A second buoy is scheduled to be moored in 2004 at the Shediac monitoring station in the southern Gulf of St. Lawrence (IML-6, Fig. 1). A third buoy is under construction and will be deployed in 2005 at the Banc Beaugé station (IML-2, Fig. 1) in the northeastern Gulf. Although this is a good starting point, we recognize that three buoys cannot provide all the data we need to fully characterize the ecosystem of the Gulf of St. Lawrence. We believe that a full network of at least eight buoys is required to adequately cover the different oceanographic features in the St. Lawrence. If equipped with instrumentation to measure vertical water properties (Doppler current profilers, SeaHorse sampler, etc.), this buoy network could become a major element of the AZMP sampling strategy in the future years, providing a source of high frequency temporal data at the most important locations in the Gulf system at low cost for operational applications and/or science projects.

Acknowledgements

The development of the first prototype buoy was successful in great part because of the dedication and competence the DFO's technical staff at MLI (Roger Pigeon, Rémi Desmarais, and Sylvain Cantin). The important contribution of Multi-Électronique in the development of the data logger and buoy control system is also acknowledged.

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The AZMP Program Contributes to the Scientific Investigation of the Smith Sound Mass Fish Kill of April 2003

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Résumé

L'existence du Programme de Monitorage de la Zone Atlantique (PMZA) a grandement facilité l'enquête scientifique concernant une mortalité massive de poissons observée en avril 2003 dans Smith Sound, un fjord situé dans la baie Trinity sur la côte est de Terre-Neuve. Il s'agit en fait de la plus importante mortalité naturelle de poissons jamais observée dans les eaux côtières du Labrador et de Terre-Neuve. L'existence d'une importante agrégation de morues dans Smith Sound avait tout d'abord été établie en 1995 à l'occasion d'évaluations acoustiques. On a par la suite estimé que cette biomasse a varié entre 10 000 tonnes métriques durant le milieu des années 1990 jusqu'à environ 25 000 tonnes métriques au début des années 2000. Au début du printemps 2003, les résidents de Smith Sound ont observé un nombre important de morues et de sébastes flottant à la surface ou encore accumulés le long de la berge. Huit cent tonnes métriques de morues flottant à la surface et représentant environ 4 % de la biomasse maximale estimée ont subséquemment été recueillies par des pêcheurs sur une période de trois semaines pour être traitées dans une usine locale de transformation de poissons. Après examen, on a déterminé que ces poissons étaient morts gelés ou encore parce qu'ils contenaient des cristaux de glace. Les conditions climatiques dans l'Atlantique canadien durant cette période étaient parmi les plus froides jamais observées au cours de la dernière décennie. Des mesures océanographiques, effectuées au début du printemps durant cet événement de mortalité massive, ont révélé que la colonne d'eau s'était considérablement refroidie depuis le mois de janvier précédent, et aussi par rapport aux dix années précédentes. Il a ainsi été découvert que le détroit Smith Sound tout entier avait été envahi par une masse d'eau très froide, caractérisée par des températures minimales de -1.73 °C à mi-profondeur et d'environ -1.6 °C près du fond, à 200 m. Il a par la suite été établi que ces eaux extrêmement froides qui ont envahi Smith Sound au cours du printemps 2003 provenaient d'un événement de convection hivernale très intense qui a eu lieu sur le plateau continental de Terre-Neuve et du Labrador au cours des mois d'hiver précédents. Ces eaux très froides qui subissent une advection continuelle vers le sud en raison du courant du Labrador ont ensuite pénétré à l'intérieur de Smith Sound au début d'avril. Le taux de diminution de la température qui est passé de 0.5 °C à la fin janvier à un minimum de -1.73 °C au début d'avril est anormalement élevé et a probablement été un facteur significatif qui a mené à la mortalité massive de poissons observée.

Introduction

The existence of the Atlantic Zone Monitoring Program has greatly facilitated the scientific investigation of the mass fish kill of Smith Sound in April 2003. Smith Sound is a fjord of about 20 km in length located on the east coast of Newfoundland on the north side of Random Island within Trinity Bay (Fig. 1). The fjord is about 1-2 km wide with water depths to 210 m and a sill depth of 155 m. During April 1995, a large and dense aggregation of cod was discovered in Smith Sound. Subsequent hydroacoustic surveys of the aggregation estimated the biomass to range from about 10,000 metric tons (t) during the mid-1990s to about 25,000 t during the early 2000s (Rose 2003). This group of fish now represents the largest known single spawning aggregation of the once abundant northern cod stock. Recaptures from tagging studies determined that most of these fish move out of Smith Sound during late spring and early summer and migrate north along the east and northeast coasts of Newfoundland, remaining in the inshore regions. They return to Smith Sound in late autumn to overwinter. In early April 2003, this group of fish suffered the largest documented natural mortality in Newfoundland and Labrador waters. On Saturday 5 April, residents of the Sound discovered a significant number of cod and redfish floating on the surface and washing onto the shoreline. Dead cod were subsequently harvested from the surface by fishers during a three-week period, and approximately 800 t, representing nearly 4% of the maximum estimated biomass, was processed by local fish plants. An examination determined that the fish were either frozen or contained ice crystals.

The Atlantic Zone Monitoring Program (AZMP) of the Department of Fisheries and Oceans first surveyed Smith Sound during its annual fall survey in November of 2002. On 8-10 April 2003, AZMP team members participated in a special DFO mission to Smith Sound to determine the extent of the fish kill and to conduct an oceanographic survey of the area. A follow-up survey was conducted by the AZMP on 1-2 May 2003 to measure changes in the oceanographic conditions immediately after the mass mortality incident and to sample cod for antifreeze testing. Detailed biological sampling and dissolved oxygen measurements were also made. During the remainder of 2003, the AZMP team conducted two more surveys of Smith Sound, one in early August on the annual summer survey and one in early December during the fall survey. Historically, the first systematic set of oceanographic observations available in Smith Sound and vicinity were made in March of 1991 during acoustic studies of cod behaviour and migration (Wroblewski et al. 1993). Throughout the 1990s and early 2000s, several studies on cod in Smith Sound by Memorial University of Newfoundland and the Department of Fisheries and Oceans have collected oceanographic data within the Sound. The most recent survey by Memorial University took place in late January of 2003, immediately preceding the fish kill.

In this article we present some of the results of the scientific investigation of factors surrounding the fish kill, specifically the oceanographic conditions encountered in the Sound in 2003 and how they compare with previous data.

Historical Oceanographic Conditions in Smith Sound

Water temperatures during the March 1991 survey indicate that conditions were very cold throughout the Sound, with minimum values of around -1.5°C. Near-surface values were about -1.0°C and near-bottom temperatures were approximately -1.2°C. In general, temperatures throughout the inshore waters of Newfoundland and Labrador during the early 1990s were among the coldest on record. Moreover, other data collected by Wroblewski et al. (1993, 1994a) in adjacent fjords showed that minimum temperatures of -1.7°C were not unusual in this area during the winter and early spring. In fact, temperatures along the east coast of Newfoundland observed at Station 27 indicate that these cold conditions were established in the late 1980s, reached a minimum in the early-1990s, and started to moderate in 1995. During 1996, water temperatures increased to above normal values over most regions; from 1997 to 1999, ocean temperatures continued to increase, with 1999 being one of the warmest years in the past couple of decades (Colbourne 2002). Temperatures measured within Smith Sound during an April 1996 survey showed that conditions had warmed considerably, with surface values of 0.5°C, minimum temperatures at mid-depth of around -0.75°C, and near-bottom values of -0.5°C (Fig. 2). An April 1997 survey showed nearly identical temperatures. Oceanographic data collected in January of 2000 and 2003 generally showed warmer temperatures at depth than those from the spring months due to the intense vertical mixing of the summer-heated upper layers in the previous fall. In January 2000, temperatures ranged from 0.5°C near the bottom to 0.75°C in the upper water column; slightly cooler conditions prevailed in January 2003, with upper layer values generally <0°C and near-bottom values near 0.3°C (Fig. 3). These water temperatures are in sharp contrast to the cold conditions observed during the winters of the early 1990s (Wroblewski et al. 1993, 1994a, 1994b).

Environmental Conditions During the Winter and Spring of 2003

The North Atlantic Oscillation (NAO) index was slightly positive (0.4) during the winter of 2003, similar to 2002. The sea-level pressure anomaly pattern, however, was not that of a typical positive NAO index year, as anticyclonic conditions persisted over Scandinavia and a deep cyclonic circulation pattern dominated the Labrador Sea (ICES 2003). Sea-level pressure anomalies over the northeastern regions of Newfoundland and the Labrador Sea decreased to >5 mb below the long-term average during the winter months. Consequently, cold Arctic outflow dominated the atmospheric circulation pattern over much of eastern Canada. Historically, these conditions are typical of a strongly positive NAO index, which normally brought cold ocean conditions to this region. During February of 2003, air temperatures had dropped to below normal values over much of eastern Canada, by 1.3°C over Labrador and nearly 1°C over southern Newfoundland. During March, air temperatures had decreased even further, to 3.5°C below normal over Labrador (Cartwright) and to 2.5°C below normal over Newfoundland (St. John's). By April, conditions improved somewhat, but air temperatures remained near 1.5°C below the long-term average (Environment Canada, 2003 Web Site). These anomalies were among the lowest observed in almost a decade and resulted in heavier and more extensive sea-ice cover than normal on the Newfoundland and Labrador Shelf during the winter and spring of 2003 (Canadian Ice Service 2002). The sea-ice edge, for example, reached as far south as Cape Race in the inshore regions and as far south as 45.5°N latitude in the offshore areas by late March (Canadian Ice Service 2003 Web Site).

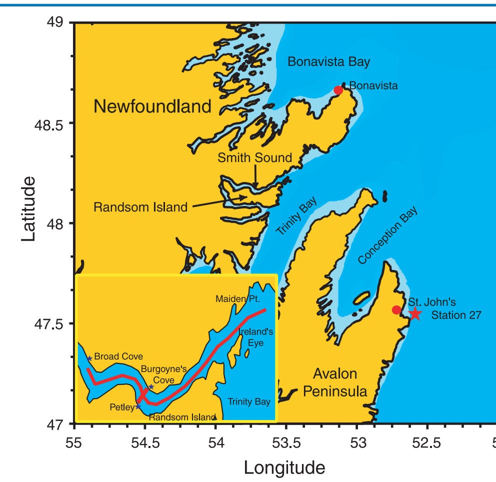

Fig. 1 Map showing the location of Smith Sound within Trinity Bay on the east coast of Newfoundland. The inset shows the positions of oceanographic sections sampled within the Sound during the surveys of 8-10 April and 1-2 May 2003.

Carte localisant Smith Sound dans la baie Trinity sur la côte est de Terre-Neuve. L'encart montre les positions des transects océanographiques qui ont été échantillonnés dans le fjord durant les missions océanographiques du 8-10 avril et du 1-2 mai 2003.

Oceanographic Conditions in Smith Sound During 2003

Oceanographic data collected during the late fall of 2002, both by the AZMP and during DFO multi-species surveys, provided the first indication of a significant negative temperature anomaly developing on the Newfoundland and Labrador Shelf. During these surveys, upper-layer temperatures along standard AZMP sections across the Grand Bank showed temperatures as low as 2-3°C below normal over the entire Grand Bank (Colbourne 2003). Temperatures measured in Smith Sound in late January, however, were still above 0°C near bottom and around -0.25°C at the surface (Fig. 3). By the time of the April 2003 survey to Smith Sound, the water column had cooled significantly, with temperatures ranging from -1.4°C at the surface to -1.73°C near 100 m, and about -1.6°C near bottom at 200 m (Fig. 4). In effect, the entire Sound was flooded by extremely cold water.

The only areas with water temperatures above -1.4°C were outside of the fjord in the deeper waters of Trinity Bay, where values were >0.5°C below 300 m, and near shore at the head of the fjord, where surface temperatures were about -1.2 to -1°C. In general, temperatures decreased by 1°C at the surface and by about 2°C near bottom from late January to early April, a period of only two months (Fig. 3 and 4). The vertical temperature cross-section constructed along the axis of the fjord shows evidence of a tongue of cold intermediate layer water (CIL) being advected into the Sound from the inner Newfoundland Shelf. Temperatures in the core of the CIL were near freezing, with values generally below -1.65°C and minimum values as low as -1.73°C (the freezing point is -1.78°C at a salinity of 32.8 at atmospheric pressure). The main aggregation of cod in the Sound during the early April survey was detected below this tongue of cold CIL water in the general vicinity of Petley to Bluff Head, where most of the dead fish were found (Fig. 1 and 4).

Sea water of salinity <24.7 has a higher temperature of maximum density than its freezing point and so behaves in a way similar to a body of freshwater in which rapid overturning can occur during the winter. Salinities within the Sound during early April, however, ranged from 32.63 at the surface to 32.82 near the bottom, indicating a very weakly stratified but stable water column. In the absence of stratification, a body of seawater at salinities >24.7 must be cooled to its freezing point before surface freezing commences. The vertical salinity structure in Smith Sound during the spring of 2003 showed that while salinity values generally increased with depth, the water column was nevertheless nearly isohaline. These conditions may have promoted enhanced vertical mixing by convective currents deeper into the water column, compared to the offshore regions where the vertical salinity gradient is generally much larger. Consequently, local convection and mixing within the Sound after an icebreaker removed the ice cover in late March no doubt contributed to the extremely cold water conditions. Except in the near-shore zone, however, it is unlikely that ice crystals formed in the upper water column could have penetrated to the bottom, particularly to the depths normally inhabited by cod (~200 m) during the winter and spring months. It has been demonstrated that ice crystals can act as a seeding agent to initiate the freezing process of super-cooled cod (Fletcher et al. 1997).

Data collected on the follow-up survey in early May showed that temperatures in Smith Sound had warmed to 0.5°C at the surface and to -1 to -1.5°C near the bottom. Dissolved oxygen levels, also measured on this survey, indicated super-saturated levels (>110%) in upper layers and values ranging from 90-95% in the depth range of 100-200 m. There was no evidence of oxygen depletion anywhere in the Sound, and the concentrations were much higher than the reported 39% saturation levels that can lead to anaerobiosis in cod (Claireaux and Dutil 1992). Also, during the May survey, a large dense aggregation of cod was detected in the warm waters of Trinity Bay (temperature 0.5°C) at the entrance to Smith Sound extending all the way in the fjord to Petley, in water temperatures of -1.5°C. These fish were in excellent condition and no dead fish were observed anywhere within the fjord. Oceanographic conditions observed in the offshore areas during this survey revealed CIL minimum temperatures of -1.7°C with temperatures as low as 1.5°C below normal near the east coast of Newfoundland and 1-2°C below normal on the Grand Bank, the coldest in nearly a decade. Temperatures in Smith Sound by early August had warmed to >12.5°C at the surface and to 0.0 to -0.5°C at the bottom. Dissolved oxygen levels, also measured on this survey, still indicated super-saturated levels (>110%) in upper layers and values ranging from 80-90% near bottom.

Discussion and Conclusion

In summary, ocean temperatures during early spring of 2003, both on the Newfoundland Shelf and in the inshore regions along the east coast, were among the coldest observed since the early 1990s. This followed an unusually cold winter that brought the heaviest ice cover to the region in about a decade. The available data from Smith Sound indicate

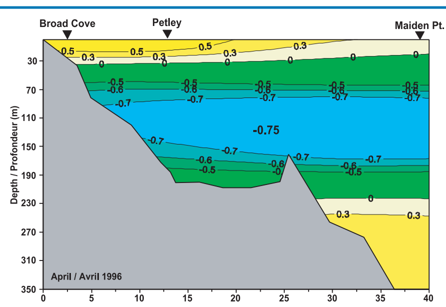

Fig. 2 Vertical distribution of water temperature (°C) along the longitudinal axis of Smith Sound during mid April of 1996.

Répartition verticale de la température de l'eau (°C) selon l'axe longitudinal de Smith Sound vers la mi-avril 1996.

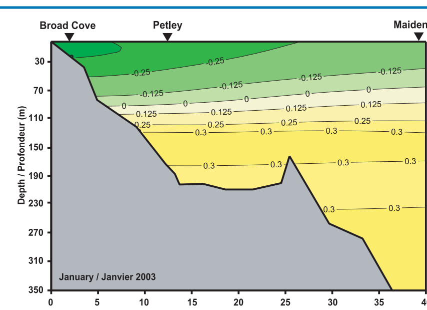

Fig. 3 Vertical distribution of water temperature (°C) along the longitudinal axis of Smith Sound during late January of 2003.

Répartition verticale de la température de l'eau (°C) selon l'axe longitudinal de Smith Sound à la fin janvier 2003.

that cold conditions prevailed during the early 1990s and lasted at least until 1994. During 1995, conditions began to moderate and increased to above normal values over most regions during 1996. From 1997 to 1999 ocean temperatures continued to warm, with 1999 being one of the warmest years on record. Since 1999, however, ocean temperatures have been decreasing from the record highs but remained above normal in most areas until the spring of 2003.

It appears likely that the extremely cold subsurface water within Smith Sound during the spring of 2003 was the result of intense winter convection and mixing on the Newfoundland and Labrador Shelf. These cold subsurface waters that are continuously advected southward by the Labrador Current penetrated deep into Smith Sound by early April. Since the Sound was covered with sea ice during most of the winter, local cooling within the Sound would have been reduced. However, after an icebreaker removed the ice cover in late March, local convection and mixing probably contributed to further cooling of the water column since air temperatures remained below normal. In addition, an examination of local wind data at Bonavista and St. John's in late March indicates that the prevailing direction was generally from the west, with average speeds in excess of 30 km h^{-1} and peak gusts of over 70 km h^{-1}, which were significantly stronger than normal. Similar wind conditions most likely existed in Smith Sound; this would have cleared the ice rapidly and may have contributed to the local circulation, allowing the cold sub-surface CIL shelf waters to penetrate into the Sound.

Many unanswered questions remain as to why the fish, cod in particular, but also an undetermined number of redfish, froze to death. Experiments by Wroblewski et al. (1994b) successfully overwintered cod during the cold winter of 1993-1994, when temperatures dropped to -1.7ºC. These fish had developed antifreeze protection to -1.1ºC and were therefore super-cooled by -0.6ºC with a 4% mortality rate. Incidentally, the number of fish processed by fish plants amounted to about 4% of the hydroacoustic estimate of the biomass (20,000 t) in January 2003, although there were an undetermined number of dead fish also observed on the bottom. According to Fletcher et al. (1997), cod can develop antifreeze protection to a minimum temperature of -1.2ºC, but can be further super-cooled by at least 0.5ºC. The reason why so many fish in Smith Sound during the spring of 2003 did not adapt to the ambient temperature (-1.6º to -1.73ºC) of the surrounding water is not clear. However, it is certain from existing data that the 2003 temperatures were near critical values, substantially colder than the previous 8-10 years. It is possible, therefore, that this may have been the first time that this fish population was exposed to near-freezing water. Furthermore, the rate of decrease in temperatures at 200 m depth, from near 0.5ºC in late January 2003 to a minimum of -1.73ºC by early April 2003, is anomalous and may have been a significant factor that led to the mass mortality.

There are numerous other observations that are currently being compiled surrounding this incident. Further research to determine the full circumstances that led to perhaps the largest documented natural mortality of cod in Newfoundland and Labrador waters is currently being carried out both at Memorial University and by Fisheries and Oceans Canada. We do not yet have a hypothesis that is consistent with all observations, but it is becoming clear that the extremely cold water that these fish were subjected to during early spring was the underlying cause of the mass mortality.

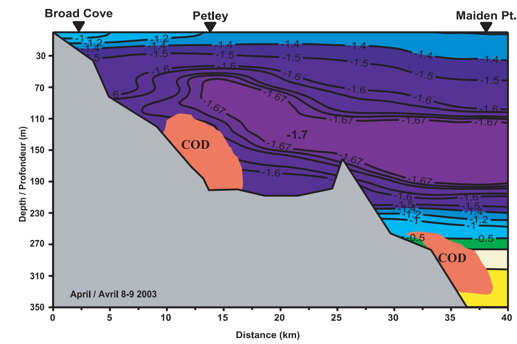

Fig. 4 Vertical distribution of water temperature along the longitudinal axis of Smith Sound during 8-10 April 2003. Locations where cod were detected are indicated schematically by the red areas.

Répartition verticale de la température selon l'axe longitudinal de Smith Sound durant la période du 8-10 avril 2003. Les positions où ont été détecté les bancs de morues sont indiquées approximativement par les zones rougeâtres.

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