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Ice Conditions on the Chesapeake Bay as Observed from Landsat During the Winters of 1977, 1978 and 1979

J. L. Foster

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

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James L. Foster

Earth Survey Applications Division

Hydrological Sciences Branch

Goddard Space Flight Center

Greenbelt, Maryland 20771

ABSTRACT

The winters of 1977, 1978 and 1979 were unusually cold in the northeastern U.S. and in the Chesapeake Bay area. Abnormal atmospheric circulation patterns displaced cold polar air to the south, and as a result, the Chesapeake Bay experienced much greater than normal icing conditions during these three years. Landsat observations of the Chesapeake Bay area during these winters has demonstrated the satellite's capabilities for monitoring ice growth and melt, for detecting ice motions and for measuring ice extent.

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INTRODUCTION

The fall and winter of 1976-1977 will be remembered as one of the coldest and iciest on record in the Chesapeake Bay area (Figure 1). Ice was extensive throughout the entire bay and its tributaries. The extreme ice cover conditions were a result of unusually cold temperatures that prevailed from late October through the middle of February. The fall and winter of 1977-78 did not experience the same degree of record breaking cold as occurred a year earlier, but temperatures were consistently below normal from late December through early March. The ice was extensive in the bay, but not as severe as in the preceding year. This was the first time since 1917 and 1918 that two consecutive extremely cold winters occurred in the Chesapeake Bay area. The fall and winter of 1978-79 were generally more temperate in the Chesapeake Bay area than during the two previous years. However, because February was so extremely cold, the ice cover extent was again much greater than normal.

Satellite surveillance is perhaps the only means to gather synoptic ice data over a body of water the size of the Chesapeake Bay. Studies by Rango et al. (1973), Barnes et al. (1973), Wiesnet (1974), McGinnis and Schneider (1978) and others have demonstrated the ability of satellites to observe various ice features. In this study, high resolution Landsat satellite imagery was used to observe ice conditions for three different years in the Chesapeake Bay.

FALL AND WINTER OF 1976-77

North American Atmospheric Circulation

The extremely cold fall and winter of 1976-77 over the eastern U.S. was associated with the southward displacement of the cold polar Low, normally located over northern Canada, by an exceptionally strong and persistent blocking High. During the autumn of 1976 the circulation pattern became strongly amplified over most of the Northern Hemisphere. Over the eastern U.S. the greater than normal component of northerly flow caused a cold, dry autumn. The positions of the troughs and ridges remained nearly constant from fall to winter, but the cyclonic circulation around the troughs intensified and expanded southward as a massive blocking system filled the Arctic region with strong positive pressure anomalies (Wagner, 1977). This unusual circulation pattern produced record cold weather and snow as far south as southern Florida during the month of January. The trough and blocking High weakened in mid February and allowed moderate temperatures to replace the cold Arctic air.

Chesapeake Bay Area Weather

The Chesapeake Bay area experienced harsh weather during the fall and winter of 1976-77 (Table 1). October, November and December were very cold and in January many locations were 10-12°F (4-5°C) colder than normal. Wilmington, Delaware and Norfolk, Virginia, located at the opposite ends of the bay, recorded their coldest January ever. BWI was 10.5°F (4.3°C) below normal for the month and for a 52 day period from December 21 through February 10 the maximum temperature only exceeded 32°F (0°C) 7 times. Not since 1881 had the January maximum temperature failed to reach 50°F (10°C). Due to the persisting cold, snow remained on the ground for 40

Table 1
Average Monthly Air Temperatures (°F) and Departures from Normal at Baltimore During the Fall and Winter of 1976-77, 1977-78 and 1978-79

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Ave.
Normal Temp.	57.1	46.0	36.3	33.4	35.4	43.1	41.9
Fall, Winter 1976-77	-4.5	-5.2	-3.7	-10.5	+1.7	+7.2	-2.5
Fall, Winter 1977-78	-1.4	+3.1	+0.3	-4.2	-7.5	-1.1	-1.8
Fall, Winter 1978-79	-1.3	+2.1	+4.9	-0.3	-9.2	+5.7	+0.4

days in many locations, from early January through the first week of February. In mid-February temperatures began to moderate and by March, with the arrival of unusually warm air, the severe winter came to an end.

In response to the cold weather, water temperatures in the Chesapeake Bay were well below normal during the fall of 1976 (Table 2), and thus freezing occurred rapidly when blasts of Arctic air penetrated the area during the first part of January. The water temperature remained below freezing throughout January and for most of February. Reflecting the rapid turnabout in air temperature, the water warmed by almost 12°F (6.5°C) from February to March.

Table 2
Average Monthly Water Temperatures (°F) and Departures from Normal near Baltimore During the Fall and Winter of 1976-77, 1977-78 and 1978-79*

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Ave.
Normal Temp.	64.6	54.2	43.1	37.6	37.2	43.0	46.6
Fall, Winter 1976-77	-2.1	-6.2†	-4.6	-6.0	-4.1	+1.8	-3.5
Fall, Winter 1977-78	-3.0	+0.1	-2.4	-2.1	-3.2	-1.7	-2.1
Fall, Winter 1978-79	-2.0	+1.2	+2.7	-1.1	-4.0	+1.2	-0.3

*From Coast and Geodetic Survey records – temperature measured 1 ft (0.3 m) beneath water surface. Data collected since 1914.

†All time record.

ICE CONDITIONS ON THE CHESAPEAKE BAY DURING JANUARY AND FEBRUARY OF 1977 AS OBSERVED FROM LANDSAT

In most winters ice in the Chesapeake Bay is confined to the upper bay and its tributaries, but in January and February of 1977 the ice cover was extensive in the lower bay, south of the Potomac

River, as well as the upper bay. Ice began to form in the tributaries of the upper bay during the last few days of December, 1976 and by the middle of January the ice had expanded well into the southern part of the upper bay.

The January 15 Landsat image (Figure 2A) shows the ice cover in the upper Chesapeake Bay.* Note the large areas of consolidated ice in the northern part of the upper bay and the areas of newly formed ice in the southern part of the upper bay. Due to a light snowcover, ice appears white in the uppermost part of the bay.

The maximum ice cover extent was reached in early February. Figures 2B, 2C, and 2D are Landsat images taken on February 1, 2, and 7, respectively. The ice cover as observed in the early February imagery is concentrated in the eastern part of the bay. The region had been subjected to strong northwest and west winds for several days at the end of January and the beginning of February which forced the ice against the eastern shores of both the Chesapeake and Delaware Bays (Figure 2B). The ice cover in the central Chesapeake Bay shows definite patterns of longitudinal cracking and compression fracturing which is largely a result of the constant winds (Figure 2C).

The rivers entering the lower bay from the western shore also show the effect of the wind; the ice in these rivers is pushed against their lee banks (Figure 2B). In addition, note the extension of ice off the tip of Cape May, New Jersey (Figures 2B and 2D) which has been driven into the open Atlantic by the force of the wind. Further evidence of a strong westerly wind can be seen by the smoke plumes drifting eastward across the Delaware Bay on the February 1 image (Figure 2B).

*Figures 2-4 are Landsat images of the Chesapeake Bay area. The images are taken at an altitude of about 555 mi. (905 km) and each image covers approximately 10,000 sq. mi. (16,000 sq. km). The spatial resolution is about 260 ft (80 m). The images in this paper are taken in the 0.6-0.7 wavelength bands. Figures 2B and 2D are mosaics of two Landsat images.

Changes in the ice cover were detected between the February 1 and the February 7 images. The most noticeable change is that subsiding winds have permitted the ice to reform in those areas of the Chesapeake and Delaware Bays which were previously ice-free (Figures 2B and 2D). The extension of ice off Cape May has changed dramatically during the week. On the February 1 image, the ice extension is only about 5 mi. (8 km) off Cape May, but 6 days later the ice has drifted 30 mi. (48 km) to the south and east and has also greatly increased in size.

In addition, differences in ice cover conditions were also observable in the overlap areas between the February 1 and 2 Landsat images (Figures 2B and 2C). The most conspicuous changes have taken place in the lower Potomac River and in the Chesapeake Bay between the Potomac and the Choptank Rivers. On February 1, the ice in the lower Potomac is packed against the north shore of the river, but just 24 hours later the ice is drifting into the bay. The ice/open water boundary in the bay between the Potomac and Patuxent Rivers is nearly straight as viewed on the February 1 image; however, the next day, a portion of the ice boundary is concave rather than straight. Presumably, these changes are the result of strong winds and tidal currents. Although tidal currents are relatively weak throughout the bay (less than 2 kt. (1 m/sec)), some ice floes may be transported by this mode.

Approximately 85% of the Chesapeake Bay was ice covered as measured from Landsat on the February 7 image (Figure 2D). In a normal year only about 10% of the bay is covered with ice. The ice cover during the winter of 1977 rivals that of 1918, which was probably the most severe this century.

Because the ice conditions were so severe during the winter of 1977, Coast Guard cutters were kept very active keeping shipping lanes open, freeing vessels that became locked in the ice, and leading convoys into the ice choked harbors and tributaries of the bay. Ship passage and navigation was very hazardous in the entire bay for many consecutive days from the middle of January through the middle of February, and many tributaries were impassable. One Coast Guard cutter, the Chinook, was called upon to make 87 assists during this period (Moyer, 1977).

The ice and freezing waters also took their toll on fish and marine life, particularly shellfish, such as crabs and oysters. Marine life in the upper bay and its tributaries suffered the greatest damage.

In some areas the mortality rate of large crabs was as high as 77%. Furthermore, piers, marinas, light houses and other such structures received considerable damages from the crushing ice pressure produced by ice floes shifting on the ebb and flood tides.

The Coast Guard, and Maryland Department of Natural Resources (which was also involved in icebreaking activities) routinely took ice thickness measurements at various locations in the bay. In early February, at the time of the greatest ice cover extent, the thickest ice was reported in the tributaries and estuaries of the upper bay where thicknesses of between 10-24 in. (25-61 cm) were not uncommon. Ice thicknesses in the tributaries of the lower bay ranged from about 4-14 in. (10-36 cm). The ice in the upper bay was generally about 6-12 in. (15-30 cm) thick, and in the lower bay the ice was about 2-8 in. (5-20 cm) thick. Differences in ice thickness in the upper bay and lower bay are mainly due to differences in air and water temperature.

The ice finally began to break up and melt as above normal temperatures worked their way into the bay area during the last half of February 1977. The ice melted from a south to north direction and from the shore to the middle of the bay. By the end of February only a few concentrations of rotten ice could be detected in the upper bay (Figure 2E). Note that the ice does not appear as bright or white as it does on earlier images. This is because the melting ice has become dirty due to pollution, dust and sludge which has accumulated on its surfaces and edges. By this time the snowcover has completely melted.

FALL AND WINTER OF 1977-1978

North American Atmospheric Circulation

Although the fall and winter of 1977-78 did not experience the extreme cold of the previous fall and winter, temperatures over the eastern U.S. were below normal for a longer period of time. During the fall and winter of 1977-78, a strong, persistent blocking High again displaced cold polar air to the south. A deep trough was centered more inland during the fall and winter of 1977-78 than during the preceding year so that the core of cold air was located farther to the west. During the fall of 1977 the circulation pattern did not become as strongly amplified as in 1976. Consequently a northerly flow did not develop, and the eastern U.S. experienced near normal temperatures. In December, however, the circulation intensified as the blocking High forced the polar Low southward. This pattern persisted until early March.

Chesapeake Bay Area Weather

In the Chesapeake Bay area the temperatures during the fall of 1977 were much above those during the previous autumn, even though they were near normal for the period (Table 1). Cold air pierced the bay early in early January and remained until early March. At BWI the daytime maximum temperature never exceeded 50°F (10°C) from January 1 until February 25. Because of the enduring cold, snow remained on the ground for about 60 days in many areas, from early January through early March. This is probably the longest period of continuous snowcover in the Chesapeake Bay area in this century.

Water temperatures in the Chesapeake Bay were generally below normal during the autumn of 1977, although they were well above the water temperature of the preceding autumn (Table 2). Although January was cold, the water temperature did not reach its freezing point until late in the month in the upper bay. The water temperature during February and March remained below normal.

ICE CONDITIONS ON THE CHESAPEAKE BAY DURING JANUARY, FEBRUARY AND MARCH OF 1978 AS OBSERVED FROM LANDSAT

Some ice began to form in the tributaries of the upper bay during the middle of January, and by the end of the month, ice could be detected in the northern end of the upper bay (Figure 3A). The milky, light colored areas in the tributaries of the Patuxent, Potomac, and Rappahannock River as viewed on January 28, 1978 Landsat scene are not ice, but rather sediment in the water which resulted from a heavy rain and snow storm two days before the image was taken. The January 28 image shows that most of the tributaries of the upper bay are frozen solid.

Eighteen days later on February 15, 1978 (Figure 3B) it can be seen that ice has formed well into the southern part of the upper bay. The Coast Guard report on February 14, 1978 indicated that only minor unconsolidated ice floes were observed in the lower bay. In the upper bay, although the ice cover is not as continuous as in 1977, the ice is extensive and has become evident in nearly all of the tributaries, estuaries and inlets. As was the case in 1977, prevailing west and northwest winds dislodged the ice from the western shore of the bay, however the ice was not compacted against the eastern shore as it was the previous year. The effect of the wind on the ice can also be seen in the lower Potomac River. The maximum ice cover extent in 1978 was reached in mid February. This is about one week later than the maximum cover occurred the year before. Approximately 25% of the bay was covered with ice on February 15 as measured from Landsat imagery (Figure 3B).

Navigation was somewhat impeded by the ice cover in 1978 but never brought to a standstill as in 1977. The Coast Guard report on February 15, 1978 stated that shipping channels in the Chesapeake Bay and Potomac River had limited ice and were easy to moderately easy to transit. There were no horsepower limitations in effect in 1978 and commercial fishing boats and oyster tongers did not lose any working days because of the ice. Furthermore the ice and freezing waters did not have the same devastating effect on fish and other marine life in 1978 as the year before. Only relatively minor damage occurred to marine life during the winter of 1978.

According to Coast Guard reports in 1978, the ice thickness was generally between 2-5 in. (5-13 cm) at the time of maximum ice cover in the upper bay and between 1-2 in. (2.5-5 cm) in the lower bay. The ice thickness in the tributaries was somewhat greater, being 4-8 in. (10-20 cm) in the upper bay and 2-6 in. (5-15 cm) in the lower bay tributaries.

FALL AND WINTER OF 1978-1979

North American Atmospheric Circulation

During the fall and winter of 1978-79 temperature conditions were generally more temperate than during the two previous years in the eastern U.S., however, because February 1979 was extremely cold, overall winter temperatures were again below normal for the third consecutive year. A deep trough with its core of cold air was positioned over the central and northern Rocky Mountains during most of November and December. The mean axis of the trough progressed slowly eastward in December and January, and the storm track was located over the Ohio Valley. By February the coldest air was positioned over the northeastern U.S. and the storm track was aligned east of the Appalachian Mountains. This resulted in some of the most severe weather of the century in the Middle Atlantic States. At the end of February the trough was centered off the North American continent and thus warmer air from the south and west replaced the frigid Arctic air.

Chesapeake Bay Area Weather

Temperatures in the Chesapeake Bay area were above normal during the fall of 1978 (Table 1). January temperatures were near normal in 1979, and not nearly as cold as in January 1977 or 1978. But February 1979 was the coldest, wettest and snowiest February this century in the Chesapeake Bay area (Foster et al., 1979). The average temperature at BWI was 25.6°F (−3.5°C) which is 9.2°F (5.1°C) below normal. During the first three weeks of the month maximum temperatures reached 40°F (4.4°C) on only two occasions and minimum temperatures plummeted below 0°F (−17.6°C) on as many as 7 occasions in some places in the Chesapeake Bay area. Unlike the two previous Februarys which were exceptionally dry, February 1979 was the wettest since 1884. Over 7 in. (178 mm) of precipitation was recorded at BWI. In addition it was the snowiest February since 1899, with BWI receiving 33 in. (84 cm) of snow. Owing to the record cold and heavy snowfall, snow remained continuously on the ground for about 30 days, from the end of January through the end of February. This was the third consecutive winter that a snowcover persisted for more than 30 consecutive days in the Chesapeake Bay area.

Water temperatures in the Chesapeake Bay were above normal during November and December of 1978 (Table 2). But by mid January the water temperature was near normal and by mid February, due to the extremely cold air, the water temperature dropped well below normal resulting in rapid ice formation.

ICE CONDITIONS ON THE CHESAPEAKE BAY DURING JANUARY AND FEBRUARY OF 1979 AS OBSERVED FROM LANDSAT

Figure 4A taken on January 23, 1979 shows ice forming in some of the tributaries and along the eastern shore of the upper bay. The milky areas north of the Chesapeake Bay Bridge and in the Potomac River south of Washington are due to sediment from heavy rains occurring two days before the image was taken. Only the higher elevations of the piedmont and the Blue Ridge Mountains were snowcovered at this time (Figure 4A – upper left).

The ice-covered area increased dramatically as extremely cold air settled over the Chesapeake Bay region. Figure 4B, which was taken on February 10, 1979, shows that most of the upper bay north of the Chesapeake Bay Bridge is clogged with ice, and new ice is forming throughout the upper bay to the south of the bridge. This image demonstrates how the bridge acts as a dam by preventing the passage of the larger ice floes. All but the largest estuaries entering the bay are jammed with ice. When this image was taken the Chesapeake Bay area was covered by about 6 in. (15 cm) of snow. The ice cover reached its maximum extent on about February 20 as the record breaking cold persisted. At this time approximately 60% of the entire Chesapeake Bay was covered by ice. This was verified by NOAA satellite imagery.

The Coast Guard reported that navigation was nearly as difficult in February 1979 as in January and February of 1977. However navigation was seriously hampered only about two weeks in 1979 compared to about five weeks in 1977. In February 1979 the large volume of snow on the ice hindered ice-breaking activities and the icing conditions were such that the imposition of certain shipping restrictions was necessitated. For example in the northern part of the upper bay all shipping traffic was required to be part of Coast Guard convoys regardless of the cargo, and tugboats were required to have a minimum of 1000 horsepower. Because the ice and freezing waters did not persist as long in 1979 as in 1977 the damage to fish and other marine life was not as severe.

On February 21, 1979 at about the time of the maximum ice cover extent, the Coast Guard reported that the ice thickness was generally between 4-12 in. (10-30 cm) in the upper bay with ice rafting to about 5 ft. (1.5 m). In the lower bay ice floes had thicknesses varying between about 2-6 in. (5-15 cm). The tributaries of the upper bay were completely frozen over and ice thicknesses were typically between 6-18 in. (15-46 cm). In the tributaries of the lower bay the ice was about 2-12 in. (5-30 cm) thick.

The ice began to break up during the last week of February in 1979 (Figure 4C), as was the case in 1978. Rising temperatures and heavy rains quickly melted the ice and snow. Most of the remaining ice was concentrated in the middle of the upper bay, but many of the tributaries were still choked with ice. Remnant snow from storms earlier in the month was confined generally to rural areas of the western shore. By March 9 (Figure 4D) there was virtually nc ice to be found in the bay or its tributaries. Note the bright appearing sediment loads in the lower Potomac River and the upper bay. At this time large volumes of sediment were being released into the Chesapeake Bay drainage system as a result of the heavy rains and rapidly melting ice and snow.

SEVERE ICE CONDITIONS ON THE CHESAPEAKE BAY

Ice formation on a water body occurs in response to the heat exchange between the water surface and the ambient air, resulting in an upward net heat loss from the water surface. Heat is lost primarily through convection, evaporation, and radiation. Periods of warming and cooling prior to the formation of ice affect this heat exchange and consequently the date when ice formation occurs. The degree of cooling after the ice has formed largely determines how thick and extensive the ice will become. The longer and more intense the cooling period, the thicker and more extensive the ice. The amount of ice on the Chesapeake Bay is a complex function of temperature, wind, precipitation, shape of the bay, total water mass in the bay, surface area of the bay, and salinity. When ice is forming on the Chesapeake Bay, even though the net energy balance of the bay is negative (the water body is losing heat), rapid and extensive changes in ice extent and thickness can occur due to wind and current induced ice movement, tides, upwelling of warmer waters, and mid-winter thaws. The break up period begins when the energy balance of the ice cover becomes positive and may be well defined and short if a warming trend starts, or it may drag on as cold and warm periods alternate in frequency and intensity (Quinn et al., 1978).

Since the average air and water temperatures for January and February, which are the two coldest months in the Chesapeake Bay area, are about 32°F (0°C), it is evident that for ice conditions to become severe, temperatures that are much below normal must be experienced for an extended period of time. A history of the past freezes on the Chesapeake Bay since 1900 indicates that the most severe freezes occurred during those years that the December and January air temperatures were at least 3.3°F (1.8°C) below normal and 2.6°F (1.4°C) below normal respectively, and the December and January water temperatures were at least 1.4°F (0.8°C) below normal and 2.8°F (1.6°C) below normal respectively (Tables 3 and 4). During these years the upper bay and its tributaries were nearly totally ice covered and navigation was brought to a halt. For the two years that ice conditions were most severe in the Chesapeake Bay (1918 and 1977), it can be seen from Tables 3 and 4 that the air temperatures were below normal for each month from October through January and averaged 5.8°F (3.2°C) below normal for the four month period in 1917-18 and 5.9°F (3.3°C) below normal for the four month period in 1976-1977. The water temperatures for each month from October through February were also below normal for each of these two years and averaged 5.2°F (2.9°C) below normal for the five month period in 1917-18 and 4.6°F (2.6°C) below normal for the five month period in 1976-77. Because of the lengthy period of unusually cold weather the entire bay was nearly completely ice covered in late January and early February in each of these two winters. Additional winters in which ice was noteworthy on the Chesapeake Bay during this century include 1917, 1920, 1923, 1934, 1940, 1959, 1968, 1970, 1978, and 1979. During these years the ice was generally confined to the upper bay and its tributaries, but the upper bay was not completely iced over and navigation was impeded but not halted.

Knowledge of early weather records and ice conditions in the Chesapeake Bay area during the 17th, 18th, and 19th centuries is inadequate. There were few continuous meteorological observations over substantial periods, and no voluminous personal diaries exist that shed light on the weather and climate of these times. Only certain outstanding events with a minimum of detail have been recorded and documented. However, from the sketchy evidence that is available it can be surmised that severe ice conditions probably existed on the Chesapeake Bay during the winters of 1642, 1646, 1681, 1698, 1705, 1733, 1741, 1765, 1780, 1784, 1807, 1821, 1836, 1856 and 1893. Of these years it is likely that the most severe freezes occurred on the Chesapeake Bay during 1698, and during the Revolutionaly War in 1780 and again in 1784. It is reported that Baltimore harbor remained closed to shipping traffic from January 2 until March 25 in 1784 (Ludlum, 1966).

Table 3
Average Monthly Air Temperatures (°F) and Departures from Normal at Baltimore
For Years Having Severe Ice Conditions

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Ave.
Normal Temp.	57.1	46.0	36.3	33.4	35.4	43.1	41.9
Fall, Winter 1903-04	+1.3	-2.8	-3.3	-6.0	-6.8	+1.5	-2.7
Fall, Winter 1917-18	-4.5	-1.4	-7.9	-9.2	0.0	+4.1	-3.2
Fall, Winter 1935-36	+1.4	+4.4	-3.5	-2.6	-5.7	+5.7	-0.1
Fall, Winter 1960-61	-0.5	+0.9	-7.9	-5.8	+1.6	+1.9	-1.6
Fall, Winter 1962-63	+0.6	-4.5	-5.4	-4.6	-7.6	+1.8	-3.2
Fall, Winter 1976-77	-4.5	-5.2	-3.7	-10.5	+1.7	+7.2	-2.5

Table 4
Average Monthly Water Temperatures (°F) and Departures from Normal near Baltimore
For Years Having Severe Ice Conditions

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Ave.
Normal Temp.	64.6	54.2	43.1	37.6	37.2	43.0	46.6
Fall, Winter 1903-04	No Records Available						
Fall, Winter 1917-18	-4.9	-5.5	-5.9	-5.8	-3.8	-0.6	-4.4
Fall, Winter 1935-36	-0.7	+2.3	-2.1	-3.3	-4.7	-0.2	-1.5
Fall, Winter 1960-61	+2.2	+0.2	-1.4	-2.8	-1.0	+1.8	-0.5
Fall, Winter 1962-63	+1.5	-2.6	-1.6	-3.4	-4.1	-0.8	-1.8
Fall, Winter 1976-77	-2.1	-6.2	-4.6	-6.0	-4.1	+1.8	-3.5

FREEZING DEGREE DAYS

The growth of ice is closely related to the accumulation of freezing degree days (FDDs) which are defined as negative departures of mean daily air temperature from 32°F (0°C). Since the average air temperature during the coldest months is above 32°F (0°C) at Baltimore, FDD accumulations are negligible during most winters. However as can be seen from the graphs in Figure 5, FDD accumulations were substantial during the winters of 1977, 1978 and 1979.

The maximum ice cover extent in the Chesapeake Bay occurred at about the same time as the peak FDD accumulation, as would be expected, during the winters of 1977 and 1979. During the winter of 1978 the maximum ice cover extent (mid February) occurred three weeks earlier than the peak FDD accumulation (March 8). Evidently the brief thaw after February 13 was sufficient to break up much of the ice. It is interesting to note that during the winter of 1978 the peak FDD accumulation was reached at about the time that the FDD accumulation approached zero during the winters of 1977 and 1979.

During the winter of 1978 there were 92 days when the accumulated FDDs reamined above zero; this compares to 82 days for the winter of 1977 and 75 days for the winter of 1979. Accordingly the ice remained on the Chesapeake Bay a longer period of time during the winter of 1978 than for the other two years.

There was a total accumulation of 350 FDDs during the winter of 1977 compared to 255 for 1978 and 245 for 1979. This demonstrates the importance of the total accumulation of FDDs in determining the severity of ice conditions, as the ice conditions on the Chesapeake Bay were more severe during the winter of 1977 than during the winter of 1978 and 1979. But during the winter of 1979 the ice cover was more extensive in the Chesapeake Bay than during the winter of 1978, despite the fact that the total accumulation of FDDs was slightly less. This can be attributed to the record breaking cold of February 1979 which resulted in the upper bay freezing over in a very short period of time. From Figure 5 it can be seen that during February of 1979 the accumulation of FDDs was near zero on February 4 and peaked at 245 just seventeen days later on February 21. During the previous winter (1978), however, 58 days were required for the FDDs to accumulate from near zero on January 9 to the peak value of 255 on March 8.

The steepest part of the slopes on the FDD curves in Figure 5 is of course the time of maximum cooling and ice formation. During the winter of 1977 the most rapid cooling occurred from about December 28 to January 24 and for the winter of 1979 from about February 4 to February 23. The more gradual slope of the curve during the winter of 1978 is indicative of the slower rate of ice growth that occurred that year. Maximum cooling occurred between January 26 and February 13 during the winter of 1978. For these three winter regimes, it is noteworthy that the coldest period of each winter occurred later in each subsequent year, and also the time of maximum ice cover extent occurred about one week later in each subsequent year.

As illustrated on the graphs in Figure 5, the ice cover curve falls off much more rapidly than does the FFD curve. It should be remembered, though, that the FDD curve is cumulative and does not represent the freezing line or the average daily temperature.

SUMMARY

The Chesapeake Bay experienced much greater than normal icing conditions for three consecutive winters from 1977 to 1979. Landsat observations during these winters have demonstrated the satellites capabilities to monitor ice growth and melt, to detect ice motions and to measure ice extent. By utilizing imagery and data from Landsat and other satellites, information on ice conditions in the Chesapeake Bay and other inland waterways can be obtained which is essential for modeling and forecasting ice conditions. When a larger historical base is acquired from remotely sensed data, it might be possible to predict the ice extent and the onset of ice formation and breakup and thereby anticipate the hazards to navigation and marine life that icing presents.

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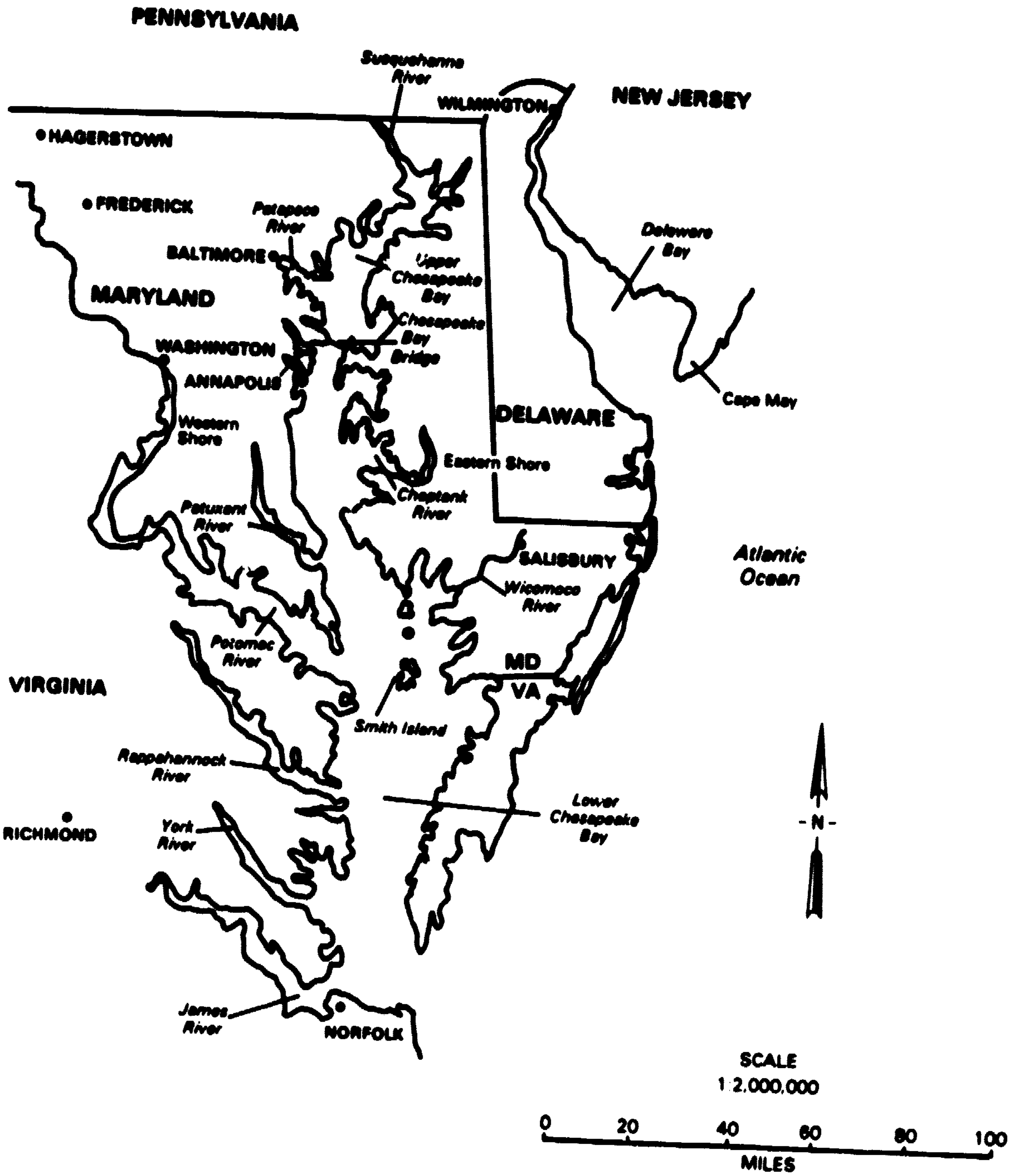

Figure 1. Map of Chesapeake Bay Area

Figure 2A. Landsat Image Taken on January 15, 1977

Figure 2B. Mosaic of Two Landsat Images Taken on February 1, 1977

Figure 2C. Landsat Image Taken on February 2, 1977

Figure 2D. Mosaic of Two Landsat Images Taken on February 7, 1977

Figure 2E. Landsat Image Taken on February 26, 1977

Figure 3A. Landsat Image Taken on January 28, 1978

Figure 3B. Landsat Image Taken on February 15, 1978

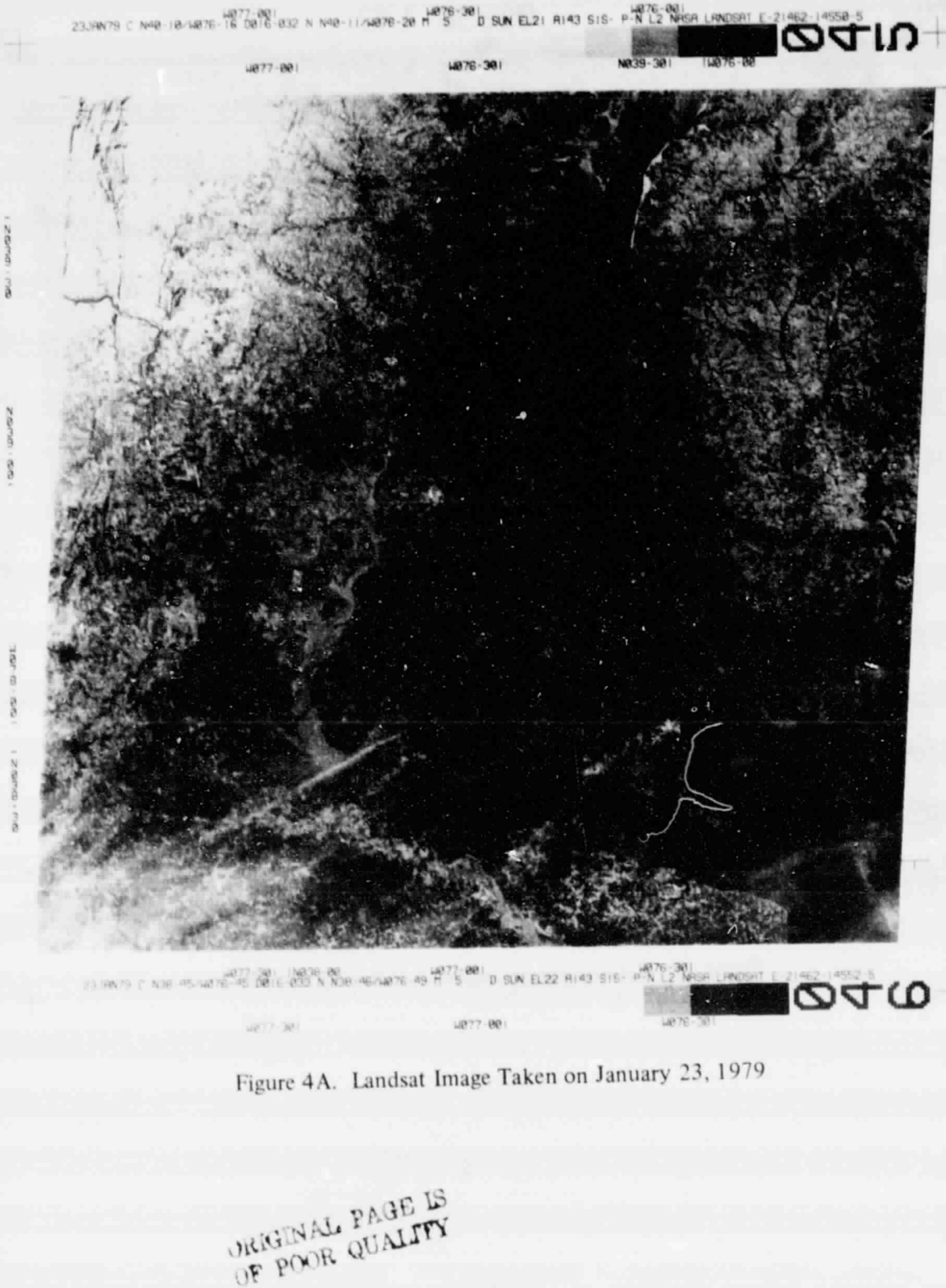

Figure 4A. Landsat Image Taken on January 23, 1979

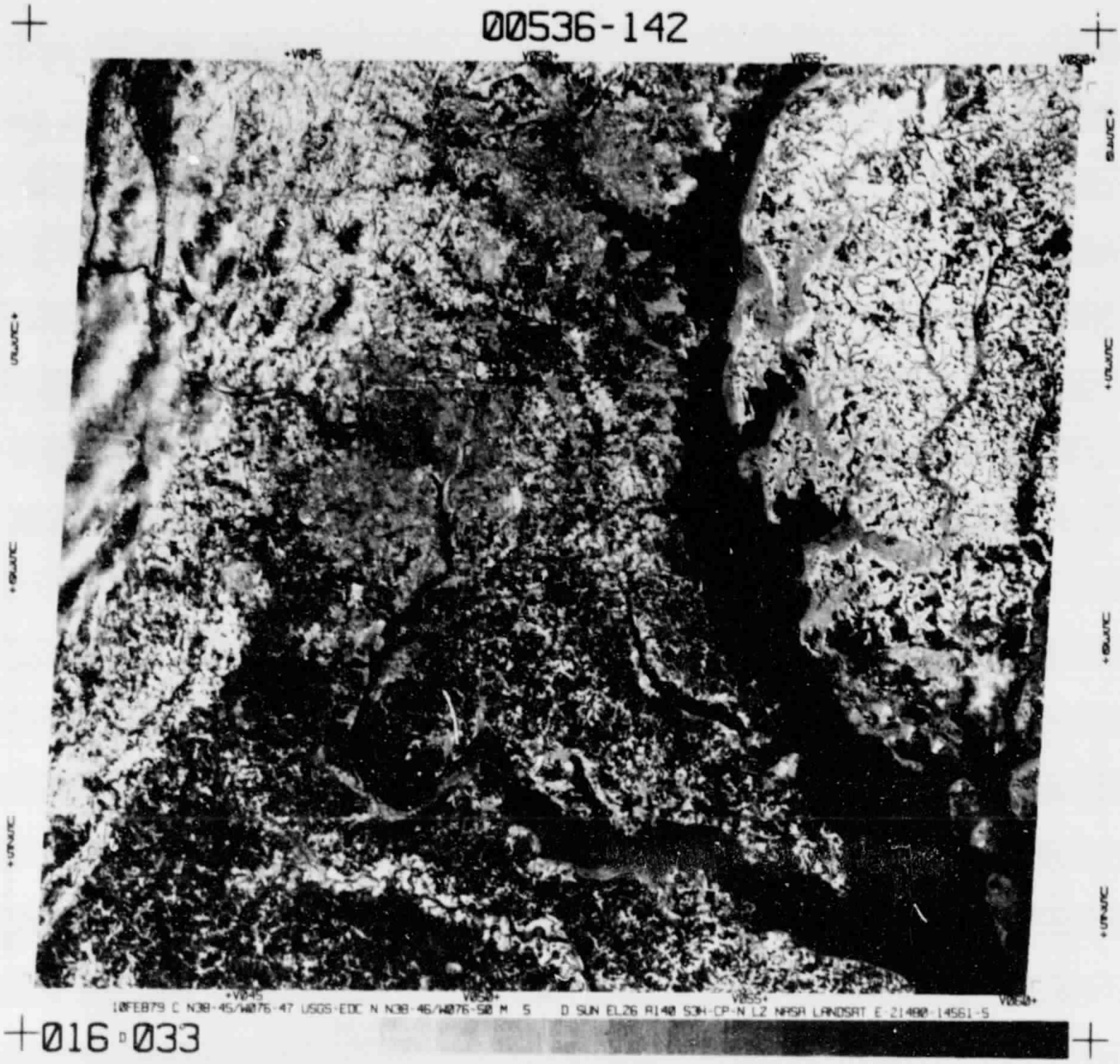

Figure 4B. Landsat Image Taken on February 10, 1979

Figure 4C. Landsat Image Taken on February 28, 1979

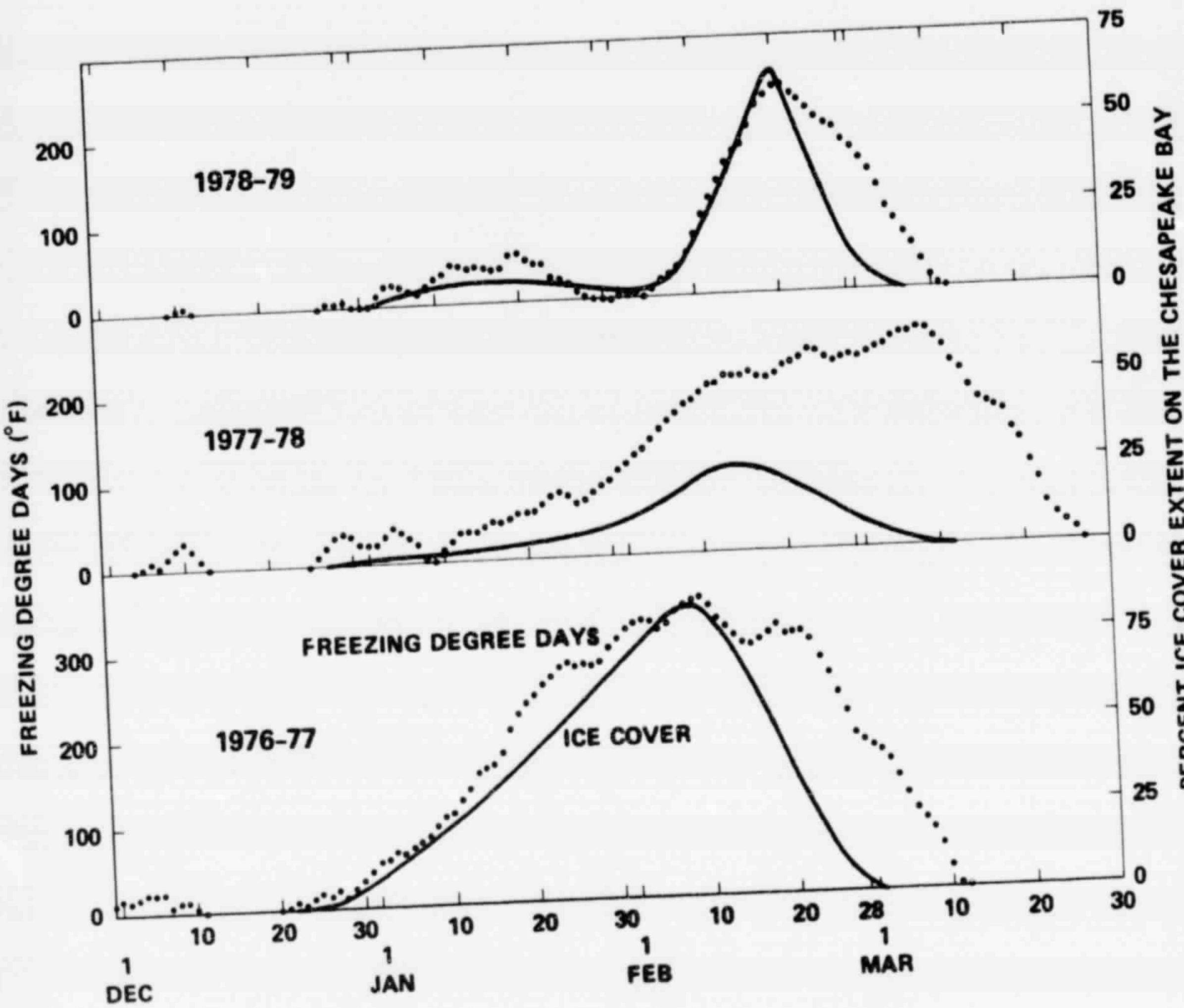

Figure 5. Freezing Degree Day and Ice Cover Curves for 1977, 1978, and 1979

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