Report on the workshop on climate impacts on Pacific salmon • February 6, 2009 • Vancouver, BC

Contents

Welcome, introductions

Dick Beamish, Chair

The PSC's Committee for Scientific Cooperation was tasked with looking at climate impacts on salmon. As scientists working on these issues, this group was invited to offer advice on the most urgent research needs to respond to expected impacts of global warming on salmon. This input will be used to draft a short report to the Commission, outlining what a subset of the scientific community thinks needs to be done.

Participants briefly introduced themselves, noting their research interests:

- **Tony Farrell**, UBC Centre for Aquaculture and Environmental Research: fish physiology
- **Gordon Reeves**, US Forest Service, Pacific Northwest Research Station: work on freshwater, temperature effects on interspecies competition, disease, etc
- **Nate Mantua**, School of Aquatic Fisheries Science, University of Washington: forest, hydrology, looking at retrospective studies to identify patterns
- **Carrie Holt**, Pacific Biological Station, DFO: Working on implementation of the Wild Salmon Policy and methodologies to develop benchmarks and metrics to indicate biological status of salmon conservation units
- **Dave Hankin**: Humboldt State University, CSC committee member

- **Paul LeBlond**, Chair, Pacific Fisheries Resource Conservation Council: physical oceanographer.
- **Brian Wells**, NOAA Fisheries: Works on chinook in coastal California and growth patterns on the Alaska coast, including ecosystem effects of changing climate.
- **Kate Myers**, School of Aquatic Fisheries Science, University of Washington: High seas salmon research; recently shifted to working on climate change impacts on salmon in the high seas.
- **Dick Beamish**, Pacific Biological Station, DFO, CSC committee member
- **Steve Pennoyer**: Alaska, Committee Chair
- **Laura Richards**: Regional Director, Science, DFO and Committee Co-chair
- **Greg Ruggerone**, Natural Resources Consultants, Inc.: independent researcher – freshwater and marine issues in Alaska
- **Karl English**, LGL Consulting, Inc.: research with PSC, DFO and BC on salmon, including tracking studies in the Fraser and elsewhere since 2002.
- **Kristi Miller**, head of Molecular Genetics, Pacific Biological Station, DFO: works on salmon genetics and recently on functional genomics in salmon migration physiology, looking at conditional difference during migration.
- **Mike Lapointe**, Chief biologist, PSC: In-season management, including how to react/deal with fallout from climate change.

Opening remarks

Laura Richards

Membership of the Committee on Scientific Cooperation consists of Hankin, Beamish, Pennoyer and Richards. Their role includes advising the Commission on emerging issues. The CSC anticipates that factors relating to climate change will be important for how the PSC operates in future and wants to ensure that advice is provided now on what research should be done in the next few years in order to position science advisers to answer the urgent questions that may be asked five years from now.

Recent changes in Fraser River sockeye: Fodder for climate change hypothesis

Mike Lapointe

Freshwater productivity: Data from the Chilko sockeye smolt program data show smolt abundance ranged from 1 to 40 million between 1951 and 2006. Abundance for 2007 and 2008 was about 75 million. Smolt size was also larger or average both years. The number of smolts per spawner for both years was far outside anything seen before, with little evidence for density-dependent effect on size, as would be expected given the very large smolt abundances.

Why? A theory is that melting glaciers and reduced glacial inputs increase water clarity, light and food. (The lake was fertilized before the early 1990s). Why the explanation is just a hypothesis, this example points out that not all climate impacts at all life stages should expected to be negative. Futhermore prediction of such a response from climate change is impossible without a mechanistic model linking biology to future changes in physical inputs.

Marine productivity: All Fraser sockeye stocks that went to sea in 2005 did poorly. That year there was a very warm sea surface temperature (SST) anomaly in June/July.

Migration behaviour: Monitoring, including marine test fishing in Johnston Strait and Juan de Fuca, showed extreme early timing in 2008 and extreme late return timing in 2005. In the last four years, more extremes in return migration timing have been observed than in the last 30 years. Coastal waters of the North Pacific were unusually cold in 2008 and unusually warm in 2005, and it is hypothesized that ocean temperatures are a key determinant of return timing.

- Ruggerone: Bristol Bay research also indicates that if the ocean is warming up faster, returns are earlier.

Consequences of a warm ocean and extreme late timing include reduced marine survival, increased stock overlaps in fisheries and reduced body size and energy reserves for upstream migration.

Consequences of a cold ocean and extreme early timing include increased marine survival, optimistic early in-season assessments, early up-stream migration and higher pre-spawn mortality.

The 2005 episode raises several key questions for managers about the effects of climate change on marine productivity: Will 2005 become the norm. Will there be more extremes in behaviour and survival? Will ocean regimes patterns change? A key concern is that mechanisms linking physical changes to changes in survival and behaviour are poorly understood.

Fraser upstream migration conditions: Since the 1940s, peak summer water temperature has risen about 2 C, with record highs in recent years. Earlier-migrating Late-run sockeye are encountering upstream migration temperatures around 5 C warmer than normal and climate models predict an increase in summer water temperatures of at least 2 C. In 2004, stocks in the Early Summer, Summer and Late run-timing groups encountered significantly higher river temperatures during most of July and August.

Lower river projections of upstream escapement estimates at Mission (Mission escapement estimates less in-river catches between Mission and the spawning grounds), temperature monitoring at Qualark and spawning ground assessments show that average up-river migration losses correlate strongly with high river temperatures. In 2004, when very warm migration conditions were experienced, spawning escapement was 70% less than the lower river estimates for Summer-run stocks. While regional scale predictions of future climate effects are uncertain, if the predicted 2 C or greater increase in summer water temperature materials, average conditions in 50-80 years would be more like the 2004 extreme event that generated 50 - 80% migration mortality in Fraser sockeye? Thus the success of upstream migration may pose the most significant survival bottleneck for Fraser sockeye in the face of climate change.

Aerobic scope and river migration temperature

Farrell's work has built a mechanistic understanding of migration temperature effects. His model explains how aerobic scope (i.e. gap between maximum oxygen consumption rate and minimum required for routine body function = capacity available to perform other activity) at first rises with increasing temperature, with an optimal temperature (T_{opt}) that maximizes aerobic scope. As temperature continues to rise, maximum oxygen consumption rate starts to decline, while the amount required to maintain basic function rises, until a critical temperature (T_{crit}) is reached where aerobic scope is reduced to zero.

Aerobic scope temperature profiles have now been developed for three Fraser salmon stocks. The results show that absolute aerobic scope and T_{crit} vary among the stocks, with a difference of only 6 – 7ºC between the T_{opt} and T_{crit}. Comparing these profiles to historic river temperatures during each stock's migration period shows that T_{opt} for each stock is consistent with (adapted to?) the historic river temperatures they've experienced during their migration.

In a year like 2004, river temperatures during migration exceed T_{crit} for some stocks. At T_{crit} they can't move upstream; at temperatures exceeding T_{crit} salmon must resort to anaerobic metabolism which can lead to exhaustion and even death. For Weaver sockeye, one of the three stocks studied, there are no thermal refuges available during river migration. High mortality would be expected for fish that experienced river temperatures $\geq$ 20ºC (Weaver's approximate T_{crit} value), and indeed over 70% of the Weaver run perished when such temperatures were experienced during migration in 2004.

Temperature refugia

Scott Hinch's lab experiments with adult Late-run Fraser sockeye have highlighted the potential importance of thermal refugia in mitigating mortality rates due to high temperatures. Data from i-buttons used to track the thermal experience of tagged fish show that the returning adults sought out cool water refugia in the deeper waters of lakes to aid survival during their up-river migration in 2006.

Climate & fishery interactions

Ditson monitoring at Qualark in the Fraser Canyon shows that fisheries push the migration of salmon further offshore, which increases the energy fish will require to swim against the current. This could exacerbate the effects of warmer water on upstream migration difficulties. Since 1952, the proportion of Fraser sockeye catch taken in river fisheries has increased significantly.

Other issues

How does the scope and possible rate for adaptation compare to the rate of climate change? What parts of the life history and habitats will experience the fastest rates of change? How will this impact selection, rates of adaptation, etc?

Climate research to improve salmon-climate policy

Defining the right mix in a climate change research portfolio will depend on the purpose and specific objectives. A possible framework for evaluating research topics would include assessing the severity of the threat to sustainability, certainty (likelihood of impact/ability to predict), the breadth of benefits offered by the research topic and the timeframe for getting answers.

Discussion

English: Monitoring done in the Fraser for the last 5 years shows the water temperatures encountered and also how the fish react when they encounter fisheries. Some fish that encounter fisheries (especially gillnets) turn around and go back down. They appear to be moribund fish that just can't make it any further. The plan is to marry the two data sets to look at relative temperature exposure for these "drop-back" fish.

Discussion: Are tagged fish behaving like others? There may be subtle changes, but much work has been done to minimize tagging trauma and it's known that tagged fish are mostly staying with the bulk of the run. For fish tagged in the ocean, early effects are over by the time they reach the river.

Marine survival

Dick Beamish

Marine survival of chinook and coho in Georgia Strait has decreased.

(Discussion: Mortality can occur anytime between leaving the hatchery and returning, but comparing total returns to releases provides a reasonable estimate of marine mortality. There may be issues and biases (fewer hatchery fish in earlier years, fisheries reduction) but the best available hatchery data leave no question that the rate of return has declined.)

Twelve years of abundance estimates based on hatchery data for juvenile coho entering Georgia Strait and September abundance surveys (it's known that coho don't leave the Strait until November) indicate the early marine survival rate has declined from 15% to 1%. There appears to be a progressing increase in coho mortality happening in Georgia Strait. It's speculated that this could be due to metabolic issues, possibly related to disease and coho becoming more susceptible, and that this is due to ecosystem changes.

Pink and chum juveniles dominate survey catches in Georgia Strait, which indicate they're doing quite well in terms of abundance and also growing well. It was no surprise that a decline was seen for those that went to sea in 2005. Abundance estimates of pink salmon are tracking with Puget Sound, though there may be problems with the escapement estimate for the Fraser in 2007. Allowing more pink escapement in recent years means more juveniles going out into Georgia Strait and this may result in competition with other salmon species.

Physical conditions

Annual average sea temperatures measured at different depths at Nanoose Bay show increases at all depth levels. Lighthouse data shows the same trend. In comparison, Puget Sound is cooler, though on a similar trajectory. The difference between Georgia Strait and Puget is important, because the same patterns can be expected for the latter, just a few decades later.

(Discussion: The warming trend from the 1960s is much more obvious.)

The Fraser freshet has moved 9 – 10 days earlier over the last 100 years. The number of windy days in Georgia Strait has changed since the 1990s. Wind intensity in summer may be more critical than temperature. The change in pattern appears to correlate with early marine survival.

The average size of juvenile coho sampled in September since 1997 has been smaller than the 1970s average. The opposite is being seen for pink and chum juveniles, which appear to be growing faster and to larger sizes.

For Cowichan chinook, recent DNA analysis of stock composition was done for samples taken in July, September and November in the Southern Gulf islands. The results indicate that Cowichan chinook may be staying put around the Gulf Islands. This means that it is the local ecosystem that most influences their survival.

(**Discussion:** GSI shows proportions of stock; it can't infer abundance.)

Abundance estimates have been made and show that the Cowichan chinook juveniles stay in the local area. This is the critical time that we think determines brood year strength. If Cowichan is restricted to a very small part of the Georgia Strait ecosystem and that's affected by climate change, that population may not survive very well in a changing environment.

Discussion

- Q/A: Low winds appear to be beneficial for the first four months, but recent patterns have included more high wind days. Temperature is critical, but also winds. We're back to fed fry and the range in which animals are comfortable metabolically and if you stress that range, impacts like disease may be significant.
- Farrell: When you layer salinity changes on top of other things, it has a big impact on the behaviour of juveniles, which love the halocline. Higher winds would be disrupting that, adding an ionic challenge.

Roundtable: Impacts, research priorities

Participants were invited to offer advice on research priorities, including coordination of research, management strategies and other considerations

Tony Farrell

Temperature is not the only challenge; other issues like ocean acidification will layer on the challenges. But whether you're a salmon or human, temperature controls your metabolism. When you add it up at the ecosystem level, all the food generated for animals to eat will be governed by these same principles, so you start building up food chain effects.

We know the challenges are population specific, so we need to break down each species into populations that are adapted to their local environments. A change of 4^{o}C plus acidification may be lethal compared to the very stable models to which they're adapted. We don't know what populations can tolerate and how fast they can adapt. We have good data on a few populations but it would take a lot of work to define aerobic scope for everything else. Instead, you could use river temperatures as a rough guideline – a predictive tool. You still have to expand the database on temperature tolerance to prove the principle, but it would be easier to use river temperatures as a proxy for populations.

There are misconceptions regarding a loss of aerobic scope killing the fish. What it does is it reduces the overall life fitness: it can't swim as fast, defend against diseases or find food (aerobic scope is the energy you can muster to do anything above and beyond simply existing).

Salmon populations are not all equal in terms of aerobic scope. When fish move from the cool ocean to the warm river, aerobic scope is taxed to the limit. So do you want to further harass the fish in-river vs. leaving them alone? Studies show they can't swim in the middle of the river where current is strongest. Qualark observations show they choose the edges. The higher the temperature, the less chance they can cope, and 15 ^{o}C is the highest optimal temperature we've seen.

The trend shows temperature increasing overall, but on a year-to-year basis it's unpredictable. We can't predict temperature or fish behaviour. We may be dealing with some populations that we can't save (T_{crit} for Weaver is 20 ^{o}C) if temperatures increase two degrees, while others have a better chance (T_{crit} for Gates Creek sockeye is 24 ^{o}C).

On coordination: Work on early marine survival, high seas and up-river migration should be coordinated.

Discussion

- Q/A: The higher the river flow, the smaller the temperature range the fish can exploit. Fish exploit the boundary layer that requires less energy to get up-river. If you do something to move them out into the higher flows, they're less likely to make it.
- LeBlond: You might do things to modify flow rates to extend that boundary layer.
- **Discussion:** There would be First Nations implications but there are alternatives and dip net fisheries are far less wasteful than gillnets (30% – 40% of fish that encounter gillnets are not caught).
- Mantua: In-season management might be adjusted in response to temperature and flow
  - Lapointe: We do make adjustments in season; we do real-time temperature forecasting and adjust TAC.
- English: Giving preferential TAC for different gear is another approach. But to change the fishery, it must be clear that this is an issue now vs. the future.
- Historically, First Nations have used more selective gear like weirs. From Sawmill up, nets are out 24/7 once fisheries are open.

Gordon Reeves

The focus is on high temperatures, but it may be equally important that temperature lows are also going up. Many effects may be set in motion very early: e.g. the Carnation Creek study, where a major effect was the early emergence of coho. They entered the ocean early and everything went to hell.

Sub-lethal impacts: There may be significant impacts at sub-lethal levels. The difference between 16 and 18 degrees affected the dominance of steelhead vs. shiners. Steelheads were more susceptible to disease and it changed the competitive equation. The same thing was seen with chinook. At colder temperatures, the shiners died from *columnaris*, which we thought was a warm-water disease.

Hydrograph: Research shows changes to hydrograph timing won't be equal over the network, with more dramatic impacts in mid and upper parts of network that affect availability of habitat etc.

Smolt patterns: Data from smolt monitoring in several systems is being reviewed for indications of any variations in departure timing. Smolt patterns mimic life history and it can be argued that what carries the fish is variability, not just genetic adaptations. Look at otoliths to see if there's anything different about the patterns of those that succeeded. Valuable information is already available.

Discussion

- English: That offers greater value than technological approaches like tagging/tracking fish.
- Reeves: Survivors may provide tremendous insights. There may be something different in the signal for Georgia Strait vs. the ocean and it can tell how long they're spending there.
- Myers: Chinook over-wintering in reservoirs are the ones with high ocean survival
- Wells: Re otolith chemistry, if Georgia Strait does have a different signal, you'd have to have a library of everything they can encounter to be able to tell anything. But they are really good at giving freshwater information, such as which stream it comes from. Scales also provide a lot of power in terms of long-term patterns.
- Miller: The different gene expression patterns we're seeing in brain tissue could be related to different migration routes. There is a distinctive pattern for fish that migrated through Johnston Strait vs. Juan de Fuca and that pattern doesn't change over time. We could potentially also look in the river and what goes on there and how that relates to broader survival.

G. Reeves Research and Monitoring Recommendations

- Development of classification system of sensitivity of watersheds/freshwater habitats and species/populations of potential effects of climate change
    - Could be done across the distributional range of salmon or the area of responsibility of the Pacific Salmon Commission
    - Could also include areas where salmon could potentially colonize previously new areas
- Examination of potential changes in timing of key freshwater life-history events and compare trends through time in systems where data are already available.
    - Focus on timing emergence and smolting
        - Should consider elevated "low" temperatures

        - With smolting could couple with potential changes in nearshore ocean conditions at time of saltwater entry
    - Could also look at potential changes in age of smolting within populations along a latitudinal line
- Examination of otoliths and scales from returning adults to discern successful life-history pattern
- Examination of sub-lethal effects of elevated temperatures
    - This could be expanded to species other than steelhead (own work)
    - Should be done in the context of the fish assemblage and not on a species in isolation (i.e. consider ecological processes such as competition and predation)

Nate Mantua

1) Regarding the notion that adaptation will be key, it's been documented pretty well in the Columbia that fish are coming back earlier. However, for the Fraser, where they could get cooler temperatures if they returned later, they are actually coming in earlier. So there must be other signals. Our ability to think through a response to climate change is weaker because of how the marine and freshwater experience adds up.

2) Tools for evaluating habitat sensitivity: there are very good tools for predicting where you would get the most change in temperature and flow. A lot of work was done on the Columbia and the Fraser and there is now a project to expand this around the Pacific Rim at crude resolution. Where people focused at finer scales (we can resolve topography at 10 m. grids) they found the most sensitivity is in the headwaters. In warmer climates, there would be a shift to rainwater hydrology, which represents a huge change and a major limiting factor for chinook, whose eggs are very vulnerable to peak flows. So the higher sensitivity is the watersheds that are close to the snow/rain transition point and it's pretty straightforward to identify that.

Stream temperature modeling can provide more complexity because less fine-scale mapping has been done on the hydrological features that create refugia. So in prioritizing watersheds, it could be a valuable investment to identify those places, if they are critical to helping salmon survive, and that's doable over broad regions.

3) Ocean habitat is very complex, though we don't treat it that way. Information is weak on where the fish go, how sensitive migration patterns are to changes in climate, and what are key problems (e.g. suggestion that it's harbour seals). There are tools to do modeling but we lack the data to do models and current climate models are too crude to do coastal-level analysis. There's been some effort to look at coastal processes retrospectively but not in a coordinated way for the Northeast Pacific. It could be a good contribution to link coastal regional circulation with food web models to start resolving what the habitat features are. Variability in the ocean, in terms of links to food, is almost entirely wind-driven. Maps on ocean warming are all based on radiation back. But if there are changes in the Aleutian low and more winds from the south, that is an entirely different process. Temperature is temperature but the food web also changes.

Climate models predict wind pattern changes, with the Aleutian low moving to the Bering Sea and more southerly winds in the Bering Sea. Along the coast in summer, there is some evidence that coastal upwelling could increase. There is big warming over land, which affects winds, so you could have sustained cold water. There are challenges in predicting hypoxia, anoxia or acidification, and it's not clear whether it could be positive.

Carrie Holt

Three points relating to management action/advice:

1) For Canada's Wild Salmon Policy, we are tasked with assessing status of salmon Conservation Units by setting benchmarks that delineate Red, Amber, and Green zones. One category of benchmarks is based on capacity of freshwater and marine habitats to produce spawners. However, estimates of that capacity based on historical data (e.g., deriving estimates of freshwater capacity for sockeye salmon from historical values for euphotic lake volume) will not be appropriate if future conditions differ from the past. It may be prudent to revise benchmarks for assessment (and targets for management) according to anticipated changes in capacity. For example, estimates of freshwater capacity could be based on real time observations of chlorophyll concentration (colour) from satellite images of lakes (lake colour). Alternatively, benchmarks (targets) that are robust to uncertainties in future conditions could be chosen.

2) To prevent loss of salmon Conservation Units, conserving the capacity to adapt to changes in conditions (adaptive capacity) will be essential. Although individual populations within CUs may be lost under climate change, the CU itself will persist given sufficient genetypic, phenotypic and/or life-history diversity to respond to future changes and sufficient time. At the population level, we've found a lot more structure than anticipated and the intent is to choose management actions that maintain fine-scale diversity in run timing and habitat uses. We also need to better understand how adaptive capacity relates to habitat use: is it possible to project how fish will use different habitats in future?

3) Evaluate management strategies before they are implemented in terms of scenarios for climate change. For example, FRSSI (Fraser River Sockeye Spawning Initiative) has been evaluating long-term productivity implications of harvest scenarios. Such efforts could be improved by evaluating climate impacts on different life history stages.

Discussion

- Q: At what level are you applying "adaptive capacity?" / A: Individual level.
- Holt: We're thinking within a conservation unit (finer scale) not at the species level, to maintain diversity. Within a CU you could lose a population but you'd maintain the ingredients that would allow it to recolonize and replace groups that are lost.
- Farrell: It comes down to an ethical issue if we know some groups likely won't make it. If someone says Cultus will die anyway because of temperature, why even try vs. putting those efforts elsewhere where you could have success.
- Beamish: In defining what constitutes a CU, we may find that that the criteria that are important in a changing climate aren't necessarily those in the original definition.

Dave Hankin

Comparison of survival rates of fish released from two California hatcheries showed there was easily two orders of magnitude difference in (annual?) survival rates but no discernible trends. We think survival is primarily driven by the marine signal but they also have a long downstream migration where things can happen. Wells' work on the catastrophic crash in the Sacramento indicates a strong marine signal.

There is an important difference between short-term management issues (whether it's climate change or other things, how to act in a context of much greater uncertainty) and the long-term issue of dealing with climate change looking 40 years out. These require two different types of advice:

1) Advice on how to better incorporate uncertainty in decision making
2) Advice on what to do down the road, if things really do get to these greatly elevated levels where it may not even be feasible to try to save a stock. In this context, a further consideration that's emerged is the importance of protecting habitats that salmon aren't using yet, but which may be important in 40 years.

Discussion

- Mantua: Data from about 20 stocks showed four patterns of marine survival: wild, hatchery, Puget Sound wild and Puget Sound hatchery. Puget Sound hatcheries all had a similar downward trend, but the coast had lots of variability vs. a clear trend
- Hankin: There is striking co-variability between the two stocks from the same system. You wouldn't get that strong a signal if it was not good data. The weakness in CWT results is escapement – ocean survival is much better.
- Q: Are there fishery affects? / A: This is based on two-year olds.
- Hankin: It works out to a variation between less than .1% to 5% in survival rates. A second graph for TRH Fall and Spring chinook shows very tight co-variability. This is yearling survival rate to Age 2 and is based on all tag recoveries – i.e. how many fish had to survive to that point.

Paul LeBlond

These comments focus on salt water.

1) We see changes in temperatures and other properties that seem to relate to salmon (survival, migration timing, etc.) Especially in the coastal environment, the variability in temperature and other conditions that are most relevant are not the averages from year to year, but the variability on shorter time scales, within and between years. So it may be dangerous to make inferences about biological effects based on data that are pretty coarse. For example, the plankton bloom might depend on spring storm, tides, river runoff, etc. We need a much better understanding of coastal oceanography if we want to understand impacts on the marine ecosystem. This is not just true for climate change, thought this may force us to look into things that we always needed to know.

2) There is a tendency to relate changes in temperature to salmon, but there are many steps in between. So it's important to remember that while impacts at the higher trophic

levels, like salmon, may be direct environmental effects, there are also indirect effects through the food web, e.g. the role of hake.

3) It seems that changing environmental conditions diminish the predictability of salmon stocks and this, as noted, is a different problem than addressing the long-term problems.

What's to be done? From the point of view of the PSC, having a research plan would be a good idea to help recognize and focus on long-term problems; such a research plan should mesh in with those of supporting organizations (DFO, NOAA, PICES, NPAFC…); stimulating exchange of ideas and results between all those groups and academic institutions (where significant research is also done) would be a worthwhile endeavour. Shortcut relations between environmental changes and salmon survival are worth looking for, but they remain empirical black-box relationships unless they are linked to an ecosystem understanding (through a food-web model, probably); hence continuing an ever more pressing need to understand the ecosystem, starting with the Strait of Georgia.

Brian Wells

In comparing life histories, we need more complicated models about what's happening on the coast and how SST directly and indirectly affects salmon. The following discusses a mechanistic model to better understand how climate affects salmon via changes in wind patterns, and work in coastal California on trends relating to the climate food web and how it relates to salmon.

Do we see a difference between stream- and ocean-type and coho in relation to changes in larger-scale indices? BC coho had a negative relationship with the PDO (cool water = larger fish). Doing this for other rivers revealed different patterns. Ocean-type chinook showed a positive track with ENSO, with a flip above/below a transition zone. Analysis of scales going back 20 years from Alaska showed a distinct growth pattern relating to the ENSO in 1984.

Mechanistic models were built looking at growth rates and path analysis: e.g. various pathways linking northern wind stress, positive effects on upwelling and how that trickles down to growth rate in the first year. You can look at each variable and its effect on every other and how it works through and around other variables to ultimately affect growth rate. You can plot out weightings and see that the cold season is what drives growth in the first to third years. The fish don't just stay in BC – they move into Alaska. You model the area around them and the area they can go to. You can model growth rate at each age relative to the environment in the context of how we know the environment fits together.

BC is right at the transition zone so it becomes a very dynamic region. Climate affects where that transition zone is located and thus productivity, so the transition zone is very important and you can model it

Winter also turns out to be very important. We found the strength of the California current in winter was what was so important.

Moving this down to California, we extended these models extensively. Once you demonstrate how the environment affects growth at the second and third sea winters and that this affected maturation rates, you can understand the effects on each variable and on survival and other life history patterns.

We're now taking it further in trying to describe what happened to Central Valley chinook in 2005 -06. With this, you can also look at the increase in summer upwelling over 60 years and see how that is going to affect salmon. It will be important to think beyond SST effects. Things can hit that you that don't expect unless you look at it from a mechanistic understanding. For example, wind structure and upwelling: Analysis of stronger offshore/ weaker inshore wind patterns in the context of 30-year trends showed how changes in that specific pattern directly affect mixed area depth and primary production.

You can model trophic chain production and see that production along the coast has been declining for the last 30 years. That alone doesn't say much, but in this context, it says a lot. You get a redistribution of krill, anchovy, etc: things are moving because of the difference in wind structure. When you look at how juveniles respond, in the context of the way we modeled this, it can tell you why. We can predict growth and specifically growth in California. We compared actual abundance (Central Valley Index) to the environmental index. Once you know how it how affects salmon, you can make predictions.

SO you can look at life history, distribution and other key factors and start developing models that actually describe what's happening. If we know mechanism and distribution, we can say what's happening and use this as a predictive tool.

Discussion

- Q: Were hatchery/wild fish separated? / A: Most are hatchery fish.
- Hankin: A report indicated that huge variability in that system was due to high reliance on hatchery fish. It's a good study of what happens when you don't preserve genetic diversity. Chinook typically have a huge variability in out-migration timing, but if they're all going out at once, an adverse event could have major impacts.
- Mantua: These models often do really well fitting retrospective data, until they hit something new.
- Wells: We covered many regimes, which helps, and we chose three variables that were important
- Farrell: You could, for example, look at aerobic scope of krill and competitors to help model climate impacts.

Kate Myers

I'd like to see a more complex approach to any research program on possible effects of climate change instead of just focusing on everyone's favourite research topic. Take a comprehensive approach to how it will affect all different life history stages and habitats. Encourage development of a real science plan with a conceptual framework vs. basing it on single hypotheses.

From my own area of work, one hypothesis relates to ocean carrying capacity and what's controlling growth and survival. We're using pretty simplistic cold year/warm year thinking.

Cold year effects are bottom-up, while warm years exert top-down control of survival. It's pretty clear from the last 10 – 15 years of high seas research that carrying capacity is limited. The Japanese actually reached capacity and had to cut back. Production has stabilized, but it's still at a very high level. Fraser sockeye is affected in the Gulf of Alaska. They're sharing the Gulf with Asian stocks that are benefitting from much more productive ocean regimes (Japanese chum and Russian pinks). We're in a period of the highest salmon abundance ever recorded, driven by Asian stocks (our pinks are in the same place too). Alaskan releases of pinks are also very high. The majority of Russian pinks are wild.

No ocean research is currently being done offshore in the Gulf of Alaska. In trying to develop research priorities, winter studies in the Gulf of Alaska were identified as one of the highest priorities. There is already an infrastructure for coordinating this (NPAFC). Other priorities include getting a handle on hatchery/wild interactions and their impacts on survival. There's also been a very narrow focus on marine survival – i.e. the number of fish in coastal waters vs. size of fish.

Discussion

- Mantua: Ocean acidification could be especially problematic in the Gulf of Alaska in winter.
    - Myers: The few surveys in the Gulf in the 1990s identified terapods as one of the primary prey species and they would be strongly affected by acidification. I'd like to see some high seas research especially on hatchery/ wild interactions; because that's something we can do something about.
- Holt: Another issue might be changing distribution and changing interactions
    - Myers: We're already seeing northward shifts but we don't know if all will shift equally.
- Beamish: It's not just winter; we need summer studies as well to see where those populations are. We're proposing an international year of salmon to get countries to provide four research vessels that will survey throughout the subarctic Pacific in the summer as well as in the winter.
- Myers: Another key issue is management strategies: No mixed stock ocean fishing and eliminate large-scale hatchery production of pink and chum, or else use the hatcheries to do experimental releases (use them more scientifically). Ocean monitoring is required, since we can't predict how climate change will affect salmon. It's too chaotic. We need to do monitoring – you can do good forecasting if you have indices of survival.
- Mantua: Even if it's too complicated to model and predict, just measure key parts, especially if the key is early life – actually measure the number of young salmon
- Wells: Care is needed because they co-vary very well, except when they don't.

Dick Beamish

The linkage between climate and salmon in Georgia Strait is in the early marine period, where the issue is the amount of growth and energy. We need to do more research on the causes of mortality as part of a long-term monitoring plan. We need to better understand natural mortality. Early marine surveys are critical. These issues are especially important for chinook and coho at the southern parts of their range. Certain populations or families may be better adapted and we need to identify which ones. I think we will need hatcheries, once we make the social decisions regarding what to do about coho and chinook

Laura Richards

Prediction – even if we don't understand things mechanistically – is very important in the short term. To what extent is climate included in annual forecasts?

Invasive species are another issue. We're aware of freshwater species introduced in lakes that are important to sockeye, but there may be other changes ahead too.

One of the greatest concerns in terms of impacts is the emergence of disease and the potential for catastrophic changes, whether it's something new or greater susceptibility to existing diseases.

We will need to do things outside the normal stock assessment toolbox to be prepared.

Steve Pennoyer

These are good suggestions, though we will have trouble figuring out what to do, e.g. the issue of refugia and saving cold water areas. We will probably not able to cut hatchery production. The Commission doesn't have a lot of money. We will need to continue monitoring to see what is happening, though I don't see much we can do to change management. We can save the ability to adapt. But it's a little early to figure out what we need to do for the long term questions.

Greg Ruggerone

Pink salmon have boomed around the Pacific Rim. Worldwide, 60% of adult returns in recent years are pink salmon. Competition between species of salmon is an important question. Climate may favour one salmon species over another, leading to an interaction between climate and species interactions. Climate may differentially affect species of salmon through a mismatch in the timing of seaward migration. For example, earlier spring plankton blooms may benefit pink vs. chinook salmon because pink salmon enter the ocean at an earlier date. Perhaps this is why pink salmon populations are doing so well in most regions of the Pacific Rim. Unfortunately, there is not a long time series of salmon prey availability in coastal and offshore marine areas. If plankton blooms are occurring earlier, it may adversely affect later migrating juvenile fish such as subyearling chinook salmon.

- LeBlond: A group at UBC is studying this and found they can predict spring bloom, mostly from winds.

Refuges and maintaining stock diversity is important. The Kvichak, one of the largest Bristol Bay sockeye salmon stocks collapsed beginning with the 1991 brood year, but other stocks on the west side of Bristol Bay are doing very well. Differences in size at adult age happened just around the same time as the collapse, i.e. immediately after the 1989 regime shift. The Kvichak fish are mostly ocean age-2 fish, which are smaller vs. other stocks that are mostly ocean age-3. The small adult size of Kvichak salmon and overall below average size-at-age of Bristol Bay sockeye salmon may have contributed to the decline. An important question is whether the warmer temperature in Bristol Bay during the homeward migration and reduced growth is affecting the quality of eggs.

Discussion

- Farrell: Patterson did extensive work on eggs and up-river migration, which showed that fish were committed to laying down so many eggs at a specific size way earlier. Difference in egg size relates more to population/stock. There may be impacts on quality perhaps, but not the amount or size.
- Hankin: The literature indicates reproductive allocation is very consistent for chinook.
- Farrell: It could be the first year at sea that creates the spread.
- Ruggerone: The Fraser has a very wide spread in timing migration compared to Bristol Bay (~80% of run in 2 weeks), but we've never figured out why. Growth of salmon is important to survival. It would also be useful to do scale pattern analysis to reconstruct sockeye salmon growth patterns during each year at sea and to make north/south comparisons between northern and southern stocks and between Asian and North American stocks.

Karl English

The following offers a big picture perspective on the questions posed:

BC has a tremendous role to play in tracking because we're right in the transition and we have wild stocks to track. The Fraser has the macrocosm of interior vs. coastal systems. One of the gaps in terms of monitoring is Bella Coola. The Nass and Skeena systems are also valuable in terms of the number of species, with assessment being done for all species.

How is the management system set up to respond to uncertainty: Systems are in place on the Nass to respond. In 2007, they were able to predict in season what the escapement levels were. The in-season vs. post-season estimates were very close, despite large variations in water flow. This is done for all species. There is very solid assessment data dating back to the early 1990s, based on fish wheels, mark recapture and extensive catch monitoring. For steelhead, tagging studies were also done to improve reliability. The fish wheels are used primarily for stock assessment but also for communal fisheries.

The system in place on the Nass is robust to changes. There is value in doing this along the coast to permit comparisons. How much aerobic scope do fish in the Nass and Skeena have vs. other systems? Monitoring on the Nass includes detailed temperature data (river temperatures there range from 9 – 12 C vs. 16 – 20 C for the Fraser.

Tracking in the Fraser: Fish are tagged in the marine environment, with genetic stock identification. Survival is tracked and compared to water temperatures. Fish that didn't make it past Spence's Bridge were running in the same group with those that did make it. I-button temperature tracking showed the migrating fish side-tracked into cooler Seton Lake to escape high temperatures in the main stem.

Discussion

- Mantua: Has anyone looked at when the major glacier-fed systems may be gone?
- English: We're seeing significant reductions. Chilko Lake is next to the largest glaciers and there could be a dramatic effect. Systems like the Netchako and Chilko are very important to cooling the Fraser.
- Farrell: The devil is in the detail. You can get a pulse of colder water at the right time. For the fish we were tracking, the barrier was the Thompson rapids, and as soon as water temperature dropped, they popped right up.
- English: You could have fish getting through without a fishery, but add a fishery and it may not get through.
- Farrell: I-button data shows they get in that lake and navigate the whole lake at 12 degrees. There was an example where the fish went into Seton Lake for 5 days and came back out when main stem dropped from 21 to 17 degrees.
- The importance of glaciers and cold water systems is clearly critical in this watershed vs. cooler systems like the Nass.
- Myers: The Gulf of Alaska was getting very close to the maximum temperature (15 degrees), beyond which there are no fish.
- Mantua: The other key point is that comparative studies between these systems are useful
- English: It would be very useful to have monitoring at Bella Coola

Kristi Miller

A lot of our research focuses on the transition from saltwater to freshwater and more recently vice versa. We look at salmon migration physiology and how conditions in one environment can influence behaviour and fate in the other. Using functional genomics, we analyze thousands of gene transcripts at a time to see what physical processes (e.g. processes related to disease or navigational queuing) are being turned on or off. Every cell has the same DNA; we're looking at RNA, which is different for every cell, depending on cell function. We can look at differences between a number of individuals; at changes that occur as they migrate; or at how many different states are present at one place.

After profiling different tissues over several years, we can see certain differences: e.g. gill tissue is different for fish sampled at different locations; there were clear differences in the brain for fish that migrated through Johnston Strait; also changes in the liver linked to starvation between fish in the freshwater vs. marine stages of migration. Tracking fish along their return migration showed massive changes in muscle tissue as soon as they hit Georgia Strait.

After two years of data, there is evidence of two distinct profiles for brain tissue. These patterns associated with the choice of migrating through Johnston Strait or Juan de Fuca were set by the time they reached the Queen Charlottes. Fish that chose the inside route were using visual and olfactory cues, while the outside fish stimulated long term memory instead. The strategy didn't change as they were migrating. This suggests they had the capacity to choose one or the other. The inside fish were also turning on late stage maturation genes; we think they're more mature.

These findings show that fish are not physiologically all the same. With climate change there may be a broader range of physiology required to deal with new stresses, and it's important to consider the changes between freshwater and saltwater, when much mortality occurs.

We linked this analysis to tracking to link physiology and fate. We look at which fish go missing in the high-temperature sections of the river and then go back to our samples to see if there was any physiological signal that you could see in advance that was associated with fate. Two studies produced similar results, indicating that there are different genetic signals linked to en route mortality vs. success in reaching spawning grounds that could be developed as biomarkers.

These studies have led to the development of "unhealthy" vs. "healthy" profiles. The unhealthy fish had many genes turned on that are involved in intracellular pathogen response. In one year, 60% were entering the river infected with an intracellular pathogen.

The same profile was observed on different years, though in very different proportions (70% – 60% – 30%). There was no difference in the proportion of unhealthy fish in the different stocks that were co-migrating and they were unhealthy all the way back to the Queen Charlottes. When they hit freshwater, they may also be re-infecting each other.

Fish that had this unhealthy profile in the marine environment were 16 times less likely to reach the spawning grounds. Those that had the unhealthy profile in freshwater were 7 times less likely to make it. So the longer they were infected, the less chance they had. Fish that were unhealthy were also five times more likely to move into the river earlier.

Why would unhealthy fish enter the river faster? It may be something that affects osmoregulation (unhealthy fish may be suffering osmoregulatory dysfunction in saltwater).

Temperature challenge studies were also done on sockeye and pinks, looking at stock-specific adaptability. In 2007, Chilko was compared to Lower Adams sockeye and Chilko were found to have a higher ability to acclimate to higher temperatures, which was not surprising. Adams fish were responding very strongly to temperature stress, but it was not a very adaptive response. The study looked at Lower Adams sockeye at Savona to see which genes were differentially expressed in response to higher river temperatures, and found there were two different responses to high temperature stress. One group had a very strong response associated with stress. Some 50% of fish carried that profile but most of them didn't survive. Only 12% of the fish that reached the spawning grounds had that profile.

Work is also starting on smolt outmigration, to see how many unique physical states are present when smolts hit the ocean. Initial results did not show a large geographic pattern but they teased out four states: 1) Still acclimating to the ocean (all Southern VI fish, tested close to where they entered saltwater); 2) A large group of poor-performing fish (strong stress/defense signals); 3) Intermediate group; and 4) Most healthy and rapidly growing. Researchers can look at this and at changes over time and then compare differences in fate.

This work could be used to build straw models: potential climate impacts on smolts and adults, or the chain of impacts that could result from climate change effects on smolts.

Discussion

- Beamish: In 2005, some 80 – 90% of smolts entering Georgia Strait died by mid-July.
- Q: Were results compared to other measures of condition? / A: We looked at something like disease.
- Beamish: The 2005 mortality was so large you can't explain it without considering condition, diet, growth and competition plus other factors. The mortality was so large, there must be sources other than predation. It was not seals.
- Farrell: Could be that they're starving, more susceptible to other things.
- You can take coho and put them in a net pen, calibrate RNA profiles to different growth trajectories and then when you sample them, Miller can tell which are starving, which are feeding. Condition factors tell you about history, not the future.
- Q/A: Work is being done to identify the pathogen. We think it's a virus, but not a common one. We're hoping to at least identify the viral family in a month or so.

Future research will focus on improving predictions, linking freshwater and saltwater environments and developing tools to monitor the condition of migrating fish. Other plans include developing models to assess interactions between condition and environment, fitness and behaviour; interaction between conditional state and fisheries; pathogen screening; developing profiles of good vs. maladaptive responses; and developing markers and then looking in the natural setting at how individual stocks are coping to try to answer which are going to adapt. One question is that if a lot of climate impacts relate to energy, how important is the ability to adapt metabolic rate.

Mike Lapointe

Juvenile monitoring is important from the standpoint of understanding how the early life history is being affected by climate change, though it's not clear how useful this research would be to predicting the eventual recruitment of adults. High seas monitoring could be useful to fishery managers if it could provide information on the relative year-class of particular populations and if it could be coupled with in-season assessment of the early component of the run.

Triaging: If the goal is having sustainable salmon populations in the future in the face of climate change, is that goal achievable through attempting to save every stock? If not, do we know enough to provide advice on which aspects of biodiversity are expendable? Given examples such as Bristol Bay and east/west switches in productivity – I'm not sure we know enough to decide which stocks are or are not worth protecting.

There are two paths: short-term tools to preserve biodiversity of fish and habitat and the long-term goal of dealing with future changes.

Short term: For in-season management, given the high degree of uncertainty, it may be more useful to invest in improving the ability to react to what is actually happening in season than to invest in predictive tools.

The other key question is deciding on the right portfolio mix for investment in research.

Closing discussion

Beamish noted next steps included getting a report together for everyone to comment on. Participants were invited to discuss closing thoughts:

- Holt: Hypotheses should be reflected in evaluations of management strategies
- Juvenile sampling: Wells' program was cut in 2005. / Beamish: This can be used to support forecasting. Our September coho sampling is starting to look very good in providing an indication of what comes back the next year.
- Marine mortality: Beamish: In order to understand impacts of climate change, we need to understand marine mortality (early marine mortality and adult stage) / Mantua: There may be a predisposition that occurs at the earliest part of freshwater development. / Miller: It may be a combination of factors.
- Where to focus energy: English: Places like Georgia Strait and Puget Sound where we've seen dramatic shifts. Learn about what's happening right here, which also gives better info for in-season management. If we don't focus, there are a million variables. And we do have the potential to take action here if we find we're overloading the system.
- Assessment costs: Nass costs $1 million a year; Skeena costs about $4 million; and about $2 million for Fraser sockeye and pink; probably about $5 million for all species.
- Early marine mortality is important to understand. To make it more powerful, couple it with testing of hypotheses; use it to predict and then test it. / Beamish: If we hypothesize that it's an energy problem, we can test that. If populations or families respond differently, it's important to know that. / We think the bottleneck for Chilko smolts is the marine area: where is the variation at each life stage is the critical question.
- Farrell: We can do something about hatching and rearing and get most of them out of the river. We're saying there are two mysteries early marine and then out there in the ocean. Then out of that 1% that make it, we can lose 90% of those coming back up the river.
- Beamish: Harrison sockeye are behaving like pinks – they're doing really well.
- Hankin: Could you use Miller's and Farrell's tools to learn something about correlations between juveniles and adults – would they be the same genes? / A: It's not clear you could do that.
- Discussion re Chilko data: Abundance is based on catch plus escapement, including en route loss. Marine survival does not include en route mortality.
- Richards: Where it can make a difference for management is where to fish, how to fish, how to provide cool water, making channels easier to migrate, etc.

- Discussion: Protection of freshwater habitat and groundwater is important. Given all the independent power proposals and groundwater use for irrigation in the Thompson, clear direction is needed from science on the importance of preserving groundwater.
- Link up Georgia Strait and Puget Sound to see what's going on. It's easier to tell what's happening with massive signals. Where you answer a question is when you focus.
- Fishing in the Fraser: We need to confirm the impacts and then deliver a very clear message from science. / Can it be proven? / Farrell: Ditson can give you swimming speed and you can see the consequences. The empirical data are there, the traditional catch is based on using the stretches where fish have to cling to the sides to make it. / English: Requirements could be based on temperature: dip nets only in warm years; maybe gillnets in cool years. / Mantua: If you can show that gillnets kill more fish, give larger quotas for dip nets. You need to recruit responsible people in the fisheries to get buy-in. / English: In the Babine, they can catch more on fish wheels.
- Hankin: Suppose a major scientific task was to identify which populations won't make it. Otherwise the whole management edifice is going to come to a halt if we're trying to preserve stocks that won't survive and that are driving all our efforts (i.e. the opposite of strongholds) / Mantua: The challenge is how to predict which ones those are. / Miller: We can't predict with a high degree of certainty, it depends on the range. / Farrell: It turns out Weaver was introduced. For Adams, it's been a tough battle to get stocks to go back there. It is genetic and some have more flexibility than others. But we've only looked at two sockeye stocks and one coho. We should characterize a few more and ground-truth it before we even start thinking about triage.
- Richards: Re hatchery stocks being more homogenized, we could hypothesize that this makes them more vulnerable.
- Discussion: Wells/Hankin/Ruggerone re using chinook CWT data, models of mortality, maturation and early growth and statistical analysis to incorporate climate change and improve current management forecasting models.
- English: It's important to not ignore things that don't fit the traditional patterns of what we assess. Thousands of fish are handled on the Nass and it offers an ideal opportunity to compare and study differences between fish in a healthy system vs. the Fraser via the work that Miller does.
- Beamish: It's useful to consider working with fishermen and getting the buy-in needed re new management approaches. / Myers: Is there somewhere you can experiment on modifying fishing techniques? / The challenge is whether we can do it politically. / Our job as scientists is to warn with a clear voice, not to filter it through politics. / Lapointe: Up-river First Nations are more likely to support the benefits.

Committee members thanked all participants for their input before closing the meeting.

List of invited participants

PARTICIPANT	TITLE	AFFILIATION
Dick Beamish	Research Scientist PBS	Fisheries and Oceans Canada
Carrie Holt	Research Scientist PBS	Fisheries and Oceans Canada
Kim Hyatt	Research Scientist PBS	Fisheries and Oceans Canada
Kristi Miller	Head, Genetics PBS	Fisheries and Oceans Canada
Laura Richards	Regional Director PBS	Fisheries and Oceans Canada
Brian Riddell	Division Manager SAFE PBS	Fisheries and Oceans Canada
Rick Thomson	Research Scientist IOS	Fisheries and Oceans Canada
Diane Lake	Managing Director, PFRCC	Pacific Fisheries Research Conservation Council
Kate Myers	Research Scientist, High Seas Salmon	School of Aquat. Fish. Sci. U. Wash.
Nate Mantua	Research Associate Professor	School of Aquat. Fish. Sci. U. Wash.
Dave Hankin	Professor and Dept. Head	Dept. of Fisheries Biology, Humboldt State U.
Tony Farrell	Professor and Research Chair	Centre for Aquaculture & Environ. Research UBC
Mike Lapointe	Chief Biologist, Fishery Management	Pacific Salmon Commission
Paul LeBlond	retired	
Steve Pennoyer	consultant	Juneau, AK
Karl English	consultant	LGL
Greg Ruggerone	consultant	Natural Resources Consultants
Marcel Shepert	Executive Director	Fraser River Aboriginal Fisheries Secretariat
Dawn Steele	consultant	Pacific Fisheries Research Conservation Council
Brian Wells	Research Fishery Biologist	Southwest Fisheries Science Center, NOAA