Fisheries and Oceans Canada / Pêches et Océans Canada

Ocean conditions INSIDE and OUTSIDE the Strait of Georgia are important contributors to the Fraser Sockeye situation, including the high seas.

T. Beacham, R. Beamish, P. Cummins, K. Hyatt, J. Irvine, D. Masson, K. Miller, C. Neville, A. Peña, R. Sweeting, R. Thomson, M. Trudel, S. Tucker
Fisheries and Oceans Canada

P. Whitfield
Environment Canada

Canada

Plan of the Presentations

- Background: The Fraser Situation

- Physical Oceanography: Inside/Outside SOG

  Thomson: Spring transition, winds, precipitation

  Peña: Lighthouse data and models

- Biology: Inside/Outside SOG

  Beamish: The SOG Anomaly

  Trudel: Anomalous Anomaly

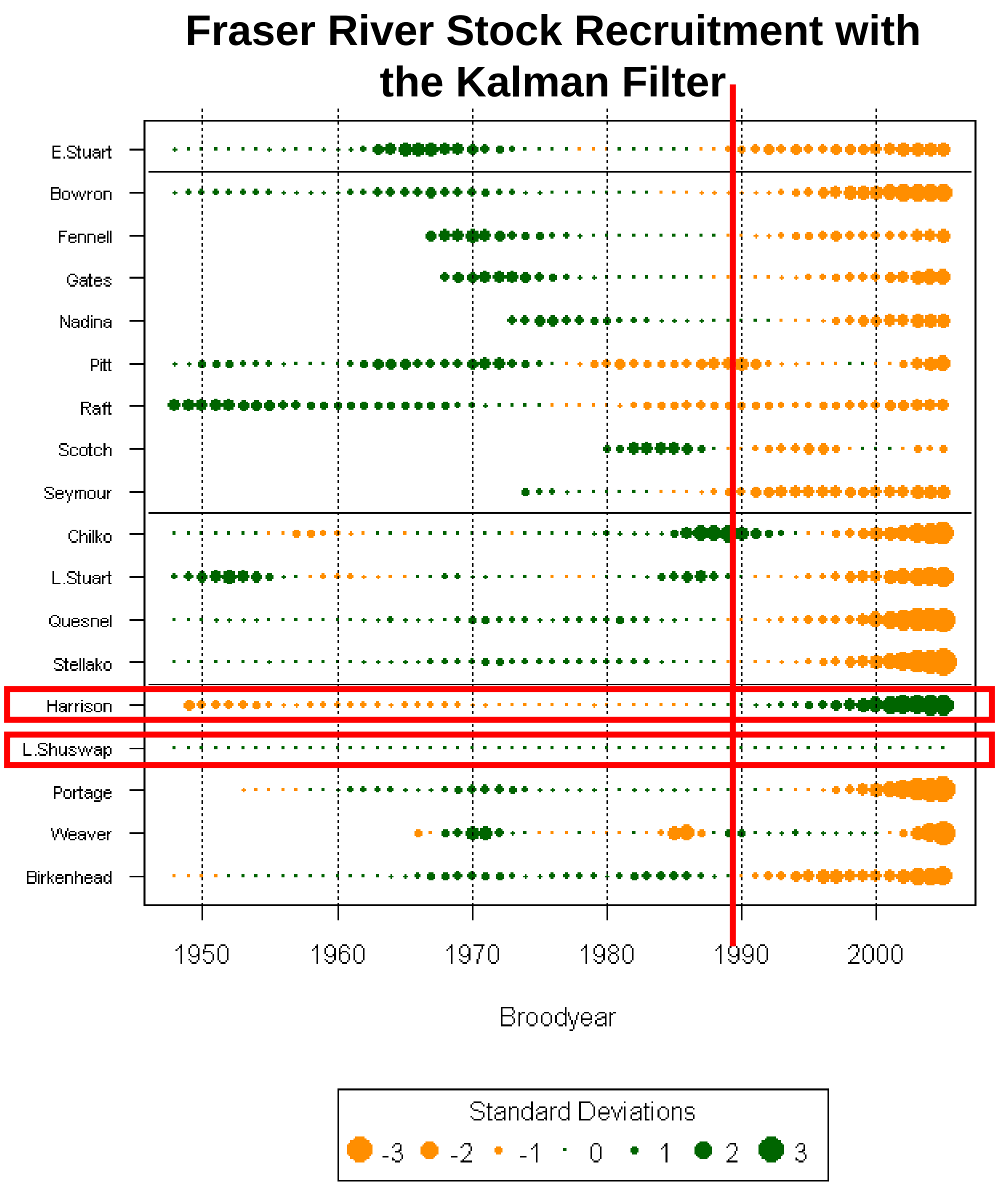
  Miller: Smolt Physiology

- High Seas

- McKinnell's Report

- Next Steps

Background: The Fraser Situation



- Most stocks started to decline in the early 1990's, except …

- Harrison River sockeye started to increase in the early 1990's.

- L. Shuswap sockeye remained relatively stable.

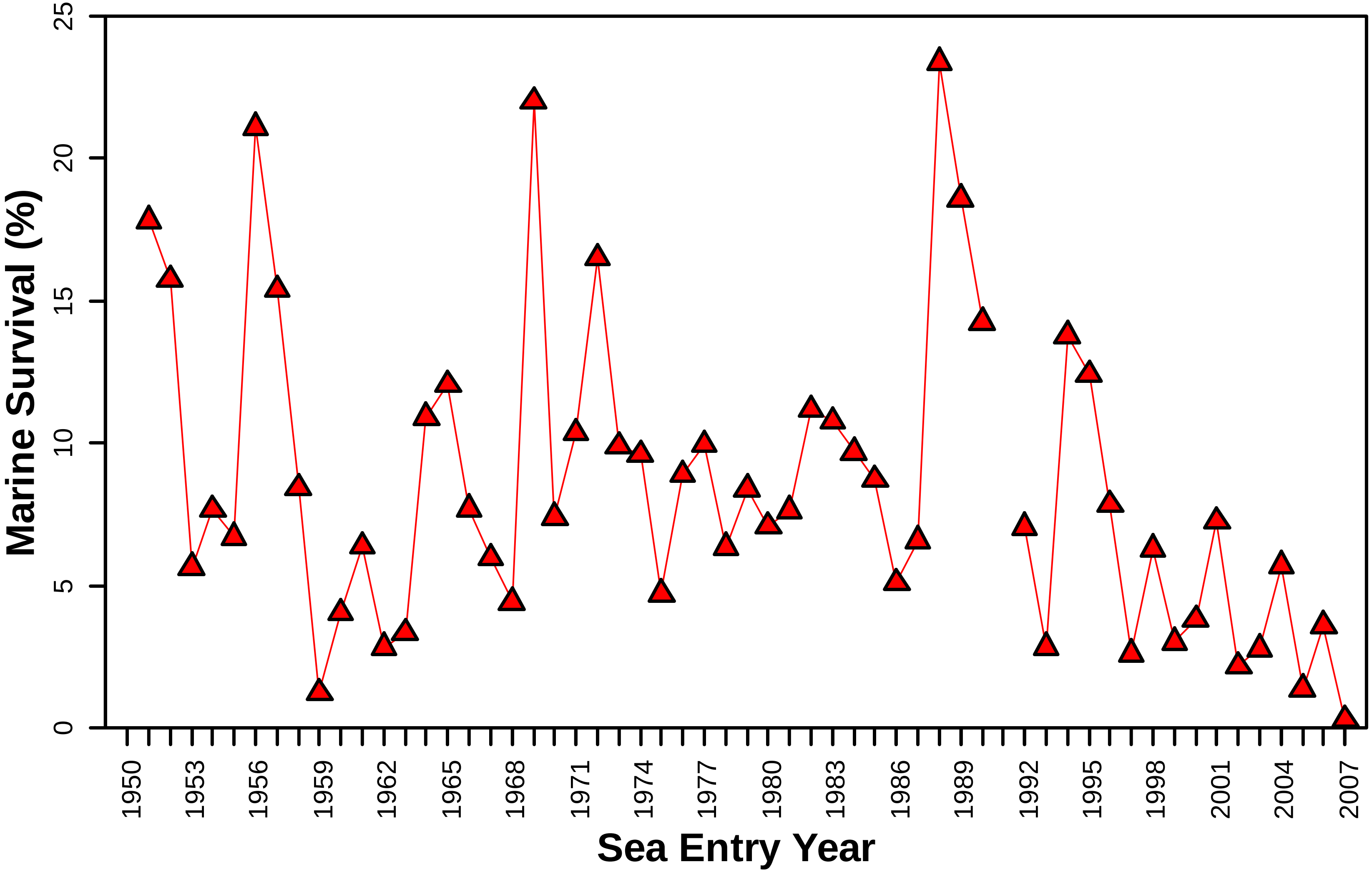
- 2009 was a continuation of a trend, though at a much higher intensity.

- Barkley Sound sockeye and Columbia River sockeye salmon performed average to above average in 2009, and exceptionally well in 2010.

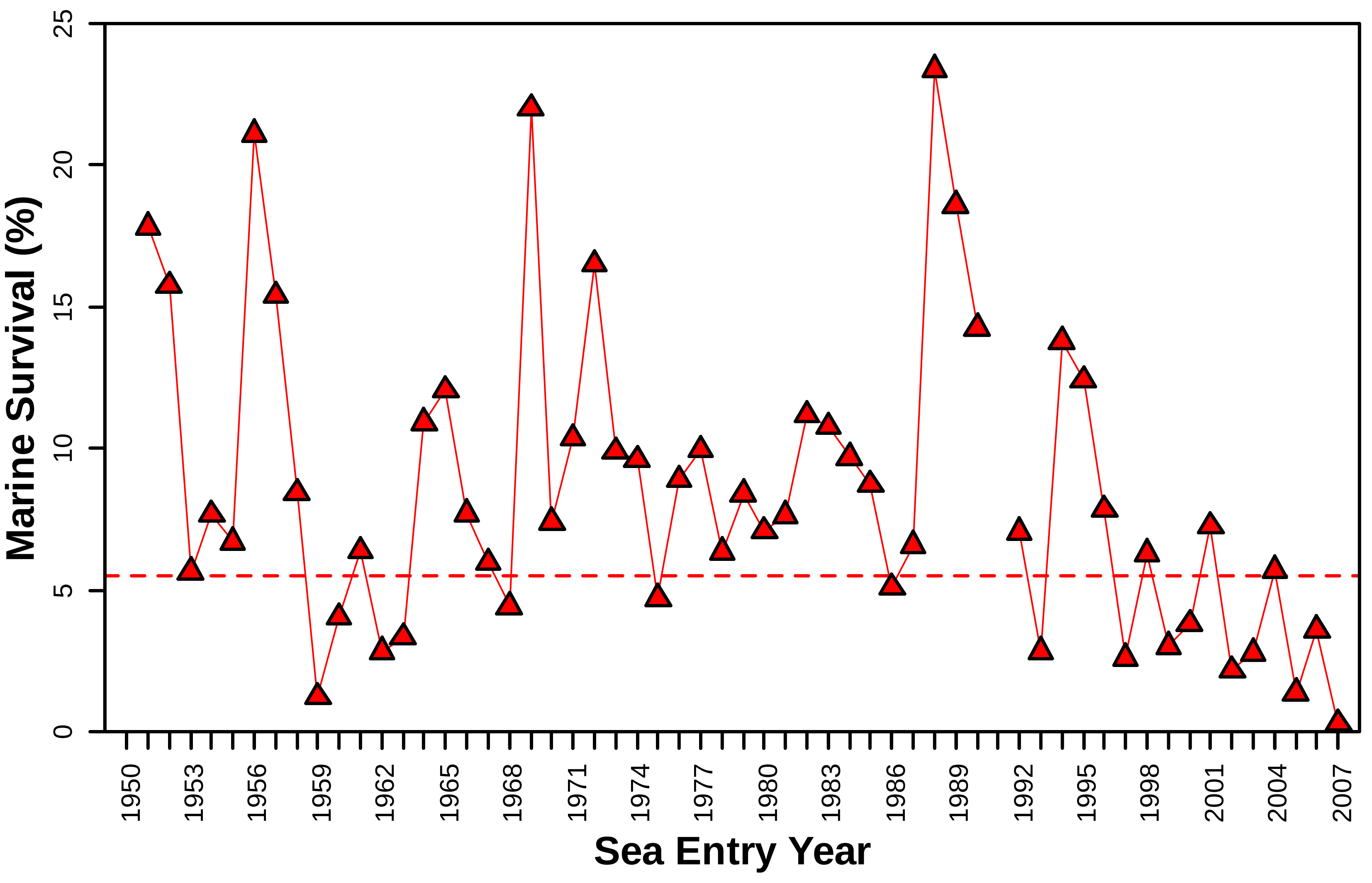
- Although marine survival of Smith Inlet was low in 2009, it was not extremely low.

Source: M. Lapointe, S. Grant, and C. Michielsens

Background: Chilko Marine Survival

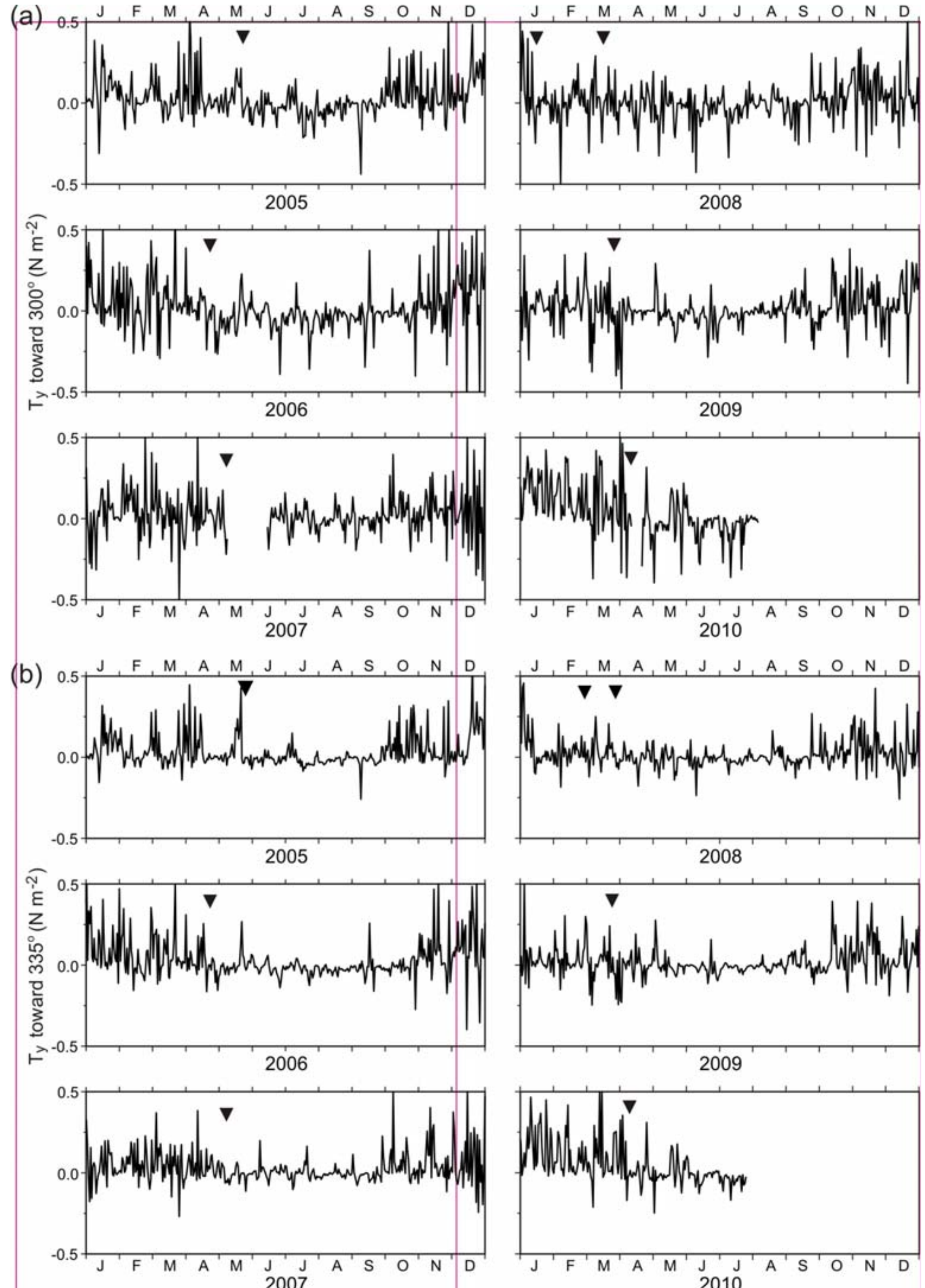


Background: Chilko Marine Survival

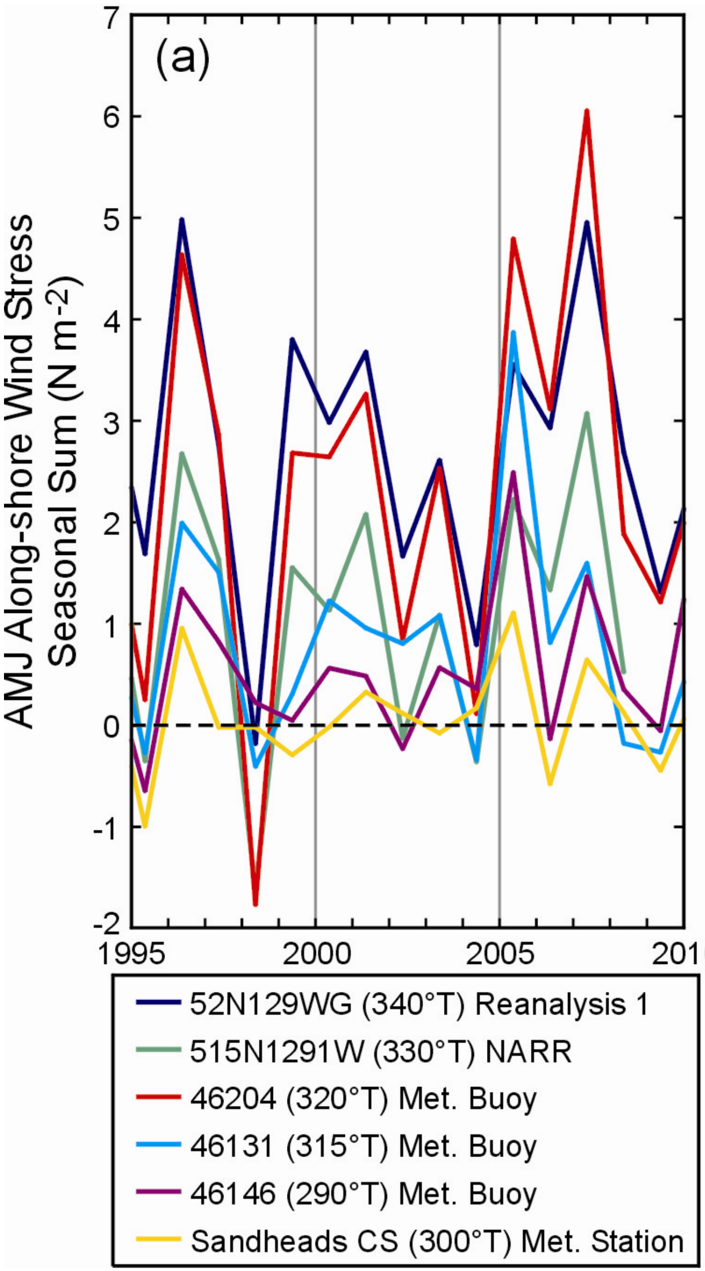


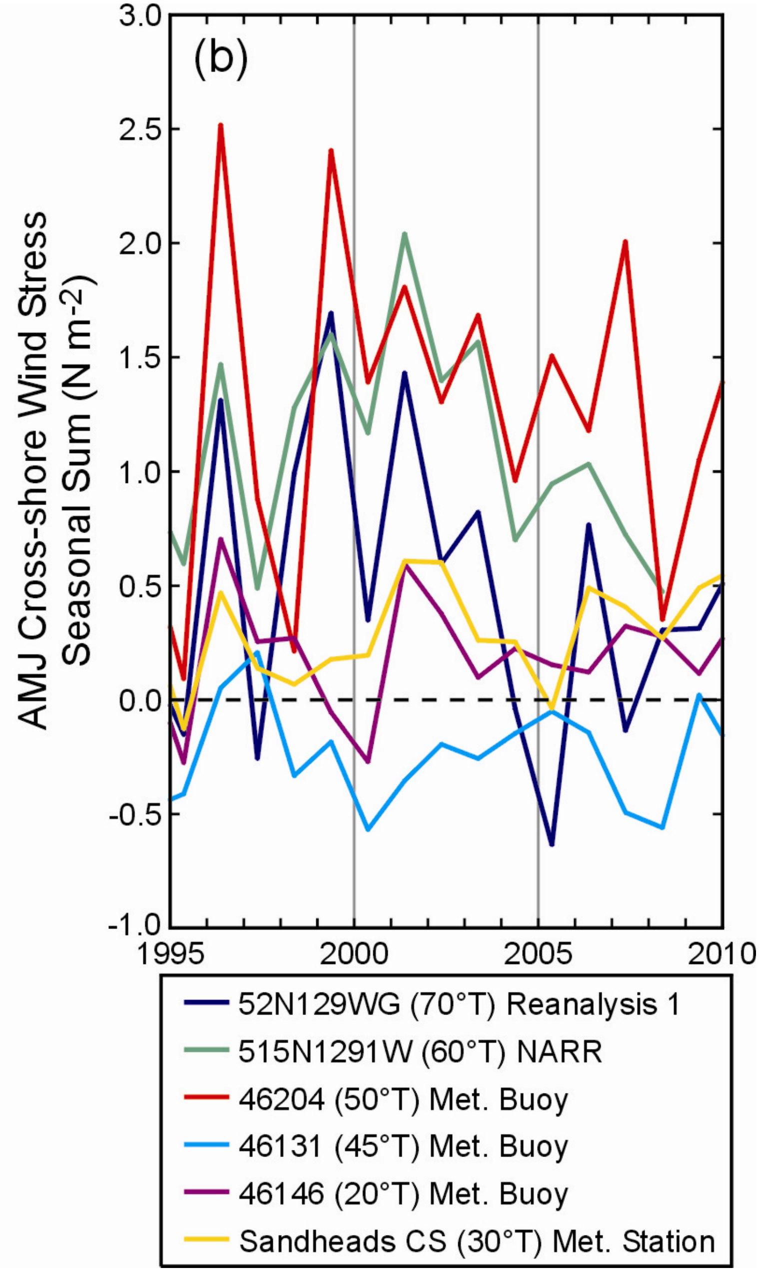
Physical Oceanography: Thomson et al.

Spring Transition

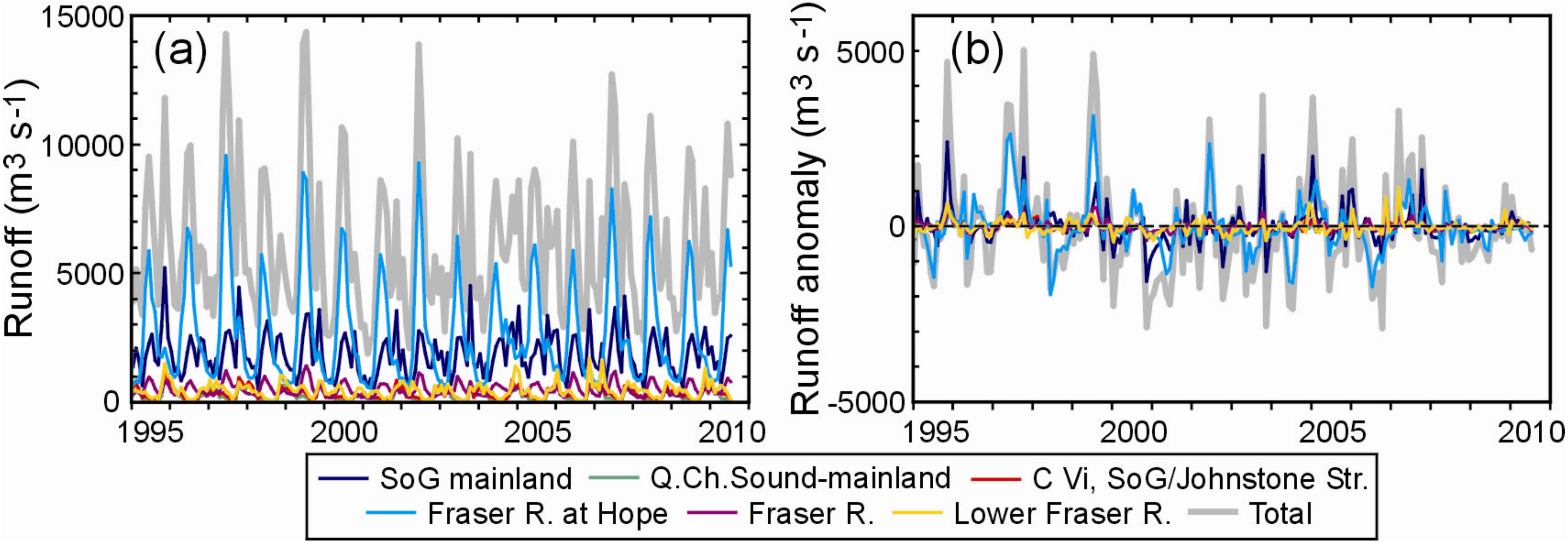


Integrated Winds

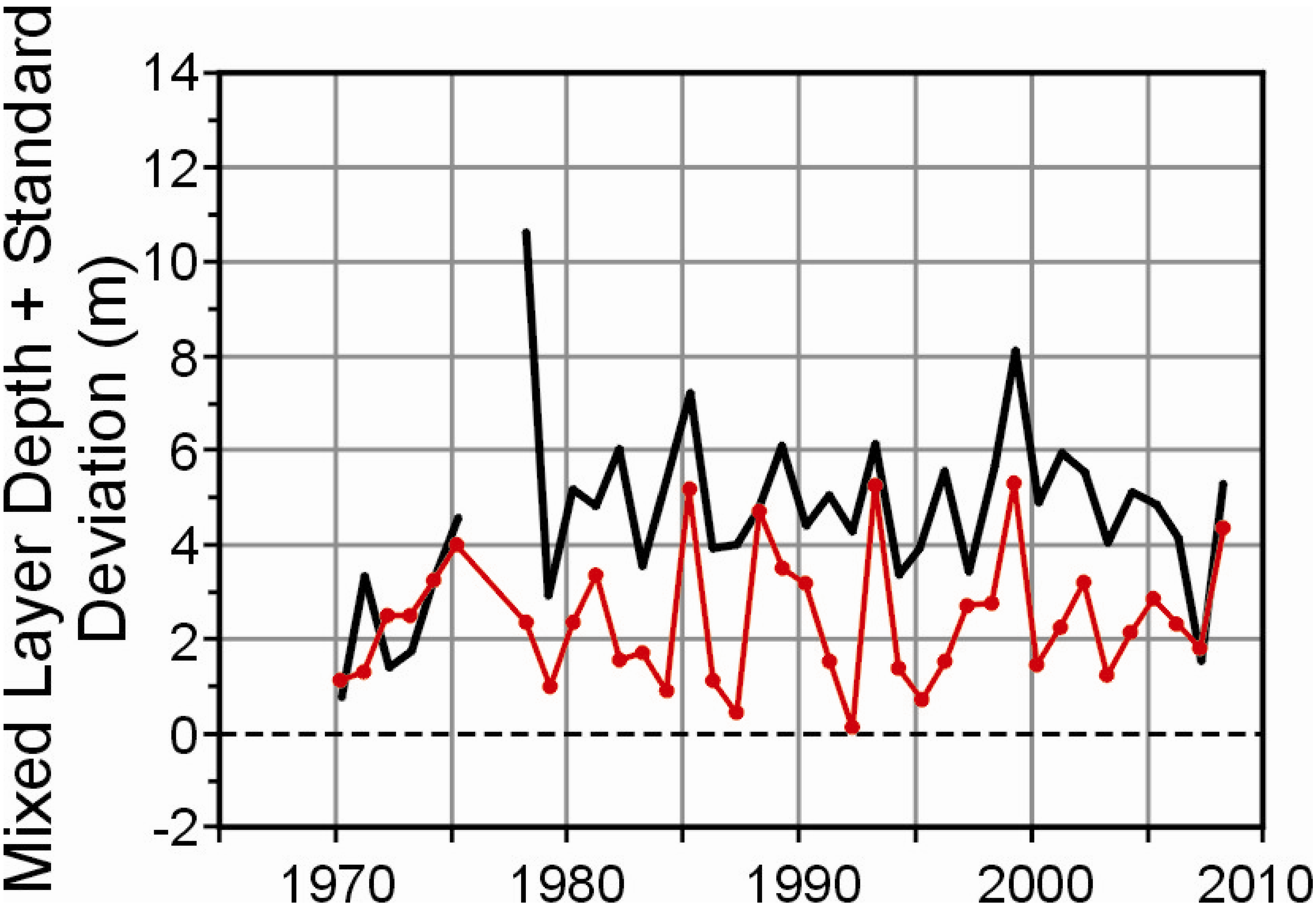




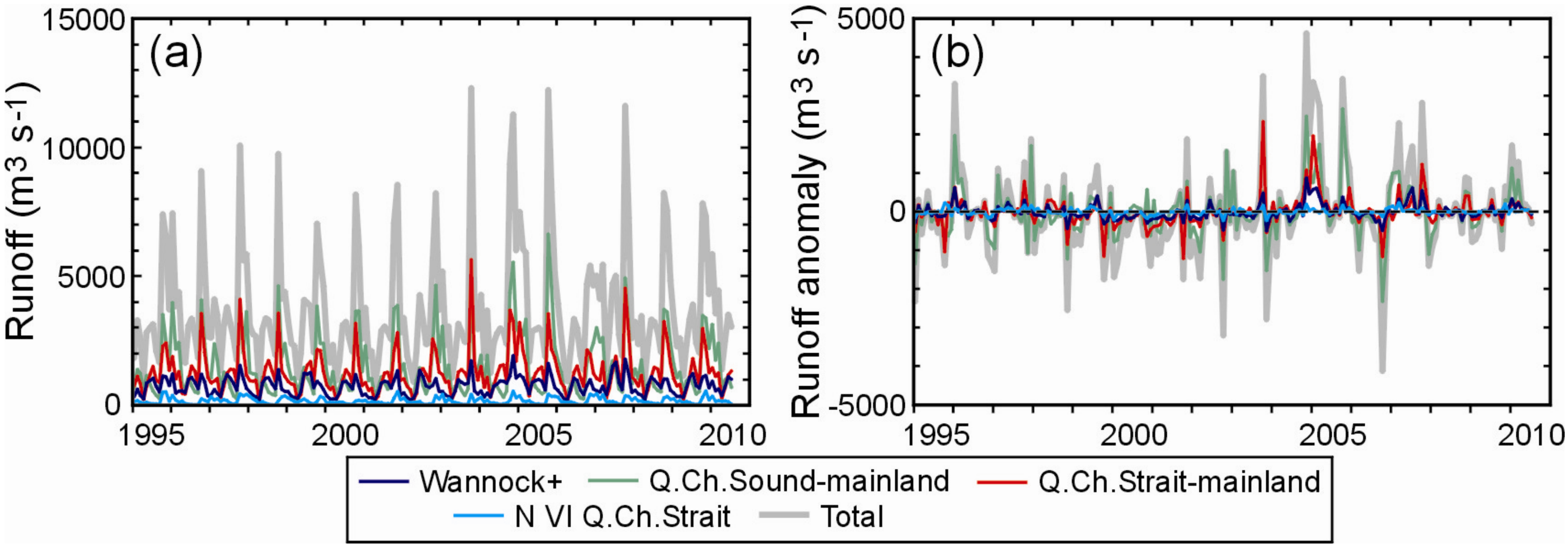
Strait of Georgia Freshwater Runoff



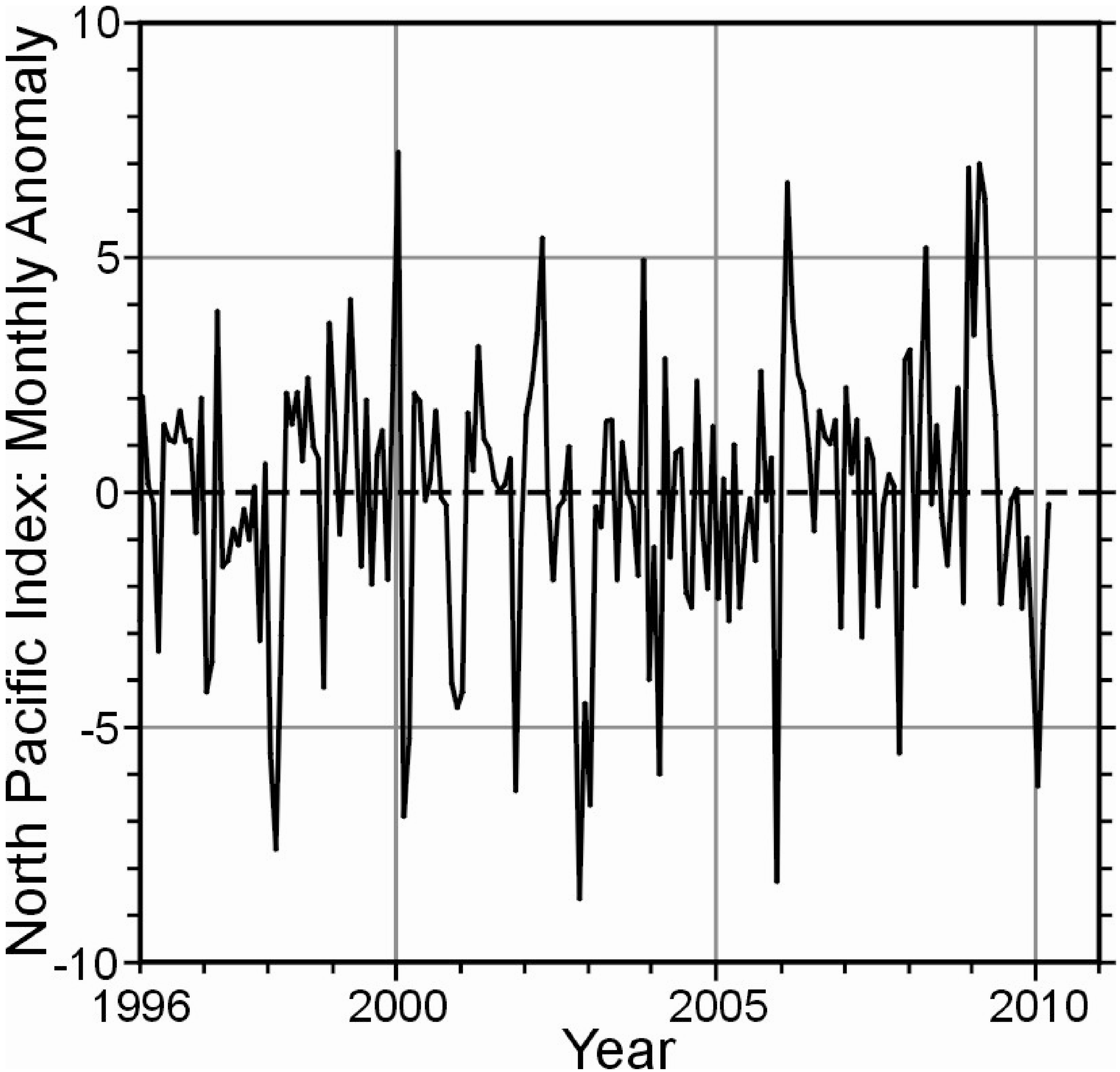
Nanoose Mix Layer Depth

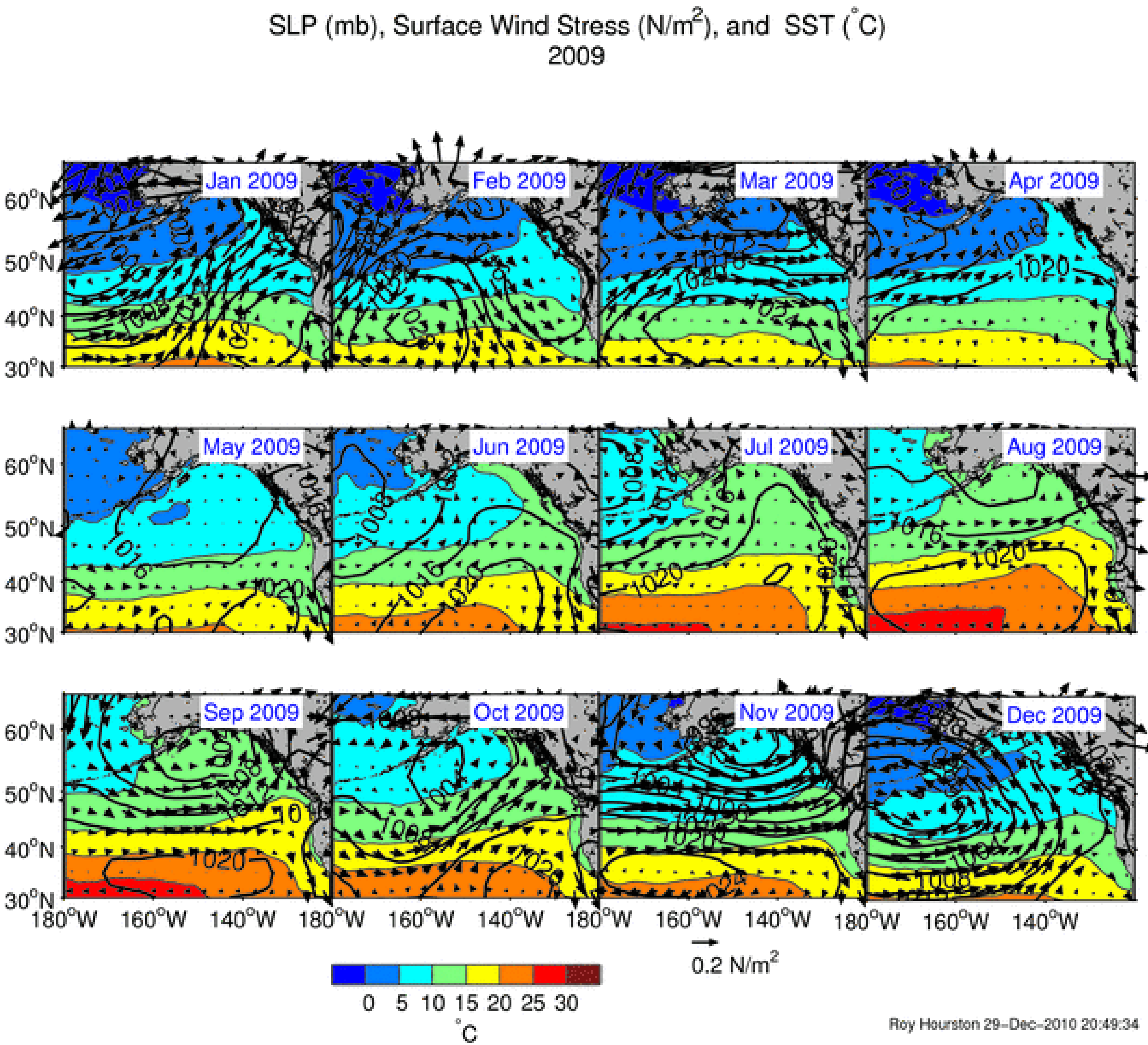


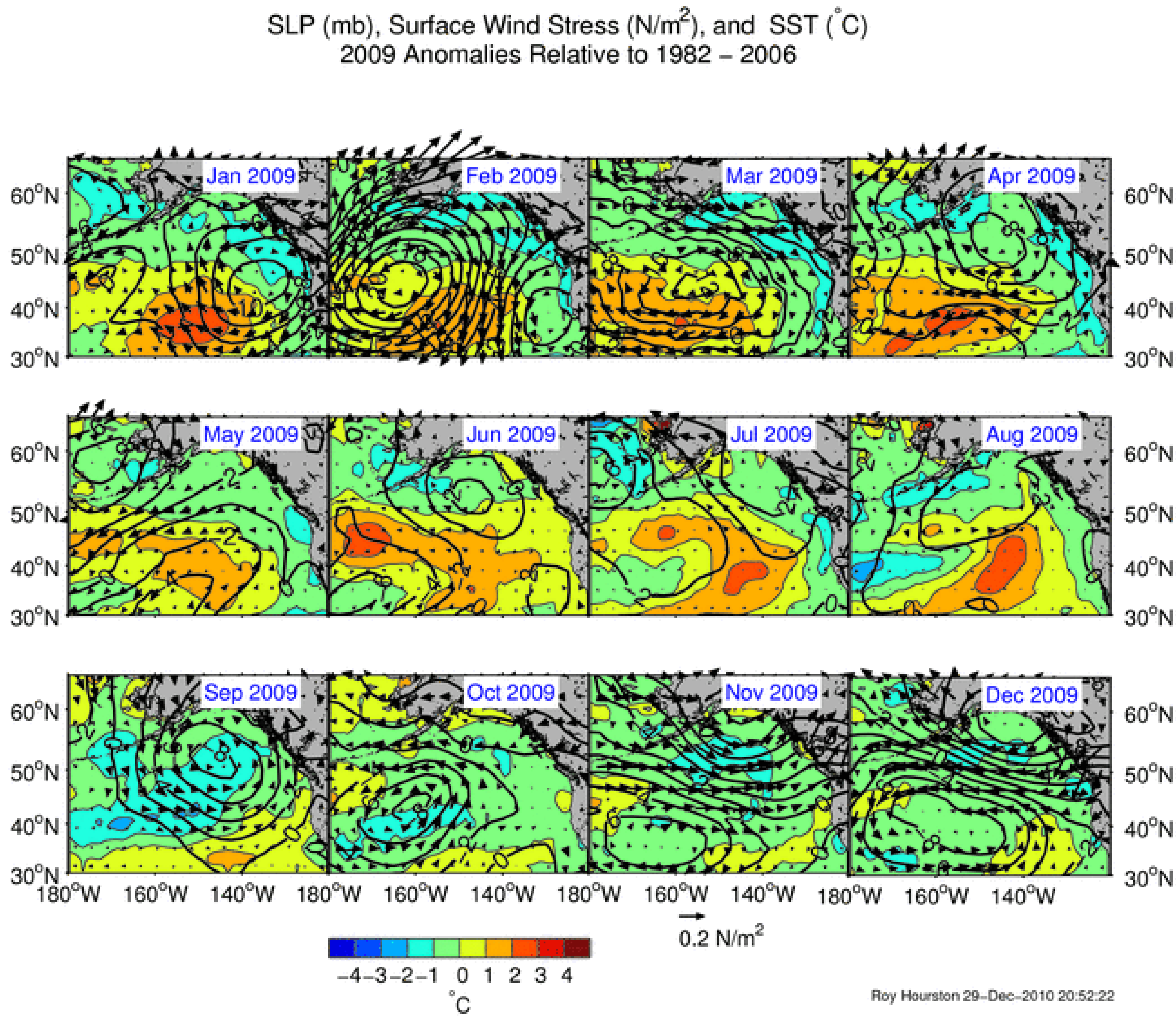
Queen Charlotte Sound Freshwater Runoff



North Pacific Index Anomalies




SLP (mb), Surface Wind Stress (N/m2), and SST (˚C)
2009
Jan 2009
Feb 2009
Mar 2009
Apr 2009
May 2009
Jun 2009
Jul 2009
Aug 2009
Sep 2009
Oct 2009
Nov 2009
Dec 2009
60˚N
50˚N
40˚N
30˚N
180˚W
160˚W
140˚W
0.2 N/m2
0 5 10 15 20 25 30
˚C
Roy Hourston 29-Dec-2010 20:49:34


SLP (mb), Surface Wind Stress (N/m2), and SST (˚C)
2009 Anomalies Relative to 1982 – 2006
Jan 2009
Feb 2009
Mar 2009
Apr 2009
May 2009
Jun 2009
Jul 2009
Aug 2009
Sep 2009
Oct 2009
Nov 2009
Dec 2009
60°N
50°N
40°N
30°N
180°W
160°W
140°W
0.2 N/m2
−4 −3 −2 −1 0 1 2 3 4
˚C
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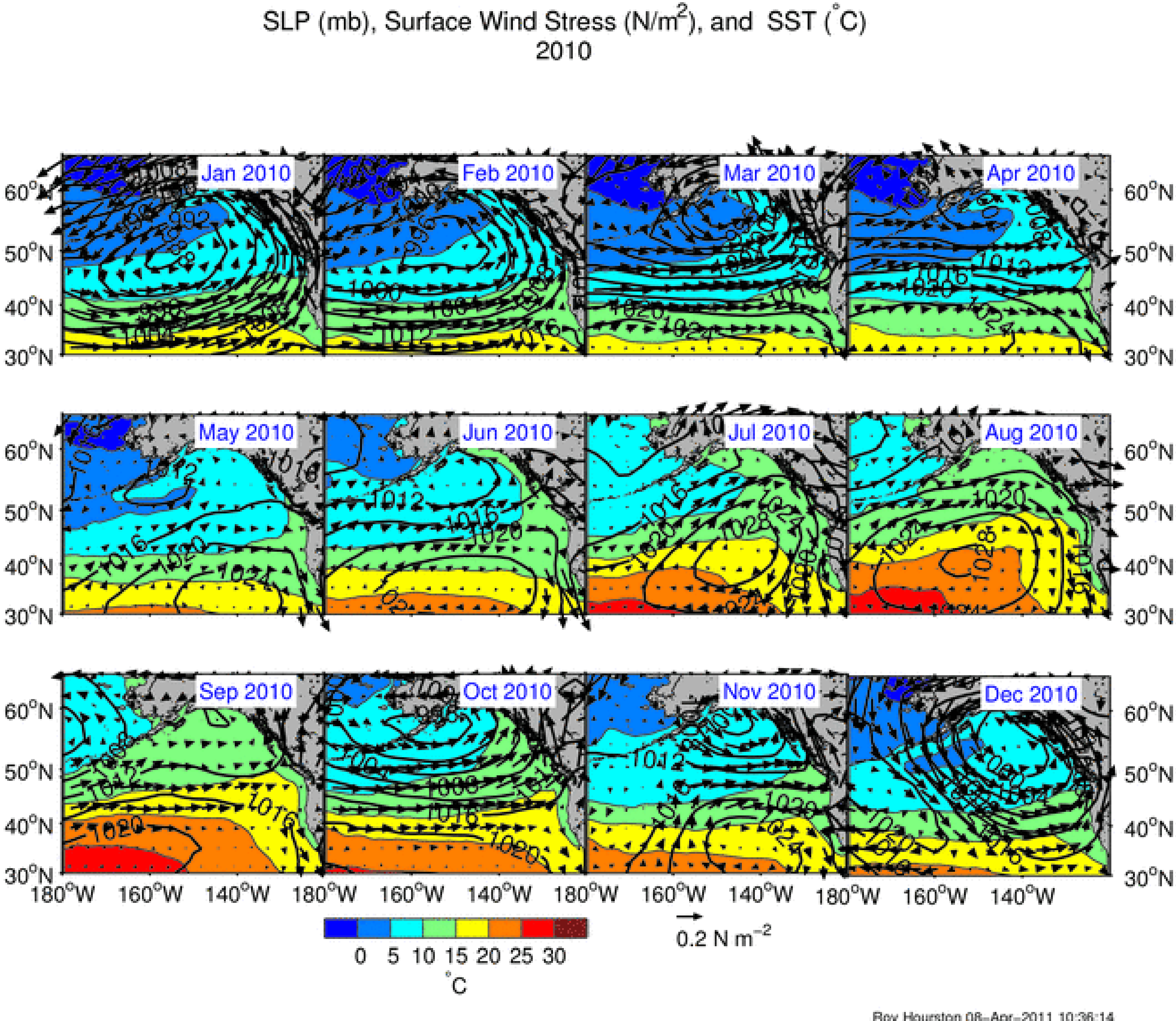
SLP (mb), Surface Wind Stress (N/m2), and SST (°C)
2010
Jan 2010
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Nov 2010
Dec 2010
60°N
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180°W
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140°W
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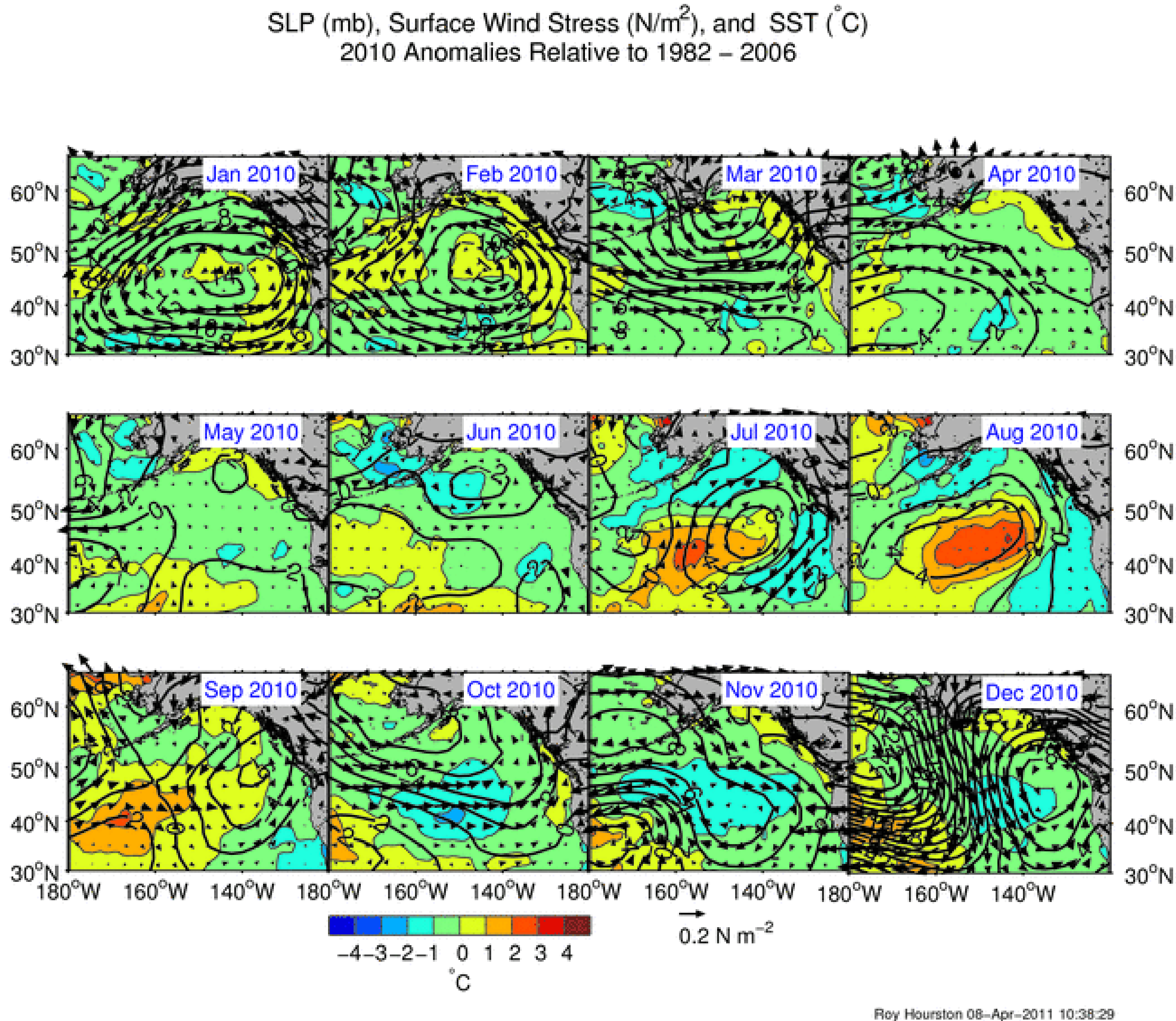
0.2 N m-2
Roy Hourston 08-Apr-2011 10:36:14


SLP (mb), Surface Wind Stress (N/m2), and SST (˚C)
2010 Anomalies Relative to 1982 – 2006
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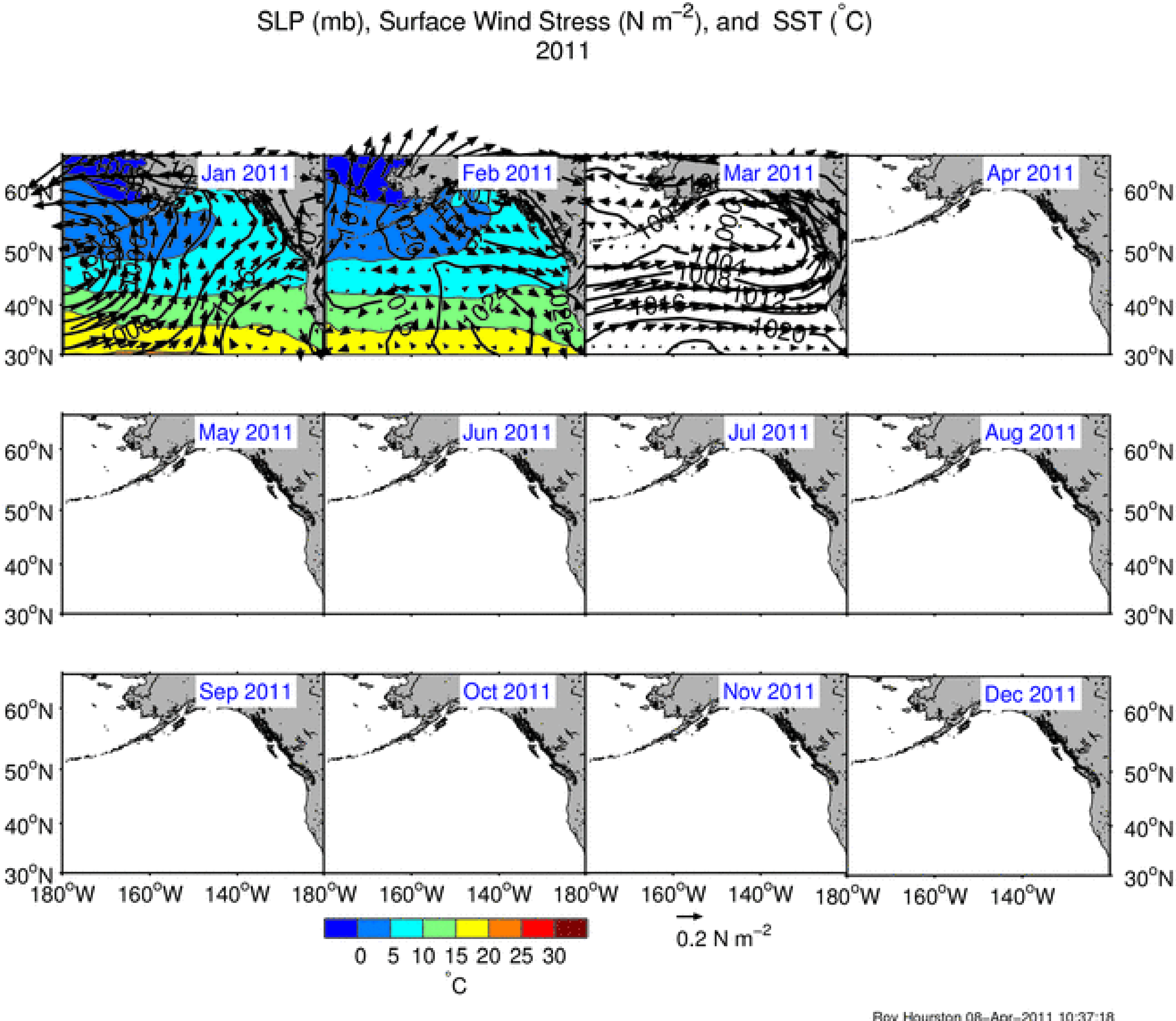
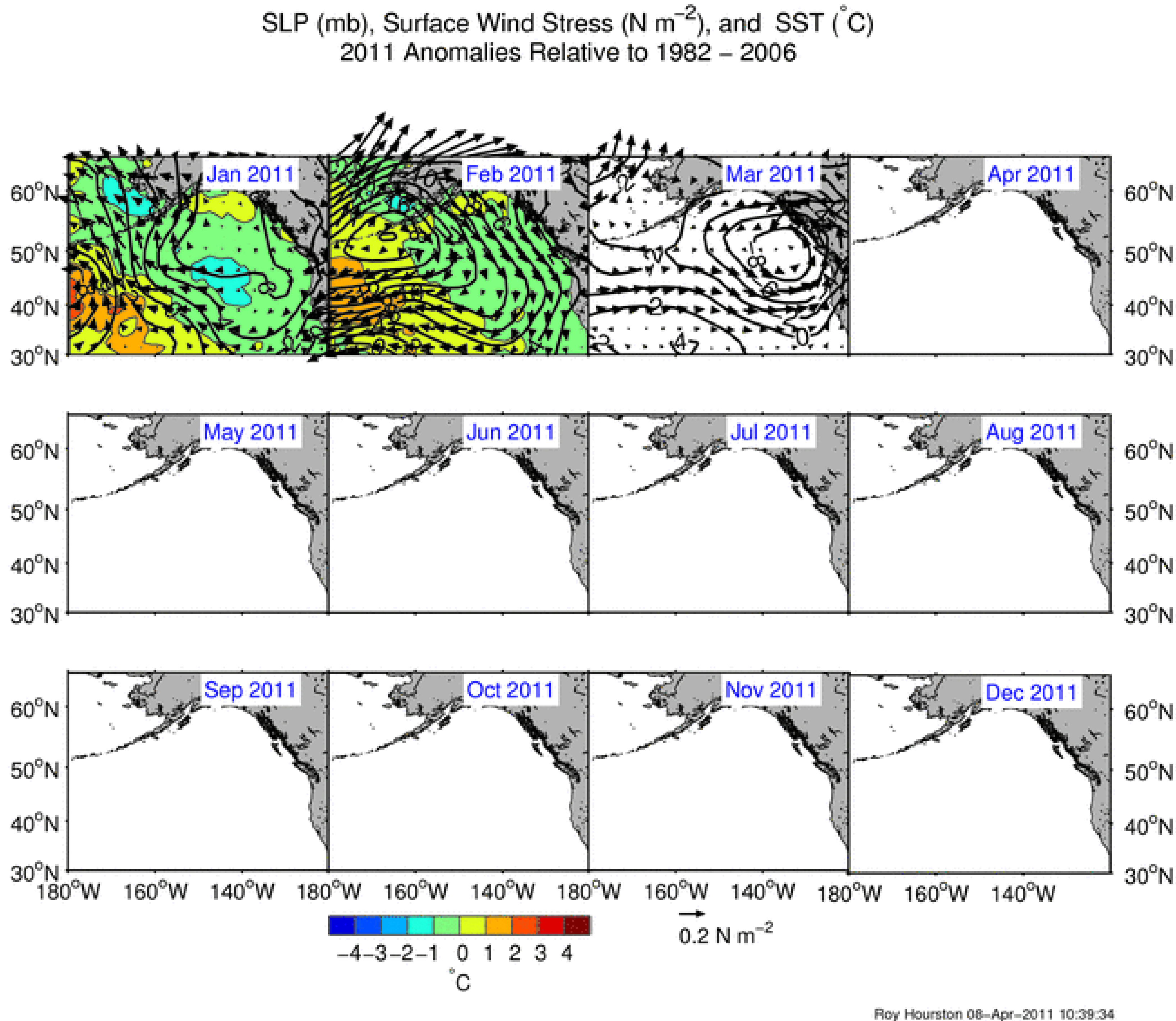
Oct 2010
Nov 2010
Dec 2010
60°N
50°N
40°N
30°N
180°W
160°W
140°W
−4 −3 −2 −1 0 1 2 3 4
˚C
0.2 N m−2
Roy Hourston 08–Apr–2011 10:38:29


SLP (mb), Surface Wind Stress (N m^{-2}), and SST (°C)
2011
Jan 2011
Feb 2011
Mar 2011
Apr 2011
May 2011
Jun 2011
Jul 2011
Aug 2011
Sep 2011
Oct 2011
Nov 2011
Dec 2011
60°N
50°N
40°N
30°N
180°W
160°W
140°W
0 5 10 15 20 25 30
°C
0.2 N m^{-2}
Roy Hourston 08-Apr-2011 10:37:18



SLP (mb), Surface Wind Stress (N m^-2), and SST (°C)
2011 Anomalies Relative to 1982 – 2006
Jan 2011
Feb 2011
Mar 2011
Apr 2011
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Aug 2011
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Nov 2011
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60°N
50°N
40°N
30°N
180°W
160°W
140°W
−4 −3 −2 −1 0 1 2 3 4
°C
0.2 N m^-2
Roy Hourston 08–Apr–2011 10:39:34

Physical Oceanography:
Peña et al.

Biology Inside/Outside SOG: Beamish et al.

Biology Inside/Outside SOG: Trudel et al.

Hypothesis 1:

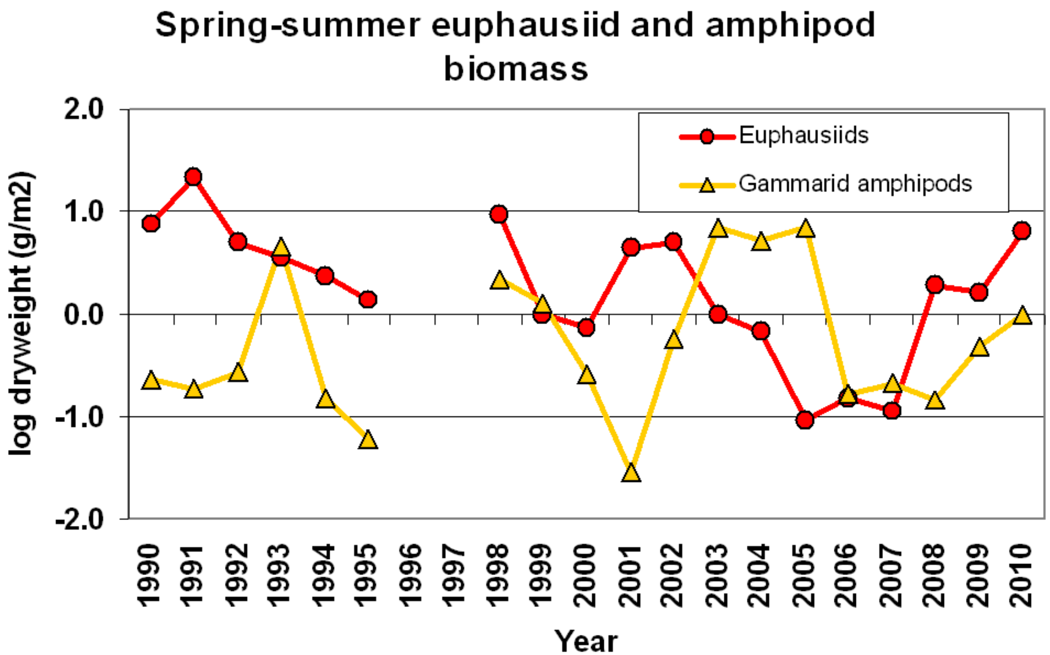
Is the unusually low return of Fraser R. sockeye in 2009 is due to events occurring inside the Strait of Georgia?

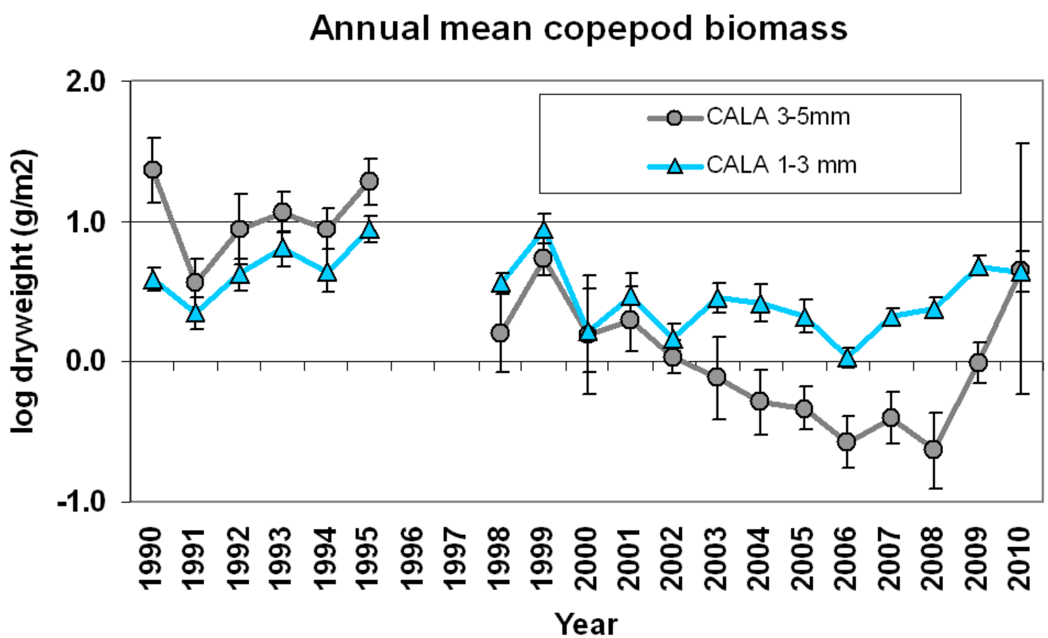
<u>Evidence for:</u>

- Below average zooplankton biomass
- Delayed production from *in situ* measurements (i.e. Allen et al.)
- Extremely low herring recruitment
- See Beamish's presentation

<u>But …</u>

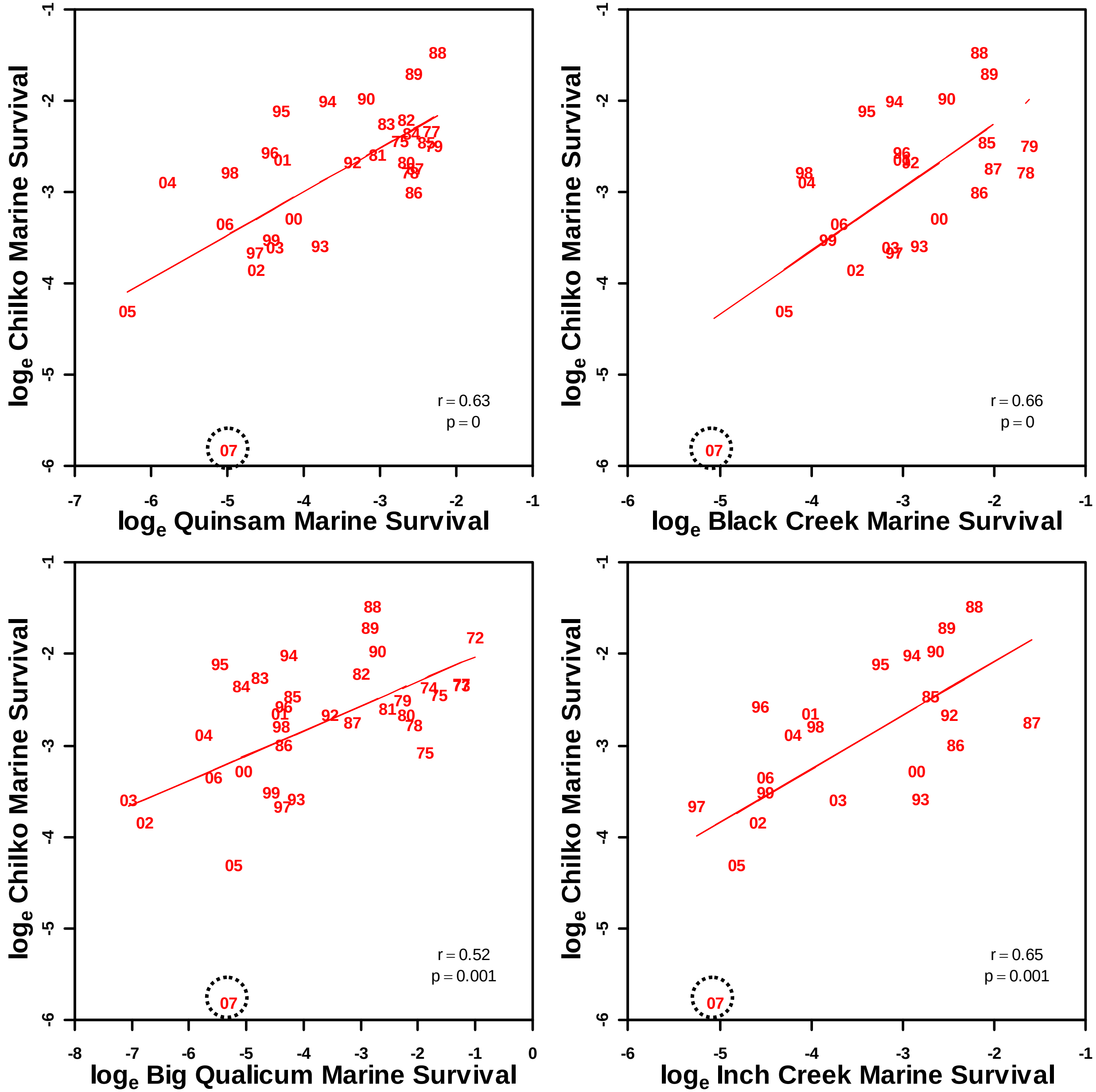
- Not necessarily the lowest prey biomass on record
- Early production from satellite images (i.e. Gower)





Source: D. Mackas (DFO)

Chilko L. Sockeye and SOG Coho Marine Survival



Data from PSC and S. Baillie (DFO)

Hypothesis 2:

Is the unusually low return of Fraser R. sockeye in 2009 is due to events occurring outside the Strait of Georgia?

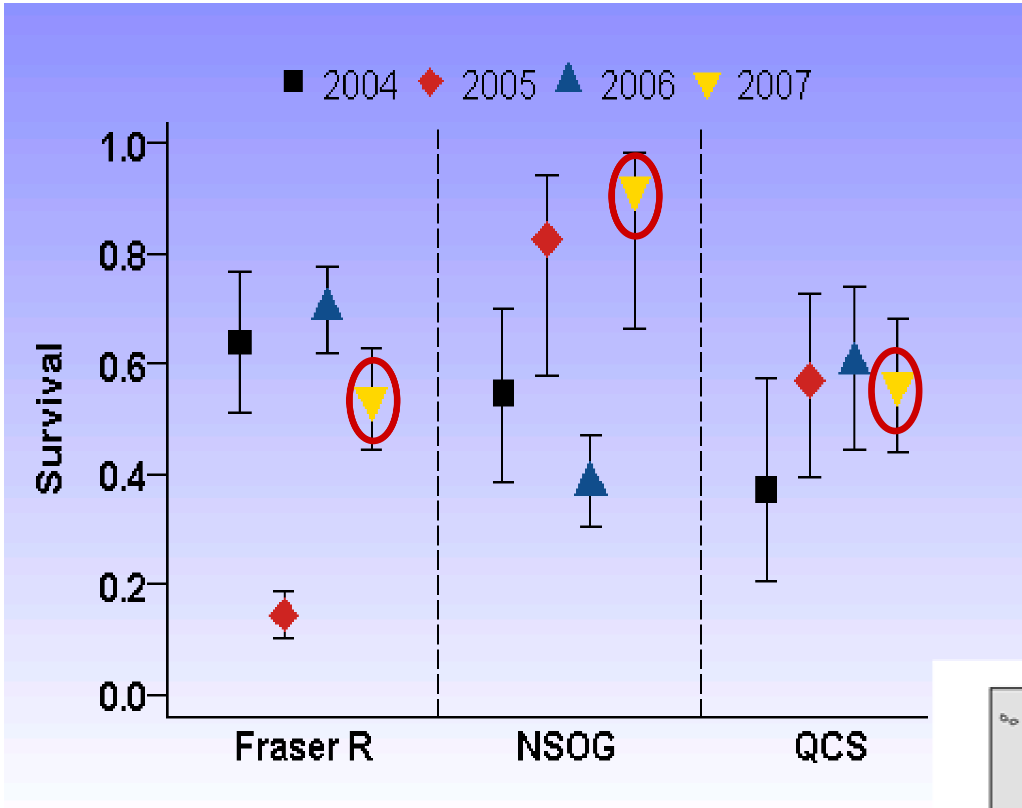
Evidence for:

- Acoustic tags indicate higher mortality of juvenile Cultus L. sockeye after leaving the Strait of Georgia then within

But …

- Large smolts were tagged
- Small sample size
- Does Cultus L. sockeye represent Fraser R. sockeye?
- Low proportion of juvenile Fraser R. sockeye in Hecate St.

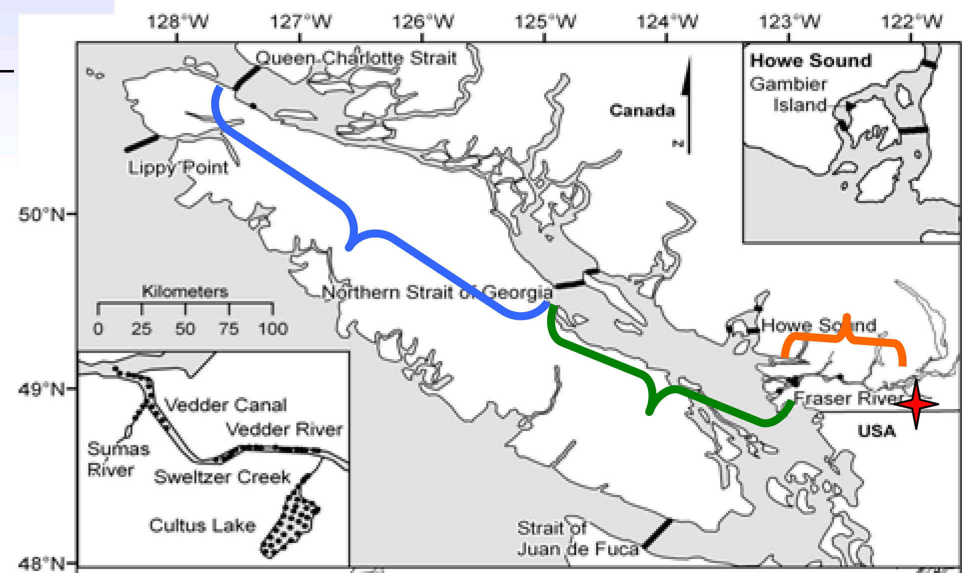
Cultus Lake Sockeye & 2009 Fraser River Sockeye Collapse



■ **2004**
◆ **2005**
▲ **2006**
▼ **2007**

2007 Outmigrating Smolt Survival (±95% Confidence Intervals)

Survival as high or higher than in prior years~ So where did the 2009 adult sockeye fail to survive?



Welch et al (*2009*). "*Freshwater and marine migration and survival of endangered Cultus Lake sockeye salmon smolts using POST, a large-scale acoustic telemetry array*".

Can. J. Fish. Aquat. Sci. 66(5):736-750.

Fraser River Sockeye Salmon Math

~1% Smolts survive to return in 2009, so:

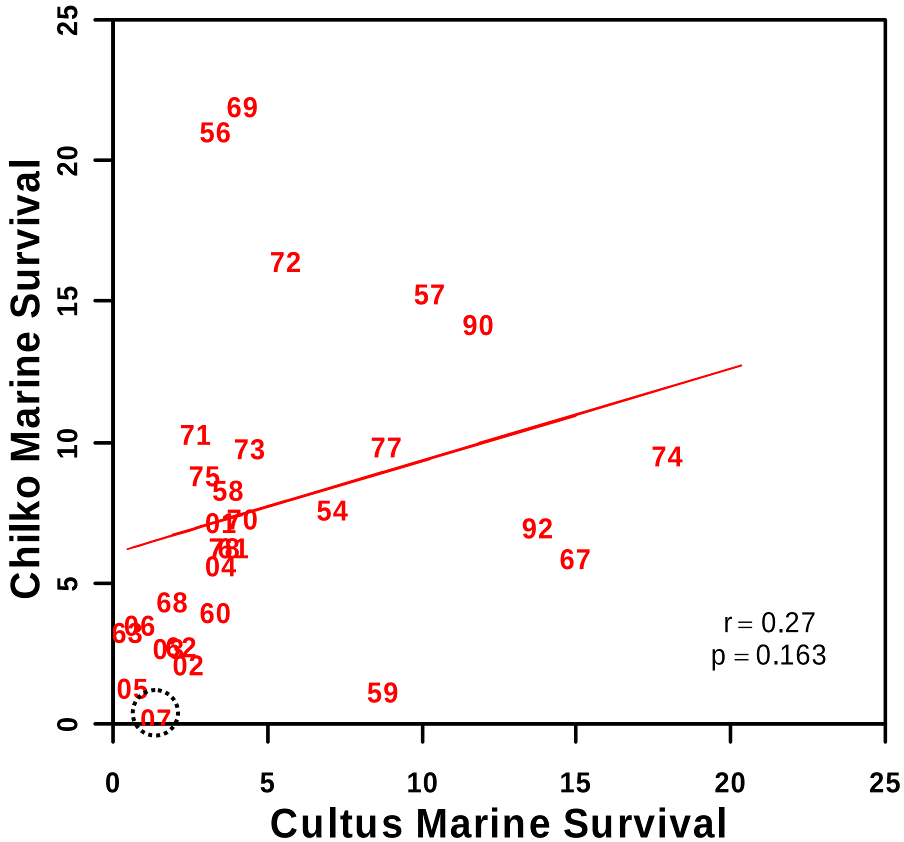
1/100 SAR	=	1/4	x	1/25
Smolt to Adult Fraser R		*Fraser R & SOG Survival (28% & Stable)*		*Outside SOG Survival*

Mortality "*beyond*" the Strait of Georgia ~7-8 times mortality in Fraser River & Strait of Georgia

Therefore, low return of Cultus L. sockeye in 2006-2009 likely caused by mortality occurring beyond Fraser R/Strait of Georgia ecosystem.

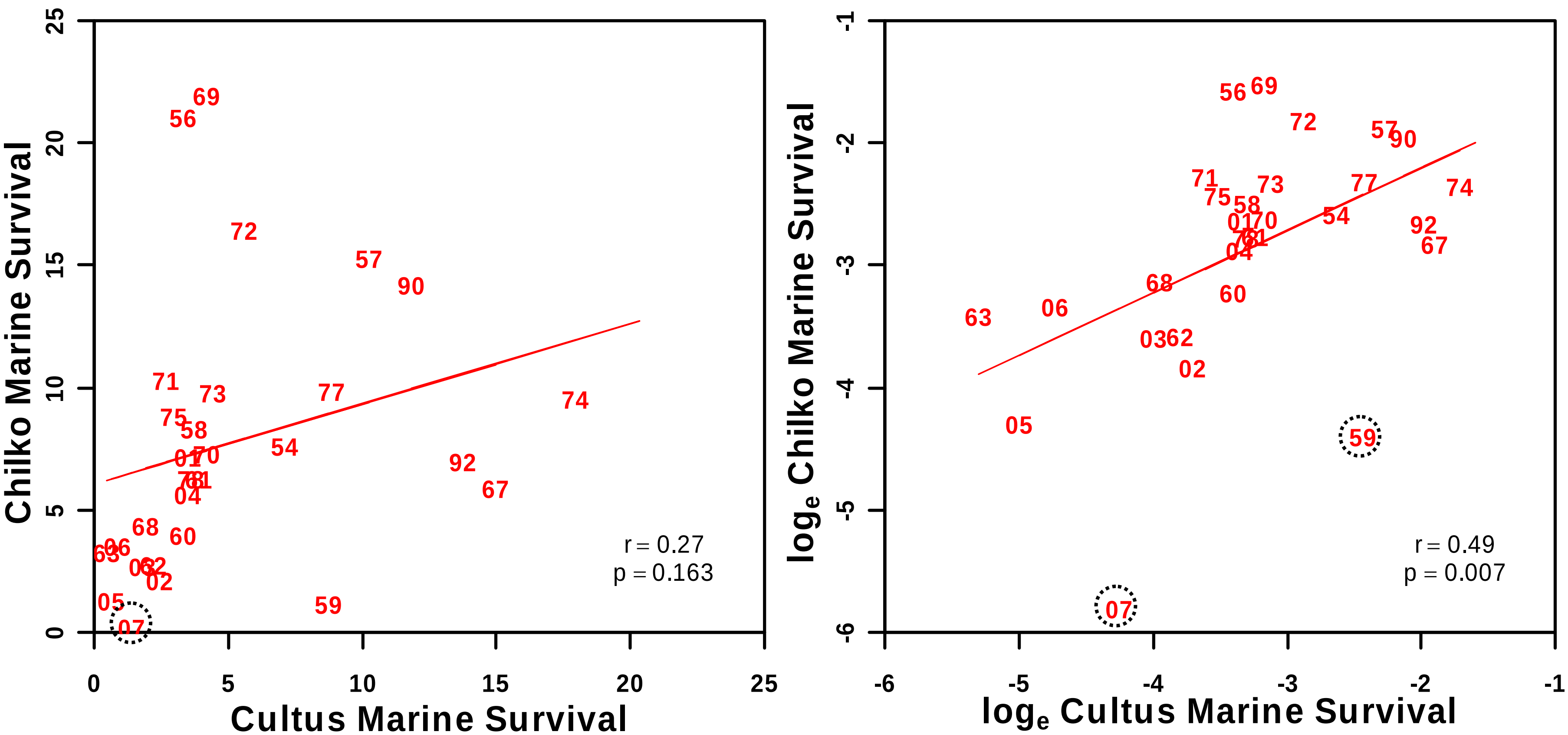
HOWEVER, the largest fish were tagged (~90 g vs 10 g)

Chilko L. and Cultus L. Sockeye Marine Survival



Data from PSC and M. Bradford (DFO)

Chilko L. and Cultus L. Sockeye Marine Survival



Data from PSC and M. Bradford (DFO)

Ricker Residuals vs Marine Survival

Stock	Marine Survival Cultus Lake		Marine Survival Chilko Lake	
	r	p	r	p
Early Stuart	0.45	0.013	0.45	0.001
Late Stuart	0.41	0.026	0.50	0.000
Stellako	0.52	0.003	0.64	0.000
Bowron	0.24	0.211	0.48	0.000
Raft	0.26	0.162	0.26	0.052
Quesnel	0.41	0.025	0.60	0.000
Chilko	0.56	0.001	0.79	0.000
Seymour	0.24	0.195	0.51	0.000
Shuswap	0.42	0.022	0.38	0.005
Birkenhead	0.52	0.003	0.51	0.000
Portage	0.21	0.305	0.46	0.001
Weaver	0.64	0.002	0.24	0.111
Fennel	0.44	0.05	0.56	0.000
Scotch	-0.03	0.901	0.40	0.012
Gates	0.43	0.073	0.51	0.001
Nadina	0.34	0.255	0.61	0.000
Pitt	0.14	0.447	0.32	0.016
Harrison	-0.04	0.852	-0.23	0.082

22% significant **72% significant**

Data from PSC and M. Bradford (DFO)

Hypothesis 3:

Is the decline in Fraser R. sockeye productivity and low returns in 2009 related to ocean productivity in Queen Charlotte Sound?

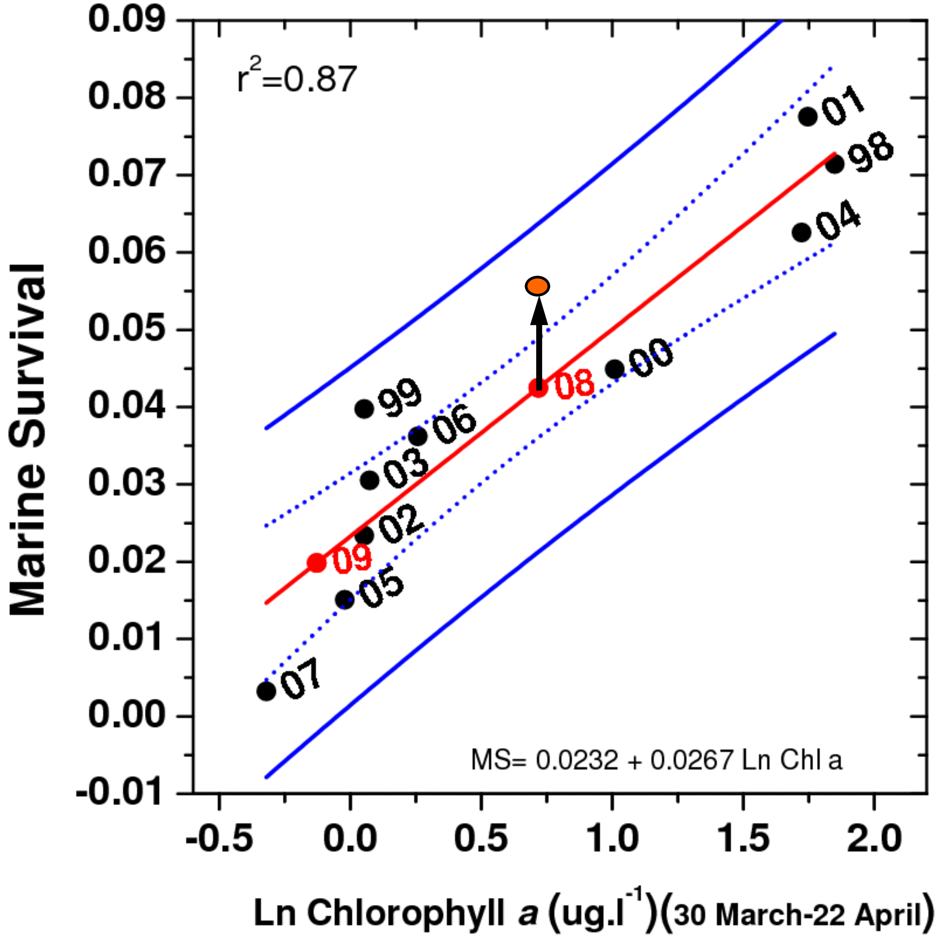
Evidence for:

- Strong positive correlation between Chilko sockeye survival and cholorophyll concentration in Queen Charlotte Sound
- Anomalous fresh water and low bird production

Evidence against:

- Marine survival of Smith Inlet sockeye was not abnormally low.
- Salmon growth was not poor north of Vancouver Island

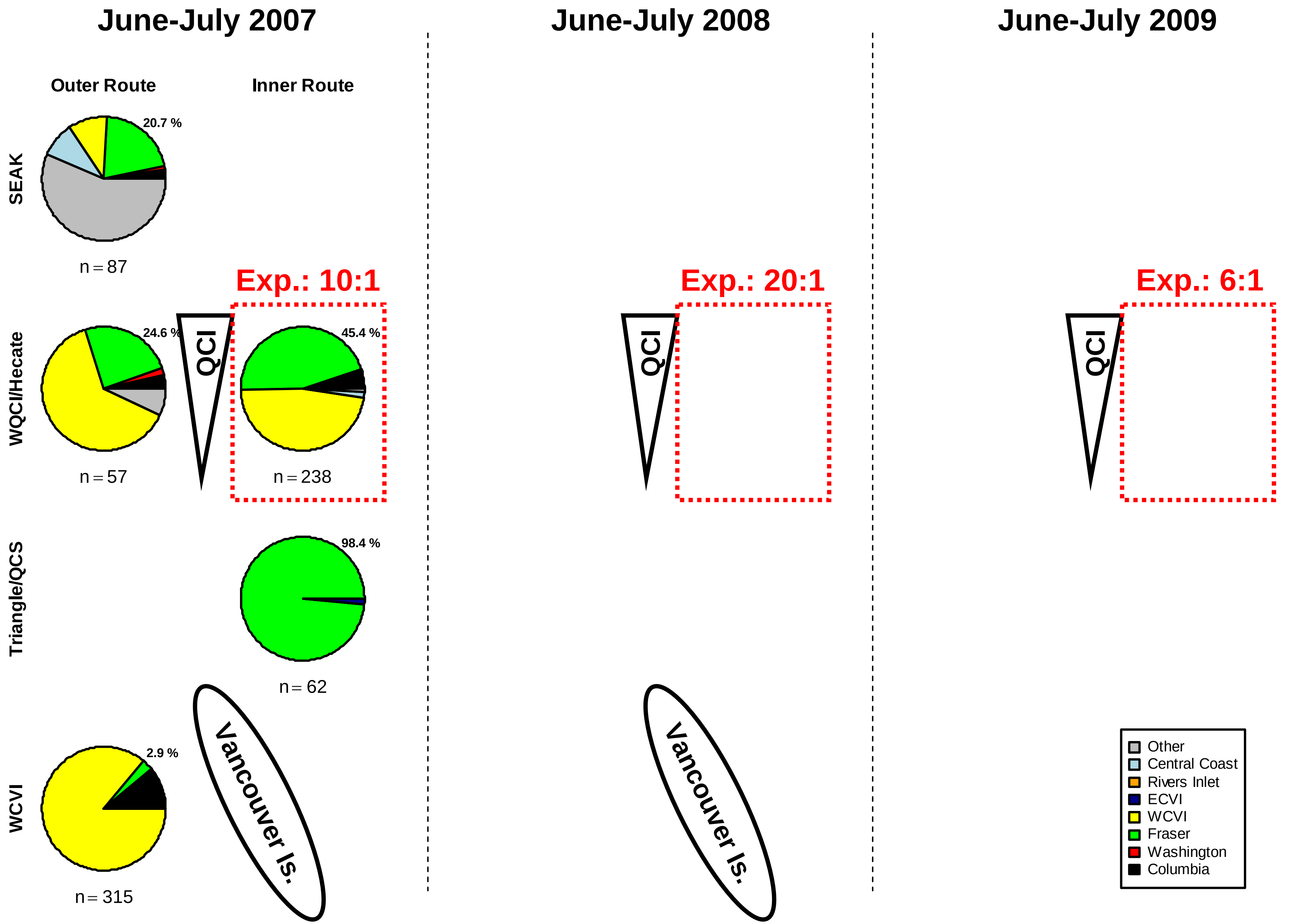
Chilko Survival vs Chlorophyll concentration anomalies in Queen Charlotte Sound



MS for Chilko sockeye salmon vs. the natural logarithm of the QCS chlorophyll concentrations (black dots) between 30 March and 22 April in the ocean entry year. The central (red) line is the regression line based on data from 1998-2007, adjacent (dotted blue) lines are the upper and lower 95% confidence limits for the regression line, the outer (solid blue) lines are the 95% confidence limits for the data (i.e. 95% of the data are predicted to occur within these lines), and the labels refer to ocean entry years.

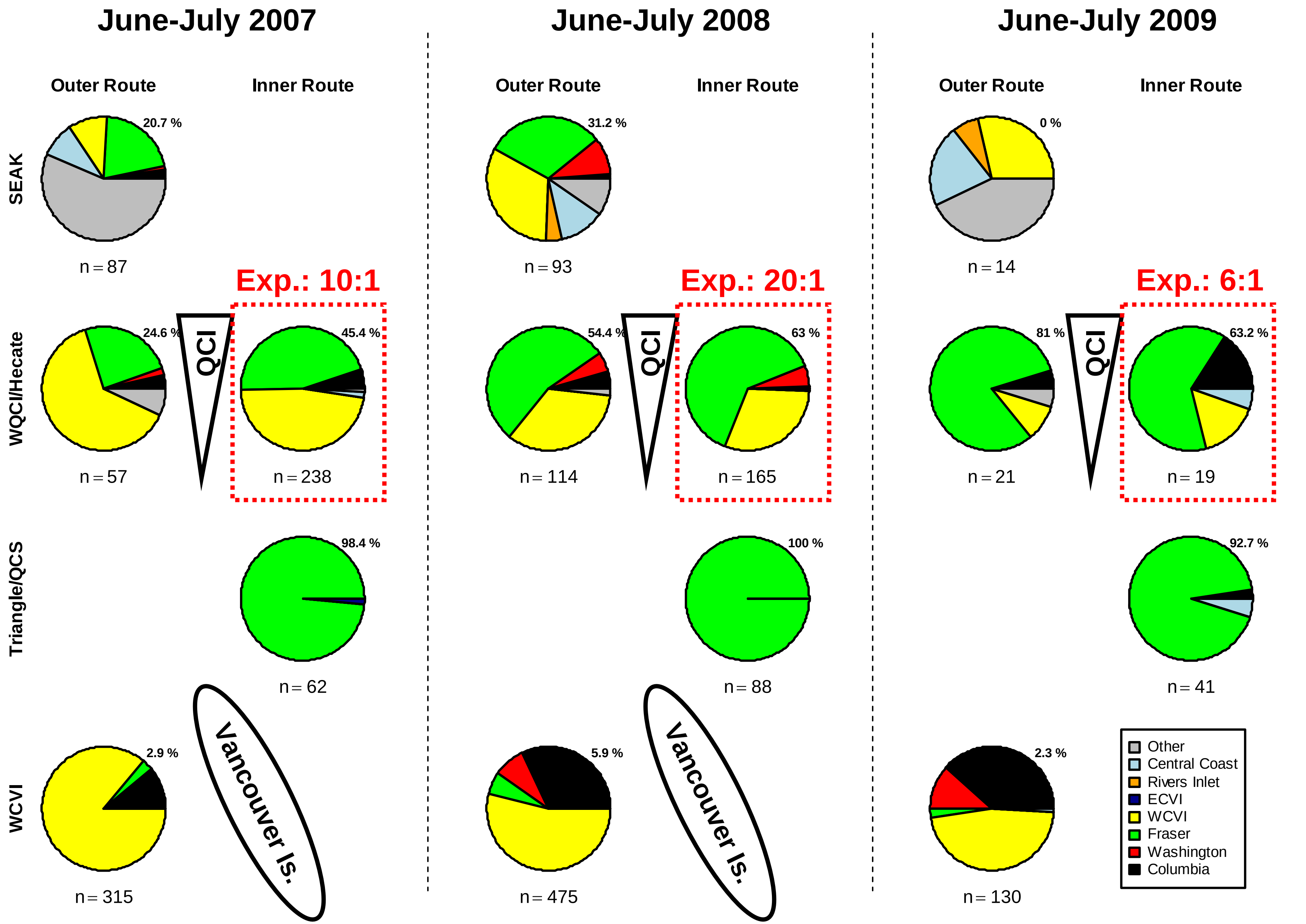
Source: Irvine et al. (2010)

Interannual Variation in Juvenile Sockeye Salmon Stock Composition



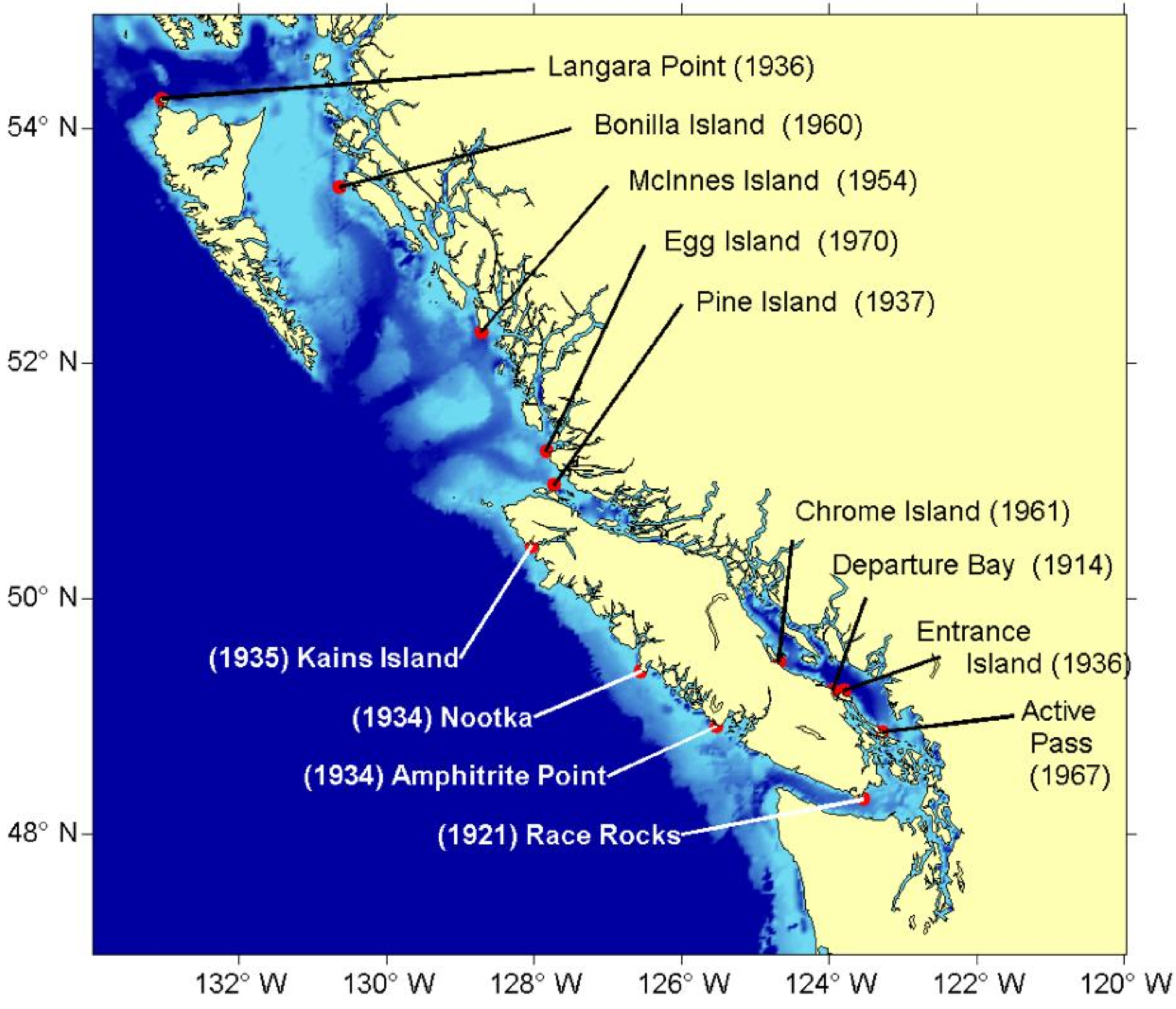
Updated from Tucker et al. 2009. Trans. Am. Fish. Soc. 138: 1558-1580.

Interannual Variation in Juvenile Sockeye Salmon Stock Composition



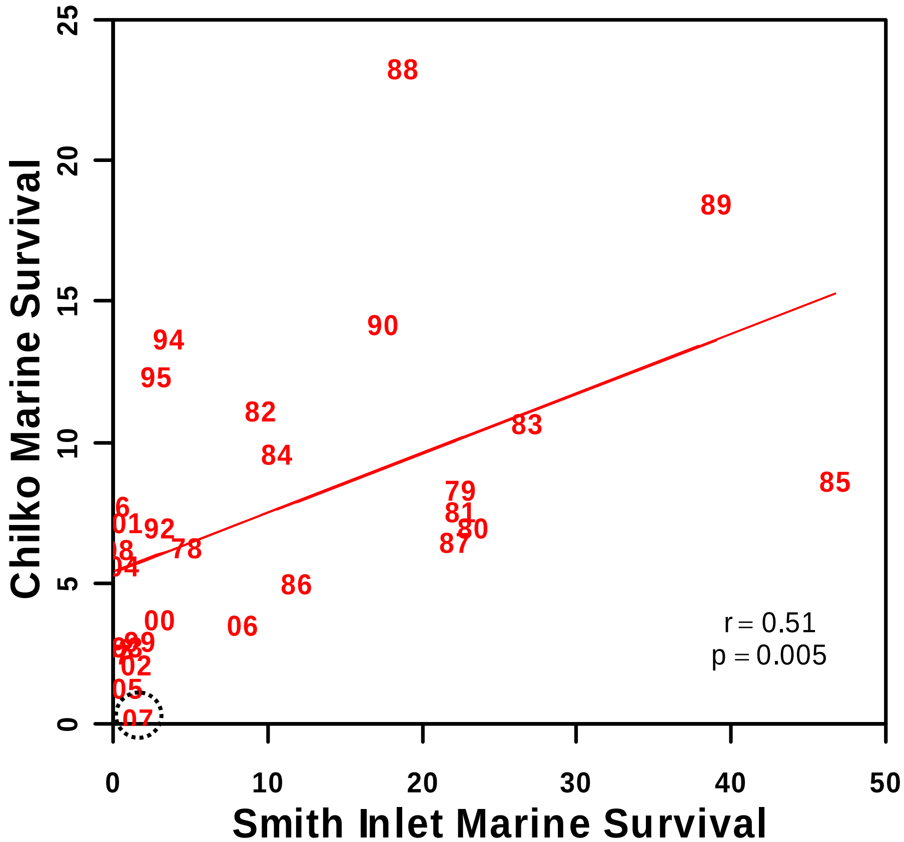
Updated from Tucker et al. 2009. Trans. Am. Fish. Soc. 138: 1558-1580.

British Columbia Lighthouses



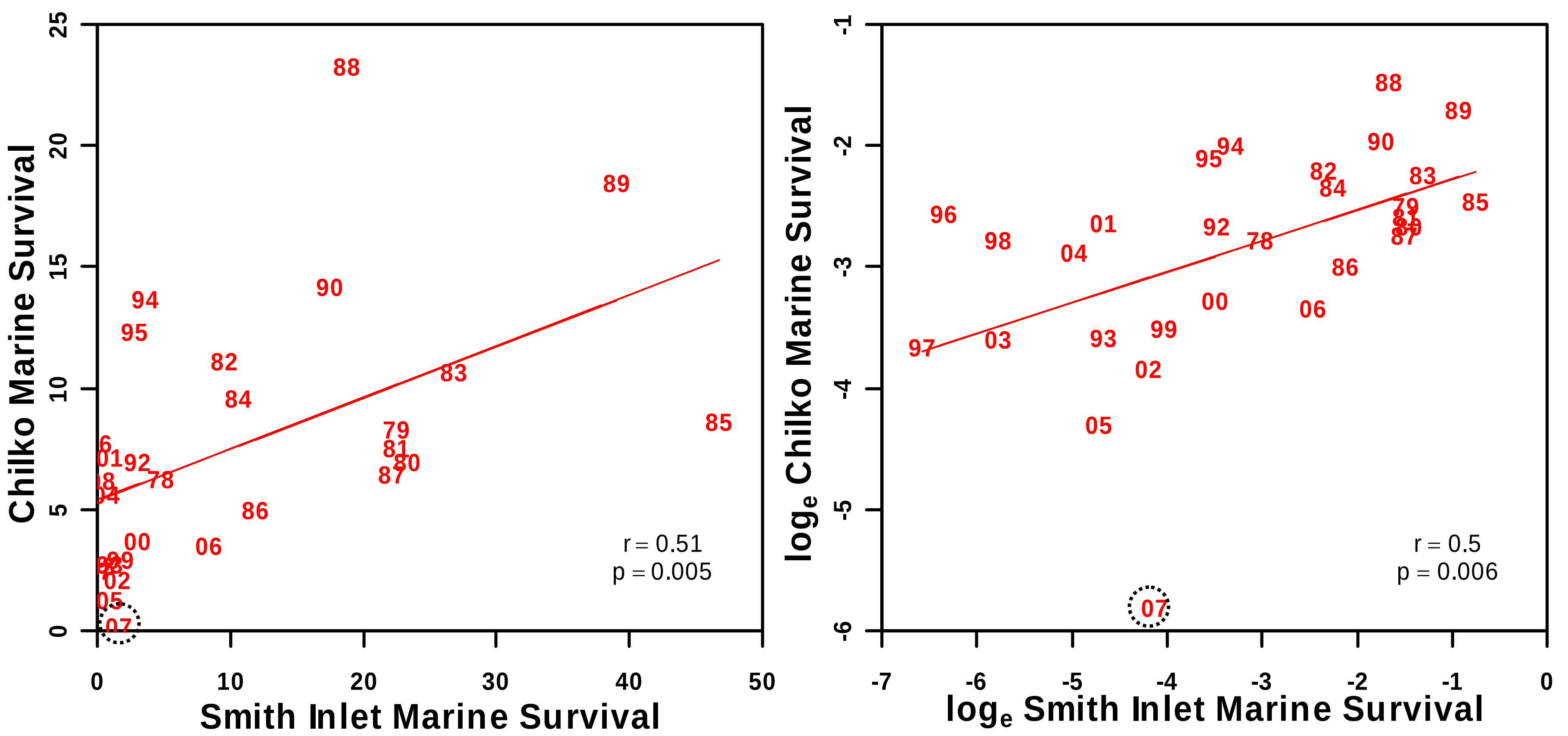
Data from P. Chandler (DFO)

Chilko L. and Smith I. Sockeye Marine Survival



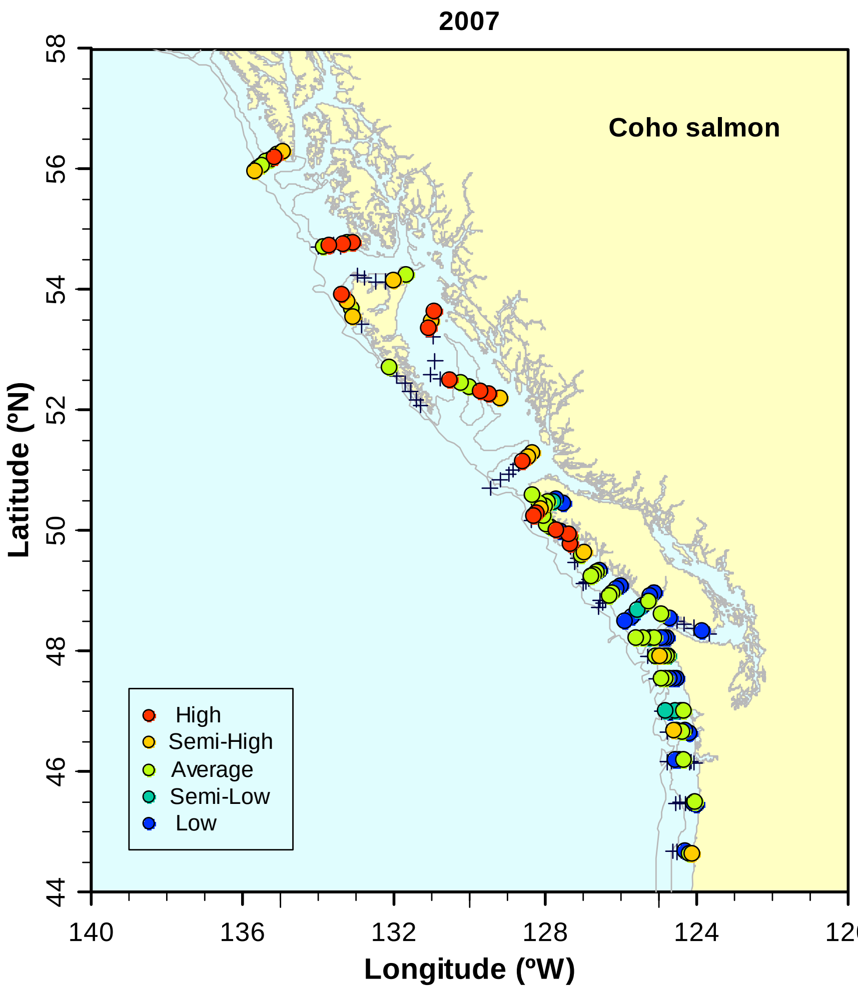
Data from PSC and K. Hyatt (DFO)

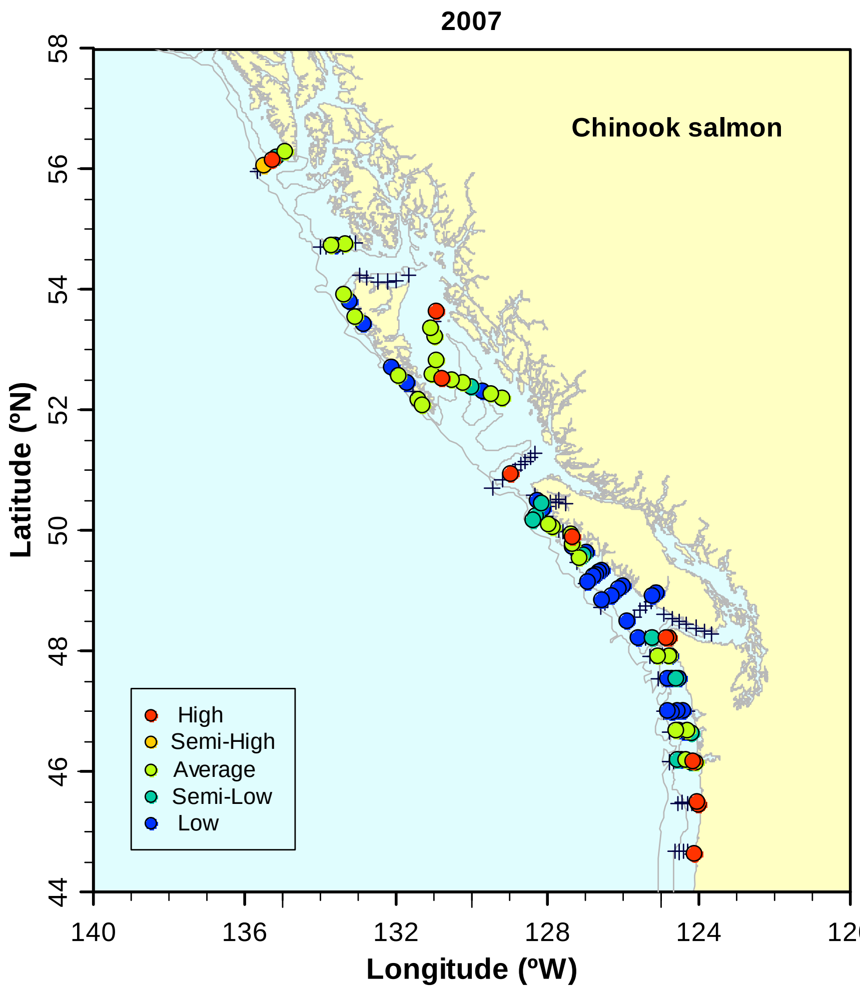
Chilko L. and Smith I. Sockeye Marine Survival



Data from PSC and K. Hyatt (DFO)

Growth Hormones in Juvenile Coho and Chinook (Mid-June to early-July 2007)





Data from B. Beckman (NOAA) and M. Trudel (DFO)

Biology Inside/Outside SOG:
Miller-Saunders et al.

NEW DATA

2007 versus 2008 Genomics Contrast Study

	Low Survivorship	High Survivorship
	2007	2008
Fraser FW	10	10
Fraser SW	10	10
WCVI SW	10	5

Liver – diet and disease
Brain – hormonal control of feeding/migration/other
White muscle – growth

Ho: 2007 Fraser fish may be more conditionally compromised due to poor ocean productivity, resulting in reduced prey abundance and quality (poor feeding—liver) leading to poor growth (muscle).

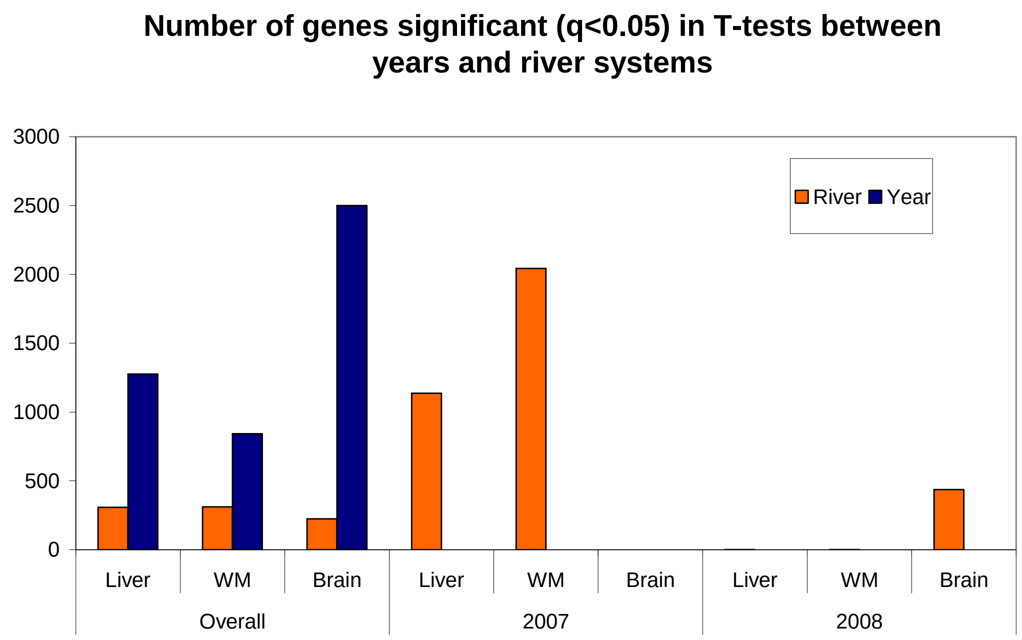
Ho: that 2007 WCVI – that did not migrate through the Strait of Georgia and survived well – were in better condition than Fraser fish, but that differences may not have existed in 2008.

4x44K Agilent Array

Miller et al. in prep

NEW DATA

2007 versus 2008 Contrast Study: SW



Year is more significant than River-system (Fraser vs WCVI) overall
River-system significant in liver and white muscle in 2008 but not 2008

4x44K Agilent Array

Miller et al. in prep

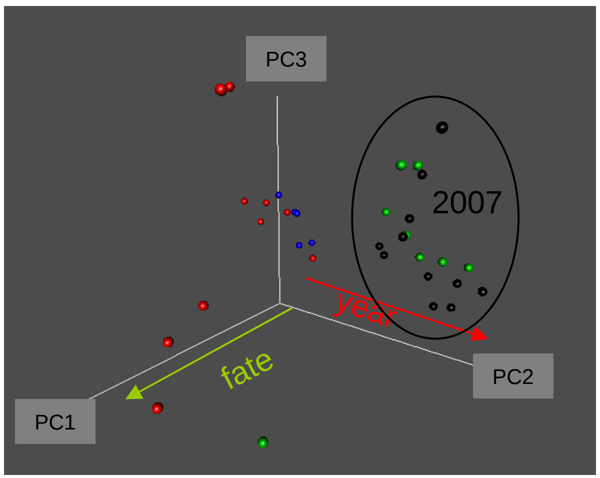
NEW DATA

SW Date: River System (Fraser versus WCVI) x Year

Ho: Fraser will be more distinct from WCVI in 2007 than in 2008 (as survival was similar in 2008, but not 2007)

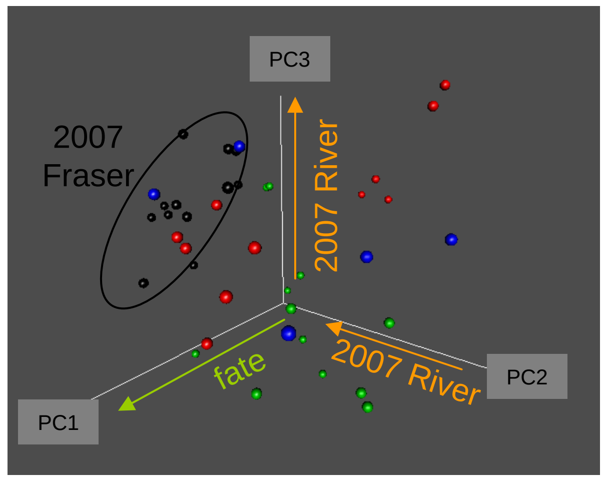
Higher distinction Black vs. Green than Red vs Blue

Brain



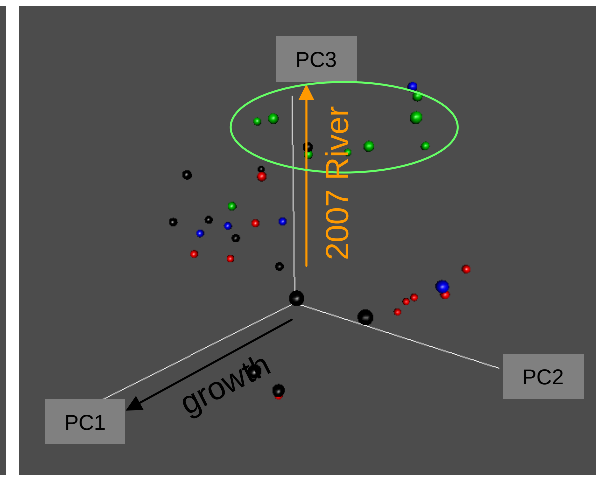
Not supported

Liver



Supported

White Muscle



Mildly supported

Fraser	**2007**
Fraser	**2008**
WCVI	**2007**
WCVI	**2008**

Stock x Year (SW)

4x44K Agilent Array

Miller et al. in prep

NEW DATA

Functional Liver Signatures Reveal Immunosuppression and Stress in 2007 Fraser salmon smolts

- **Mortality-related signature** (PC1)
  - 90% of Fraser 2007 fish contained the MRS vs. <50% in 2008
  - MRS also observed in WCVI salmon, but lower prevalence in 2007 than 2008

- **Immunosuppression** (PC3 SW, PC1 2007 SW, t-tests)
  - Signatures differentiating Fraser 2007 vs 2008 and 2007 Fraser vs WCVI indicate Immunosupression in Fraser 2007 fish
    - Innate and humoral immunity most strongly affected
- **Stress** (PC2 SW)
  - Numerous stress pathways also stimulated in 2007 Fraser fish
    - Oxidative stress (main contributor to tissue damage under starvation)
    - DNA damage response
    - Cellular response to stress
    - Xenobiotic metabolism

While food deprivation could explain the immunosuppression and stress, metabolic elements associated with prolonged starvation are relatively weak

Note: hypoxia and metabolic shifts potentially associated with starvation were stronger when the MRS was removed by contrasting only MRS fish in both years

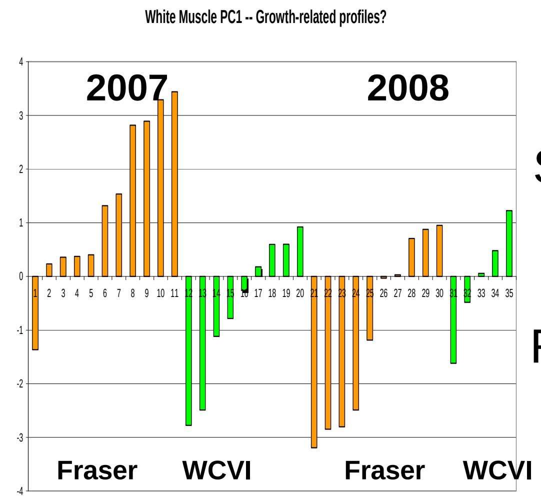
Miller et al. in prep

NEW DATA

“DFO summer surveys of Queen Charlotte Sound in 2007 had the smallest mean size since sampling began in the late 1990’s”

PC1 of White Muscle—Potentially a Growth-Related Profile

	Rapid	Slow
Up 2007 end of PC1		
DNA metabolism/replication/protein-DNA complex/kinetocore		x
regulation of mitotic cell cycle.cell cycle/cell proliferation		x
carbohydrate metabolism		
nucleasome organization		
microtubule cytoskeleton		
glycoprotein biosynthesis		
protein AA glycosylation		
vesicle-mediated transport		
melanosome		
ER/protein folding		
cellular response to DNA damage stimulus		
alcohol catabolism		
Up 2008 end of PC1		
protien AA phosphorylation/AA transport	x	
structural constituent of muscle/contractile fiber/myofibril	x	
ubiquitin ligase		
insulin receptor signaling pathway	x	
cellular carbohydrate biosynthetic process		
transcription	x	
T-cell activation/JNK	x	
apoptosis,		
microtubule assembly		
regulation of homeostasis	x	



Slow Growth

Rapid Growth

Functional analysis of genes highly loaded in PC1 shows a strong signal related to growth, with numerous pathways stimulated under rapid growth turned in the negative end of the PC1 distribution

Most 2007 Fraser fish are at the extreme PC1 positive end—the slow growth end; higher variability existed in 2008 and for 2007 WCVI

Genomic data are consistent with the purported slower growth of Fraser sockeye post-smolts in the ocean, relative to 2008 post-smolts

Miller et al. in prep

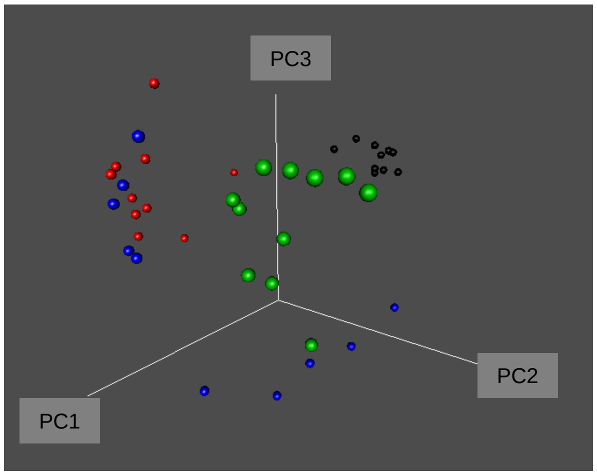
Environment (FW/SW) x Year
Fraser River Stocks Only

Ho: If ocean productivity is *the* key factor, 2007 Fraser will be more distinct from 2008 in SW than FW

Ocean Green vs. Blue

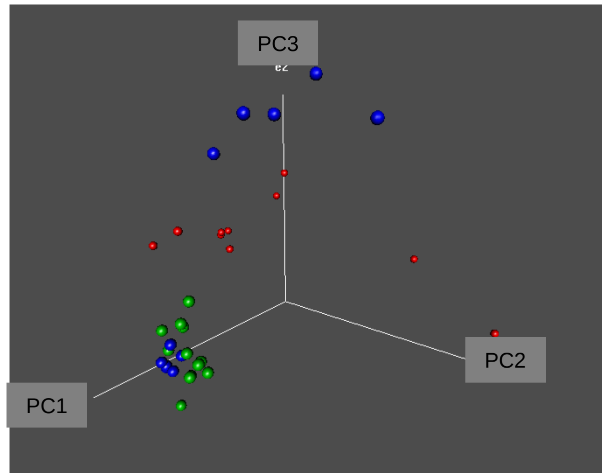
FW Black vs. Red

Brain



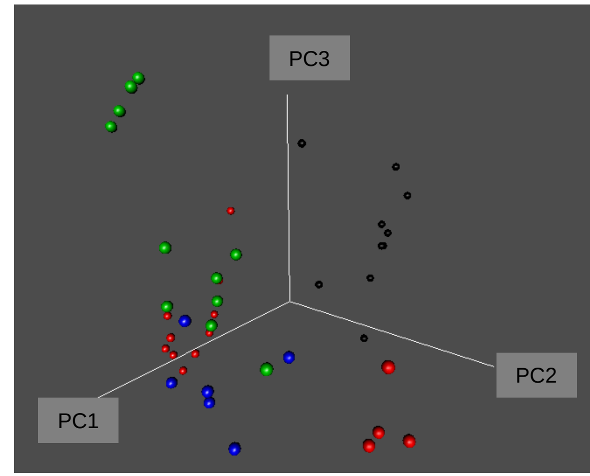
Ocean and FW distinct between years

Liver



Some 2008 SW distinct
No FW 2007 data

White Muscle



Ocean and FW distinct between years

It appears that while there are SW differences in physiology between years, the SW environment alone does not explain all physiological variation in the data

FW	2007
FW	2008
SW	2007
SW	2008

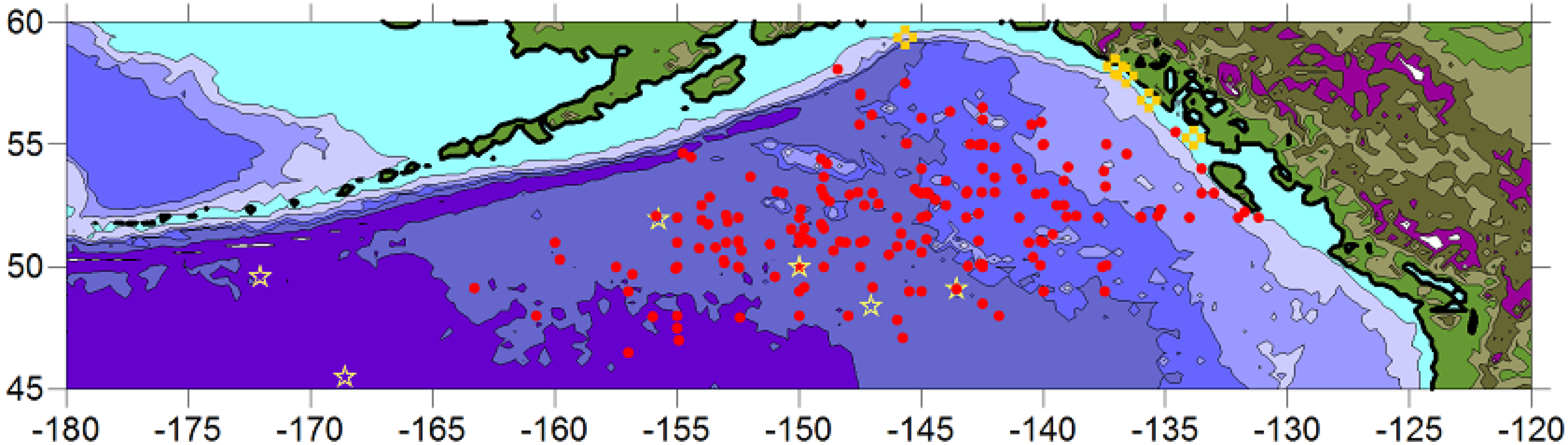
4x44K Agilent Array

Miller et al. in prep

Genomic Summary of 2007 Fraser Sockeye

- **High prevalence of Mortality-related signature (MRS) in brain and liver hypothesized to result from a novel viral disease**
  - **Fish with the MRS signature in brain in FW quickly disappear in the ocean**
- **2007 Fraser sockeye were highly stressed in the marine environment (liver)**
  - **some indication of hypoxia, possibly from heterosigma blooms**
- **Immunosuppression in the marine environment (liver), may relate, in part, to stronger MRS**
- **Ho: reduced feeding (but not outright starvation) may be a factor (liver)**
- **A high proportion of 2007 Fraser sockeye carried a low-growth type signature in the ocean, whereas fewer 2008 fish and WCVI fish carried this signature**
- **However, the marine environment may not explain all of the variance in physiology and fate of 2007 sockeye salmon, as the brain and muscle tissues from 2007 and 2008 Fraser sockeye salmon were highly divergent even in the FW environment**

Fraser River Sockeye on the High Seas



- **Stock-specific distribution?**
- **Age-specific distribution?**
- **Competition with pink salmon?**
- **Volcanoes?**

Source: McKinnell et al. (2010)

Conclusions from Report #4: McKinnell et al. (2010)

- **Poor return in 2007 due to coast wide poor ocean conditions observed in 2005. Very likely.**

- **Poor return in 2008 due to low escapement in 2004.**

- **Poor return in 2009 due to anomalous conditions in Queen Charlotte Sound in 2007. Very likely, but incomplete story.**

- **High return in 2010 due to large escapement in 2006. Very likely, but smolt data are missing for most lakes.**

- **Abrupt shift in 1992, rather than gradual decline, linked to large scale atmospheric changes. More analyses required.**

Summary of Marine Conditions: Triple Jeopardy?

- **Physiologically compromised in freshwater and in the marine environment (i.e. genomics).**

- **Poor ocean conditions in the Strait of Georgia (coho, Chinook, Herring, Chum, Sockeye).**

- **Poor ocean conditions in Queen Charlotte Sound (i.e. anomalous winds, salinity, production).**

- **Harrison River sockeye utilize the Strait of Georgia differently (i.e. timing).**

-

Next Steps

- **How many smolts leave the Fraser River?**

- **How long do they remain in the Strait of Georgia?**

- **Where and when significant mortality occurs in the marine environment?**

- **What is killing salmon in the marine environment? Pathogens? Predators? Starvation?**

- **To what extent ocean conditions in the Gulf of Alaska affect the recruitment variability of Fraser River sockeye?**

-

Concluding remarks

- **The cause of the decline of Fraser River sockeye and the exceptionally low return in 2009 is likely to have occurred prior to reaching Hecate Strait.**

- **The poor ocean conditions that prevailed in Queen Charlotte Sound and Hecate Strait in 2007 may have been exacerbated the poor conditions they experienced previously in the Strait of Georgia.**

Additional Work

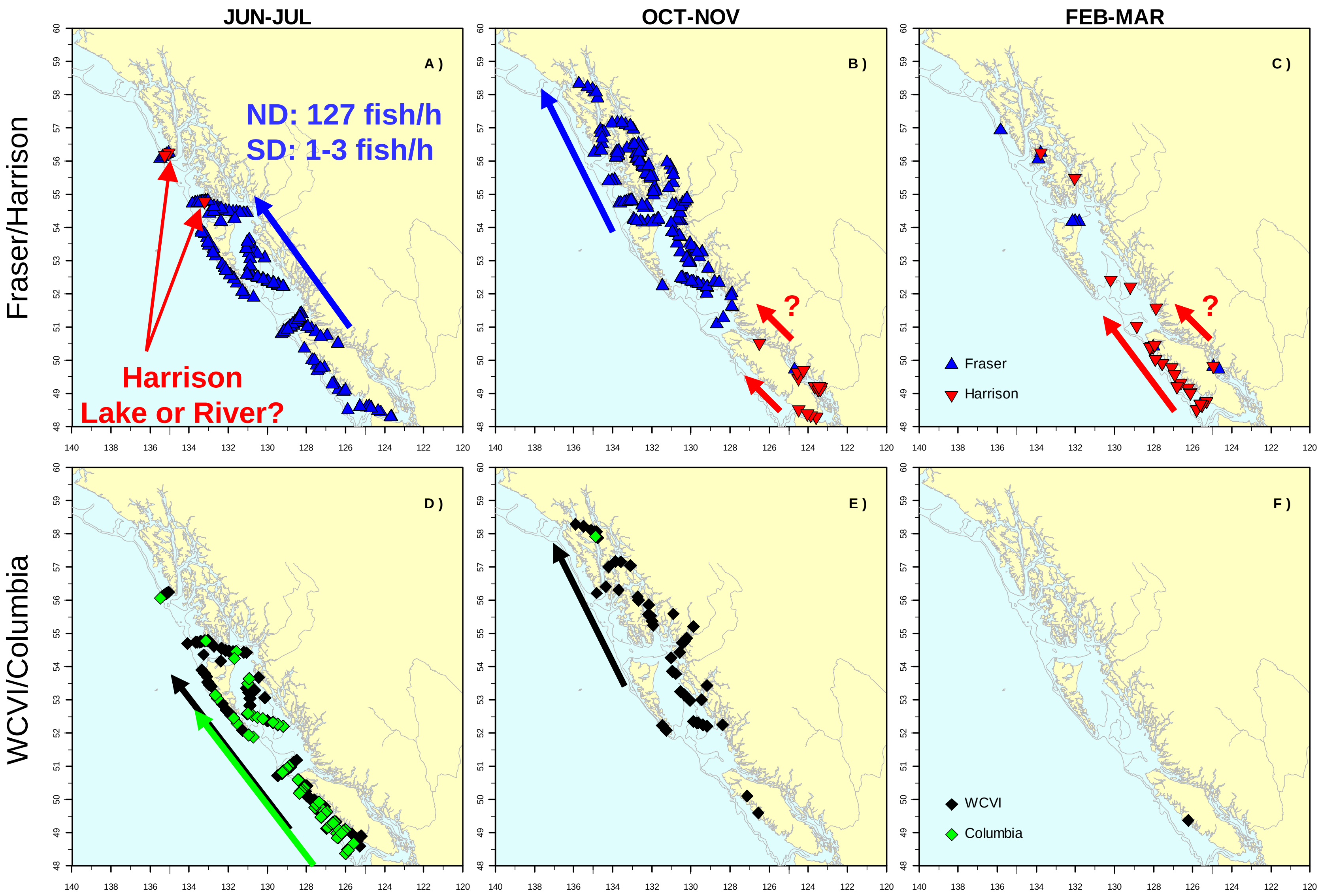
- **Where are the significant areas of mortality for sockeye salmon?**
  = > Partition freshwater and marine survival
  = > Acoustic tagging of juvenile sockeye salmon

- **Where and when do juvenile Harrison River sockeye leave the Strait of Georgia?**
  = > Acoustic tagging of juvenile sockeye salmon caught in the fall

- **Were Fraser River sockeye growing at an unusually low rate in 2007?**
  = > Otolith microstructure and early marine growth

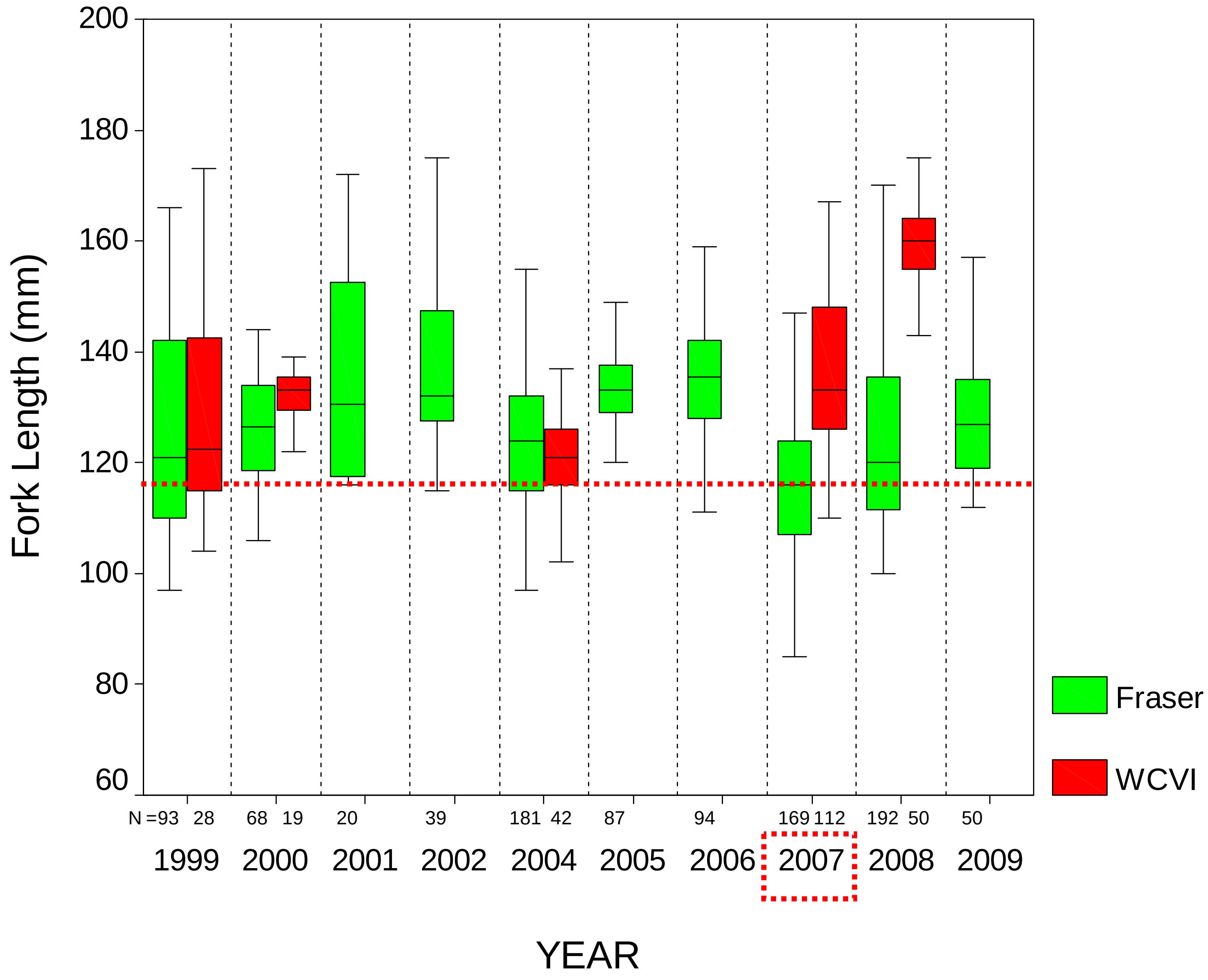
- **Were juvenile Fraser River sockeye in poor condition in 2007?**
  => Lipid analyses on archived samples

Juvenile Sockeye Distribution



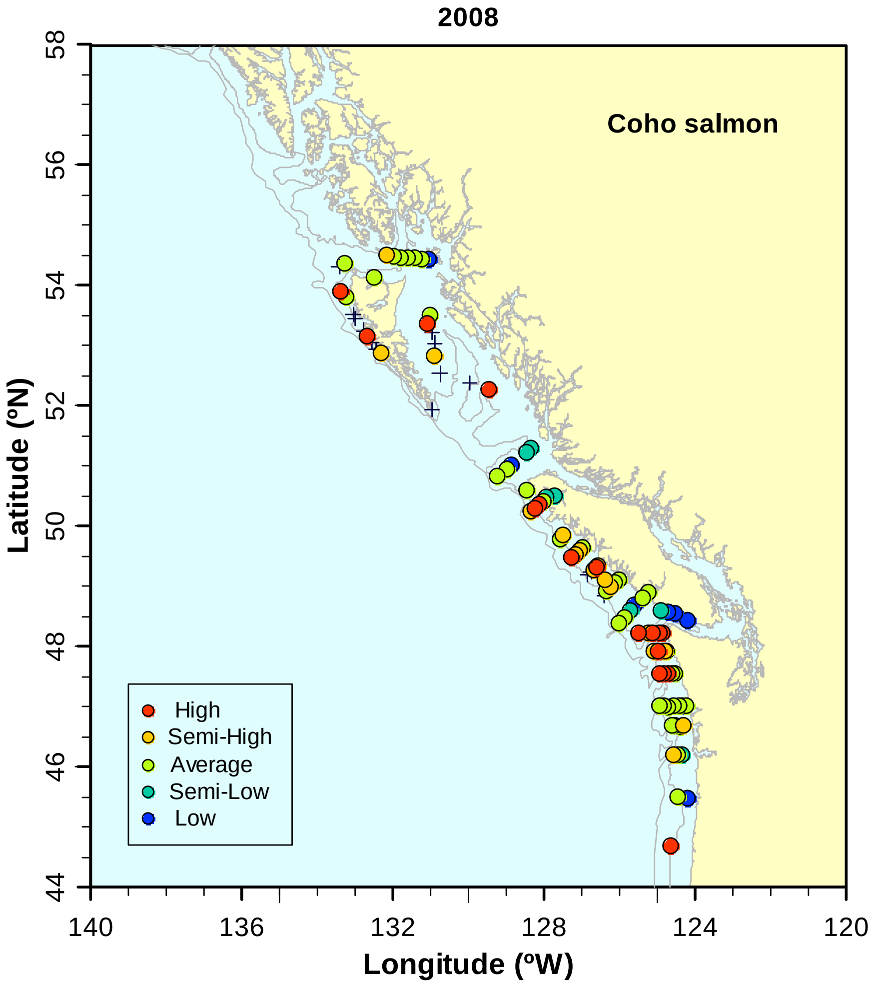
Updated from Tucker et al. 2009. Trans. Am. Fish. Soc. 138: 1558-1580.

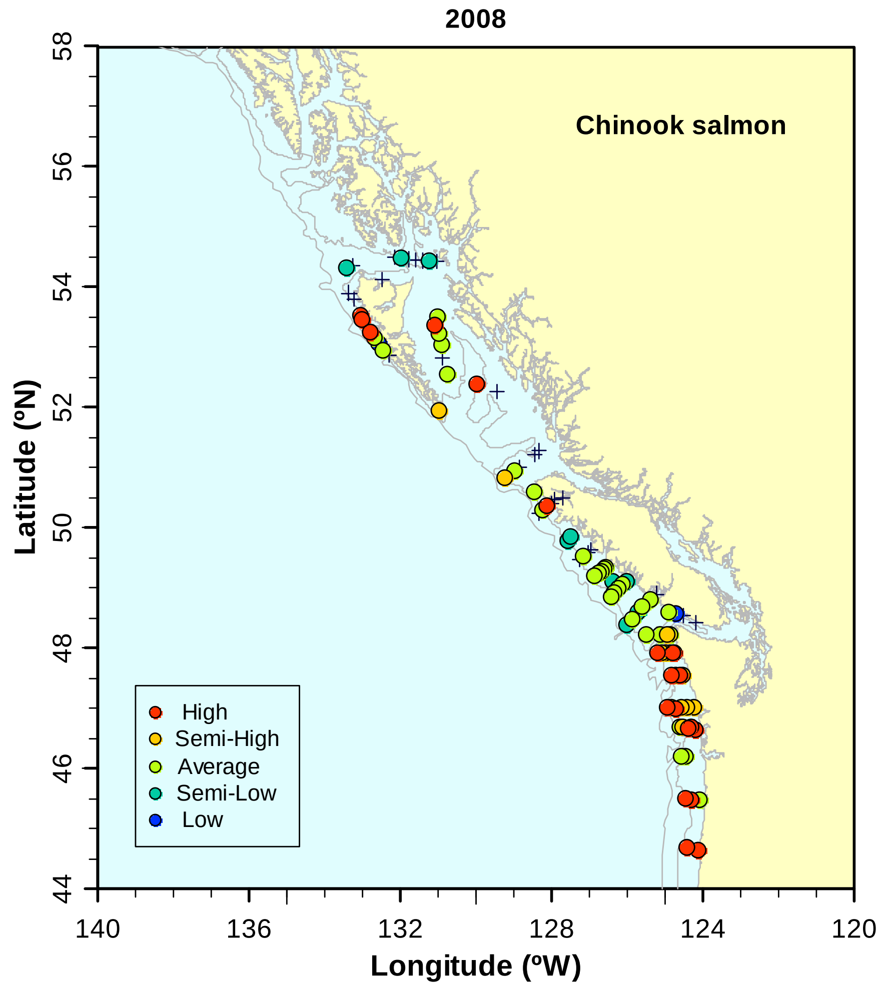
Juvenile Fraser River vs Barkley Sound Sockeye Salmon in Central BC: Summer



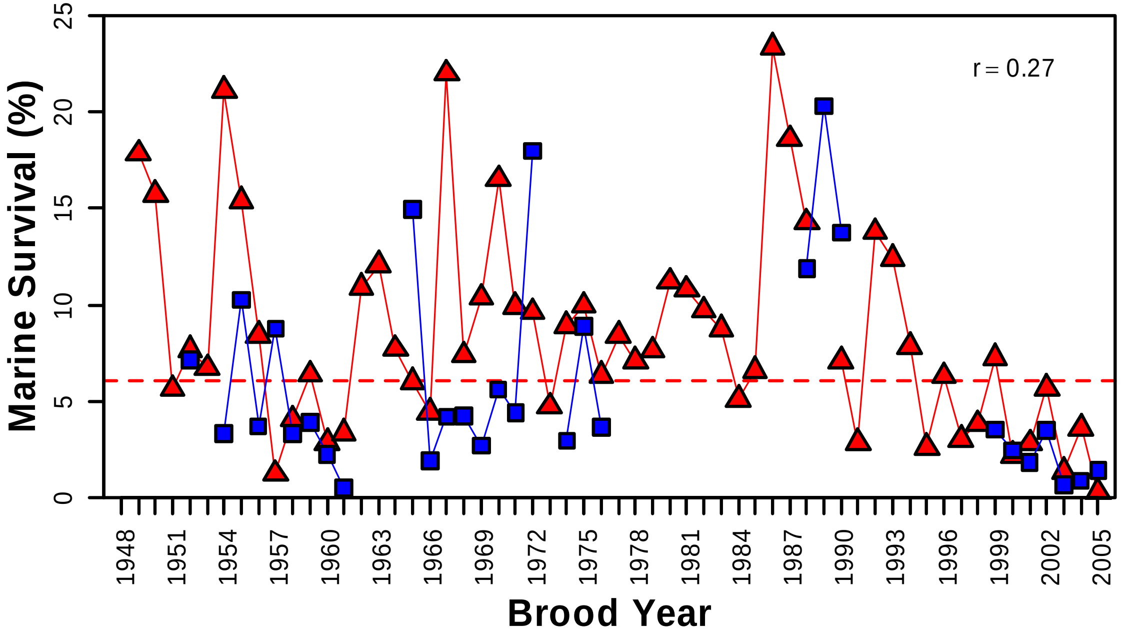
No sampling in 2003 due to ship malfunction

Growth Hormones in Juvenile Coho and Chinook (Mid-June to early-July 2008)

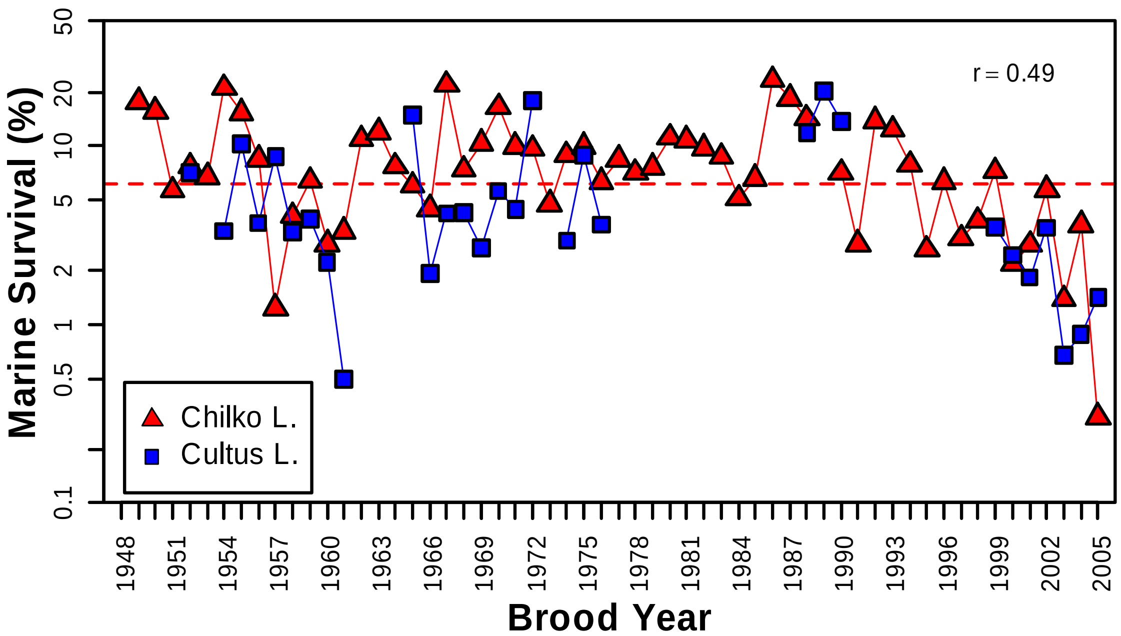




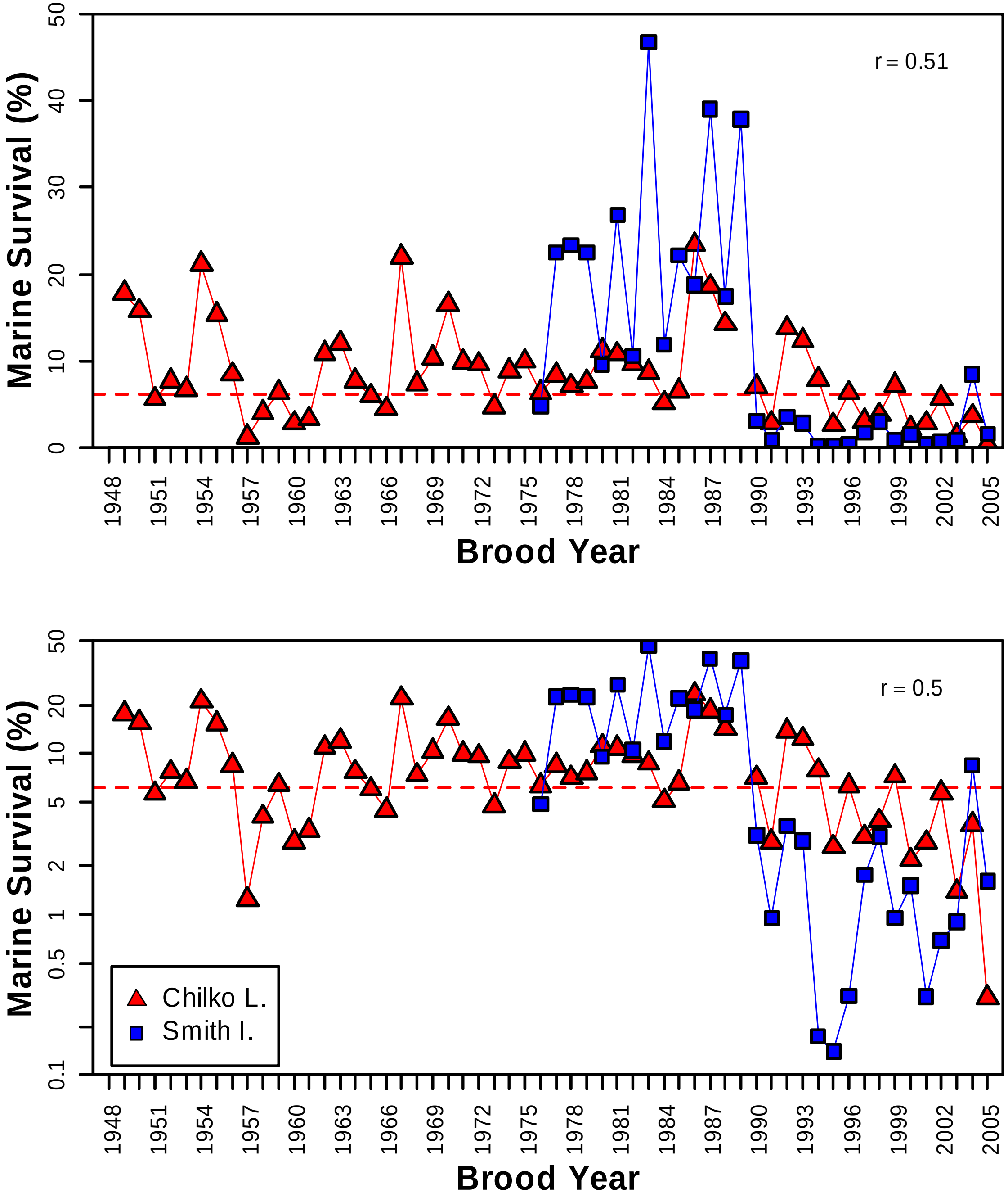
Data from B. Beckman (NOAA) and M. Trudel (DFO)



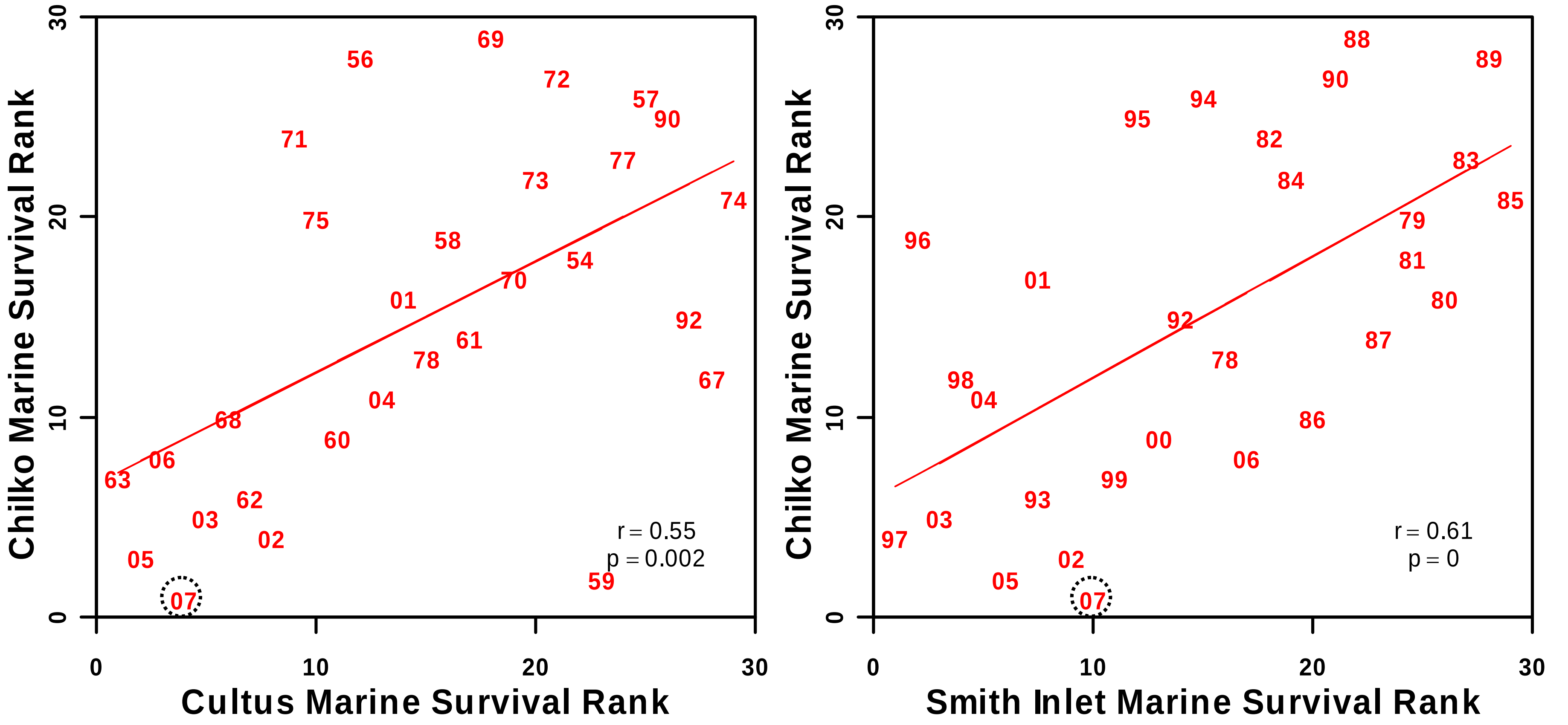
r = 0.27
Marine Survival (%)
Brood Year



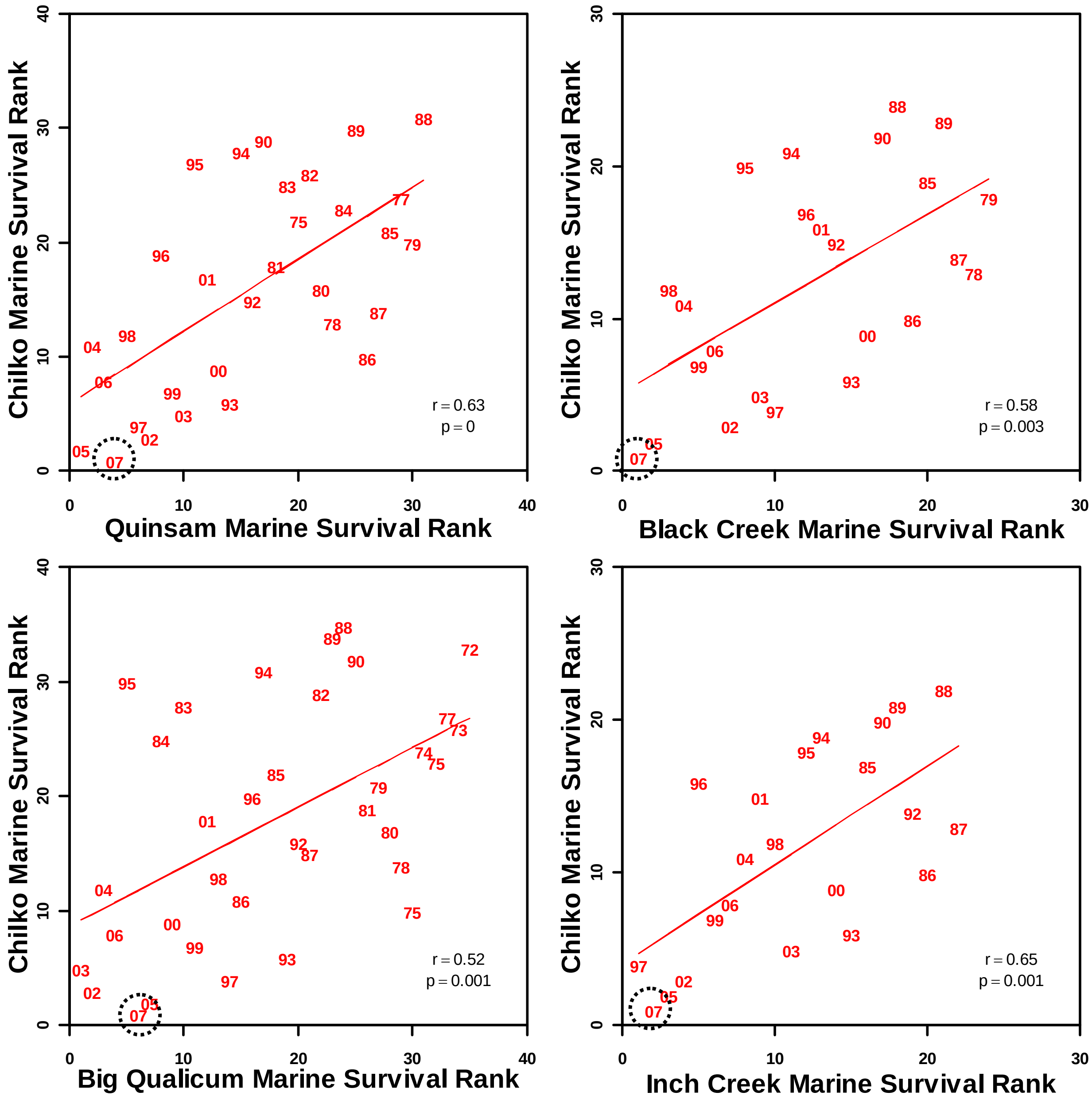
r = 0.49
Marine Survival (%)
Brood Year
Chilko L.
Cultus L.



Marine Survival (%)
r = 0.51
0
10
20
30
40
50
1948
1951
1954
1957
1960
1963
1966
1969
1972
1975
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
Brood Year
Marine Survival (%)
r = 0.5
0.1
0.5
1
2
5
10
20
50
Chilko L.
Smith I.
1948
1951
1954
1957
1960
1963
1966
1969
1972
1975
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
Brood Year

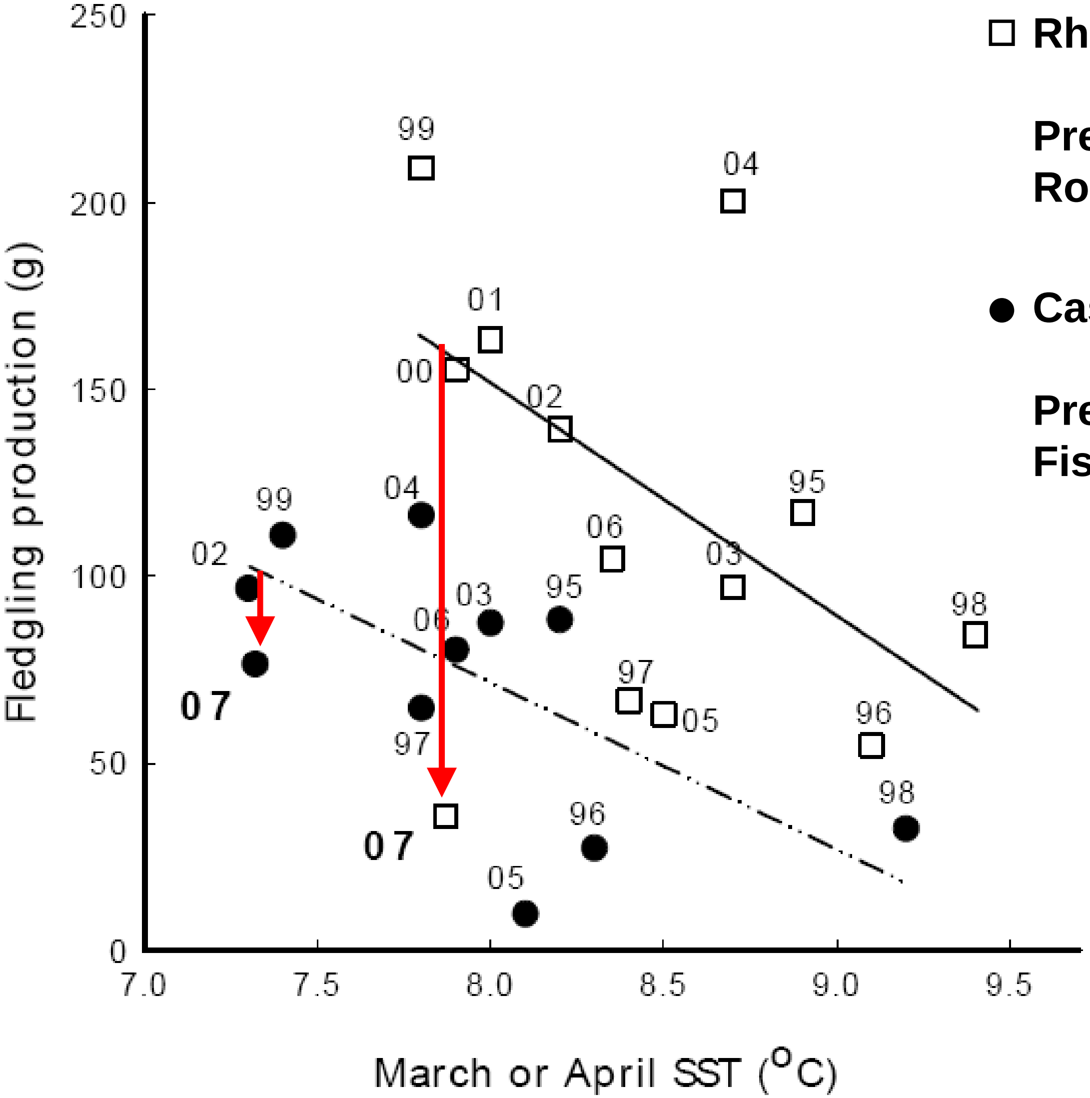


Chilko Marine Survival Rank
Cultus Marine Survival Rank
r = 0.55
p = 0.002
Chilko Marine Survival Rank
Smith Inlet Marine Survival Rank
r = 0.61
p = 0



Chilko Marine Survival Rank
Quinsam Marine Survival Rank
r = 0.63
p = 0
Black Creek Marine Survival Rank
r = 0.58
p = 0.003
Big Qualicum Marine Survival Rank
r = 0.52
p = 0.001
Inch Creek Marine Survival Rank
r = 0.65
p = 0.001

Breeding success of birds on Triangle Island



□ **Rhinoceros Auklet: Piscivorous**

Prey: Sandlance, Saury, Juv. Rockfish, Herring, Juv. Salmon

● **Cassin's Auklet: Planktivorous**

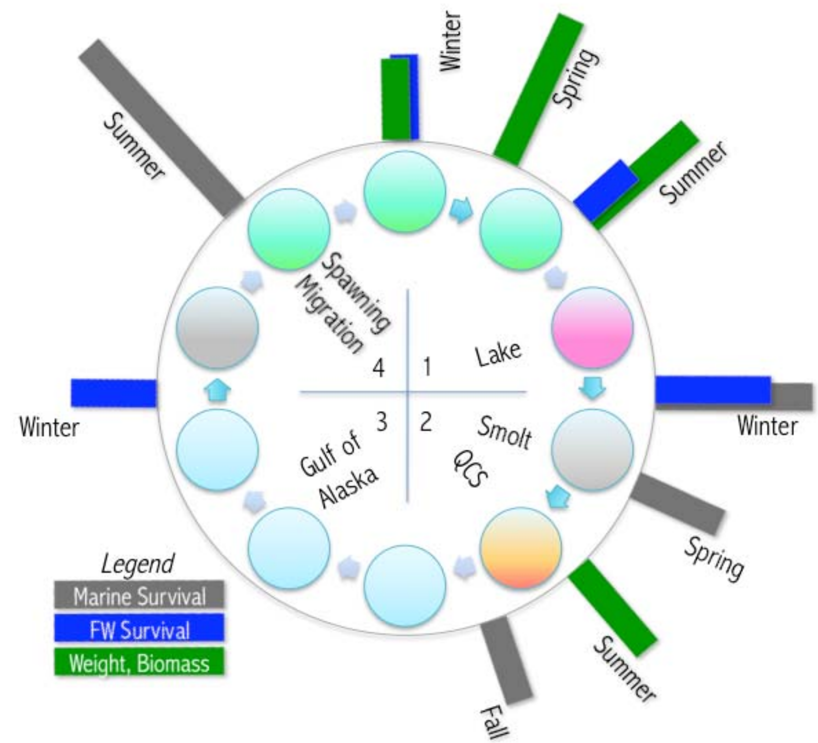
Prey: Copepods, Euphausiids, Fishes, Amphipods, Crabs

Sources: Hedd et al. (2001) MEPS; Hedd et al. (2006) Mar. Ecol.;Hipfner 2008

Background: The Fraser Situation

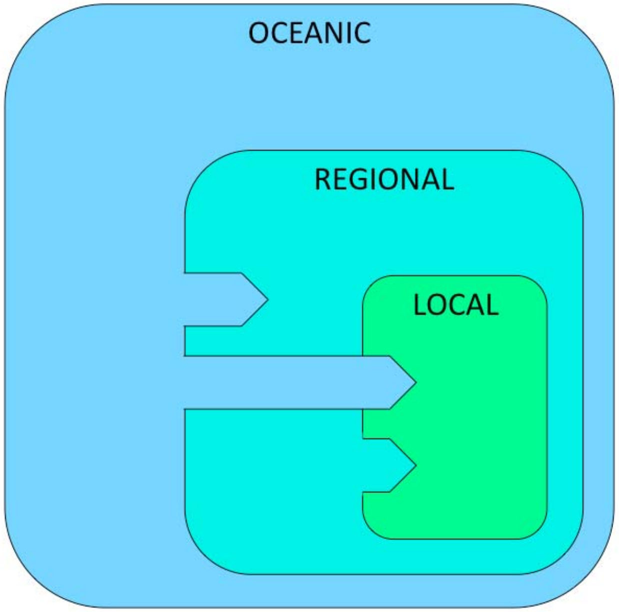
Problem #1: Cumulative Impacts

- Unlikely to be a single environmental effect.
- All life stages have varying survivals.
- Additive consequences across life stages and generations.
- Piece-meal approach is weak. An integrated approach is required.



Background: The Fraser Situation

Problem #2: Multiple Scales within Environmental Signals



- ***Oceanic***: PDO, El Niño/La Niña, etc.
- ***Regional***: Fraser R and estuary
  Queen Charlotte Sound
  Strait of Georgia
- ***Local***: Chilko Lake and watershed
- How much of small-scale signals is from larger scales? Are signals nested or are there non-linear "interactions"?
- Will confounded environmental data hide mechanisms behind correlations?