OBSERVATIONAL STUDIES OF ARCTIC OCEAN ICE-ATMOSPHERE INTERACTIONS[1]

R. G. Barry and J. R. Key
(National Snow and Ice Data Center/
Cooperative Institute for Research in Environmental Sciences,
University of Colorado, Boulder, CO 80309-0449)

Abstract: Our understanding of ocean-ice-atmosphere interactions in the Arctic on synoptic to interannual time scales is improving steadily through the use of observations from satellite remote sensing (visible, IR, and passive microwave), submarine sonar, airborne lidar, and drifting buoys. Effects on the summer ice conditions of the snow melt regime on sea ice and of synoptic-scale circulation variability forcing variations in ice concentration are described. The characteristics of winter leads and their atmospheric associations also are discussed. The possible causes of fluctuations in ice export and their significance for North Atlantic salinity anomalies are examined. The findings are discussed within the overall context of the importance of polar ice and climate studies for analysis and detection of global climate change.

INTRODUCTION

Our understanding of the close coupling of atmosphere-ocean-sea ice in the Arctic has been significantly advanced in recent years by the integration of remote sensing and *in situ* measurements of the surface characteristics, their annual cycle, and their variability on synoptic, interannual, and decadal time scales. There have been visible and infrared data from the Very High Resolution Radiometer (VHRR) sensors since 1972 and the Advanced Very High Resolution Radiometer (AVHRR) and TIROS Operational Vertical Sounder (TOVS) since 1979, single and multichannel passive microwave data beginning in 1973, drifting buoy records from 1979, and Synthetic Aperture Radar (SAR) data since 1991. Particularly important is the recent availability of data products on sea ice from the Electrically Scanning Microwave Radiometer (ESMR), 1973-1976 (Parkinson et al., 1987), Scanning Multichannel Microwave Radiometer (SMMR), 1978-1987 (Gloersen et al., 1992), and Special Sensor Microwave Imager (SSM/I), 1987-present (LeDrew et al., 1992), as well as the International Satellite Cloud Climatology Project (ISCCP) data on clouds, 1983-present (Rossow and Schiffer, 1991), SAR data on ice sheets (Fahnestock et al., 1993), buoy-derived sea ice motion, 1979-present (Thorndike and Colony, 1980), submarine sonar thickness measurements of sea ice (McLaren, 1989; McLaren et al.,

[1]This work was supported under NAGW-2407 through the University of Washington. Thanks are due to Lyn Ryder for word processing.

Polar Geography and Geology, 1994, **18**, 1, pp. 1-14.

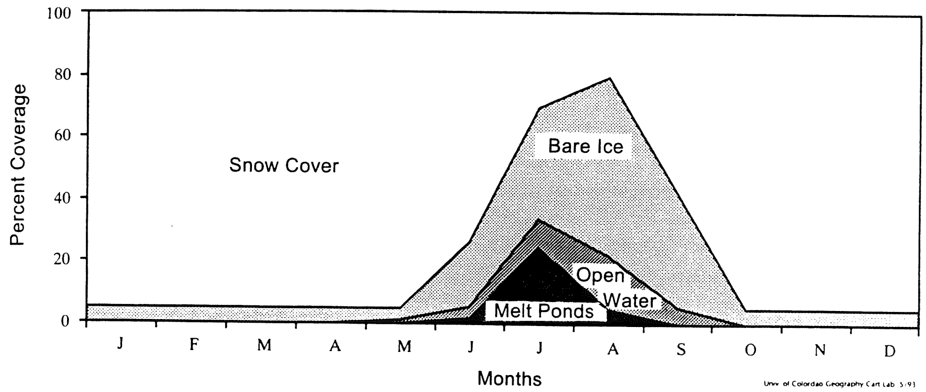

Fig. 1. Schematic seasonal trend of surface types in the central Arctic plotted as fractional surface coverage in percent (from Barry et al., 1993).

1992, Wadhams, 1990), and atmospheric soundings from land and drifting stations (Kahl et al., 1992a). This paper focuses on a review of the contributions of remote sensing and *in situ* data, combined with theoretical and modeling studies, to our characterization of the Arctic sea ice-climate system, its internal and external interactions, and their potential importance for global climate.

SURFACE CHARACTERIZATION

The Arctic Ocean is unique in having a permanent sea ice cover averaging about 3.5- 4 m in thickness near the Pole (McLaren et al. , 1992). However, the surface character varies considerably during the annual cycle (Fig. 1; Barry et al., 1993a). In particular, in summer, the progression of snowmelt, including the extent and depth of meltponds, the fractional coverage of leads and open water in the marginal seas, and the cloud cover have a significant effect on surface albedo and the absorbed radiation. Estimates of the spatial pattern of surface albedo and its temporal evolution have been made by two approaches. Robinson et al. (1992) mapped categories of snowmelt for 10 summers from visible-band Defense Meteorological Satellite Program (DMSP) images by visual methods and then used parameterized albedo values for each category, checked by graytone scaling between snow-covered ice and open water. Additionally, adjustments were made for ice concentration and cloud amount. The patterns for each month compare well with those based on surface reflectance estimates from the ISCCP data (Rossow and Garder, 1993), but the actual values obtained by Robinson et al. are 0.08-0.10 higher than the ISCCP data in May and June and

0.05-0.06 lower in July and August. These differences represent an uncertainty in current estimates and appear to be a result of the combined effect of biases in the parameterized values of Robinson et al. and in the ISCCP cloud-clearing algorithm (Schweiger et al., 1993).

The annual cycle of surface albedo for the Arctic reaches a minimum in about the middle of August; the central Arctic value is approximately 0.51 with means 0.06-0.16 lower in the marginal seas where there is more variability associated with the degree of ice retreat in the individual sectors. There is also considerable interannual variability in the surface albedo in June (Robinson et al., 1992). Barry et al. (1989) estimated that the extreme range in surface albedo values between years may result in a cumulative summer difference in surface net radiation sufficient to account for the melt of 66 cm of ice, compared with the early suggestion by Fletcher (1966) of up to 2 m ice melt if the snow melt season were a month ahead of its usual regime. Hence, under the present climatic regime the sea ice cover seems stable to the typical interannual variability of thermodynamic forcing.

The absorption of shortwave radiation by the ice-ocean surface is affected by the extent and depth of melt ponds; pond extent reaches an average maximum of about 25% of the surface in the central Arctic in mid-July (Nazintsev, 1964; Barry, 1983), but pond depth may peak several weeks later (Ebert and Curry, 1992). Overall reductions in ice concentration, associated with greater ice divergence because of a tendency for cyclonic activity over the Beaufort Sea in late summer (Barry and Maslanik, 1989; Serreze et al., 1989, 1990; LeDrew et al., 1991), also peak in August or early September when the frequency of new snowfalls already is increasing. Melt ponds and open water areas are important because of the penetration of solar radiation and lateral ice melt effects. However, ponds that refreeze in the winter do not represent a net contribution to the ice energy balance, in contrast to ones that eventually drain. Currently, there are no appropriate measurements of these surface parameters and their regional and interannual variability.

During the winter season, limited areas of open water appear in leads and coastal polynyi associated with wind forcing of the central pack ice or ice in the lee of coasts and islands. Leads are a major source of turbulent heat transfer to the atmosphere, having flux rates one to two orders of magnitude greater than that through ice ≥1 m thick (Maykut, 1986). A typical lead is ≥100 m wide and refreezes within 1-3 days. Even in polynyi, only about 1% of the area is open water in winter, with 30% new ice (<10 cm thick) and the rest being young ice (Steffen, 1991; Barry et al., 1993b). Lead fields are broadly parallel to the geostrophic wind direction (Miles and Barry, 1989) but, when a pattern has been set up, it has a tendency to persist until refreezing or convergent motion causes closure and/or strong wind forcing is re-initiated. The lead area accounts for only 1-2% of the Arctic in midwinter, based on submarine sonar statistics (Bourke and McLaren, 1992). Lead detection and mapping from satellite data is problematic in visible and IR signatures because of atmospheric effects and spatial measurement scale (Key et al., 1993) and ambiguous signatures associated with wind effects on open water in SAR data (Steffen and Heinrichs, 1994).

The ice thickness distribution is a crucial parameter for sea ice models, but is poorly known. Submarine sonar data indicate mean drafts in winter of about 4 m near the Pole, increasing to 6-7 m off northern Greenland and the Canadian Arctic Archipelago (Bourke and McLaren, 1992); total ice thickness is approximately 1.130 times the draft for ice with ridges. The annual cycle of ice thickness and its regional variability also is uncertain. It appears that mean drafts are 0.5-1.0 m lower in summer than winter at the same locations; in the central Beaufort Sea, McLaren (1989) reports an average summer thickness of only 1.7 m. Large interannual variability also is evident north of Greenland (Wadhams, 1990) and at the North Pole (McLaren et al., 1992), associated with varying fractions of first-year and multiyear ice as a result of variations in large-scale ice motion and the climatic character of individual seasons (Serreze et al., 1989, 1990; LeDrew et al., 1991). To date, no trends in ice thickness can be identified in the available data.

Snowfall and snow depth on the ice also are not well known. Modelling studies usually rely on crude climatological estimates of annual accumulation. Limited *in situ* data have been published (Barry et al., 1993a) and extensive Russian data are known to exist. A recent summary of Russian field observations primarily for the period 1972-1984 indicated average April snow depths on level ice of about 20 cm in the central Arctic and 60 cm off northeast Greenland, with average depths in ridged ice of about 80-100 cm in the former area and 140-160 cm off northern Greenland (Romanov, 1993a, 1993b). Lindsay and Rothrock (1993) have presented a method of estimating snow depth and ice thickness using albedo and temperature data from the AVHRR. However, their energy balance approach has not been applied, or validated, on a large scale.

ATMOSPHERIC FACTORS

The key atmospheric factors involved in the Arctic Ocean ice-climate system are the surface radiative and energy fluxes, the atmospheric temperature profile, and air motion. Radiation is particularly affected by cloud cover, which is still inadequately known. The ISCCP data for the Arctic (Rossow and Garder, 1993) give total cloud amounts 10-30% lower than ground-based observations in summer and 5-10% lower in winter (Warren et al., 1988; Schweiger and Key, 1992; Rossow et al., 1993). Cloud amount in winter is particularly uncertain; tropospheric ice crystal concentrations may contribute to the higher satellite-derived estimates (Curry et al., 1990). A key problem in Arctic climate studies is that of cloud detection and classification over polar surfaces in winter and summer (Ebert, 1987; Key and Barry, 1989). Improvements in the ISCCP algorithm to address this issue are in progress. Studies using visual analysis of DMSP imagery support previous work indicating that stratiform cloud amounts increase sharply from May to June, associated with moisture advection and surface melt onset (Barry et al., 1987), and also point to greater cloud opacity in late summer Robinson et al. (1987), perhaps associated with increased cyclone frequency (Serreze et al., 1993a). This apparent tendency for thicker cloud cover in late summer merits further investigation via aircraft measurements of cloud microphysical properties, as does the question of winter ice crystal concentrations.

The atmospheric temperature profile in the Arctic, featuring a persistent low-level inversion during the cold season, has been well documented using *in situ* sounding data (Kahl et al., 1992b; Serreze et al., 1992a). Accurate methods of retrieving temperature and humidity profiles from TOVS data have only recently been developed and applied on a basin-wide scale (Francis, 1994; Khalsa et al., 1994), but they show considerable promise. The persistence of a stable lower troposphere is important in relation to turbulent mixing, stratiform cloud formation, aerosol concentrations, and radiative fluxes.

Satellite-derived estimates of radiative fluxes at the surface have been obtained by Schweiger and Key (1994) using ISCCP cloud data in conjunction with a radiative transfer model. Spatially averaged shortwave fluxes agree well with climatological estimates, but calculated downwelling infrared radiation is significantly lower than observed. A possible reason for this involves the neglect of ice crystals that may enhance downwelling infrared radiation (Curry et al., 1990). There is also a potential for estimating turbulent heat fluxes from leads and polynyi based on satellite mapping of new and young ice types and surface temperatures via AVHRR (Steffen, 1991; Key and Haefliger, 1992; Lindsay and Rothrock, 1994).

Air motion is the principal driver for sea ice motion and the associated ice divergence/convergence manifested by the development of leads and ridges. Pressure and wind fields are reasonably well defined by the modern buoy network with pressure sensors (Thorndike and Colony, 1980), although improved data on surface drag coefficients and coincident boundary-layer stability measurements are also required (Overland, 1985). The ice motion itself is determined by three-hourly reports from buoy position data but can also be derived from sequential satellite imagery. In cloud-free conditions AVHRR data provide extensive spatial coverage at a medium resolution (a few kilometers) (Emery et al., 1991), while SAR data provide all-weather high resolution (10-100 m) for limited swaths. Merging of these different data sets offers the possibility of combining the unique advantages of each system (Maslanik et al., 1994).

INTERACTIONS

Recent theoretical and modeling studies provide a framework for understanding the interactions of the key components of the Arctic Ocean ice-climate system and their potential sensitivity to perturbations (LeDrew, 1992; Ebert and Curry, 1993). Figure 2 illustrates the range of interactions that need to be taken into account in considering fluctuations in ice thickness and net ice flux. Ebert and Curry identify six important feedback loops in a one-dimensional ice model: (1) surface-albedo feedback affecting ice thickness and/or extent; (2) oceanic heat conduction feedback influencing ice melting rates; (3) lead fraction feedback affecting summer absorption of solar radiation and winter ocean heat loss; (4) lead absorption of solar radiation feedback warming the mixed layers and producing basal ablation; (5) outgoing infrared radiation-surface temperature (negative) feedback; and (6) turbulent flux-surface temperature (negative) feedback. The first four all are positive feedbacks. Some observational results bearing on these processes now are reviewed.

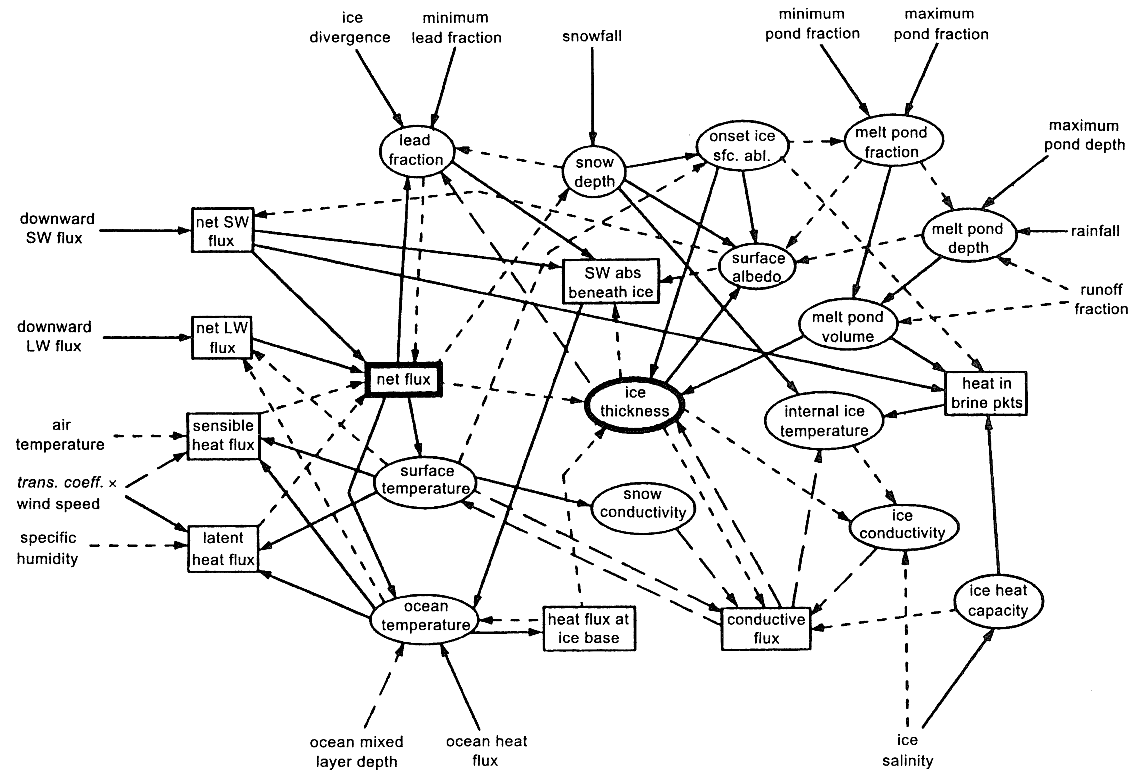

Fig. 2. Illustration of the interactions between external forcings (bold) and parameter values (italics) with internal variables (ovals) and fluxes (boxes). Solid arrows denote positive interactions, short-dashed arrows represent negative interactions and long-dashed arrows indicate interactions that may be positive or negative according to season (from Ebert and Curry, 1993).

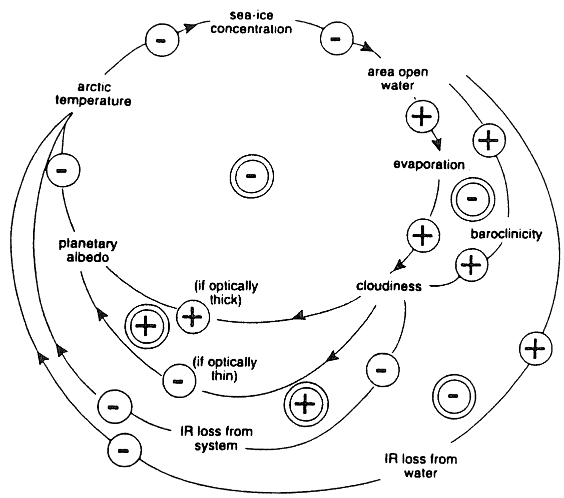

Fig. 3. Cloud-sea ice-albedo feedback loop in the marginal ice zone (from LeDrew, 1992). A plus sign indicates that a change in one parameter causes a change in the same direction in the effect. The net effect of the loop is indicated in the center of each circle.

The surface albedo data discussed earlier provide a baseline climatology, but data on albedo variability cannot yet be combined with ice extent and/or thickness. Case studies of ice extent and coastal temperatures in relation to melt onset suggest that early melt and lower surface albedos are favored by off-land winds, whereas late melt and higher albedos are associated with over-ice circulations (Serreze et al., 1993b). Responses of ice extent or thickness to lower/higher summer albedo values have not been analyzed empirically. The complex effect of cloud optical depth on planetary albedo was investigated by Barry et al. (1984), who showed that in the sea ice marginal zone there may be either positive or negative feedbacks in the surface albedo-ice extent interaction associated with cloud optical depth, zenith angle, and surface type (Fig. 3; LeDrew, 1992).

The spatial and temporal variability of lead fraction is insufficiently known to model surface energy fluxes and their effect on regional ice growth and ablation in individual years. The effect of leads on the transfer of turbulent heat and ice crystals into the atmosphere also is uncertain. Using backscatter data from airborne lidar, condensate plumes have been identified emanating from open leads (estimated to be ≥10 km wide) and extending to 2-4 km altitude and persisting up to 200 km downwind (Schnell et al., 1989; Andreas et al., 1990). The conditions required to generate such deep convection events appear to be rare under Arctic conditions, although wide flow leads are observed in the shelf seas off Siberia (Serreze et al., 1992b). Nevertheless, shallow convection over narrow leads is believed to produce enhanced concentrations of ice crystals near the surface that may substantially modify infrared radiative fluxes.

Atmosphere-sea ice interaction has been extensively studied in terms of the mutual variability of the two systems on the annual scale (Walsh and Johnson, 1979; Walsh, 1986), for example. Seasonal differences in the forcing and lag

Fig. 2. Illustration of the interactions between external forcings (bold) and parameter values (italics) with internal variables (ovals) and fluxes (boxes). Solid arrows denote positive interactions, short-dashed arrows represent negative interactions and long-dashed arrows indicate interactions that may be positive or negative according to season (from Ebert and Curry, 1993).

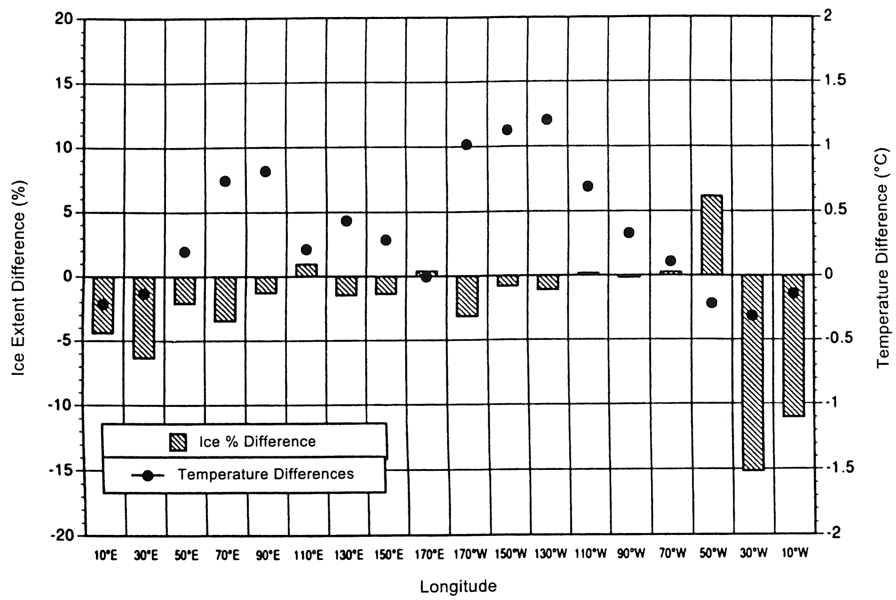

Fig. 4. Changes in 15-year annual mean extent of Arctic sea ice and surface air temperature (65°-70° N) from 1976-1990 (from Chapman and Walsh, 1993).

responses also have been identified. During summer ice retreat, anomalies in ice extent respond to atmospheric forcing up to four months earlier, whereas during autumn anomalies in the atmosphere and ice extent essentially are in phase. At the synoptic scale, which may determine the character of the seasonal forcing, LeDrew (1987) used a diagnostic analysis to distinguish the roles of surface heat and momentum fluxes, on the one hand, versus advective transports of vorticity and temperature, on the other, in the development and maintenance of arctic low pressure systems. The advective components were shown to predominate except in a few special cases (LeDrew et al., 1991).

Interannual to decadal scale variations in ice extent tend to be highly variable regionally. There are out-of-phase variations in ice anomalies between the North Atlantic and Beaufort-Chukchi sea according to Mysak and Manak (1989), and during 1979-1986 the ice season lengthened in the Beaufort Sea and Davis Strait sectors but shortened in the Eastern Hemisphere (Parkinson, 1992). The longitudinal pattern of sea ice advance/retreat between 1961-1975 and 1976-1990 is inversely correlated with changes in annual air temperature in the latitude zone 55°-75° N as shown in Figure 4 (Chapman and Walsh, 1993).

The ice flux through Fram Strait is of great importance to the balances of ice mass and of fresh water in the Arctic Ocean (Aagaard and Carmack, 1989). This outflow is forced primarily by the mean high pressure over the Beaufort Sea and the low pressure trough that extends northeastwards from the Icelandic Low. Variability in the ice and water outflow is related to variability in cyclonic activity over the Arctic and associated variability in the Beaufort Gyre and TransPolar Drift Stream (TPDS) (Serreze et al., 1989; Walsh and Chapman, 1990; Maslanik et al., 1991). Even more significant is the postulated connection between ice outflow and anomalies in surface salinity and water temperature in the Greenland and Iceland seas. The "Great Salinity Anomaly" (GSA), which began in the late 1960s, is the best known manifestation of this anomaly pattern (Dickson et al., 1988). Mysak et al. (1990) and Mysak and Power (1992) propose a conceptual model linking Mackenzie River runoff, Beaufort Sea ice anomalies 12 months later, and subsequent anomalous ice export via the TPDS into the Greenland Sea. Other potential mechanisms exist, however (Barry et al., 1993a). Observational data on atmospheric circulation anomalies over the Arctic (Serreze et al., 1992c) and results from simulations with a coupled ice-ocean model, forced by observed winds (Häkkinen, 1993), suggest that enhanced export of thick, low-salinity multiyear ice from north of Greenland could account for most of the freshwater required to explain the GSA salinity deficit.

CONCLUDING REMARKS

The contributions of *in situ* and remote sensing studies to our knowledge of the surface and atmospheric properties in the Arctic is readily apparent. Considerable advances are being made in understanding ocean-ice-atmosphere interactions by providing validation data for modelling results and by empirical findings that stimulate process modeling or large-scale model sensitivity studies. Both types of contribution have been illustrated here. Unfortunately, at the present time, GCMs fail to simulate adequately many basic characteristics of the Arctic climate regime (Walsh and Crane, 1991). This raises concerns as to the validity of such models for climate perturbation experiments. Most simulations of the potential temperature response to CO_2 doubling, for example, depict greatly enhanced high-latitude warming in the lower troposphere, related largely to substantial reductions in sea ice. However, the representation of thermodynamic and dynamic sea ice processes in current models is inadequate for a high degree of confidence to be attached to these results.

The 1990s are witnessing an accelerating increase in the availability of remotely sensed data. Existing SAR data from the European Remote Sensing Satellite-1 (ERS-1) and Japan's Earth Resources Satellite-1 (JERS-1), and those that will be provided by the Canadian Radarsat in 1995, as well as the expanded Arctic Ocean buoy network and moored upward-looking sonars, offer an entirely new capability. The key to their full utilization, however, will be their merging with other data streams, such as AVHRR and the DMSP suite of sensors.

LITERATURE

Aagaard, K. and E. C. Carmack. "The role of sea ice and other freshwater in the Arctic circulation," *Jour. Geophys. Res.*, Vol. 94(C10), 1989, pp. 14,485-14,498.

Andreas, M. W., M. W. Miles, R. G. Barry, and R. C. Schnell. "Lidar-derived particle concentrations in plumes from arctic leads," *Ann. Glaciol.*, Vol. 14, 1990, pp. 9-12.

Barry, R. G. "Arctic Ocean ice and climate: Perspectives on a century of polar research," *Ann. Assoc. Am. Geogr.*, Vol. 73, No. 4, 1983, pp. 485-501.

__________. "The present climate of the Arctic Ocean and possible past and future states," in: Y. Herman, ed., *The Arctic Seas: Climatology, Oceanography, Biology and Geology*. New York: Van Nostrand Reinhold Co., 1989, pp. 1-46.

__________, **A. Henderson-Sellers, and K. P. Shine.** "Climate sensitivity and the marginal cryosphere," in: J. E. Hansen and T. Takahashi, eds., *Climate Processes and Climate Sensitivity.* Washington, DC: Geophys. Monogr. Ser., Vol. 29, AGU, 1984, pp. 221-237.

__________, **R. G. Crane, A. Schweiger, and J. Newell.** "Arctic cloudiness in spring from satellite imagery," *Jour. Climatol.*, Vol. 7, 1987, pp. 423-451.

__________, **M. W. Miles, R. C. Cianflone, G. Scharfen, and R. C. Schnell.** "Characteristics of Arctic sea ice from remote sensing data and their relationship to atmospheric processes.," *Ann. Glaciol.*, Vol. 12, 1989, pp. 9-15.

__________ **and J. A. Maslanik.** "Arctic Sea ice characteristics and associated atmosphere-ice interactions in summer inferred from SMMR data and drifting buoys, 1979-1984," *Geojournal*, Vol. 18, No. 1, 1989, pp. 35-44.

__________, **M. C. Serreze, J. A. Maslanik, and R. H. Preller.** "The Arctic sea ice-climate system: Observations and modeling," *Rev. Geophys.*, Vol. 31, No.4, 1993a, pp. 397-422.

__________, **J. Maslanik, K. Steffen, R. L. Weaver, V. Troisi, D. J. Cavalieri, and S. Martin.** "Advances in sea ice research based on remotely sensed passive microwave data," *Oceanography*, Vol. 6, 1993b, pp. 5-13.

Bourke, R. H. and A. S. McLaren. "Contour mapping of Arctic Basin ice draft and roughness parameters," *Jour. Geophys. Res.*, Vol. 97(C11), 1992, pp. 17,715-17,728.

Chapman, W. L. and J. E. Walsh. "Recent variations of sea ice and air temperature in high latitudes," *Bull. Am. Meterol. Soc.*, Vol. 74, 1993, pp. 33-47.

Curry, J. A., F. G. Meyer, L. F. Radke, C. A. Brock, and E. Ebert. "Occurrence and characteristics of lower tropospheric ice crystal in the Arctic," *Int. Jour. Climatol.*, Vol. 10, 1990, pp. 749-764.

Dickson, R. R., J. Meincke, S. A. Malmberg, and A. J. Lee. "The 'Great Salinity Anomaly' in the northern North Atlantic, 1968-1982," *Prog. Oceanogr.*, Vol. 20, 1988, pp. 103-151.

Ebert, E. E. "A pattern recognition technique for distinguishing surface and cloud types in the polar regions," *Jour. Clim. Appl. Meterol.*, Vol. 26, 1987, pp. 1412-1427.

__________ **and J. A. Curry.** "An intermediate one-dimensional thermodynamic sea ice model for investigating ice-atmosphere interactions," *Jour. Geophys. Res.*, Vol. 98(C6), 1993, pp. 10,085-10,109.

Emery, W. J., C. W. Fowler, J. Hawkins, and R. H. Preller. "Fram Strait satellite image-derived ice motions," *Jour. Geophys. Res.*, Vol. 96, 1991, pp. 4,751-4,768.

Fahnestock, M., R. Bindschadler, R. Kwok, and K. Jezek. "Greenland ice sheet surface properties and ice dynamics from ERS-1 SAR imagery," *Science*, Vol. 262, 1993, pp. 1530-1534.

Francis, J. A. "Improvements to TOVS retrievals over sea ice and applications

Francis, J. A. "Improvements to TOVS retrievals over sea ice and applications to estimating Arctic energy fluxes," *Jour. Geophys. Res.*, 1994, Vol. 99(D5), pp. 10395-10408.

Fletcher, J. O. "Ice extent on the Southern Ocean and its relation to world climate," Memorandum RM-5793-NSF. Santa Monica, CA.: The Rand Corporation, 1966, 111 pp.

Gloersen, P., W. J. Campbell, D. Cavalieri, J. C. Comiso, C. L. Parkinson, and J. J. Zwally. *Arctic and Antarctic Sea Ice, 1978-1987: Satellite Passive-Microwave Observations and Analysis*. Washington, DC: National Aeronautics and Space Administration, *NASA SP-511*, 1992, 290 pp.

Häkkinen, S. "An Arctic source for the Great Salinity Anomaly: A simulation of the Arctic ice-ocean system for 1955-1975," *Jour. Geophys. Res.*, Vol. 98(C9), 1993, pp. 16,397-16,410.

Kahl, J. D., M. C. Serreze, S. Shiotani, S. M. Skony, and R. C. Schnell. "In situ meteorological sounding archives for Arctic studies," *Bull. Amer. Met. Soc.*, Vol. 73, 1992a, pp. 1824-1830.

__________, __________, and R. C. Schnell. "Tropospheric low-level temperature in the Canadian Arctic," *Atmos. Ocean.*, Vol. 30, 1992b, pp. 511-529.

Khalsa, S. J. S., J. Key, and J. Bates. "Spatial and temporal variability in Arctic temperatures as revealed in the upper air and TOVS data record," *Proceedings. Sixth Conference on Climate Variations*. Boston, MA: American Meteorological Society, 1994, pp. 373-376 (preprint).

Key, J. R. and R. G. Barry. "Cloud cover analysis with Arctic AVHRR data. 1. Cloud detection," *Jour. Geophys. Res.*, Vol. 94(D15), 1989, pp. 18,521-18,535.

__________ and M. Haefliger. "Arctic ice surface temperature retrieval from AVHRR thermal channels," *Jour. Geophys. Res.*, Vol. 97(D5), 1992, pp. 5885-5893.

__________, R. Stone, J. A. Maslanik, and E. Ellefsen. "The detectability of sea ice leads in satellite data as a function of atmospheric conditions and measurement scale," *Ann. Glaciol.*, Vol. 17, 1993, pp. 227-232.

LeDrew, E. F. "Development processes for five depression systems within the Polar Basin," *Jour. Climatol.*, Vol. 8, 1987, pp. 125-153.

__________. "Remote sensing of atmosphere-cryosphere interactions in the Polar Basin," *Canad. Geogr.*, Vol. 36, 1992, pp. 336-350.

__________, D. Johnson, and J. A. Maslanik. "An examination of atmospheric mechanisms that may be responsible for the annual reversal of the Beaufort Sea ice field," *Internat. Jour. Clim.*, Vol. 11, 1991, pp. 841-860.

__________, D. Barber, T. Agnew, and D. Dunlop. "Canadian Sea Ice Atlas from microwave remotely sensed imagery: July 1987 to June 1990," *Climatol. Studies*, No. 44. Ottawa: Atmospheric Environment Service, Canada, 1992, 80 pp.

Lindsay, R. W. and D. A. Rothrock. "The calculation of surface temperature and albedo of Arctic sea ice from AVHRR," *Annals Glaciol.*, Vol. 17, 1993, pp. 391-397.

__________ and __________. "Arctic sea ice surface temperature from AVHRR," *Jour. Clim.*, Vol. 7, 1994, pp. 174-183.

Maslanik, J. A., E. F. LeDrew, and D. Johnson. "An examination of atmospheric mechanisms that may be responsible for the annual reversal of the Beaufort Sea ice field," *Int. Jour. Climatol.*, Vol. 11, 1991, pp. 841-859.

__________, C. Fowler, W. J. Emery, W. J. Heinrichs, and R. G. Barry. "Ice-atmosphere interactions in the central Arctic: Remotely-sensed and sim-ulated ice concentration and motion," in: *Proceedings of the Second ERS-I Symposium, "Space in the Service of our Environment," Hamburg, November 1993.* Paris: European Space Agency, ESA SP-361, 1994, pp. 373-378.

Maykut, G. A. "The surface heat and mass balance," in N. Untersteiner, ed., *The Geophysics of Sea Ice, NATO ASI Ser., Ser. B Phys.*, Vol. 146. New York: Plenum, 1986, pp. 395-464.

McLaren, A. S. "The under-ice thickness distribution of the Arctic Basin as recorded in 1958 and 1970," *Jour. Geophys. Res.*, Vol. 94(C4), 1989, pp. 4971-4983.

__________, J. E. Walsh, R. H. Bourke, R. L. Weaver, and W. Wittman. "Variability in sea-ice thickness over the North Pole from 1979 to 1990," *Nature*, Vol. 358, 1992, pp. 224-226.

Miles, M. W. and R. G. Barry. "Large-scale characteristics of fractures in multi-year Arctic pack ice," in: K. B. E. Axelsson and L. A. Fransson, eds., *Proceedings, 10th International Conference of Port and Ocean Engineering Under Arctic Conditions (POAC 89)*, Vol. 1. Luleå, Sweden: Department of Engineering, Luleå University of Technology, 1989, pp. 103-112.

Mysak, L. A. and D. K. Manak. "Arctic sea ice extent and anomalies, 1953-84," *Atmos. Ocean*, Vol. 27, No. 2, 1989, pp. 346-505.

__________, __________, and R. F. Marsden. "Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901-1984 and their relation to an interdecadal Arctic climate cycle," *Clim. Dyn.*, Vol. 5, 1990, pp. 111-133.

__________ and S. B. Power. "Sea-ice anomalies in the western Arctic and Greenland-Iceland Sea and their relation to an interdecadal climate cycle," *Climatol. Bull.*, Vol. 26, 1992, pp. 147-176.

Nazintsev, Yu. L. "The heat balance of the surface of the multiyear ice cover in the central Arctic," *Tr. Arkt. Antarkt. Nauchno Issled. Inst.*, Vol. 267, 1964, pp. 110-126.

Overland, J. "Atmospheric boundary layer structure and drag coefficients over sea ice," *Jour. Geophys. Res.*, Vol. 90, 1985, pp. 9029-9049.

Parkinson, C. L. "Spatial patterns of increases and decreases in the length of the sea ice season in the north polar region, 1979-1986," *Jour. Geophys. Res.*, Vol. 97(C9), 1992, pp. 14,377-14,388.

__________, J. Comiso, H. J. Zwally, D. J. Cavalieri, P. Gloersen, and W. J. Campbell. *Arctic Sea Ice, 1973-1976: Satellite Passive Microwave Observations.* NASA Spec. Publ., SP-489, 1987, 295 pp.

Robinson, D. A., G. Scharfen, R. G. Barry, and G. Kukla. "Analysis of inter- annual variations of snow melt on Arctic sea ice mapped from meteorological satellite imagery," in: *Large-Scale Effects of Seasonal Snow Cover.* IAHS Publ. No. 166, 1987, pp. 315-327.

__________, G. J. Kukla, and M. C. Serreze. "Arctic summer cloudiness," in:

Proc. 6th Conference on Atmospheric Radiation. Boston, MA: Amer. Met. Soc., 1986, pp. 176-179.

__________, **M. C. Serreze, R. G. Barry, G. Scharfen, and G. Kukla.** "Large-scale patterns and variability of snow melt and parameterized surface albedo in the Arctic Basin," *Jour. Clim.* Vol. 5, No. 10, 1992, pp. 1109-1119.

Romanov, I. P. *Ice Cover of the Arctic Basin*. St. Petersburg: Arctic and Antarctic Research Institute, 1993a, 192 pp.

__________. *Atlas. Morphometric characteristics of Ice and Snow in the Arctic Basin*. St. Petersburg: Arctic and Antarctic Research Institute, 1993b, 152 pp.

Rossow, W. B. and R. A. Schiffer. "ISCCP cloud data products," *Bull. Amer. Met. Soc.*, Vol. 72, 1991, pp. 2-20.

__________, **and L. C. Garder.** "Validation of ISCCP cloud detections," *Jour. Clim.*, Vol. 6, 1993, pp. 2370-2393.

__________, **A. W. Walker, and L. C. Garder.** "Comparison of ISCCP and other cloud amounts," *Jour. Clim.*, Vol. 6, 1993, pp. 2394-2418.

Schnell, R. C., R. G. Barry, M. W. Miles, E. L. Andreas, L. F. Radke, C. A. Brock, M. P. McCormick, and J. L. Moore. "Lidar detection of leads in Arctic sea ice," *Nature*, Vol. 339, pp. 530-532, 1989.

Schweiger, A. J. and J. Key. "Arctic cloudiness: Comparison of ISCCP-C2 and Nimbus-7 satellite-derived cloud products with a surface-based cloud climatology," *Jour. Clim.*, Vol. 5, No. 12, 1992, pp. 1514-1527.

__________ **and** __________. "Arctic Ocean radiative fluxes and cloud forcing estimated from the ISCCP-C2 cloud data set, 1983-1990," *Jour. Appl. Meteorol.*, 1994 (in press).

__________, **M. C. Serreze, and J. R. Key.** "Arctic sea ice albedo: A comparison of two satellite-derived data sets," *Geophys. Res. Lett.*, Vol. 20, No. 1, 1993, pp. 41-44.

Serreze, M. C., R. G. Barry, and A. S. McLaren. "Seasonal variations in sea ice motion and effects on sea ice concentration in the Canada Basin," *Jour. Geophys. Res.*, Vol. 94(C8), 1989, pp. 10,955-10,970.

__________, **J. A. Maslanik, R. H. Preller, and R. G. Barry.** "Sea ice concentrations in the Canada Basin during 1988: Comparisons with other years and evidence of multiple forcing mechanisms," *Jour. Geophys. Res.*, Vol. 95(C12), 1990, pp. 22,253-22,267.

__________, **J. D. Kahl, and R. C. Schnell.** "Low-level temperature inversions of the Eurasian Arctic and comparisons with Soviet drifting station data," *Jour. Clim.*, Vol. 5, No. 6, 1992a, pp. 615-629.

__________, __________, **E. L. Andreas, J. A. Maslanik, M. C. Rehder, and R. C. Schnell.** "Theoretical heights of buoyant convection above open leads in the winter Arctic pack ice cover," *Jour. Geophys. Res.*, Vol. 97(C6), 1992b, pp. 9411-9422.

__________, **J. A. Maslanik, R. G. Barry, and T. L. Demaria.** "Winter atmosphere circulation patterns in the Arctic Basin and possible relationships to the Great Salinity Anomaly in the northern North Atlantic," *Geophys. Res. Lett.*, Vol. 19, No. 3, 1992c, pp. 293-296.

__________, **J. E. Box, R. G. Barry, and J. E. Walsh.** "Characteristics of Arctic synoptic activity," *Meteorol. Atmos. Phys.*, Vol. 51, 1993a, pp. 147-164.

Serreze, M. C., J. A. Maslanik, G. R. Scharfen, R. G. Barry, and D. A. Robinson. "Interannual variations in snow melt over Arctic sea ice and relationships to atmospheric forcings," *Ann. Glaciol.*, Vol. 17, 1993b, pp. 327- 331.

Steffen, K. "Energy density estimation over sea ice based on satellite passive microwave estimates," *Ann. Glaciol.*, Vol. 15, 1991, pp. 178-183.

__________ and J. Heinrichs. "Feasibility of sea ice typing with synthetic aperture radar: Merging of Landsat Thematic Mapper and ERS-1-SAR satellite imagery," *Jour. Geophys. Res.*, 1994 (in press).

Thorndike, A. S. and R. Colony. *Arctic Ocean Buoy Program Data Report, 1 January 1979-31 December 1979.* Seattle: Polar Sci. Cent., Univ. of Wash., 1980, 127 pp.

Wadhams, P. "Evidence for thinning of the Arctic ice cover north of Greenland," *Nature*, Vol. 345, 1990, pp. 795-797.

Walsh, J. E. "Diagnostic studies of large-scale air-sea-ice interactions," in: N. Untersteiner, ed., *The Geophysics of Sea Ice*. New York: Plenum Press, 1986, pp. 755-784.

__________ and W. L. Chapman. "Arctic contribution to upper-ocean variability in the north Atlantic," *Jour. Clim.*, Vol. 3, No. 12, 1990, pp. 1462-1472.

__________ and R. G. Crane. "A comparison of GCM simulations of Arctic climate," *Geophys. Res. Lett.*, Vol. 19, 1992, pp. 29-32.

__________ and C. M. Johnson. "Interannual atmospheric variability and associated fluctuations in Arctic sea ice extent," *Jour. Geophys. Res.*, Vol. 84(C11), 1979, pp. 6915-6928.

Warren, S. G., C. J. Hahn, J. London, R. M. Chervin, and R. L. Jenne. Global Distribution of Total Cloud Cover and Cloud Type Amounts over Land. Boulder, CO: NCAR Tech. Note TN 273 + STR, 1986, 29 pp.

__________, __________, __________, __________, and __________. Global Distribution of Total Cloud Cover and Cloud Type Amounts over the Ocean. Boulder, CO: NCAR Tech. Note TN 317 + STR, 1988, 41 pp.