A HISTORY OF PHYSICAL OCEANOGRAPHIC RESEARCH IN THE JAPAN/EAST SEA

BY MIKHAIL A. DANCHENKOV, VYACHESLAV B. LOBANOV, STEPHEN C. RISER, KUH KIM, MASAKI TAKEMATSU, AND JONG-HWAN YOON

Oceanographic research in the Japan/East Sea (JES) has a history similar to other marginal seas that are surrounded by countries that play a central role in world economics and politics (Figure 1). However, due to the specifics of the region's history, its varied cultures, and the different languages of the nations in the region, most regional oceanographic research has been carried out independently by each country. This research has often taken place without complete knowledge of neighboring nations, although in recent years a new degree of international cooperation in the region has emerged.

Perhaps the first truly international oceanographic forum in the region was provided by JECSS (the Japan and East China Sea Study), started under the close collaboration between Japanese and Korean scientists in 1981. This program was followed by the CREAMS (Circulation Research of East Asian Marginal Seas) project in 1993, where, for the first time, Russian oceanographers joined the international team. Consequently, all reviews of the history of the oceanographic research in the region prior to these two programs mostly described national investigations (e.g., Istoshin, 1950; Kawai, 1974; Hahn, 1994). The *Bibliography on the Japan Sea Oceanography* (Danchenkov et al., 2000) tried to list and annotate briefly all available literature, published before the end of last century, from countries in the region. The relative numbers of results published (Russia: 40 percent; Japan: 36 percent; Korea: 20 percent; USA: 3 percent) were similar, indicating the existence of a substantial research community in each country. Yet, because of language difficulties and a lack of availability of some national publications, much of this published material is not familiar to the international community. In this paper we try to partially remedy this problem by describing the history of oceanographic research in the region and the development of our knowledge of physical oceanography of the JES, indicating the most important results and publications.

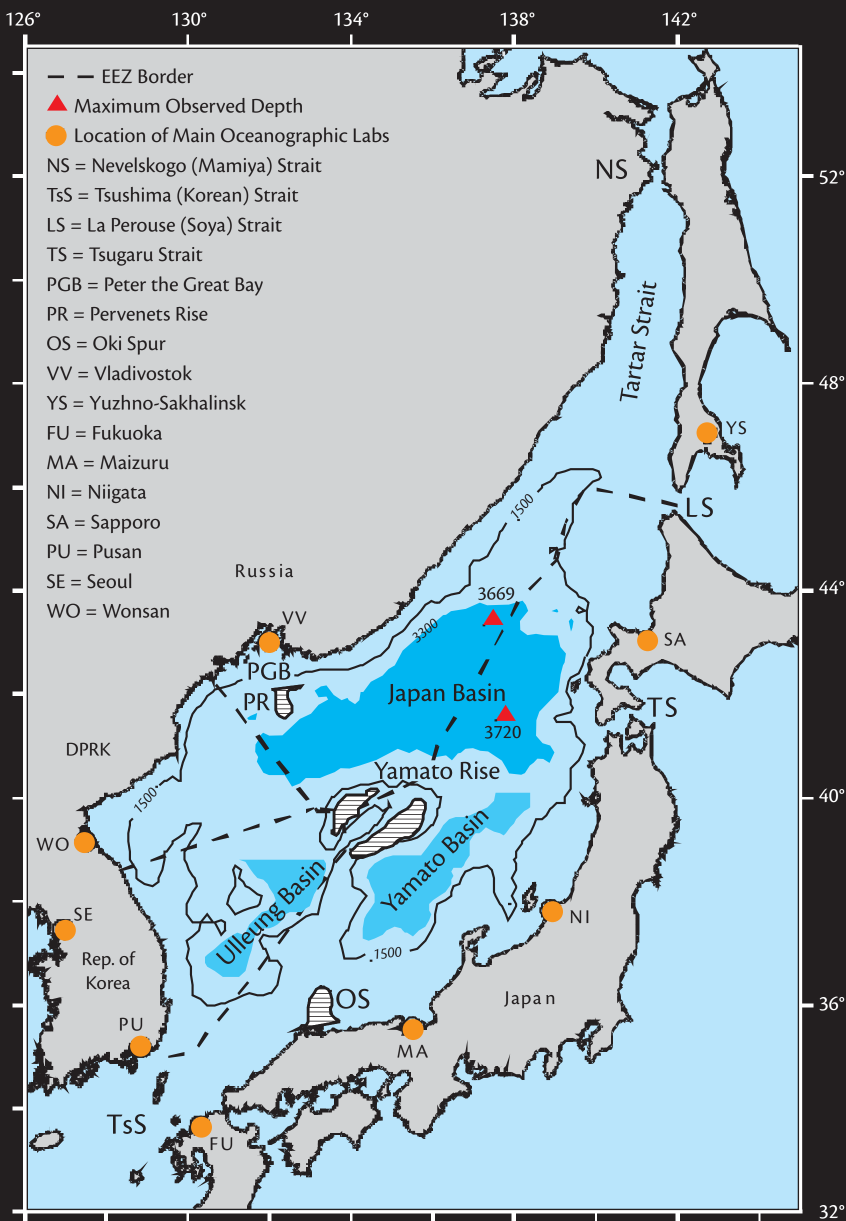

Figure 1. Main geographic features of the Japan/East Sea region.

A CHRONOLOGY

As late as the end of the eighteenth century, knowledge of the large-scale circulation of the JES was lacking, mostly due to the fact that China and Japan, the main national powers in the region at the time, did not sail far from their shores because of a lack of appropriate vessels. The first European voyages with scientific groups on board included a French expedition led by J.F. La Perouse in 1787, an English study of the region under the supervision of W.R. Broughton in 1796, and Russian cruises led by I.F. Kruzenshtern in 1805. Such studies resulted in the first detailed maps of coastal areas, including data on bottom topography and surface currents. These forays into the region by Europeans also stimulated Japan to increase its marine research in the area, leading to the exploration of Hokkaido. By mid-century, the Opium Wars of 1840–1842 and 1856–1860 had weakened China and led to a chain of geopolitical changes in the region that had important influences on oceanographic research activities. Perhaps the most important of these changes was the Beijing Treaty of 1860, effectively confirming Russian jurisdiction of the northwestern coast of the JES and stimulating intense marine exploration of this area. Half a century later, the transfer of southern Sakhalin Island to Japan following the Russian-Japanese War of 1904–1905 and the annexation of Korea in 1910 initiated wider research in the region by Japan. The Russian Revolution in 1917, followed by five years of civil war in Russia, greatly interrupted scientific research activity in the region. Little new work took place during World War II (1941–1945), but after the war's end, the independence of South Korea in 1948 and the end of the Korean War in 1953 allowed for important developments in South Korean research efforts. The political and economic changes that took place in Russia in 1991 had the effect of significantly decreasing Russian national activities in the region; however, these changes resulted in Russian portions of the JES being opened for wide international collaboration for the first time.

In 1859, the Russian Navy conducted the first systematic hydrographic surveys of the JES that included observations of water temperature, density, and currents. A decade or so later, the first two monographs on the physical oceanography of the region appeared based on these investigations (Shrenk, 1870, 1874). The monographs suggested for the first time a scheme for the surface circulation in the basin, and they coined the names for its major components—the Tsushima Current transporting warm water from the East China Sea through the Tsushima Strait, and the Liman Current carrying cold water from the north along the Russian coast (Academician Shrenk believed that the Liman Current originated in the Amur River estuary, or "liman" in the Russian language). Later investigations yielded fifteen more papers on the thermal structure of the sea, the sea-ice regime, and surface currents, all published before 1917. With the exception of the monograph by Admiral Makarov in 1894, most of these papers are rarely referenced but are quite important works, including Maidel (1877, 1878, 1879, 1880), Zuev (1887), Kolchak (1899) and Zhdanko (1913). These works provided more details on the distribution of water temperature, density, and currents in the northern and western parts of the Sea. In particular, the Krillion Cold Current, carrying water from the Okhotsk Sea into the JES through the Soya Strait, was found, and the lack of a relationship between the Liman Current and Amur River discharge was noted. It should be mentioned that special care was taken in to ensure the accuracy of the observations. The thermometers were calibrated at the Greenwich Observatory in Great Britain and an areometer was used to measure density of sea water. During this period, Russian research efforts dominated in the basin. However, the Russian studies were abruptly ended after the October revolution of 1917 and the following civil war; for a period, oceanographic research in the region was concentrated mostly in coastal areas. But, the synthesis of the data collected before the revolution, and reviews of Japanese publications at the time continued (Vize,

Mikhail A. Danchenkov *is Leading Research Scientist, Far Eastern Regional Hydrometeorological Research Institute, Vladivostok, Russia.* **Vyacheslav B. Lobanov** *(lobanov@poi.dvo.ru) is Deputy Director, V.I. Il'ichev Pacific Oceanological Institute, Far Eastern Branch, Russian Academy of Sciences, Vladivostok, Russia.* **Stephen C. Riser** *is Professor, School of Oceanography, University of Washington, Seattle, WA, USA.* **Kuh Kim** *is Professor, School of Earth and Environmental Sciences/Research Institute of Oceanography, Seoul National University, Seoul, Republic of Korea.* **Masaki Takematsu** *is Professor Emeritus, Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka, Japan.* **Jong-Hwan Yoon** *is Professor, Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka, Japan.*

1923; Rudovits, 1927, 1929, 1934; Deryugin, 1930; Bubnov, 1939; Batalin, 1941; Rumyantsev, 1951).

After the Russian Revolution, Japanese investigations in the region intensified and became the dominant research efforts in the Sea during the period of 1922–1945. These studies provided new data on the basin interior. During that era, the major topographic features of the sea (the Yamato Rise and the deep Japan Basin, with depths in excess of 3500 m) were found (Figure 1). The first oceanographic observations reaching depths of more than one thousand meters were carried out in the western part of the Sea by the Kobe Marine Observatory research vessel *Shumpu Maru* in 1928–1930. In the 1930s, newly established marine observatories in Pusan (Korea), Maizuru (Japan), and at other locations began oceanographic observation programs, with the emphasis shifting from mostly coastal studies to large-scale surveys of the JES. The expeditions of 1932 and 1933, conducted by M. Uda using the research vessels *Soya* and *Misago* and more than 50 fisheries vessels, were the first known systematic, basin-scale surveys of physical oceanographic characteristics, including properties of the deep waters, of the JES (Uda, 1934). Although the first important Japanese papers appeared well in advance of this work (e.g., Wada, 1916 [as cited by Kawai, 1974]; Suda, 1932), Uda (1934) presents a comprehensive description of the surface circulation and the main water masses of the JES. These reports form the foundation for our contemporary view of JES circulation—the Uda study has long been referred as the basic source of oceanographic knowledge of the JES. In particular, Uda remarks on the extremely low temperature, high oxygen content, and remarkable homogeneity of the deep waters of the JES, indicating their formation by wintertime convection and frequent renewal. It should be mentioned, however, that for Japan and Russia/Soviet Union, the JES was not considered as the highest priority for national oceanographic research because geographically it was located at the periphery of each country's economic activity. After 1941, research in the region was severely limited by World War II and the Korean War, events that destroyed all of the national economies in the region. No significant new results were obtained for some time.

These two wars, however, stimulated interest in the JES region by other countries (Air Ministry, 1944), particularly the United States. This interest continued for many years and resulted in the publication of important works such as an atlas of temperature, salinity, and density (La Violette and Hamilton, 1967), reviews on oceanographic conditions (Boyd, 1995; Preller and Hogan, 1998), and original research papers (e.g., Martin and Kawase, 1998; Riser et al., 1999).

A new round of intensive investigations in Russia (then, the Soviet Union) began with a few surveys of the JES implemented in 1949, 1951, and 1955 by the Soviet Academy of Sciences using the Research Vessel (R/V) *Vityaz*. Observations were conducted in various seasons and resulted in new data concerning the distributions of physical and chemical properties, a new scheme for the circulation, and detailed charts of bottom relief with newly found topographic features (Russian Academy of Sciences, 1961). In addition to oceanographic surveys, the investigation of tides and currents using mooring systems were initiated in the northwestern and northern coastal areas. Other Russian/Soviet monographs were published during that time. One of the most important was prepared by the Far Eastern Regional Hydrometeorological Research Institute (FERHRI) in 1956 (Pokudov and Supranovich, 1975). Although this work contained the best summary of knowledge of the physical oceanography of the JES available at that time, it is considered confidential even today and not generally available to the wider oceanographic community. Another monograph, based on analyses of data obtained before World War II, is a now well known and often quoted monograph by A.K. Leonov issued in 1960. The work contains analyses of JES

...because of language difficulties and a lack of availability of some national publications, much of this published material is not familiar to the international community.

meteorology, waves, tides, currents, and water masses. Following 1959, Russian/Soviet research expeditions in the JES were episodic.

Early in the 1960s, oceanographic research by South Korean scientists began in the JES. For various reasons, it was mostly limited to the areas adjacent to South Korea; later, these regions were defined as the exclusive economic zones (EEZ). By this time the number of dedicated field programs in the basin had decreased considerably. Instead, each country in the region had turned to routine monitoring rather than groundbreaking new programs. Observations along repeated sections were started in Japan, South Korea, and Russia; most of these efforts continue today, providing many valuable time series 40–50 years long. These sections are generally limited by the EEZs of each country and have quite good coverage in Japan and South Korea. There are only four repeat sections still being carried out by fisheries research institutes in Russia. There are no known sections being occupied regularly in the EEZ of North Korea. At larger spatial scales, there are four long sections, crossing the entire JES from coast to coast, implemented by Russian/Soviet scientists at FERHRI in the 1960–1970s and continuing periodically to the present.

With the huge growth in the research fleet by the 1970s, Russia returned to carrying out large-scale surveys of the JES. The group at FERHRI implemented three cruises by the R/Vs *Okean* and *Priliv* in 1974–1976 and 12 more cruises by R/Vs *Vyacheslav Frolov*, *Shokalsky*, and *Valerian Uryvaev* during the period 1984–1990. The purpose of these surveys was to examine the circulation and water-mass characteristics. Accuracy constraints of the first-available conductivity-temperature-depth (CTD) systems, and the use of the salinity titration method, did not permit studies of the homogeneous deep waters. As a result, the research at that time was mostly focused on the upper 500 m of the JES. An immense quantity of data was accumulated during that period, but no breakthroughs were made concerning the deeper waters of the JES because of these constraints.

Despite the already extensive studies of the Japan/East Sea there is still great potential for further research.

Among the synthesis monographs of that period, the detailed Japanese atlases of bottom topography (Mogi, 1979) and marine environment (*Marine Environmental Atlas*, 1975, 1978), as well as the *Oceanographic Atlas of Korean Waters* (Hahn, 1978) should be mentioned. Analysis of moored current-meter data and diagnostic calculations of the circulation were presented in a monograph on JES currents (Yurasov and Yarichin, 1991). The most recent FERHRI monograph, *The Sea of Japan*, contains a description of the hydrography of the JES based on extensive databases of mean physical and chemical properties of the water, meteorological characteristics and their statistics, and a summary of basic knowledge of the JES accumulated through 2000 (FERHRI, 2003).

The modern period in the exploration of the JES (the late 1970s through the present) can be characterized by the application of new technology to oceanographic research, including high-accuracy CTD systems, current meters, the use of chemical tracers, and remote sensing. These technical developments opened new opportunities for discovery. The first satellite infrared images showed the detailed thermal structure of the JES, with numerous frontal features associated with mesoscale dynamics (e.g., Huh, 1976). Observations with a high-accuracy Neil Brown MK-III CTD system carried out during this period by Japanese scientists (Gamo and Horibe, 1983; Gamo et al., 1986) presented vertical fine structure of temperature and salinity profiles, allowing identification of intermediate and deep waters, and estimation of the degree of vertical variation in deep-water salinity. Previous values of deep-water salinity (34.15–34.20) (e.g., Pokudov et al., 1976; Pischalnik and Arkhipkin, 2000) were seen to be in error. An extremely important result, the long-term decrease in dissolved oxygen content in deep water of the JES, was noted for the first time. The first long-term moored current measurements

(Kitani, 1987, 1989) resulted in the first ideas on abyssal circulation patterns and their variability.

A new era in basin-scale, systematic research activities in the JES was stimulated by the beginning of international collaboration in the region. International conferences organized by the East-West Center based in Hawaii resulted in well-received monographs presenting multidisciplinary knowledge of the JES (e.g., Valencia, 1989; Morgan and Valencia, 1992). The biennial symposia of the Japan and East China Sea Study (JECSS)—the first international program in the region, started in 1981, and involved close collaboration between Japanese and Korean scientists (Ichiye, 1984)—provided an opportunity for close interactions between colleagues of the region and other countries. By the initiative of scientists from Japan (M.Takematsu and J.-H.Yoon), Korea (K.Kim), and Russia (G.Yurasov, M.Danchenkov and Y.Volkov) a new international project specifically dedicated to circulation and physical properties of the JES waters (i.e., CREAMS) was created (Takematsu, 1994). The field portion of CREAMS began with an expedition using the Russian R/V *Professor Khromov* in 1993 and was conducted jointly by Japanese, Korean, and Russian oceanographers. This work was followed by seven more cruises conducted through 1999. The CREAMS project was led by a team of scientists from Kyushu University (Japan), Seoul National University (South Korea), and FERHRI (Russia), with the additional participation of colleagues from more than ten other organizations. Important components of the project were annual (1994–2000) symposia that provided a strong impetus for expansion of international collaboration and further research in the JES. CREAMS, including the international expeditions and workshops, was the first truly international, long-term research program in the JES. The program yielded highly productive results.

CREAMS was followed by another international effort initiated by the U.S. Office of Naval Research (ONR) during 1997–2001. The ONR program included more than 15 research projects that collected detailed, basin-scale observations using a variety of techniques, including highly accurate hydrographic surveys, chemical and biological sampling, sophisticated mooring systems, profiling floats, and remote sensing. Advanced numerical modeling of the circulation of the JES was also emphasized. Some of the results of this program are presented elsewhere in this issue. In 2005, an entire issue of *Deep-Sea Research II* was devoted to papers based on this effort.

The interactions of physical, chemical, and biological studies have been strongly supported in recent years by the North Pacific Marine Science Organization (PICES), which co-sponsored the CREAMS/PICES workshop on *Recent Progress in Studies of Physical Processes and Their Impact to the Japan/East Sea Ecosystem* at Seoul National University in South Korea in 2002. Nine comprehensive papers out of this workshop were published in a Special Issue of *Progress in Oceanography* (2004, 61[2–4]). Recently, PICES established a new program called CREAMS/PICES in 2004 to expand international collaboration of interdisciplinary research on the state of the JES and its changes in the future (PICES, 2005).

PRESENT KNOWLEDGE OF MAJOR FEATURES AND FUTURE CHALLENGES

Despite the already extensive studies of the JES there is still great potential for further research. There remain some uncertainties in the basic properties of the JES, such as reliable estimates of its mean area and the maximum depth of the basin. There are a variety of estimates for the maximum depth presented in the literature, ranging from 3610 m (Harada and Tsunogai, 1986), to 3670 m (Russian Academy of Sciences, 1961), to 3700 m (Gamo and Horibe, 1983), to 4018 m (Leonov, 1948), to 4038 m (Leonov, 1960), and to 4049 and 4224 m (Hidaka, 1966). In spite of extensive Russian investigation, depths in excess of 4000 m have not been confirmed, and it is not clear that depths exceeding 3669 m (Russian Academy of Sciences, 1961) are actually present even though some navigation charts show an area close to Tsugaru Strait with a depth reaching 3720 m (Figure 1). More studies are required to better understand the physical properties of water masses and circulation, although these were studied quite intensively over the historic period. Geographically, among the less-studied areas is the northern part of the JES, including Tartar Strait.

Water Masses

Some argue the circulation and ventilation of the JES interior, and the mechanism of formation and distribution of its water masses, are the most intriguing topics in physical oceanography of the sea. Here we present a brief history of development of our knowledge of these processes.

The first known classifications of JES water masses were based on the deep observations by Japanese researchers in the late 1920s and early 1930s. The classification by Suda (1932) showed that the southern part of the JES contained warm surface water (0–25 m), more saline intermediate water with a core at 200–250 m, deep water centered around a minimum of *in situ* temperature (around 1500 m), and underlying bottom water. Soon after, Uda (1934) suggested a better classification. It included the whole basin and identified two surface water masses, corresponding to the warm southern and cold northern regions of the JES divided by the Polar Front. (This front has also been referred to as the Subpolar or Subarctic Front, which is more consistent with the classification of oceanic fronts suggested later). Although he distinguished the deep and bottom waters, Uda noted the high homogeneity of temperature and salinity in these layers and integrated them into one single water mass with temperature below 1°C, which has since been known as Japan Sea Proper Water.

A careful examination of temperature, salinity, dissolved oxygen, and nutrient profiles suggested that the Proper Water consisted of several water masses. Based on the vertical gradient of potential temperature, Nitani (1972) inferred the existence of Deep Water, Upper Bottom Water, and Lower Bottom Water, the latter characterized by extreme vertical homogeneity. He found differences in the Lower Bottom Water properties of three deep basins—Japan, Yamato, and Ulleung—and their interannual fluctuations. Sudo (1986) and Senjyu and Sudo (1993, 1994) identified the Upper Portion of the Proper Water near 1000 m as having high oxygen content and weak stratification, suggesting that it is well ventilated in winter. On the other hand, Gamo and Horibe (1983) inferred the boundary between deep and bottom water to be around 2000 m, based on a discontinuity of temperature, dissolved oxygen, and silica profiles. This finding confirmed the outstanding vertical homogeneity of the layer located below. This work slightly simplified Nitani's classification (Lower Bottom Water). A similar three-layer classification was also suggested based on CREAMS observations, distinguishing central, deep, and bottom waters in this depth range (Kim et al., 2001).

Miyazaki (1953) suggested a detailed classification of surface and intermediate waters. In particular, he noted a large layer of low-salinity intermediate water with high oxygen content, probably formed near the Polar Front. Later, a distinct salinity-minimum layer was found in the areas around Korea, underlying Tsushima Warm Water (Kim and Chung, 1984). This layer was also common to the southwestern part of the JES and was referred to as East Sea Intermediate Water (e.g., Kim et al., 1991). CREAMS observations covering the western and eastern part of the JES modified these intermediate water observations. CREAMS found that, typically, intermediate waters of the western part of the JES have low salinity (below 34.06) and waters of the eastern part have salinity in excess of 34.07. This latter water mass was named High-Salinity Intermediate Water (Kim and Kim, 1999). Watanabe et al. (2001) and Zhabin et al. (2003) presented more studies on the high-salinity intermediate water characteristics and origin. The high oxygen content of these waters suggests their recent origination from surface water, with differing salinities in the west and east parts of the JES.

Leonov (1960) and Zuenko and Yurasov (1995) classified water masses for the northern areas of the JES, with an emphasis on the northwestern shelf and Tatar Strait. The latter paper presents various local modifications of waters masses. One of the specific features of these areas is the existence of a cold subsurface layer (inversion of temperature at 20–75 m) in summer (Zuenko, 1994; Danchenkov, 2004).

In spite of relatively good agreement on water-mass classification, the particular mechanisms and sites of formation are not clear. Noting the low temperature and high oxygen content of intermediate, deep, and bottom waters, it has been speculated/hypothesized in works since the 1930s that their formation occurs to the north of Polar Front and is associated with winter convection due to cooling, evaporation, and ice formation. As for the intermediate low-salinity water, subduction along the front followed by advection to the south and east could be the main mechanism of its formation (Yoon and Kawamura, 2002). There is no consensus, however, on the major source of low-salinity surface water in the northern part of the sea—in this regard, intense summer precipitation, melting of sea ice, local river discharge, remote summer input from the Amur River, or inflow from the East China Sea are all possible candidates. As for the High-Salinity Intermediate Water, its formation mechanism is often considered to be related to mixing between waters formed by deep convection in winter in the northern area and saline water of Tsushima Current origin advected toward the Russian coast (Watanabe et al., 2001; Zhabin et al., 2003).

Martin et al. (1992) and Martin and Kawase (1998) examined the role sea ice and heat fluxes play in deep and bottom water formation in the Tatar Strait. Low-salinity surface water seems to prevent deep convection in this area. Extremely strong heat fluxes in the northwestern area off Peter the Great Bay were confirmed by Kawamura and Wu (1998), based on satellite scatterometer and infrared data, suggesting this area is a key location for deep convection. Talley et al. (2003) confirmed this deep convection with winter observations in 2000 and 2001, when open-sea convection was observed penetrating down to 1100–1500 m. Direct observations of bottom water ventilation were obtained by several studies during the severely cold winter of 2000–2001 (Lobanov et al., 2002; Kim et al., 2002; Senjyu et al., 2002; Talley et al., 2003), when new bottom water is first found at the slope of Peter the Great Bay in layers 300–800-m thick at the bottom (2000–3000 m). This newly formed water was distributed over the western part of Japan Basin down to 40°N by April–June of the same year and down to 38°N toward Ulleung Basin by the following year (2002). Although it was suggested that the major mechanism for the bottom water renewal is associated with brine rejection and slope convection off Peter the Great Bay, the observed variations in the properties of recently formed bottom water suggest that there are several formation mechanisms and locations (Lobanov et al., 2002).

It is understood that ventilation processes in the interior of the Sea depend on heat, mass, and momentum fluxes at the surface, which impose interannual variations and long-term trends associated with climatic changes over the region. Thus, changes in the nature and intensity of wintertime convection and ventilation modify the subsurface water properties from year to year and should be extremely important in determining the properties of the bottom water, whose renewal depends on deep convection. Nitani (1972) observed and Gamo et al., (1986) confirmed the long-term changes in deep and bottom water properties in the JES (the tendency toward increasing temperature and decreasing of dissolved oxygen content for the deep and bottom waters). These changes have become perhaps the most interesting topic in JES oceanography (e.g., Ponomarev et al., 1996; Kim et al., 1999; Gamo et al., 2001; Kim et al., 2002; Kwon et al., 2004)

> ...good international collaboration is essential for success, as was proved by first the CREAMS program and the following multinational efforts.

Surface Currents

A review by Kawai (1974) provides abundant information on the evolution of knowledge of water circulation in the JES. Shrenk (1874) presents the first known scheme of surface circulation. It was based on observations of water temperature and ship drift by Russian navy vessels of opportunity. Shrenk gave the names to the Tsushima Current flowing from the Tsushima Strait to the northeast along the Japanese coast and the Liman Current originated in the north and directed southwestward along the coasts of Russia and Korea (Figure 2a). A number of schemes constructed later by Japanese investigators were forgotten once the scheme by Uda (1934) was introduced (Figure 2b). He deduced the main features of the sea surface circulation that were confirmed by subsequent studies, including the existence of at least three cyclonic gyres in the northern part of the JES. Thus, these gyres divide the southwestern flow along the Asian continent into three segments named the Liman, Primorye, and North Korean cold currents. Seasonal variations of surface circulation were presented in more detailed schemes by Naganuma (1977) (Figure 2c,d). Although not many data were available for the winter season, these schemes indicated important changes of the flow pattern in the northwestern part of the JES that were later studied in more detail. Uda's scheme is still in use today, with various modifica-

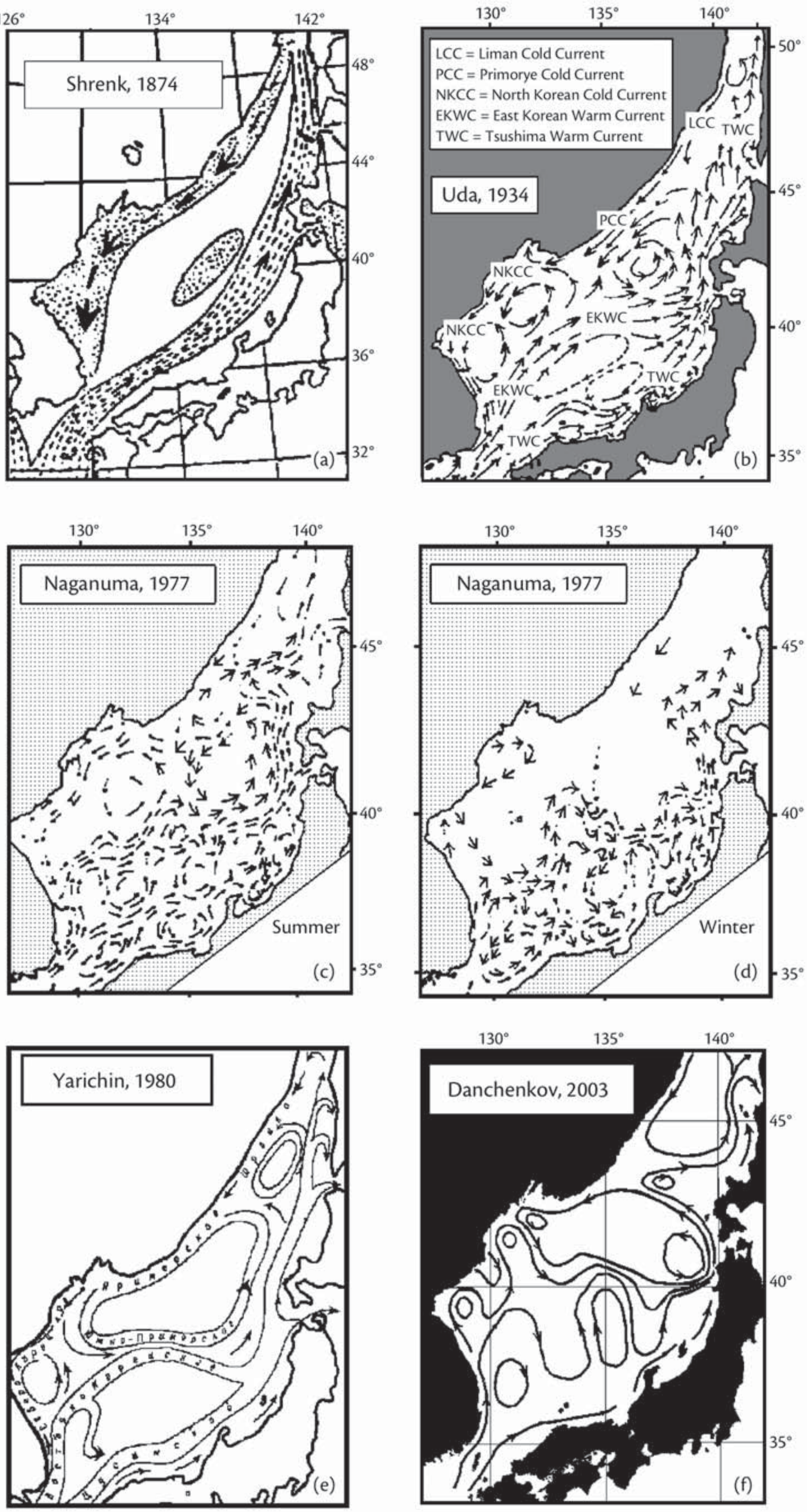

Figure 2. The schemes of surface circulation adopted from (a) Shrenk (1874), (b) Uda (1934), (c, d) Naganuma (1977), (e) Yarichin (1980) and (f) Danchenkov (2003a,b).

tions. For example, Yarichin (1980), and later Yurasov and Yarichin (1991) (Figure 2e), added some additional elements to the circulation and suggested modified names for the northernmost part of the along-slope flow in the northwest, such as the Shrenk Current (previously named Liman Current by Shrenk and Uda). The latter flows along the Russian region known as Primorye (not Siberia), and as such this name is geographically more correct. Recent studies have added a few more elements of circulation, such as an anticyclonic gyre off Northern Korea (e.g., Yoon and Kawamura, 2002) that forms a northwestern branch of the Subarctic Front with a corresponding southeastern flow along the front that starts just to the west of Peter the Great Bay (Danchenkov, 2003a); a western branch of the Tsushima Current that transports warm saline water from the area of Tsugaru Strait to the west towards the Russian coast (Figure 2f) (Danchenkov et al., 2000a, b); and a seasonal reversal of the North Korea Current (Danchenkov et al., 2003a; Lee and Niiler, 2005). These flows control salinity in the northwestern part of the JES, where deep convection occurs in winter, and thus are important for the ventilation of the JES interior.

Application of numerical models showed results similar to the observed large-scale circulation pattern and revealed the major causes of its structure and variability. The pioneering works by J.H. Yoon helped to clarify the causes of the branching of the Tsushima Current after it enters the JES (e.g., Yoon, 1982); these works were followed by many modeling efforts (e.g., Holloway et al., 1995; Kim and Yoon, 1999; Hogan and Hurlburt, 2000; Yoon and Kawamura, 2002). Although steady improvements in the models have been made, in most cases the models still fail to accurately represent some important features of water-mass formation.

Although the general features of circulation in the southern part of the JES and transport through Tsushima Strait are quite well studied (e.g., Teague et al., 2005a,b), the scheme of currents for the northern regions is not so clear, especially for the areas of Tatar Strait, La Perouse (Soya) Strait, and the Amur Liman (estuary) (Danchenkov, 2004). Even in the narrow and shallow Nevelskogo (Mamiya) Strait, long-term measurements show currents in both directions (20 days from the sea and 20 days into the sea; see Danchenkov and Rykov, 2005). But long-term measurements across these straits have generally been scarce until very recently. The cold current in the La Perouse Strait (mentioned above as the Krillion Cold Current) and the branches of the Sakhalin Current have not been well investigated (Danchenkov et al., 1999). The penetration of cold water near Cape Krillion could be explained by the so-called West Sakhalin Current (e.g., Yurasov and Yarichin, 1991), although this would seem to contradict the accepted salinity distribution.

Circulation of Intermediate and Deep Waters

In spite of many attempts, the circulation of intermediate and deep waters has still not been clarified completely. The circulation of the upper portion of Japan Sea Proper Water (above around 1000 m) was deduced from the property distribution on the relevant isopycnal surfaces (Senjyu and Sudo, 1993, 1994). It circulates from the Japan Basin following the continental slope and part of it spreads south to the Ulleung Basin and then to the Yamato Basin. Experiments with ALACE floats showed an antycyclonic gyre in the eastern part of Japan Basin at the intermediate layer (300 m), a strong eastward current along the Polar Front, and southeastward flow off the area of Peter the Great Bay corresponding to the northwestern branch of the Front (Yanagimoto and Taira, 2003). Later extensive deployments of profiling floats by S. Riser (University of Washington) have confirmed a general anti-clockwise circulation in the Japan Basin, a stable deep (800-m) cyclonic gyre in the eastern part of the basin, a strong current along 43°N (the western branch of Tsushima Current), and a southeastward current along the northwestern front (Danchenkov et al., 2003b).

For the deeper layers, it has been suggested, based on the distribution of chemical parameters, that a similar circulation pattern to that of the upper layers exists (Gamo and Horibe, 1983; Gamo et al., 1986). The homogeneity of water properties in these layers has made it difficult to form reliable estimates of the circulation. The first long-term moored measurements of currents were implemented by Kitani (1987, 1989) and were followed by the intensive work of the CREAMS group in the 1990s. These measurements showed vertically coherent flows in the Proper Water and strong bottom currents exceeding 5 cm sec^{-1} (Takematsu et al., 1999a). Korean oceanographers carried out a multi-year research program on deep circulation in the Ulleung basin (Chang et al., 2002, 2004). Senjyu et al. (2005) recently presented a synthesis of those data and subsequent instrumental observations obtained though the period 1986–2003 by 177 current meters at 69 sites. The synthesis confirmed relatively strong cyclonic circulation along the peripheries of the basin, with the currents intensifying at the western edges; a similarity of flow patterns for the upper (400–1000 m) and lower (1000 m-bottom) layers; and a significant dominance of eddy versus mean kinetic energy of the flow in the basin interior.

In recent years, great strides have been made in understanding the character of mesoscale variability in the southern portion of the JES. As part of the U.S.-sponsored program, a high-resolution array of instruments was deployed in the Ulleung Basin over a two-year period to examine the length and time scales of eddy motions in the region, eddy energetics, and the interactions of eddies with the mean currents in the region. These results have been reported by Mitchell et al. (2005) (for the upper ocean) and Teague et al. (2005b) (for deep circulation). The observations show strong mesoscale variability throughout the water column, strongly tied to local bathymetry and the presence of nearby strong mean currents.

Mesoscale Water Dynamics

The existence of mesoscale eddies was recognized in the JES since the first detailed hydrographic surveys were undertaken. After satellite images were available, it became clear that these features were an essential component of the circulation, playing an important role in water-mass modification and fluxes (e.g., Ichiye and Takano, 1988). The first eddy studies were focused on the southern part of the JES, where strong anticyclonic features with typical diameters of 50–150 km related to the branches of Tsushima Current were found around Oki Spur. Other features were found to the east (Isoda, 1994), off the Korean Peninsula (e.g., Isoda and Saitoh, 1993; An et al., 1994), over the Ulleung Basin (Lie et al., 1995; Gordon et al., 2002) and near the Yamato Rise (Isoda et al., 1992). Features showing less contrast in the satellite images, though still recognizable, were also found in the area to the north of Subarctic Front (e.g., Sugimoto and Tameishi, 1992). It was shown recently that at least some of these eddy structures are stable and long-lived, existing over the deep Japan Basin from a few months to more than a year and drifting southeastward and eastward out of the northwestern corner of the Sea (Danchenkov et al., 1997). This observation has been supported by satellite altimetry analysis (Morimoto et al., 2000) and moored current measurements (Takematsu et al., 1999b). Current-meter measurements have shown a deep penetration of the eddies and a strong barotropic component. Extreme values of water properties inside eddy cores, corresponding to both low-salinity and high-salinity intermediate water masses, have suggested that these features play an important role in the water-mass transport and distribution through the basin (Lobanov et al., 2001). Because of the compact location of eddies, they have interacted with each other by the generation of streamers, resulting in the merging and splitting of various eddies. This water movement has created chain-like structures that can provide for the rapid transport of warm waters and biological species from the subtropical areas at the southern end of the JES to the more northern regions (Sugimoto and Tameishi, 1992; Danchenkov et al., 1997). The role of eddies in the horizontal and vertical fluxes of physical and chemical parameters and their impact on living marine organisms needs further investigation.

> This miniature ocean still keeps its secrets, perhaps to be discovered in time through continuing, long-term international collaborations.

CONCLUSION

The JES is often referred to as a miniature ocean (e.g., Ichiye and Takano, 1988), as it has many of the major features of global oceanic circulation, such as boundary currents, frontal zones, eddies, and deep-water formation associated with both open-sea and slope convection. It resembles a self-maintained system, sensitive to variations of external forcing caused by climate changes. These characteristics, coupled with its relatively small size, make the JES a manageable site for carrying out sustained observations. Studying the JES is very attractive for researchers, both from neighboring countries and elsewhere. Mainly questions concerning physical oceanography have been mentioned here, and biogeochemical issues have not been touched on. Biogeochemical issues are present in the JES, and are being treated in detail at the present time in a new round of sustained field experiments.

The history of oceanographic study of the JES is largely a history of separate attacks rather than permanent impacts. The dramatic historical events in the region are responsible not only for weak communication among the surrounding countries, but also for discontinuities in oceanographic knowledge within each of them. In spite of the fact that many oceanographic research papers have been published, a considerable portion of the literature has never been cited. Unfortunately, official policy plays an important role in the progress of oceanography. Formally, the JES has essentially no truly international waters and instead is divided into exclusive economic zones, each carrying some restrictions for foreign scientific research. Most areas of the JES where we have the scarcest knowledge are located in the north and northwest, in particular, off North Korea. Under these circumstances, good international collaboration is essential for success, as was proved by first the CREAMS program and the following multinational efforts. This miniature ocean still keeps its secrets, perhaps to be discovered in time through continuing, long-term international collaborations.

REFERENCES

Air Ministry. 1944. *Monthly SST and Surface Current Circulation of the Japan Sea and Adjacent Waters*. Air Ministry, London, 15 pp.

An, H., K. Shim and H.-R. Shin. 1994. On the warm eddies in the southwestern part of the East Sea (the Japan Sea). *Journal of Korean Oceanographic Society* 29:152–163.

Batalin, A.M. 1941. *Atlas of Surface Currents of the Japan Sea.* Hydrometeorological Office of USSR Pacific Navy, Vladivostok, 24 pp.

Boyd, J.D. 1995. Descriptive physical oceanography of the North Pacific, Sea of Japan (East Sea) and Sea of Okhotsk. *Arctic Research* 9:72–80.

Bubnov, V.K. 1939. *Hydrological conditions of the Japan Sea.* Hydrographic Office of USSR Navy, Leningrad, 13 pp.

Chang, K.-I., N. Hogg, M.-S. Suk, S.-K. Byun., Y.-G. Kim, and K. Kim. 2002. Mean flow and variability in the southwestern East Sea. *Deep-Sea Research* 49:2,261–2,279.

Chang, K.-I., W.J. Teague, S.J. Lyu, H.T. Perkins, D.-K. Lee, D.R. Watts, Y.-B. Kim, D.A. Mitchell, C.M. Lee, and K. Kim. 2004. Circulation and currents in the southwestern East/Japan Sea: Overview and review. *Progress in Oceanography* 61:105–156.

Danchenkov, M.A. 2003a. Non-periodic currents of the Japan Sea. Pp. 313–326 in *Hydrometeorology and Hydrochemistry of RF Seas—The Japan Sea*, vol. 8. Gidrometeoizdat, St. Petersburg, Russia.

Danchenkov, M.A. 2003b. Sea water density distribution in Peter the Great Bay. *Pacific Oceanography* 1(2):179–184.

Danchenkov, M.A. 2004. Spatial structure of the Tartar Strait waters. *Pacific Oceanography* 2(1–2):20–43.

Danchenkov, M.A., and N.A. Rykov. 2005. *Water Transport Through the Nevelskogo Strait*. Report at Symposium on Amur-Okhotsk project. Kyoto, March 22-24, 17 pp.

Danchenkov, M.A., V.B. Lobanov, and A.A. Nikitin. 1997. Mesoscale eddies in the Japan Sea, their role in circulation and heat transport. In: *Proceedings of the CREAMS-97 Symposium*, 81–84.

Danchenkov, M.A., D.G. Aubrey, and S.C. Riser. 1999. Oceanographic features of La Perouse strait. *PICES Scientific Report* 12:159–171.

Danchenkov, M.A., D.G. Aubrey, and G.H. Hong. 2000a. Bibliography of the oceanography of the Japan/East Sea. *PICES Scientific Report* 13, 99 pp.

Danchenkov, M.A., D.G. Aubrey, and V.B. Lobanov. 2000b. Spatial structure of the northwestern Japan Sea waters. *FERHRI Special Works* 3. Far Eastern Regional Hydrometeorological Research Institute (FERHRI), Vladivostok, Russia, 92–105.

Danchenkov, M.A., D.G. Aubrey, and K.L. Feldman. 2003a. Oceanography of area close to the Tumannaya river mouth (the Japan Sea). *Pacific Oceanography* 1(1):61–69.

Danchenkov, M.A., S.C. Riser, and J.-H. Yoon. 2003b. Deep currents of the central Sea of Japan. *Pacific Oceanography* 1(1):6–15.

Deryugin, K.M. 1930. Japanese hydrological investigations in the Japan and Okhotsk Seas. *Zapiski po Gidrographii* 59:35–51.

FERHRI (Far Eastern Regional Hydrometeorological Research Institute). 2003. *The Sea of Japan*. Hydrometeorological conditions. Gidrometeoizdat, St. Petersburg, 398 pp.

Gamo, T., and Y. Horibe. 1983. Abyssal circulation in the Japan Sea. *Journal of the Oceanographic Society of Japan* 39(2):220–230.

Gamo, T., Y. Nozaki, H. Sakai, T. Nakai, and H. Tsubota. 1986. Spacial and temporal variations of water characteristics in the Japan Sea bottom layer. *Journal of Marine Research* 44(4):781–793.

Gamo, T., M. Momoshima, and S. Tolmachyov. 2001. Recent upward shift of the deep convection system in the Japan Sea, as inferred from the geochemical tracers tritium, oxygen and nutrients. *Geophysical Research Letters* 28(21):4,143–4,146.

Gordon, A.L., C.F. Giulivi, C.M. Lee, H.H. Furey, A. Bower, and L. Talley. 2002. Japan/East Sea intrathermocline eddies. *Journal of Physical Oceanography* 32(6):1,960–1,974.

Hahn, S.D., ed. 1978. *Oceanographic Atlas of Korean Waters: 1. Temperature Structure*. Korea Ocean Research and Development Institute (KORDI), Seoul, Korea, 293 pp.

Hahn, S.D. 1994. *Physical Oceanography in Korea: History and Perspectives*. *KODC Newsletter* 23:39–61.

Harada, K., and S. Tsunogai. 1986. 226-Ra in the Japan Sea and the residence time of the Japan Sea water. *Earth and Planetary Science Letters* 77:236–244.

Hidaka, K. 1966. The Japan Sea. Pp. 417–424 in *The Encyclopedia of Oceanography*, R.W. Fairbridge, ed. Reinhold Publishing Corporation, New York, NY.

Hogan, P.J., and H.E. Hurlburt. 2000. Impact of upper ocean-topography coupling and isopycnal outcropping in Japan/East Sea models with 1/8° to 1/64° resolution. *Journal of Physical Oceanography* 30:2,535–2,561.

Holloway, G., T. Sou, and M. Eby. 1995. Dynamics of circulation of the Japan Sea. *Journal of Marine Research* 53(4):539–569.

Huh, O.K. 1976. Detection of oceanic thermal front off Korea with the defense meteorological satellites. *Remote Sensing of Environment* 5:191–213.

Ichiye, T. 1984. Some problems of circulation and hydrography of the Japan Sea and the Tsushima Current. Pp. 15–54 in *Ocean Hydrodynamics of the Japan and East China Seas*, T. Ichiye, ed. Elsevier, Tokyo, Japan.

Ichiye, T., and K. Takano. 1988. Mesoscale eddies in the Japan Sea. *La Mer* 26(2):69–75.

Isoda, Y. 1994. Warm eddy movements in the eastern Japan Sea. *Journal of Oceanography* 50(1)1–16.

Isoda, Y., and S. Saitoh. 1993. The northward intruding eddy along the east coast of Korea. *Journal of Oceanography* 49:443–458.

Isoda, Y., M. Naganobu, and H. Watanabe. 1992. A warm eddy above the Yamato Rise. *Memoirs of the Faculty of Engineering, Ehime University* 12(3):355–365.

Istoshin, Yu.V. 1950. Hydrological conditions during the 1949 spring fishing season at south-west Sakhalin coast. *Trudy TCIP* 21:53–64.

Kawai, H. 1974. Transition of current images in the Japan Sea. Pp. 7–26 in *Tsushima Warm Current-Ocean Structure and Fishery*. Fishery Society of Japan, Tokyo.

Kawamura, H., and P. Wu. 1998. Formation mechanism of the Japan Sea Proper Water in the flux center off Vladivostok. *Journal of Geophysical Research* 103(C10): 21,611–21,622.

Kim, C.H., and J.H. Yoon. 1999. A numerical modeling of the upper and the intermediate layer circulation in the East Sea. *Journal of Oceanography* 55:327–345.

Kim, K., and J.-Y. Chung. 1984. On the salinity minimum layer and dissolved oxygen-maximum layer in the East Sea (Japan Sea). Pp. 5,565 in *Ocean Hydrodynamics of the Japan and East China Seas*, T. Ichiye, ed. Elsevier, Tokyo.

Kim, K., K.-R. Kim, J.Y. Chung, and H.S. Yoo. 1991. Characteristics of physical properties in the Ulleung Basin. *Journal of the Oceanological Society of Korea* 26:83–100.

Kim, K., Y.-G. Kim, Y.-K. Cho, M. Takematsu, and Y. Volkov. 1999. Basin-to-basin and year-to-year variation of temperature and salinity characteristics in the East Sea. *Journal of Oceanography* 55:103–109.

Kim, Y.-G., and K. Kim. 1999. Intermediate waters in the East/Japan Sea. *Journal of Oceanography* 55(2):123–132.

Kim, K.-R., G. Kim, K. Kim, V. Lobanov, V. Ponomarev, and A. Salyuk. 2002. A sudden bottom-water formation during the severe winter 2000–2001: The case of the East/Japan Sea. *Geophysical Research Letters* 29(8):14,498, doi 10.1029/2001GLO14498.

Kitani, K. 1987. Direct measurements of the Japan Sea Proper Water. *News of the Japan Sea National Fisheries Research Institute* 341:1–6.

Kitani, K. 1989. Movement of the Japan Sea Proper Water. In: *International Conference on the Sea of Japan* held in Okhotsk, Nahodka, USSR, September 1989, M. Valencia, ed. East West Center, Honolulu, HI.

Kolchak, A.V. 1899. Observations of surface temperature and density of sea water aboard ships “Ryurik” and “Kreiser” from May 1897 to March 1898. *Zapiski po gydrographii* 20.

Kwon, Y.-O., K. Kim, Y.-G. Kim, and K.-R. Kim. 2004. Diagnosing long-term trends of the water mass properties in the East Sea (Sea of Japan). *Geophysical Research Letters* 31(1): L20306, doi:10.1029/2004GL020881.

La Violette, P.E., and D.R. Hamilton. 1967. Temperature, salinity and density of the world’s seas: Sea of Japan. Intern. Rep. N 68-1. Naval Oceanographic Office, Washington, 110 pp.

Lee, D.-K., and P.P. Niiler. 2005. The energetic surface circulation patterns of the Japan/East Sea. *Deep-Sea Research II* 52:1,547–1,563.

Leonov, A.K. 1948. Water masses of the Japan Sea. *Meteorologiya i Gidrologiya* 6:61–78.

Leonov, A.K. 1960. The Japan Sea. Pp. 291–463 in *Regional Oceanography Part 1*. Gydrometeoizdat, St. Petersburg.

Lie, H.J., S.K. Byun, I. Bang, and C.H. Cho. 1995. Physical structure of eddies in the southwestern East Sea. *Journal of the Korean Society of Oceanography* 30(3):170–183.

Lobanov, V.B., V.I. Ponomarev, P.Y-. Tishchenko, L. Talley, S. Mosyagina, S.G. Sagalaev, A.N. Salyuk, and V. Sosnin. 2001. Evolution of the anticyclonic eddies in the northwestern Japan/East Sea. In: *Proceedings of the 11th PAMS/JECSS Workshop*, April 11–13, 2001, Cheju, Korea, 37–40.

Lobanov, V., A. Salyuk, V. Ponomarev, L. Talley, K. Kim, K.-R. Kim, P. Tishchenko, A. Nedashkovskiy, G.-B. Kim, and S. Sagalaev. 2002. Renewal of bottom water in the Japan/East Sea. In: *Proceedings of the 17th International Symposium, Okhotsk Sea and Sea Ice*, 24–28 February 2002, Mombetsu, Japan, 31–36.

Maidel, E.R. 1877. Magnetic and hydrological works in the Eastern Ocean. *Morskoi Sbornik* [Russian Naval proceedings] N. 10, 24 pp [in Russian].

Maidel, E.R. 1878. Hydrographic works in Amur Bay, at the coasts of the Japan Sea, Tartar Strait and the investigation of the currents in La Perouse Strait. *Morskoi Sbornik* [Russian Naval proceedings] N 1 [in Russian].

Maidel, E.R. 1879. Extra notes on the cold current in La Perouse Strait. *Morskoi Sbornik* [Russian Naval proceedings] 171(4):47–53 [in Russian].

Maidel, E.R. 1880. Spots of cold waters in the La Perouse Strait. *Morskoi Sbornik* [Russian Naval proceedings] 180(2) [in Russian].

Makarov, S.O. 1894. “Vityaz” and Pacific Ocean. Sankt-Petersburg, v.1, 337 pp.; v.2, 511 pp [in Russian].

Marine Environmental Atlas. 1975. Japan Hydrogrographic Association, Tokyo, 164 pp.

Marine Environmental Atlas. 1978. Japan Hydrogrographic Association, Tokyo, 157 pp.

Martin S., and M. Kawase. 1998. The southern flux of sea ice in the Tatarskiy Strait, Japan Sea and the generation of the Liman Current. *Journal of Marine Research* 56(1):141–155.

Martin S., E. Munoz, and R. Drucker. 1992. The effect of severe storms on the ice cover of the northern Tatarskiy Strait. *Journal of Geophysical Research* 97(11):17,753–17,769.

Mitchell, D., D. Watts, M. Wimbush, W. Teague, K. Tracey, J. Book, K.-I. Chang, M.-S. Suk, and J.-H. Yoon. 2005. Upper circulation patterns in the Ulleung Basin. *Deep-Sea Research II* 52:1,617–1,638.

Miyazaki, M. 1953. On the water masses of the Japan Sea. *Bulletin of the Hokkaido Regional Fisheries Research Laboratory* 7:1–65.

Mogi, A. 1979. *An Atlas of the Sea Floor Around Japan. Aspects of Submarine Geomorphology*. Tokyo University Press, Tokyo, 96 pp.

Morgan, J., and M.J. Valencia, eds. 1992. *Atlas for Marine Policy in the East Asian Seas*. University of California Press, Berkeley, 170 pp.

Morimoto, A., T. Yanagi, and A. Kaneko. 2000. Eddy field in the Japan Sea derived from satellite altimetric data. *Journal of Oceanography* 56:449–462.

Naganuma, K. 1977. The oceanographic fluctuations in the Japan Sea. *Kaye Kagaku* 9(2):137–141.

Nitani, H. 1972. On the deep and bottom waters in the Japan Sea. Pp. 151–201 in *Researches in Hydrography and Oceanography*, D. Shoji D., ed. Hydrographic Department of Japan, Tokyo.

PICES (North Pacific Marine Science Organization). 2005. *Annual Report 2005: PICES 14th Annual Meeting, September 29–October 9, 2005, Vladivostok, Russia*. North Pacific Marine Science Organization, Sidney, British Columbia, Canada. [Online] Available at: http://www.pices.int/publications/annual_reports/Ann_Rpt_05/and_rep_2005.aspx [last accessed August 7, 2006].

Pischalnik, V.M., and V.S. Arkhipkin. 2000. *Oceanographic Atlas of the Sakhalin Shelf. Part 1*. Sakhalin Fishery and Oceanography Research Institute (SakhNIRO), 173 pp.

Pokudov, V.V., and T.I. Supranovich. 1975. Development of oceanographic investigations in FERHRI for 25 years. *Trudy DVNIGMI* 50:3–10.

Pokudov, V.V., A.N. Manko, and A.N. Khluso. 1976. Peculiarities of hydrological conditions of the Japan Sea regime in a winter. *Bulletin of Far-Eastern Regional Hydrometeorological Research Institute* (*Trudy DVNIGMI*) 60:74–115.

Ponomarev, V.I., A.N. Salyuk, and A.S. Bychkov. 1996. The Japan Sea water variability and ventilation processes. In: *Proceedings of the CREAMS’96 Workshop*, Vladivostok, Russia, 63–69.

Preller, R.H., and P.J. Hogan. 1998. Oceanography of the Sea of Okhotsk and the Japan/East Sea. Pp. 429–481 in *The Sea*, v. II, A. Robinson, and K. Brink, eds. John Wiley and Sons, Inc., New York, NY.

Riser, S., M.J. Warner, and G.I. Yurasov. 1999. Circulation and mixing of water masses of Tatar Strait and the northwestern boundary

region of the Japan Sea. *Journal of Oceanography* 55(2):133–156.
Rudovits, L.F. 1927. The oceanographic investigations of Japan. *Meteorologicheskii Vestnik* 10:221.
Rudovits, L.F. 1929. Oceanographical research in the Sea of Japan (1926–1928). *Bulletin of the Pacific Committee* [Russian Academy of Sciences] 2:1–4.
Rudovits, L.F. 1934. M. Uda hydrologic investigations of the Japan Sea in May–June of 1932. *Zapiski po Gydrographii* 2:138–145.
Rumyantsev, A.I., ed. 1951. *Charts of Averaged Multi-Year Water Temperature and Salinity of the Japan Sea*. TINRO, Vladivostok, Russia, 114 pp.
Russian Academy of Sciences. 1961. *Basic Features of Geology and Hydrology of the Japan Sea*. Academy of Sciences Publishing House, Moscow, 218 pp.
Senjyu, T., and H. Sudo. 1993. Water characteristics and circulation of the upper portion of the Japan Sea Proper Water. *Journal of Marine Systems* 4:349–362.
Senjyu, T., and H. Sudo. 1994. The upper portion of the Japan Sea Proper Water: Its source and circulation as deduced from isopycnal analysis. *Journal of Oceanography* 50:663–690.
Senjyu, T., T. Aramaki, S. Otosaka, O. Togawa, M. Danchenkov, E. Karasev, and Y. Volkov. 2002. Renewal of the bottom water after the winter 2000–2001 may spin-up the thermohaline circulation in the Japan Sea. *Geophysical Research Letters* 29(7):1,149, doi: 10.1029/2001GL014093.
Senjyu ,T., H.R. Shin, J.H. Yoon, Z. Nagano, H.S. An, S.K. Byun, and C.K. Lee. 2005. Deep flow field in the Japan/East Sea as deduced from direct current measurements. *Deep-Sea Research II* 52:1,726–1,741.
Shrenk, L.I. 1870. Notes on physical geography of the northern Japan Sea. *Memoires of Emperor Academy of Sciences* 16(2) Suppl.3: 1–254.
Shrenk, L.I. 1874. On the currents of the Okhotsk, Japan and adjacent seas. *Memoires of Emperor Academy of Sciences* 23(2) Suppl.3: 1–112.
Suda, K. 1932. On the bottom water of the Japan Sea. *Journal of Oceanography* 4(1)221–240.
Sudo, H. 1986. A note of the Japan Sea Proper Water. *Progress in Oceanography* 17(3–4): 313–336.
Sugimoto, T., and H. Tameishi. 1992. Warm core rings, streamers and their role in the fishing ground formation around Japan. *Deep-Sea Research* 39(Suppl.1):183–201.
Takematsu, M. 1994. CREAMS plan and Japan Sea studies. *Kaiyo Monthly* 26(12):745–746.
Takematsu, M., Z. Nagano, A.G. Ostrovskii, K. Kim, and Y.N. Volkov. 1999a. Direct measurements of deep currents in the northern Japan Sea. *Journal of Oceanography* 55(2):207–216.
Takematsu, M., A.G. Ostrovskii, and Z. Nagano. 1999b. Observations of eddies in the Japan Basin interior. *Journal of Oceanography* 55(2):237–246.
Talley, L.D., V. Lobanov, V. Ponomarev, A. Salyuk, P. Tishchenko, I. Zhabin, and S. Riser. 2003. Deep convection and brine rejection in the Japan Sea. *Geophysical Research Letters* 30(4):1159, doi:10.1029/2002GLO16451.
Teague, W.J., P.A. Hwang, G.A. Jacobs, J.W. Book, and H.T. Perkins. 2005a. Transport variability across the Korea/Tsushima Strait and Tsushima Island wake. *Deep-Sea Research II* 52:1,784–1,801.
Teague, W., K. Tracey, D. Watts, J. Book, K.-I. Chang, P. Hogan, D. Mitchell, M.-S. Suk, M. Wimbush, and J.-H. Yoon. 2005b. Observed deep circulation in the Ulleung Basin. *Deep-Sea Research II* 52:1,802–1,826.
Uda, M. 1934. The results of simultaneous oceanographical investigations in the Japan Sea and its adjacent waters in May and June 1932. *Journal of the Imperial Fisheries Experimental Station* 5:57–190.
Valencia, M.J., ed. 1989. *International Conference on the Sea of Japan held in Okhotsk, Nahodka, USSR, September 1989.* East West Center, Honolulu, HI, 239 pp.
Vize, V.Y-. 1923. Sea surface water temperature in the Japan Sea by Japanese investigations. *Izvestiya Tcentralnogo Gydrometbyuro* 2:44–47.
Watanabe, T., M. Hirai, and H. Yamada. 2001. High-salinity intermediate water of the Japan Sea in the eastern Japan Basin. *Journal of Geophysical Research* 106(C6):11,437–11,450.
Yanagimoto, D., and K. Taira. 2003. Current measurements of the Japan Sea Proper Water and the Intermediate Water by ALACE floats. *Journal of Oceanography* 59:359–368.
Yarichin, V.G. 1980. Status of the research of the Japan Sea water circulation. *Trudy DVNIGMI* 80:46–61.
Yoon, J.H. 1982. Numerical experiment on the circulation in the Japan Sea. Part 1. Formation of the East Korean Warm Current. *Journal of the Oceanographic Society of Japan* 38(2):43–51.
Yoon J.-H. and H. Kawamura. 2002. The formation and circulation of the intermediate water in the Japan Sea. *Journal of Oceanography* 58:197–211.
Yurasov, G.I., and V.G. Yarichin. 1991. *Currents of the Japan Sea*. Vladivostok, Dalnauka, 176 pp.
Zhabin, I.A., S.N. Taranova, and L. Talley. 2003. Intermediate water of high salinity in the northern part of the Japan Sea. *Meteorologiya i Gidrologiya* 4:63–72.
Zhdanko, M.K. 1913. On the problem of sea currents study. *Zapiski po Gidrographii* 36:97–108.
Zuenko, Y-.I. 1994. Cold subsurface layer in the Japan Sea. Pp 40–45 in *Complex Study of Marine Resources and their Environments*, by Y-.I. Zuenko, ed. Pacific Institute of Fisheries and Oceanography, Vladivostok, Russia.
Zuenko, Y.I., and G.I. Yurasov. 1995. Water masses of the northwestern Japan Sea. *Meteoroloiya i Gidrologiya* 8:50–57.
Zuev, A. 1887. Observations of water temperature in the northern Japan Sea. *Zapiski po Gidrographii* 2:53–59.