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Report of the ESSAS Workshop

Development of Methods for Comparisons of the Sub-Arctic Seas

St. Petersburg, Russia

12-14 June 2006

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Table of Contents

1. Background

The purpose of the ESSAS Workshop held in St. Petersberg on the 12-14 June, 2006 was to explore how fruitful approaches for comparative studies Sub-Arctic marine ecosystems might be developed. To this end, four regions were selected for the first set of comparisons: two from the Pacific (the Okhotsk Sea/Oyashio region and the Bering Sea), and two from the Atlantic (Newfoundland/Labrador Shelf and the Barents Sea). These four regions included areas with currents both to and from the Arctic and those with marginal ice zones at quite low and rather high latitudes. Twenty-seven scientists from 6 nations (Canada, Greenland, Japan, Norway, Russia and the USA) attended. The workshop was co-sponsored by the International Project Office of GLOBEC and by PICES, both of whom contributed travel funds, while the latter also arranged and provided logistic support at the meeting. The local host was the State Scientific and Projecting Institute "Giprorybflot."

Many of the synthesis products available to date have provided excellent compendia of information about a particular sub-arctic ocean basin, but few have explicitly compared mechanisms and responses to climate forcing across basins or between Atlantic and Pacific systems. If the comparative method is to be used successfully, it will be necessary to identify important underlying structuring features of the ecosystems and how climate forcing, acting on those mechanisms, will result in ecosystem change. It will also be necessary to develop data sets that can be used in predictive modeling efforts. These data sets will have to be sufficiently closely aligned that inter-regional comparisons will be fruitful. Although all systems are unique, there must be a search for basic elements common to many, if not all, that can be usefully employed in a comparative approach.

The participants in the ESSAS St. Petersburg Workshop reviewed syntheses of North Pacific data sets and comparisons with data from North Atlantic system and provided a framework for the development of revisions and updating of the first version of the PICES North Pacific Ecosystem Status Report. The Workshop built upon extant syntheses and on-going and planned synthesis efforts. Additionally, papers such as those by Aydin et al. (2002) examining the similarities and differences between the eastern and western Bering Sea, Hunt and Megrey's (2005) comparison of the Bering and Barents Sea ecosystems, and the recent work by Ciannelli et al. (2005) comparing the Barents Sea and the Gulf of Alaska systems provide a solid basis for moving forward with the analyses of these ecosystems. The workshop also took advantage of advances made in the January 2006 PICES CFAME workshop on developing indices for North Pacific comparisons, and the results of workshops in the Norwegian funded program, Norway-Canada Comparisons of Marine Ecosystems (NORCAN), held in the autumn of 2005 and the late spring of 2006. The NORCAN workshops will develop specific plans for comparisons between the Barents Sea and the Labrador Shelf, including the use of biophysical models, and will initiate research on physical forcing, zooplankton dynamics and climate impacts on fish populations in these sub-arctic seas.

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Ciannelli L., Hjermann D.Ø., Lehodey P., Ottersen G., Duffy-Anderson J.T.and N.C. Stenseth. (2005) Climate forcing, food web structure andcommunity dynamics in pelagic marine ecosystems. Invited chapter in:'Aquatic Food Webs: an ecosystem approach'. Belgrano A., Scharler U.,Dunne J., and R. Ulanowicz (Editors). Oxford University Press. Pp 143-169.

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2. Goals

The goals of the workshop were:
1) To lay the groundwork for developing the data sets needed to achieve the appropriate comparisons by:
    a) Outlining fruitful approaches to assess which processes, mechanisms, or aspects of populations are most sensitive to the expected changes in physical forcing that will result from climate change.
    b) Developing methodologies for comparing responses of the different Sub-Arctic seas to climate variability. Do similar changes in climate cause similar responses in all of the Sub-Arctic seas?
2) To commence developing the teams necessary to synthesize available data and develop models for predicting the effects of climate variability on these ecosystems;
3) To examine how future editions of the PICES Special Publication, "*Marine Ecosystems of the North Pacific*", might be augmented to facilitate comparative studies within the North Pacific and between the Pacific and Atlantic regions.

3. Reports Presented

To familiarize the participants from the different regions with the climate forcing and ecosystem responses from all of the regions, the Workshop began with two general reviews, one on atmospheric forcing and another on ocean circulation modelling. These were followed by regional reviews of the four Sub-Arctic regions.

3.1. General Reviews

Comparison of Atmospheric Forcing in Four Sub-Arctic Seas

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A comparative analysis was conducted on the climate variability in four sub-arctic seas: the Sea of Okhotsk, the Bering Sea shelf, the Labrador Sea, and the Barents Sea. The focus was on air-sea interactions, which influence ice cover, ocean currents, mixing, and stratification on sub-seasonal to decadal time scales, based on data from the NCEP/NCAR reanalysis. The magnitude of the seasonal cycle of the areal averaged sea level pressure (SLP), surface air temperature (SAT) and heat fluxes show remarkable similarity among the four sub-arctic seas (Fig. 1). With respect to variation in climate, all four seas experience changes of comparable magnitude on interannual to interdecadal time scales, but with different timing. In the last few years, warm SAT anomalies are found during most of the year in three of the four sub-arctic seas, excluding the Sea of Okhotsk. A seesaw (out of phase) pattern in winter SAT anomalies between Labrador and Barents Sea in the Atlantic sector is observed during the 50 years before 2000, a similar type of co-variability between Okhotsk Sea and the eastern Bering Shelf in the Pacific is only evident since the 1970s. Recent positive anomalies of net heat flux are more prominent in winter and spring in the Pacific sectors, and in summer in the Atlantic sectors. There is a reduced magnitude in wind mixing in the Okhotsk Sea since 1980, in the Barents Sea since 2000, and in early spring/late winter in the eastern Bering Shelf since 1995.
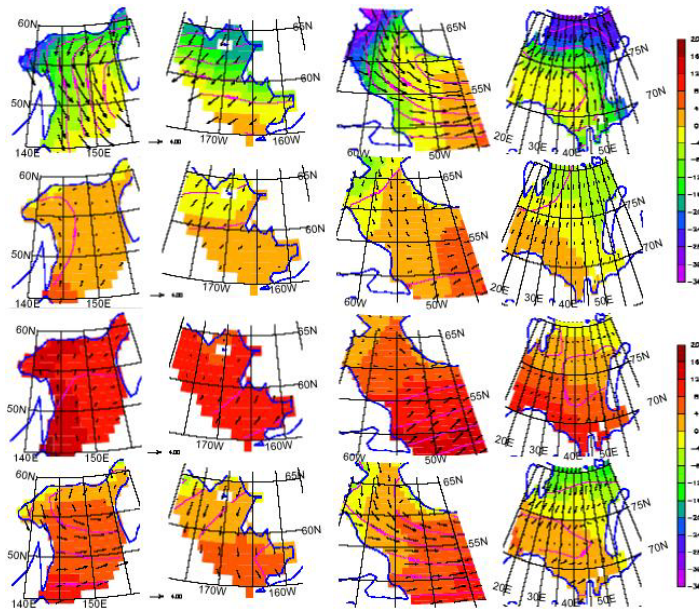
Fig. 1. The climatology of surface air temperature (shaded), SLP (contour) and surface wind (vectors) for selected months over each of the sub-arctic seas. Contour interval is 2 hPa for SLP. From left to right it is for Okhotsk Sea, eastern Bering Sea shelf, Labrador Sea, and Barents Sea. From top down, it is for Winter (Jan), Spring (May), Summer (Aug), and Fall (Oct).

Overview of ocean circulation patterns and modeling

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The Naval Postgraduate School (NPS) coupled sea ice-ocean model is an example of a general circulation model (GCM), which could be employed for ESSAS studies to provide physical background on ocean and sea ice conditions and to facilitate description, inter-comparison, and synthesis of multiple ecosystems of the northern high latitudes (Fig. 2). The regional model domain is large enough to include all the northern hemisphere sea ice covered oceans and seas. It contains the sub-Arctic North Pacific (including the Sea of Japan and the Sea of Okhotsk) and North Atlantic (including the Labrador Sea and Gulf of St. Lawrence) oceans, the Arctic Ocean, the Canadian Arctic Archipelago (CAA) and the Nordic Seas. However, the model grid is configured at relatively high resolution, i.e. 1/12° (or ~9 km) and 45 vertical depth layers with 8 levels in the upper 50 m. This horizontal grid permits calculation of flow through the narrow and / or shallow passages common and critical to sub-polar marginal sea ecosystems.
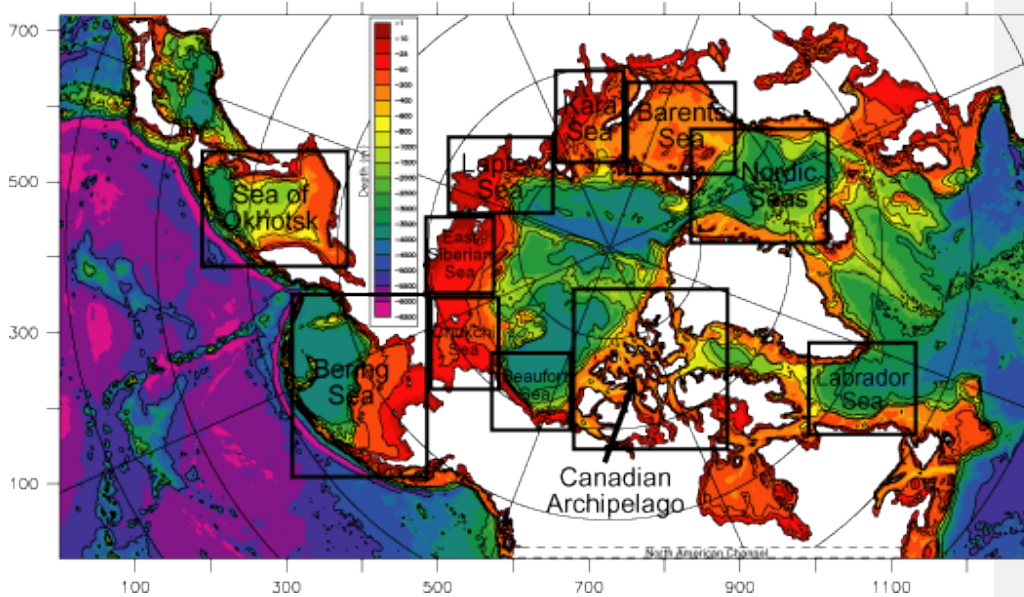
Fig. 2. The NPS model domain (in meters; color shading) showing selected multiple ecosystems (black boxes) of interest to ESSAS studies included in a single model domain.

The ocean model was initialized with climatological, 3-dimensional temperature and salinity fields (Polar Science Center Hydrographic Climatology; PHC) and integrated for almost five decades in a spinup mode. During the spinup we initially used daily-averaged annual climatological atmospheric forcing derived from 1979-1993 reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 27 years. We then performed an additional run using repeated 1979-1981 interannual fields for the last 21 years of spinup. This approach is especially important for establishing realistic ocean circulation representative of the time period at the beginning of the actual interannual integration. This final run with realistic daily-averaged ECMWF interannual forcing starts in 1979 and continues through 2004. Results from this integration (26-years) are used for the analyses in this paper. Yukon (and other Arctic) river runoff is included in the model as a virtual freshwater flux at the river mouth. However, in the Gulf of Alaska the freshwater flux from runoff is introduced by restoring the surface ocean level (of 5 m) to climatological (PHC) monthly mean temperature and salinity values over a monthly time scale (as a correction term to the explicitly calculated fluxes between the ocean and overlying atmosphere or sea ice). Additional details on the model including sea ice, river runoff, and restoring have been provided elsewhere (Maslowski et al., 2004, Clement et al., 2005).

We analyzed model output to determine winter and summer climatological distributions of temperature, salinity, sea ice, and eddy kinetic energy in each of the four

7

ecosystems, i.e. Barents Sea, Bering Sea, Sea of Okhotsk, and Gulf of St. Lawrence. The mean ocean circulation, and volume and property fluxes, are derived to provide preliminary insights into the role of physical forcing on each ecosystem. Exchanges through the main passages and gateways are calculated to identify key geographic features where observations are limited and further studies are needed to enhance understanding of these marine ecosystems. These analyses show a relatively high model skill and potential for satisfying the main goals of ESSAS program. Future requirements for model improvements are discussed in terms of their significance of physical forcing of ecosystem response.

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Clement, J.L., W. Maslowski, L. W. Cooper, J. M. Grebmeier, and W. Walczowski. 2005. Ocean circulation and exchanges through the northern Bering Sea--1979-2001 model results. Deep Sea Research Part II 52: 3509-3540.

3.2. Regional Reviews

3.2.1 Okhotsk Sea and Oyashio Region

Climatic regime shifts and their effects on the Okhotsk Sea ecosystems

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SakhNIRO

A new classification of the atmospheric processes and their synoptic patterns (Glebova, 2001) shows a close relationship between the atmospheric circulation and the water exchange between the Sea of Okhotsk and the Pacific Ocean. In the 1970s–1980s, the transition from meridional to zonal atmospheric circulation was followed by an intensification of sea surface currents and the water renewal occurred in the Sea of Okhotsk. In contrast, meridional circulation decreases water exchange. In the 1990s, the decreased water exchange with the Pacific Ocean contributed negatively to the heat budget of the upper pelagic layers in the Sea of Okhotsk. Changes in indices of atmospheric circulation in the late 1990s occurred, similar to the changes before the "cold decades" of the 1960s–1970s.

Since the late 1990s, cooling of shelf waters also occurred more intensively in the Okhotsk Sea due to the variability of atmospheric processes and air temperature in the region. During January–March of 2000, the intensity of active northern and eastern air

transfer was the highest in comparison with the recent years (Glebova and Khen, 2002). Under the air transfer effect, cold arctic air masses shifted constantly to the Sea of Okhotsk water area and contributed to the development of the severe weather conditions. It lead to a drop in air temperature and subsequent cooling of surface water, and an increased duration of the cold season (Fig. 3). All these factors resulted in intensive winter cooling of shelf waters. Ice cover expanded over the greater part of the Sea of Okhotsk than in the first half of 1990s (Fig. 4).
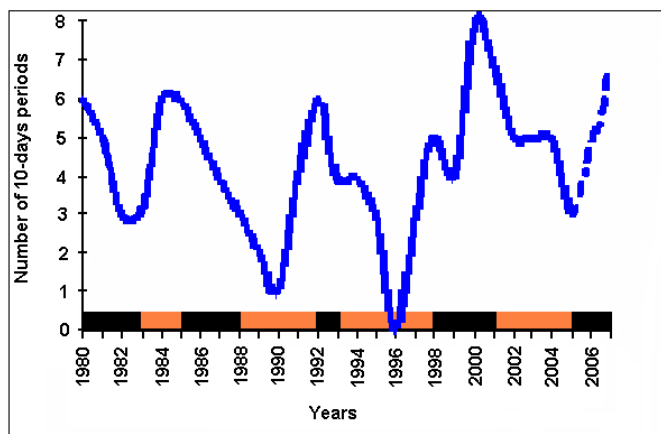

Fig. 3. Interannual dynamics of "cold-type" atmospheric processes over the Sea of Okhotsk and local trend of ice cover expansion (Glebova, 2005). Black bars indicate periods of increased ice cover and light bars periods of decline in ice cover.

These processes suggest an increase of temperature and salinity gradients in the layers separating water masses, vertically as well as horizontally. Continuing frontogenesis establishes conditions that accelerate water transport along fronts and for the interaction of water masses through frontal zones. The acceleration of water transport along fronts can be the major cause of the relative increase in the water exchange between the Pacific Ocean and Bering and Okhotsk Seas in the late 1990s. Therefore, at the beginning of this century, some preconditions for the next climatic and oceanological regime shifts began to occur in far-eastern sea ecosystems.
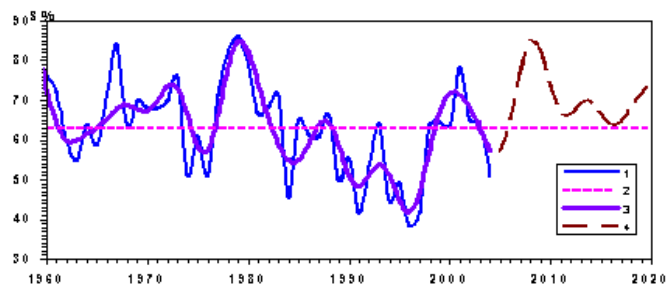
Fig. 4. Interannual variability of mean winter ice cover (January – April, % of the total
sea area) of the Sea of Okhotsk (1), long-term average (2), smoothing average
(3), and forecast for future years (4), after Glebova, 2005.

The unique features of the Sea of Okhotsk ecosystem arise from its geography: its area
stretches from the subtropical through the subarctic zones and nearly reaches the Arctic
climatic zone. In the southern part of the Sea of Okhotsk, in particular on the Sakhalin
Island coast, the average annual temperature can change synchronously with that in the
Japan/East Sea and on the Pacific Ocean coast of Japan (Shuntov, 2001), while the
tendency of the temperature change could be opposite in the northern part of the Sea of
Okhotsk. The regional character of climatic and oceanological phenomena has
exceptional significance for the evaluation of changeability tendencies of climate-
oceanological regime and state of biota in specific seas or even their parts.

Long-term data series on the biological elements of the Sea of Okhotsk ecosystem
mostly deal with the dynamics of commercially important fish species. Among the most
significant events, a strong year-class of Japanese sardine emerged in 1972, after
prolonged interruption, from an extremely low number of spawners (Shuntov and
Vasilkov, 1982). An increase of Japanese sardine biomass suggested a considerable
expansion of its feeding area northward from waters around Japan into the Sea of
Okhotsk, and eastward into the Pacific Ocean. In the Sea of Okhotsk pelagic zone, the
average sardine biomass was estimated to be 0.5×10^6 mt during the 1980s (Shuntov et
al., 1997), and in the northern part of the Japan/East Sea, it could reach 4×10^6 mt
(Shuntov et al., 1993). The predominance of zonal processes in the atmosphere was
also observed in the 1920–1930s, when an earlier increase in Japanese sardine
abundance occurred (Shuntov and Vasilkov, 1982).

A sharp reduction in the abundance of Okhotsk herring occurred during the same
period. The Okhotsk herring was the subject of a large-scale fishery until the early
1970s. The combined Russian and foreign catches peaked in 1968–1969 at a level of
600,000 t. During that period, herring contributed 42.7–45% of Russian fish catches in
the Sea of Okhotsk (Shuntov, 1985). The next period of significant Okhotsk herring
abundance appeared in the 1990s.

Walleye pollock biomass increased and reached its highest historical level in the far-
eastern seas after the 1976/77 regime shift. In the first half of the 1970s, there were no

strong year-classes of walleye pollock in the Sea of Okhotsk. Abundant year-classes appeared after 1976, especially in the northern part of the Sea of Okhotsk (Shuntov et al., 1993). It led to quick growth of walleye pollock biomass and a fishery harvest of up to 1.7–2 x10^6 mt in 1984–1991 (Fig. 5). Some strong year classes of walleye pollock appeared in the 1960s, and the annual combined harvest of Russian and foreign fisheries reached 1.5 x10^6 mt once in those years. This phenomenon supports the high carrying capacity of the Sea of Okhotsk pelagic ecosystem. Further evidence of this was that: even after a stock and fisheries decline, herring biomass was estimated at no less than 0.8–1.2 x10^6 mt in the northern Sea of Okhotsk in the 1980s (Shuntov et al., 1993).
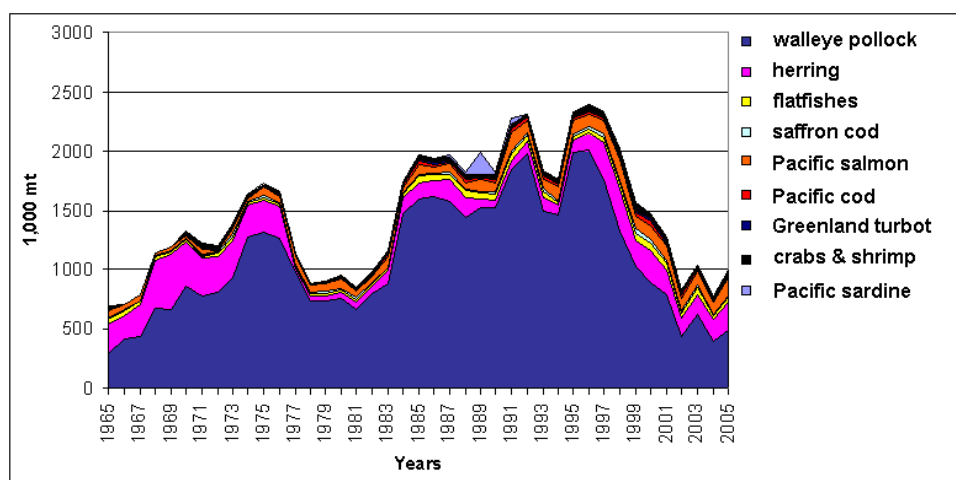
Fig. 5. Russian fisheries catch in the Sea of Okhotsk, 1965-2004

The 1976/77 climate regime shift in the North Pacific was also observed in the Sea of Okhotsk and was characterized by a general sea surface warming, intensive cyclogenesis in the overlying atmospheric domain, and the intensification of water exchange with the Pacific Ocean. Decline of water temperature since 1999 and its persistence for the last years established colder thermal regime than was experienced before (PICES, 2004). The Sea of Okhotsk biota responded to the climate change by a notable decrease of pelagic and semi-demersal fish biomass and total biological productivity.

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Overview of Oyashio Ecosystem and Japan-ESSAS

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The western sub-arctic Pacific, including the Oyashio shelf region and seasonal sea ice areas in the northern Hokkaido, is one of the high-productivity zones of the world. The Oyashio region, from northern Honshu Island, Japan, to the Kamchatka Peninsula of Russia, has a narrow continental shelf and steep slope along its southeast coast (Fig. 6), and is dominated by the Oyashio Current, a western boundary current that flows southward from the Sub-Arctic North Pacific Ocean. Northeast of Hokkaido (Doto area) including off the Shiretoko Peninsula is considered to be the southernmost limit among seasonal sea ice areas in the northern hemisphere. This region supports a wide range of commercially important marine species, marine mammals and seabirds. These include not only gadids such as the walleye pollock and Pacific cod, but also subarctic migratory pelagic fish such as chum salmon and pink salmon. The western Sub-Arctic Pacific is also an important summer feeding ground for subtropical migrants like the Japanese sardine, Japanese anchovy, Pacific saury, mackerels and Japanese common squid, whales and sea birds.
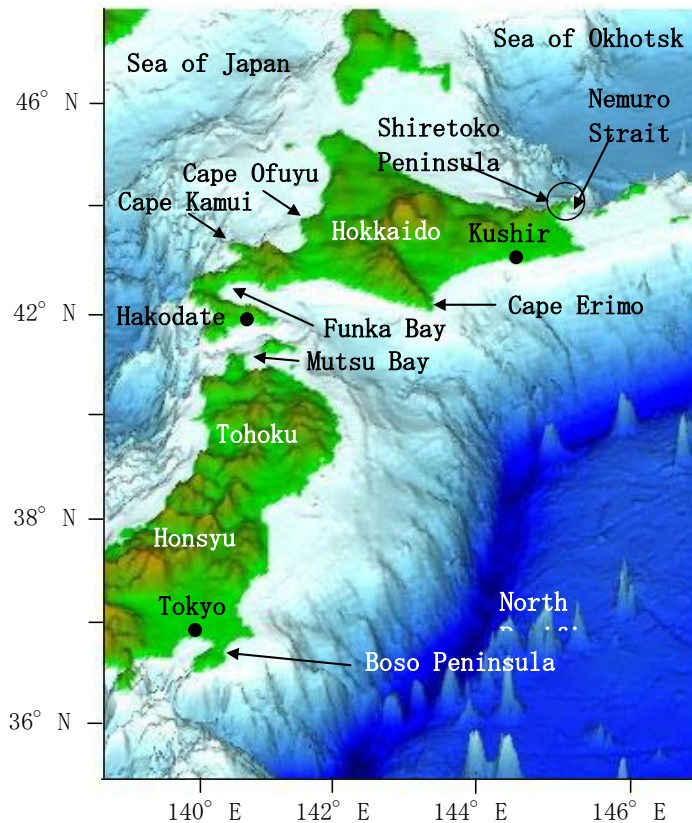
Fig. 6. Topography of Oyashio region and the adjacent areas. (JODC,http://www1.
      kaiho.mlit.go.jp/KAN9/sodan/kaiteitikei/japan006.jpg)

Seasonal and interannual dynamics of the Oyashio and seasonal sea ice, which are
closely linked to climate change, influence the migrations and fluctuations of pelagic,
demersal fishes and higher trophic animals in the northwesten Pacific (Fig. 7, 8). A time
series of the spatial extent of the Oyashio water shows large interannual variation over
the whole period. The spatial extent denotes an increase during the 1980s and a
decrease since the late 1980s (Fig. 9). The Oyashio forms a couple of southward
tongue-shape intrusions off northern Honshu, which are called the First Oyashio
Intrusion (SLO1: coastal intrusion) and the Second Oyashio Intrusion (SLO2: offshore
intrusion), respectively (PICES, 2004). The decadal cycle in the SLO1 was observed as
well as a multi-year cycle (Fig. 10). The SLO1 moved north from the mid-1960s and
shifted south from the late-1970s to 1980s, and north again from the mid-1990s.
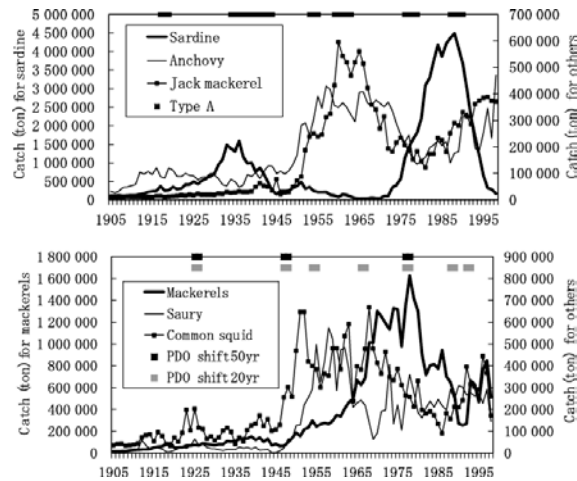
Fig. 7. Time series of catches for Japanese small pelagic fisheries. Selected environmental information includes time periods when the Kuroshio Current followed 'type A' paths (large meandering), and pentadecadal (50 yr) and bidecadal (20 yr) shifts in the Pacific Decadal Oscillation (PDO, Minobe, 2000) Mackerels include chub and spotted mackerel. (Yatsu et al., 2005)

In the Oyashio region bounded by 40-45°N, 141-150°E (see Fig. 6), the sea surface temperature (SST) in spring decreased after the late 1970s, increased after the late 1980s, and remained high during the 1990s (Fig. 11) (Tadokoro et al., 2005). Although the sea surface salinity (SSS) had a similar pattern to SST, it decreased after the mid-1990s. Comparing mean values before and after the regime shifts, SST significantly decreased after the 1976/77 regime shift, and SST and SSS increased after the 1988/89 regime shift. In the summer, the data showed an unclear pattern of interannual variation in SST and SSS (Fig. 11). In the mid-1970s, mesozooplankton biomass in spring was high; however, it decreased significantly in the late 1970s (Fig. 12) (Tadokoro et al., 2005). In summer, mesozooplankton biomass significantly decreased and increased synchronously with the 1976/77 and 1988/89 climatic regime shifts (Fig. 12). Tadokoro et al. (2005) suggested that Japanese sardine (*Sardinops melanostictus*), an important predator of *Neocalanus* copepods, exhibited interannual variation in standing stock that was inversely related to mesozooplankton biomass (see Fig.7, 12).

In recent decades, components of the Oyashio ecosystem (i.e., primary production, mesozooplankton, gadid fish, and subtropical migrants) have shown changes in abundance or distribution that correlate with the environmental change such as the 1976/77 and 1988/89 regime shifts (Fig.7, 8, 12). In the Sea of Okhotsk, the large interannual variation in sea ice volume depends on the strength and duration of northerly winter winds. In the 20th century there were at least two large-scale cycles in
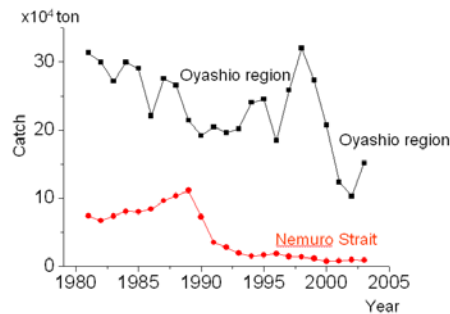
Fig. 8. Time series of walleye pollock catches in the Oyashio region and the Nemuro Strait, northern Hokkaido.

the extent of sea ice cover with a period of about 50 years (Khen, 1997). The extension of ice cover in the Sea of Okhostk decreased in the latest warming during the 1980s - 1990s and increased again since the late 1990s (see the section of Sea of Okhotsk). In the southwestern part of the sea, the East Sakhalin Current transports thick "first-year" ice to the coastal areas of northern Hokkaido and their ice floes pass through straits along the Kuril Islands and Nemuro Strait to the Oyashio region by the Cape Erimo, Hokkaido (Fig. 13). However, the relationship between the extent of sea ice and the strength of the Oyashio intrusion is not well known. Further investigation is needed to understand the long-term variation of the sea ice conditions and the Oyashio intrusions.

Fig. 9.   The time series of the spatial extent of Oyashio water from 1961 to 2005 showing the annual changes and thier 5-yr running mean.

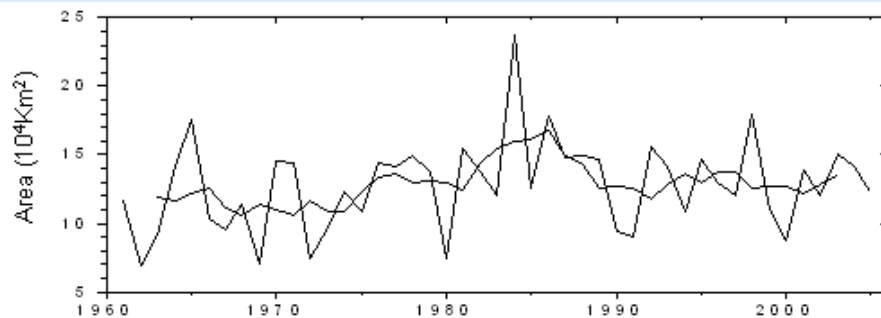Fig. 10. Changes in the annual mean latitude of South Limit of First Oyashio Intrusion (SL01: coastal intrusion) from 1960 to 2005 and their 5-yr running mean.

In the seasonal sea ice areas of the Oyashio region, UNESCO decided on July 14, 2005 to add the Shiretoko area of Hokkaido, Japan, to the World Natural Heritage list (see Fig. 6 for location). The Shiretoko is located in the northeast of Hokkaido and is considered to be the southernmost limit among seasonal sea ice areas in the northern hemisphere. The physical oceanographic structure in this area is very similar to the Sea of Okhotsk. Due to the nutrients provided by the melting of sea ice, winter vertical mixing, and seasonal upwelling, a rich and unparalleled marine ecosystem in the world is created, which supports diverse wildlife such as phytoplankton, zooplankton, fish, seabirds, pinnipeds, and cetaceans. This landscape-marine ecosystem is strongly connected with the Sea of Okhotsk and Oyashio ecosystems.

Fig. 11. Interannual variation in annual mean SST (°C) and SSS of the Oyashio waters in spring and summer from 1970 to 1999. Solid and broken lines show the 5-yr running means. (Tadokoro et al., 2005)

16
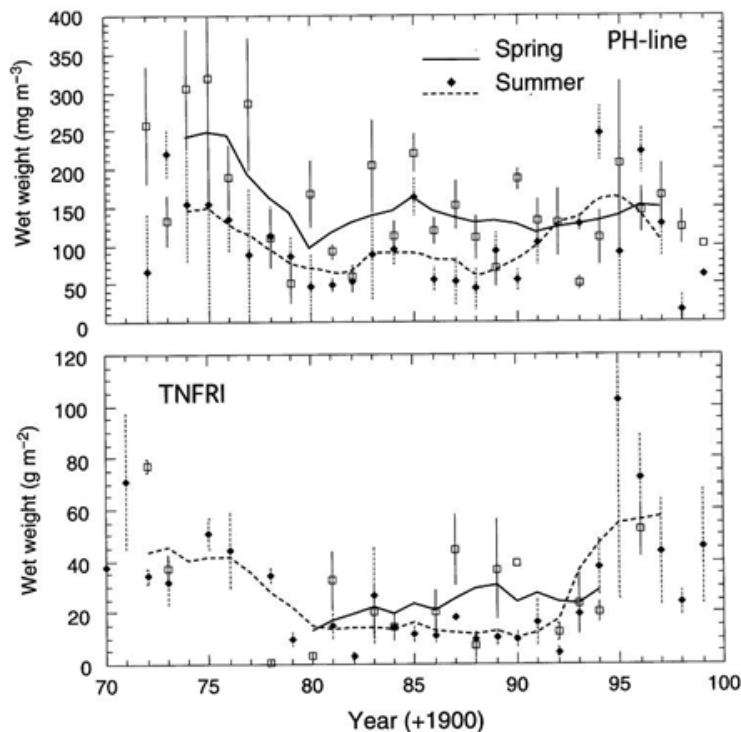
Fig. 12. Interannual variation in annual mean zooplankton biomass in spring and summer determined from surveys along the PH-line from 1972 to 1999 and f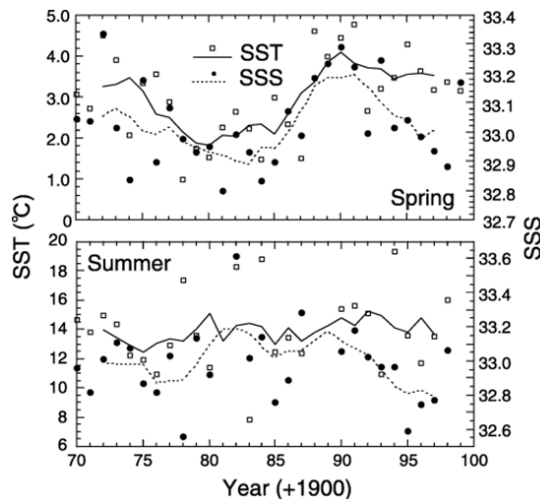rom surveys conducted by the Tohoku National Fisheries Research Institute (TNFRI) during 1970 – 99 in the area bounded by 36 and 45°N, 155°E. Units are mg wet wt m^{-3} for the PH-line and mg wet wt m^{-2} for THFRI data. Bars denote ±SD. Solid and broken lines show the 5-yr running means. (Tadokoro et al., 2005)

> **Comment [k1]:** The plot indicates gms. Not sure which is correct.

The overall goal of J (Japan)-ESSAS is to quantify the impact of climate variability on the structure and function of the Oyashio marine ecosystem including seasonal ice sea areas in the northern Hokkaido to predict the ecosystem response to possible future climate change and its possible economic impact. J-ESSAS is intended to link and cooperate with the international and regional ESSAS and is part of Japan-GLOBEC in which the following projects are already funded and ongoing: "Predicting of stock fluctuations of marine key species around Japan related to climate change and human activity" (funded by JFA and JSPS, 2004-2008), and "The Shiretoko World Natural Heritage including marine and land ecosystems: Towards coexistence with marine diverse and fisheries" (funded by JSPS and Agency of Ecology, 2005-2010). Collaborative research cruises are planned using the *T/S Oshoro-Maru*, Hokkaido

University, in the Arctic Sea and the Bering Sea during the summers of 2007 and 2008 as an IPY collaborative research program.
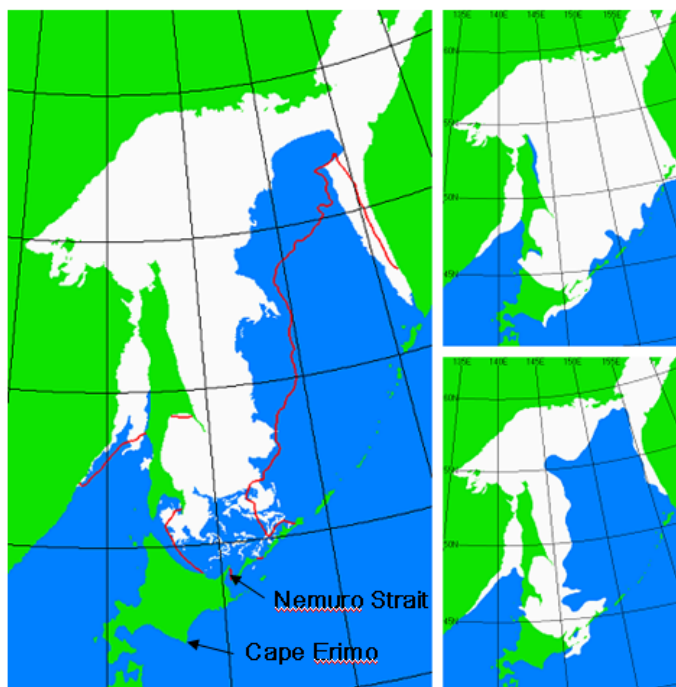
Fig. 13. Maximum ice cover area in each year. Left: March 10, 2006, 9.03x10^5 km^2. Red line denotes the edge of sea ice in normal year. Right (upper): Year of maximum sea ice cover: Feb. 28, 1978, 15.25x10^5 km^2. Right (lower): Year of minimum sea ice cover: Feb. 25, 1984, 8.58x10^5 km^2.

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3.2.2 Bering Sea

Dynamics of the eastern Bering Sea shelf

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Among the Sub-Arctic seas, the Eastern Bering Sea stands out because of its broad (> 500 km) and shallow (mostly < 100 m) shelf (Fig. 14). The currents on the shelf and along the slope form part of the larger Sub-Arctic gyre of the North Pacific. Extensions of the Alaska Coastal Current and the Alaskan Stream enter the Bering Sea through several Aleutian passes and flow northward along the inner shelf (Alaska Coastal Current) or along the slope (Bering Slope Current, an extension of the Alaskan Stream). Most of the shelf is characterized by diffuse flows to the north, which exit through Bering Strait into the Arctic Ocean (Schumacher and Stabeno 1998). Unlike the Sub-Arctic seas in the Atlantic sector, there is little advection of Arctic waters into the Bering Sea. The shelf is seasonally ice-covered and both the spatial extent of ice cover and the timing of ice retreat vary considerably from year to year (Niebauer 1998).

Fig. 14. Bathymetry of the Eastern Bering Sea with minimum and maximum spatial extent of sea ice in March. Base map from NOAA Pacific Marine Environmental Laboratory. Ice extent based on Niebauer et al. (1999).

Variability in ice cover, wind mixing, and temperature conditions on the shelf are largely determined by the strength and position of the Aleutian Low pressure system, which determines the frequency and the path of storms over the shelf (Fig. 15, Overland et al. 1999). The Aleutian Low, in turn, varies in response to decadal climate variability over

the North Pacific and in the Arctic, as well as to shorter term variability in the tropical Pacific. In the recent past, regime-like shifts in climate conditions have been observed around 1976/77 and around 1988/89. The 1976/77 shift was characterized by an intensification of the Aleutian Low with a shift to warmer conditions in the Eastern Bering Sea, whereas the main characteristic of the 1988/89 shift was a strengthening of the polar vortex as indicated by a change in the sign of the Arctic Oscillation index. These changes were associated with marked changes in numerous biological time series throughout the Northeast Pacific (Hare and Mantua 2000).
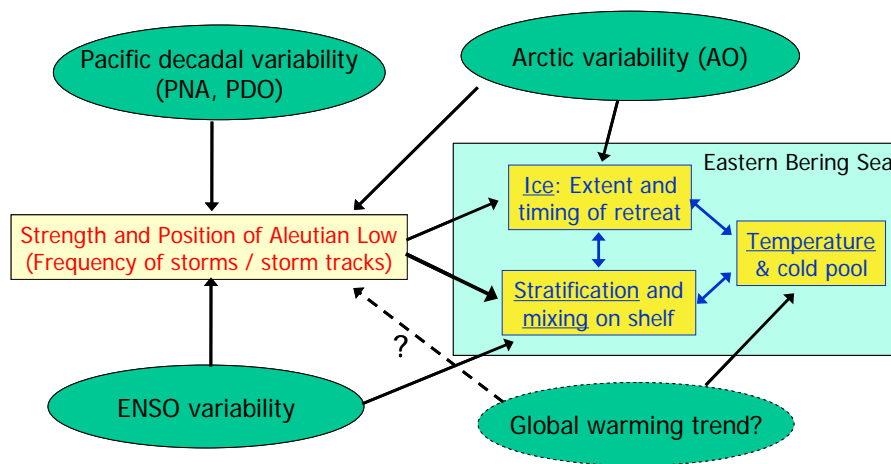

Fig. 15. Major climate drivers affecting the Eastern Bering Sea ecosystem through changes in ice cover, temperature conditions, and stratification. Main sources of climate variability and corresponding indices are shown in green ovals (PNA = Pacific North American pattern, PDO = Pacific Decadal Oscillation, AO = Arctic Oscillation, ENSO = El Nino/Southern Oscillation). For details see text.

The Eastern Bering Sea shelf is an area of very high biological productivity, which is fueled by nutrient rich waters supplied to the Bering Sea basin via the global ocean "conveyor belt". Concentrations of nitrate, phosphate, and silicate in the deep waters of the Bering Sea basin are among the highest observed in the world's oceans and these nutrient-rich waters are the source for replenishing nutrients on the shelf (Whitledge and Luchin 1999). Cross-shelf fluxes are essential to supporting the high production observed on the shelf, but are poorly understood at present. The southern part of the shelf is divided into the well-mixed inner domain, which is separated by an inner front near the 50 m depth contour from the two-layer middle domain (Coachman 1986). The latter is separated by a middle front (near the 100 m depth contour) from the weakly stratified outer domain, which extends to the shelf-break front. In the inner domain and in the surface mixed layer of the middle domain, nutrients are rapidly depleted during the spring phytoplankton bloom. The bloom on the inner shelf domain occurs when sufficient sunlight becomes available, whereas the bloom in the middle domain also requires ice melt or insolation, combined with the cessation of winter storms, to stratify

20

the water column and allow a phytoplankton bloom to develop (Sambrotto et al. 1986). Additional production may occur periodically or throughout the summer when additional nutrients are mixed into the surface layer or into the inner shelf domain through wind and/or tidal mixing.

The timing of ice retreat from the shelf plays an important role in the timing, amount, and fate of primary production over the shelf (Hunt and Stabeno 2002). Melting ice stratifies the water column to form a shallow, low-salinity surface layer. An early, ice-associated phytoplankton bloom can occur in this layer, but only when the ice retreats after sufficient sunlight becomes available. If the ice retreats before the availability of sufficient sunlight, stratification from ice melt is eroded by frequent spring storms and a bloom on the middle shelf cannot develop until thermal stratification stabilizes the water column in late spring or early summer. The relative contribution of ice-associated blooms to annual primary production is therefore highly variable and may be substantial in years with extensive ice. It is believed that much of the ice-associated production sinks to the bottom to support a rich benthic food web, although this has not been quantified (BEST Science Plan 2004). Therefore, an earlier ice retreat or the absence of sea-ice from the eastern Bering Sea shelf, as observed in recent years, has the potential to result in a redirection of energy flows from the benthic to the pelagic system.

The high primary productivity on the Southeast Bering Sea shelf (up to 200-250 gC m^{-2} y^{-1}, Hunt and Drinkwater 2005) supports a large community of demersal and pelagic fish and shellfish, large populations of seabirds and marine mammals, and a number of important commercial fisheries. The fishery annually removes up to 2 million tonnes of demersal fishes from the Southeastern shelf and the Aleutian Islands (NPFMC 2005). Both the fish biomass and commercial catches are dominated by gadids, in particular walleye pollock (*Theragra chalcogramma*), and flatfishes (*Pleuronectidae*). Because of their high abundance and wide-spread distribution, walleye pollock currently play a key role in the food web of the Eastern Bering Sea (Springer 1992) and juvenile pollock are a major prey item for numerous predatory fishes (including adult pollock), seabirds, and marine mammals (Fig. 16, Aydin et al. 2002). Therefore, much of the primary productivity on the eastern Bering Sea shelf is transferred to higher trophic levels through the larvae and juveniles of walleye pollock.

Although the composition of the fish community has remained relatively stable for several decades, a large-scale community reorganization that affected all trophic levels was observed following the 1976/77 climate regime shift (Francis et al. 1998). The recruitment and abundance of walleye pollock and of other demersal and pelagic fishes, such as Pacific cod (*Gadus macrocephalus*), flatfishes, and sockeye salmon (*Oncorhynchyus nerka*) increased substantially after the 1976/77 climate regime shift (Adkison et al. 1996, Conners et al. 2002). These species support some of the largest commercial fisheries in the United States. In contrast, several crab stocks declined to very low levels in the early 1980s and some, in particular red king crab (*Paralithodes camtschaticus*), have not recovered to date (Zheng and Kruse 2006). Other notable changes include large declines in Steller sea lions (*Eumetopias jubatus*) and northern fur seals (*Callorhinus ursinus*), as well as several seabird populations on the Pribilof
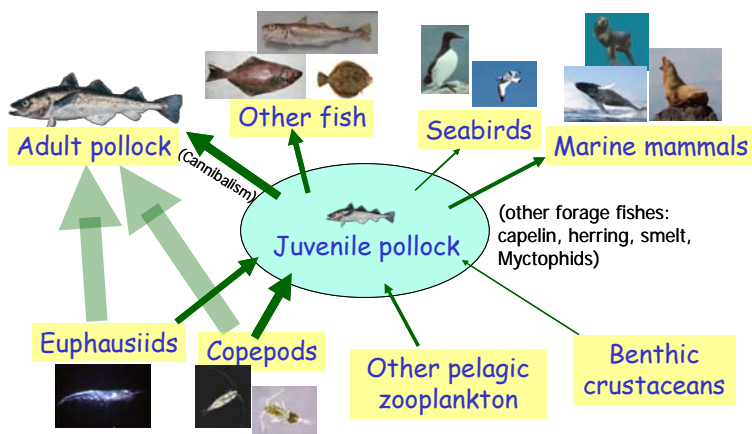
Fig. 16. Simplified food web depicting the central role of walleye pollock (*Theragra chalcogramma*) in the Eastern Bering Sea. Arrows depict biomass flows from lower trophic level prey items to juvenile pollock and from juvenile pollock to major predators. Widths of arrows are proportional to estimated consumption based on Ecopath model (Kerim Aydin, AFSC, NOAA, pers. comm.)

Islands. Pinniped populations were overharvested in the latter part of the 19th and in the first part of the 20th century, underwent a period of recovery, and have experienced severe declines in abundance in recent decades. The causes of these declines are still not understood and may include both anthropogenic (e.g. competition for prey) and natural factors (e.g. changes in relative prey composition associated with the 1976/77 regime shift). Unlike pinniped populations, whale populations on the Eastern Bering Sea shelf appear to be increasing (Moore et al. 2000) after being nearly driven to extinction by the 1960s (NRC 1996).

In contrast to the Southeast Bering Sea, the northern Bering Sea shelf does not support any commercially important fish populations. Primary production on the northern Bering Sea shelf are estimated to be substantially higher (>500 gC $m^{-2}y^{-1}$, Springer et al. 1996) than on the southeastern shelf. High primary productivity is supported by the direct advection of nutrient-rich waters onto the shelf via the Anadyr Current and northward flows along the outer shelf. High abundances of zooplankton are supported by local production as well as by the advection of oceanic species onto the shelf (Springer et al. 1996). Much of the high production in this region settles to the benthos, supporting very high benthic productivity (Highsmith and Coyle 1990). The resulting biomass of lower trophic level benthos on the northern Bering Sea shelf (primarily bivalves and amphipods) is an order of magnitude higher than on the southeast shelf (Alton 1974). The abundance of large demersal fish and crustaceans on the northern shelf is limited by cold bottom temperatures and much of the benthic production is consumed by benthic-feeding seabirds and marine mammals such as gray whales (*Eschrichtius robustus*), and walrus (*Odobenus rosmarus*) (Grebmeier et al. 1989). However, the flow

22

of carbon to the benthos, as well as benthic productivity, has declined in recent years and the northern Bering Sea may be changing from Arctic to subarctic conditions (Grebmeier et al. 2006). It is unclear whether this is the result of a reduced nutrient supply and decreased primary productivity or increased consumption within the water column.

In summary, the Eastern Bering Sea shelf supports an extraordinary diversity and abundance of marine life that forms the basis of important commercial fisheries, as well as important subsistence harvests by Alaska Natives. Marine fish, seabird, and mammal populations have undergone large changes in the past in response to both harvesting and changes in climate. The location of the Eastern Bering Sea at the transition point between the Sub-Arctic and the Arctic makes the region particularly sensitive to climatic changes. In particular, changes in the extent and timing of ice retreat may have profound effects on the flow of energy through the system and on the relative importance of benthic vs. pelagic pathways. There are indications that the region is currently undergoing a transition from Arctic to Sub-Arctic conditions related to recent warming trends (Overland and Stabeno 2004, Grebmeier et al. 2006). If warming trends continue as predicted (IPCC 2001), profound changes in the structure and functioning of the Eastern Bering Sea ecosystem are likely to occur. However, the cascading effects of a warming climate on the ecology of the Eastern Bering Sea cannot be predicted with any certainty based on our current understanding of system dynamics.

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3.2.3 Newfoundland/Labrador Region

The Climate and Physical Oceanography of the Labrador/Newfoundland Region

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The Newfoundland/Labrador shelves are situated on the western side of the Labrador Sea, stretching from Hudson Strait (65°N) to the southern Grand Bank (50°N). The Labrador Shelf consists of numerous shallow offshore banks (typically 100-200 m deep) separated by a series of channels and gullies called saddles. The generally shallower (>100 m) Grand Bank is a broad extensive shelf extending in places more than 300 km from the coast. Offshore lies the deep (3500-4000 m) Labrador Basin.

The region is generally under the influence of northwesterly winds associated with the Icelandic Low. North-to-south monthly mean air temperatures range from 8°-15°C in summer and –27° to -5°C in winter. Sea ice begins to form by December in the north and spreads southward, reaching a maximum extension by March. On average, it reaches the northern Grand Bank, but in heavy ice years it can cover the entire Grand Bank. In the southern regions, ice usually lasts from 1-2 months, whereas at the northern end of the Labrador Shelf it lasts for an average of around 8 months.

The circulation is dominated by the southward flowing Labrador Current. The main branch is concentrated over the continental slope with surface speeds of 0.3-0.4 ms^{-1} and an estimated transport of 3.2 Sv (1Sv=106 m^{3}s^{-1}), while the inshore branch over the shelf has typical surface currents of 0.15-0.25 ms^{-1} and a transport of 0.6 Sv. The waters in the offshore branch are an extension of the West Greenland Current, steered by the topography across Davis Strait, mixed with the colder southward flowing waters from Baffin Bay. The hydrographic characteristics of the waters over the shelf originate in Hudson Strait from a mixture of waters from off the Baffin Island Shelf, relatively warm West Greenland waters, and low salinity waters flowing out from Hudson Bay. These water masses converge at the eastern entrance of Hudson Strait where strong tidal currents lead to intense vertical mixing. The residual current carries the resultant mixture, with high surface nutrients, out onto the northern Labrador Shelf. These lead to high phytoplankton production throughout the summer on the northern Labrador Shelf.

Ocean temperatures range from about –1º to 14º C. An important hydrographic feature south of the mid-Labrador Shelf is the existence of a late spring to autumn subsurface temperature minimum called the Cold Intermediate Layer (CIL) (Fig. 17). The CIL, defined by <0ºC waters, is sandwiched between surface solar-heated, upper-layer waters and the warmer offshore waters that penetrate onto the shelf near bottom. Warm conditions with
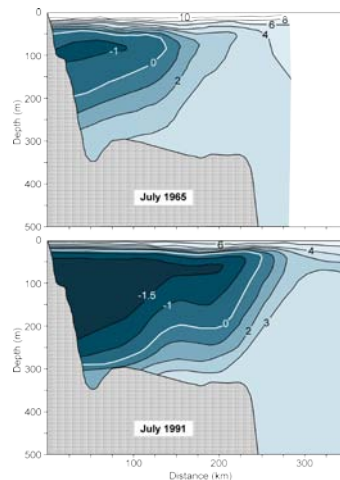
Fig. 17. |Temperature transects across the northeast Newfoundland Shelf showing years
of near minimum (1965) and maximum (1991) extent of the Cold Intermediate
Layer (waters < 0° C).

above normal ocean temperatures, less sea ice and reduced amounts of CIL water
dominated during the 1950s and the 1960s. These were followed by a general decline
in climate superimposed on three major cool periods, in the early to mid-1970s, the
1980s and the 1990s. Cold conditions continued until 1996, when conditions warmed
dramatically. After above-normal sea temperatures and reduced sea ice through most
of the remainder of the 1990s, conditions have been near average in recent years.
Salinity variability shows similar trends as temperature, with fresher-than-normal periods
generally corresponding to the colder-than-normal conditions up to at least the early-
1990s, although the phase of the salinity cycle tends to precede temperature by 1-5
years. The 1990s saw the longest single period of fresher-than-normal salinities on
record in the Newfoundland region and may be a response to increased outflow of
Arctic water through the Canadian Archipelago.

Interannual changes in atmospheric forcing, coupled with changing advection patterns,
are responsible for most of the observed variations in the ocean climate on the Labrador
and Newfoundland Shelves. The NAO index can account for between 40-50% of the
variance in sea-ice, ocean temperatures, CIL area, and shelf stratification off Labrador
and Newfoundland. During low NAO years, the Icelandic Low weakens, resulting in
weaker northwest winds. Less cold arctic air is carried south, resulting in relatively
warm air temperatures, less ice formation, and generally higher ocean temperatures
(Fig. 18). In high NAO years, the opposite happens. Convection in the central Labrador
Sea tends to be shallower during low NAO years and deeper in high NAO years.
However, spatial variations in the positions and extent of the atmospheric pressure
fields that define the NAO index can lead to exceptions to these patterns, e.g. in the late
1990s and the early 2000s, the eastward shift in the pressure cells maintained a high

26

NAO index but weak northwest winds, resulting in relatively warm conditions, little sea ice and reduced convection.
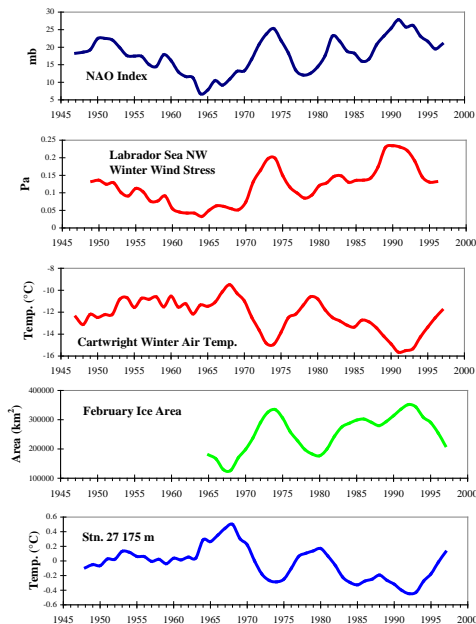
Fig. 18. Time series of the 5-yr running means of the NAO index, the amplitude of the northwesterly wind stress over the Labrador Sea, the winter air temperatures at Cartwright located on the southern Labrador coast, the ice area south of 55°N (southern Labrador) in February, and the bottom temperatures at Station 27 off St. John's, Newfoundland.

Plankton in the Labrador/Newfoundland Shelf Ecosystem

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Sea-surface chlorophyll concentration (SSC) is monitored in the Northwest Atlantic by the Canadian Department of Fisheries and Oceans (DFO) using satellite imagery (Fig. 19). Spatial and temporal averaging for the Labrador/Newfoundland Shelf show that spring blooms are earliest in the south and proceed north, as the ice recedes. Bloom start times (when SSCs reach 1 mg m^{-3}) vary by up to 6 weeks and intensities by up to 4-fold among years. Short spring and fall blooms occur in the south, but in Hudson Strait the spring bloom, which starts late (June), lasts until September, probably because of a continuous nutrient supply due to tidal mixing. Annual primary production is also highest in the Hudson Strait region.

DFO scientists have been monitoring plankton along a section (AR7W line) between S. Labrador and S. Greenland since 1994. Over Hamilton Bank (Labrador Shelf), concentrations of large phytoplankton have decreased, while those of small phytoplankton have slightly increased. This may be related to the 1°C increase in temperature that has also been observed.

Hudson Strait   211 gC m^{-2} y^{-1}

Labrador Shelf   173 gC m^{-2} y^{-1}

Hamilton Bank   153 gC m^{-2} y^{-1}

Model inputs:
- Surface irradiance (includes clouds)
- Modelled underwater light field
- Sea-surface chlorophyll biomass
- Seasonally varying chlorophyll profiles
- Seasonally varying PI parameters

SeaWiFS Chlorophyll-a Concentration
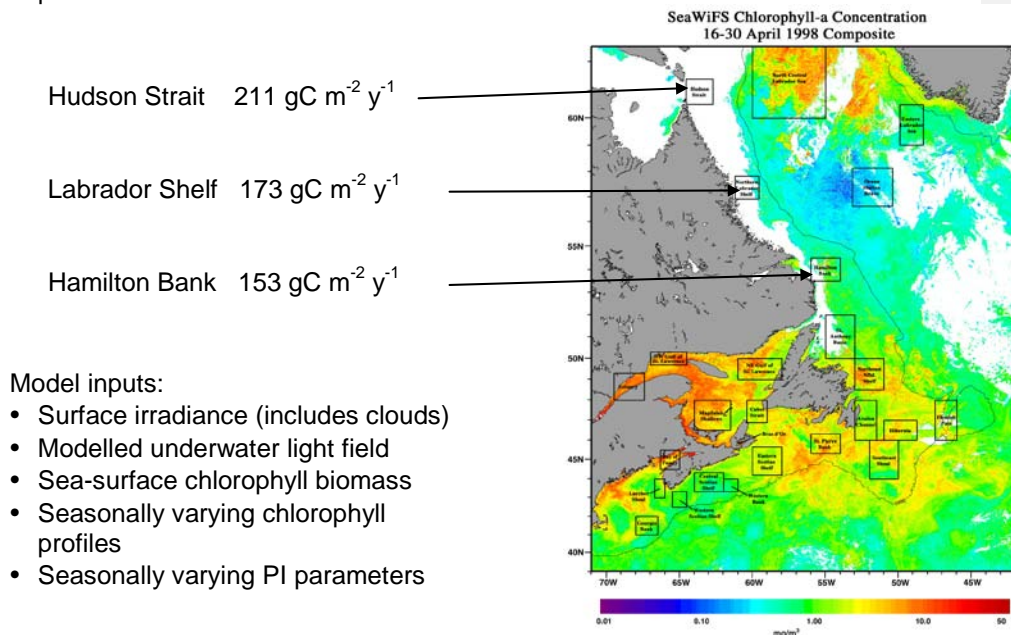16-30 April 1998 Composite

Fig. 19. Multi-annual average primary production rates estimated according to the model of Sathyendranath and Platt

The mesozooplankton biomass along the AR7W line is dominated by copepods, specifically 3 species of the genus *Calanus*. Two (*C. hyperboreus* and *C. glacialis)* are of Arctic origin. *C. hyperboreus* is found everywhere, and its biomass dominates over Hamilton Bank in spring and summer and in the Labrador Slope waters in spring. *C. glacialis* is restricted to the Labrador Shelf and only contributes significantly to the biomass in summer. The third species, *C. finmarchicus*, is a N. Atlantic species, which dominates the biomass in the central Labrador Sea in spring and summer and in the Labrador Slope waters in summer. *C. finmarchicus* is the smallest of the species and is numerically dominant in all regions.

All three *Calanus* species spend the winter in a dormant state at depth. *C. finmarchicus* has a 1 year life cycle, with copepodite stages V and VI as the overwintering stages. *C. glacialis* has a 2 year life cycle and stages IV-VI can overwinter. *C. hyperboreus* has a 2-3 year life cycle and stages III-VI can overwinter. Seasonal cycles of abundance have been observed on the Newfoundland Shelf at Station 27, just off St. John's, downstream from the Labrador Shelf since 1999. Samples are collected between the bottom (175

m) and the surface. For *C. finmarchicus* the young stages (I-IV) show a peak in abundance in July. The overwintering stages start to accumulate in September and peak in December. For *C. glacialis* the young stages show a peak in June and the overwintering stages are never abundant. For *C. hyperboreus* the young stages show a small peak in May and the late stages, a larger peak in July. *C. glacialis* and *C. hyperboreus* are very scarce between August and April, and advection must be important in supplying these species to the area. The timing of the spring bloom (late March-early May) is consistent with the idea that *C. finmarchicus* reproduction is cued by the bloom and that the other species can reproduce before the bloom. Numbers of *C. finmarchicus* over Hamilton Bank in spring and summer are similar to those at Station 27 and lower in fall, while young stages of *C. glacialis* are less abundant in spring, and *C. hyperboreus* young and overwintering stages are more abundant in spring and summer. A recent modelling study has suggested that for this region *C. finmarchicus* production should increase by at least 50% for a 1°C increase in temperature, such has occurred since 1994.   Since 1995, however, there has been no observable increase in *C. finmarchicus* abundance on Hamilton Bank.

Long-term changes in plankton abundance on the Newfoundland Shelf have been observed using the Continuous Plankton Recorder. Two periods have been well sampled; the 1960s-early 1970s and since the 1990s. Annual average abundances of phytoplankton, *C. glacialis* and *C. hyperboreus* have been higher since 1991 than they were in the earlier period, while that of *Calanus* I-IV (mainly *C. finmarchicus*) has been lower.   These changes may be linked to an increased contribution of fresher, Arctic water to the shelf.

Trends in upper trophic levels on the Newfoundland-Labrador shelf.

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Capelin (*Mallotus villosus*) is the primary planktivorous fish and is responsible for much of the transfer of energy from zooplankton to predatory demersal fish, marine mammals, and sea birds. This species has been commercially fished since the early 1970s but there is no evidence that it has been over-exploited. Population trends are unclear because of large discrepancies among abundance indices. There have been substantial changes in capelin biology that coincided with cold conditions in the early 1990s. These changes included changes in distribution, with capelin virtually disappearing from the northern portion of their distribution off Labrador, and extending south of their normal range of distribution to the Scotian Shelf. Also capelin distributions shifted to greater depths, and their vertical diurnal movement was reduced. Other changes in biology in the early 1990s included reduced fish size and poor condition. Spawning occurred later than during the pre-1990s and off-beach spawning became more prevalent. While these changes coincided with cold conditions in the early 1990s, they have persisted throughout the warm regime of the past decade. It is now felt that the changes in capelin biology in the early 1990s may have been due more to changes at lower trophic

levels than to changes in the physical environment (e.g. temperature). There is no evidence that the fishery has been a contributing factor.

Polar cod (*Boreogadus saida*) is another important forage species on the Labrador and Northeast Newfoundland Shelves, whereas sand lance (*Ammodytes spp.*) is important on the Grand Bank. Polar cod increased in biomass and abundance during the cold early 1990s and declined during the warm late 1990s. Meanwhile the species distribution shifted south in the cold period and back north in the warm period.

The main predator on forage fishes, and capelin in particular, has historically been Atlantic cod (*Gadus morhua*), which consists of two stocks on the Labrador and Eastern Newfoundland Shelf (Fig. 20). The larger 'northern cod' stock extends from southern
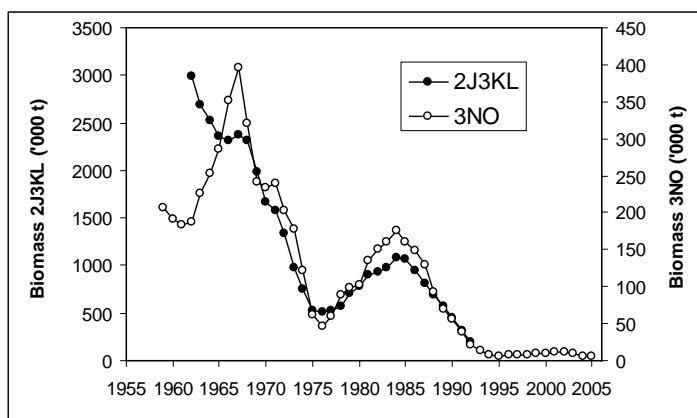

Fig. 20. Trends in biomass of Atlantic cod stocks from the southern Labrador shelf to the northern Grand Bank (NAFO Divisions 2J3KL) and from the southern Grand Bank (NAFO Divisions 3NO); estimates are for ages 3+ from sequential population analysis.

Labrador to the northern Grand Bank (NAFO Divisions 2J3KL), whereas the smaller stock occupies the southern Grand Bank (NAFO Divisions 3NO). These stocks declined from the late 1960s to the mid 1970s, under heavy fishing pressure. They increased over the next decade to the mid 1980s, but declined again after 1985. Directed commercial fishing was banned in1992 (2J3KL) and 1994 (3NO), but there have been no sustained signs of recovery. All other commercially important groundfish stocks also declined during the 1980s and early 1990s, and most remain severely depressed.

Many researchers believe that these declines in cod and other groundfish species were entirely due to fishing, whereas others infer from concurrent changes in biological characteristics that a cold oceanographic regime also played a role. The changes in biological characteristics of cod include truncated size and age distributions, reduced growth, poor condition and small size and age at maturation. Similar declines in

biomass, abundance, and biomass/abundance ratios were evident in all other large demersal species that were not targeted by fisheries, again suggesting that declines were not entirely due to fishing. It has also been noted that the declines in commercial groundfish stocks are greater than can be accounted for by recorded landings or bycatch. This implies that there was a high level of unreported landings and/or discarding, or that there was an increase in natural mortality associated with cooling. An increase in natural mortality is consistent with changes in distribution and migration as well as reduced growth and condition.

Despite the persistence of a warm regime for the past decade (and a moratorium since 1992) there has been no recovery of Atlantic cod in the offshore of 2J3KL. Spawner biomass remains very low, as does recruitment. Mortality remains extremely high, but the major source of this mortality is uncertain.

Since the collapse of most groundfish stocks, fisheries for commercial crustaceans have expanded. Fishery data indicate that the biomass of northern shrimp (*Pandalus borealis*) has increased on the Labrador-northeast Newfoundland Shelf since the early 1990s (Fig. 21).
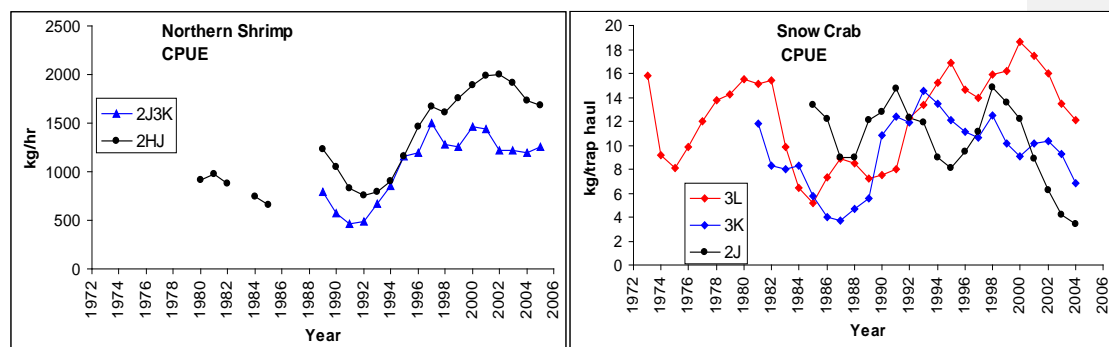

Fig. 21. Trends in commercial catch per unit effort (CPUE) for northern shrimp (left) from the northern Labrador shelf (NAFO Divisions 2HJ) and the southern Labrador-northeast Newfoundland shelf (NAFO Divisions 2J3K) and for snow crab (right) between the southern Labrador shelf (NAFO Division 2J) and the northern Grand Bank (NAFO Division 3L).

Similarly, biomass of snow crab (*Chionecetes opilio*) from the southern Labrador shelf to the Grand Bank increased from a low in the mid-1980s (Fig. 21), although recent trends have varied among areas. The relative effects of release from predation by demersal fishes versus a cold regime during early life stages on these increases in crustacean biomass are unclear. However, if crustacean populations were historically controlled by 'top-down' effects, that has not been the case in recent years, and an inverse association between catch rates and bottom temperatures during early life

stages has persisted for snow crab in particular. Exploitation rates on northern shrimp have remained very low, whereas the fishery exerts a greater effect on snow crab.

A large number of marine mammal species inhabit the Newfoundland-Labrador Shelf, including several pinnipeds, small toothed whales, and baleen whales. The majority of species are thought to feed predominately on pelagic forage species (eg. capelin, polar cod, sand lance and herring). Population trajectories are unknown for most species. One, notable exception is the harp seal population (Fig. 22), which has almost tripled since quotas were introduced in 1971.
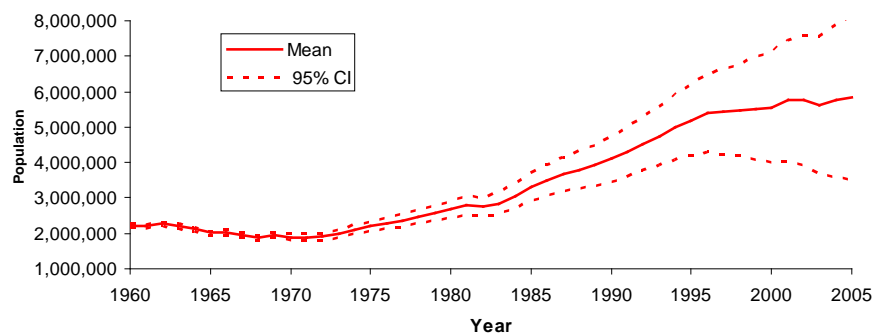

Fig. 22. Trend in population size of northwest Atlantic harp seals since 1960.

There is considerable controversy regarding whether predation by harp seals may represent an important source of mortality limiting the recovery of Atlantic cod stocks. Atlantic cod make up only a small proportion of the diet of harp seals. However, given the high abundance of seals, it is conceivable that even this level of predation may impose a high mortality on cod stocks at their current very low levels of spawning stock biomass.

3.2.3 Barents Sea

The Barents Sea: Climate Variability and Climate Impact on the Ecosystem

Harald Loeng
Institute of Marine Research

The Barents Sea is a shelf area is part of the continental shelf area surrounding the Arctic Ocean. The extent of the Barents Sea is limited by the continental slope between Norway and Svalbard in west, the continental slope bordering the Arctic Ocean in north, by Novaja Zemlya in the east, and the coast of Norway and Russia in the south.

The Barents Sea covers an area of approximately 1.4 million km^2. The average depth is 230 m, with a maximum depth of about 500 m at the western entrance. There are several bank areas, with depths around 100-200 m. The three largest are the Central bank (Sentralbanken), the Great bank (Storbanken) and the Svalbard bank.

The general circulation pattern is strongly influenced by topography. Warm Atlantic waters (from the Norwegian Atlantic Current) with a salinity of approximately 35 flows in through the Fugløya-Bjørnøya section at the eastern entrance. This current divides into two, the southern branch flowing eastwards towards Novaja Zemlya and then northeastward while the northern branch flows into the Hopen Trench. The relative strength of these two branches depends on the local wind conditions. South of the Norwegian Atlantic Current in the Barents Sea is the extension of the Norwegian Coastal Current. The Coastal Water is fresher than the Atlantic water and has a higher amplitude seasonal temperature signal. In the northern part of the Barents Sea, fresh, cold Arctic water flows from northeast to southwest. The Atlantic and Arctic water masses are separated by the Polar Front, which is characterised by strong gradients in both temperature and salinity. In the western Barents Sea, the position of the front is relatively stable being tied to the topography, but in the eastern region, the position of this front has large seasonal, as well as interannual, variations.

The Barents Sea is characterised by large inter-annual variations both in heat content and ice conditions. The most important cause of this is variation in the amount and temperature of the Atlantic water that enters the Barents Sea.

The Barents Sea is a spring bloom system and during winter primary production is low and chlorophyll concentrations are close to zero. The timing of the phytoplankton bloom is variable throughout the Barents Sea. Primary production in this area is mainly limited by light during winter. At this time the water is mixed and nutrients are transported to the surface. In early spring, the water is still mixed and even though there are nutrients and light enough for production, the main bloom does not appear until the water becomes stratified. The stratification of the water masses in the different parts of the Barents Sea may occur in different ways. Along the marginal ice zone, the increased sun radiation during spring leads to melting of the sea ice and thereby to a thin upper layer of relatively fresh melt water. As the ice melting continues and the ice retracts northwards, the upper layer gets heated and this increases the stratification and gives the necessary conditions for the spring bloom to start in this area. In the Atlantic water masses, the stratification is a consequence of solar heating of the surface waters. In the southern part close to the Norwegian coast, the bloom may start following increased vertical stability caused by lateral spreading of coastal water from the Norwegian Coastal Current (Rey, 1981). The timing and development of the spring bloom in the Barents Sea show high interannual variability, particularly in regions where there are interannual variability in sea ice cover that, when it melts, may cause stratification to appear earlier than if no ice were present (Olsen et al., 2003).
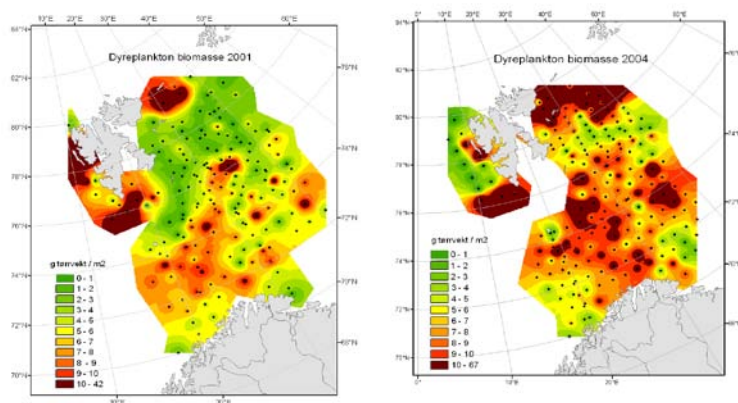
Fig. 23. Horizontal distribution of zooplankton (g dry weight m^{-2} from bottom - 0 m) in August/September based on WP2 and MOCNESS for 2001 (left panel) and 2004 (right panel).

The zooplankton biomass in 2004, based on net sampling, had an average dry weight of 7.8 g m^{-2} and was higher than in 2001 (5.9 g m^{-2}) and 2003 (6.5 g m^{-2}). Possible reasons for large variations in zooplankton biomass are the differences in advective transport, temperature conditions and predation pressure. 2004 was one of the warmest years recorded and with very high salinity values. The high temperatures may have lead to increased growth rates of zooplankton. In addition, increased observed inflow may have lead to high zooplankton transport into the Barents Sea. Another explanation could be low predation pressure from capelin. The capelin stock had declined from about 3.5 million tonnes in 2001 to a very low level (ca 0.5 million tonnes) in 2004. Horizontal distribution of zooplankton for 2001 and 2004 in August/September are shown in Fig. 23.

In the Barents Sea ecosystem, capelin plays a very important role, on one hand as a major predator and on the other hand as a major prey. Capelin is the main predator on zooplankton, feeding mainly on copepods, krill and amphipods. Investigations in the Barents Sea have demonstrated a several fold variation in zooplankton biomass in the period 1979-2004 (Fig. 24). The observations of low zooplankton abundance when the capelin stock is large is not surprising as capelin is the most important predator on zooplankton in the Barents Sea ecosystem and probably exploits most of the secondary production, during its feeding season (Fig. 24). During periods when the capelin stock was at very low levels, the predation pressure on zooplankton was at a minimum, thus causing an increase in the zooplankton biomass. These observations seem to indicate strong interactions between capelin and zooplankton in the Barents Sea.

The Barents Sea is a highly productive area, which provides food for large pelagic fish stocks that serve as food for other species in the food web, including man. It is a relatively simple ecosystem with a few fish species of potentially high abundance. These are Northeast Arctic cod, haddock, Barents Sea capelin, Polar cod and immature Norwegian Spring-Spawning herring. The last few years there has in addition been an increase of blue whiting migrating into the Barents Sea. Their abundance in 2004 was estimated to be 1.4 million tons (IMR, 2004). The composition and distribution of species in the Barents Sea depend considerably on the position of the polar front. Variation in the recruitment of some species, including cod and herring, has been associated with changes in the influx of Atlantic waters into the Barents Sea.
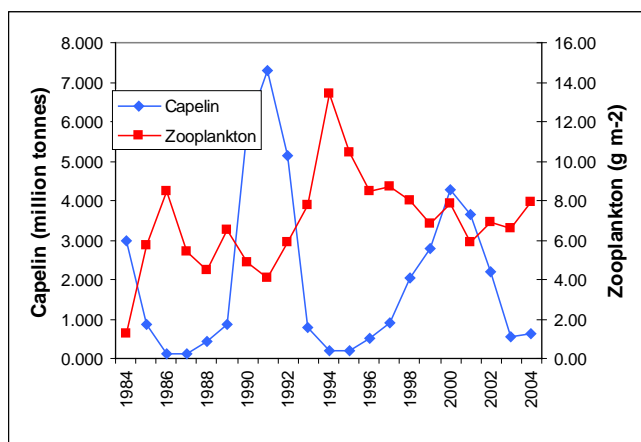

Fig. 24. Annual fluctuations in zooplankton biomass and size of capelin stock in the Barents Sea.

Cod, capelin and herring are key species in this system. Cod prey on capelin, herring and cod, while herring prey on capelin larvae. Cod is the most important predator fish species in the Barents Sea, and feeds on a large range of prey, including the larger zooplankton species, most of the available fish species and shrimp (ICES 2004a). The diet of cod is a good indicator of the state of the Barents Sea ecosystem. Fig. 25 shows the diet of cod in the period 1984-2004, calculated from stomach content data, gastric evacuation rate and number of cod by age. The cod diets are taken from the Joint IMR-PINRO stomach content database. The model for gastric evacuation rate for cod is based on experiments conducted at Norges Fiskerihøgskole in Tromsø. The consumption calculations show that the total consumption by cod in 2003 and 2004 was about 4.5 million tonnes. The consumption per cod for the various age groups was also approximately the same in both years. In 2004, capelin was the most important prey item for cod, followed by amphipods, polar cod, krill, shrimp, blue whiting, herring, haddock and cod. The proportion of capelin in the diet of cod decreased from 2002 to 2004, but not as much as the decrease in the abundance estimate of capelin should indicate. This phenomenon was, however, also observed during the previous capelin collapse. Cod

35

cannibalism is now at a low level. The individual growth of age 1 and 2 cod is below average, while it is average for older cod. The cod migrate out of the Barents Sea and spawn in the Lofoten area in March. The average age at first maturation has been declining in recent decades.
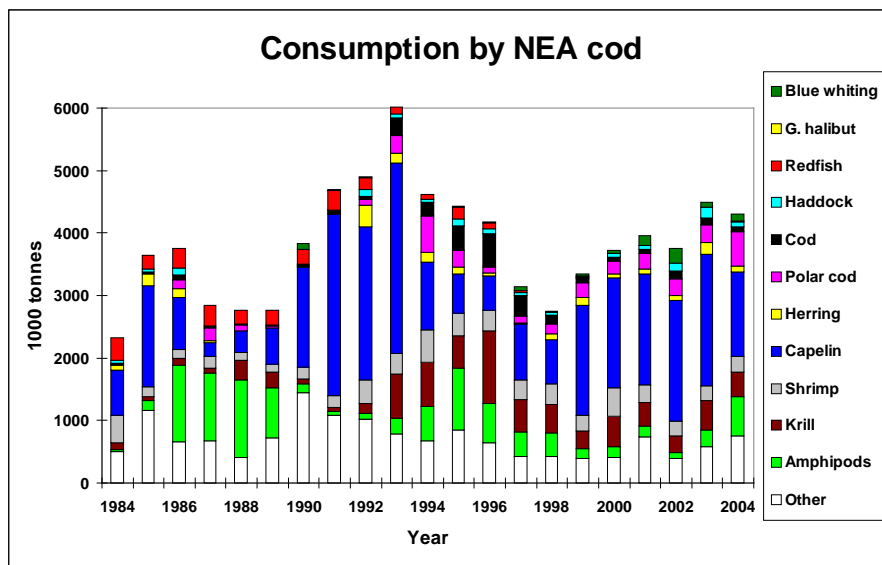
Fig. 25. Consumption by Northeast Arctic cod in the period 1984-2004.

4. Summary of discussion on mechanisms controlling energy flow in Sub-Arctic systems

Franz Mueter, Compliler
Sigma Plus Consulting

The open discussion was loosely structured around the following questions:
- What are the mechanisms controlling energy flow that are most susceptible to being affected by climate variability/change?
- Are these mechanisms the same in all four systems?
- Are the mechanisms of equal importance in all systems?
- For a given type of perturbation, are the systems expected to respond similarly?

All of the main points raised during the discussion are summarized below by topic. Topics include the main forcing mechanisms (ice, stratification, and advection of

nutrieen and zooplankton), the linkages between climate and fish populations, and the role of modeling.

4.1. Sea Ice

A primary mechanism controlling energy flows in the Sub-Arctic seas is the formation and melting of sea ice. The amount and duration of sea-ice cover is very susceptible to changes in climate. Biological production and energy flows are linked to the presence of sea ice in several important ways:

- The occurrence of and the magnitude and duration of an ice-associated spring bloom affects energy flows to the benthos. Ice –associated blooms in cold water are not effectively grazed by zooplankton and much of the primary production presumably sinks to the bottom.
  - o In the eastern Bering Sea, the ice-associated bloom uses up most of the available nutrients and may constitute a substantial portion of annual productivity. Hence years with an ice-associated bloom may have enhanced benthic productivity. This mechanism may be most important in the Bering Sea, which has a much broader and/or shallower shelf than the other systems.
  - o Similarly, shallow-water blooms in the Sea of Okhotsk are very important for benthic productivity.
  - o In other areas (e.g. Barents Sea) the ice-associated bloom, which consists of a narrow spatial band of high productivity and has a short duration, may be less important to benthic productivity. In the Barents Sea, the amount of material reaching the benthos is higher in the area underlying Atlantic waters than those underlying Arctic waters.
- The presence of sea ice affects the species composition at all trophic levels, therefore influencing food web structure, primarily as a result of different temperature tolerances or preferences.
  - o Sub-Arctic seas in the Pacific sector are dominated by Sub-Arctic species because of the overwhelming influence of the Sub-Arctic gyre on water circulation. While cold water masses are formed in the winter there is only a limited exchange with the Arctic and little inflow of Arctic waters and their associated fauna into the Bering Sea, Sea of Okhotsk, or the Oyashio region.
  - o In contrast, the Barents and Labrador Seas have an open connection with the Arctic Ocean and Arctic water masses occupy a portion of these seas throughout the year and there is a clear separation between Arctic and Sub-Arctic waters. Food webs in Artic and Sub-Arctic water masses differ markedly.
- The timing of ice retreat in the spring affects the timing of the spring bloom and the length of the productive season. A longer productive season is expected to increase overall annual productivity. In the eastern Bering Sea, the timing of retreat determines whether an ice-associated bloom can develop or not.

4.2. Stratification

The generation of and maintenance of stratification is an important mechanism and is necessary for a phytoplankton bloom to occur in open water. Stratification in Sub-Arctic seas may result from melting ice, freshwater input, or solar heating. Stratification may be broken down if the wind or tidally induced mixing is strong. The mechanisms causing stratification may change over the course of the spring and summer season, and the relative importance of different mechanisms varies among regions and may change with climate conditions.

- For example, a warmer climate may imply reduced stratification early in the season due to reduced ice cover and increased stratification in the summer due to increased temperatures and increased precipitation and freshwater discharge.
- In the Barents Sea thermal stratification may be stronger and set in earlier leading to reduced productivity
- Changes in wind mixing also affect stratification. At present we do not know how a changing climate may impact the balance between stratification and mixing.
- In the Labrador Sea, stratification during the summer is largely driven by freshwater discharge.

4.3. Advection and nutrient supply

In all of the Sub-Arctic seas, the amount of primary production is a function of nutrient supply. Horizontal advection of nutrient-rich waters plays an important role in all of the systems and the magnitude of advection may be strongly impacted by climate variability. Therefore future climate changes may change nutrient supplies to these systems.

- For example, primary production in the Labrador Sea and in the eastern Bering Sea is highest in the northern part of these regions because of the inflow of tidally-mixed nutrient-rich waters from Hudson Strait in the case of the former and of subarctic (Bering Sea) waters in the latter.
- In contrast, production in the Barents Sea is higher in the south because of the inflow of nutrient-rich Atlantic waters.
- The advection of Pacific waters into the Sea of Okhotsk is the most important source of nutrients that fuel the high productivity in the Sea of Okhotsk.
- There may be important differences between systems (or regions within a system) that receive inflows primarily from temperate waters and those that receive inflows primarily from Arctic waters. Presumably, the latter may be more susceptible to climate changes.

4.4. Advection of zooplankton

In addition to supplying nutrients, advection plays an important role in the supply of zooplankton to the Sub-Arctic seas. Many zooplankton species have overwintering stages in deep oceanic waters that need to be transported to more productive regions on the continental shelf and into coastal regions to complete their life history. This may be more difficult (and more easily disrupted) in regions with a shallow shelf such as the

eastern Bering Sea than in deeper and highly advective regions such as the Barents Sea or the Oyashio region.

4.5. Linkages: climate to fish

The Sub-Arctic seas differ in the efficiency of energy transfer from phytoplankton to fish, in the relative importance of benthic versus pelagic pathways, and in the importance of bottom-up versus top-down forcing. All of these linkages and forcing mechanisms are likely to be impacted by climate change.

- While we have a reasonably good understanding of the physics and phytoplankton dynamics in most of the systems and detailed information on at least the most abundant, commercially important fish species, there is a large gap in our understanding in the "middle". That is, we have very limited understanding of the zooplankton and other prey species that link primary production to fish production.
- Our lack of understanding of zooplankton dynamics is at least in part due to our lack of understanding of their behavior.
- In some systems, (meso-)zooplankton species consume a much larger proportion of primary production (Barents Sea, Labrador Sea) than in others (Oyashio). These proportions may differ in response to climate change and affect the efficiency of energy transfers to upper trophic levels.
- Understanding the trophic structure of fish populations can help in understanding the mechanisms that link climate variability to fish productivity.
- The role of bottom-up and top-down controls may change in response to climate changes as well as fishing. Fishing, which primarily targets large fishes, exerts a different type of (and stronger?) top-down control than other predators.
- Climate changes are likely to affect the spatial distribution of all trophic levels including fishes, particularly at the boundary between Sub-Arctic and Arctic systems.

4.6 Modeling

Models can help to quantify the amount of ice-cover, strength and timing of stratification, and the supply of nutrients to the photic zone. Some lower trophic (NPZ) models have been developed but much remains to be done to predict primary production and zooplankton production. To examine effects of climate changes, these models also need to be linked to circulation models on the one hand and models of upper trophic levels on the other hand.

- There is a clear need to develop more models that include both physics and lower trophic levels through large zooplankton, as well as fish.
- While we have detailed single-species and multi-species models to describe the dynamics of fish populations, these are at present not predictive in the sense of incorporating environmental information to predict fish productivity.
- Incorporating behaviour into models (such as individual-based models) also presents an important challenge.

- Models should be constructed that explore specific mechanisms underlying the rules of how a particular Sub-Arctic system works. These rules appear to have changed in response to observed climate regime shifts (e.g. eastern Bering Sea) and may change in response to warming.
- An all-inclusive model from phytoplankton to fish is unrealistic at the present time. There are several approaches one could take. GLOBEC has suggested the trapezoidal approach where a model focus on one aspect (e.g. zooplankton) with less information needed for lower (phytoplankton) and upper (fish) trophic levels.
- Validation of models is very important and for this there needs to be a match between the temporal and spatial resolution of the model and observations.
- There is also a great need for expressing the uncertainty of model results indicated, perhaps as probabilities.
- More laboratory and field studies are needed to determine for phytoplankton and zooplankton rates for sub-arctic species as most data are from temperate species.

5. The role of regional reports: **The PICES "Marine Ecosystems of the North Pacific" report**

George Hunt
University of Washington

In 2005, PICES published the first edition of its report on the Marine Ecosystems of the North Pacific, also known as the North Pacific Ecosystem Status Report (NPESR). This exciting new effort provides a wealth of information on the individual ecosystems of the North Pacific, on selected species of commercial and conservation interest, and a synthesis of how these ecosystems have been changing in recent years. The purpose of this report, according to the foreword, is to:

1) "describe the present state of the marine ecosystems of the North Pacific Ocean (status), in the context of their recent (past five years) and longer variability (trends);"
2) "summarize these regional assessments into a broad basin-wide synthesis;"
3) "identify critical factors that cause changes in these ecosystems; and"
4) "identify key questions and critical data gaps that inhibit understanding of these marine ecosystems."

The foreword goes on to say that the intended audience for the report is a combination of "… scientists working on or interested in the climate and marine systems of the North Pacific Ocean, governments who deal with issues of understanding, use, and management of North Pacific marine systems, and the general public." This is a challenging set of goals, particularly in regard to the communication of material to a very diverse audience. In anticipation of the next edition of the NPESR, it was suggested that the 2006 ESSAS Workshop should examine features that might be incorporated

into the NPESR that would facilitate its use by scientists interested in understanding the effects of climate variability on the sub-arctic seas. This was seen to be the beginning of a ongoing dialogue between PICES and ESSAS as they develop their approaches to regional comparisons of marine ecosystems.

A major goal of ESSAS is to predict the potential impacts of climate variability on the sustainable use of the Sub-Arctic seas. A basic tenet of the ESSAS approach to achieving this goal is that it is essential to identify and understand the processes that determine the amount and fate of primary production. This requires not only the examination of those bottom-up processes that determine the amount of primary production, but also an understanding of the processes that determine how the assimilated energy moves through the ecosystem. How do the timing of blooms and the environmental conditions during these blooms (e.g., water temperature) influence the partitioning of production along pelagic or benthic pathways? How does timing affect the match or mis-match between trophic levels, and what is the role of the life-histories of organisms? What is the largely heretofore overlooked role of micro-plankton in these systems? And, finally, how do top-down effects, especially the effects of fisheries removals, interact with these bottom-up effects?

To address these questions, ESSAS has elected to employ a comparative approach, investigating in each of the Sub-Arctic seas which processes seem to be particularly vulnerable to the effects of climate variability. By using information garnered from more than one system, responses to similar impacts can be compared across systems to obtain a clearer picture of the range of responses to a particular climate variable. To be effective, the approach taken by ESSAS will require comparable data on the responses of a particular aspect of an ecosystem to changes in features, such as wind mixing, stratification, water temperature and sea-ice cover, across many ecosystems. Where organisms are concerned, it will be important to know the species and its life history traits so that true comparability can be accomplished.

It was specifically suggested that the workshop participants should examine the NPESR and provide suggestions for changes that might be incorporated in subsequent editions. The workshop participants also noted that the NPESR might be used as a source of information about aspects of North Pacific marine ecosystems that are changing and for which an understanding of the underlying processes is sought, or alternatively, a source of information about data sets essential to comparative studies, such as those at the core of ESSAS. Workshop participants focused on the comparative aspects of the NPESR and did not address the complete set of challenges embodied in the NPESR goals set out above.

The ESSAS workshop participants agreed that the PICES NPESR provides a good start on comparing how climate variability at various time scales is affecting the marine ecosystems of the North Pacific. However, these ecosystems are very diverse, ranging from the sub-tropical Gulf of California, to the seasonally ice-covered Bering and Okhotsk seas. It was suggested that grouping the PICES regions in the synthesis chapter by common aspects might facilitate the understanding of climate impacts on

these systems. For example, group comparisons of the PICES areas into those with exposure to seasonal sea-ice cover and which are dominated by gadids such as pollock (e.g., the Bering Sea, Sea of Okhotsk, Oyashio Current System, and possibly the Gulf of Alaska), and those with more temperate or sub-tropical affinities that are dominated by small pelagics (e.g., California Current System, Gulf of California, Kuroshio Current, Japan/East Sea, Yellow Sea and East China Sea). This would facilitate east-west comparisons, and comparisons with similar systems elsewhere. It was also suggested to compare latitudinal gradients along a given coast, with the assumption that, as warming continues, some of the northern ecosystems will come to look more like their neighbors to the south. One could then explore the likelihood of such climate-driven change given the physical and biological structure of the region.

One approach taken by the ESSAS workshop participants to the challenge of building comparisons was to construct a series of tables that laid out what are believed to be the most critical species supporting each of several commercially important top predators in each of the systems examined. Although far from easy to fill out and not universally popular with the workshop participants, these tables brought into strong relief the similarities and differences in the food chains (webs) thought to be of greatest importance to commercial species, as well as gaps in information. A second set of tables addressed the mechanisms by which climate variability might be expected to impact the transfer of energy from one trophic level to the next. The magnitude of these impacts would be expected to be very sensitive to the life histories of the species involved. These discussions were followed by evaluation of modeling strategies that could be employed to elucidate how climate variability may impact these marine ecosystems.

The workshop participants liked that the individual chapters on each of the PICES regions had a similar structure (listing of topics), though they noted that coverage of these topics varied considerably from one region to another. It was suggested that the coverage could be standardized, at least to the point that a minimum set of tables and graphs should be presented, and this would greatly facilitate the use of the report for comparative studies. Likewise, within the synthesis chapter, having a set of figures or tables that compared all or sub-sets of the PICES regions in terms of physical and chemical characteristics, biological rates, and trends in populations would highlight the similarities and differences among PICES regions. On-line sources of the data used for the summary tabulations and figures would be of great help to others wishing to explore the data in alternate ways.

6.   Recommendations about future activities

The workshop participants decided that ESSAS should systematically investigate the major mechanisms by which climate change might be expected to affect the Sub-Arctic seas. To this end, it was proposed to hold a series of annual workshops, each of which would be focused on a different aspect or mechanism by which climate would be expected to influence the Sub-Arctic seas. Initial topics for these proposed workshops

included the role of sea ice, the importance of advection and its sources, and determinants of stratification, among others. Emphasis would be on developing papers that compared all or as many of the ESSAS areas as possible.

An ESSAS Working Group (WG) on modeling was proposed that would include numerical, statistical and conceptual models. The focus would be to investigate specific mechanisms with different models. A WG to deal with future climate change and ecosystem responses was also suggested

Workshop participants also agreed to discuss with PICES about ways in which ESSAS could aid with the development of the next edition of the PICES North Pacific Ecosystem Status Report (NPESR) One suggestion was the possibility of contributing a Chapter comparing the various sub-arctic marine ecosystems within the PICES region.

Noting the strong support of ESSAS by PICES in the past, the view was expressed that ESSAS hopes that PICES would continue to be involved with the sponsorship and organization of our workshops. Past support included co-sponsoring and hosting the initial ESSAS GLOBEC symposium, *Climate Variability and Sub-arctic Marine Ecosystems*, held in Victoria in May 2005 and providing travel support for several of the speakers. PICES helped to organize the St. Petersburg ESSAS Workshop and provided travel support for scientists to participate in the Workshop. It was noted that cooperation with PICES on ESSAS workshops and other activities would gain the support of a strong international organization that shared ESSAS interests in climate impacts on marine ecosystems and the effects of these impacts on the sustainability of sub-arctic marine fisheries. It also would strengthen ESSAS's position in the North Pacific, and facilitate the ability of ESSAS to develop comparative studies there. In return, it was seen that ESSAS could provide PICES with a strong connection to the North Atlantic marine community, provide an entry to IPY activities through the lead role played by ESSAS in ESSAR, and could complement the activities of the PICES CCCC program and potentially that of the new Integrative Science Program to be undertaken by PICES.

6.1. Recommendations

The Workshop made the following recommendations that should be considered by the ESSAS SSC.

1. A Modelling WG should be formed. B. Megrey, L. Cianelli, W. Maslowski and S. Ito are willing to draft a modelling strategy document to plot the way forward.
2. A Predictions WG should be formed. J. Overland agreed to lead this and seek other members. He proposed presenting the new IPCC model results for each subarctic region during a 1-day workshop at the next ESSAS annual meeting as a means of generating discussion on what impact they will have on the ecosystems.

3. A Biophysical Coupling WG should be formed. G. Hunt agreed to head this WG with help from F. Mueter, E. Head, Y. Sakurai, V. Radchenko, K. Wieland, and K. Drinkwater.
4. The WGs should develop terms of reference and indicate their expected duration.
5. ESSAS should conduct annual workshops on focused topics with invitations to outside experts.
6. The 2007 ESSAS meeting should consist of a 1.5 day workshop on the role of sea ice in Sub-Arctic marine ecosystems under the guidance of the WGBC; 1 day of discussion lead by the WGBC; a 1-day workshop on Future Climate under the guidance of the WGP; a ½ day on ESSAS business; and a 1-day ESSAS SSC meeting. Japan agreed to host the meeting in Hakodate in June.
7. The SSC should review the published ESSAS Implementation and Science Plans to develop the long-term (5-year?) objectives.
8. WGBC should develop a strategy with regards to the PICES Marine Ecosystems of the North Pacific report and report back to PICES.

Acknowledgments

Appendix 1: Agenda

ESSAS Workshop

12-14 June 2006
St. Petersburg, Russia

Agenda

Monday, 12 June
08:30: Welcome from the Giprorybflot Institute and from Alex Bychkov of PICES
09:00: Introductions, goals of workshop and adoption of the Agenda (George Hunt and Ken Drinkwater)
09:30: Overview of Climate forcing patterns and mechanisms (Jim Overland)
10:00: Overview of Circulation Patterns and Modeling (Wieslaw Maslowski)
10:30 Break
11:00: Barents Sea (Harald Loeng, Vladimir Ozhigin, and others)
12:00: Lunch
13:30: Newfoundland/Labrador Shelf (Erica Head, Ken Drinkwater, Earle Dawe)
14:30: Sea of Okhotsk and Oyshio Current: (Yasunori Sakurai, Sei-ichi Saito, Valdimir Radchenko, and others)
15:30: Break
16:00: Bering Sea (east and ?west) (Frantz Mueter, Lorenzo Cianelli, and others?)
17:00: Discussion: What are the major pathways of energy flow in common or that are different among these regions?
17:30: End of Monday sessions

Tuesday 13 June:
08:30: What are the mechanisms controlling energy flow that are most susceptible to being affected by climate variability/change? Are they the same in all four systems? Are they of equal importance in all systems? For a given type of perturbation, are they expected to respond similarly? (Discussion leaders: Paul Wassermann, Franz Mueter)
10:00: Break
11:00: Summing up and building a table of pathways, mechanisms and potential responses.
12:00: Lunch
13:30: Do we have appropriate models to address the issues? (Discussion leaders: Wieslaw Maslowski, Bern Megrey, Lorenzo Ciannelli)
14:30: Breakout Sessions: What are the appropriate data sets and are they available?
   a) Climate and Physics
   b) Lower Trophic Levels (Phytoplankton, Zooplankton and Microplankton)
   c) Upper Trophic Levels (Fish, Seabirds, Marine Mammals, and People)
15:30: Break
16:00: Continue Breakouts
16:45: Plenary: What have we learned? Reports from the Breakout Groups

17:30: End of Session

17:45: Dinner Cruise Bus from meeting venue; spouse meet bus at hotel at 17:30

Wednesday, 14 June
09:00: What are the ways forward? (Ken Drinkwater and George Hunt)
      a) Brief reports from other regional studies (e.g., BEST, NORCAN, etc)
      b) How do we structure comparative studies and collaborations?
      c) What is the role of regional ecosystem status reports?
      d) How can reports such as the PICES North Pacific Ecosystem Status
         Report be strengthened?
      e) How does ESSAS strengthen collaborations and exchanges with
         PICES and ICES?
10:30: Break
11:00: Develop Report Outline
11:30: Breakout Sessions for Report preparation
      a) Climate and Physics
      b) Lower Trophic Levels (Phytoplankton, Zooplankton and Microplankton)
      c) Upper Trophic Levels (Fish, Seabirds, Marine Mammals, and People)
12:00: Lunch
13:30: Report Preparation as Breakout Groups
17:00: Plenary Summary of Workshop and future directions (Ken Drinkwater and
      George Hunt)
17:30 Close of Workshop

Appendix 2: Participants:

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