Phase 2

Summary of the PICES/NPRB Workshop on
Forecasting Climate Impacts
on Future Production of Commercially Exploited Fish and Shellfish

October, 30, 2007
Victoria, British Columbia, Canada

Background

This report is a summary of the activities and results of a workshop (Phase 2) on *Forecasting Climate Impacts on Future Production of Commercially Exploited Fish and Shellfish* held on October 30, 2007, in conjunction with the PICES Sixteenth Annual Meeting, in Victoria, Canada. Twenty-two scientists attended the workshop (Appendix 2.1), including members of Ecosystem Studies of the Sub-Arctic Seas (ESSAS), PICES' Biological Oceanography, Fishery Science, and Physical Oceanography and Climate Committees (BIO, FIS, and POC), Working Group on *Evaluations of Climate Change Projections* (WG 20) and Climate Forcing and Marine Ecosystem Response (CFAME) Task Team of the Climate Change and Carrying Capacity Program (CCCC). Participants from all PICES member countries except China were present. The workshop provided an interdisciplinary forum for communication of the data needed to forecast climate change impacts on commercial fish species, discussion of candidate modeling approaches that could be applied to develop such forecasts, and the potential constraints associated with fulfilling these data needs and modeling efforts.

Workshop Agenda

1. Progress report
2. PICES workshop reports
3. Review handouts and requests
4. Discuss national data requests
   a. China
   b. Japan
   c. Korea
   d. Russia
   e. Canada
   f. U.S. Bering Sea
   g. U.S. West Coast
5. Discuss timeline
6. ICES/PICES/IOC Climate Change symposium
7. State of North Pacific Ecosystem Status Report
8. Proposal for a PICES Working Group

Prior to the meeting, the following requests were made to the workshop participants:
1. Oceanographers and climatologists should identify what techniques they recommend for forecasting oceanographic responses to climate change.
2. Fisheries scientists should provide reports on the current state of knowledge regarding mechanisms linking climate forcing and fish production, and the uncertainty associated with these mechanisms.
3. Fisheries scientists should identify what physical or bio-physical drivers or environmental thresholds would be needed to forecast future fish or shellfish production. These requests should specify the location (latitude and longitude) and time period for the requested physical variable.

Responses were discussed at the workshop and written summaries of these are included in this report. The following is a summary of the key outcomes of discussion.

Forecast Feasibility

The presented reports revealed that hypotheses linking climate and fish production (or distribution) exist for the majority of commercially fished species that were identified previously as potential candidates for quantitative forecasts (Phase 1 workshop report, this report). Several participants commented that there is considerable uncertainty surrounding the proposed linkages between climate forcing and fish production or distribution.

It was pointed out that a PICES interdisciplinary forecasting effort should include a decision analysis tool that could be used to communicate the uncertainty associated with our forecasts. Uncertainty in future climatic conditions could be provided using ensembles based on several IPCC scenarios. Uncertainty associated with links to the population dynamics of selected species could be conveyed by developing forecasting tools that track true and perceived stock status where perceived stock status would incorporate measurement error and process errors associated with the assessment. Management Strategy Evaluations could be used to evaluate the performance of different harvest policies under changing environmental conditions.

Format of Information

The workshop provided an opportunity for information exchange between members of WG 20 and fisheries biologists. Participants concluded that requests for data/information/model output should be compiled in spreadsheet format and accompanied by written descriptions of the rationale for the requested information. This combination of tabular and written formats is expected to improve communication

between the two groups and would allow the climatologists and oceanographers to assess the workload associated with downscaling IPCC models to regional scales of interest.

Modeling Approaches

Participants discussed the modeling approach that they planned to use to develop the forecast. Three general approaches were identified: coupled bio-physical models, stock assessment projection models, and comparative approaches.

Coupled bio-physical models

Japanese scientists are planning to downscale IPCC model output to force regional circulation models with ensembles of future climate scenarios. They are exploring the possibility of modifying NEMURO.FISH type models for use in forecasting the response of small pelagic species to climate change. They are also planning to evaluate model performance by making a reconstruction of past oceanographic events and comparison of observed and predicted estimates of the distribution and abundance of target species. Scientists in the California Current region are coupling population dynamic models to ATLANTIS.

Dr. Clarence Pautzke announced that the North Pacific Research Board (NPRB) had funded a major research effort as part of NPRB's Bering Sea Integrated Ecosystem Research Program (BSIERP; www.nprb.org). The Program will support the development of several models for use in forecasting climate impacts on walleye pollock in the eastern Bering Sea. Some elements of the BSIERP modeling approach expand on the NEMURO.FISH type modeling by including fish behavior and complex feedback behavior between all trophic levels.

Stock assessment projection models

Scientists from several PICES nations plan to use ocean conditions from regional ocean models forced with IPCC climate change scenarios. Time trends in ocean conditions will be incorporated into population dynamics models for selected commercial species. Forecast models that track observed and perceived stock status will be used to assess the impacts of climate and fishing on the status of commercial species.

Comparative approaches

PICES and ICES have previously sponsored symposia on ecosystem comparisons. These comparisons have identified differences in the structure, organization and energy flow of marine ecosystems. Knowledge of similarities and differences between systems may be helpful in predicting responses of marine fish to climate change. Participants at the workshop agreed that the comparative approach could also be applied to the study of climate change impacts on commercially exploited marine species.

Although coupled bio-physical models and stock assessment projection models differ in terms of spatial and temporal complexity, the coupled bio-physical modeling approach has the distinct advantage of tracing complex interactions within the system. The stock assessment forecasting approach tracks the results of climate change using time trends in system forcing at population scales, based on proposed mechanisms linking population dynamics to ocean conditions. While less complex in terms of feedbacks, this approach provides statistical performance metrics that track sources of uncertainty associated with forecasting population dynamics.

Similarities in Data Requests

Common among the requests for bio-physical information were: sea surface temperature (SST), bottom temperatures (BT), seasonal advection (direction and intensity), timing of production (including spring blooms), stratification and upwelling events, zooplankton community structure, and time trends in the spatial overlap of habitats of predators and prey (Table 2.1). The marked similarity is encouraging because it implies that a common suite of core drivers influences production of commercial species. While regional features of North Pacific shelf regions may act to influence production of marine fish and shellfish, the commonality of drivers suggests that application of the comparative approach may provide insight as to how species will respond to climate change. This confirms the importance of moving forward with a coordinated international effort to develop a forecast of climate forcing on commercial species.

Given the similarity in the drivers identified for each region, workshop participants discussed the

possibility that physical oceanographers and climatologists might coordinate their efforts to provide regional nodes where fisheries biologists could submit requests. Drs. James Overland and Muyin Wang offered to serve as the regional node for the eastern Pacific. A regional node for the western Pacific should be identified.

Opportunities for Coordination with Other PICES Groups and International Efforts

Representatives of CFAME and WG 20 attended the workshop and reported that both CFAME and WG 20 plan to attempt forecasting climate change impacts on small pelagic species in the California Current System, Kuroshio/Oyashio Current System, and Yellow Sea/East China Sea region. After the meeting it was noted that scientists at the Scripps Institution of Oceanography, UCSD, and the Southwest Fisheries Science Center, NOAA, had received funding for a project titled "*Using ocean data assimilation to incorporate environmental variability into sardine and squid assessments*." It is anticipated that this project will provide important contributions to the PICES forecasting effort.

The workshop organizers planned to attend the ICES/PICES/IOC Symposium on *Climate Change in the World's Oceans* in Gijón, Spain, from May 19–23, 2008 and to hold a workshop during the symposium to promote communication with other programs.

After the Phase 2 workshop, it was found that there were several international programs that have goals which are similar to the PICES/FIS forecasting effort. A schedule for production of a coordinated international forecasting effort was discussed by the workshop participants with the following proposed timelines:

March 2008	Physical oceanographers and climatologists to identify regional nodes for submission of data requests
April–May 2008	Oceanographers and climatologists from each regional node to review requests and discuss the feasibility of extracting the requested data with fisheries biologists
April 2008	PICES inter-sessional CFAME/WG 20 workshop in Honolulu, U.S.A.
May 2008	ICES/PICES/IOC symposium in Gjión, Spain. Discussion of PICES/FIS forecasting approach with QUEST – Fish and other representatives of international programs
June–September 2008	Preliminary forecasts for selected species
October 2008	Joint meeting with WG 20 to discuss preliminary forecasts
October–June 2009	Development of written reports for PICES' North Pacific Ecosystem Status Report

Table 2.1 Ocean indices by region, species and season that could be extracted from IPCC scenarios downscaled to PICES regions.

Species	Index	Mechanism	1	2	3	4	5	6	7	8	9	10	11	12
U.S. California Current System														
Rockfish	Wind advection	Larval drift to nursery areas	–	–	44N, 126W	44N, 126W	44N, 126W	–	–	–	–	–	–	–
	Temperature at 40 m depth	Larval metabolic rate (growth out of predator range)	–	–	44N, 126W	44N, 126W	44N, 126W	–	–	–	–	–	–	–
	Upwelling (intensity)	Summer prey availability (upwelling)	–	–	–	–	44N, 126W	44N, 126W	44N, 126W	44N, 126W	–	–	–	–
	Salinity	Settlement habitat	–	–	–	–	44N, 126W	44N, 126W	44N, 126W	44N, 126W	–	–	–	–
	Temperature at 40 m depth	Age-0 growth rate	–	–	–	–	44N, 126W	44N, 126W	44N, 126W	44N, 126W	–	–	–	–
	Turbulence + solar heating + salinity + upwelling = MLD	Prey availability	–	–	–	–	44N, 126W	44N, 126W	44N, 126W	44N, 126W	–	–	–	–
	Time signature and direction of wind forcing (SST/SSH gradients)	Duration of summer feeding season (time of spring transition)	–	–	–	44N, 126W	44N, 126W	44N, 126W	44N, 126W	44N, 126W	–	–	–	–
	Turbulence + solar heating + salinity + upwelling = MLD_{t-1}	Maternal condition dependent on prey availability	–	–	–	–	–	–	–	44N, 126W	44N, 126W	44N, 126W	44N, 126W	44N, 126W
Northern California Current System, Canada														
Pink and chum salmon	Timing of spring freshet and duration	Pink and chum salmon abundance in the ocean is regulated by growth and by predation	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–		–	–	–	–
	Wind intensity and direction	Growth is important because rapid early marine growth reduces the amount of predation and allows fish to better survive the marine winter	–	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–				–	–
	Intensity of Aleutian Low Pressure Index	Growth in the first few months in the nearshore areas is critical	49-54N, 122-134W	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	49-54N, 122-134W	49-54N, 122-134W
	SST	An earlier and stable mixing layer favours improved survival	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–	–
	Pacific Circulation Index	Hatchery production may override natural controls	49-54N, 122-134W	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	49-54N, 122-134W	49-54N, 122-134W

Table 2.1 Continued

Species	Index	Mechanism	Month											
			1	2	3	4	5	6	7	8	9	10	11	12
Northern California Current System, Canada														
Sockeye salmon	River flows and temperatures	Size at ocean entry and growth of juveniles in fresh water	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–	–	–	–
	Ocean entry time and size	Rate of early marine growth (first 6 weeks)	–	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–	–
	Rate of growth in first 6 weeks	SST in summer and winter	49-54N, 122-134W	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	49-54N, 122-134W	49-54N, 122-134W
	Aleutian Low Pressure Index	Spawning stock size and freshwater rearing conditions	49-54N, 122-134W	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	49-54N, 122-134W	49-54N, 122-134W
		Spawning stock size and freshwater rearing conditions	–	–	–	–	–	–	–	–	–	–	–	–
	Pacific Circulation Index	Spawning stock size and freshwater rearing conditions	49-54N, 122-134W	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	49-54N, 122-134W	49-54N, 122-134W
Chinook and coho salmon	Timing of spring bloom	Timing of ocean entry must match with abundant plankton	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–	–	–	–
	Wind direction and intensity	Prey must be plentiful and available within the first 6 weeks in the ocean; results in greater lipid storage and improved marine survival	–	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–	–
	SST	Faster early growth facilitates a switching to larger prey such as Pacific herring	–	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–	–
		Hatchery fish compete with wild fish	–	–	–	–	–	–	–	–	–	–	–	–
	Summer river temperature	Stream conditions influence survival	–	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–	–
Sablefish	Timing of spring transition	Matching of copepod abundance with first feeding larval sablefish	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–	–	–	–
	Aleutian Low Pressure Index	Matching of coastal plankton production with the onshore movements of juveniles	–	–	–	–	–	–	–	–	–	–	–	–

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Table 2.1 Continued

Northern California Current System, Canada

Species	Index	Mechanism	1	2	3	4	5	6	7	8	9	10	11	12
Sablefish	Wind advection	Matching of coastal plankton production with the onshore movements of late larvae–early juveniles	–	–	–	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	49-54N, 122-134W	–	–	–	–	–
	SSH	Matching overall productivity of the CCS, namely north–south movement of water, which ties into first feeding	–	–	–	50N, 120-125W	50N, 120-125W	50N, 120-125W	–	–	–	–	–	–

West coast of Vancouver Island, BC, Canada

Species	Index	Mechanism	1	2	3	4	5	6	7	8	9	10	11	12
Ocean shrimp	SST	Temperature-related larval survival rate	–	–	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	–	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W
	Upwelling	Prey availability	–	–	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	–	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W
	Sea level height	Spring transition related larval advection	–	–	48-50N, 124-128W	48-50N, 124-128W	48-50N, 124-128W	–	–	–	–	–	–	–

Hecate Strait, BC, Canada

Species	Index	Mechanism	1	2	3	4	5	6	7	8	9	10	11	12
Pacific cod	Barometric pressure-adjusted sea level height	Egg and larval advection	52-55N, 130-132W	52-55N, 130-132W	52-55N, 130-132W	–	–	–	–	–	–	–	–	–
	SST, because water column is highly mixed during winter	Egg and larval growth rate	52-55N, 130-132W	52-55N, 130-132W	52-55N, 130-132W	–	–	–	–	–	–	–	–	–
	MLD	Herring as food sources for maturing cod	–	–	–	–	–	–	–	–	52-55N, 130-132W	52-55N, 130-132W	52-55N, 130-132W	52-55N, 130-132W

Gulf of Alaska

Species	Index	Mechanism	1	2	3	4	5	6	7	8	9	10	11	12
Walleye pollock	Wind advection	Spawning pre-conditioning (subsurface flow into Shelikof Strait)	–	57N, 156W	57N, 156W	–	–	–	–	–	–	–	–	–
	Wind advection	Larval transport to nursery area	–	–	–	57N, 156W	–	–	–	–	–	–	–	–

Table 2.1 Continued

Gulf of Alaska

Species	Index	Mechanism	1	2	3	4	5	6	7	8	9	10	11	12
Walleye pollock	Temperature at 40 m depth	Hatch date	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–	–	–	–	–
	Precipitation	Larval encounter with prey (eddy formation)	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–	–	–	–	–
	Wind mixing	Larval encounter with prey	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–	–	–	–	–
	Temperature at 40 m depth	Larval metabolic rate (growth out of predator range)	–	–	–	57N, 156W	57N, 156W	–	–	–	–	–	–	–
	Solar heat + wind mixing (timing of stratification)	Duration of summer feeding season (time of stratification)	–	–	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–	–	–
	Temperature at 40 m depth	Age-0 metabolic rate (growth overwintering success)	–	–	–	–	–	56N, 157W	56N, 157W	56N, 157W	–	–	–	–
	MLD	Summer prey habitat concentration	–	–	–	–	–	56N, 157W	56N, 157W	56N, 157W	–	–	–	–
	Wind advection	Summer prey availability (basin–shelf exchange)	–	–	–	–	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–
	Cross-shelf transport (4 years earlier)	Predation by arrowtooth flounder	–	–	58N, 156W	58N, 156W	–	–	–	–	–	–	–	–
Arrowtooth flounder	Cross-shelf transport (4 years earlier)	Larval drift to coastal nursery areas	–	–	57N, 156W	57N, 156W	–	–	–	–	–	–	–	–
	SST	Summer growth rate (critical size)	–	–	–	–	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–
Pink salmon	SST	Timing of summer emigration	–	–	–	–	58N, 154W	–	–	–	–	–	–	–
	Solar heat + wind mixing	Duration of summer feeding season (time of stratification)	–	–	–	58N, 154W	58N, 154W	58N, 154W	58N, 154W	–	–	–	–	–
	Wind advection, intensity of Alaska coastal current	Summer alongshore advection	–	–	–	–	58N, 154W	58N, 154W	58N, 154W	–	–	–	–	–
	SST	Smolt growth rate (metabolic rate)	–	–	–	–	58N, 154W	58N, 154W	58N, 154W	58N, 154W	–	–	–	–
Pacific cod	Bottom temperature	Hatch date	–	–	57N, 156W	57N, 156W	–	–	–	–	–	–	–	–
	SST	Larval metabolic rate (growth out of predator range)	–	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–	–	–	–

Table 2.1 Continued

Species	Index	Mechanism	1	2	3	4	5	6	7	8	9	10	11	12
Gulf of Alaska														
Pacific cod	Temperature 40 m depth	Age-0 growth rate	–	–	–	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–	–
	MLD	Summer prey habitat concentration	–	–	–	–	–	56N, 157W	56N, 157W	56N, 157W	–	–	–	–
	Wind advection	Summer prey availability (basin–shelf exchange)	–	–	–	–	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–
Pacific halibut	Cross-shelf transport (4 years earlier)	Larval drift to coastal nursery areas	–	–	58N, 156W	58N, 156W	–	–	–	–	–	–	–	–
	MLD	Summer prey habitat concentration	–	–	–	–	–	56N, 157W	56N, 157W	56N, 157W	–	–	–	–
	Wind advection	Summer prey availability (basin–shelf exchange)	–	–	–	–	–	57N, 156W	57N, 156W	57N, 156W	–	–	–	–
Pacific herring	SST (Prince William Sound)	Larval growth	–	–	–	–	58N, 154W	58N, 154W	–	–	–	–	–	–
	Wind advection	Summer prey availability (basin–shelf exchange)	–	–	–	–	–	58N, 154W	58N, 154W	58N, 154W	–	–	–	–
	SST	Summer growth rate (critical size)	–	–	–	–	–	58N, 154W	58N, 154W	58N, 154W	–	–	–	–
Bering Sea – Aleutian Islands														
Arrowtooth flounder	Cross-shelf transport (4 years earlier)	Larval drift to coastal nursery areas	–	–	56N, 165W	56N, 165W	–	–	–	–	–	–	–	–
	SST	Summer growth rate (critical size)	–	–	–	–	–	56N, 165W	56N, 165W	56N, 165W	–	–	–	–
Tanner crab	Minimum bottom temperature	Cold temperatures interrupt or delay gametogenesis	–	–	–	–	–	56-58N, 164-166W	56-58N, 164-166W	56-58N, 164-166W	–	–	–	–
	SST	Warm temperatures promote production of copepod nauplii	–	–	–	55N, 165W	–	55N, 165W	55N, 165W	55N, 165W	55N, 165W	55N, 165W	–	–
	Winds from the northeast (60°)	Winds alongshore the north side of the Alaska Peninsula promote coastal upwelling and production of copepod nauplii	–	–	–	60N, 165W	–	60N, 165W	60N, 165W	60N, 165W	60N, 165W	60N, 165W	–	–
	Winds from the northeast (60°)	Northeast winds promote retention of larvae in offshore, deep-water, fine sediment nursery habitats	–	–	–	60N, 165W	–	60N, 165W	60N, 165W	60N, 165W	60N, 165W	60N, 165W	–	–

Table 2.1 Continued

| Species | Index | Mechanism | Month | | | | | | | | | | | |
			1	2	3	4	5	6	7	8	9	10	11	12

Bering Sea – Aleutian Islands

Species	Index	Mechanism	1	2	3	4	5	6	7	8	9	10	11	12
Tanner crab	ROMS output of Tanner crab advection relative to cold pool in area	Larval settlement in cold pool adversely affects survival	–	–	–	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	–	–
	ROMS output of Tanner crab advection relative to Pacific cod geographic distribution in area	Larval settlement in areas occupied by cod adversely affects survival	–	–	–	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	–	–
Red king crab	North Pacific Index or Aleutian Low Pressure Index	Stronger winds, associated with deeper Aleutian Lows, increase water column mixing, reducing the proportion of *Thalassiosira* diatoms (prey of crab larvae)	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	–	–	–	–	–	–	–	–	55.5-58N, 165-174W
	Winds in Bristol Bay	Same mechanism as above, but direct measure of wind	–	–	–	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	–	–
	Bottom temperature in Bristol Bay	Distribution of brood stock shifts to northeast with warming	–	–	–	–	–	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	–	–	–	–
	ROMS drift tracks from start locations within	Survival depends on successful advection to nearshore nursery areas in Bristol Bay	–	–	–	55.5-57.5N, 161-163W	55.5-57.5N, 161-163W	55.5-57.5N, 161-163W	55.5-57.5N, 161-163W	55.5-57.5N, 161-163W	55.5-57.5N, 161-163W	55.5-57.5N, 161-163W	–	–
	Timing of spring bloom	Match/mismatch of crab larvae and diatoms	–	–	–	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	55-58N, 158-164W	–	–
	Biomass of Pacific cod, yellowfin sole	Predation of ages 0–3 years	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W	55.5-58N, 165-174W
Snow crab	Bottom temperature in eastern Bering Sea shelf	Distribution of brood stock shifts to northwest with warming	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W

Table 2.1 Continued

Species	Index	Mechanism	Month											
			1	2	3	4	5	6	7	8	9	10	11	12
Bering Sea – Aleutian Islands														
Snow crab	ROMS drift tracks from start locations in area	Survival depends on successful advection to the northeast, shallower waters	–	–	–	–	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	–	–
	SST	Temperature in upper water column affects rate of development and settlement time	–	–	–	–	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	–	–
	ROMS output of snow crab advection relative to Pacific cod geographic distribution in area	Larval settlement in areas occupied by cod adversely affects survival	–	–	–	–	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	–	–
	Timing of spring bloom	Match/mismatch of crab larvae and spring bloom	–	–	–	56.5-62N, 168-175W	56.5-62N, 168-175W	–	–	–	–	–	–	–
	Abundance of immature snow crabs	Settling snow crabs are cannibalized by juveniles already occupying the nursery areas	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W	56.5-62N, 168-175W
Korean coastal waters														
Chub mackerel	Spring currents and salinity from about 50 m depth to the surface for the same areas as described above	Transport to nursery areas	–	32-35N, 123-131E	32-35N, 123-131E	32-35N, 123-131E	32-35N, 123-131E	32-35N, 123-131E	–	–	–	–	–	–
Jack mackerel	Probability that a surface particle would land in the 'touch down zone' where larval jack mackerel settle out of the planktonic larval stage	Recruitment is related to success of settlement in nursery ground transported by the Kuroshio Warm Current	–	–	–	32-35N, 125-131E	32-35N, 125-131E	32-35N, 125-131E	–	–	–	–	–	–
	Temperature and salinity at the surface and 50 m layer depth	Growth is a function of metabolic rate	–	–	–	32-35N, 125-131E	32-35N, 125-131E	32-35N, 125-131E	–	–	–	–	–	–
	Zooplankton abundance April–June	Growth is a function of prey availability	–	–	–	32-35N, 125-131E	32-35N, 125-131E	32-35N, 125-131E	–	–	–	–	–	–

Table 2.1 Continued

| Species | Index | Mechanism | Month | | | | | | | | | | | |
			1	2	3	4	5	6	7	8	9	10	11	12
Japanese coastal waters														
Walleye pollock	Wind advection	Larval transport (retention)	–	–	–	Hidaka Bay	–	–	–	–	–	–	–	–
Pacific cod	SST	Summer growth rate (critical size)	–	–	Hidaka Bay	–	–	Tohoku Bay	–	–	–	–	–	–
	Salinity	Summer growth rate (critical size)	–	–	–	–	–	–	–	–	–	–	–	–
	Wind advection	Circulation	–	–	–	–	–	–	–	–	–	–	–	–
Sardine	SST	Summer growth rate (critical size)	–	–	–	–	30-40N, 130-140E	30-40N, 130-140E	30-40N, 130-140E	30-40N, 130-140E	–	–	–	–
	Wind advection	Larval transport (retention)	–	–	–	–	–	–	–	–	–	–	–	–
Chum salmon	SST	Summer growth rate (critical size)	–	–	–	–	30-40N, 130-140E	30-40N, 130-140E	30-40N, 130-140E	30-40N, 130-140E	–	–	–	–
Pacific herring	SST	Summer growth rate (critical size)	–	–	–	–	30-40N, 130-140E	30-40N, 130-140E	30-40N, 130-140E	30-40N, 130-140E	–	–	–	–
	Salinity	Summer growth rate (critical size)	–	–	–	–	30-40N, 130-140E	30-40N, 130-140E	30-40N, 130-140E	30-40N, 130-140E	–	–	–	–
	Sea ice retreat	Growing season	–	–	–	–	–	–	–	–	–	–	–	–
Japan/East Sea														
Walleye pollock	Subsurface water temperature (the warmer, the better)	Prey availability for larvae and juveniles	–	–	–	43N, 132E	43N, 132E	43N, 132E	43N, 132E	43N, 132E	–	–	–	–
Pacific herring	Area of bottom areas with suitable substrate (recently destroyed by pollution and other reasons)	Spawning substrate availability and quality (sea grass or artificial substrates are necessary)	–	43N, 132E	43N, 132E	43N, 132E	–	–	–	–	–	–	–	–
Saffron cod	Siberian High Index (the higher/colder, the better)	Spawning period duration (spawns under ice in conditions of temperature below zero)	43N, 132E	43N, 132E	–	–	–	–	–	–	–	–	–	43N, 132E
Sardine	SST ratio in winter and spring (stable anomalies are preferable)	Larval encounter with prey (match the times of hatching and blooming)	135E, 35N	135E, 35N	135E, 35N	135E, 35N	35N, 135E	–	–	–	–	–	–	35N, 135E

Table 2.1 Continued

Species	Index	Mechanism	Month											
			1	2	3	4	5	6	7	8	9	10	11	12
Japan/East Sea														
Sardine	Spring SST, subsurface temperature (low SST and high subsurface temperature are preferable)	Parents feeding success	–	–	–	–	42N, 132E	42N, 132E	42N, 132E	42N, 132E	–	–	–	–
Pacific saury	SST, subsurface temperature (low SST and high subsurface temperature are preferable)	Prey availability for larvae and juveniles	–	–	–	–	135E, 35N	135E, 35N	135E, 35N	135E, 35N	–	–	–	–
Japanese common squid	SST, subsurface temperature (low SST and high subsurface temperature are preferable)	Prey availability for paralarvae and juveniles	135E, 35N	135E, 35N	135E, 35N	135E, 35N	135E, 35N	135E, 35N	135E, 35N	135E, 35N	135E, 35N	135E, 35N	135E, 35N	135E, 35N
	Wind direction and rate (upwelling is favorable, downwelling is dangerous)	Paralarvae pelagic habitat (MLD must be shallow enough)	135E, 35N	135E, 35N	135E, 35N	135E, 35N	35N, 135E	35N, 135E	35N, 135E	35N, 135E	35N, 135E	35N, 135E	35N, 135E	35N, 135E
Yellow Sea														
Pacific herring	Area of bottom with suitable substrate	Climate conditions	–	–	–	–	–	–	–	–	–	–	–	–

SSH – sea surface height, SST – sea surface temperature, MLD – mixed layer depth, ROMS – Regional Ocean Model System

Background Reports Prepared for
the Phase 2 Workshop

Northern California Current (U.S.) groundfish production

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Relatively few mechanistic hypotheses regarding groundfish production (recruitment) have been proposed and rigorously tested for individual species on the U.S. west coast. The most compelling hypotheses for environmental effects occur at early life stages, and as year-class strength is determined in the first year, processes acting on recruitment are of highest priority. This short paper attempts to outline

Table 2.2   Summary of proposed processes forcing groundfish recruitment.

Process	Variable	Time scale	Spatial scale
Advection of larvae away from or towards areas amenable for settlement	Variables indicative of upwelling habitat conditions, perhaps surface winds, salinity, and SST	Less than 2 weeks, monthly, seasonal (winter/spring)	
Prey abundance for larvae influenced by currents, upwelling, turbulence and/or water mixing	Variables indicative of upwelling habitat conditions, mixed layer depth, lower trophic level model output including nutrient concentrations, the density and distribution of phytoplankton and zooplankton, SST and/or SST gradients, and frontal occurrence and complexity	Less than 2 weeks, monthly, seasonal (winter/spring)	
Food availability for adult females before and during copulation	SST, lower trophic level model output including nutrient concentrations, the density and distribution of phytoplankton and zooplankton	Monthly, seasonal (autumn/winter)	
Environmentally driven larval metabolic rates and resulting growth/ developmental rates	SST and SST gradients	Less than two weeks, monthly, seasonal (winter/spring)	
Distribution of predators in relation to larvae	SST, SST gradients, and current strength	Less than 2 weeks, monthly, seasonal (winter/spring)	
Timing of the spring transition in the California Current System when the predominantly northward winter currents reverse to predominantly southward currents which is thought to impact many of the above processes	This would likely be a composite index which might consist of a number of physical variables including timing and/or duration of upwelling periods, magnitude of upwelling, and SST/SSH gradients. Lower trophic level model output including nutrient concentrations, the density and distribution of phytoplankton and zooplankton	Less than 2 weeks, seasonal (spring)	Little is known about the spatial scale of the process important for groundfish recruitment. Small spatial scales on the order of 10s of kilometers are likely important for recruitment success; however, the spatial scale of SST covariation in the California Current ranges between 500–2000 km and is also potentially important

the processes which may influence groundfish recruitment, the physical variables which may be indicative of the processes and conditions in the California Current, and the time and spatial scales at which they occur. Important processes, variables, and their time and spatial scales will vary by species, but some similarities across groups of species may emerge.

This paper is primarily a synthesis of workshops and discussions from a project on incorporating climate information into rebuilding analyses for overfished rockfish led by Drs. Carrie Holt (University of Washington), Andre Punt (University of Washington), and Nathan Mantua (University of Washington) with participation from Elizabeth Clarke (NOAA), Richard Methot (NOAA), Ed Armstrong (NASA), Ben Holt (NASA), Yi Chao (NASA), Nick Tolimieri (NOAA), Ian Stewart (NOAA), and Melissa Haltuch (NOAA). Table 2.2 proposes the process which may be forcing recruitment, variables which might be used to describe the process, and the time and spatial scales of likely importance.

Results from Carrie Holt's work on identifying dates of spring transition and the relationship between spring transition and west coast groundfish recruitment can be summarized as follows:

- Caution is advised when interpreting results of studies that relate dates of spring transition to biological variables due to uncertainty in defining those dates. For example, three methods examined for identifying the timing of spring transition pertain to seasonal shifts in different features of ocean conditions. It is unclear which metric best reflects conditions important for groundfish recruitment.
- Identifying dates of spring transition that are appropriate for both northern and southern regions of the California Current has proven difficult.
- Modeling results to date have found statistically significant negative relationships between dates of spring transition and recruitment deviations for U.S. west coast groundfish for only a few northern species that spawn in winter offshore and rear nearshore.

This summary is meant to provide a basis for further discussion of mechanistic hypotheses and the physical data that are available from IPCC climate models which might be used to forecast fish production as part of the PICES project on "*Forecasting climate impacts on future production of commercially exploited fish and shellfish*", should a hypothesis stand up to testing.

Changes in sablefish (*Anoplopoma fimbria*) recruitment in relation to oceanographic conditions

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Sablefish (*Anoplopoma fimbria*) range from the southern west coast of the United States, north to Alaska, the Bering Sea, and west to Japan. The species supports substantial fisheries in both the eastern and western Pacific Ocean. Juvenile recruitment along the west coast of the continental United States has been highly variable over the past three decades. Examining the estimates of spawning stock biomass from extensive surveys made over this same period point to the fact that factors external to the sablefish population dynamics have significant effects on population level recruitment. Using a General Additive Model (GAM), it was demonstrated that there are physical oceanographic variables that significantly interact with sablefish recruitment. Significant relations were found between juvenile recruitment and northward Ekman transport, eastward Ekman transport, and sea level during key times and at key locations within the habitat of this species (Schirripa and Colbert, 2006). The overall model explains nearly 70 percent of the variability in sablefish recruitment between the years 1974 and 2000. Bootstrapping techniques were applied to the parameter estimates, and the resulting distributions were found to support the modeling assumptions of normality. Given the above model, it is possible to draw preliminary conclusions concerning year-class strength of cohorts, not yet available to the survey gear, as well as historic year-class strengths.

We used data from Neah Bay and Toke Point, Washington, and Astoria and Newport, Oregon and averaged the monthly sea surface height (SSH) over April, May, and June to arrive at a coastal SSH between 44° and 50°N latitude. Data on annual zooplankton (copepod) anomalies were those reported in Mackas *et al.* (2006). Total dry weights of northern and southern species of copepods from southern Vancouver Island were used as an index to deviations from the stock-recruitment curve (Fig. 2.1). These anomalies are used to characterize the zooplankton species composition of the larval/juvenile sablefish habitat.
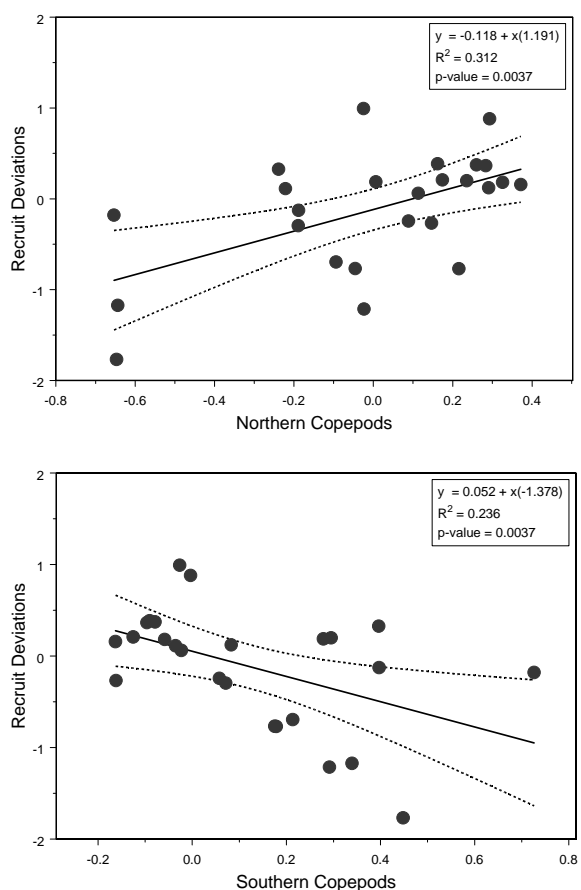
Fig. 2.1 Relation between sablefish recruitment deviations and northern (top) and southern (bottom) copepod species.

Recruitment deviations were estimated either from 1971–2005, or from 1925–2006, depending on whether or not the long-term SSH data were used. The variance of the stock-recruit function (sigma-R) was estimated through iteration and matching the assumed variance to the resulting residual mean square error.

The three environmental variables, SSH, northern zooplankton anomalies, and southern zooplankton anomalies were considered as covariates for

$$y = -0.321 + x(-0.566)$$
$$R^2 = 0.403$$
$$\text{p-value} < 0.0001$$
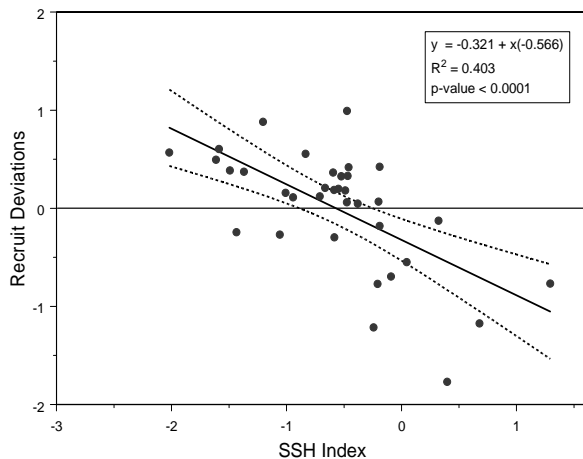
Fig. 2.2 Relation between sablefish recruitment deviations and sea surface height (SSH).

recruitment deviations from the fitted stock-recruit relation. The method employed in this assessment treats the natural log of the z-score of the environmental data in the same manner as all other survey data and is used as a tuning index for recruitment deviations from the stock-recruit function. The link between zooplankton and sablefish survival was first reported by McFarlane and Beamish (1992). To determine if these indices could be used to track changes in sablefish survival, each was regressed against the recruitment deviations from the model that included none of the indices (Fig. 2.2). While all three indices had highly significant (P < 0.05) relations to recruitment deviations, the most variation was explained by the SSH time series (P < 0.0001, R^2 = 0.403).

In late spring and early summer, young-of-year sablefish have developed from the larval stage, are free swimming and free feeding. At this stage, they search for zooplankton and other food while moving onshore to the nursery grounds. Low sea level and low values of the North Pacific Index suggest higher than expected recruitment. The tide gauge sea level data we use are not adjusted for barometric pressure, so they integrate both the atmospheric effects and the large-scale ocean conditions. That is, they integrate both the large-scale northeastern Pacific Ocean conditions with local upwelling and pressure. Sea level is also a good predictor of near-bottom ocean temperature along the shelf. Lower sea level is associated with colder than average water, more

upwelling, stronger southward currents and lower salinity. All these factors provide better habitat for young sablefish, as they occupy the shelf at this time of year. The timing of the spring transition may be as critical as the SSH level itself. That is, the contribution of the April SSH may have more of an influence on sablefish survival than the contributions from May and/or June.

There is little doubt at this point that sablefish larval survival is modulated, at least in part, by climate and the manner in which climate affects the annual strength of the California Current System. This was evident in 2005, a remarkable year off the West Coast (Kosro *et al.*, 2006), when in spring and early summer, the northern California Current System was anomalously warm because the spring transition to a wind-driven upwelling was delayed by 2–3 months. This delay worked its way up the food chain and resulted in the zooplankton community off the West Coast being dominated by small, southern species of copepods, which are of relatively poor nutritional value. It is this chain of events that presumably led to, among other things, poor sablefish recruitment in 2005. While one year does establish a theory such as this, the significant regressions on recruitment deviations and zooplankton anomalies are convincing in this regard; as goes the climate, so goes sablefish recruitment. Furthermore, SSH was well above average for the month of April, an early indication that 2005 survival would be low. In April 2006, SSH was similar to that of April 2005 but eventually decreased to below average levels in May and June, indicating that the spring transition was late in 2006. As a result, the 2006 year-class abundance may also be below average. This outcome should be evident in the 2007 shelf survey.

While the significant relation between the SSH index and sablefish age-0 survival demonstrates that this should be a reliable (at least near term) index, the association with the zooplankton index may support the underlying biological mechanism for WHY this relationship exists. Investigations of the food habits of age-0 fish, especially during the spring months, could help provide this understanding. Also, further research should be conducted to evaluate alternative methods for incorporating ecosystem metrics into the assessment.

Northern California Current (British Columbia) Pacific cod (*Gadus macrocephalus*) production

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Biology

Pacific cod (*Gadus macrocephalus*) grow rapidly in Canada in the first year, reaching 30 cm by age 1, and are sexually mature by ages 2 to 3 years (Westrheim, 1987). Length at first maturity is approximately 40 cm, and length at 50% maturity is 55 cm. Pacific cod tend to disperse into deeper waters to feed, and congregate to spawn in shallower waters from February to March. They undergo a seasonal migration from shallow waters in the spring and summer to deeper waters in the fall and winter. Pacific cod in Canada are at the southern limit of their distribution and are therefore vulnerable to the expected climate and ocean changes. Four stocks of Pacific cod are defined for management in British Columbia: Strait of Georgia, west coast of Vancouver Island, Queen Charlotte Sound and Hecate Strait. In Hecate Strait, stock abundance remains at historic lows, recruitment of the last 9 year classes has been below historic levels, and the 1998 year class was the smallest ever. Abundance off the west coast of Vancouver Island also remains low. Pacific cod were common in the Strait of Georgia in the past. Presently, few remain, possibly because of the increase in water temperatures in recent years.

Fishery

Small Pacific cod fisheries take place in Queen Charlotte Sound and off the lower west coast of Vancouver Island. The major fishing occurs in Hecate Strait. Spawning stock biomass and recruitment has been estimated for Hecate Strait using stock reconstruction based on ages estimated from lengths. The species is a significant component of the multi-species groundfish fishery in Hecate Strait. Annual yields have varied between a high of 8,870 t in 1987 to a low of approximately 200 t in 2001. Landings since the mid-1990s have been very low (Fig. 2.3). The trawl fishery has undergone a number of significant changes in recent years. Prior to 1992, the total catch of Pacific cod was unrestricted and the main management measures were area and season closures. Total allowable catches were introduced in the Hecate Strait area in 1992, in response to declining abundance. Trip limits were also introduced in the same year and these decreased steadily until 1995. For the 1996 season, trawl catches were limited to bycatch only because of stock concerns. Stock declines resulted from a decade of below average recruitment. The pattern of recruitment (age 2+) in Hecate Strait from 1960 to 1988 was similar but the recent regime (1989–1997) is characterized by 9 years of very poor recruitment.
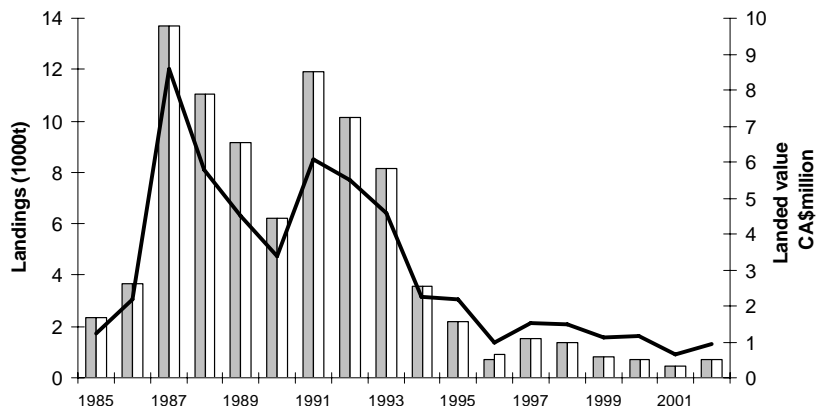
Fig. 2.3 Food and Agriculture Organization landings (grey bars), Fisheries and Oceans landings (white bars) and landed value (solid line) of Pacific cod in British Columbia fisheries.

Table 2.3   Summary of mechanisms underlying production of commercial species in Canada.

Region	Species	Index	Mechanism
British Columbia	Pink and chum salmon	• Timing and duration of spring freshet, • Strength of winds, • Intensity of Aleutian Low, • Sea surface temperature, • Pacific Circulation Index.	• Pink and chum salmon abundance in the ocean is regulated by growth and by predation, • Growth is important because rapid early marine growth reduces the amount of predation and allows fish to better survive the marine winter, • Thus growth in the first few months in the nearshore areas is critical, • An earlier and stable mixing layer favours improved survival, • Hatchery production may override natural controls.
	Sockeye salmon	• River flows and temperatures, • Ocean entry time and size, • Rate of growth in first 6 weeks, • Aleutian Low, • Sea surface temperature in summer and winter, • Pacific Circulation Index.	• Size at ocean entry and growth of juveniles in fresh water; • Rate of early marine growth (first 6 weeks), • Sea surface temperature in summer and winter, • Spawning stock size and freshwater rearing conditions.
	Coho and chinook salmon	• Timing of spring river flows, • Wind direction and intensity, • Aleutian Low, • Sea surface temperature; • Timing of ocean entry, • Snow pack depth, • Summer river temperature.	• Timing of ocean entry must match with abundant plankton; • Prey must be plentiful and available within the first 6 weeks in the ocean, • Rapid growth by the end of June results in greater lipid storage and improved marine survival over the winter, • Faster early growth facilitates a switching to larger prey such as Pacific herring, • Hatchery fish compete with wild fish.
British Columbia	Sablefish	• Timing of spring transition, • Aleutian Low, • Wind advection.	• Matching of copepod abundance with first feeding larval sablefish, • Matching of coastal plankton production with the onshore movements of juveniles.
	Pacific cod	• Bottom temperature, • Cross-shelf transportation, • Aleutian Low, • Wind direction and intensity.	• Cooler bottom temperature required for eggs to hatch; • Matching of prey and larval feeding, • Wind direction and intensity move juveniles into suitable nursery areas.
Strait of Georgia, BC	Pacific hake and walleye pollock	• Fraser River flow, • Aleutian Low, • Timing of spring transition, • Behaviour of *Neocalanus plumchrus*, • Bottom temperature, • Wind duration and intensity.	• Timing of spring bloom, • Size and abundance of adult fish, • Abundance of predators, • Productivity of the Strait of Georgia.

Climate and ocean effects

The potential impacts of climate change on Pacific cod off British Columbia are summarized in Table 2.3. High sea levels in the Prince Rupert area are associated with high transport rates through Hecate Strait, resulting in poor recruitment for Pacific cod. Sea levels were high in the Prince Rupert area up until 2003 when they began to decline. The relationship between sea level and recruitment can be

interpreted as an indication of the sensitivity of Pacific cod to ocean conditions. Temperatures in the range of 6.0 to 7.0°C appear to be optimal for Pacific cod recruitment. Temperatures higher than 7.0°C will likely decrease recruitment. Laboratory studies on the effect of temperature on Pacific cod egg survival indicate that the optimal temperature is between 3.5 to 4.0°C, with an acceptable range of 2.5 to 8.5°C (Alderdice and Forrester, 1971). Bottom temperatures in February that exceed 8.5°C would most probably reduce or eliminate recruitment. The southern limit of the commercial abundance of Pacific cod is northern Oregon and the southern limit of landings has been southern Oregon. Thus, there is little doubt that Pacific cod in British Columbia are at the southern limit of their distribution and are a

sensitive indicator of temperature increases.

Projections of temperature changes are for both surface waters and ocean temperatures in general to change more slowly than land temperatures. However, in 2006 bottom temperatures in March at the Nanoose Lighthouse in the Strait of Georgia were approximately 9.6°C. Thus, it is apparent that several degrees of warming will change the southern limit of Pacific cod distribution, and will perhaps move it as far north as southern Alaska. Pacific cod recruitment is therefore a sensitive indicator of ocean changes affecting groundfish. It is predicted that Pacific cod will gradually disappear from the Strait of Georgia and off the west coast of Vancouver Island as bottom temperatures warm.

Northern California Current (British Columbia) sablefish (*Anoplopoma fimbria*) production

Richard Beamish

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Biology

In Canada, most juvenile sablefish (*Anoplopoma fimbria*) inhabit the shallow waters of Hecate Strait and the west coast of Vancouver Island, and move to slope waters off northern and southern British Columbia as they mature. It is believed that there are two sablefish populations of the west coast of North America, separated at approximately 50°N into an Alaskan population and a west coast population. There is debate about the degree of movement between these two populations. Recent information using stable isotopes found in otoliths indicates that a third population may exist at the southern limit of the distribution. Adult sablefish are abundant in coastal British Columbia waters at depths greater than 200 m, and are most abundant between 600 and 800 m. Spawning occurs from January to March along the entire Pacific coast, at depths of about 300 to 500 m, with no appreciable latitudinal spawning migration. Larval fish hatch at about 300 to 400 m, and then descend to 1000 m by 18 days after spawning. Within a few days of their descent, larval sablefish begin to ascend and feed on copepod larvae. Recruitment appears to be determined at the larval stage. Juveniles are found in more shallow (< 200 m) inshore waters and rear in nearshore and shelf habitats until age 2–5. As sablefish mature, they move back into the deeper water where spawning occurred.

Growth of sablefish is rapid in the first few years, and then slows appreciably in this long-lived species. Length and age at 50% maturity are 58 cm, age 5 for females, and 53 cm, age 5 for males. Males tend to undergo a reduction in growth rate earlier than females. The majority of fish in the fishery are between the ages of 4 and 35, but the oldest sablefish aged to date is 113 years. In Canadian waters important prey items for sablefish include rockfish, Pacific herring and squid.

Fishery

The sablefish fishery is one of the few and oldest deep water fisheries of the world. The fishery was reported to be as large as about 6000 t in the 1910s. This early fishery provided a smoked or salted meat product and used the livers for vitamin A and D production. The fishery was encouraged as a way to adapt to a shortage of meat during the First World War. Catches declined into the 1920s, possibly because of a reduced demand after the war. It was not until the late 1960s that catches of sablefish increased as a consequence of a Japanese fishery established outside of Canada's exclusive fishing zone. Following the extension of the exclusive fishing zone in 1977, the fishery was exclusively Canadian and accounted for annual catches ranging from 830 t in 1978 to 5,381 t in 1989. The average commercial landings from 1978 to 2002 have been 4,071 t (Fig. 2.4).

Sablefish landings fluctuated in the 1990s, with declines in recent years (Fig. 2.4). The declines in catch are related to declines in biomass as indicated by the trend in catch per unit effort (Fig. 2.5). Since 1973 the dominant fishing gear used by the fishery has been Korean conical traps (73% of the annual landings). In 1990, the fishery switched to an individual quota for each vessel in an attempt to stabilize the length of the fishing season, to improve management, to optimize the landed value, and to reduce quota over-runs.

Climate and ocean effects

Potential impacts of climate change on sablefish off British Columbia are summarized in Table 2.3. Sablefish exhibit decadal-scale patterns in the relative success of year classes. By combining estimates of relative abundance of year classes determined from commercial catches and research surveys for adults and juveniles, McFarlane and Beamish (1992) and King *et al.* (2000) were able to reconstruct an index of year-class success. Year classes from 1960 to 1976 were generally poor, with no indication of good year-class success. The 1977 year class was exceptionally large and year classes from 1978 to 1988 were generally good or average.
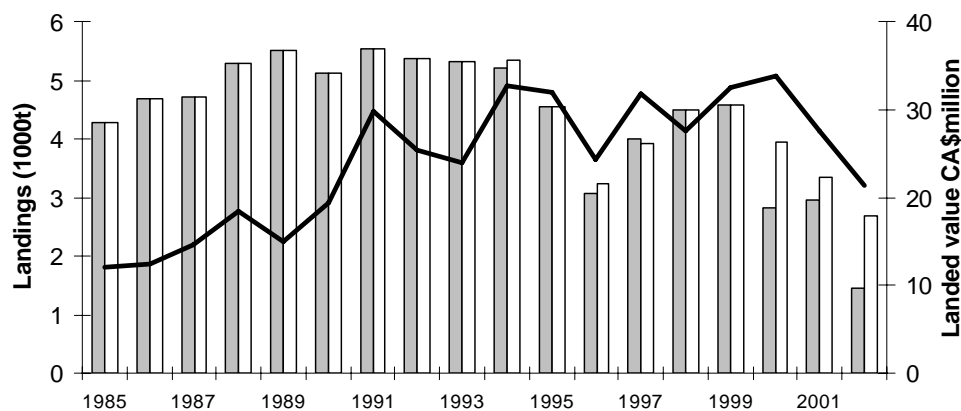
Fig. 2.4 Food and Agriculture Organization landings (grey bars), Fisheries and Oceans Canada landings (white bars) and landed value (solid line) of sablefish in British Columbia fisheries.
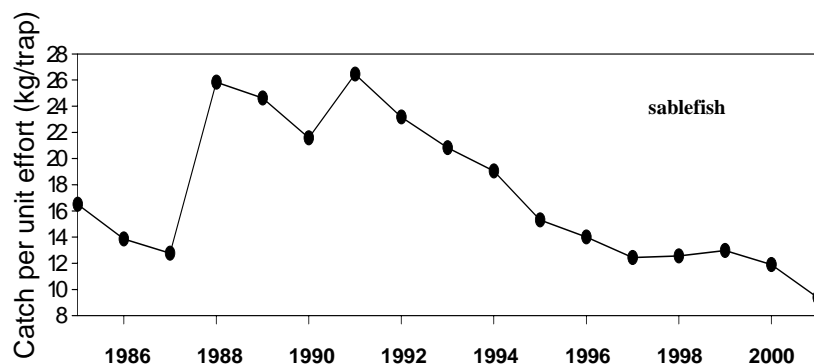
Fig. 2.5 Sablefish average catch per unit effort.

Year classes following 1989 and 1990 were generally poor. McFarlane and Beamish (1986) proposed that sablefish live up to > 70 years because their ability to reproduce successfully each year was restricted by their biology and habitat. Their longevity, therefore, represented the longest period of unsuccessful reproduction over evolutionary time. If this hypothesis is valid, sablefish recruitment is closely related to specific kinds of climate-related ocean conditions. One limiting factor would be the ability of the fragile eggs to remain suspended in mid-depths, and for the larval sablefish to find copepod eggs and nauplii immediately after they begin exogenous feeding. It was observed that despite a large fecundity, strong year classes resulted from both large and small spawning biomass (McFarlane and Beamish, 1986). It was also observed that the production of strong year classes was closely associated with copepod production at a site off the west coast of Vancouver Island

(McFarlane and Beamish, 1992). The periods of above average year-class strength coincided with stronger Aleutian Lows, more frequent southwesterly winds, below average temperatures in the subarctic Pacific and warmer sea surface temperatures off the west coast of British Columbia (King *et al.*, 2000). In general, the pattern of year-class success matches the patterns of regimes and regime shifts. This is evidence that there are trends in sablefish production that are related to climate and ocean conditions on a decadal scale. The recent declines in biomass (Fig. 2.5) reflect fishing removal and declining recruitment, which is related to the generally less productive regime in the 1990s.

There is concern that fishing is reducing the number of age classes in the population, resulting in a population of relatively young fish (Beamish *et al.*, 2006). However, because adult sablefish appear to be able to adapt to natural short-term and long-term

shifts in ocean conditions, it is probable that global warming will not have impacts on adult sablefish in a time frame of 50 years that will threaten the long-term dynamics of the population. This does not mean that specific global warming impacts on the survival of eggs, larvae and juveniles will not occur, but rather that the adult fish may be able to survive such adverse conditions. Also, there will be time to detect changes in the population dynamics and to consider management options, but this also does not mean that the population will be able to support current levels of exploitation, particularly at rates of around 15%.

An immediate concern is the impact of fishing on the population structure and the natural ability of sablefish to survive in unfavourable conditions.

Fishing impacts over the past 30 years have reduced the percentage of older fish in the population. It is possible that resilience to long periods of unfavourable climate may be lost. If the remaining fish still have the ability to live for extended periods, this resiliency may not be lost. If the impacts of global warming are negative and reproduction is less successful or fails, it may be important to ensure that a percentage of the existing population is allowed to live to the older ages that existed prior to commercial fishing. This may be best accomplished by establishing no fishing zones that are in the most favourable spawning areas. If periods of intense Aleutian Lows increase as a consequence of global warming, there is a possibility that recruitment periods may increase relative to the past 50 years.

Northern California Current (British Columbia) pink (*Oncorhynchus gorbuscha*) and chum (*O. keta*) salmon production

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Pink and chum salmon will probably respond in a similar way to a changing climate as the fry for both species spend only short periods in fresh water and enter the ocean at about the same time. In the Strait of Georgia their early growth is strongly correlated among years (Fig. 2.6). Pink salmon are the better indicator of climate impacts as their shorter life span and genetically distinct odd- and even-year runs provide more information sooner.

Pink salmon biology

Pink salmon (*Oncorhynchus gorbuscha*) are the most abundant of the Pacific salmon in British Columbia waters. They have the shortest life span, approximately two years from hatching, and are the smallest salmon species. Pink salmon form distinct spawning brood-lines, with some stocks spawning in years with even numbers (*i.e.*, 1996) and some with odd numbers (*i.e.*, 1997). The largest stocks of pink salmon occur in the Fraser River, where spawning takes place only in odd-numbered years. Farther north, spawning occurs in all years, with a tendency for the even-year spawning stocks to predominate.

Although pink salmon exist farther south than British Columbia, the center of distribution is north of British Columbia. Fraser River stocks, therefore, are close to the southern limit of the range. Females may produce 1,200 to 1,900 eggs, depending on the stock and the body length of the female. Spawning occurs from July through to early fall in riverbeds with coarse gravel. Pink salmon prefer to spawn in swift currents along the borders of streams or in riffle areas.

Pink salmon fishery

Pink salmon are not held in high esteem in British Columbia, thus catches probably are not a good indicator of abundance. This is particularly true in recent years when there has been exceptional production in some stocks with virtually no commercial fishery. In Canada, annual total catches of pink salmon averaged 19.7 thousand t or approximately 14.7 million fish from 1959 to 2000. Total catches of pink salmon increased after the 1977 regime shift, reaching a maximum in the early 1980s. Since the early 1990s, there has been a dramatic reduction in catch (Fig. 2.7A).
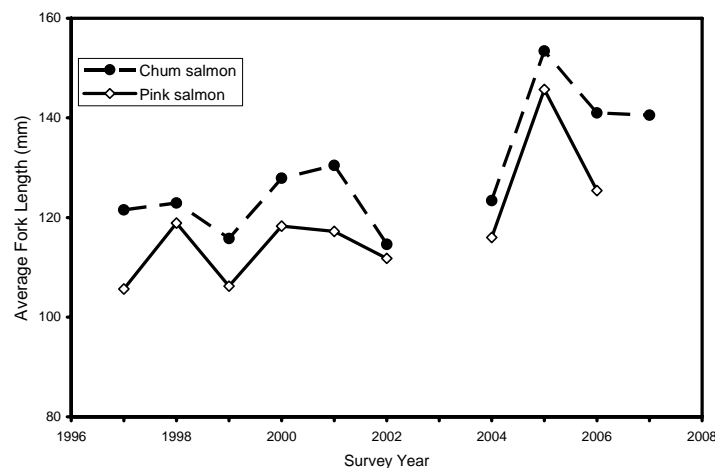
Fig. 2.6   Average fork lengths (mm) for juvenile chum (close circles, dashed line) and pink (open diamonds, solid line) salmon captured in July surveys in the Strait of Georgia from 1997–2007, using a mid-water trawl. The regression equation for the two datasets has an R^2 value of 0.86, with an F-value of 43.40 (highly significant). Note that no survey was conducted in 2003. Juvenile pink salmon catches are very low in odd-numbered years (0 in the 2007 survey).
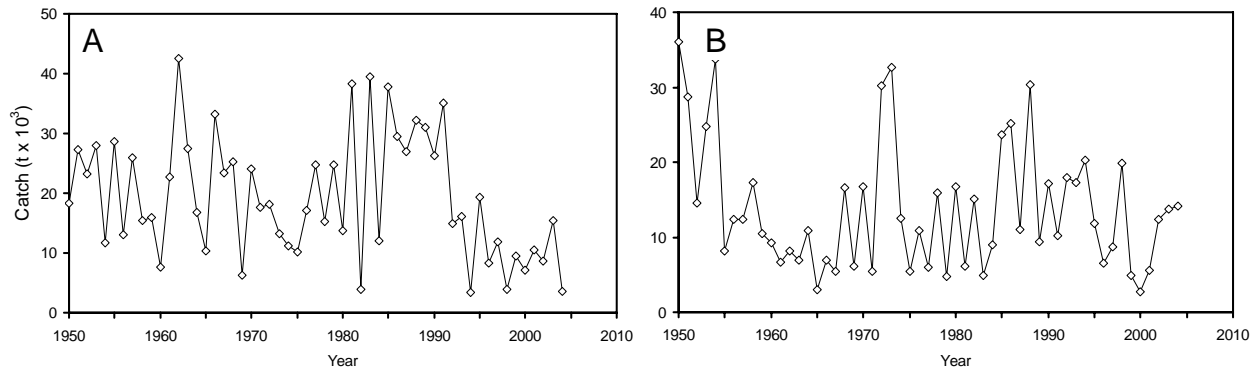
Fig. 2.7 Canadian catches of (A) pink salmon and (B) chum salmon from 1950 to 2004.
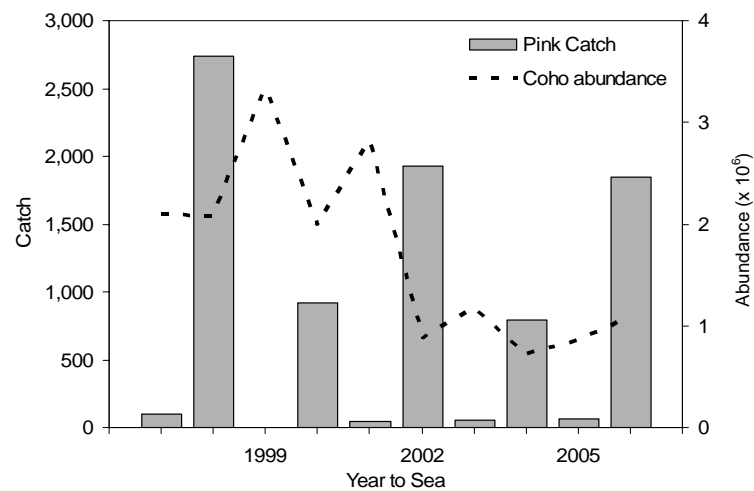
Fig. 2.8 Strait of Georgia juvenile coho salmon abundance and pink salmon catch in July from 1997 to 2007.

A recent analysis of the coast-wide production of pink salmon indicated that over the past decade, the spawning abundances may have doubled or tripled compared to numbers in the 1960s and 1970s. Pink salmon produced in the Fraser River historically account for about 60% of the total British Columbia catch, although some of this 60% is caught by the United States. Their population dynamics and the response of the fishery is probably a good indicator of the dynamics of most pink salmon stocks. As mentioned, virtually all stocks of pink salmon in the Fraser River spawn in odd-numbered years. The reason for the persistent dominance of these "odd-year stocks" and the general phenomenon of dominance among pink salmon stocks is unknown. In 2001 and 2003, there was a large return of pink salmon to the Fraser River. Management policy resulted in an exploitation rate on this return that was

very low, resulting in a spawning escapement that was approximately two times the highest estimated escapement on record and at least a magnitude larger than escapements in the 1950s. These exceptional returns were the production from one of the lowest escapements on record in 1999. Clearly, there was a dramatic increase in the marine survival of pink salmon fry entering the Strait of Georgia in 2000.

Juvenile pink salmon in the Strait of Georgia compete with other juvenile salmon. Because pink salmon spawn in the Fraser River in odd-numbered years, the juveniles are abundant in the Strait of Georgia in even-numbered years. The abundance of juvenile coho salmon is frequently reduced in July in even-numbered years, compared to odd-numbered years (Fig. 2.8).

Chum salmon biology

Chum salmon (*Oncorhynchus keta*) may exist in about 800 rivers in British Columbia (Salo, 1991). There are distinct summer and fall spawning stocks, with the runs in the north being earlier than in the south. In the south, spawning can occur from October to January. In the spring, chum salmon are some of the first salmon to enter the ocean, remaining in the nearshore areas until the end of May (Healey, 1980). Chum then move into more coastal waters, and by mid-summer they leave the inshore areas and migrate offshore and into the Gulf of Alaska (Hartt and Dell, 1986). In recent years, chum salmon have remained inshore in large numbers through to mid-September (Beamish and Folkes, 1998). Most chum salmon (about 60%) spend three winters in the ocean. The remaining fish spend two or four years at sea. Very few spend five years at sea. The average size at return is about 70–75 cm. Since the late 1970s, chum salmon have been produced in hatcheries. The total production reached a maximum in the early 1990s, and in recent years has declined. Chum eggs are hatched in hatcheries, and the fry are fed in channels prior to release. In some cases, the fed fry are placed in sea pens and reared in salt water prior to release.

Chum salmon fishery

Chum salmon are generally the last species caught in the commercial fisheries. Most fisheries occur near river mouths, or what are called "terminal areas." Fishing is with purse seines or gillnets. Smaller fisheries occur that use troll gear. Chum salmon that retain their "silver colour" are frequently marketed for smoking. Chum salmon that are coloured externally are valued mainly for their roe. In recent years, catches increased in the late 1980s through to the early 1990s (Fig. 2.7B). Catches were low in the mid- to late 1990s through to the present. Assessments of total production generally show that it has been stable for the past 30 years (Godbout *et al.*, 2004; Spilsted, 2004).

Climate, ocean and global warming impacts

The specific factors that regulate salmon abundance in the ocean are not clearly identified, making it difficult to predict the impacts of altered marine ecosystems. Changes that could occur in fresh water as a consequence of climate change would have a major impact on Pacific salmon. These would impact on the migrations, spawning, hatching, and early rearing

phases. Physical changes in temperature, precipitation, groundwater discharge, and increased ice-free periods for lakes could affect community structure and the survival, growth, and distribution of salmon species.

The Fraser River drainage in British Columbia is a major producer of Pacific salmon, accounting for 30 to 40% of all Pacific salmon produced in Canada. Because numerous stocks of the five species of salmon are at or near the southern limit of their range, the early impacts of climate change should be detectable in these stocks. We know that a warmer climate will increase water temperatures and decrease flows during spawning migrations, increasing pre-spawning mortality and reducing egg deposition (Figs. 2.9 and 2.10). A warmer climate will increase water temperatures during egg incubation stages, causing premature fry emergence and increased fry-to-smolt mortality. At the same time, a warmer climate will increase the severity and frequency of winter floods, thereby reducing egg-to-fry survival rates. The productivity of lakes will be altered, but impacts on their suitability as nursery habitats for juvenile sockeye salmon is not known.
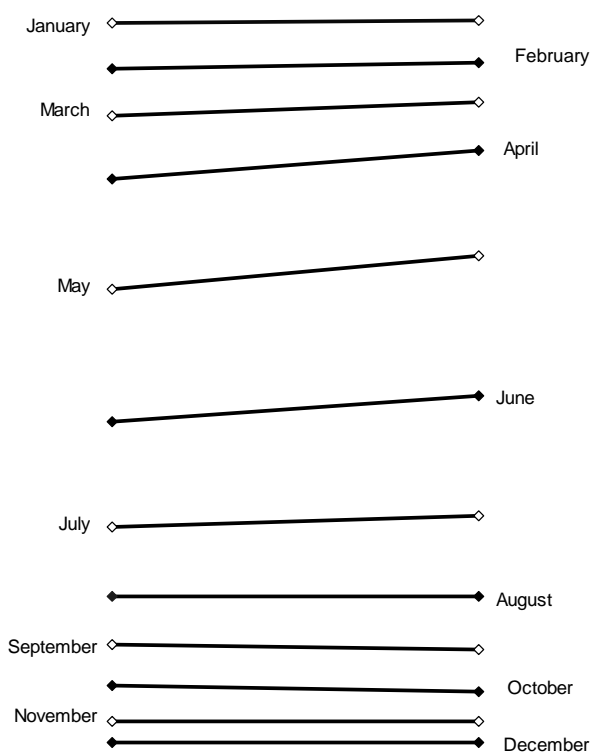
Fig. 2.9 Monthly percentage contribution to the total Fraser River flow (1913–2007) showing the increased discharge in the spring months and slightly declining discharge in the fall months.
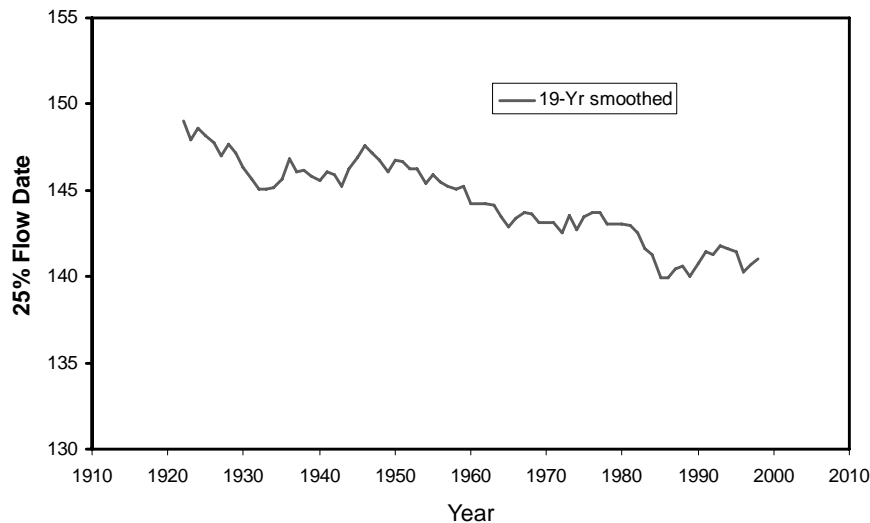
Fig. 2.10 Date that 25% of annual Fraser River total flow achieved (1913–2007), smoothed by a 19-yr running average, showing that over the last 80 years that date is about one week earlier.

It is highly probable that there will be a direct relationship between increased river temperatures and pre-spawning mortalities for all salmon. In fact, in the late 1990s, abnormally high pre-spawning mortality occurred, and one of the explanations related the mortality to changes in climate. The impact of climatic warming on winter water temperatures is uncertain. Winter water temperatures are related to groundwater base flows, lake water runoff, precipitation levels, and perhaps changes in snowmelt patterns. It is probable, however, that both summer and winter temperatures will be higher.

Pacific salmon are particularly susceptible to temperature fluctuations because they have adapted to thermal regimes in both fresh and salt water. At the southern limits of salmon distribution, projected climatic changes would warm both marine and freshwater habitats, especially in the winter. High temperature has a profound effect on fishes because they cannot regulate their body temperature. Extreme temperatures may kill eggs, juveniles, or adult salmon; less extreme temperatures can affect growth, reproduction, and movement. Recommended temperatures for most Pacific salmon in fresh water range from about 7° to 16°C, with extremes from 3° to 20°C. Upper lethal temperatures are 25° to 26°C. Southern rivers could approach these higher limits under projected climatic scenarios.

Stream discharge patterns have a high degree of variation, and changes in the variability of timing and the expected increase in variation could reduce

the accuracy of management and result in the need for reduced exploitation rates. Warming of fresh water in the north may also improve production. Much of the increases in total Pacific salmon abundance in the 1980s occurred in Alaska stocks, possibly indicating that warming in fresh water and coastal areas at this time was beneficial for salmon production. However, the function of northern aquatic systems has not been well documented, and large temperature increases could have unforeseen effects on Pacific salmon survival.

Beamish and Noakes (2004) examined the role of climate change on the past, present and future of Pacific salmon species off the west coast of Canada. They suggested that existing stock assessment models might be inadequate to predict the dynamics of a stock in a future of climate change. They provided one scenario that predicts an increase in the total production of Pacific salmon as climate changes. This contrasts with other interpretations, such as that of Welch *et al.* (1998), who used estimates of sea surface temperature increases to propose that the ocean habitat available to sockeye salmon would diminish and would move farther north. Both scenarios are possible and need to be evaluated as climate changes become more extreme. Beamish and Noakes (2004) also noted that Pacific salmon in general, and pink salmon in particular, may move into the Canadian Arctic in increasing numbers.

Pacific salmon are well known for their homing ability from feeding areas in the open ocean to the exact areas of their birth in coastal freshwater rivers.

Less well known is their ability to stray. This straying rate can range up to 10% and provides Pacific salmon with an ability to adapt to large-scale climate change such as past periods of glaciation.

The Arctic is one area that may be exhibiting early impacts of global warming. Model predictions indicate that a doubling of CO_2 would reduce the extent of sea ice by 60% and the volume by 25–45% (Gordon and O'Farrell, 1997). There would also be greater freshwater runoff. During the period 1978–1996 there has been a 2.9–3.5% per decade decrease in the extent of Arctic sea ice (Cavalieri *et al.*, 1997, Serreze *et al.*, 2000). If such dramatic changes were to continue, conditions favorable to straying and perhaps feeding for pink and chum salmon may improve.

In the ocean, we expect that the major sources of early marine mortality will become more variable and more extreme. Predation may increase as more pelagic predators such as Pacific hake and mackerel move north. Growth-based mortality (Beamish and Mahnken, 2001) may become more important and more variable. It may be possible to mitigate climate-related changes in fresh water; however, adjusting management to adapt to climate-related changes in the ocean would range between challenging and impossible. Nonetheless, if climate-related impacts could be identified quickly, it may be possible to use this information to show that

reductions in greenhouse gases are essential for the protection of Pacific salmon at their southern range.

The short life span of pink salmon of two years between spawning, as well as their abundance and extensive distribution, makes pink salmon a desirable species for studies of environmental impacts such as greenhouse gas-induced climate change on the long-term population dynamics of all Pacific salmon. The increase in marine survival of this species in 2000 coincided with a major shift in the trend of climate indicators. Thus, there is evidence that pink salmon respond to climate changes in a time frame that could be used to detect the impacts of greenhouse gas-induced climate change. Pink salmon are an excellent indicator species because they are distributed throughout the subarctic Pacific and there is a long history of careful management. The single year class and the short life span facilitate associations between climate change and estimates of production. Additionally, the tendency for pink salmon to stray may also become an important indicator of factors affecting distributions.

Mechanisms underlying production of Pacific salmon in British Columbia are summarized in Table 2.3. The possible impacts of global warming and a changing climate on these species are listed in Table 2.4. In general, Pacific salmon from the Fraser

Table 2.4   Potential affects of global warming on the ecology of Pacific salmon in British Columbia.

Fresh water	Salt water
Earlier timing of returning adults	Earlier time and size of ocean entry
Earlier time of entry into rivers	Changes in predator composition
Higher river temperatures	Changes in ocean productivity will affect species differently
River flow rates	Changes in growth in the first marine year
Reduced access to spawning areas	Changes in juvenile migratory routes in response to temperature
Earlier changes in the hatching times	Increase in temperature
• Changes in the productivity of freshwater ecosystems, • Impact of species new to the ecosystem.	• Decrease in salinity, • Changes in the Aleutian Low and Pacific Decadal Oscillation that are currently unknown.
More variability in growth	Earlier timing of spring transition
Increased percentage of hatchery salmon	• Changes in competitors for food, • Reduced marine growth.
Reduced ability to adapt to changes in habitat	• More variability in straying rates, • Loss of ability to adapt because of the loss of wild fish.

River stocks will suffer major impacts in fresh water and in the ocean. Pink and chum salmon from the Fraser River will be reduced in abundance as a consequence of reduced fresh water survival as juveniles and spawning adults. Pink and chum salmon stocks from the Skeena and Nass rivers and to the north could increase in abundance as a result of improved ocean productivity. Pacific salmon probably will begin to reproduce in Arctic rivers. Basin-scale changes in growth, survival and straying rates will all indicate when large-scale changes occur. Pink salmon will be excellent indicators of climate-related change and could be used as biological indicators of the changing ecosystems.

Northern California Current (British Columbia) ocean shrimp (*Pandalus jordani*) production

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See Table 2.1 for mechanisms and indicators.

Alaska salmon production

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Mechanisms underlying the production of Alaskan salmon stocks are summarized in Table 2.5.

Table 2.5 Proposed mechanisms underlying salmon production in Alaska.

Index	Mechanism	Season	Citation
Spring temperature, out-migration timing, timing of spring bloom	Ice breakup affects timing of outmigration	Spring	Rogers (1988); Burgner (1991); Shotwell *et al*. (2006)
Timing of spring bloom, apparent growth effect	Match/mismatch; critical period	Spring	Cushing (1972); Beamish and Mahnken (2001); Mackas *et al.* (2001)
Temperature effect on predation; diet composition of predators, spatial distribution of predators, year-class strength of young-of-the-year pollock	Alternative prey for predators and daily ration for predators	Spring–Summer	Pearcy (1992); Farley *et al.* (2007)
Timing of spring transition	Match/mismatch; critical period	Spring–Summer	Logerwell *et al.* (2003); Peterson and Schwing (2003)
Prey availability to smolts, zooplankton abundance and species composition	Growth, foraging success	Summer	Cushing (1972); Willette *et al.* (1997); Beamish and Mahnken (2001); Peterson and Schwing (2003)
Ocean habitat volume, mixed layer depth, and fronts	Competition for prey – partitioning predators and prey	Summer	Coachman (1986); McRoy *et al.* (1986)
Euphausiid abundance	Reduced predation risk when alternative prey abundant – high prey availability leads to accelerated growth; critical size	Summer	Cooney (1993); Willette *et al.* (1997); Beamish and Mahnken (2001)
Diet composition of predators, abundance of predators	Predation	Summer–Fall	Pearcy (1992)
Winter survival	Critical size/critical period; winter survival of larvae and juveniles	Winter	Beamish and Mahnken (2001)

U.S. walleye pollock (*Theragra chalcogramma*) production in the eastern Bering Sea and Gulf of Alaska

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Walleye pollock, *Theragra chalcogramma*, is a marine fish species that is highly fecund, producing millions of eggs per individual spawner, and has highly variable mortality rates in early life stages (Bailey and Ciannelli, 2007). A consequence of this reproductive strategy (producing lots of young with high expected mortality) is fluctuating annual recruitment levels (the number of young fish entering the population each year). The instability of fluctuating year classes must be buffered by the averaging effect of many age classes in the population. Although the recruitment of walleye pollock in the Gulf of Alaska is one of the better studied processes in the world, admittedly there is still much that is not well understood.

Pollock is an opportunistic species that has a broad distribution range and has adapted to different environments (Bailey *et al.*, 1999). On the other hand, the population is limited by finding and adapting to local conditions that favor successful spawning (maximizing reproduction) and survival (minimizing mortality) of the early life stages. Local populations of pollock respond differently to shifting environmental regimes, as warming periods have seen those stocks at the southern margins of the pollock distribution falter or fail (Bailey *et al.*, 1999). In the center of its distribution of mass in the eastern Bering Sea, pollock have been (if at all) favorably impacted by periods of environmental warming (Hollowed *et al.*, 2001; Quinn and Niebauer, 1995). Delayed springtime blooms may be a factor negatively influencing recruitment in the Bering Sea (Mueter *et al.*, 2006). However, another recent study correlates cool temperatures in the Bering Sea with increasing recruitment (Megrey, Alaska Fisheries Science Center, Seattle, WA, pers. comm.). In the Gulf of Alaska the situation appears more complex, as pollock have been initially favored by a warm environmental regime (*e.g.*, stock increase in the late 1970s and mid-1980s) but negatively impacted afterwards (Hollowed *et al.*, 2001), possibly in association with an increase of predator biomass. However, a recent study has tentatively and weakly linked cool springtime sea surface temperature (SST) with increasing recruitment (A'mar, University of Washington, Seattle, WA, pers. comm.). These conflicting findings illustrate the difficulty in relating environmental indices near the birth of the cohort to highly variable recruitment 3–4 years later.

Pollock spawn once per year, in an event that involves individual pairing and courtship (Baird and Olla, 1991), and that is highly concentrated in space and time (Kendall and Picquelle, 1990). Given the fragility of eggs and larvae to environmental conditions, and their concentration in space and time, the survival of a whole year class is vulnerable to the vagaries of the ocean and weather, such as storms passing through Shelikof Strait, the major spawning site. On the other hand, pollock dynamics are buffered partly by multiple spawning stocks, spawning in different locales, compensatory mortality and by multiple age groups in the population. Spawning in different locations moderates the effects of temporal variation in habitat suitability by taking advantage of spatial variation. While the long life span of pollock is an adaptation that tempers the high variation in year-class strength, a high abundance of predators on adults, as well as commercial fishing that removes older age groups, reduces the age span over which mean abundance is averaged (and perhaps other aspects of the contribution of older fish to the population's viability). As a consequence, the population could be dependent on fewer age groups, hence contributing to overall stock variability (Longhurst, 2002).

The spawning regions of pollock are noted for mixing of coastal and nutrient-laden oceanic waters and stratification of the water column, which leads to enhanced productivity. These conditions favor the survival of early life stages of pollock. In the Gulf of Alaska pollock typically spawn during the last week in March and first week in April in Shelikof Strait (Ciannelli *et al.*, 2007). In this area, mixing of the Alaska Coastal Current, the Alaska Stream and coastal water, along with springtime increases in sunlight, warming and water column stratification, leads to a spring bloom and increasing zooplankton production. Zooplankton prey of pollock larvae are concentrated by

eddies and fronts (Napp *et al.*, 1996), resulting in favorable feeding conditions. Larvae are advected toward favorable nursery areas, such as the waters around the Shumagin Islands.

Mortality rates of pollock eggs and young larvae are high, with estimates ranging from 4 to 40% per day, but they decline as larvae develop. Larval conditions can vary from year to year and by location, and high percentages of larvae in the ocean have sometimes been observed in poor feeding condition (Theilacker *et al.*, 1996). Egg and early larval development and survival are suboptimal at temperatures below about 0° and above 10°–13^oC (Blood, 2002). Very high and low temperatures can be lethal to eggs and larvae, but generally for the Gulf of Alaska population, in the central part of the species distribution (4°–6^oC springtime SST), higher temperatures may favor survival of early stages, perhaps through one or more indirect mechanisms (Bailey, 2000). Optimal prey levels for successful feeding depend on many other conditions affecting predator–prey encounters, including larval size, temperature, light levels, turbidity and turbulence (Porter *et al.*, 2005), but generally they range between 20 and 40 prey/liter (Theilacker *et al.*, 1996). In very high density patches, pollock may deplete their prey (Duffy-Anderson *et al.*, 2002), leading to slower growth and higher mortality. At later stages, predation on juveniles is an important source of mortality. Large piscivorous fishes, including halibut, cod, arrowtooth flounder and flathead sole contribute significantly to mortality of juvenile pollock (Livingston, 1993).

An evolving perspective of the recruitment of pollock is that it is a complex process, influenced by both high frequency changes in the environment of young fish stages and by bounding effects of low frequency changes in the ecosystem (Bailey *et al.*, 2005). As a consequence, recruitment is caught in the push-pull between these scales. Larval mortality is highly variable and subject to many interacting high frequency factors (such as storms and prey availability), with feedback and non-linearity (Bailey *et al.*, 2004). Larvae show sophisticated behaviors involving choice and decisions when confronted with multiple and perhaps conflicting stimuli (Olla *et al.*, 1996). For example, they avoid turbulence by descending (Davis, 2001), taking them out of the photic zone and into colder water where growth is less optimal and prey are less abundant

(Kendall *et al.*, 1994). Under normal circumstances, these conditions are associated with poor feeding and high mortality. However, when prey are driven deeper by turbulence and there is bright daylight, these conditions are then optimal for feeding (Porter *et al.*, 2005). Thus, environmental factors driving recruitment are governed by complex relationships. On the other hand, although juveniles also show complicated behaviours in response to the environment (*e.g.*, Sogard and Olla, 1996), they are less impacted by small-scale physics, and juvenile mortality seems to be more stable and predictable, occurring largely as a result of predation and density-dependent mechanisms. The role of density-dependent mechanisms also seems to be influenced by environmental factors (Ciannelli *et al.*, 2004). Environmental and ecosystem structure shifts may also have indirect effects on pollock survival, such as causing changes in the operation of density-dependent mechanisms. For example, Ciannelli *et al.* (2004) found that the level of density-dependent mortality in juvenile pollock increases when water temperature and predation intensity are high. The build-up of predators in the community represents a low frequency, slowly changing pattern with lagged effects. Changes in ecosystem structure may be related to the relative stage in life history when recruitment is determined (*i.e.*, larval versus juvenile control) (Bailey, 2000). Therefore, control points may change from year to year, and depend on longer-term changes in the environment and community structure, such as those occurring with environmental and biological regime shifts. General patterns in recruitment have been well described by models incorporating stochastic mortality related to environmental conditions during the larval period and by deterministic factors and constraints during the juvenile period (Ciannelli *et al.*, 2004; Ciannelli *et al.*, 2005). It should be noted that although we have a fairly good understanding of how small-scale factors affect survival of early life stages, knowing how these factors combine and interact over larger and longer space and time scales (scale up), thus determining how pollock populations respond to the environment, fluctuating and shifting prey and predator abundances, and to self-regulation, is a difficult problem.

Proposed mechanisms underlying production of walleye pollock in the eastern Bering Sea are summarized in Table 2.6.

Table 2.6 Proposed mechanisms underlying production of walleye pollock in the eastern Bering Sea.

Index	Mechanism	Season/stage	Citation
Pelagic ocean habitat volume (Winter) – location of fronts + MLD + temperature + sea ice extent	Location of spawning	Winter	Proposed – NPRB BSIERP
Winter temperature, and onset of maturation	Timing of spawning	Winter	Blood (2002)
Timing of spring bloom	Prey availability for larvae; "critical period"	Winter preconditioning–Spring	Cushing (1972); Napp *et al.* (1996)
Transport to the northeast (northern part of inner and middle front)	Transport to suitable nursery grounds – spatial separation from cannibalistic parents	Winter–Spring	Wespestad *et al.* (2000)
Seasonal temperature	Metabolic rates – stage duration	All	Bailey *et al.* (1996); Bailey (2000)
Predator abundance	Predation (by salmon, ATF and cannibalism) of age-0 pollock	Summer	Livingston (1993); Bailey (2000); Farley *et al.* (2007)
Pelagic ocean habitat volume MLD and location of fronts + temperature (cold pool)	Competition for prey and spatial overlap of predators and prey	Summer	Ciannelli *et al.* (2004); Kotwicki *et al.* (2005); Porter *et al.* (2005)
Strength of MLD	Partitioning predators and prey	Summer	Bailey (1989)
Summer productivity/wind mixing	Age-0 prey availability	Summer	Bond and Overland (2005)
Prey availability/size at age	Growth of age-0 out of cannibalism size range	Summer	Foy and Paul (1999; GOA example); Brodeur *et al.* (1999); Swartzman *et al.* (2002);
Euphausiid, copepod abundance for pollock	Reduced predation risk when alternative prey abundant – high prey availability	Summer	Cooney (1993); Willette *et al.* (1997)
Fall size at age	Critical size amount of energy on board and large enough to reduce predation and continue foraging – a measure of overwintering survival	Fall	Beamish and Mahnken (2001)

ATF – arrowtooth flounder, GOA – Gulf of Alaska, BSIERP – Bering Sea Integrated Ecosystem Program,
NPRB – North Pacific Research Board, MLD – mixed layer depth

U.S. groundfish production in the eastern Bering Sea

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An important discovery in Bering Sea fisheries oceanography in recent years was the realization that climate variability at the scale of decades may have a direct effect on the productivity of winter spawning flatfish (Wilderbuer *et al.*, 2002). The mechanism under consideration is related to the advection/ dispersal of larvae to favorable nearshore nursery habitat. To better understand the variability in the transport of larvae to these areas, an understanding and description of the following physical oceanographic variables would be needed:

- Spring winds over the eastern Bering Sea shelf from April–June (Alaska Peninsula north to Nunivak Island, shelf margins to inner Bristol Bay);
- Spring currents (April–June) from about 40 m depth to the surface for the same areas as described above. Starting points should vary about 56°N latitude and 165°W longitude;
- The influence and extent of the tidal cycle on the Bering Sea shelf oceanography. Flatfish are known to take advantage of selective tidal transport and this may be the mechanism that takes them to their settlement areas once they get close enough.

U.S. crab production in the eastern Bering Sea

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The general state of knowledge on the mechanisms linking climate to crab production in the eastern Bering Sea can be summarized as follows:

- Good progress has been made to compare the geographic distributions of crabs with respect to topography, bottom temperature, and life stage.
- Reconstructed time series of abundance and recruitment have been generated by length-based population estimation models.
- Hypotheses have been generated, but testing of hypotheses is very limited.
- Forecasts of future crab abundances under global climate change using IPCC model outputs is difficult until further research is conducted to identify and confirm evidence for hypothesized recruitment mechanisms.

Tanner crab (*Chionoecetes bairdi)*

- A workshop of Tanner crab experts was convened to generate a list of hypothesized biophysical mechanisms by life stage as well as a conceptual model of recruitment mechanisms (Tyler and Kruse, 1997). Recruitment is only weakly related to stock size; residuals suggest a 13- to 14-year cycle likely driven by environmental factors (Zheng and Kruse, 2003).
- Statistical testing of a few hypotheses has been completed, with results pointing toward adverse effects of cold bottom temperatures on gametogenesis and favourable effects of northeasterly winds on larval advection and/or prey production. However, regression models with these two variables explained only 50% of the variability (Rosenkranz *et al.*, 1998, 2001). An update of the wind relationship explains even less variability than previously identified.
- There is no relationship between Pacific cod biomass and Tanner crab recruitment, but Zheng and Kruse (2006) found some evidence that spatial distributions of predator and prey are more important that predator abundance.

Other mechanisms need more thorough investigation through statistical testing and simulation modeling.

These include the positive effect of warmer sea surface temperatures on production of copepod nauplii, thus enhancing larval Tanner crab feeding success (Tyler and Kruse, 1997; Rosenkranz *et al.*, 2001).

Table 2.7 lists six potential mechanisms linking climate and Tanner crab production. Many more could be examined (Tyler and Kruse, 1997). There is a high level of uncertainty about mechanisms affecting Tanner crab recruitment, but work to date sets a good foundation for additional research into these mechanisms. Development of a recruitment model for Tanner crab is currently being proposed to the North Pacific Research Board. A length-based model, already developed for previous management strategy evaluations (Zheng and Kruse, 1999, 2000), could form the basis for such projections once the climate–recruitment linkages become better elucidated.

Red king crab *(Paralithodes camtschaticus)*

- A workshop of red king crab experts was convened to generate a list of hypothesized biophysical mechanisms by life stage, as well as a conceptual model of recruitment mechanisms (Tyler and Kruse, 1996). A Ricker stock-recruit relationship is indicated, but autocorrelated recruitment trends are also consistent with decadal climate shifts (Zheng and Kruse, 2003).
- Limited correlation analysis points toward potential relationships between recruitment and the strength of the Aleutian Low (perhaps through a wind-mixing, prey (*Thalassiosira* diatom) availability mechanism (Tyler and Kruse, 1996; Zheng and Kruse, 2000, 2006). Also, red king crab recruitment is negatively correlated with the biomass of both Pacific cod and yellowfin sole (Zheng and Kruse, 2006). Correlations with barometric pressure, cod abundance and yellowfin sole abundance explain only 36%, 36%, and 69% of the variability, respectively, but comprehensive statistical testing of hypotheses has not been conducted.
- Northeastward shifts in red king crab brood stock are associated with increased bottom shelf

temperatures in the late 1970s and early 1980s, possibly reducing the successful drift of larvae to juvenile nursery areas in nearshore areas of Bristol Bay (Loher and Armstrong, 2005).

- Another recruitment mechanism may be that reduced sea ice leads to better matching of the spring bloom with larval hatching times (Kruse, 2007), which may be opposite for snow crab that may benefit in cold years (Orensanz *et al.*, 2004). It has been proposed that increased heat in the ocean causes a shift of energy flow away from benthic invertebrates to pelagic species (Grebmeier *et al.*, 2006).

- All mechanisms require more thorough investigation through statistical testing and simulation modeling.

Table 2.8 lists six potential mechanisms linking climate and red king crab production. Many more could be examined (see Tyler and Kruse, 1996). There is a high level of uncertainty about mechanisms affecting red king crab recruitment. Work to date has focussed primarily on the generation of hypotheses and the cursory examination of evidence for a handful of them. A more thorough retrospective analysis of red king crab recruitment mechanisms has not yet been conducted. A length-based model, already developed for management strategy evaluations (Zheng *et al.*, 1997a,b), could perhaps form the basis for such projections once the climate–recruitment linkages become better elucidated.

Table 2.7 Summary of proposed mechanisms linking climate to Tanner crab production.

Index	Mechanism	Season	Citation
Minimum bottom temperature by T/V *Oshoro Maru* at 56–58°N and 164–166°W	Cold temperatures interrupt or delay gametogenesis.	Annual minimum	Rosenkranz *et al.* (2001)
Mid-shelf sea surface temperature (possibly use a quadrangle centered at 55°N, 165°W)	Warm temperatures promote production of copepod nauplii.	May–June (full range, April–October)	Rosenkranz *et al.* (2001)
Wind from the northeast (60°)	Winds alongshore the north side of the Alaska Peninsula promote coastal upwelling and production of copepod nauplii.	May–June (full range, April–October)	Rosenkranz *et al.* (1998); Rosenkranz *et al.* (2001)
Wind from the northeast (60°)	Northeast winds promote retention of larvae in offshore, deep-water, and fine sediment nursery habitats.	May–June (full range, April–October)	Rosenkranz *et al.* (1998); Rosenkranz *et al.* (2001); Zheng and Kruse (2006)
ROMS output of Tanner crab advection relative to cold pool at 55.5–58°N, 165–174°W	Larval settlement in cold pool adversely affects survival.	May–June (full range, April–October)	Tyler and Kruse (1997)
ROMS output of Tanner crab advection relative to Pacific cod geographic distribution in area (55.5–58°N, 165–174°W)	Larval settlement in areas occupied by cod adversely affects survival.	May–June (full range, April–October)	Tyler and Kruse (1997); Zheng and Kruse (2006)

Table 2.8 Summary of proposed mechanisms linking climate to red king crab production.

Index	Mechanism	Season	Citation
North Pacific Index or Aleutian Low Pressure Index	Stronger winds, associated with deeper Aleutian Lows, increase water column mixing, reducing the proportion of *Thalassiosira* diatoms (prey of crab larvae).	December–March	Tyler and Kruse (1996); Zheng and Kruse (2000, 2006) based on APPRISE studies in 1980s in Auke Bay (Bienfang and Ziemann (1995); Ziemann *et al.* (1991))
Winds in Bristol Bay (55–58°N, 158–164°W)	Same mechanism as above, but direct measure of wind	April–June (full range, April–October)	Same as above
Bottom temperature in Bristol Bay (55–58°N, 158–164°W)	Distribution of brood stock shifts to northeast with warming.	Annual (summer proxy)	Loher (2001); Loher and Armstrong (2005)
ROMS drift tracks from start locations within 55.5–57.5°N, 161–163°W	Survival depends on successful advection to nearshore nursery areas in Bristol Bay.	April–June (full range, April–October)	Hsu (1987); Loher (2001); Loher and Armstrong (2005); Zheng and Kruse (2006)
Timing of spring bloom	Match/mismatch of crab larvae and diatoms	April–May (full range, April–October)	Many citations, including Tyler and Kruse (1996)
Biomass of Pacific cod, yellowfin sole	Predation of ages 0–3 years	Annual	Zheng and Kruse (2006)

Snow crab (*Chionoecetes opilio)*

- A workshop of snow crab experts was convened to generate a list of hypothesized biophysical mechanisms by life stage, as well as a conceptual model of recruitment mechanisms (Kruse *et al.*, 2007).
- Analysis of stock and recruitment data does not suggest a density-dependent relationship; residuals indicate favorable environmental conditions in the 1980s and poor conditions in the 1990s (Zheng and Kruse, 2003).
- Snow crab brood stock shifted to the northwest after the 1970s (Zheng *et al.*, 2001, Orensanz *et al.*, 2004, 2005; Zheng and Kruse, 2006). The shift north may be related to warming bottom temperatures in the late 1970s; return shifts may be prevented by predation by cod (Orensanz *et al.*, 2004).
- Snow crab nursery habitat is located in the northeast shallow waters of the eastern Bering Sea (Somerton, 1981; Zheng *et al.*, 2001; Zheng and Kruse, 2006; Ernst *et al.*, 2005). Crabs appear to follow temperature gradients during their cross-shelf, ontogenetic migrations with age/size (Ernst *et al.*, 2005).

- Recruitment may be driven by larval advection from hatching locations to nursery areas. Recruitment success may be affected by changing brood stock location driven by bottom temperature, advection by ocean currents, duration of pelagic stage dependent upon development rates driven by upper water column temperature, and survival affected by cod predation (Orensanz *et al.*, 2004; Zheng and Kruse, 2006). Examination of these processes is ongoing by the National Marine Fisheries Service and University of Washington scientists (Parada *et al.*, pers. comm.).
- Recruitment may be driven partly by the match between snow crab larvae and the spring bloom, which may be timed best in cold years (Orensanz *et al.*, 2004).
- Cannibalism among year classes is likely an important density-dependent survival mechanism, with successful older year classes suppressing young of the year (Lovrich and Sainte-Marie, 1997; Sainte-Marie and Lafrance, 2002).
- To date, work has focussed on hypothesis generation rather than testing. Ongoing research using an individual-based model incorporating ROMS output is the first substantive effort to examine recruitment processes for snow crabs in the eastern Bering Sea.

Table 2.9   Summary of proposed mechanisms linking climate to snow crab production.

Index	Mechanism	Season	Citation
Bottom temperature in eastern Bering Sea shelf (56.5–62°N, 168–175°W)	Distribution of brood stock shifts to northeast with warming	Annual (summer proxy)	Orensanz *et al.* (2004)
ROMs drift tracks from start locations in area (56.5–62°N, 168–175°W)	Survival depends on successful advection to northeast, shallower waters	May–October	Orensanz *et al.* (2004); Parada *et al.* (pers. comm.)
Sea surface temperature (56.5–62°N, 168–175°W)	Temperature in upper water column affects rate of development and settlement time	May–October	Kon (1970)
ROMS outputs of snow crab advection relative to Pacific cod geographic distribution in area (56.5–62°N, 168–175°W)	Larval settlement in areas occupied by cod adversely affects survival	May–October	Orensanz *et al.* (2004); Zheng and Kruse (2006); Kruse *et al.* (2007); Parada *et al.* (pers. comm.)
Timing of spring bloom	Match/mismatch of crab larvae and spring bloom	April–May	Orensanz *et al.* (2004)
Abundance of immature snow crabs	Settling snow crabs are cannibalized by juveniles already occupying the nursery areas	Annual	Lovrich and Sainte-Marie (1997); Sainte-Marie and Lafrance (2002)

Table 2.9 lists six potential mechanisms linking climate and snow crab production. Many more could be examined (see Tyler and Kruse, 1996). There is a high level of uncertainty about mechanisms affecting snow crab recruitment. Retrospective analyses have been constrained by the lack of a length-based population model for snow crabs. Recent development of this model now provides a recruitment time series and could give the framework for projections of future recruitment. However, analyses of linkages between climate and recruitment may need to be concluded before projections could be reasonably attempted.

Forecasting Japanese commercially exploited species

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In this short paper, we briefly answer the requests sent by the workshop convenors in advance of the workshop.

Request 1. *Oceanographers and climatologists should identify what techniques they recommend for forecasting oceanographic responses to climate change.*

To make better predictions, we must have knowledge of the performance of the models, *i.e.*, "which model can properly represent the target area". There is a good example, described by Overland and Wang (2007), that only 10 of 22 tested Atmosphere–Ocean Coupled General Circulation Models (AOGCM) can reproduce an appropriate Pacific Decadal Oscillation (PDO) pattern in the 20th century. Therefore, the first step is to select models that are capable of being applied to the target regions (space) and phenomena (space and time).

To make better predictions, we should also have a comprehensive understanding of the mechanisms that link environments and ecosystem responses. However, even the environmental data are usually limited in time and space. Therefore, we recommend testing model performance by reconstructing past environments using the data assimilation method. Especially for physical models, adjoint methods can fit the model to observational data while conserving model dynamics. For example, to examine bottom-up forcing, coupled bio-physical models would be used to predict lower trophic productivity. Output from these models could be compared to observed patterns of plankton variability to assess model performance.

We cannot eliminate the uncertainties in forecasting. Uncertainties arise not only from the models but also from the scenarios. Therefore, we recommend ensemble forecasts using several models under several scenarios.

It is obvious that computer power is limited, even in the current IT era. The horizontal resolution of AOGCMs is becoming finer, but usually ¼° is the limit. One way to save the computational costs of contemporary models is to nest higher resolution regional models into coarser resolution global models. Another possibility is to run higher resolution regional models under the predicted atmospheric conditions. However, in those cases, the selection of the horizontal boundary conditions becomes an issue.

In summary, the following steps are recommended:
- verification of model performance (bias + variability);
- reconstruction of past environments by lower trophic level model simulation on the data assimilated physical model outputs;
- ensemble forecasts;
- nesting model or simple regional model run.

Request 2. *Fisheries scientists should provide reports on the current state of knowledge regarding mechanisms linking climate forcing and fish production, and the uncertainty associated with these mechanisms.*

Walleye pollock

Spawning is restricted to a very narrow area with the main spawning ground occurring in Hidaka Bay, Hokkaido. The environmental conditions of Hidaka Bay and the flow field inside and outside of the bay is the most important factor for determining recruitment (see the VENFISH special issue in *Fisheries Oceanography*, Vol. 13, Suppl. 1, 2004).

Pacific cod

The landings of Pacific cod in the Tohoku area (northern part of Honshu) have a good correlation with the recruitment of the 1+ year class. This suggests the importance of recruitment to the total biomass. A recent study by Shimizu and Narimatsu (2006) showed that sea surface temperature in June is a critical control of recruitment. The mechanism is still unclear but June is the season when the life stage of Pacific cod changes from pelagic to demersal.

Pacific herring

The abundance of herring remains low in Japan. Several local herring increases have occurred since the late 1990s. Recently Ookouchi *et al.* (2008) showed that this increase was associated with the southward shift of the Oyashio in summer.

Sardine, anchovy, jack mackerel, Pacific saury

Small pelagic species alternate with an inter-decadal time scale. The cycle changes from "sardine" to "saury and anchovy and horse mackerel" to "jack mackerel", correlating well with the PDO (Yatsu *et al.*, 2005). Takasuka *et al.* (2007) and subsequent studies simply explained this alternation by an "optimal growth temperature hypothesis". We guess this means that the larvae always meet with prey limitations, then higher temperatures decrease the growth by higher metabolism. Another possibility is predator migration dependency on temperature.

An additional important aspect of these small pelagic fish is migration. They spawn in the subtropical ocean and make feeding migrations to the subarctic region. Therefore, the transportation of larvae by the Kuroshio and migration mechanism is a key factor for their survival (*e.g.*, Ito *et al.,* 2007).

Pacific salmon

Pacific salmon utilize fresh water, coastal and open ocean habitats so the background ecosystems are totally different from each other. Therefore, we must take into account not only marine life stages but also freshwater stages (*e.g.*, Rand *et al.*, 2006). Azumaya and Ishida (2004) and Kamezawa *et al.* (2007) applied a model of Pacific salmon, and their results showed that summer conditions are most important to salmon growth.

Request 3. *Fisheries scientists should identify what physical or bio-physical drivers or environmental thresholds would be needed to forecast future fish or shellfish production. These requests should specify the location (latitude and longitude) and time period for the requested physical variable.*

Based on the mechanisms mentioned in Request 2, we declare the drivers we need to know for the following species:

Walleye pollock

- Temperature and salinity structures in Hidaka Bay and its offshore region;
- Circulation in Hidaka Bay and its offshore region with 1/108° resolution;
- Primary and secondary production in Hidaka Bay and its offshore region (krill and benthos biomass around the Hokkaido coast).

Pacific cod

- Circulation around Japan, especially the Oyashio variability with 1/12° resolution;
- Temperature and salinity structure around Japan;
- Primary and secondary production around Japan (krill and benthos biomass along the coast of Japan).

Pacific herring

- Circulation around Japan, especially the Oyashio variability with 1/12° resolution; if local stocks are considered, 1/216° resolution will be needed;
- Temperature and salinity structure around Japan;
- Sea ice distribution;
- Primary and secondary production around Japan.

Sardine, anchovy, jack mackerel, Pacific saury

- Circulation around Japan, especially the Kuroshio variability with 1/12° resolution; if fluctuations in spawning grounds are considered, 1/108° resolution will be needed;
- Temperature and salinity structure around Japan;
- Primary and secondary production around Japan;
- For saury, circulation, T, S, production are needed for the Pacific Basin;
- Predator index;
- Migration index.

Chum salmon

- Circulation in the North Pacific including coastal areas with 1/108° resolution; if local stocks are considered, 1/216° resolution will be needed;
- Temperature and salinity structure in the North Pacific;
- Sea ice distribution;
- Primary and secondary production in the North Pacific;
- Freshwater systems (lakes, ponds, rivers).

Russian fish production in the Japan/East Sea

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The recent commercial fishery in the Russian sector of the Japan/East Sea (JES) is based on two fish species: Japanese sardine, *Sardinops melanostictus,* and walleye pollock, *Theragra chalcograma*, with landings exceeding 10,000 tonnes/year. The catches of other pelagic and groundfish species such as mackerels, herring, flounders, salmon, greenlings, cod, and smelts, as well as bottom invertebrates are considerably lower (although valuable for some crabs, shrimps, and sea urchins). Russian fisheries for Pacific saury and squids are almost absent in the JES, in spite of their high abundance. Annual catches of both sardine and pollock fluctuate greatly (Fig. 2.11), due mainly to variability in environmental conditions.

Japanese sardine

Fluctuations of the sardine stock and catch in the JES are synchronous with the stock and catch fluctuations in the Pacific Ocean, and have a decadal scale. Both "sardine disasters" in the 20th century were initiated by climate shifts but the directions of environmental changes were opposite. The early 1940s were characterized by ocean cooling, but the more recent cooling in the early 1990s occurred after ocean temperatures increased. The apparent contradiction becomes clear under the match-mismatch hypothesis (Cushing, 1972) and its relevance to larval survival. The sardine has a very early (in late winter) spawn timing in the southeastern JES, with timing dependent on winter temperatures. The spring bloom in these spawning grounds also begins very early (in early spring) but its timing depends on spring temperature conditions. So, to match the larval hatch with the spring bloom, a thermal regime should be stable, as occurs with a warm-spring-after-warm-winter or cold-spring-after-cold-winter. The former was observed in the 1930s and the last one occurred in the late 1970s–1980s. Stability was disrupted by sudden winter warming in the late 1980s, causing a mismatch of timing, and consequently, low survival of the sardine larvae.

Sardine reproduction is also determined by parental stock value (adults in the range of age from 3+ to 6+), individual fecundity, and population density. Moreover, the adult survival rate is important. Therefore, the commercial stock of this species in year *j* can be roughly estimated by the following multiple regressive model:
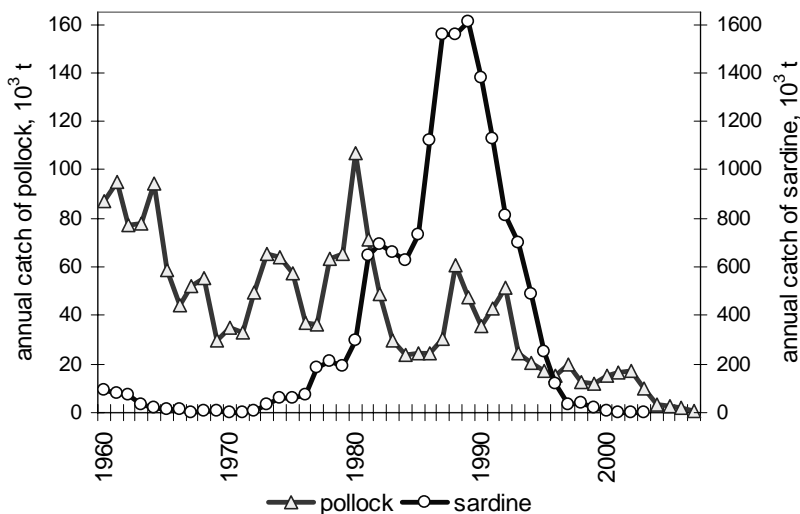
Fig. 2.11   Annual all-nation catch of Japanese sardine and Russian catch of walleye pollock in the JES.

$$S_j = \sum_{i=3}^{6} \left[S_{j-i} \cdot \left(f - k_M M_{j-i} - k_D S_{j-i} \right) \cdot s^i \right],$$

where f is a fecundity parameter, M is the match-mismatch factor ($M = 0$ in the case of stable winter–spring sea surface temperature (SST anomalies), s is the annual adult survival, and k_M, k_D are empirical coefficients. This model generates stock abundance forecasts for at least 3 years in advance. To predict the climate change consequences, we need to couple the model with long-term forecasts of SST.

Walleye pollock

Walleye pollock is a long-lived species so its stock is made up of several generations. That is why its

catch does not respond clearly to climate changes. However, the relative abundance of cohorts does. Year-to-year fluctuations have a strong correlation with zooplankton biomass in the spawning grounds during spring–summer when the pollock larvae and fingerlings develop (Fig. 2.12). Zooplankton abundance in the JES depends on thermal conditions in the subsurface and intermediate layers where large-sized adult copepods have their dormancy and maturation.

On decadal scales, cohort abundance is negatively correlated with the thermal regime (Fig. 2.13), in spite of the positive correlation between the subsurface temperature and zooplankton.
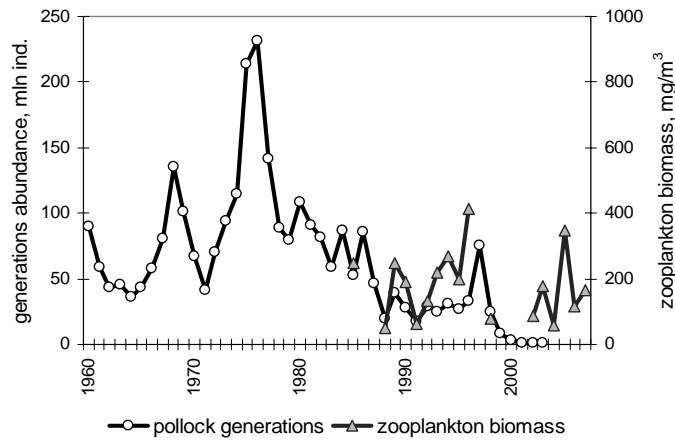
Fig. 2.12 Interannual variation of walleye pollock cohort abundance in the northwestern JES. In the last two decades abundance was correlated positively with zooplankton biomass in the main spawning grounds in Peter the Great Bay (no zooplankton data for early years).
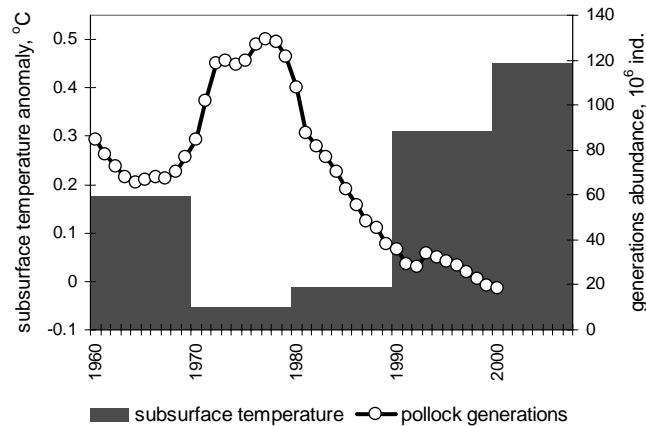
Fig. 2.13 Decadal-scale changes of walleye pollock abundance in the northwestern JES (9-year running mean smoothing) in relation to mean decadal temperature anomalies in the thermocline–200 m layer on the section 41°30′–42°20′ N, 132°00′ E.

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These statistical links are explained by simple ecological mechanisms: (i) the larvae mortality dependence on prey abundance and (ii) appearance–disappearance of competitive warm-water species (sardine or common squid) on the biogeographic boundary where Peter the Great Bay is situated. Thus, these links could be used for pollock stock and catch forecasting with lead times of up to 3 years. Long-range forecasts are available on the basis of subsurface temperature predictions.

Forecasting of environmental factors important for fish populations

An Intermediate Water mass is formed in the JES at the Polar (Subarctic) Front in winter, and its temperature is determined by winter SST. The spreading of this water is a mechanism to transfer climate change impacts into the subsurface and intermediate layers of the JES, which are so important for zooplankton and walleye pollock. We suppose that this spreading has an anticyclonic route, and estimate that the transfer time of the impacts from the sea surface to the subsurface layer is 0–3 years (the maximal delay is observed in the northwestern part of the JES).

Winter SST in the JES is strongly correlated (negatively) with the development of the Siberian High: lower air temperatures arise from higher atmospheric pressures in Siberia, which create strong winter monsoon winds and lower SSTs (Fig. 2.14).

Thus, the consequences of climate change for SST, subsurface temperature, and zooplankton abundance could be modeled using significant statistical links, at least until the system works. Temporal lags between climate shifts and zooplankton responses can be as long as 5–6 years, mainly because of the time taken for Intermediate Water to be transported to the most distant areas of the JES.

Spatial and temporal scales of environmental variables useful for fish production forecasting

The location and time period of physical predictors for fish production forecasting are determined by the mechanisms of influence and are presented in Table 2.10. In as much as some populations depend on prey abundance, zooplankton biomass is included as one of the subjects for forecasting.
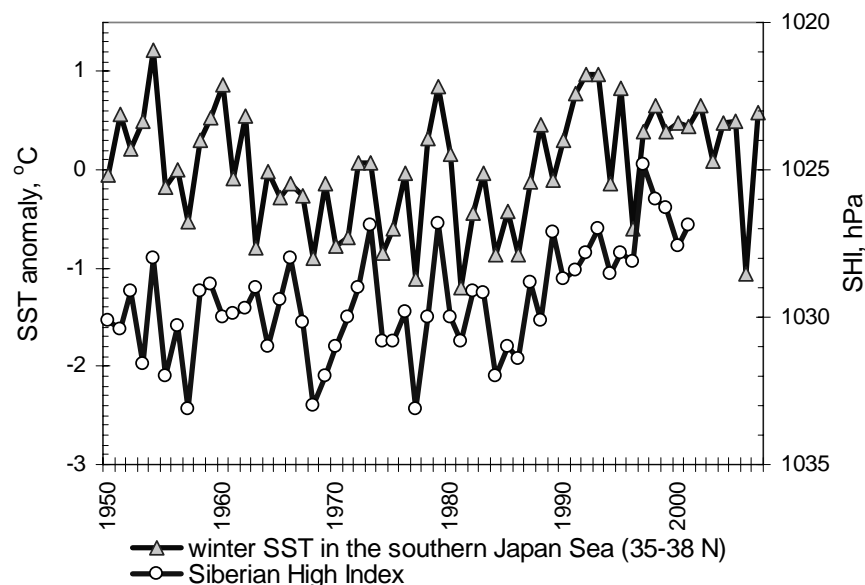
Fig. 2.14 Siberian High Index (mean surface pressure in the area 40–65°N, 80–120°E in December–February, after Panagiotopoulos *et al.*, 2005) and winter SST anomalies in the southern JES relative to 1970–2000 (JMA data averaged within 35–38°N for December–February).

Table 2.10   Proposed mechanisms underlying fish production in the JES and their spatio-temporal scales.

Species, group	Index	Mechanism	Season	Location
Japanese sardine	SST	Match/mismatch of larvae and spring bloom	Winter–Spring	Spawning grounds in the southeastern JES
Walleye pollock	Zooplankton biomass; subsurface temperature	1) Survival of larvae and fingerlings dependent on prey ability, 2) Competition with warm-water species.	• Spring–Summer, • The whole life span.	• Spawning grounds at Primorye and Hamgen coasts, • The whole northern and central JES.
Pacific saury	Zooplankton biomass; subsurface temperature	Survival of larvae and fingerlings dependent on prey ability	Spring–Summer	Wide spawning area in the coastal areas of southern and central JES
Arabesque greenling	SST	Unclear, possibly related to larvae survival	Winter	Peter the Great Bay
Saffron cod	SST; Siberian High Index; ice cover	Spawning duration depended on ice cover period	Winter	Coastal areas of Peter the Great Bay
Zooplankton biomass in deep-water areas (mostly large cold-water copepods)	Subsurface temperature	Optimal window for maturation in the period of dormancy	Summer–Fall–Winter	Deep-water areas
Zooplankton biomass in the coastal zone (mostly copepods)	Winds at Primorye coast; NPI	Wind-induced advection into coastal zone	Spring, Summer, Fall (depending on species)	Primorye shelf

SST – sea surface temperature, JES – Japan/East Sea, NPI – North Pacific Index

Chum salmon (*Oncorhynchus keta*) production in Korea

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Biology

Chum salmon (*Oncorhynchus keta*) are distributed widely across the North Pacific Ocean and in the Bering Sea, generally north of about 40–45°N latitude (Salo, 1991). Chum salmon production in Korea hinges on the release of fry salmon from hatcheries. The released fishes are thought to migrate from coastal areas to the Bering Sea and subarctic North Pacific (Fig. 2.15). Release of fingerlings by artificial stocking programs occurs annually from mid-February to late March. There is very little information about the ocean distribution and migration of Korean chum salmon in the North Pacific Ocean, but for now we assume that it is similar to that of chum salmon from Japanese hatcheries that are released from western Honshu and western Hokkaido. The juveniles remain in the Okhotsk Sea from summer to late autumn and overwinter in the western North Pacific Ocean, and the immature salmon (age 2 to 5) then migrate back and forth between the Bering Sea and the North Pacific seasonally (Azumaya and Ishida, 2001; Urawa *et al.*, 2001). Spawning adults return to their natal rivers on the Korean Peninsula between mid-September and mid-December. Main diets of chum salmon caught from the Subarctic Current and Alaskan Gyre areas consist of zooplankton such as copepods, pteropods, amphipods, euphausiids, and jellyfish (Kaeriyama *et al.*, 2004).

Fishery

Escapement of chum salmon to Korean streams was very poor until the late 1980s. Since 1990, catches from the set net fisheries were included in these statistics so that an abrupt increase appears in 1990 (Fig. 2.16). The proportion of salmon catch by set net fisheries in total catch was about 70~80% for the 1990s and decreased to 50~70% in the 2000s. Salmon catch was seriously reduced from 553 million t in 1997 to 51 million t in 2000. It increased slightly in 2002 though it was still less than 200 million t.
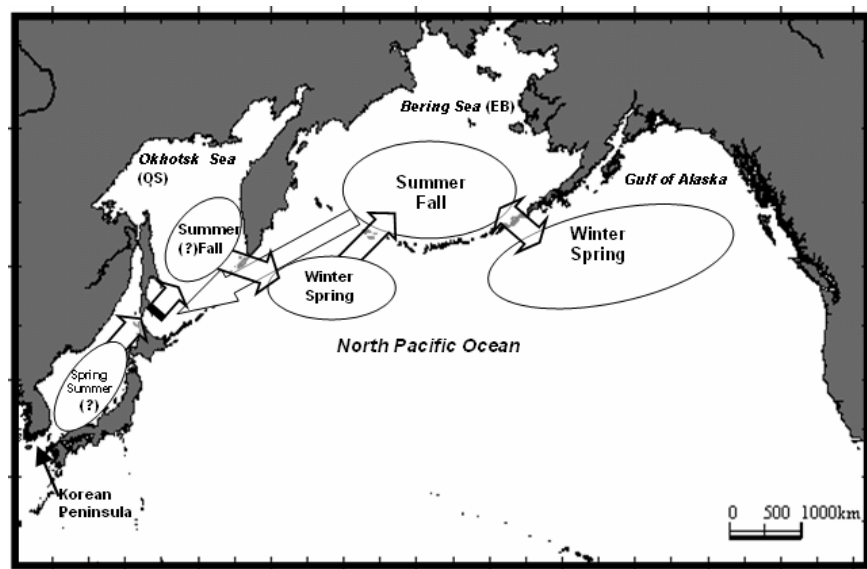

Fig. 2.15 Schematic migration model of chum salmon released in Korea (modified from Urawa *et al.*, 2001) (Seo *et al.*, 2006).
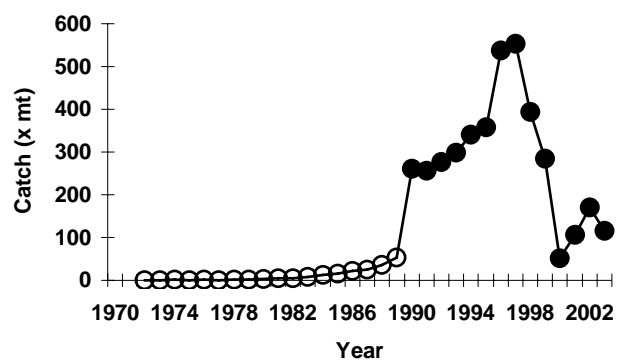
Fig. 2.16 Annual catches of chum salmon in Korean waters, 1991–2003. Open circles represent the catch in Korean rivers. Dark circles mean total catch from rivers and the set net fishery.
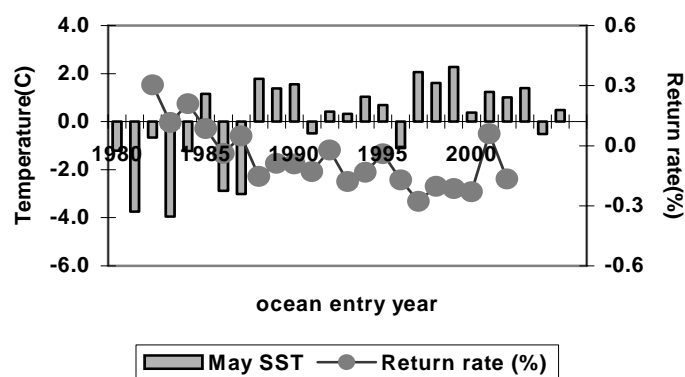
Fig. 2.17 Interannual variability in water temperature at river mouths and the return rate to Namdae-cheon, a major release site in Korea.

Year
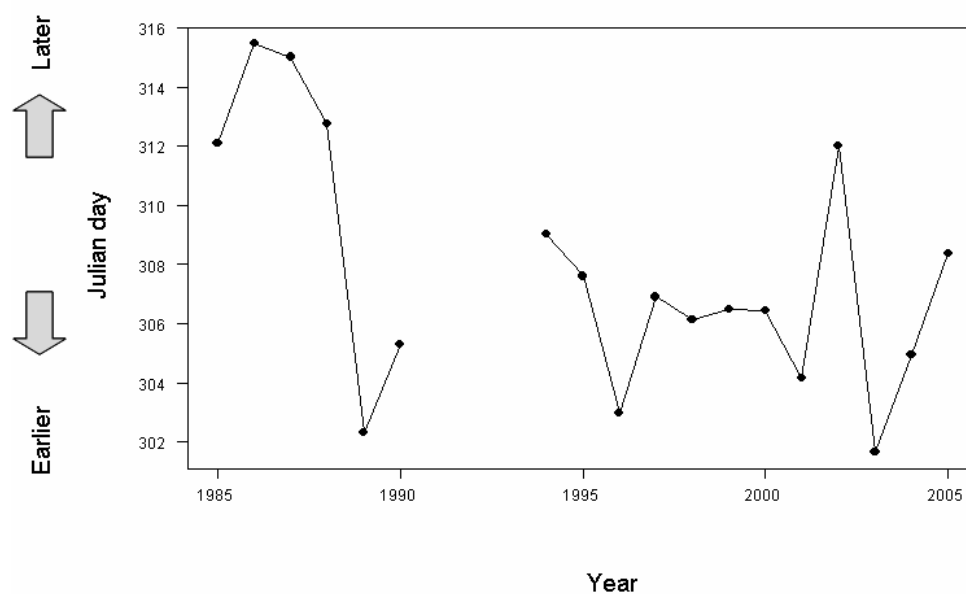
Fig. 2.18 Interannual variation in return timing of Korean chum salmon.

Climate and ocean effects

The return rates of chum salmon to Korean waters were less than 0.4% for the broods released in the mid- and late 1980s, but escapement increased after the set net fishery was allowed in 1990. Return rates ranged from 1.0 to 1.5% and suddenly dropped to 0.1% for the 1997 brood stock which is still struggling to recover. The return rate has a negative correlation with the mean water temperature of the coastal waters in April and May ($r = -0.485$, $p < 0.05$ in April; $r = -0.599$, $p < 0.01$ in May) (Fig. 2.17). High water temperature after late April could affect the survival of juvenile chum salmon and might be a reason for their mass mortality. Maturing chum salmon returned in mid-November in the 1980s, in early November and/or in late October in the 1990s and in 2000s. The return timing in 2003 was almost 2 weeks earlier than in the 1980s (Fig. 2.18). Zooplankton biomass in the coastal waters of Korea in the year of release was not correlated with the return rate of Korean chum salmon. However, early growth of chum salmon did correspond with trends of zooplankton biomass. In river mouths and coastal areas, growth rates of fingerling salmon were higher in the 1990s than in the 1980s. On the east coast of Korea, zooplankton abundance increased after the late 1980s, which may have caused favorable growth conditions for young salmon in the 1990s (Seo *et al.*, 2006). They reported that food availability is more important than seawater temperature in chum salmon growth in the North Pacific, although it is not easy to decouple the effects of these factors on fish growth.

Jack mackerel (*Trachurus japonicus*) production in Korea

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Biology

Jack mackerel (*Trachurus japonicus*) migrate to the northern area of the East China Sea during January–March, and to the spawning grounds near the western Kyushu Islands and areas between Jeju Island and Tsushima Island during April–May (Lee, 1970; Nakashima, 1982). Jack mackerel spawn in water temperatures from 16° to 22°C. In the East China Sea, jack mackerel larvae are mainly distributed in the Kuroshio frontal area along the continental margin in winter and spring. They usually feed on zooplankton, including the larvae of anchovy (*Engraulis japonicus, E. mordax*) and bigeye sardine (*Etrumeus teres*). As the fish grow older, they move to deeper water and feed on larger prey such as Amphipoda and Mysidacea, but usually not Copepoda (Cha, 1991).

There is evidence that the recruitment of jack mackerel is determined by the degree to which eggs and larvae are affected by environmental factors. These include seawater temperature, salinity, volume transport of the Kuroshio Current, and zooplankton biomass in the Korean waters (Zhang and Lee, 2001). Increases in salinity in April, volume transport of the Kuroshio Current, and zooplankton biomass were significantly correlated with increased recruitment of jack mackerel in the following year (Table 2.11).

Fishery

Jack mackerel are found throughout the Yellow Sea, the East China Sea, and the southern East/Japan Sea (Kim, 1970). They are caught with large purse seines, bottom trawls, and drift gill nets in Korean waters. About 80% of the total catches are from the large purse seine fishery, mostly in the Korean region of the East China Sea. The history of catches is characterized by a cyclic behavior at a relatively low frequency (30 years) with a high coefficient of variation (CV = 0.74). Annual catch reached the highest level of 48 thousand t in 1956, and then declined below 10 thousand t in the late 1960s. In the early 1980s, the annual catch increased and it has been about 28 thousand t in recent years, 2002–2006 (Fig. 2.19).

Climate and ocean effects

The volume transport of the Kuroshio increased after 1977. This intensified the Tsushima Warm Current connected with the Kuroshio in the inshore waters of southern Korea. Warm saline waters have a positive correlation with the density of jack mackerel distribution (Cho, 1981). Therefore, the increase in salinity of the East China Sea may have triggered the increases in recruitment and biomass of jack mackerel in the early 1980s, resulting in the

Table 2.11   Correlation coefficient matrix between recruitment of jack mackerel and environmental factors (Zhang and Lee, 2001).

|	Recruitment	Temperature	Salinity	Volume transport	Zooplankton biomass
Recruitment	1.000	–	–	–	–
Temperature	0.043	1.000	–	–	–
Salinity	0.529*	0.153	1.000	–	–
Volume transport	0.487*	– 0.264	0.230	1.000	–
Zooplankton biomass	0.547*	– 0.288	0.248	0.399**	1.000

* $P < 0.01$, ** $P < 0.05$
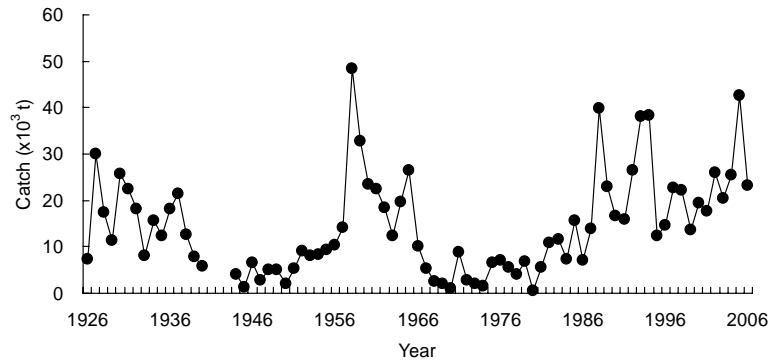
Fig. 2.19 Annual catches of jack mackerel in Korean waters, 1926–2006.
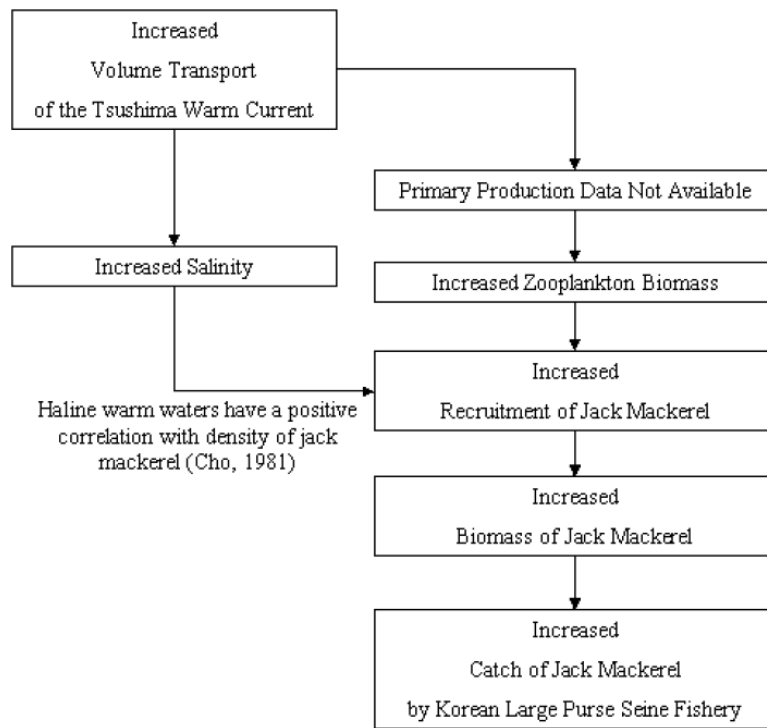
Fig. 2.20 Diagram showing the effects of the early 1980s environmental shift of the jack mackerel population based on the bottom-up hypothesis (Zhang and Lee, 2001).

increased fish catches. The effects of the early 1980s environmental shift are hypothesized to have affected the productivity of the jack mackerel population (Fig. 2.20). As the volume transport of the Tsushima Warm Current increases, resulting in higher salinity in the East China Sea, spawning grounds for jack mackerel become optimal. Consequently, high concentrations of the spawning stock were observed in this area. As the intensity of the Tsushima Warm Current increased, the variation

of zooplankton biomass in the Korean waters of the East China Sea was expected to correspond to the variation in the stratification of the ocean. Since the thermocline in the East China Sea is formed at 30–50 m depth, and the water is relatively shallow (75–150 m) (NFRDI, 2005) where photosynthesis can be active in all seasons, the increase in zooplankton biomass may not be directly related to the primary production in the early 1980s in the Korean waters of the East China Sea. The increase of recruitment and

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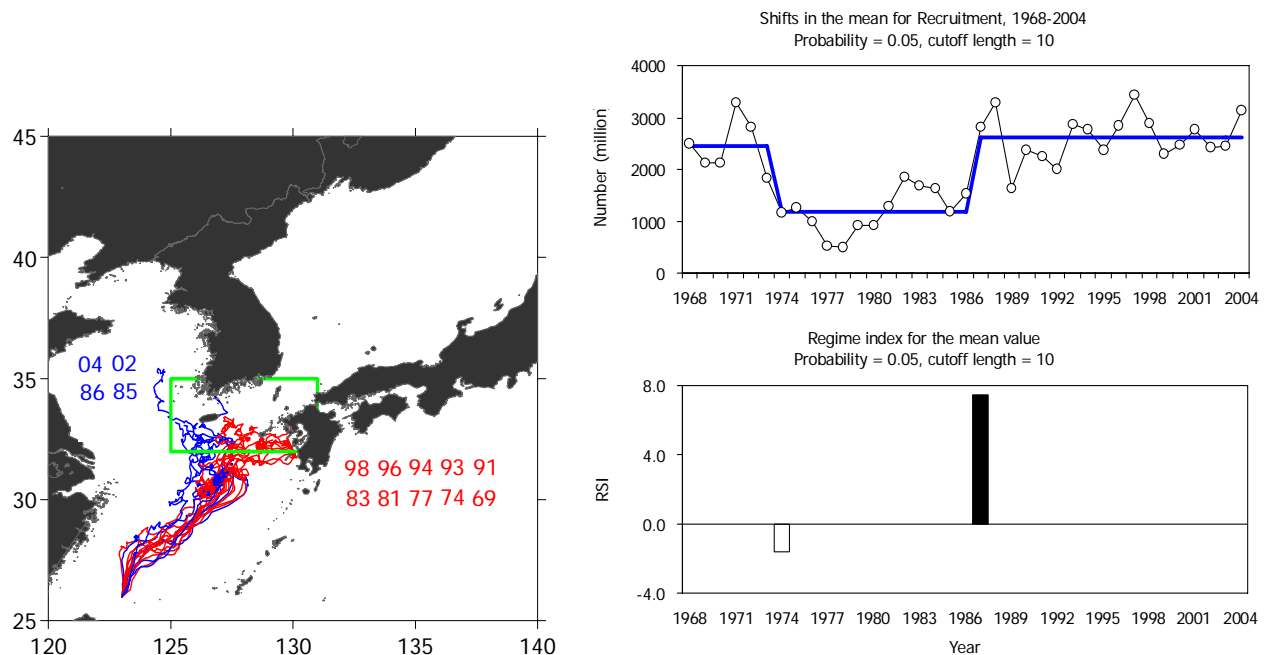
Fig. 2.21 Ocean surface currents from spawning ground (rectangle) in the East China Sea (left) and variation in recruitment of jack mackerel (right) in Korean waters, 1968–2004 (Lee, 2005).

biomass in plankton-feeding jack mackerel stock after the early 1980s can be attributed to the aggregation of spawning stock and the increase of prey organisms in the East China Sea (Zhang and Lee, 2001). Jack mackerel share 63.4% of their habitat with chub mackerel in Korean waters (Zhang and Lee, 2001). Jack mackerel share 36.6% of their habitat with both chub mackerel and Japanese sardine, and further, they were not found to co-exist with Japanese sardine exclusively during the period of 1980–1998 (Fig. 2.19). The 1988 climatic regime shift affected the habitat of jack mackerel by shifting their distribution southward to 27°N. After 1988, the distributional overlap of jack mackerel and chub mackerel decreased. These shifts in the habitats of both species resulted in Pacific sardine occupying a habitat area separated from the shared mackerel distributions (Zhang *et al.*, 2004).

An important discovery in Korean fisheries oceanography in recent years is the realization that climate variability, at the scale of decades, may have a direct effect on the productivity of winter spawning jack mackerel (Fig. 2.21). The mechanism under consideration is the advection/dispersal of larvae to favorable nearshore nursery habitats.

To better understand the variability in the transport of larvae to these favorable areas, an understanding and description of the following physical oceanographic variables are needed:

- Springtime winds over the southern East China Sea from February–June. Future winds from IPCC models have been provided by Dr. Nicholas Bond.
- Springtime currents (February–June) from about 50 m depth to the surface for the same areas as described above. Starting points should vary about 26°N latitude and 123°E longitude.

Recruitment is related to successful settlement in nursery grounds transported by the Kuroshio. Within a "touchdown zone" where larval jack mackerel settle out of the planktonic larval stage within 32°–35°N and 125°–131°E, environment data needed are:

- temperatures and salinities at the surface and 50 m layer depth,
- zooplankton biomass during April–June,
- number of days of ocean current trajectory within the zone during April–June.

Possible impacts of changing climate on jack mackerel are listed in Table 2.14.

Chub mackerel (*Scomber japonicus*) production in Korea

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Biology

Chub mackerel (*Scomber japonicus*) that migrate throughout the warm water are widely distributed and caught in the western, southern, and southeastern seas around the Korean peninsula, in the East China Sea, and around Japan. This species is distributed on the continental shelf from the surface to 300 m depth in the Yellow Sea and the East China Sea (Fig. 2.22). Chub mackerel spawn from February to May when the water temperature ranges from 15° to 23°C, and migrate to wintering grounds between Jeju Island and Tsushima Island in the East China Sea during December–February. The fecundity of chub mackerel ranges from 112,000 to 570,000 eggs, and the fork length of 50% mature females is 28.7 cm (Choi, 2003).

Mean length of chub mackerel has tended to decrease since the 1970s, and the proportion of small mackerel has increased (Fig. 2.23). The fork length was about 32 cm in the early 1970s, but it has continuously decreased, with a mean fork length in 2002 of 29.2 cm. Some biological parameters such as natural mortality, maturity length, and recruitment age have been estimated (Table 2.12).
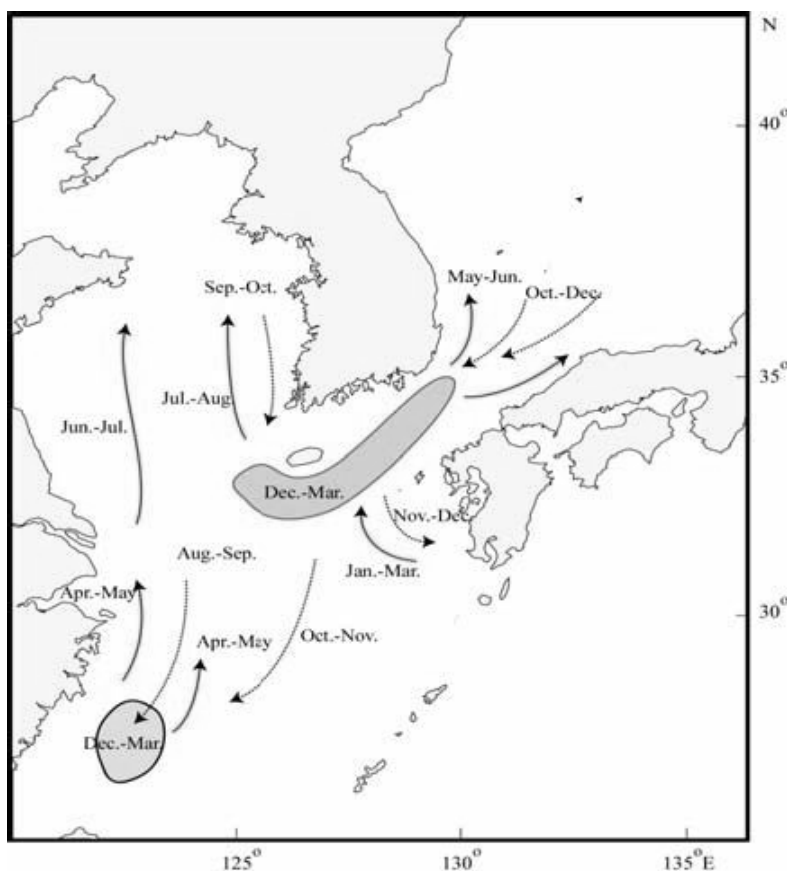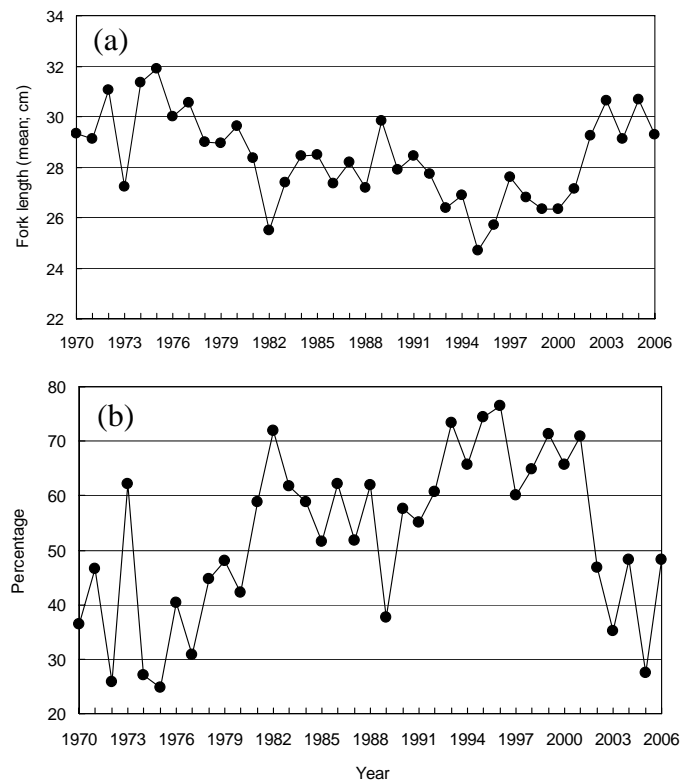

Fig. 2.22   Seasonal migration route of chub mackerel near the Korean Peninsula.

Table 2.12   Estimated biological parameters of chub mackerel.

Parameter	Estimate	Unit
Natural mortality	0.6	year^{-1}
Maturity length (50%)	24.0	fork length, cm
Recruitment age	0.5	year
Mean length (2006)	29.3	fork length, cm
Mean age (2006)	2	year

Fig. 2.23   (a) Long-term variation of mean length of captured chub mackerel, and (b) percentage of fish smaller than the 50% maturity length to the total catch of chub mackerel from Korean waters, 1970–2006.
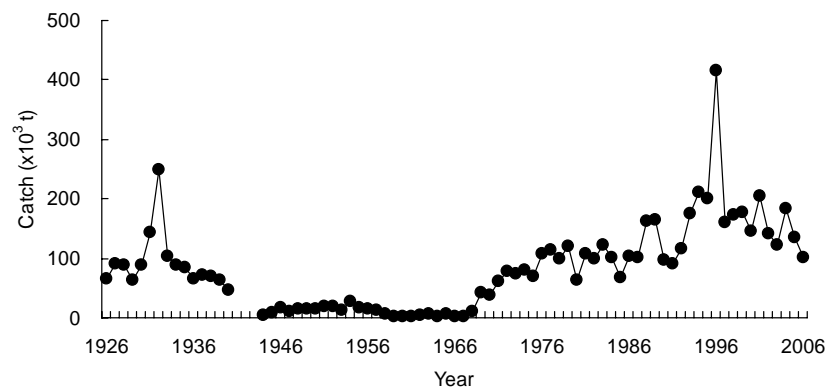
Fig. 2.24   Annual catches of chub mackerel in Korean waters, 1926–2006.

Fishery

About 70–80% of the global catch of chub mackerel by countries, including Korea, Japan, and China, occurs in the northwestern Pacific Ocean (FAO, 2002). Korean annual catches were below 100 thousand t until the mid-1980s, and increased to 150 thousand t in 1988 and 1989 (Fig. 2.24). The annual catch was just 100 thousand t in the early 1990s. However, it started to increase to over 150 thousand t from the mid-1990s and reached the highest level of 415 thousand t in 1996. Currently, the catch is about 170 thousand t. This species is usually caught by large purse seines, drift gill nets, and set nets in Korean waters. About 90% of total chub mackerel catches are from the large purse seine fishery, mainly in the East China Sea and in the western and southeastern seas of Korea.

Climate and ocean effects

Recruitment is correlated with salinity (r = 0.454, P < 0.05), with zooplankton biomass (r = 0.692, P < 0.01), and with copepod biomass (r = 0.815, P < 0.01) (Choi *et al.*, 2000). Chub mackerel catches were highly correlated with sea surface temperature (SST) in December, Chl-*a* in June, and large zooplankton in the fall and early winter (Table 2.13).

Chub mackerel share 35.7% of their habitat with both jack mackerel and Pacific sardine, and 28.6% with jack mackerel or 3.1% with Pacific sardine in Korean waters (Zhang *et al.*, 2004).
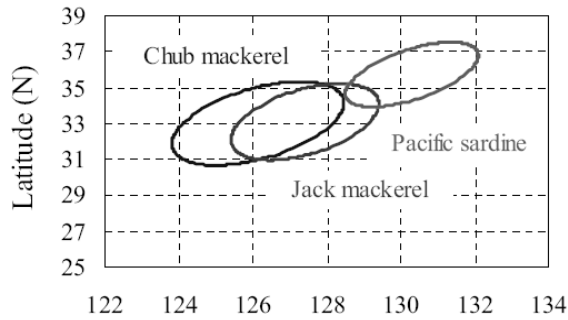
The 1988 climatic regime shift affected the habitat of chub mackerel by widening and moving it to the west of 128°E (Fig. 2.25). After 1988, the distributional overlap of chub mackerel and jack mackerel decreased. These shifts in the habitats of jack mackerel and chub mackerel resulted in Japanese sardine occupying a habitat area separated from the shared mackerel distributions. Replacement in biomass between chub mackerel and Japanese sardine stocks came from the continuous competition of prey and space among major small pelagics in Korean waters (Zhang *et al.*, 2000).

Table 2.13 Selected correlation coefficients, which were statistically significant for fish catch vs. their biotic and abiotic environmental factors (Kim and Kang, 2000).

Variable	Anchovy *Engraulis japonica*	Mackerel *Scomber japonicus*	Sardine *Sardinops melanosticta*
Anchovy	1.0	0.790[**]	0.453[*]
Mackerel	0.790[**]	1.0	0.602[**]
Sardine	0.453[*]	0.602[**]	1.0
SST (December)	0.419[*]	0.436[*]	0.327
Chl-*a* (April)	0.186	0.019	0.561[**]
Chl-*a* (June)	0.635[**]	0.523[**]	0.264
Chl-*a* (August)	0.442[*]	0.377	0.276
Zooplankton (February)	− 0.559[**]	− 0.406[*]	− 0.339
Zooplankton (April)	− 0.304	− 0.408[*]	− 0.291
Copepods (April)	0.563[*]	0.434	− 0.398
Copepods (June)	0.121	0.571[*]	− 0.042
Copepods (December)	0.635[*]	0.477	− 0.277
Chaetognaths (April)	0.647[**]	0.307	− 0.499
Chaetognaths (October)	0.728[**]	0.512[*]	− 0.321
Chaetognaths (December)	0.558[*]	0.129	− 0.427
Euphausiids (June)	0.349	0.356	− 0.550[*]
Euphausiids (December)	0.768[**]	0.603[*]	− 0.492
Amphipods (April)	0.713[**]	0.504[*]	− 0.395
Amphipods (December)	0.712[**]	0.616[*]	− 0.423

Sampling month in parenthesis; * indicates that the correlation is significant at the 0.05 level, and ** at the 0.01 level.

(a) 1980-1988

(b) 1989-1998
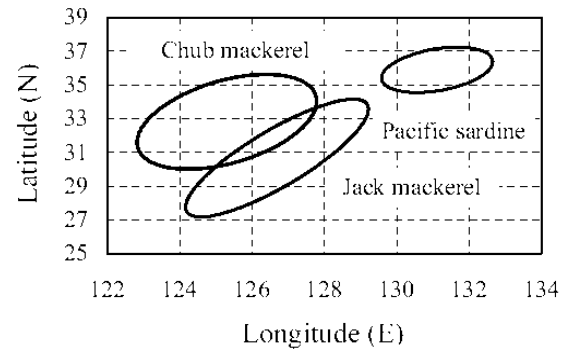
Fig. 2.25 Joint confidence regions in the habitat of major small pelagics in Korean waters during the periods of (a) pre- and (b) post-1988 climatic regime shift (Zhang *et al.*, 2004).

Table 2.14 Potential impacts of climate changes on the population ecology of mackerels in Korean waters.

Species	Impact factor	Impacts of climate and ocean condition
Chub mackerel	• Seawater temperature, Kuroshio/Tsushima Warm Current, • Phytoplankton bloom, • Zooplankton biomass	Chub mackerel abundances increased in the mid-1990s, a period of high SST in December due to ENSO seemed to cause high growth and good year classes in Korean waters (Kim and Kang, 2000; Zhang *et al.*, 2004).
Jack mackerel	• Kuroshio/Tsushima Warm Current, • SST, • Phytoplankton bloom, • Zooplankton biomass	As the Kuroshio transports eggs and larvae of jack mackerel to the fishing grounds, recruitment of jack mackerel increased. Increase in zooplankton biomass contributed to increase in spawning biomass of jack mackerel (Lee, 2005; Zhang *et al.*, 2004).

The possible impacts of global warming and a changing climate on mackerels are listed in Table 2.14. In general, these fishes will be influenced by seawater temperature and the Kuroshio/Tsushima Warm Current in Korean waters.

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