AYK SSI Final Report September 2010

Project Title: **Future Climate/Habitat of AYK Ecosystems**

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1. Project Objectives

Objective 1. Provide the future trend and variability of environmental variables important to salmon abundance out to 2030.

Objective 2. Work with communities and other AYK SSI investigators to provide confidence estimates on future salmon abundance potential.

Objective 3. Be a community resource on retrospective and future climate change issues through direct contact and an interactive website where communities and investigators can provide information and pose questions.

Objective 1.

This objective comprised the bulk of our effort. Our projections are based on 23 available global atmosphere-ocean climate simulations carried out in preparation for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. There are two steps to the completed analyses. The first was to restrict the analysis to the climate models which are best suited for anticipating changes in the overall climate of Alaska. The basic criterion we have used here has been the fidelity with which the various models are able to replicate the observed climate variability of the last half of the 20th century model. For air and sea temperatures in the AYK region and related variables such as ocean mixing we compared the models with the variability of Pacific Decadal Oscillation (PDO). The PDO is an index of North Pacific sea temperature variability that responds to large scale weather and climate, especially the Aleutian low pressure system and associated air sea fluxes. We have found that 12 of these models capture the essence of the PDO in their 20th century hindcasts. For sea ice, which responds more to northerly wind in the AYK region, we use the results for Arctic sea ice- that the ice summer extent value and annual range of ice must match observations. The method and results from these studies are published (Wang et al. 2010; Wang and Overland 2009; Overland and Wang 2007a, Overland and Wang, 2007b). As a second step we evaluated the results for specific variables in the AYK region. This evaluation is also based on the model hindcasts for the 20th century and involved comparisons between the individual model runs and observations with respect to means, variances, and in some cases, the seasonality of the variable of interest. The procedure was summarized in Hollowed et al. (2009) and Overland et al. (2010, in final review). The climate community has not yet established a single "best" way to account for the differences in the model projections. For example, some groups assign relative weights to individual model projections (e.g., Hollowed et al. 2009) while others contend that there is insufficient evidence to unambiguously rate the models based on past performance. Our experience is that using weights in the formation of an ensemble mean tends to produce only modest differences compared with that from a simple ensemble mean. There can be more substantial differences in the tails of the distributions, as discussed below.

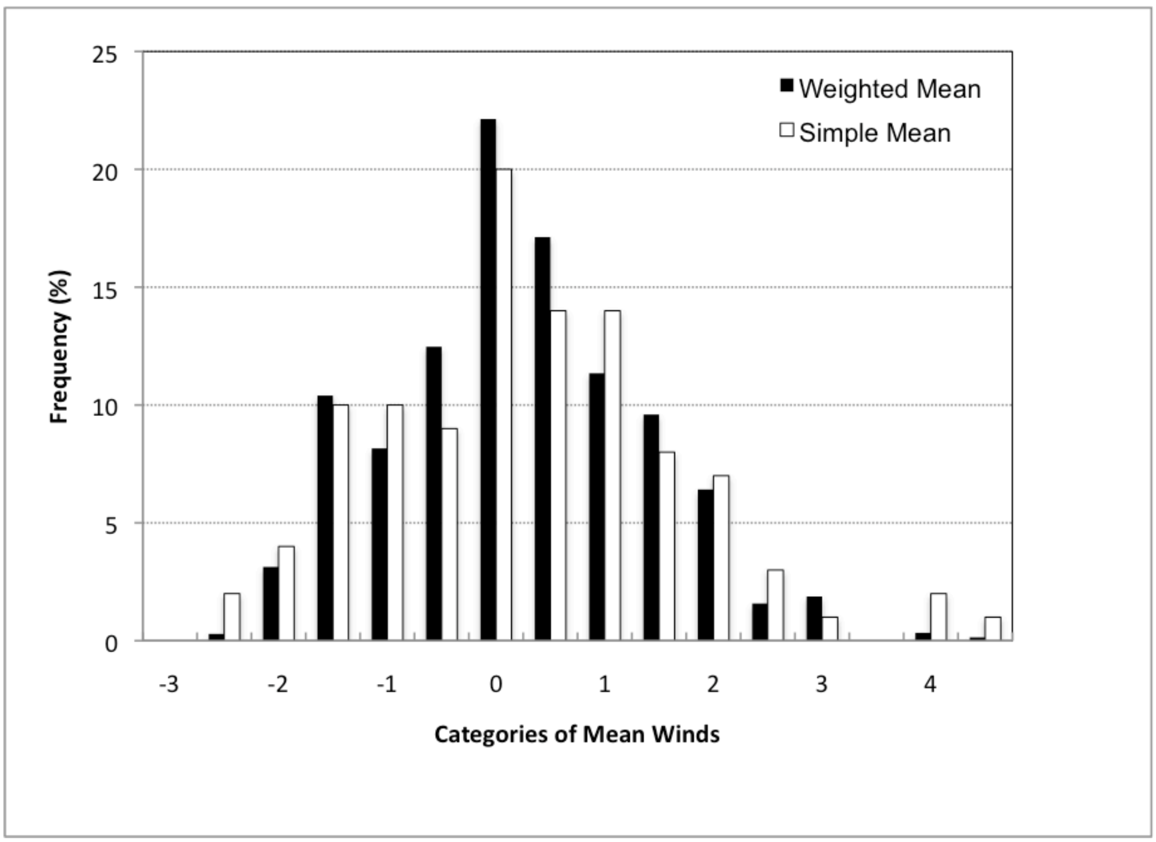

Figure 1. Comparison of histograms between simple and weighted ensembles for onshore wind component projections in the southeast Bering Sea using 21 ensemble members and samples from five individual years (2043-2047). There is a shift in mean and a reduction in extremes when the influence of models with poor comparisons to observed winds are given reduced weight.

Our analysis of the onshore wind component in the southeast Bering Sea provide an example of a comparison between a simple and weighted ensemble. Histograms of the simulated springtime averaged (April-June) onshore wind component for 104 samples (21 ensemble members and yearly samples from a 5-year period of 2043-2047) are shown in Fig. 1. The 12 models used are the ones that replicated the PDO in their 20th century hindcasts. The weighted ensemble has a mean and median that is shifted slightly relative to the simple, unweighted ensemble. Perhaps more importantly, the tails of the distribution are less pronounced in the weighted versus unweighted ensemble. Individual models yielding strongly negative and positive wind anomaly projections were among the group that received lower weights based on 20th century hindcasts. While the two ensembles are similar, the reductions in extreme projections suggest that weighting may be appropriate for some applications.

Our analysis of the IPCC model projections focused on thermodynamic variables. We have found that the model projections yield relatively modest overall changes in wind and weather patterns, and gyre-scale currents, over the first half of the 20th century. On the other hand, there are much more prominent trends in temperatures and sea ice extent. Therefore, it is expected that these trends will dominate the signal associated with the systematic changes in the climate. We have examined a variety of parameters. Our choices here were based on present understanding of the role of climate in the marine ecosystem of the Bering Sea in general, and some issues related to AYK salmon stocks in particular. The specific parameters considered here (others have been considered in related work) are as follows: (1) sea ice extent on the eastern Bering Sea shelf due its structuring of the ecosystem, i.e., favoring pelagic versus benthic communities, (2) late summer SST due to its relationship to stratification and ultimately lower-trophic level production going into autumn, (3) spring air temperatures due to their association with western Alaskan pink salmon success (Mantua 2009), and (4) summer air temperatures over interior Alaska due to their presumed impact on Yukon River temperatures and ultimately the susceptibility of king salmon to parasites. The last element was selected based on a discussion of climate/AYK salmon relationships with Dr. Katherine Myers and Dr. Nathan Mantua of the University of Washington's School of Aquatic and Fishery Sciences.

Our evaluation of sea ice in the eastern Bering Sea (54-66° N, 175°W-155° W) started with the six models identified by Wang and Overland (2009). We then further required that these models be able to simulate the spring (April and May) sea ice extent over eastern Bering Sea with less than 20% error of the observed value. The process indicates four models that are more reliable for projections of sea ice over the eastern Bering Sea. Their sea ice forecasts are shown in Fig. 2.

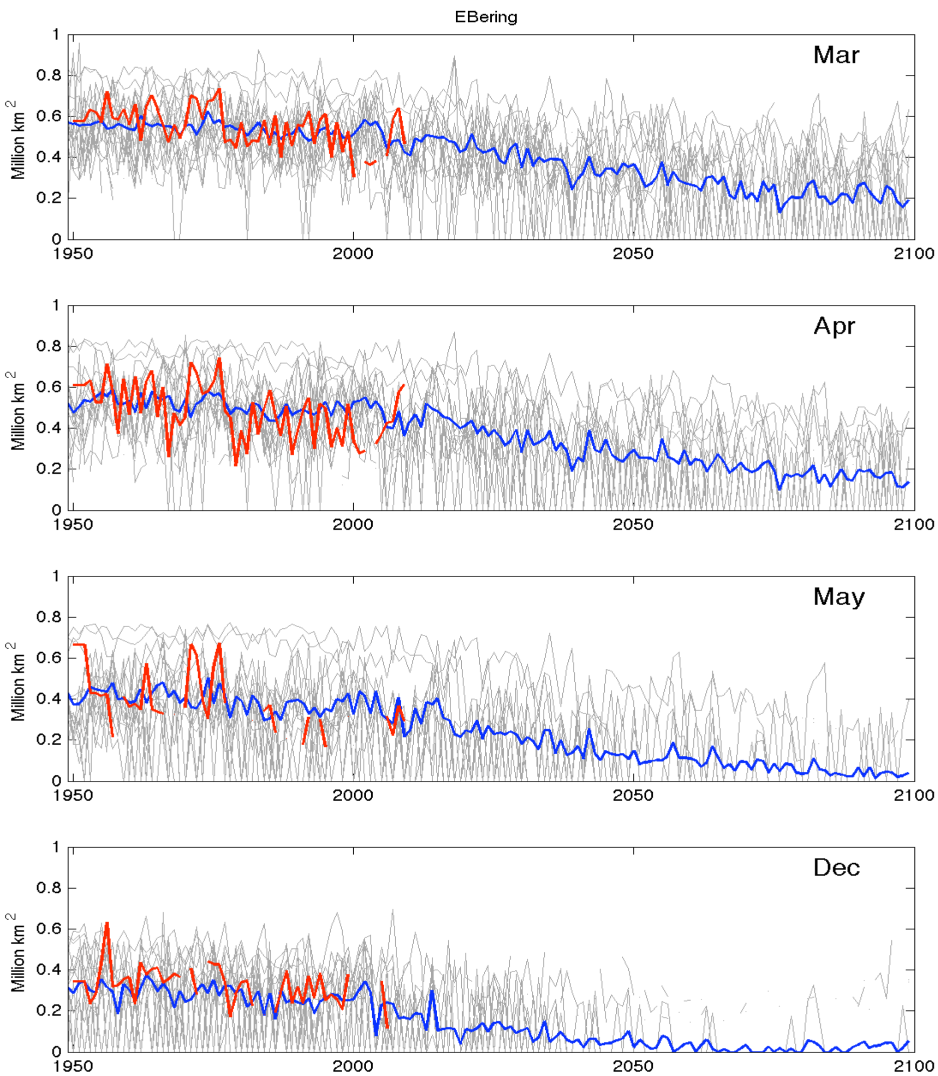

Figure 2. Model simulated sea-ice extent over the eastern Bering Sea for the months of March to June. The red lines (observations) are based on HadISST analysis and the other colored lines are the ensemble means of the four models (CCSM3, CNRM, ECHO-G, and MIROC(medres)) under A1B (blue) and A2 (magenta) emission scenarios. Each grey line represents one realization by one of these models.

The sea ice on the eastern Bering Sea shelf in late winter/early spring is a key factor in determining the extent of the cold pool in the middle shelf domain during the following summer. Since global climate models cannot simulate the cold pool properly due to their inadequacies in resolving the bathymetry and handling mixing, we have made projections of cold pool extent using an empirical technique. Specifically, we used a general additive model (GAM) to determine the robust predictors of cold pool extent (based on observations for the period of 1980-2006) from a set of potentially predictable variables that are tractable to be forecast by climate models. Two robust parameters emerged from this analysis, the sea ice extent, as anticipated, and the spring weather, as encapsulated by sea level pressure (SLP) over the eastern Bering Sea. The functional relationships between these two parameters and cold pool extent from the GAM, and the model simulations of the two parameters to 2050, formed the basis for projections of cold pool extent, as illustrated in Fig. 3. While we are unaware of any research on AYK salmon that links their success to cold pool extent *per se*, we felt that the results shown in Fig. 3 will be of general interest. Our method yields a change in average cold pool extent (as defined as the percentage of the area encompassed by NOAA's annual bottom trawl survey on the shelf) from about 40% to less than 20% by 2050. It is important to also recognize the year-to-year variability in cold pool extent, which is about 15% based on our analysis. In other words, this measure of the climate should be anticipated to undergo the magnitude of the fluctuations indicated by an individual model run (the pastel traces in Fig. 3) rather than the ensemble mean.

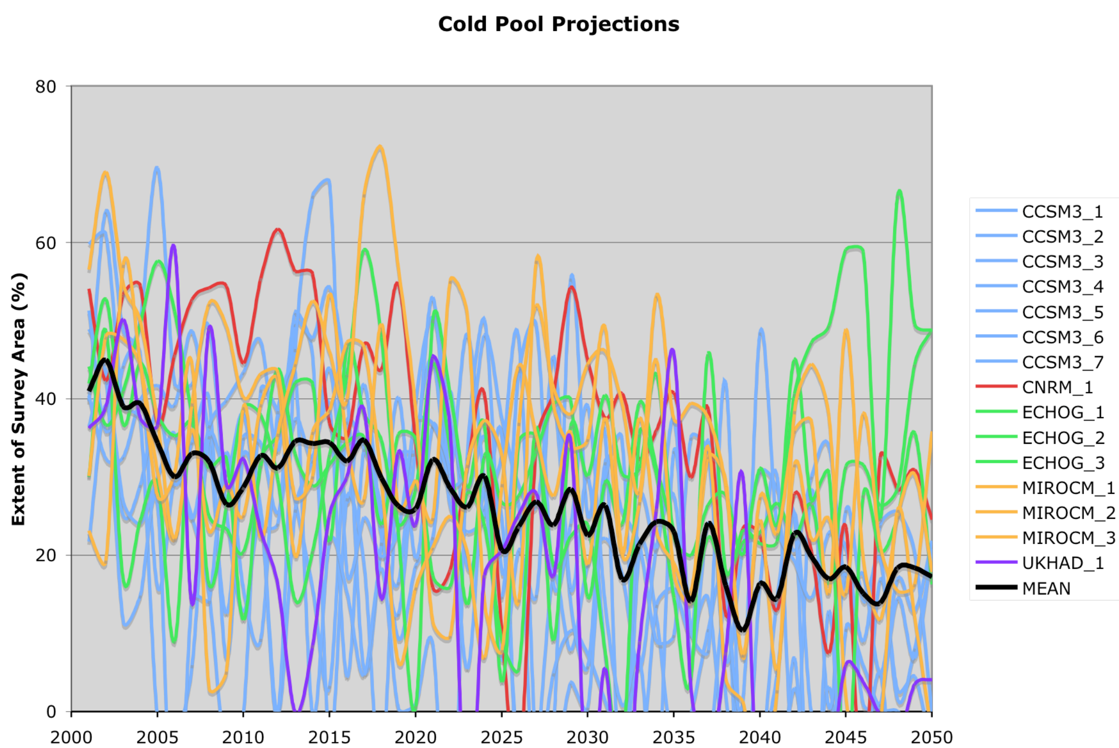

Figure 3 Projected cold pool extent (% of bottom trawl survey area) based on forecasts of sea ice and spring (April-June) SLP. The ensemble mean is shown with the heavy black line. See text for details.

The sea surface temperature (SST) in late summer is another physical ocean property that is linked to the marine ecosystem of the eastern Bering Sea (Mueter et al. 2010). Projections for this parameter appear to be relatively tractable from global climate model simulations. Figures 4a-c show these projections under the B1, A1B and A2 CO_2 emission scenarios. As with all the projections we have examined for the Bering Sea, and for that matter, anywhere in the North Pacific, the interannual variations in SST are much greater than the mean differences between the emission scenarios, at least out to about 2050.

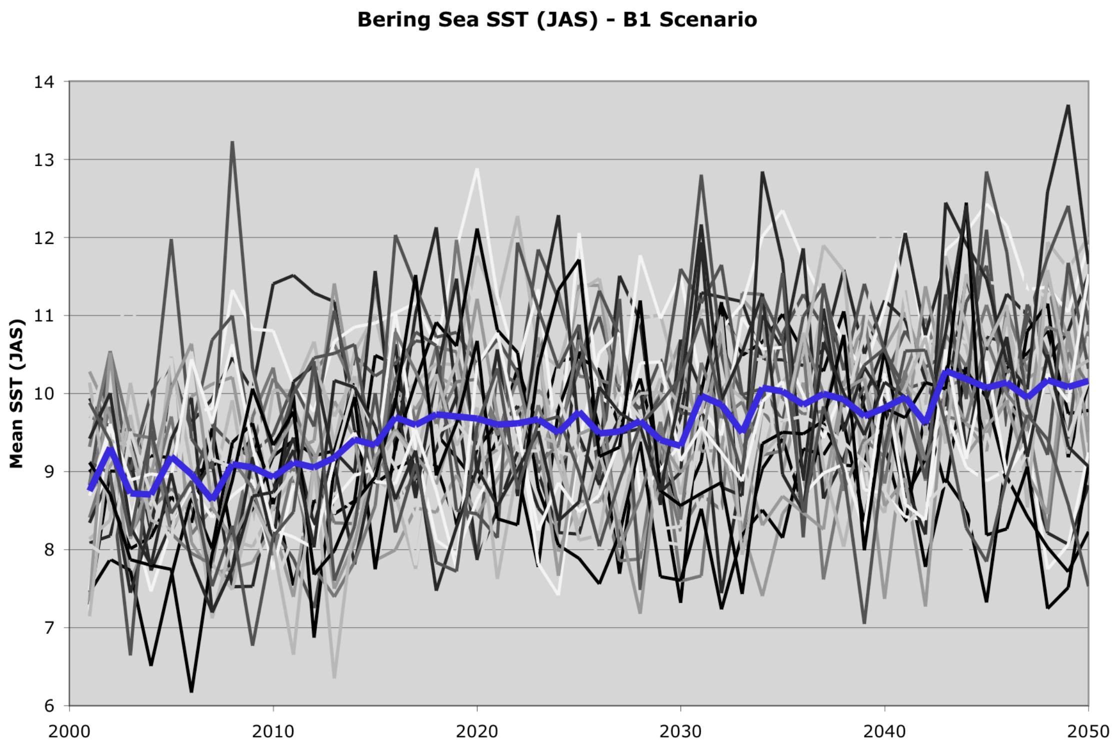

Figure 4a IPCC model projections of SST for the months of July-September on the eastern Bering Sea shelf south of 61 N. Individual model projections are show by gray lines of varying shades; the ensemble model is shown by the bright blue line. All individual model runs are bias-corrected. The standard deviation in the projected SST in any given year is about 1.2° C.

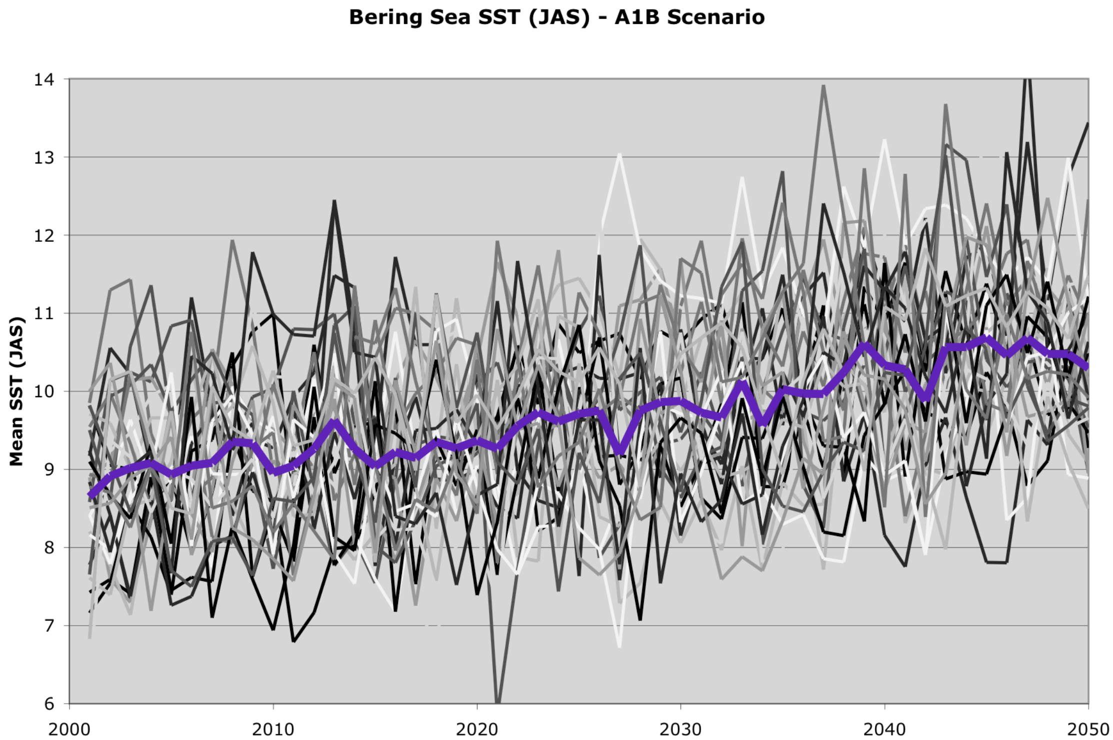

Figure 4b As in Fig. 4a, but for the middle-of-the-road A1B CO_2 emission scenario.

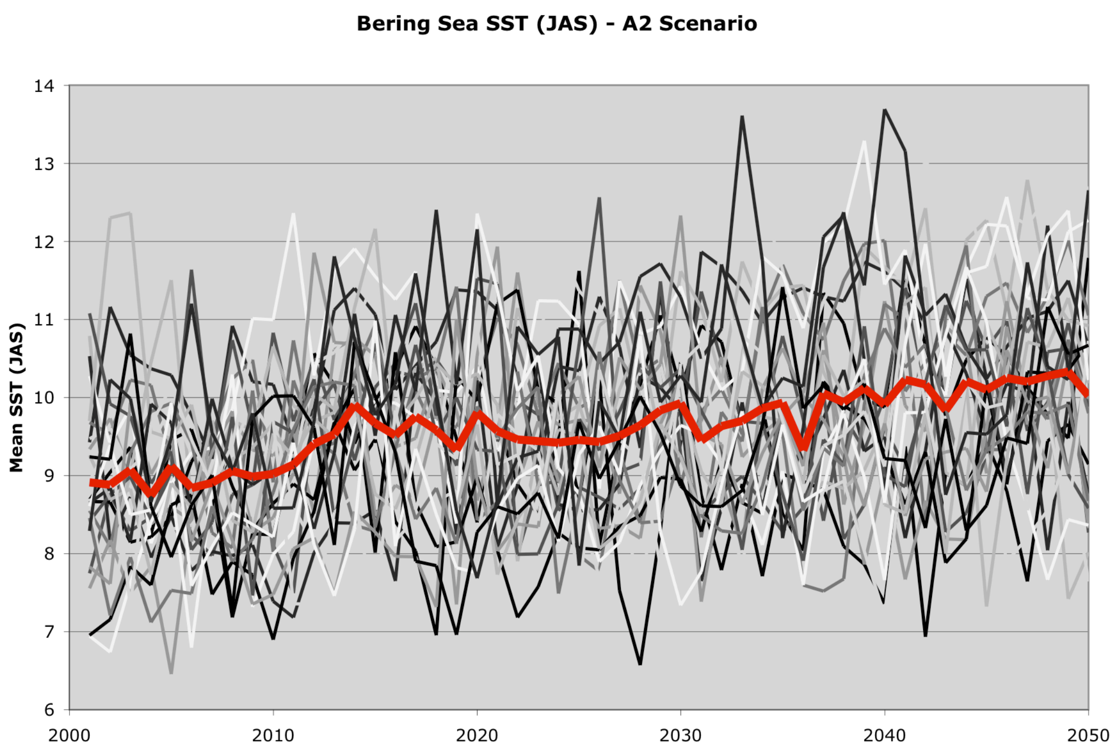

Figure 4c As in Fig. 4a, but for the A2 CO_2 emission scenario.

A recent study of Mantua (2009) indicated that the production of Norton Sound pink salmon tended to increase with January-May air temperatures in western Alaska during the period of 1962-1995. The very warm years of the early 2000s also featured relatively strong year classes. Air temperature is probably the parameter that is most reliably forecast by IPCC-class climate models. Because of its tractability, and apparent importance to at least one salmon stock, we have considered it as part of our project. The model forecasts of Jan-May average temperature anomalies, relative to a 1980-2000 mean are summarized in Fig. 5. It is interesting that the ensemble mean rise in temperature of about 3° C by the 2040s is roughly double that found for the late summer SST (Fig. 4b). The overall warming trend is robust and suggests that the habitat for this particular stock is liable to improve. This makes sense from the point of view that the Norton Sound stock of pink salmon is at the northern limit of this species range. Nevertheless, as cautioned by Mantua (2009), without a better mechanistic understanding of the sensitivities of this fish stock to environmental conditions, it is uncertain whether the much warmer climate of the middle of the 21st century will necessarily be favorable.

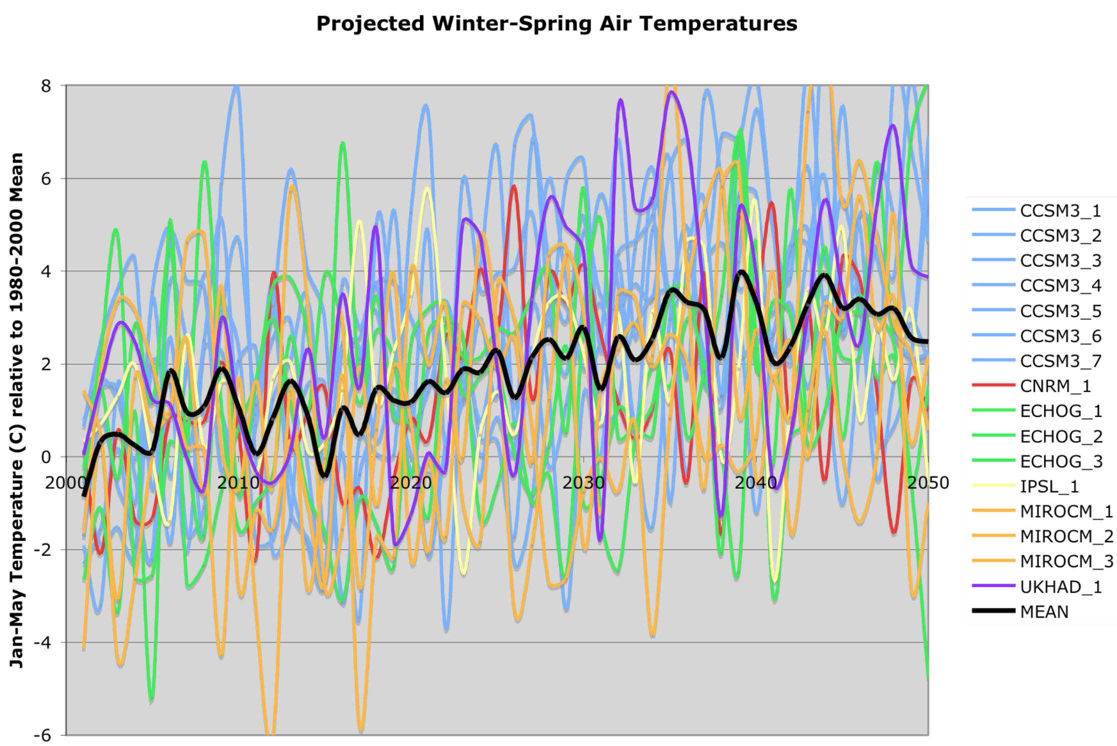

Figure 5 Projected mean winter-spring (Jan-May) air temperatures relative to 1980-2000 mean for western Alaska (60-66 N, 165-150 W). Each model run (pastel colors) is for the A1B emission scenario and is bias-corrected. The ensemble mean is shown with a heavy black line.

One way in which a much warmer climate could be deleterious to salmon relates to their freshwater habitat. Specifically, warmer weather during the summer as adults are returning to spawning grounds may exacerbate thermal stresses and susceptibility to parasites (e.g., *Icthyophonus;* Kocan et al. 2003). Mohseni et al. (1998) provide a method for estimating water temperatures from air temperatures. We do not have the necessary data required to develop the regression coefficients required by the Mohseni et al. method and so for present purposes, we have simply considered summer air temperatures over interior Alaska. The tacit assumption here is that the relationship between air temperature and stream temperature is strongly positive. Specifically, we have compiled time series of maximum monthly average temperatures (which occur in either July or August) from the climate model simulations for the period of 2001-2050 under the A1B emission scenario. The time series of these temperatures, relative to a 1980-2000 norm, are plotted in Fig. 6. Note that while there is a systematic increase in the expected monthly maximum temperatures, the probability of extremely hot summer months (i.e., anomalies exceeding 4-5° C) does not change markedly over the next 4 decades. It is also interesting that the year-to-year variability in the monthly mean maximum temperatures varies from model to model, with the CCSM3 and ECHOG models demonstrating especially large and small variability, respectively. There is little basis for determining which sets of model projections are more or less likely.

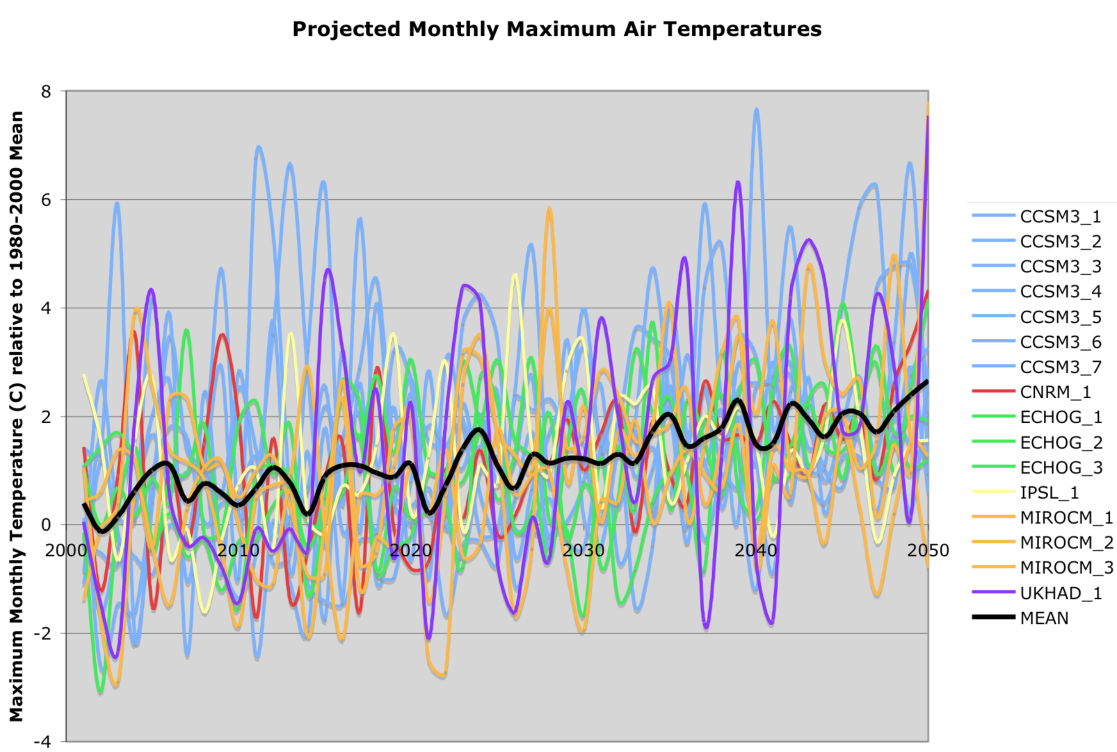

Figure 6 As in Fig.5, but for maximum summertime (monthly mean) temperatures.

Objective 2

In order to determine the impacts of the future climate on AYK salmon, quantitative relationship(s) must be established between salmon populations and physical variables such as temperature, winds and sea ice cover. In other words, projections are only feasible for specific salmon stocks that are known or at least strongly suspected to be sensitive to predictable aspects of the atmosphere-ocean system. As indicated in our proposal, the early stages of our analysis incorporated the relationships outlined by Shotwell and Adkison (2004) and Shotwell et al. (2005) pertaining to Kuskokwim and Yukon River chum salmon. These results suggest different outcomes for the two different chum salmon stocks. Two important environmental controls on past returns for the Kuskokwim River fish, springtime air temperatures for western Alaska and winds in the vicinity of Unimak Pass, are expected to exhibit overall trends that are deleterious. On the other hand, at least the leading parameter for the Yukon River chum salmon, i.e., precipitation in western Alaska during spring, is liable to increase, which at least in the historical record is a positive influence. The result of this work was presented at Alaska Marine Science Symposium, 21-24 January 2008, Anchorage, AK. Discussions with Doug Molyneaux of the Alaska Department of Fish and Game at the symposium indicated that the relationships identified by Shotwell and co-workers did not appear to be valid in recent years. For this reason, we have concentrated on describing the trends being predicted in the overall climate of the eastern Bering Sea and western Alaska by global climate models, rather than on specific parameters directly linked to salmon survival or recruitment. An exception is winter-spring air temperatures (as discussed in the previous section) because of the recent study of Mantua (2009), which demonstrates their importance to the pink salmon of Norton Sound.

There are some general results from our research that may be of relevance and direct benefit to AYK-SSI interests. Specifically, our results suggest that for virtually all of the parameters that we have examined, that the climate change signal will exceed the magnitude of the present and future interannual variability by 2030-2040. During that decade, the climate models are suggesting that the typical year will resemble the very warmest years (i.e., 1.5 to 2 standard deviations above the mean) of the present climate. Only the coldest/heaviest ice years at that point in time will resemble the present climate's "normal" years. Up until that point, which does vary depending on the parameter and season, interannual and decadal fluctuations due to the intrinsic variability of the climate system are apt to dominate. The important point here from an AYK-SSI standpoint is that the exceptionally warm years of the last couple of decades, such as the early 2000s, may represent a useful analog or proxy, for the conditions expected to occur routinely in about 25 years.

Objective 3

Our original plan included serving IPCC model simulations on our website, www.beringclimate.noaa.gov (through the "Projections" link).
This activity was delayed until we could complete our two-step model evaluation procedure as discussed under Objective 1. We completed processing the model data onto a common grid, formed area-averages for various parameters characterizing the climate of the eastern Bering Sea and western Alaska, and created some illustrative figures. This information was made available to the outside community in late August 2010. The model projections all pertain to the A1B CO2 emission scenario; we have found that other sources of uncertainty, especially differences in both the overall trends and phasing of interannual variations from model to model, dominate the projections for the region of interest.

The website includes explanatory "readme" links, which include contact information for Nicholas Bond and Muyin Wang for users needing additional information (either model data or explanation). We expect that this website will be a valuable resource in as of itself but that is not all. Even though this project is nominally finished, we will honor reasonable requests from the AYK-SSI and related communities for future assistance with IPCC model data.

Additional Activities and Outcomes

In the last year we began a collaboration with Phil Mundy of NOAA/Auke Bay Laboratory. We have helped him extend a relationship between the timing of the return of Yukon king salmon and April air temperature at Nome (Figure 7). We have provided time series of an additional variable suspected to be important, Norton Sound SST. Results from this project were presented at the Climate Change Effects on Fish and Fisheries Conference in Sendai Japan in Spring 2010. Very recent indications from the timing of the returns indicate that the predictive model continues to be valid. We plan to continue to work with Mundy and co-workers, and in particular to provide the forecasts of predictor variables to make projections of the timing of future Yukon king salmon returns. Finally, we plan to maintain our dialogue with Kate Myers of the University of Washington and other AYK salmon experts to explore the possibilities of projecting the success of other specific salmon stocks that are sensitive to physical environmental variables.

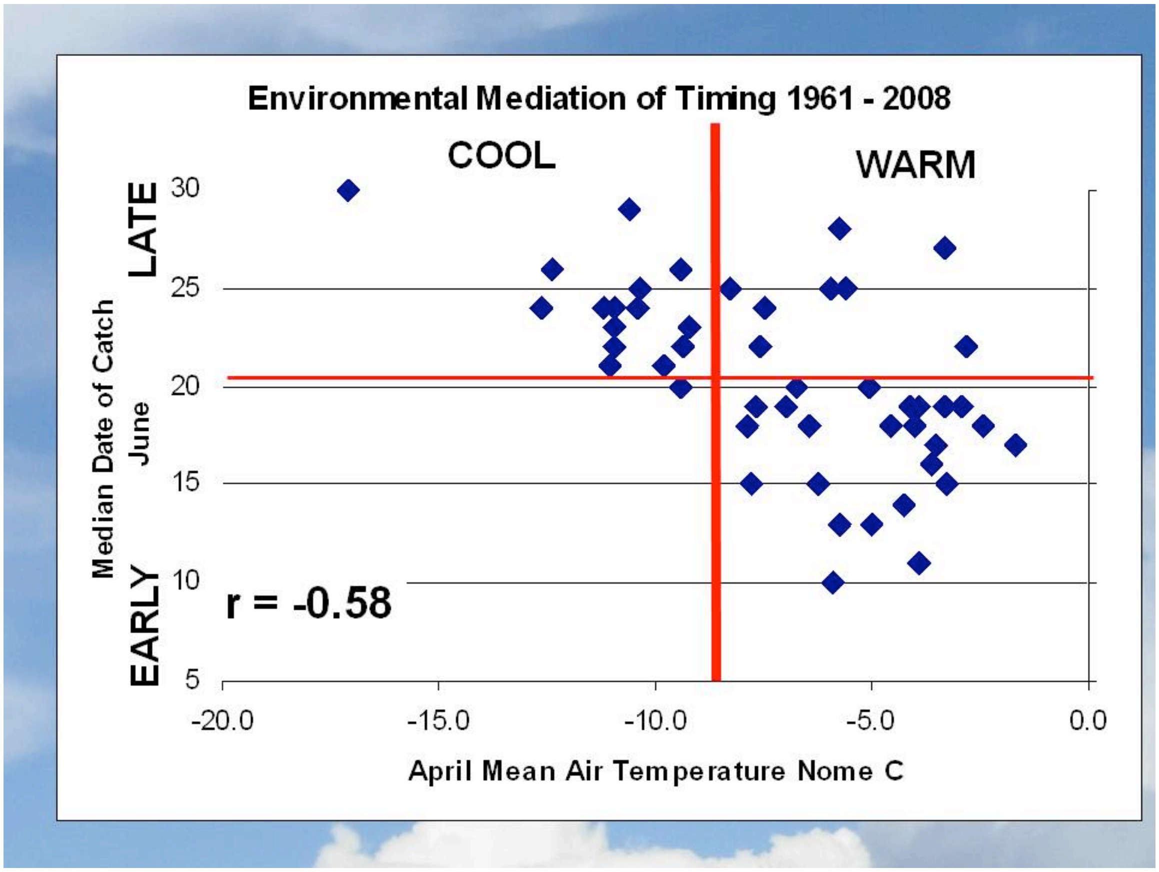

Figure 7. Relation of timing of Yukon River king salmon to April air temperatures.

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Selected presentations under the auspices of the present project

Bond, N.A.: “Projections of Kuskokwim River Chum Salmon Runs Based on IPCC Model Simulations”, Alaska Marine Science Symposium, Anchorage, AK, January 2008.

Bond, N.A.: “Implications of Climate Change on Western Alaska Chum Salmon”, 7th Republic of Korea – United States Fisheries Panel Conference, 24-26 June 2008, Busan, Korea

Bond, N.A., J.E. Overland and M. Wang: “Expected Changes in the Climate Forcing of Alaskan Waters in Late Summer/Early Fall”, Alaska Marine Science Symposium, Anchorage, AK, January 2009.

Bond, N.A: “Evaluation of the Oceanographic Component of Climate Models used by the IPCC”, 3rd Open GLOBEC Science Meeting, Victoria, BC, 22-26 June 2009.

Wang, M., J.E. Overland and N.A. Bond: “Examples of Using Global Climate Models for Regional Marine Ecosystem Projection.” Climate Change Effects on Fish and Fisheries, Sendai, Japan, 26-29 April 2010.