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Sea ice circulation in the Laptev Sea and ice export to the Arctic Ocean: Results from satellite remote sensing and numerical modeling

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Abstract. Sea ice circulation in the Laptev Sea and ice exchange with the Arctic Ocean have been studied based on remote sensing data and numerical modeling. Ice drift patterns for short- and long-term periods were retrieved from successive Okean radar images and Special Sensor Microwave/Imager data for the winters 1987/1988 and 1994/1995. Seasonal and interannual variabilities of ice drift in the Laptev Sea and ice exchange with the Arctic Ocean during the period from 1979 to 1995 were studied with a large-scale dynamic-thermodynamic sea ice model. During an "average year," sea ice was exported from the Laptev Sea through its northern and eastern boundaries, with maximum and minimum export occurring in February and August, respectively. The winter ice outflow from the Laptev Sea varied between 251,000 km^2 (1984/1985) and 732,000 km^2 (1988/1989) with the mean value of 483,000 km^2. Sea ice was exported into the East Siberian Sea mostly in summers with the mean value of 69,000 km^2. Out of the 17 investigated summers, 12 were characterized by sea ice import from the Arctic Ocean into the Laptev Sea through its northern boundary. Magnitude and direction of ice export from the Laptev Sea corresponded with the large-scale Arctic Ocean drift patterns during periods of prevailing cyclonic or anticyclonic circulation. Based on a semiempirical method that has been validated with the large-scale model and satellite data, ice exchange between the Laptev Sea and the Arctic Ocean during the period from 1936 to 1995 has been estimated as 309,000km^2 with strong interannual variability and no significant trend apparent.

1. Introduction

The Laptev Sea occupies a central geographical location among the Eurasian Arctic shelf seas and is bounded by the Severnaya Zemlya Archipelago in the west and by the New Siberian Islands in the east (Figure 1). During winter it is covered with sea ice. Melting starts in late May – early June and by the end of summer the southeastern Laptev Sea is ice free, whereas the Taymir ice massif typically covers the western sector throughout summer. A vast belt of fast ice, attached to the Siberian mainland, begins to form in October over a shallow shelf and in the end of winter its thickness can reach approximately 2 m. Under predominantly offshore winds a recurring flaw polynya develops at the edge of the fast ice boundary and drifting sea ice is advected to the north. As a result of low winter temperatures and the mostly northward ice drift, the Laptev Sea represents a major source area for sea ice in the Eurasian sector of the Arctic Ocean [e.g., *Vize*, 1926; *Karelin*, 1943; *Zakharov*, 1966, 1976; *Timokhov*, 1994].

Fram, Sedov, Lenin, and several other ships beset in ice in the Laptev Sea revealed northward ice motion in this region. Drifting radiobeacons and automated radiometeorological stations (DARMS), deployed in different parts of the Arctic Basin from 1953 to 1972, considerably improved the database of regional and seasonal variabilities of ice drift in the Arctic seas [*Volkov and Gudkovich*, 1967; *Gorbunov and Moroz*, 1972; *Gorbunov et al.*, 1995]. Analysis of their trajectories demonstrated that the average ice drift velocity in the Eurasian seas is 1.5 to 2 times higher than it is in the Arctic Ocean [*Shesterikov*, 1957]. Isobaric coefficients and deviations of ice drift from isobars were estimated based on DARMS drift data, and a free-drift model [*Zubov*, 1944] has been employed for ice motion studies in the Arctic seas [*Nikolaeva and Shesterikov*, 1970] Semiempirical methods for the calculation of sea ice exchange between the polar marginal seas and the Arctic

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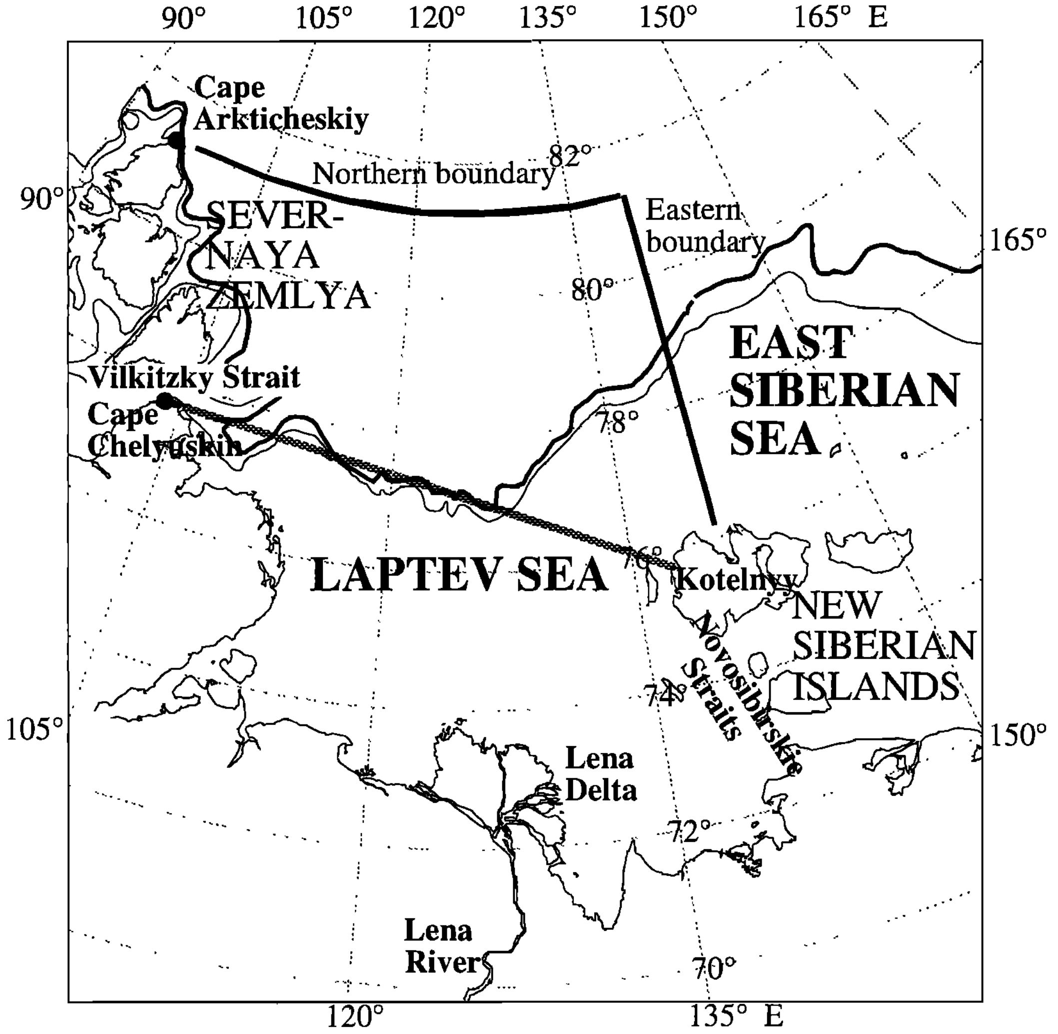

Figure 1. The geographical location of the Laptev Sea. The 50 and 100 m depth contours are overlaid. The thick solid and stippled lines show the boundaries on which estimates of the ice flux are based.

Basin, based on monthly average atmospheric pressure data at selected polar stations, have also been developed [*Nikolaeva and Gudkovich*, 1961]

Estimates of the average volume ice export from the Laptev Sea to the central Arctic range from 400 [*Eicken et al.*, 1997] to 540 km^3yr^{-1} [*Shpaiher*, 1976]. This is more than the export from the Barents (40 km^3yr^{-1}), Kara (240 km^3yr^{-1}), East Siberian (150 km^3yr^{-1}), and Chukchi (10 km^3yr^{-1}) Seas combined [*Timokhov*, 1994]. Special Sensor Microwave/Imager (SSM/I)-derived ice velocity fields support the notion that the Transpolar Drift (TPD) is supplied primarily from the Laptev and East Siberian seas, rather than from the Beaufort Gyre [*Emery et al*, 1997]. Studies by *Pfirman et al.* [1997] indicate that the East Siberian Sea is not a major source of sea ice to the Eurasian Basin.

The seasonal and interannual variabilities of sea ice exchange between the Laptev Sea and the Arctic Ocean had been investigated by *Zakharov* [1966, 1967] and *Gudkovich et al.* [1972] for the period from 1937 to 1958 based on the average monthly gradients of atmospheric pressure between Cape Arkticheski (Komsomolets Island) and Kotelnyy Island. Their studies revealed that on average 328,000 km^2 of ice was exported from the Laptev Sea during autumn, winter, and spring. During summer the ice circulation was more variable, and on average, sea ice was imported to the Laptev Sea in June and July. *Gorbunov et al.* [1979a] identified several areas with different ice circulation regimes The coastal regions and in particular the Vilkitski and Novosibirskie Straits are characterized by complex circulation patterns due to the effects of ice-coastal interaction and the role of currents and have been mostly neglected in previous studies. Based on a single set of ship-based observations, *Vize* [1938] estimated that the total ice inflow to the Laptev Sea through Vilkitski Strait could reach up to 50 km^3 with an ice drift velocity of 0.55 m s^{-1}. Short-term velocities derived from successive ERS synthetic aperture radar (SAR) scenes for the period October 24 to 25, 1995, amounted to 0.15 m s^{-1} [*Sandven et al.*, 1997]. *Kozo et al.* [1996] demonstrated that during period of higher wind forcing, ice arches could be formed across Vilkitski Strait, constraining import of sea ice into the Laptev Sea in fall. The average ice outflow through Novosibirskie Straits to the east for the period 1952 to 1977 has been calculated by *Gorbunov and Karelin* [1981] based on a dependence between ice exchange and the 10-day average pressure gradients between

Svyatoi Nos Cape and Sannikova Polar Station [*Gorbunov*, 1979]. While the straits are quite narrow and hence preclude accurate estimates of ice exchange, the estimate of 2.05 km^3 indicates that transport through Novosibirskie Straits is less than that through Vilkitski Strait. Several studies of ice drift in the inner and coastal Laptev Sea have been based on successive side-looking airborne radar surveys and ERS SAR images [*Gorbunov et al.*, 1979b; *Panfilov*, 1990, 1995, *Kolatschek et al.*, 1995]. While ice exchange across the straits in the western and eastern Laptev Sea contributes marginally to the uncertainty in the estimates of total ice outflow from the Laptev Sea, all previous studies consistently show that Siberian ice export into the Arctic Basin is dominated by Laptev Sea ice production.

After the termination of the DARMS program in early 1970s the number of ice drift observations in the Laptev Sea decreased drastically. While the deployment of drifting buoys throughout the Arctic Basin has been at a high level since the inception of the International Arctic Ocean Buoy Program in 1979 [*Colony and Thorndike*, 1984], only a few buoys have been deployed over the shallow Siberian shelves. This lack of buoy data has to some extent affected previous studies of sea ice motion in the Laptev Sea, in particular during the last 25 years, preventing proper verification of sea ice circulation models in this area. *Rigor and Colony* [1997] derived the mean winter ice motion field in the Laptev Sea for the period 1979 to 1993 from estimated monthly fields using a combination of modeling results and observations. Their analysis shows a cyclonic circulation center at approximately at 77°N 120°E, indicating an ice inflow along the coast of Severnaya Zemlya with an average velocity of 0.024 m s^{-1}. In the eastern part of the Laptev Sea ice moves northward with an average velocity of 0.019 m s^{-1}. Several other investigations showed that deviations from this cyclonic pattern are quite common [*Gudkovich and Nikolaeva*, 1963; *Bushuev et al.*, 1967].

Given the importance of the Laptev Sea as a major ice production area for the TPD, we studied the seasonal and interannual variability of ice exchange between the Laptev Sea and the Arctic Basin for the entire time period for which historical data are available. The study focuses on the sea ice circulation regime employing three different techniques to derive velocity fields: a large-scale sea ice model, a semiempirical approach, and derivation of ice drift from remote sensing data. Seasonal and interannual variabilities of ice exchange with the Arctic Ocean during the period 1979 to 1995 were investigated with a dynamic-thermodynamic sea ice model [*Harder et al.*, 1998]. Simulated ice velocity fields and areal ice fluxes were then compared with the satellite-derived fields for the two winters (1987/1988 and 1994/1995). Finally, longer-term climatological assessments of sea ice exchange for the period 1936 to 1995 were conducted based on dependence of the ice flux on the pressure gradient between the polar stations on Kotelnyy Island and at Cape Chelyuskin.

2. Methods and Models Description

Studies of sea ice motion from successive radar, passive microwave, visible, and IR satellite images have provided ample demonstration that sea ice kinematics can be reliably derived with remote sensing techniques [*Ninnis et al.*, 1986; *Kwok et al.*, 1990; *Emery and Fowler*, 1991; *Kloster et al.*, 1992; *Martin and Lemke*, 1995; *Martin*, 1996]. During winter, satellite data in the microwave band are the most appropriate for ice drift determination due to their being independent of light and cloud conditions. The analysis of sea ice drift in this study is based on radar images from the Russian Okean satellite, passive microwave data from the U.S. Defense Meteorological Satellite Program SSM/I and advanced very high resolution radiometer (AVHRR) visible range images from NOAA satellites.

2.1. Retrieval of Ice Drift Patterns From Okean Images

The side-looking radar of the Okean satellite operates at a wavelength of 3.15 cm (vertical polarization). It covers a swath of 475 km wide and has a resolution of 0.9 and 2.8 km in range and azimuth directions, respectively. Giant ice floes and fractures were tracked from sequential images in interactive mode [*Alexandrov et al.*, 1995] and the meridional displacements of the multiyear ice boundary were also determined for different winter months. There were 48 and 27 drift patterns retrieved from Okean data for the winters 1987/1988 and 1994/1995. The time intervals varied from between 3 days to 7 months. A pair of successive Okean radar images, covering the Laptev Sea, is shown in Figure 2. As it is evident in the figure, the multiyear ice boundary, identified by a sharp decrease in backscattering from high values for second-year ice to low ones for first-year ice, shifted significantly to the north during the period March 10 to April 28, 1995. The same conspicuous features in old ice could be recognized in both images. During summer, when sea ice backscattering change considerably due to melting, tracking of floes or other features is difficult or impossible. The other limiting factor in using Okean data for ice drift determination is its infrequent and limited coverage of the northern Laptev Sea.

2.2. Retrieval of Ice Drift Patterns From SSM/I Data

The investigations by *Martin and Augstein* [2000] as well as the studies of *Emery et al.* [1997] demonstrated that the ice velocity could be determined from passive microwave data based on a spatial correlation technique. Comparison between buoy- and satellite-derived ice velocities consistently yield a good correspondence [*Martin and Augstein*, 2000]. SSM/I 85.5-GHz data provide a complete coverage of the Laptev Sea regularly at a comparatively low resolution (12.5 km). The ice drift velocities were automatically derived for 3-day periods by matching large features on successive images based on the maximum-likelihood correlation technique. A total of 121 and 125 scenes were processed for the winters of 1987/1988 and 1994/1995. Melting affects microwave ice signatures and precludes feature tracking in summer. Thus for the period August to September of 1993, ice drift has been determined from 22 pairs of visible channel AVHRR NOAA images [*Alexandrov et al.*, 1994]. Feature tracking was limited by the high cloudiness typical of Arctic summer conditions.

2.3. Large-Scale Dynamic-Thermodynamic Sea Ice Model

A large-scale dynamic-thermodynamic sea ice model, developed at Alfred-Wegener Institute [*Harder and Lemke*, 1994; *Harder*, 1996; *Harder et al.*, 1998], has been employed for ice circulation studies in the Laptev Sea from 1979 to 1995. The daily atmospheric forcing of the model includes 24-hour means of the 10-m wind velocity and the 2-m air temperature fields based on the reanalyzed data from the National Center of Environmental Prediction (NCEP). The 2-m dew

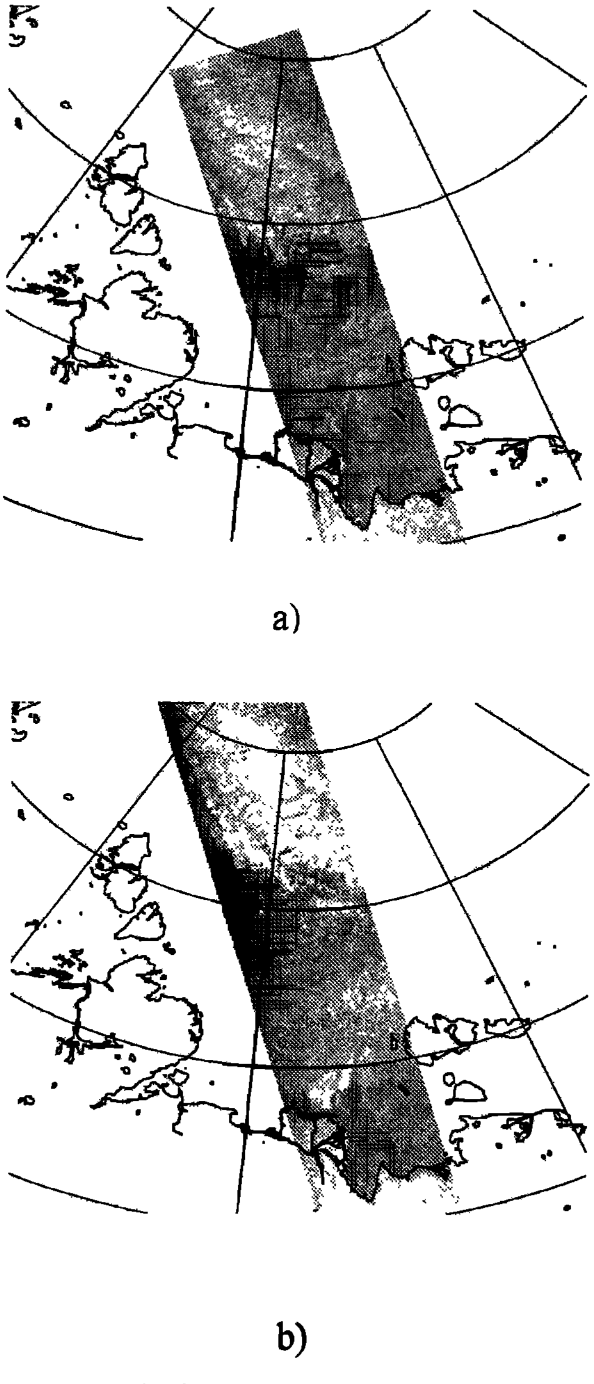

Figure 2. A pair of successive Okean radar images covering the Laptev Sea: (a) March 10, 1995, and (b) April 28, 1995.

point temperatures were taken from analysis data of the European Centre for Medium-Range Weather Forecasts. A seasonally and spatially varying heat flux from the deep ocean into the mixed layer and the annual mean geostrophic current have been obtained from a coupled sea ice ocean simulation [*Hibler and Zhang*, 1993]. Cloud coverage and precipitation were included as spatially constant climatological means, based on the data both from *Ebert and Curry* [1993] and *Vowinckel and Orvig* [1970]. The internal forces within the ice were calculated based on a viscous-plastic sea ice rheology [*Hibler*, 1979]. The computations were performed on a regular grid with a spacing of 110 km.

2.4 Semiempirical Approach

Sea ice exchange between the Laptev Sea and the Arctic Ocean was estimated using the relation between the monthly mean pressure gradient along the section Cape Chelyuskin to the New Siberian Islands for isobaric free drift of the ice. Historical sea level air pressure data for the period 1936 to 1995 from the Russian polar stations on Kotelnyy Island and at Cape Chelyuskin have been utilized for this part of the work. The drift velocity (U_n) can be expressed as

$$U_n = -k\frac{\partial P}{\partial n}, \qquad (1)$$

where k is a coefficient of isobaric drift, $\partial P/\partial n$ is the surface pressure gradient, normal to the direction of the calculated drift velocity. An expression for the ice flux through selected sections can be obtained by means of integrating this dependence.

$$F = \int_0^l U_n \partial n = \int_0^l \frac{\partial P}{\partial n}\partial n = k(P_0 - P_l), \qquad (2)$$

where P_0, P_l are the surface air pressures at the endpoints of the section.

3. Results

3.1. Ice Drift Patterns

As a first step, the trajectories of giant ice floes in the Laptev Sea, retrieved from successive Okean images for the 1987/1988 winter were simulated with the model (Figure 3). From late October until early May, sea ice generally drifted to the northwest, and Okean-derived ice drift velocities significantly exceeded the long-term winter mean, varying between 0.043 m s^{-1} in the northeastern and 0.035 m s^{-1} in the northwestern Laptev Sea. In the southern sector, ice moved northwards with an average velocity of 0.022 m s^{-1}. Simulated ice drift velocities in the central and northern Laptev Sea, averaged for all this period, did not deviate considerably from the satellite-derived ones, but for shorter time intervals the differences between them significantly increased. For the period November 1994 to May 1995, Okean-derived velocities averaged at 0.024 m s^{-1} with the drift directed toward the north. For August and September of 1993, AVHRR NOAA visible range imagery has been utilized to derive ice circulation patterns, which revealed cyclonic circulation in the Laptev Sea with ice moving predominantly to the southeast and east along the coast of Severnaya Zemlya [*Alexandrov et al.*, 1994; *Rigor and Colony*, 1997].

With the dynamic-thermodynamic sea ice model, ice motion fields were simulated for time periods coincident with the available Okean and SSM/I data. Results of these comparisons are shown in Figure 4. During the period January 10 to 30, 1988, all data indicate a northeasterly ice drift in the southern Laptev Sea and north-northwesterly drift in the northern sector (Figure 4a). In the central Laptev Sea, model, Okean-derived, and the SSM/I-based drift velocities amount to 0.079, 0.055, and 0.039 m s^{-1}, respectively. The average drift directions are within reasonable agreement with one another (9.8° for the model, 6.1° for Okean, and 3.9° for SSM/I). In the southwestern Laptev Sea the differences between the model (0.039 m s^{-1}, 48.5°) and the remote sensing data are larger (Okean, 0.049 m s^{-1}, 60.7°; SSM/I, 0.025 m s^{-1}, 72°). During the period February 16 to March 13, 1988, all data sets show a consistent reversal in ice motion with a strong onshore

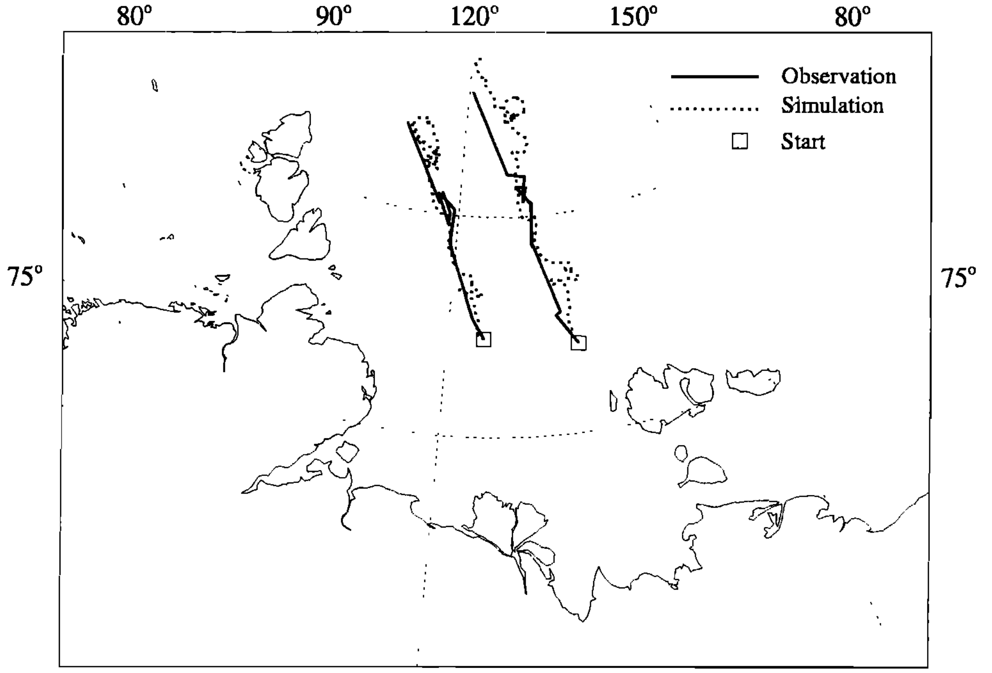

Figure 3. Comparison of satellite-derived and calculated trajectories of giant ice floes in the central part of the Laptev Sea for the period October 28, 1987, to May 6, 1988.

component and ice import from the Arctic Ocean and to a lesser extent from the East Siberian Sea (Figure 4b).

The mean velocity field for the period October 1, 1994, to March 31, 1995, based on SSM/I data and the sea ice model is shown in Figure 5. During this winter, sea ice predominantly moved to the northeast. SSM/I-derived ice drift vectors (0.023 m s^{-1}, 15°) and model ones (0.025 m s^{-1}, 20.2°) show reasonable correspondence both with respect to velocity and direction in the northeastern Laptev Sea, whereas in the coastal areas east of Severnaya Zemlya and near the mainland the differences are more significant (model, 0.023 m s^{-1}, 40.4°; SSM/I, 0.027 m s^{-1}; 78°).

3.2. Ice Export From the Laptev Sea as Derived From Satellite Data and a Large-Scale Sea Ice Model

The meridional ice flux at 81°N between 96° and 140°E and the zonal ice flux at 140°E between 76.5° and 81°N had been retrieved from both SSM/I data and model simulations for the winters of 1987/1988 (Figure 6a) and 1994/1995 (Figure 6b). SSM/I-derived ice fluxes have been determined as 3-day mean values, and model data have been calculated for 1-day integration periods, causing the higher variability as well as the more pronounced maximum and minimum of the modeled fluxes Both data sets are in general agreement. The characteristic fluctuations in ice export with periods of a few days have been linked to the synoptic wind field.

During the winter of 1987/1988, ice was exported through the northern boundary of the Laptev Sea except for a period of ice import in late February and stagnant fluxes in late November and March (Figure 6a). Along the eastern boundary export also prevailed with the exception of a period of net ice influx in December and stagnant fluxes in early November, February, and March. During the winter of 1994/1995 the net total sea ice budget was near zero during the first half of the season (October to December), with significant net export during the second half of the winter (January to March).

The average seasonal cycle of the zonal, meridional, and total areal ice fluxes as derived with the dynamic-thermodynamic sea ice model for the period 1979 to 1995 is shown in Figure 7. During the summer months, ice was imported into the Laptev Sea through the northern boundary. After attaining a seasonal maximum in December, mean monthly export steadily decreases to its summer minimum. Ice fluxes across the eastern boundary are more variable, with ice import in April, May, November, and December, and a maximum mean monthly areal export in September The total net ice flux out of the Laptev Sea peaks in February and a minimum is attained in July/August (Figure 7c).

The interannual variability in the total model-derived areal ice flux for the period 1979 to 1995 is shown in Figure 8 for the winter (October to May) and summer (June to September) seasons. During winter, sea ice was exported from the Laptev Sea in all these years. Areal ice export varied considerably between 251,000 km^2 in the winter of 1984/1985 and 732,000 km^2 in the winter of 1988/1989, with an average total winter ice export of 483,000 km^2. The summers of 1979, 1981, 1988, and 1990 were characterized by net import of sea ice into the Laptev Sea across the northern and eastern boundaries. Through the northern boundary the average winter ice export and summer import amount to 492,000 and 40,000 km^2, respectively, for the entire period of time with net export confined to the summers of 1982, 1985, 1987, 1991, and 1995. On average, sea ice was exported through the eastern boundary into the East Siberian Sea during summers with the mean value of 69,000 km^2.

While the remote sensing data provide only information on areal ice fluxes, volume ice fluxes have been obtained from the large-scale sea ice model. As it is evident from Figure 9, which shows a comparison of seasonally averaged areal versus volume fluxes across the northern boundary of the Laptev Sea, the model indicates a near-linear dependence of these two parameters. Whereas the simulated ice drift was verified

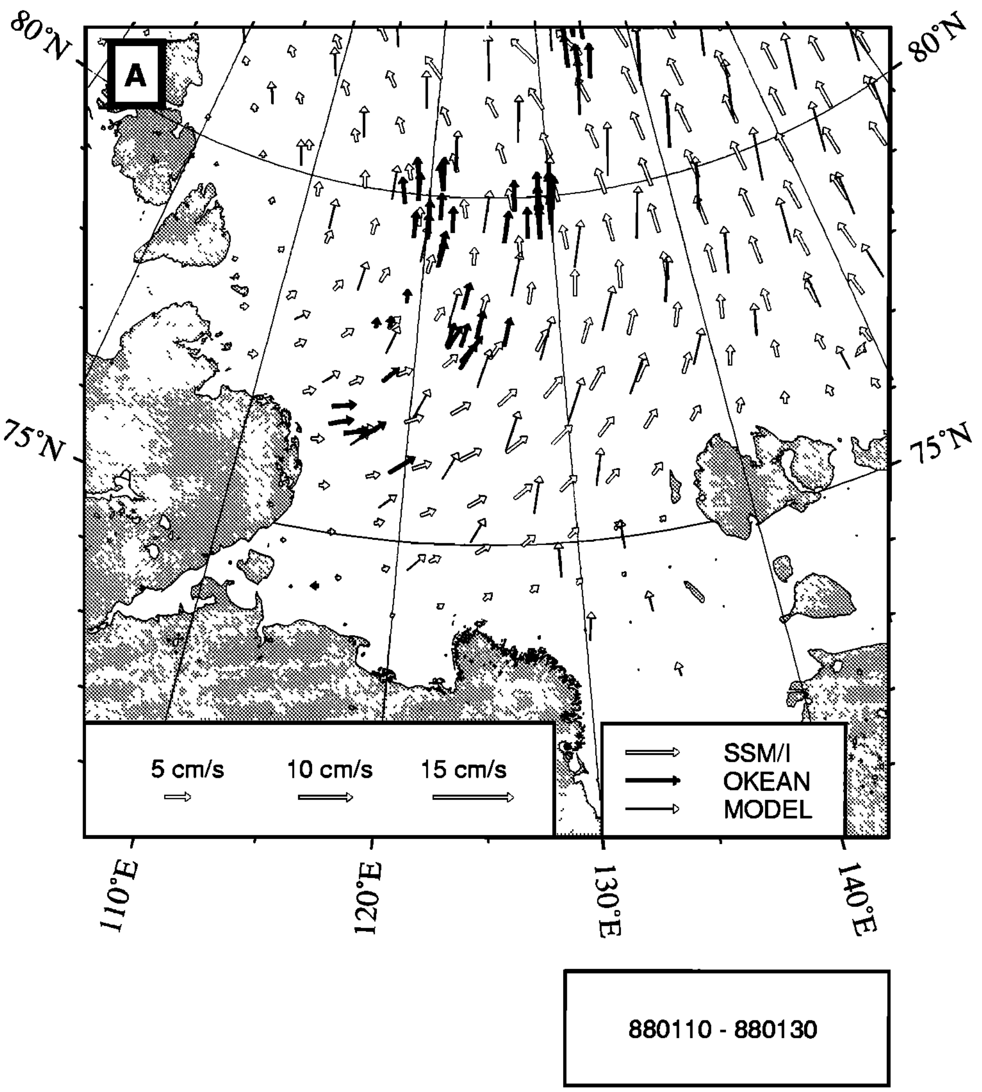

Figure 4. Ice drift patterns in the Laptev Sea retrieved from Okean and SSM/I data and a dynamic-thermodynamic sea ice model: (a) for the period January 10 to January 30, 1988, and (b) for the period February 16 to March 13, 1988.

by buoy trajectories for the adjacent sector of the Arctic Ocean and through comparison with satellite-derived velocities for the Laptev Sea, the ice volume estimates could not be properly validated due to a lack of ice thickness measurements at the required spatial and temporal density. However, in the mostly divergent ice deformation regime of the winter Laptev Sea, it appears reasonable to assume that it is in fact the velocity component (captured in the areal flux) that determines the bulk volume flux. Nevertheless, internal stress and ice deformation are known to play a more important role during periods of drift reversal or in the western branch of the summer cyclonic circulation [*Timokhov*, 1994; *Eicken et al.*, 1997]. Future work will have to resolve to what an extent such events impact the bulk volume flux of sea ice out of the Laptev Sea.

3.3. Variability of Sea Ice Exchange Between the Laptev Sea and the Arctic Basin From 1936 to 1995

The longer-term variability of sea ice exchange between the Laptev Sea and the Arctic Ocean has been derived employing the semiempirical method outlined in section 2. The monthly average air pressure gradient across the study area has been computed from historical sea level air pressure data obtained at the Russian polar stations on Kotelnyy Island and at Cape Chelyuskin from 1936 to 1995.

The seasonal cycle of the ice flux through the Cape Chelyuskin - Kotelnyy Island section is rather similar to the numerical model one (see Figure 7c). Thus, during an average summer, sea ice is imported into the Laptev Sea. Commencing with autumn freeze-up, ice is advected to the north and the areal flux increases up to a maximum in December, with values decreasing thereafter to the summer minimum. A time series of the total annual sea ice export derived with the semiempirical method and the dynamic-thermodynamic sea ice model for the period 1979 to 1995 is shown in Figure 10a and a scatterplot comparing both data sets presented in Figure 10b. Taking into account the difference in geographical location of the sections and the strong interannual variability of ice fluxes, the correlation between the data sets is reasonable (0.92, 0.61, and 0.64 for whole years, summers, and winters, respectively), although it should be noted that the large-scale model yields consistently higher average estimate (483,000 km^2 versus 294,000 km^2). The annual average ice export from the southern to the northern Laptev Sea during the period 1936 to 1995 exhibited a strong interannual variability, with a mean value of 309,000 km^2 yr^{-1} and a well-pronounced minimum in 1957, which was dominated by southward drift (Figure 11). For the period 1937 to 1958 these results have been compared to ice export through a section between Cape Arkticheski and Kotelnyy Island, which are highly correlated (r=0.93). During this period, the average ice export from the Laptev Sea to the Arctic Ocean (356,000 km^2) exceeded the average ice export from the southern to the northern Laptev Sea (282,000 km^2). This may also explain in part the offset between areal fluxes derived from the large-scale model and the semiempirical estimates (Figure 10a). An 11-year running mean ice export from the southern Laptev Sea and its standard deviation have been determined for the period 1936 to 1995 (Figure 12). The time series does not indicate any significant climatological trend during the last 60 years.

4. Discussion

4.1. Error Analysis

Influence of coastline and shallow areas significantly complicates modeling of ice motion in the shelf seas and leads to larger errors, as compared to the Arctic Ocean. Therefore quantitative intercomparison of obtained model and satellite-derived results is particularly necessary for producing more accurate estimates of ice motion fields and areal ice fluxes.

For the Okean data the error associated with the determination of ice drift vectors depends on the uncertainty in image geolocation and the identification of the same salient features in image pairs. The former is a function of the time interval between overpasses and for periods of more than 20 days, on which most of the velocity estimates are based, it corresponds to an error in the velocity of less than 0.01 m s^{-1}. The ice drift velocity from SSM/I data has been derived for 3-day averaged intervals by matching large features on successive images with an accuracy of better than 0.01 m s^{-1} [*Martin and Aug-*

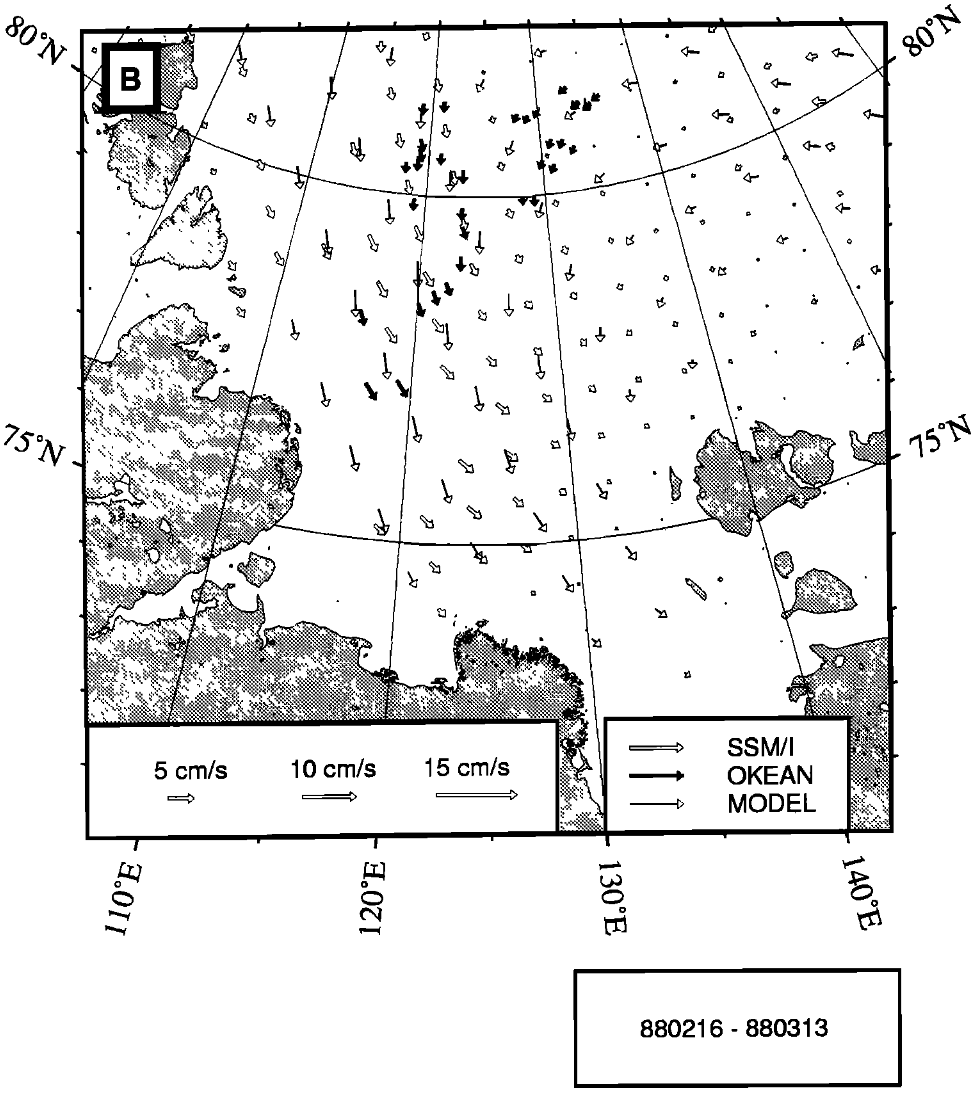

Figure 4. (continued)

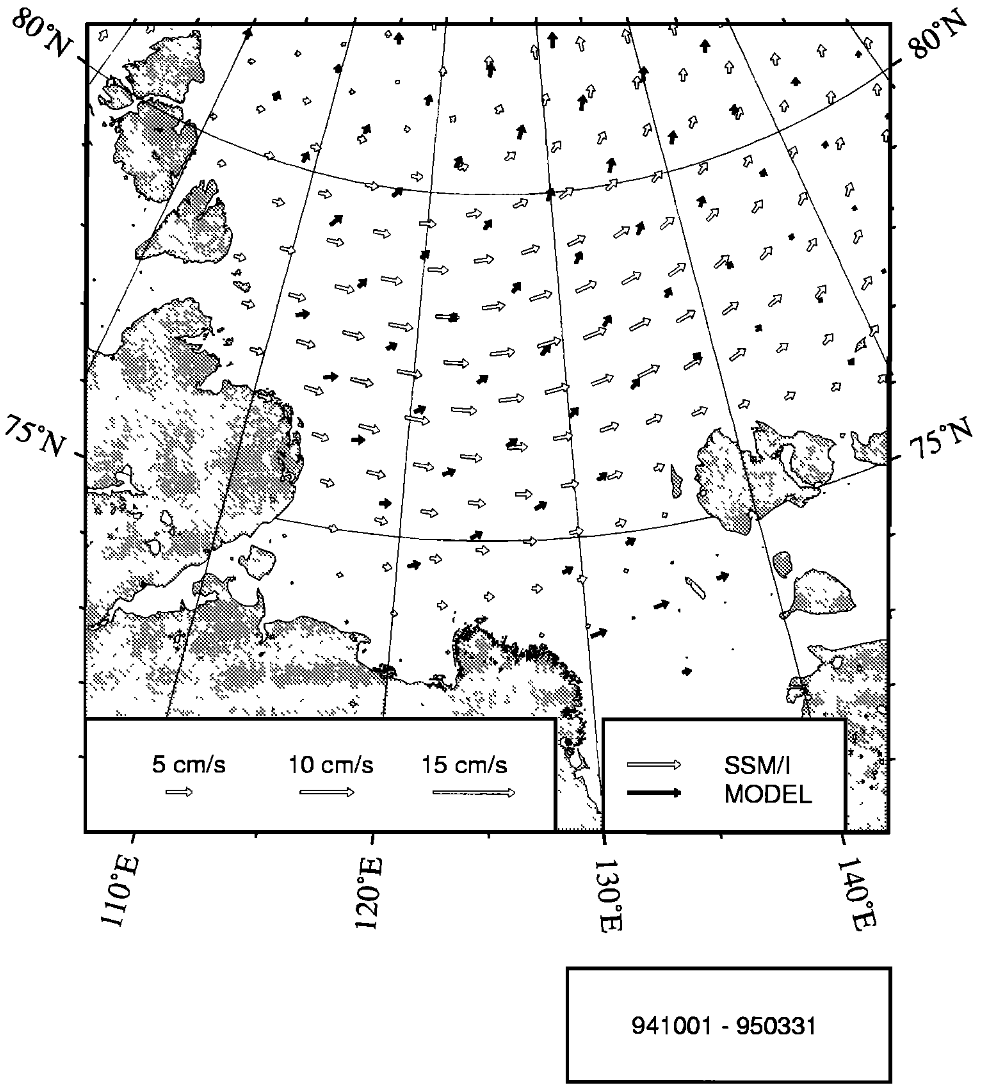

Figure 5. Ice drift patterns in the Laptev Sea retrieved from SSM/I data and the dynamic-thermodynamic sea ice model for the period October 1, 1994 to March 31, 1995

stein, 2000]. The large-scale dynamic-thermodynamic model of *Harder et al.* [1998] employed for ice drift studies in the Laptev Sea had previously been tested against buoy data in the Arctic Basin. The root-mean-square error for monthly averaged values from the model is 0.018 $m\ s^{-1}$ [*Kreyscher*, 1998] The accuracy of semiempirical method is approximately 10%, as estimated by the comparison with ice reconnaissance data [*Nikolaeva and Shesterikov*, 1970]

A quantitative comparison between Okean-derived and simulated ice drift trajectories was based on the differences in trajectory endpoints between remote sensing data and model originating at the same location (see Figure 3). While model and remote sensing data may differ considerably (by more than a factor of 2) for shorter time intervals, the difference between their short-term averages is comparatively small, with an average model ice drift velocity of 0.062 $m\ s^{-1}$ and a satellite-derived value of 0.059 $m\ s^{-1}$. The simulated and Okean-derived ice drift velocities for the period October 28, 1987, to May 6, 1988, amounted to 0.046 and 0.042 $m\ s^{-1}$, respectively. The observed differences are mostly attributed to coastline effects and insufficient resolution of internal stress, spatial variability of ice water drag coefficients, inaccurate ocean currents, errors in the forcing wind field and image geolocation errors In particular, the NCEP reanalyzed data may not adequately represent the position of the high- and low-pressure systems, which results in significant errors on shorter time intervals

For the winters of 1987/1988 and 1994/1995 the total areal ice fluxes out of the Laptev Sea, calculated with the dynamic-thermodynamic sea ice model, have been compared to SSM/I-derived ones. During all 3-month intervals the modeled fluxes exceeded that from SSM/I on average by 24%. The cross-correlation coefficient for these data sets varied from 0.65 to 0.77 The estimates of the meridional and zonal ice fluxes separately differed in larger degree. A comparison between monthly averages of model and satellite data yields correlation coefficients ranging between 0.55 and 0.87, with the modeled fluxes exceeding SSM/I-derived ones on 8 out of 10 months. Finally, the total areal ice flux out of the Laptev Sea derived from the model for the period September 20, 1987, to

May 10, 1988 (592,000 km^2) compares well with the estimate of 520,000 km^2 based on the displacement of the multiyear ice boundary retrieved from Okean images.

Lack of forcing data for the period prior to 1979 motivated us to compare results from the dynamic-thermodynamic sea ice modeling to semiempirical estimates of ice export from the southern Laptev Sea. The variability as well as the overall trend of the two time series (Figure 10a) corresponds fairly well with a correlation coefficient of 0.92 The larger amplitudes of the large-scale model results are most likely resulting from the higher temporal resolution of the forcing data and the differences in the two model sections (Figure 1) This result provides the basis for an analysis of a longer time series based on air pressure data from the polar stations at Cape Chelyuskin and on Kotelnyy Island for the period 1936 to 1995

In summary, the analysis shows that the long-term estimates of ice drift and areal ice fluxes as obtained from the different methods are in fair to good agreement. Nevertheless, the consistent positive offset of the large-scale model results as compared to remote sensing data suggests that the former estimates of the ice flux for the period 1979 to 1995 are slight overestimates of the true value

4.2. Linkages Between Ice Circulations in the Laptev Sea and the Arctic Ocean

Our results essentially confirm previous studies which concluded that considerable amounts of ice are exported from the Laptev Sea to the Arctic Basin during winter and that ice export subsides during the summer months as more complicated circulation pattern evolves. Nevertheless, annual ice export through the northern boundary for the period 1979 to 1995 (492,000km^2) exceeds previous estimates for the section Cape Arkticheski-Kotelnyy Island (328,000km^2) obtained for the period 1937 to 1958. The average ice outflow from the southern Laptev Sea between 1936 and 1995 was estimated in this study at 309,000 km^2 A finding that to our knowledge has not been reported previously is the fact that export of sea ice through the eastern boundary of the Laptev Sea is of consider-

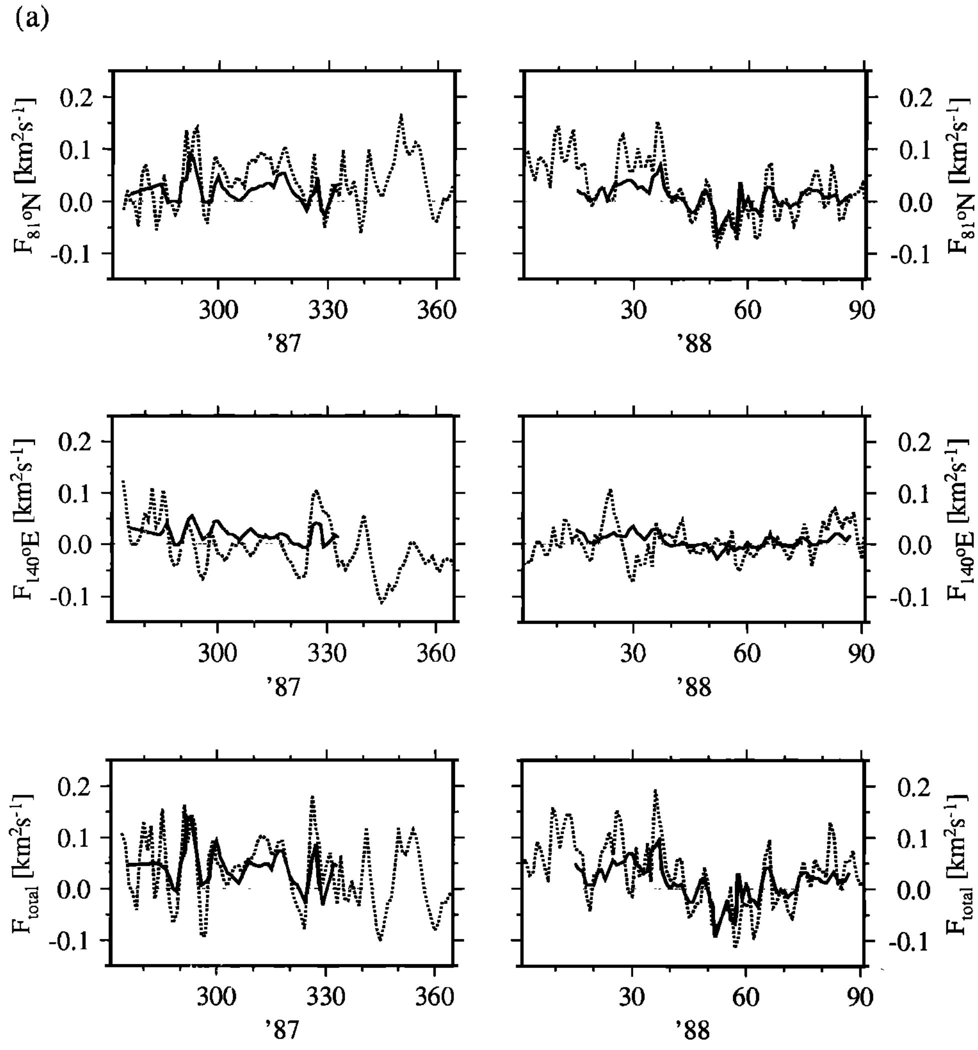

Figure 6. The (top) meridional $(F_{81^\circ N})$, (middle) zonal $(F_{140^\circ E})$, and (bottom) total (F_{total}) areal ice fluxes determined from SSM/I-derived data (solid line) and model calculations (dotted line) for the period (a) 1987/1988 and (b) 1994/1995.

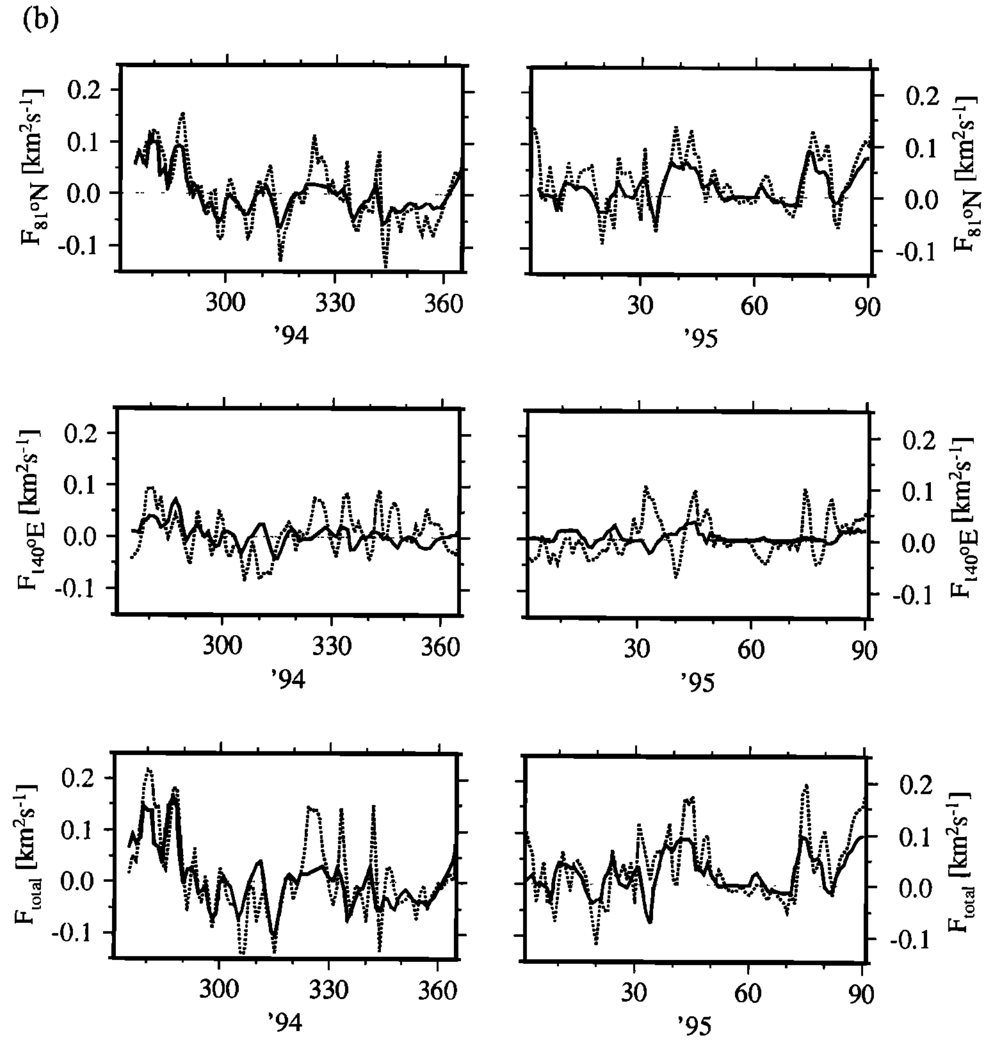

Figure 6. (continued)

able importance for the East Siberian Sea as well as the Arctic Ocean. Therefore the total annual ice export of 483,000 km^2 (1979 to 1995) exceeds previous estimates by a larger margin. Analysis of remote sensing data and model calculations showed that cyclonic circulation persists quite often in the study area, particularly in summer, but it is not stable and ice outflow in winter mostly occurs along all the northern boundary.

Modeling of the wind-driven Arctic Ocean ice circulation revealed the predominance of a cyclonic and anticyclonic circulation regime [*Proshutinsky and Johnson*, 1997], with the TPD extending further out into the North American Arctic during the cyclonic periods and a corresponding narrowing of the TPD during periods of prevailing anticyclonic circulation. Regime shifts with each regime persisting for between 5 to 7 years are forced by changes in location and intensity of the Islandic Low and the Siberian High. Given the importance of the Laptev Sea as a major source of sea ice for the TPD, the variability of ice export for the different circulation regimes has been examined for the period between 1979 and 1995. Anticyclonic wind-driven motion persisted in the central Arctic between 1984 and 1988 and cyclonic motion persisted from 1980 to 1983 and from 1989 to 1993 (see also Figure 12). From 1984 to 1988 the average areal ice flux through the northern boundary of the Laptev Sea was higher than that during the cyclonic periods, while the average areal ice import in summer was lower and the ice export in winter was higher than the corresponding mean values for the cyclonic circulation periods The impact of the cyclonic circulation regime was particularly apparent between 1989 and 1993, when ice was exported from the Laptev to the East-Siberian Sea both in winter and summer and the typical winter ice export through the northern boundary decreased to below average while the summer import increased to above average These results demonstrate that a significant fraction in the interannual variability of seasonal meridional and zonal ice fluxes in the Laptev Sea can be explained in terms of the large-scale Arctic circulation patterns

4.3. Linkages Between Reduction in Arctic Summer Sea Ice Extent and Ice Circulation in the Laptev Sea

Recent studies have revealed a considerable reduction in Arctic summer ice extent throughout the early1990s. Accord-

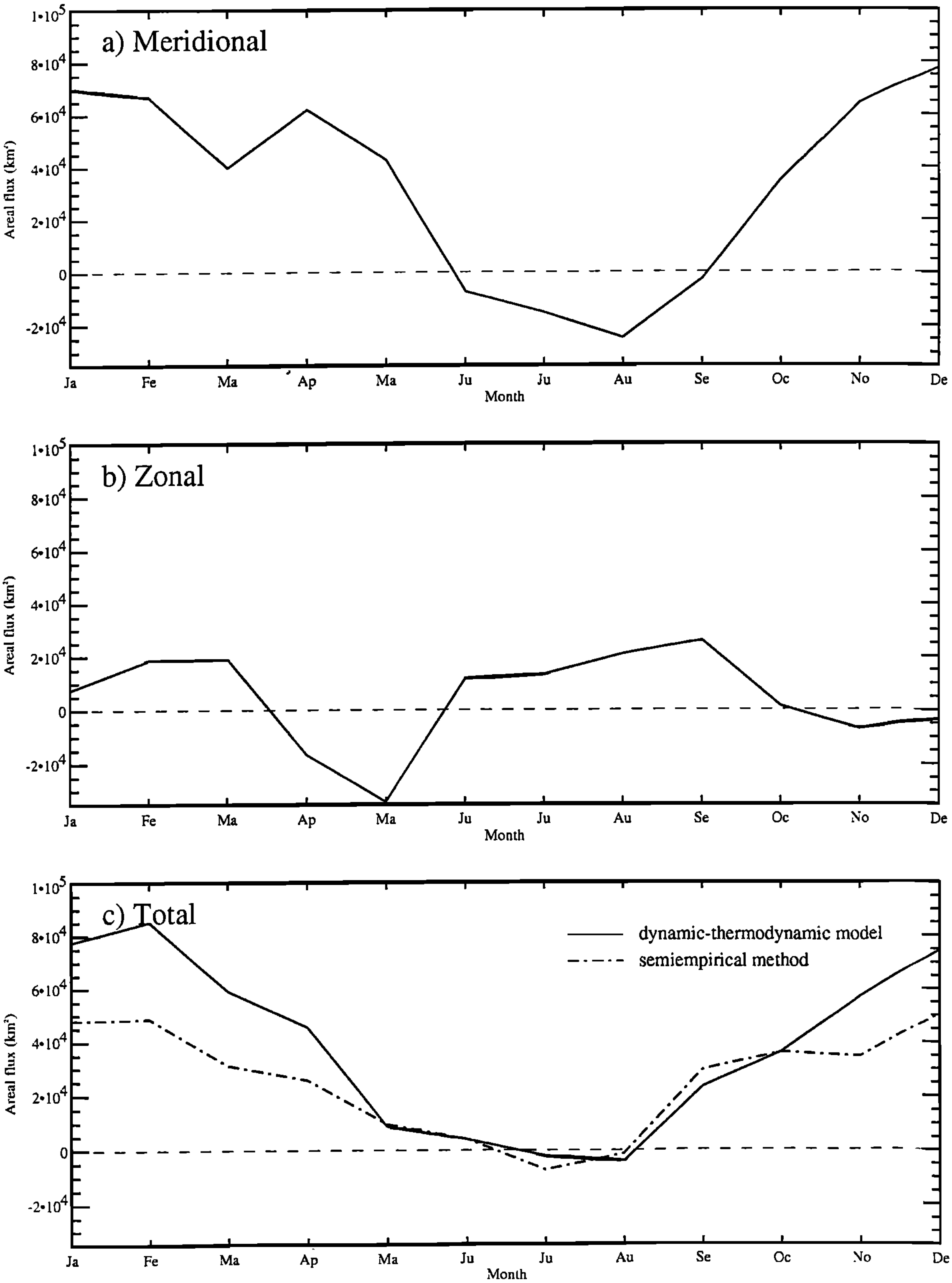

Figure 7. Seasonal cycle of average monthly (a) meridional, (b) zonal, and (c) total areal ice fluxes for the period 1979 to 1995, as estimated from model simulations.

ing to *Johannessen et al* [1995] and *Bjorgo et al.* [1997], the mean Arctic ice extent in the period 1990 to 1995 decreased by 4.5% as compared to the period 1979 to 1989. *Maslanik et al.* [1996] showed that this decrease was mostly due to substantial summer retreat of ice cover in the Siberian Arctic. According to Maslanik and coworkers, the mean perennial ice extent during the period 1990 to 1995 was reduced by 9% as compared to that of 1979 to 1989. Summer sea ice minima,

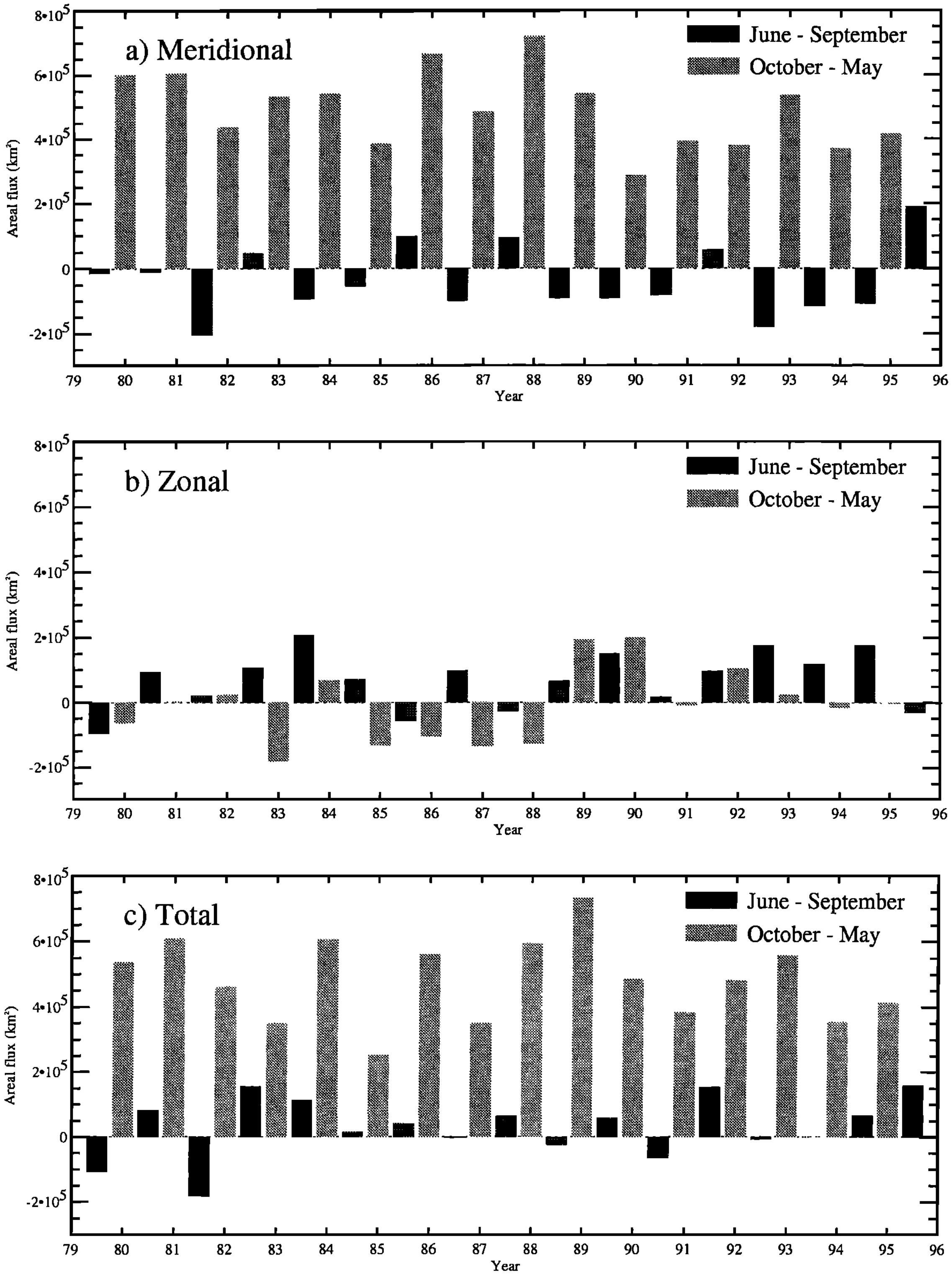

Figure 8. Model-derived (a) meridional, (b) zonal, and (c) total areal ice fluxes for the winter (October to May) and summers seasons (June to September) during the period 1979 to 1995.

both in the entire Arctic and the Laptev and East Siberian Seas, were observed in 1990, 1993, and 1995. As has been established in the previous studies [*Karelin*, 1945; *Gudkovich and Nikolaeva*, 1963], the springtime sea ice circulation in the Laptev Sea affects the location of the ice edge during the following summer. The large-scale dynamic-thermodynamic sea ice model employed in this study reveals a 9.1% increase in the average annual ice export from the Laptev Sea for the period 1990 to 1995 as compared to that of 1979 to 1989. The corresponding estimate of the average annual ice export from the southern Laptev Sea derived with the semiempirical method amounts to 27.4% increase for the same time intervals. Moreover, the total ice export during the winters of 1989/1990, 1992/1993, and 1994/1995 was above the average, indicating that the observed decrease in summer ice extent can, at least in part, be explained by the enhanced northward advection of sea ice in late winter/spring.

Based on the long-term ice transport data, no climatic trend in ice outflow from the Laptev Sea could be discerned for the period 1936 to 1995. Ice exchange varied considerably, and two periods of minimum ice export were observed in the late 1940s and 1980s. A drastic change in ice circulation was indicated for 1957, when a large influx of sea ice into the Laptev Sea took place. This influx was caused by a shorter period of ice outflow, which was reduced as a result of a reversal in the sea level air pressure gradient between Cape Chelyuskin and Kotelnyy Island. The long-term data furthermore suggest that the long-period cycle apparent in the amount of ice exported to the Arctic Basin may also be linked to similar periodicities in ice extent, casting a different light on interpretation of the passive microwave ice extent record, which commences in 1979.

4.4. Export of Particulates

During ice formation over the shallow Siberian shelves, large amounts of marine sediments can be entrained into the ice cover and are exported to the Arctic Ocean and the Nordic Seas. The Laptev Sea has been identified as a major source of sediment-laden sea ice in the Eurasian Arctic [*Appel and Gudkovich*, 1979; *Dethleff et al.*, 1993; *Neurnberg et al.*, 1994; *Reimnitz et al.*, 1994; *Eicken et al.*, 1997; *Pfirman et al.*, 1997; *Kassens et al.*, 1998]. Sedimentological studies suggest that the material transported by drifting ice contributes significantly to deep sea sedimentation in the Arctic Ocean and Greenland-Iceland-Norwegian Sea during the present interglacial period [*Pfirman et al*, 1989; *Hebbeln and Wefer*, 1991, H. Eicken et al., Identifying a major source area and constraints on entrainment for basin-scale sediment transport by Arctic sea ice, submitted to *Geophys. Res. Lett*, 2000](hereinafter referred to as (Eicken et al., submitted manuscript, 2000)) It has been shown, that the export of sediment-laden ice from the Laptev Sea is dominated by transport in the sector between 120° and 140°E, with export from the western region less well defined but likely much smaller [*Rigor and Colony*, 1997; *Eicken et al.*, 1997]. The present study indicates that export from the western Laptev Sea and past the east coast of Severnaya Zemlya may be of importance in some years, in particular, during cyclonic regime. More important, ice exchange in the New Siberian Islands region, where shallow water depths and other factors favor sediment entrainment (Eicken et al., submitted manuscript, 2000), may also play an important role in large-scale transport of sediment-laden ice. The variability in magnitude and direction of ice transport in the Laptev Sea region furthermore supports earlier observations on the episodic nature and patchy distribution of sediment-laden ice in the Arctic Ocean.

5. Summary and Conclusions

The sea ice circulation in the Laptev Sea and ice export to the Arctic Ocean have been studied based on the analysis of remote sensing data and model simulations. For the winters of 1987/1988 and 1994/1995, ice drift patterns and areal fluxes of ice from the Laptev Sea were determined from successive Okean radar images and SSM/I data. The seasonal and inter-

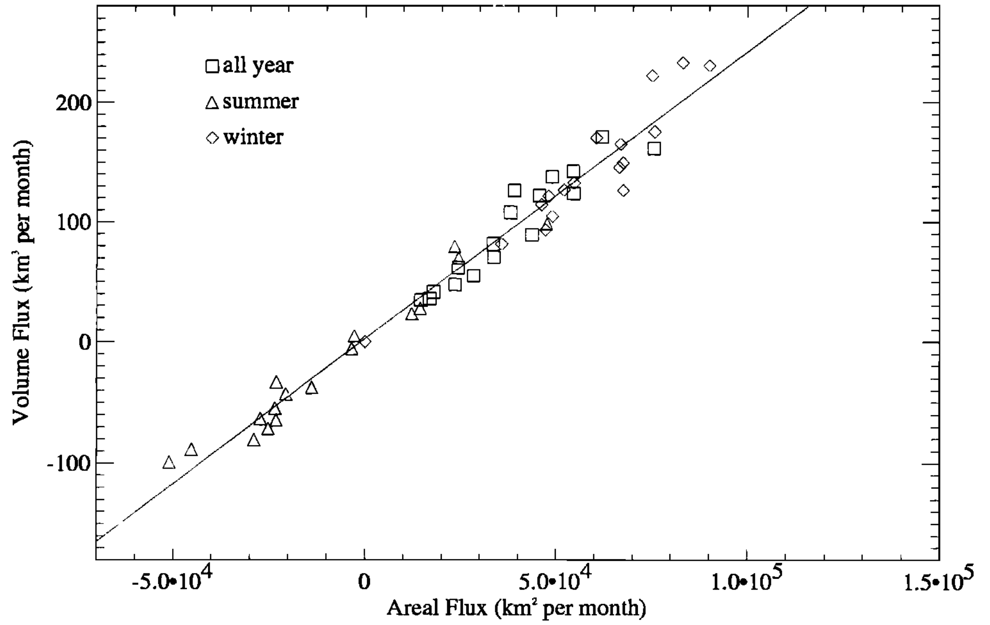

Figure 9. Scatterplot of areal versus volume ice fluxes across the northern boundary of the Laptev Sea calculated with the dynamic-thermodynamic sea ice model for the period from 1979 to 1995 (squares, mean annual ice fluxes; triangles, mean summer ice fluxes, and diamonds, mean winter ice fluxes).

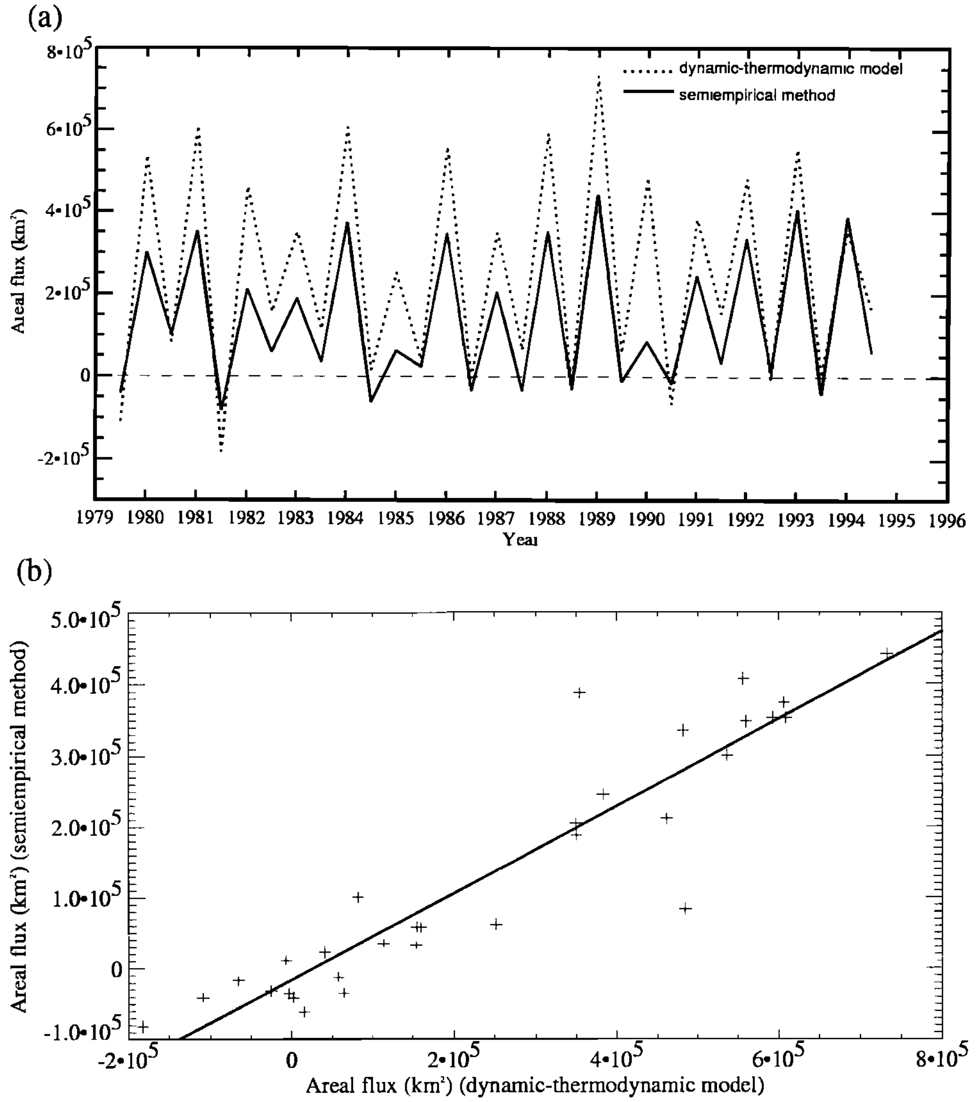

Figure 10. (a) Comparison of ice export from the Laptev Sea calculated with the semiempirical method (solid line) and the dynamic-thermodynamic sea ice model (dotted line), (b) Scatterplot of areal ice export calculated with the dynamic-thermodynamic sea ice model versus semiempirical estimates of areal ice export.

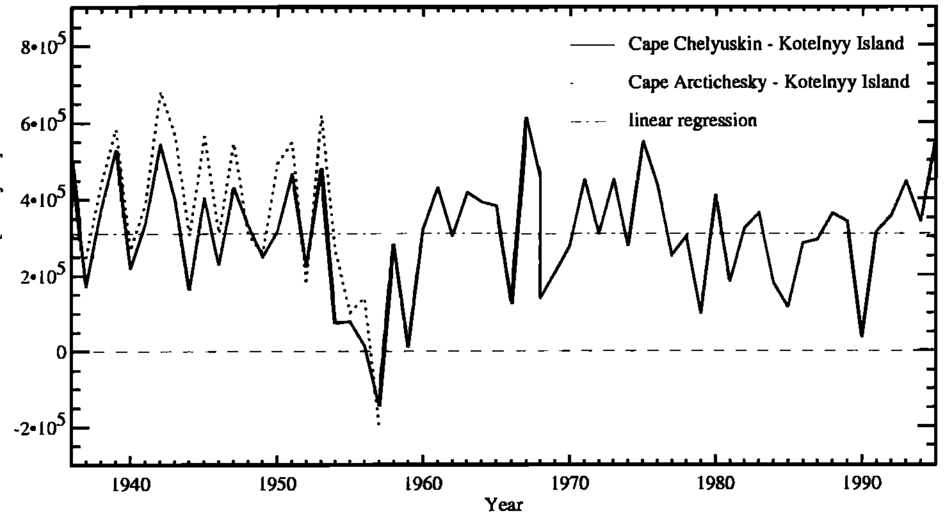

Figure 11. Interannual variability of the sea ice export from the Laptev Sea to the Arctic Basin calculated from the pressure gradient along the section Cape Chelyuskin-Kotelnyy Island and along the section Cape Arctichesky-Kotelnyy Island. The linear regression curve for the data Cape Chelyuskin-Kotelnyy Island has been overlaid.

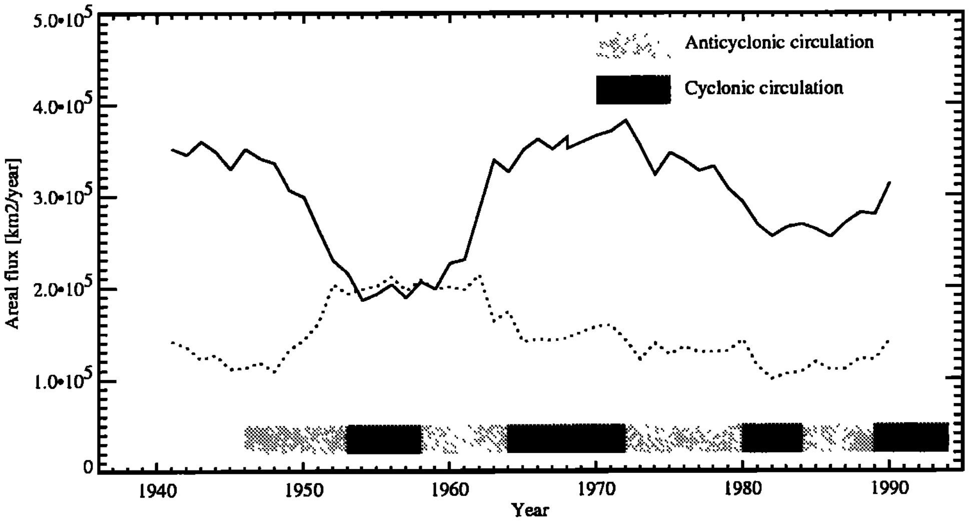

Figure 12. Annual mean ice export from the Laptev Sea, calculated with the semiempirical method. An 11-year running mean filter has been applied to the data. Overlaid are the periods of cyclonic and anticyclonic circulation as described by *Proshutinsky and Jonhson* [1997].

annual variability of sea ice exchange between the Laptev Sea and the Arctic Ocean has been investigated with the large-scale dynamic-thermodynamic sea ice model during the period 1979 to 1995 and with the semiempirical method for the period 1936 to 1995. Obtained estimates confirm each other in the basic conclusions but nevertheless agree only within certain limits. We do not think that one of these methods is the best for the estimating sea ice fluxes. Each of them has certain strengths and weaknesses. Through combination of these methods we gained a deeper insight of ice circulation in the Laptev Sea and ice export to the Arctic Ocean, its connection with Arctic Ocean ice circulation and reduction in the Arctic summer ice extent, as well as the importance for transport of sediments and pollutants. The main conclusions of this work are summarized below.

1. The study of the seasonal and interannual variabilities of ice exchange between the Laptev Sea and the Arctic Ocean during the period 1979 - 1995 revealed (1) the average seasonal cycle of monthly total ice export from the Laptev Sea was positive throughout a year, with a maximum in February and a minimum in August; (2) through the northern boundary, ice was exported from October until May, with ice import predominating between June and September; (3) along the eastern boundary, ice was imported from the East Siberian Sea in April, May, November, and December, with maximum export in September; (4) while ice export prevailed during entire winter period, events of net ice import for periods of several days/weeks occurred regularly; (5) the average winter ice outflow amounts to 483,000 km^2 and varies from 251,000 to 732,000km^2; (6) on average, 40,000km^2 of sea ice were imported through the northern boundary in summer, with ice inflow dominating in all summers except for those of 1982, 1985, 1987, 1991, and 1995, (7) on average, approximately 69,000 km^2 of sea ice were exported from the Laptev to the East Siberian Sea during summer.

2. In the period 1936 to 1995 the average sea ice export from the southern to the northern Laptev Sea amounts to 309,000 km^2 with no discernible long-term trend Only in 1957 a considerable amount of sea ice was imported to the Laptev Sea.

3 The considerable reduction in Arctic summer ice extent during the first half of the 1990s is believed to be associated with changes in ice circulation in the Laptev Sea The average annual ice area, exported from the Laptev Sea between 1990 and 1995, is larger by 9% as compared to that between 1979 and 1989, with above average export for the winters preceding the record minima of 1990, 1993, and 1995.

4. The sea ice circulation in the Laptev Sea is generally in phase with alternating regimes of cyclonic and anticyclonic wind-driven circulation in the Arctic Basin.

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