EVOSTC ANNUAL PROJECT REPORT

Recipients of funds from the *Exxon Valdez* Oil Spill Trustee Council must submit an annual project report in the following format by **Sept. 1 of each fiscal year** for which project funding is received (with the exception of the final funding year in which a final report must be submitted). **Please help ensure that continued support for your project will not be delayed by submitting your report by Sept. 1. Timely receipt of your report allows more time for court notice and transfer, report review and timely release of the following year's funds.**

Satisfactory review of the annual report is necessary for continuation of multi-year projects. Failure to submit an annual report by **Sept. 1** of each year, or unsatisfactory review of an annual report, will result in withholding of additional project funds and may result in cancellation of the project or denial of funding for future projects. **PLEASE NOTE:** Significant changes in a project's objectives, methods, schedule, or budget require submittal of a new proposal that will be subject to the standard process of proposal submittal, technical review, and Trustee Council approval.

Project Number: 070810
Project Title: An Ecosystem Model of Prince William Sound Herring: A Management & Restoration Tool

PI Name: Dale A. Kiefer and Evelyn Brown

Time period covered: February 15, 2008 to August 24, 2008 ???

Date of Report: September 21, 2009

Report prepared by: Dale A. Kiefer

Project website (if applicable): http://smbay.usc.edu/pws/

1. Summary

The goal of our project is to develop an information system for PWS herring that consists of an advanced geographic information system that houses both ecological data on PWS herring and a population dynamics model of its life stages. The population dynamics model is designed to explain why the herring have not returned to the population levels found prior to the 1989 oil spill. In addition we believe that such a model and its information system will guide future research on herring ecology by providing a means of integrating field and laboratory measurements and providing a quantitative, conceptual framework for interpreting these measurements.

During the second year of our project to develop an information system for Prince William Sound herring, we have completed both a one dimensional model of the population dynamics during the herring's life cycle and a database that stores all information necessary to develop the model. The simulation model that we have developed provides very good predictions of the time series of the adult herring population and juvenile recruitment that are found in Fish and Game's Age Structured Analysis for both Prince William Sound and Sitka Sound. The model has helped reveal that variations in adult and juvenile populations are driven by both external, climatic factors and internal factors that are due to biological interactions of specific age classes of the herring. Specifically dramatic increases in juvenile survival within Sitka Sound were stimulated by the 1976 shift in Pacific Decadal Oscillation. The pattern in population dynamics that was initiated by this event continued until 1992-93 when El Nino "catalyzed" changes in the annual recruitment cycle of both Prince William and Sitka Sounds. These changes in juvenile survival reflect "internal dynamics" since they appear to be caused by the competition for food among the juvenile cohorts of differing ages. We have derived a phenomenological routine to describe the dynamics created by "cohort dominance" and incorporated into our model. When calibrated to the ASA time series of the two regions, the model tracks annual changes in adult stocks and recruitment closely, accounting for over 90% of the variability in the size of the adult stocks. We feel that this model provides not only new insight into the factors controlling the herring population in Prince William Sound but also a solid foundation for further discoveries.

2. Work Performed

2.1. Exercise the PWS Herring Framework to Tune Model to Fish and Game' ASA time series

Our approach to developing the model is to examine the broad range of data available on herring in PWS and other locations, and then derive a series of linked equations that describes these patterns. These equations generally invoke ecological and physiological laws of energy and material flow. Finally, simulations with these equations are run and compared with the data. If the fit is good, we infer that the model is performing well and can be further tested and developed; if not, we try a different approach to deriving the equations. This is essentially a derivative of the scientific method when controlled experiments or comprehensive measurements of all variables of importance are not possible.

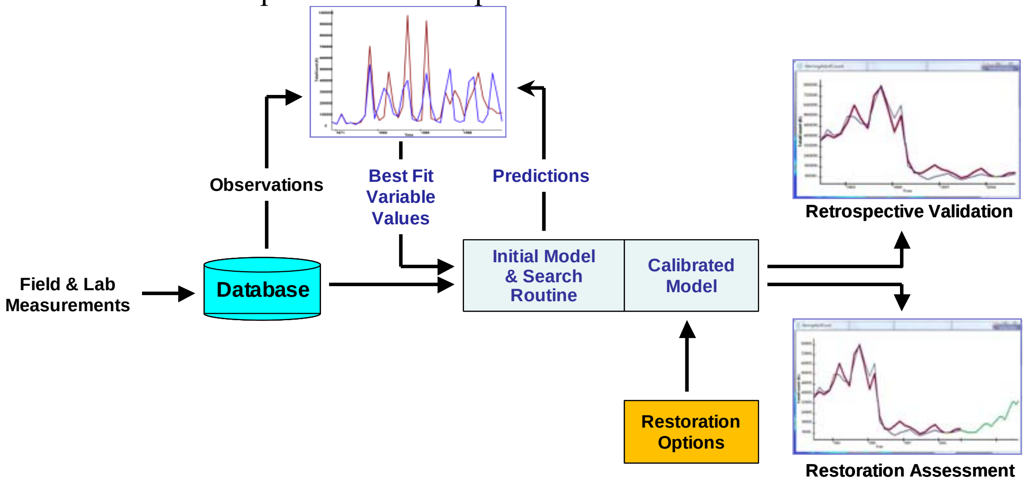

Figure 1. Components and information flow in the Prince William Sound Information System

The Prince William Sound Herring Information System was developed using the Environmental Analysis System (EASy) software. EASy is a 4-dimensional (latitude, longitude, depth, and time) geographic information system that is specifically designed to handle oceanographic data and models. It runs on either a Windows desktop or a server where the application can be run interactively over the internet. The Herring Information System contains the diverse types of biological and environmental data needed for the development and the operation of the PWS herring population dynamics model as well as the model itself. The data stored in the database includes digital maps of coastline, altimetry, and bathymetry, satellite imagery of sea surface temperature and chlorophyll concentration, and of course data on the ecology of PWS herring. This data includes the time series of the location of spawning sites, and the changes in the size of the adult herring population and its recruits, and distribution of adult and juvenile schools obtained from acoustic surveys. It also contains the values of morphometric, physiological, and the model variables for each of the stages of the herring's life cycle. Finally, the information system contains plug-ins to connect to coastal circulation models and display dynamically in 3 dimensions their flow fields. Particles can be added to the field in order to track the movement of water parcels.

Figure 1 shows the components and the flow of information that occurs when the herring population dynamics model is running. As indicated, data from the database is passed to the model; these include the values for variables found in the model and the values from field or laboratory measurements which are used to either drive the model or to test or calibrate the model. The model can be run either in either of two modes, calibration or prediction. In the calibration mode the database passes the variables of the model, its drivers, and observation to the routine. The variables of the model that are poorly known are selected and their value calculated using a search routine. As represented by the upper loop in the figure, the search routine systematically varies with each iteration the value of each of the poorly known variables until the fit between observations and model predictions is optimal. Once the values for these variables are determined, they are stored in the database. The prediction mode of the model can be run for retrospective analysis in order to test the accuracy of the model's predictions with observations; this is labeled as retrospective validation in the figure. It can also be run as a predictor of the herring response to either future events or scenarios defined by the user; this is labeled as restoration assessment in the figure. It is this latter simulation that we will exercise over the next two years to determine the sensitivity of the herring populations to perturbations to the population and in particular the expected response of the population to schemes of restoration intervention. During the 2nd year of our project, we exercised the framework software by tuning our model to the Alaska Department of Fish and Game's data Age Structured Analysis time series. As discussed below, the tuning process worked well.

2.2. The Population Dynamics Model

The PWS herring population dynamics model that we have developed draws heavy upon the extensive field and laboratory research conducted since the oil spill such as EVOS's APEX and SEA projects. It also draws heavily upon the annual herring surveys conducted by Alaska Fish and Game (Williams and Quinn, 2000a, b). Because of the generosity and ease of access provided by ADFG, its continuity and duration, we have focused much of our attention during the first two years of our project on the ASA time series. This time series proves particularly illuminating when compared and contrasted with the similar analysis in Sitka Sound. Although this data provides insights into the dynamics of the adult population and its relationship to the recruitment of juveniles, it of course provides no information on the earlier stages of the fish's life cycle.

Figure 2 shows the PWS ASA time series for the populations of adult herring as well as the ratio of age 3 juveniles born on the year indicated to the adult population of that year. This adult time series clearly shows the large adult population that grew throughout the 80s and the associated 4-year cycle in annual recruitment. It also shows the rapid decline in the population between 1992 and 1993 and the small adult population that continues from 1994 to present. The 4-year cycle of recruitment has now been replaced by a less predictable cycle that may in fact prove to have a 5-year periodicity. Figure 3. shows the Sitka Sound (SS) ASA time series for the populations of adult herring and the ratio of age 3 juveniles born on the year indicated to the adult population of that year. The adult time series clearly shows the small adult population that existed from 1971

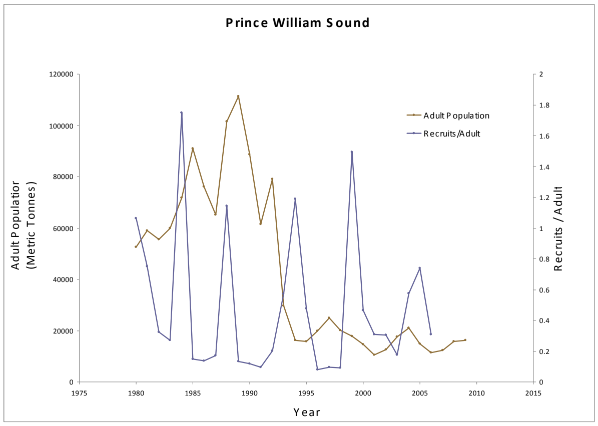

Figure 2. Fish and Game's ASA time series for PWS of the size of the adult population and the ratio of the population of age 3 juveniles to adults that spawned these recruits. Please note that this ratio is plotted for the year the juveniles were born rather than the year that they become 3 years old.

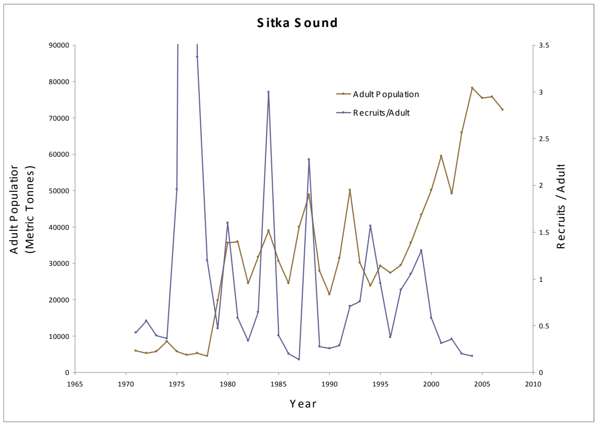

Figure 3. Fish and Game's ASA time series for Sitka Sound of the size of the adult population and the ratio of the population of age 3 juveniles to adults that spawned these recruits. Please note that this ratio is plotted for the year the juveniles were born rather than the year that they become 3 years old.

to 1979 when it suddenly increased 6-fold and maintained this level from 1980 to 1995. This sudden increase in the adult population in 1980 was catalyzed by an extraordinary increase in recruitment in 1976 (100-fold increase in the ratio of 3-year juveniles to adults) that was further supported by strong recruitment in 1975 and 1977. The large but gradual increase in the adult population that began in 1995 has been recently questioned by a number of researchers, who have suggested that this apparent increase is in fact a failure of surveys of egg deposition to provide an accurate measure of the adult population (Patrick- personal communication). Although we will not discuss this issue further in this proposal, we note that Thorne and Thomas (2008) have documented a similar breakdown in the relationship between egg deposition and the adult population in PWS. As was the case for PWS, during the 80s ratio of the population of age 3 juveniles to adults in SS was characterized by a strong 4-year cycle. In both Sitka Sound and PWS during 1992-1993 this cycle disappeared and transitioned to a less reliable oscillation that may prove to have a 5-year periodicity. However, we note that since 1993 the amplitude of these oscillations in annual recruitment appears to be considerably smaller than those in PWS. We have called the sudden changes in adult populations and the establishment of new quasi steady states the "bi-stable condition" of PWS's and SS's adult herring populations. Both the bi-stability of the adult populations and the oscillatory patterns in annual recruitment are best explained as features of a nonlinear, density dependence of the herring's population dynamics. Such dynamics are a unique feature of population dynamics model that we have developed and which hope to further test and refine with an additional year's support.

2.3. Model Results

Figures 4 and 5 display the time series of annual variations in adult herring populations and age 3 juveniles calculated with Fish and Game's age structured analysis (ASA) and predictions calculated with our simulation model for PWS and SS, respectively. The ASA time series estimates of the adult and 3 year old juvenile populations are based upon annual sampling during the spring spawn from aerial surveys of milt distribution, acoustic surveys of adult schools, and the age distribution of herring sampled at various locations within the sound.

The simulation begins by providing initial values for the size of the populations of juveniles of ages 0 through 3 and adults. The size of these populations are then updated each time step (one month) along with the populations of fertilized eggs and larvae. The only other time dependent variable in the simulation is the survival probability that age 0 juveniles survive to age 1. This key variable drives the large annual oscillations in recruitment. In this simple model the survival probabilities of juveniles of ages 1, 2, and 3 are assumed to be independent of time and the adults are here assumed to be independent of the age and invariant during a selected period. With regard to the PWS time series, the simulation catches both the increase in the adult population and the 4 year cycle in the age 3 juvenile population that occurred in the 80s. It also catches the general decrease in the adult population from 1993 to 2007, but provides a less satisfactory description of annual variations in the population of age 3 juveniles. Specifically, during the latter period, the amplitude of annual oscillations in recruitment are diminished, and the 4-year period of the cycle is lost or perhaps replaced by a 5-year cycle…as suggested by the high levels of recruitment in 1994 and 1999 and 2004.

With a few notable deficiencies, we see that the simulation tracks well the ASA time-series for Sitka Sound. It performs particularly well from 1980 to 1995. Also notable is the extraordinary larger population of age 3 juveniles that were born in 1975-1977 (figure 3) and the replacement in 1992-93 of the dramatic 4-year cycle in age 3 juveniles by a series in which annual variation is much reduced and in which there is the suggestion of a 5-year cycle. This is the same year that the 4-year cycle disappeared in PWS. The change in recruitment that occurred after 1992 was most likely caused by the El Nino of that year. We also note the divergence between the simulation and the ASA time series beginning in 1995.

The simulated values shown above were obtained by first calibrating our population dynamics model to the ASA time series. This calibration employed our Newtonian, multidimensional search routine, which searches for values of selected variables of the model that provides the □$^{□}_{.}$best fit between model predictions and observations. In the simulations shown in figures 5 and 6, the search routine calculated values for the initial size of the population of the populations of age 0, 1, 2, and 3 juveniles and the total adult population. This was necessary in order to "synchronize" the cycle of recruitment predicted by our simulation with the cycle of recruitment found in the ASA time series. During this calibration the search routine also determined values for the "calculated variable" listed in tables 2 of the appendix. These "calculated variables" include the survival probabilities of juveniles of ages 1 through 3 and the adults. It also includes the product of the probability of successful fertilization of eggs, the survival probability of eggs, and the survival probability of larvae. These variables and their values are listed in the table of the appendix. We note that calculated survival probabilities of pre-adult herring all fall well within the range of the very limited number of measurements or estimates from field surveys. (See estimates of first year survival in McGurk and Brown, 1996; Rooper, 1996; Norcross and Brown, 2001, Norcross et al., 2001) On the other hand our calculations of the survival probability of adult are somewhat lower than the ASA estimate of 0.70. We believe this discrepancy can be resolved by a careful review of the value for the constants found in table 2 of the appendix.

For both PWS and SS such a calibration was exercised for two periods in the record. As indicated in table 2 of the appendix, in the case of PWS the model was calibrated for the period between 1980 and 1990 and between 1993 and 2007. In the case of SS the model was calibrated for the period between 1971 and 1980 and between 1982 and 1995. Such breaks in the calibration were necessitated by external events that altered the size of the herring population and altered timing and character of the recruitment cycle. These events include the 1975-1976 Pacific Decadal Oscillation (PDO) regime shift in the Gulf of Alaska, whose effects were expressed in 1980 and still continue, the 1992-93 El Nino, whose effects were immediate, the 1989 oil spill, whose effects were expressed in 1992 and 1993, and the overfishing in 1991-93 of PWS herring. In the SS simulation we decided to break the calibration in 1995 because of concern over the accuracy of estimates of the size of the adult population. Finally, the simulated time series shown in figures 5 and 6 were obtained by connecting the predictions for the two periods with a straight line.

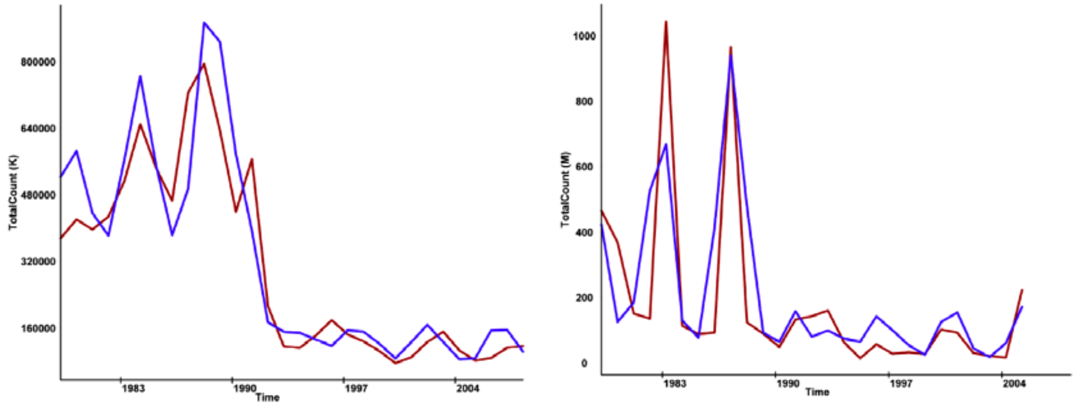

Figure 4. The simulated (blue) and measured (brown) abundance of adults (left) and age 3 juveniles (right) in Prince William Sound.

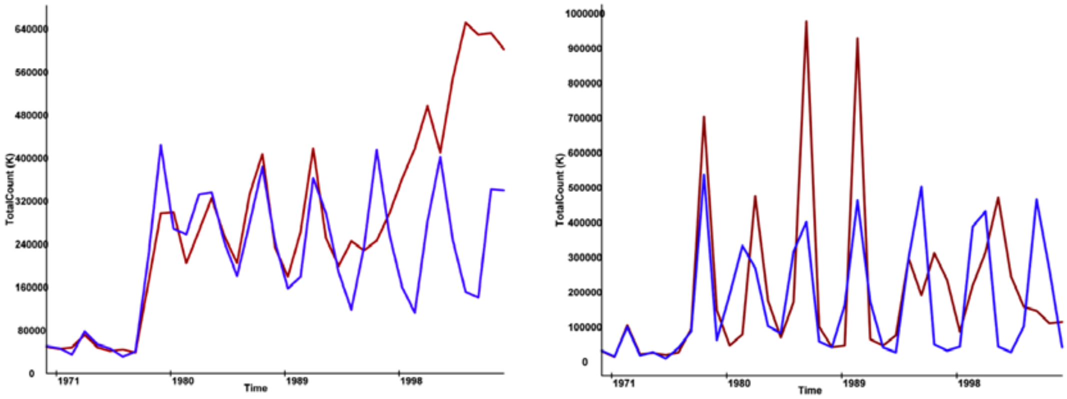

Figure 5. The simulated (blue) and measured (brown) abundance of adults (left) and age 3 juveniles (right) in Sitka Sound.

2.4. Summary of Model Results

Our model of PWS and SS herring indicates that most of the annual variability in the adult population and recruitment can explained by two factors. One factor is the internal dynamics of competition between juveniles of differing ages for food or perhaps other resources within nursery bays. This competition favors the older juveniles since they are larger, and thus they have an advantage in both foraging for plankton during the summer and surviving winter depravation. Thus we expect that the survival probability of age 0 juveniles is more variable than the survival probability of juveniles of age 1-3. Survival probabilities of age 0 juveniles are high if they colonize bays that are not already populated with older juveniles and low if the bays are fully occupied. Such dynamics can easily lead to oscillations since a high survivorship of age 0 juveniles will reduce the survivorship of age 0 juveniles entering the bay while this dominant cohort is resident in the bay. This "capping" of younger juveniles will continue until the strong cohort leaves the bay and there-by provide "room" for the next dominant cohort. We suggest that during periods when the adult population is large a dominant cohort can determine the survival probability of age 0 juveniles for 3 years, and thus set in motion the 4-year cycle. On the other hand, if external factors such as temporary reduction in food supply, outbreak in disease, or increase in predation on the juveniles reduce the population of age 1-3 juveniles in the bays, then the survival probability of age 0 juveniles will be higher and the amplitude and possibly timing of the cycle will be perturbed. We believe such a perturbation occurred in both PWS and SS during the 1992-93 El Nino. This event (Flatau, Talley, and Musgrave, 1999; Melsom et al., 1995) reduced the supply of food along coastal areas of the Gulf of Alaska. It caused the disappearance of the 4-year cycle in both regions. Although simple, our routine of juvenile dynamics was developed according to this concept of "cohort dominance". Although we have not yet conducted a serious search on publications that have recorded "cohort dominance", Sanderson et al., (1999) has described such a process in their long term study of the population dynamics of a lacustrine yellow perch.

-The second major source of the annual variability in the adult population and recruitment is the external climatic and anthropogenic processes. The two key climatic events are clearly evident by the "breaks" that occur in the ASA time series and our simulations. The first break occurred in 1975-76 when the Gulf of Alaska responded to the intensification of the Aleutian low (e.g. Francis and Hare, 1997). The long-term regime shift led to the dramatic increase in recruitment in SS that was expressed in 1980 by the dramatic increase in the population of adult herring. (Although the data are not shown here, PWS herring displayed a similar but less dramatic response.) We speculate that this shift either altered the circulation or increased the supply of plankton to the PWS and SS and thus expanded the nursery grounds (possibly spatially or in terms of carrying capacity) for the juveniles. This expansion represented a perturbation to the juveniles dynamics described in the previous paragraph and set off the 4 year cycle in both PWS and SS. We have already alluded to the second break in our simulations and in the ASA time series- the 1992-3 El Nino, which represents a short-term perturbation within the regime shift of 1975-76. In SS this perturbation caused a large reduction in the birth in 1992 of a dominant cohort of age 3 juveniles, but did not appear to impact the recruitment of age 4 juveniles in 1992 (See figure 3.) This event also appeared to distribute the distribution of juveniles in the bays sufficiently to cause the disappearance of 4-year cycle and replace it with a low amplitude oscillation that may be of a 5-year periodicity. (According to our mathematical routine, a 5-year periodicity would require age 4 juveniles to influence on conditions in the nursery ground.) The impact of the 1992-93 El Nino appears to be much greater in PWS. Not only did the expected birth of a dominant cohort in 1992 fail and the 4-year cycle disappear, but also the expected strong recruitment of age 4 juvenile also failed. In this case the lack of sufficient food for the adult population was fully documented by the large decrease in lipid and energy content of adults at this time (e.g. Brown, 2003). Most importantly, the adult population crashed and currently remains trapped at a low density. We believe that the more severe impact of the 1992-93 El Nino in PWS relative to SS is the result of compounding stresses caused by over fishing in 1992 and 1993 and the elevated mortalities of adults and juveniles by the 1989 oil spill. We propose this year to make a more quantitative assessment of such interactions impacts when we run a more advanced version of our model this coming year.

3. Future Work

During our third year of work, we will examine the transition periods caused by the external events to see if we can eliminate the need for the breaks mentioned in the paragraph above. We have made good progress in formulating the growth of juveniles and adults and predation upon adults. The dynamics that creates a bi-stable state for the adult population is now described mathematically. Our next challenge is to understand and formulate the dynamics that underlies the large annual variations in recruitment at the low and high density states as shown in Figure 5. These dynamics occur in the pre-adult stages, embryos, larvae, and juveniles. Although the variation in recruits per spawner found in figure 5 appear random, they are not. In the 80s high rates of recruitment occurred every 4 years…a remarkable and dramatic feature of the population. Throughout the period of the low density state which began in the early 90s, the 4-cycle either collapsed or was greatly reduced; none-the-less, in the low density state annual variations do not appear random but follow a cycle in which the periodicity is not as regular as that found in the 80s. We believe that the most reasonable explanation for such variation is found in the dynamics of the juvenile populations residing in bays. The cycles may be caused by predator-prey interactions such as the predation of pollock on herring, variations in infection and immunization of juvenile populations carrying VHS, variations in food availability as determined by competition or supply, and possibly interactions between year 1 and year 2 herring juveniles.

More generally, our work will also include entering the mechanistic routines into the tuning model. This will include the routines developed by Kiefer as well as modifications of the routines that Dr. Patrick has developed for PWS pink salmon. We will then run the framework search routine comparing model predictions with data found in the framework database thereby both testing the accuracy of model and obtain optimum values for system coefficients. This process requires that we complete loading the field database into the framework. In fact obtaining such data from the last 30 years, reformatting it, and subjecting it to quality control has been a difficult and time consuming job. If funds are available, additional support for this work would be most helpful. Finally, we will begin running the tuned model to test restoration proposals.

4. Co-ordination & Collaboration

Week of 7/15/08 D. Kiefer, E. Brown, V. Patrick attended EVOS Herring Workshop. Cordova

Week of 12/8/09 D. Kiefer, E. Brown, V. Patrick attended EVOS Herring & Tagging Workshops. Anchorage

January 20, 2009 Invited Presentation, D. Kiefer, E. Brown, F. O'Brien, and V. Patrick. **Modeling the Bi-Stable State of Prince William Sound Herring** Alaska Marine Symposium, Anchorage

August 17, 2009 Invited Seminar, **The Mystery of Prince William Sound Herring: A Population Dynamics Analysis,** by Dale Kiefer to faculty and students at University of Maine, Orono.

August 24, 2009 Invited Seminar, **The Mystery of Prince William Sound Herring: A Population Dynamics Analysis,** by Dale Kiefer to marine scientists at the Bigelow Laboratory of Ocean Sciences, Boothbay Harbor Maine.

September 15, 2009. D. Kiefer, E. Brown, F. O'Brien, and V. Patrick completed 6 month study with Heather Meuret-Woody on the current status of the herring of Sitka Sound for the Sitka Tribe. Final report on dramatic changes in dynamics of SS herring has been submitted.

Please submit reports electronically in ProjectView or by email to mandy.migura@alaska.gov. Also, please be sure to post your annual report on your own website, if you have one.

We appreciate your prompt submission of your annual report
and thank you for your participation.