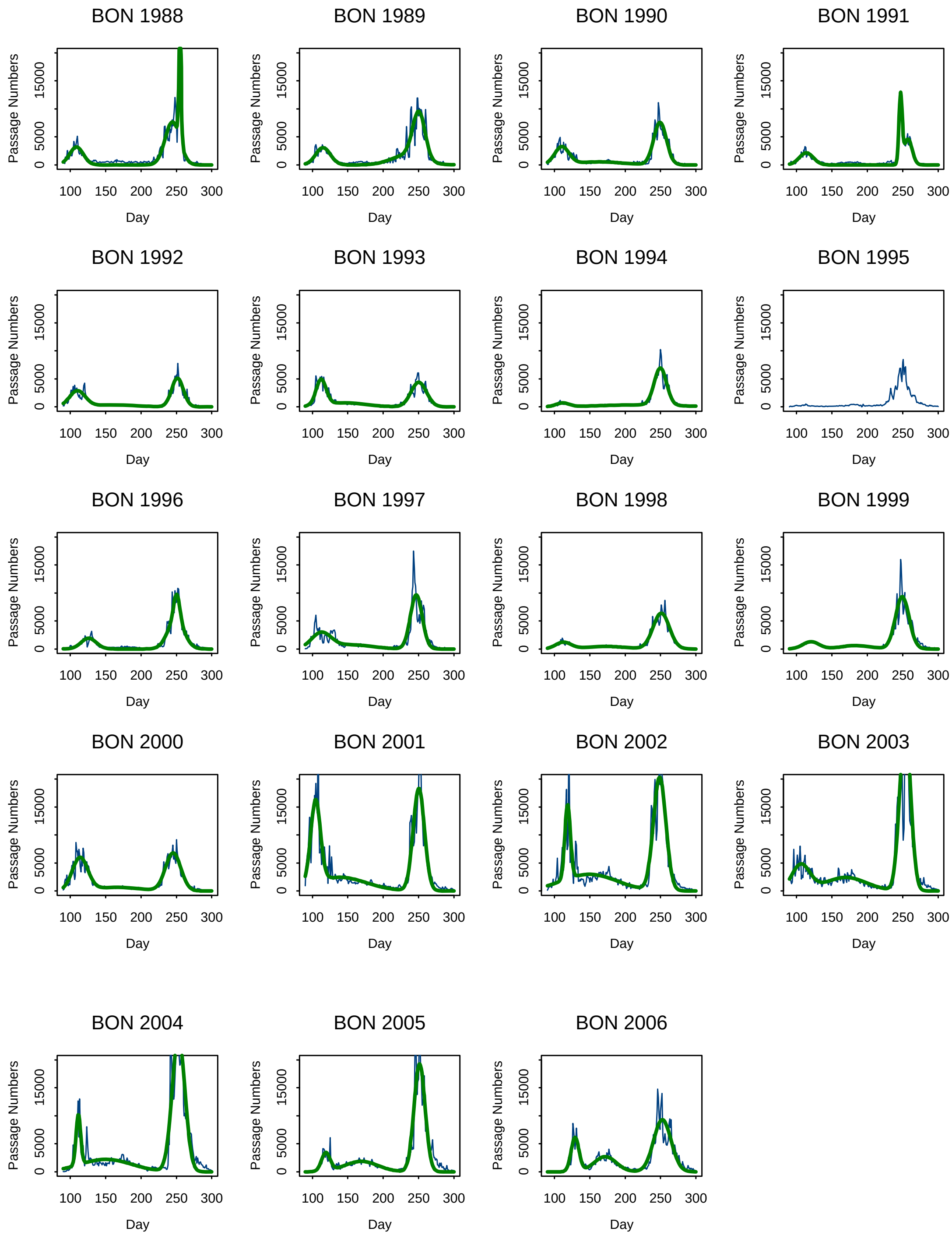


Figure continued


BON 1988
BON 1989
BON 1990
BON 1991
BON 1992
BON 1993
BON 1994
BON 1995
BON 1996
BON 1997
BON 1998
BON 1999
BON 2000
BON 2001
BON 2002
BON 2003
BON 2004
BON 2005
BON 2006
Passage Numbers
0
5000
15000
Day
100
150
200
250
300

Appendix 2 Comparison of "Triple Normal" Total Run Size fits to Observations

Year	Observed	Estimated	Error %
1940	391473	392026	0.1413
1941	460427	465798	1.1665
1942	402158	362444	-9.8752
1943	313123	314289	0.3724
1944	240493	211480	-12.064
1945	297488	300007	0.8468
1946	446007	451123	1.1471
1947	480377	0	NA
1948	404915	376788	-6.9464
1949	169608	160499	-5.3706
1950	357375	359335	0.5484
1951	331788	333957	0.6537
1952	420879	380470	-9.6011
1953	332479	338145	1.7042
1954	320947	306033	-4.6469
1955	359853	360052	0.0553
1956	300919	247649	-17.7024
1957	403286	314565	-21.9995
1958	426419	388232	-8.9553
1959	345028	337775	-2.1021
1960	256049	216057	-15.6189
1961	281440	240548	-14.5296
1962	286625	244108	-14.8337
1963	278556	264883	-4.9085
1964	340585	324419	-4.7465
1965	112664	0	NA
1966	239524	240800	0.5327
1967	366153	351679	-3.953
1968	341419	330844	-3.0974
1969	228259	228969	0.3111
1970	380416	387341	1.8204
1971	405787	408070	0.5626
1972	394456	0	NA
1973	398635	403131	1.1278
1974	366759	351237	-4.2322
1975	425566	426823	0.2954
1976	507773	515624	1.5462
1977	281659	276560	-1.8103
1978	332323	0	NA
1979	220335	223158	1.2812
1980	207967	183212	-11.9033
1981	232299	229900	-1.0327
1982	247911	250859	1.1891
1983	186214	188946	1.4671
1984	216469	219537	1.4173
1985	296450	301350	1.6529
1986	370738	376776	1.6286
1987	467966	431390	-7.816
1988	409751	358366	-12.5405
1989	373218	356802	-4.3985
1990	296551	293480	-1.0356
1991	226427	189241	-16.423
1992	218689	213178	-2.52
1993	259344	256175	-1.2219
1994	208197	210356	1.037
1995	189426	0	NA
1996	272895	249753	-8.4802
1997	356717	349926	-1.9038
1998	248839	246363	-0.995
1999	306868	293197	-4.455
2000	401779	396767	-1.2475
2001	868429	847020	-2.4653
2002	871763	863100	-0.9937
2003	921314	892173	-3.163
2004	845950	822443	-2.7788
2005	569038	534069	-6.1453
2006	493703	477477	-3.2866