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Research paper

Impact of bottom water temperature change on the southernmost snow crab fishery in the Atlantic Ocean

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ABSTRACT

Snow crab populations are found in the Northern Atlantic, Arctic and Pacific Oceans. Snow crab are generally considered to be a stenothermic species with distributions constrained by the available thermal habitat. Crab fishing area 4X on the western Scotian Shelf is at the southernmost extent of Snow Crab distribution in the Northwest Atlantic. Bottom temperatures in this area provide very limited snow crab habitat. An incursion of warm slope waters flooded the western Scotian Shelf in 2011/2012 and created positive temperature anomalies. These warmer bottom temperatures appeared to have had a negative impact on some life stages of snow crab in local populations, with juvenile stages being the most affected. Evidence of this decrease was supported by various fisheries independent and dependent data sources. Though 4X snow crab populations are now increasing, likely due to immigration from an adjacent snow crab fishing area, this warm water event was very detrimental to the commercial fishery in the area.

1. Introduction

Climate change has become a prevailing feature across many ecosystems. Of those factors expected to change, temperature receives particular attention in aquatic environments as it is known to influence numerous biological processes. These influences range from the individual organism to a population level. In marine ecosystems, increased temperatures have resulted in changing phenology (Hughes, 2000) and shifts in distribution (Perry et al., 2005a,b; Nye et al., 2009) for some species. Long term changes in mean state of climatology will likely have direct and prolonged effects on marine populations; however the influence of increased variability and frequency of extreme events may play an even greater role in altering a population's productivity (Rijnsdorp et al., 2009). Species at the limits of their geographic range may be more susceptible to increasingly variable environments (Sexton et al., 2009). Furthermore, widespread socioeconomic impacts can result from affected commercially exploited species.

Snow crab (*Chionoectes opilio*) populations are found in the Northern Atlantic, Arctic and Pacific Oceans and inhabit a wide range of habitats throughout their geographic bounds. Across their range they are the target of commercial fisheries. The Scotian Shelf snow crab fishery currently represents one of the highest value fisheries in the Fisheries and Oceans Canada Maritimes region (http://www.dfo-mpo.gc.ca/stats/stats-eng.htm) with annual landings exceeding 10,000 mt corresponding to a landed value in excess of 68 million dollar (DFO, 2014). There are four snow crab fishing areas (CFA's) on the Scotian Shelf (Fig. 1). One of these areas, CFA/NAFO 4X, located within the Gulf of Maine/western Scotian Shelf, represents the species' southernmost geographic range and fishery.

Snow crab are generally considered to be a cold-water stenothermic species with distributions constrained by the available thermal habitat and are therefore particularly susceptible to warming events. Specific work on the Scotian Shelf has shown that temperatures between −1 to 6 °C generally bound their habitat (Choi et al., 2013). Further support from lab based experiments show that temperatures above 7 °C result in a negative metabolic state as the energy required for catabolic processes surpass those available through anabolism (Foyle et al., 1989). Here we report on the impact of the warming event of 2012 in CFA 4X, show the relative impact of the high temperature anomaly on juvenile and adult snow crab abundance and impacts on commercial harvesting. Additionally, we provide results from a survey with broader spatial coverage, which yield the evidence to support an increase in snow crab mortality rather than emigration during the warming event.

1.1. Regional climatology

Bottom temperatures on the Western Scotia Shelf – 4X area are generally characterized as being warmer than are considered ideal for snow crab for much of the year (Hebert et al., 2013). In this area there

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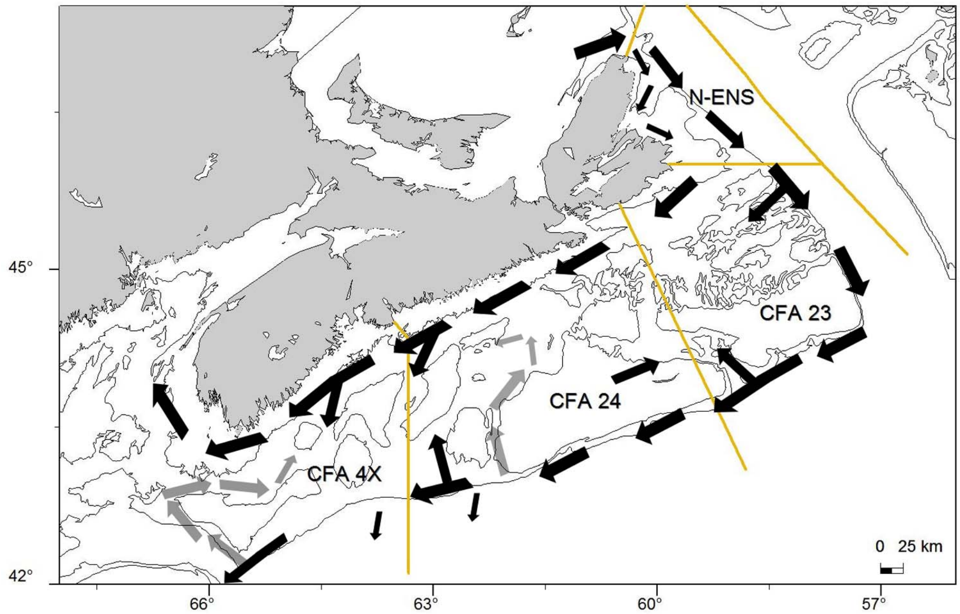

Fig. 1. Scotian Shelf with Crab Fishing Areas (CFA's). Black arrows represent cold water currents and grey arrows represent warm water currents. Yellow lines delimit each crab fishing area (N-ENS, 23, 24, 4X). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are two predominant oceanographic currents that characterize the thermal environment (Fig. 1). First, the warm slope waters from the shelf edge are pushed through the Northeast Channel east of George's Bank which creates several warm water gyres. The cold water of the Nova Scotian Current results from an outflow of cold water from the Gulf of St Lawrence and follows along the Nova Scotian coastline creating a narrow band of cold water on the inshore regions of the western Scotian Shelf with incursions into two relatively small basins, Lahave and Roseway. Snow crab (and the directed snow crab fishery) exist within this relatively narrow expanse of cold bottom water in CFA 4X. These circulation patterns do change seasonally (Hannah et al., 2000) and inter-annually (Smith, 1989; Petrie, 2007), thereby affecting the volume of cold water habitat available to snow crab.

In late 2011 through to 2012, warm slope waters flooded the western Scotian Shelf (Gawarkiewicz et al., 2012; Choi et al., 2013), creating positive anomalies in bottom temperature. This event was unpredicted and appeared to result from a northwesterly diversion of the Gulf Stream onto the continental shelf (D. Brickman, DFO pers

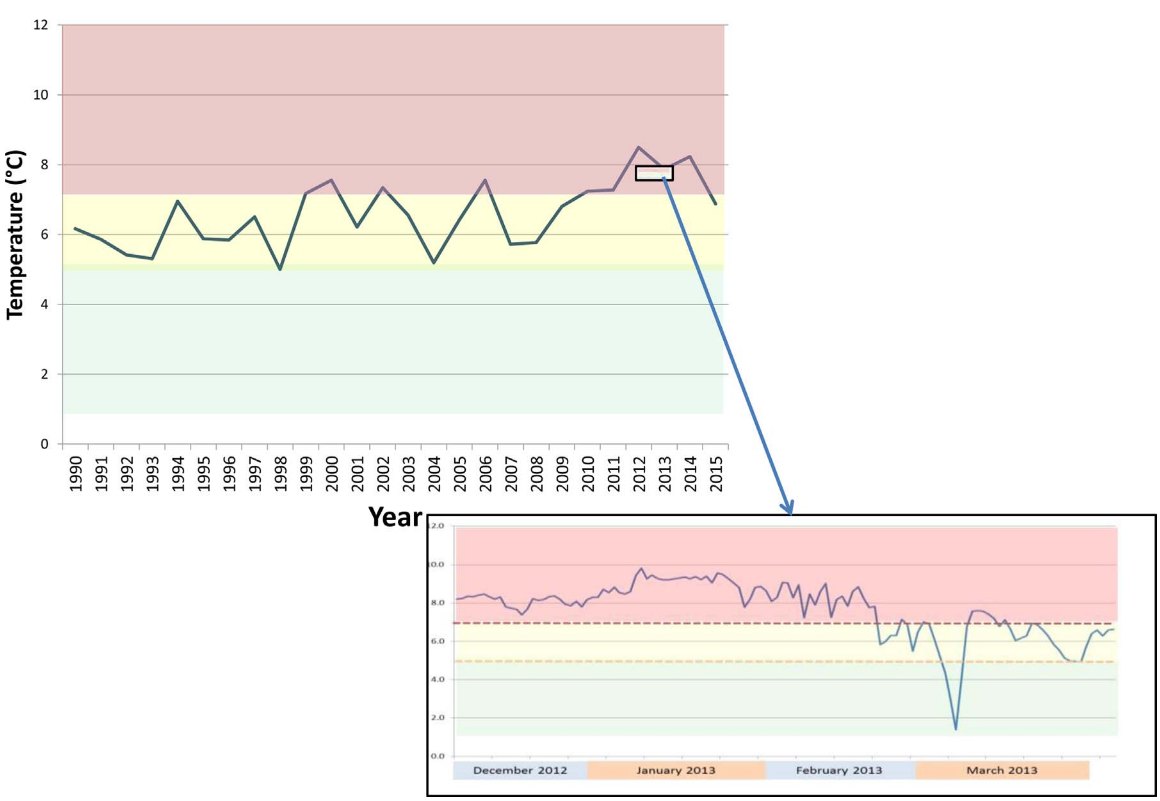

Fig. 2. Annual summer mean bottom temperatures for 4X from ecosystem survey with detailed daily mean bottom temperatures from snow crab traps in 4X for more limited temporal and geographic extent (inset). Area shaded in green denotes ideal, yellow is marginal, and red is considered unsuitable temperature conditions for snow crab. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

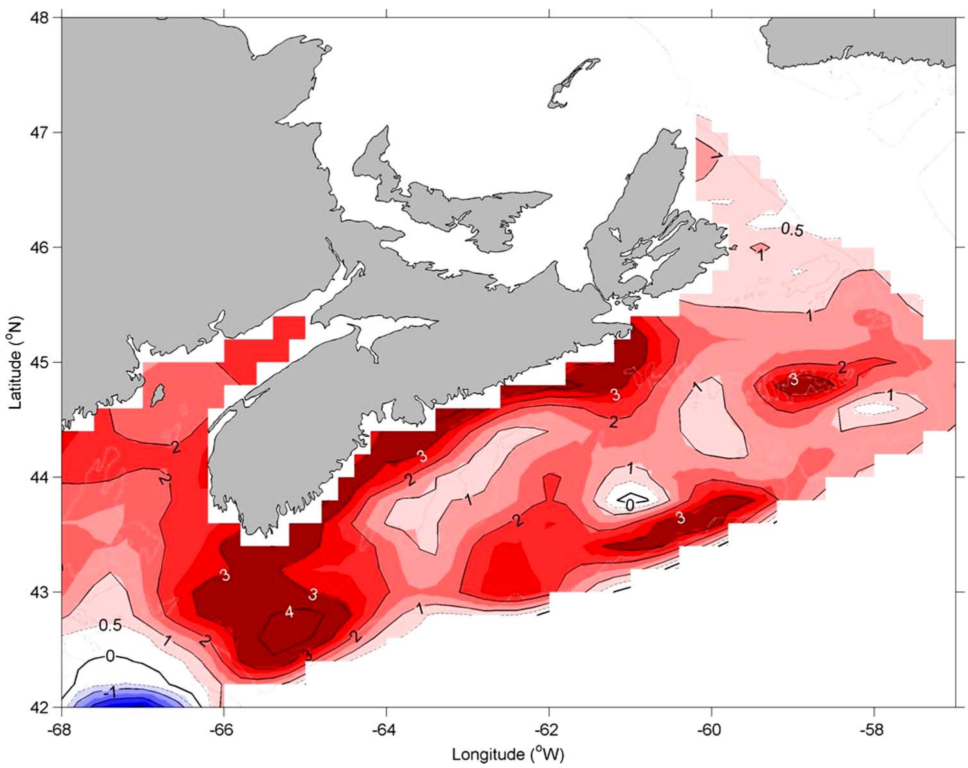

Fig. 3. July 2012 bottom temperature anomaly (relative to 1981–2010). Red shading denotes positive anomalies and blue, negative. Anomaly (in degrees Celsius) stated on contour lines of shading. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

comm; David.Brickman@dfo-mpo.gc.ca). The cooling influence of the Nova Scotian Current was reduced throughout the traditional snow crab distribution in 4X and bottom water temperature increased above the 7 °C metabolic thermal breakpoint described by Foyle et al. (1989) (Fig. 2). This warm water signal was first observed in late spring and early summer of 2012 (through oceanographic monitoring stations and vessel-based surveys) and was evident throughout the autumn of 2012. Positive temperature anomalies were observed across the Scotian Shelf though not to the magnitude observed in 4X (Fig. 3).

2. Methods

Status of the 4X snow crab population was evaluated through one fishery dependent (commercial logbook analysis) and two fishery independent (snow crab trawl survey and ecosystem trawl survey) data sources. 4X snow crab fishery information was compiled from commercial fishing logbooks submitted to Department of Fisheries and Oceans Canada (DFO). As a condition of their commercial fishing license, vessel captains are required to complete these logbooks daily throughout the course of all fishing activities. These logbooks contain effort (number of traps), location and estimated catch, along with other licensing information such as vessel and license numbers. These logbooks are validated by an independent dockside monitoring company and capture the location and effort associated with commercial catch estimates. This information was used to generate mean annual catch rates in kilograms per trap haul (kg/th, Fig. 4).

A snow crab specific trawl survey provides the primary fishery-independent measure of stock status for snow crab on the Scotian Shelf (Fig. 5). This survey is a fixed station design and has occurred annually since 2004. Each year between 26 and 34 stations are sampled before the fishing season in CFA 4X over a 5–10 day (weather depending) period. This survey uses a Nephrops bottom trawl that is has foot gear

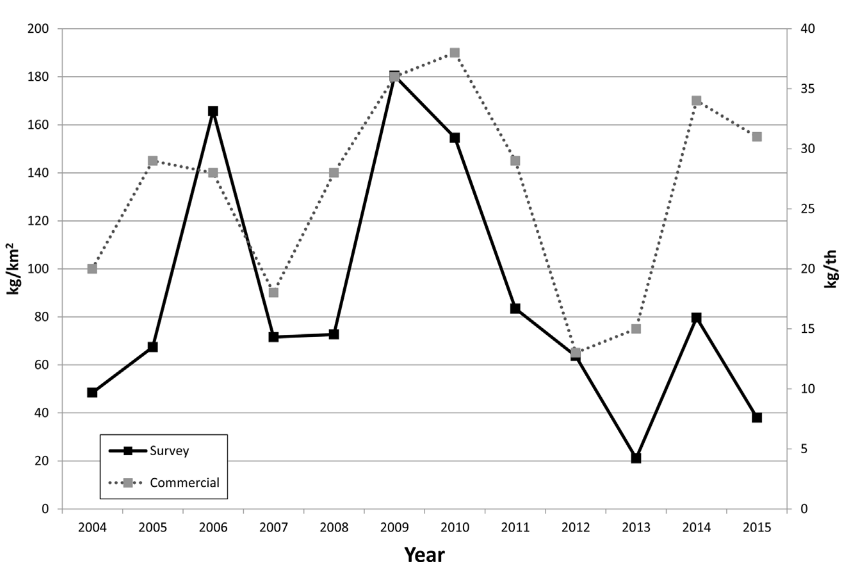

Fig. 4. Crab Fishing Area 4X commercial catch rate in kilograms per trap haul (kg/th) from commercial logbooks and snow crab trawl survey catch rate in kilograms per square kilometer (kg/km^2).

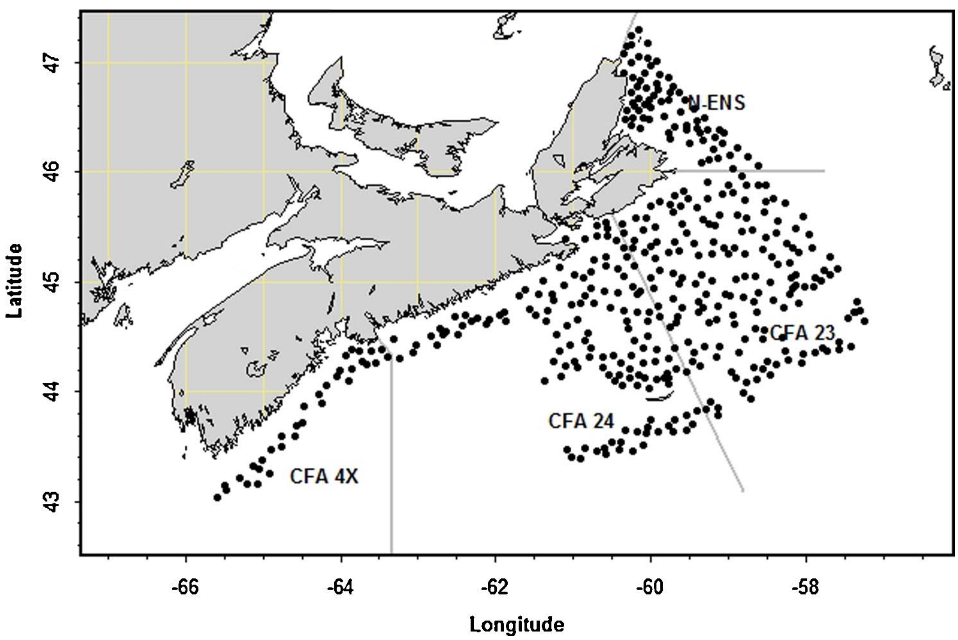

Fig. 5. 2013 Scotian Shelf snow crab survey sampling locations.

designed to dig into the soft sediments. This digging behaviour of the net coupled with small mesh size (80 mm, 60 mm and 46 mm in the wings, bellies and codend, respectively) facilitates the capture of small benthic invertebrates and has a high capture efficiency of snow crab. Further details on the sampling protocols are described in Zisserson (2015). Trends in abundance and size structure are presented as arithmetic mean densities (Fig. 6).

A DFO ecosystem based trawl survey, following a depth stratified design, is conducted annually across the entire Scotian Shelf (Doubleday and Rivard, 1981) during the spring/summer, providing an additional source of fishery-independent data. This survey partially samples the snow crab habitat, but provides greater coverage in adjacent habitats, which might provide refuge for emigrating snow crab influenced by the warm 2012 year. This survey uses a Western IIA groundfish trawl with 130 mm and 32 mm mesh opening in the trawl body and cod end respectively (Carrothers, 1988). Although the survey began in 1970, snow crab and other invertebrate groups were not regularly monitored until 1999 (Tremblay et al., 2007). The stratified estimates of snow crab abundance were calculated for the areas adjacent to the snow crab fishing and survey areas (strata 70–83 in Doubleday and Rivard, 1981 Fig. 1) with confidence intervals estimated by bootstrapping with replacement (Smith, 1997).

Spatial bottom temperature data was obtained on a per station basis from both of the fishery independent surveys covering the full range of sampled habitats. Temperature data was collected using a dedicated temperature depth recorder attached to the trawl (Seabird® SBE 15 for ecosystem survey, Seabird® SBE 39 for snow crab survey). This data was filtered to the maximum depth range (± 2 m) prior to estimating the mean bottom temperature per station.

3. Results

Both fishery independent (snow crab survey) and dependent (logbook analysis) data sources show consistent increases in catch rates of commercial sized (> 95 mm carapace width) animals from the start of the time series in 2004 through to 2010, with a moderate decrease in 2011 (Fig. 4). Coincident to the warming event of 2012, catch rates both from the survey and the fishery declined sharply to the lowest on record in 2012 and 2013 (Fig. 4). The decreases in relative abundance and catch rate during 2007–2008 were largely due to high fishing pressures in the preceding years (Table 1).

The catch rates from the commercial fishery fell from 29 kg/th in 2011–13 kg/th in 2012. However, these low catch rates do not convey the true extent of the 4X snow crab fishery's collapse. In 2012, the fleet landed only 45% of its 263 mt total allowable catch (TAC)/quota, even with a season extension from five to six months and a TAC reduction from 346 mt in 2011. Typically, the 4X TAC is landed within three months of the starting date at the beginning of November. In spite of direct fishery-based evidence of this 4X snow crab population collapse, the 4X snow crab fleet maintained a belief that warm temperatures in 2012 had altered short-term snow crab behaviour (burrowing, reduced foraging or moving to non-traditional environments), negatively impacting commercial catches.

Decreases in commercial biomass are potentially attributable to both fishery removals and anomalous temperature shifts. However, similar decreases in abundance were observed in juvenile snow crab in 4X of both sexes without commercial fishery removals. Minor reductions of juvenile crab abundance were evident during the 2012 survey though in the following year (2013), there was an almost complete disappearance of juvenile snow crab (Fig. 6a). The mature (egg-bearing) female component of the population persisted through the warm water event of 2012 and was still evident in 2013 snow crab survey (Fig. 6a) though at reduced levels. This reduction was consistent with expected losses through natural mortality of mature female crab. By comparison, the adjacent snow crab fishing area (CFA, 24) did not show the same declines in snow crab abundance for any life stages during the 2012 warming event (Fig. 6b).

The DFO ecosystem trawl survey does not typically cover as much potential snow crab habitat in 4X as the snow crab survey; it does however, sample adjacent habitats, thereby providing a source of information on the potential emigration of snow crab out of the fishing area. Though survey design and trawl dimensions are quite different

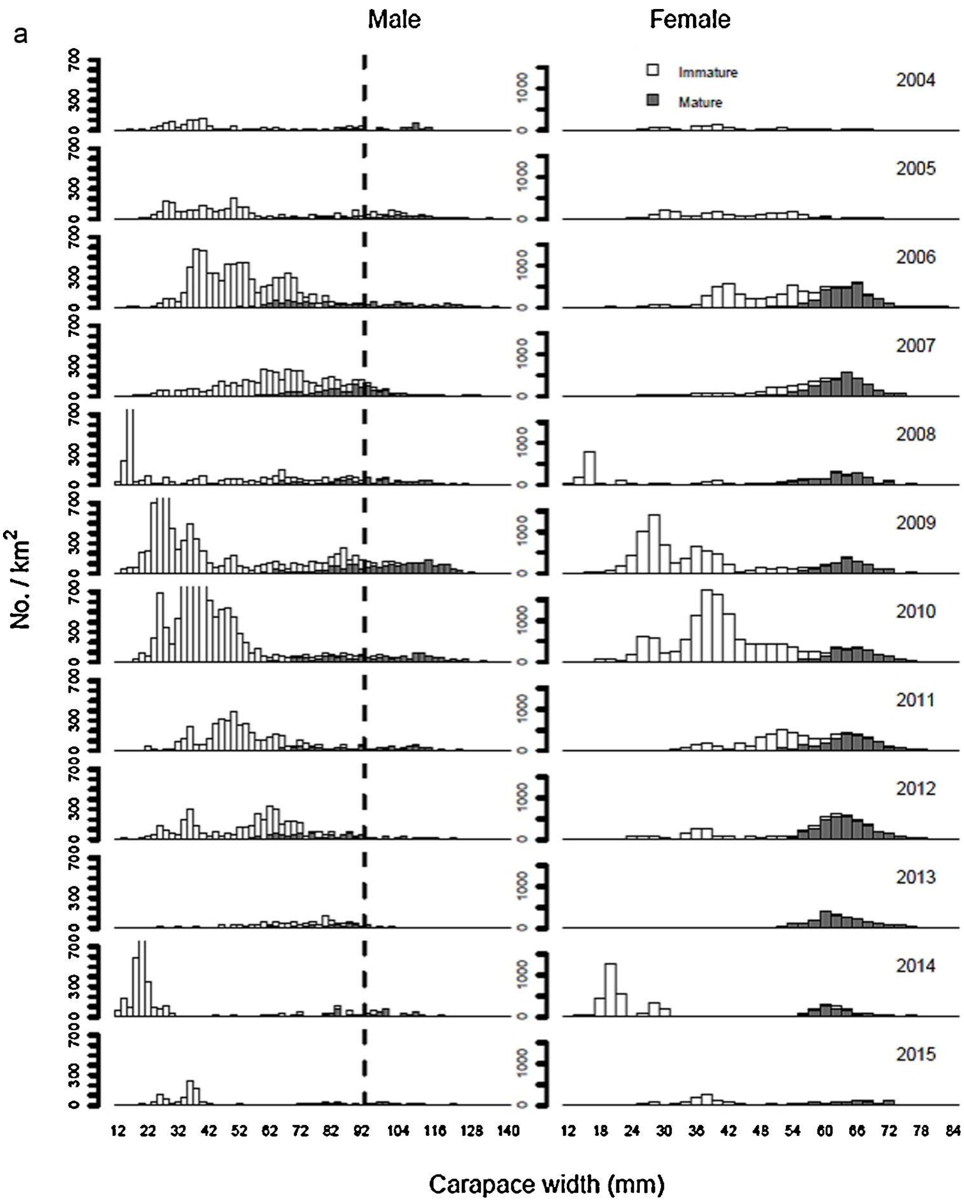

Fig. 6. (6a. CFA 4X; 6b Adjacent CFA 24) Length frequency of snow crab males (left panel) and females (right panel) in CFA4X obtained from the annual snow crab survey from 2004 to 2015. Dashed line in the male column represents the minimum commercial size (95 mm CW). In each, solid bars represent [morphometrically] mature snow crab whereas open bars represent immature.

between the two surveys, a similar carapace width frequency of crab are captured in both surveys (Fig. 7). Commercial snow crab abundance trends of each of these surveys followed a similar pattern with high abundance in 2009–2010, and decreases to 2011 and 2012, with a further decrease to 2013. There was no evidence of an emigration of snow crab into adjacent habitats as catch rates remained low throughout the wider area during and following the warm water event (Fig. 8).

The 4X snow crab fishery has begun to rebound since the historic low catch rates of 2012 and 2013. The appearance of commercial-sized snow crab is likely due to immigration from adjacent CFA 24, an area characterized by more stable thermal conditions and a broader suite of habitat types with high populations of snow crab relative to 4X. The continued presence of mature female crab in 4X coupled with a return to more favourable environmental conditions (particularly in the eastern portion of 4X) would provide incentive for mature commercial crab to relocate to 4X. Moreover, there has not been a substantial increase in the abundance of smaller size classes of snow crab. Smaller animals are less able to move substantial distances, which is further evidence of immigration of commercial males as opposed to local recruitment.

Table 1
Annual CFA 4X total allowable catch (TAC) and landings in metric tonnes. Note relatively low TAC's since 2013 and inability of fleet to land the TAC in 2012.

Year	TAC	Landings
2001	520	376
2002	600	221
2003	600	289
2004	600	413
2005	338	306
2006	338	317
2007	230	220
2008	230	229
2009	230	229
2010	346	345
2011	346	344
2012	263	118
2013	80	79
2014	80	82
2015	150	141

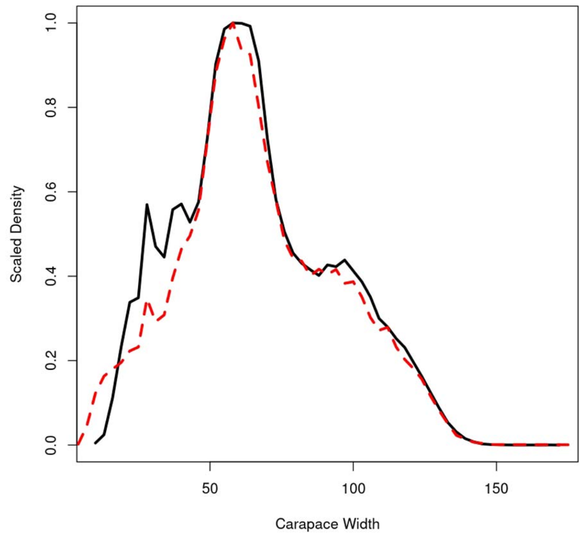

Fig. 7. Relative distribution of carapace widths of snow crab captured (2004–2015) in the snow crab trawl survey (solid black) and ecosystem survey (dashed red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

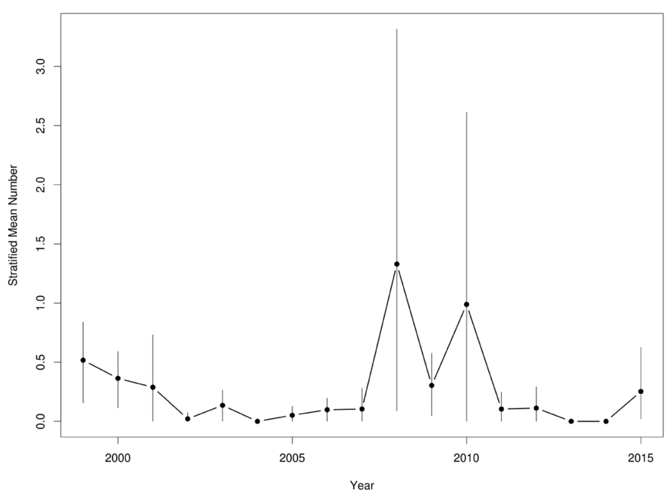

Fig. 8. Snow crab catch rate (stratified mean number of animals per tow) and accompanying bootstrapped confidence intervals from the DFO's summer ecosystem survey in 4X.

The increased catch rates (since 2014) in CFA 4X are quite localized and fishing effort is predominately focused on the border of CFA 24 (Fig. 9). Relatively low TAC's (Table 1) have further bolstered annual catch rates by limiting potential exploitation levels.

4. Discussion

The effect of temperature changes on marine populations has been examined in many regions throughout the globe. Observational and experimental studies have suggested changes in water temperatures can affect marine ecosystems in numerous ways including changes in species distribution (Perry et al., 2005a,b), changes in growth rates (Burmeister and Sainte-Marie, 2010), shifts in predator/prey relationships (Winder and Schindler, 2004), changes in primary productivity (algal and phytoplankton development Holding et al., 2015), and in the most extreme cases mortality (e.g. Rijnsdorp et al., 2009). The majority of these studies focus primarily on longer-term effects (10+ years) and marine fish populations which have increased locomotory abilities as compared to benthic invertebrates such as snow crab.

Here, results from the southernmost snow crab population in the North Atlantic suggest that the warm water event of 2012 led directly to a massive decrease in the abundance of both commercial-sized (> 95 mm carapace width) and sub-commercial sized snow crab in the area. Moreover, adjacent CFA 24 did not show the same decrease in abundance, as the potential snow crab habitat is much greater and there was presumably a greater potential for the local population to find thermal refugia (Choi et al., 2013). Thermal stress from long-term (> 21-day) elevated temperatures has been shown in experimental conditions to negatively impact snow crab. Specifically, temperatures above 7 °C result in a negative energy state where metabolic costs are higher than metabolic gains (Foyle et al., 1989). This metabolic stasis or thermal break point may vary locally depending on external factors such as food availability. However, snow crab distributions along the Scotia Shelf support this assertion as negligible concentrations of snow crab are found in warm bottom water environments (Choi et al., 2013), particularly the commercial fraction of large male crab. In other snow crab populations, annual or regional temperature variations within the normal geographic distribution has been suggested to alter population processes including localized recruitment (Marcello et al., 2012; Mullowney et al., 2014) and molting frequency (Dawe et al., 2012) and size at terminal molt (Orensanz et al., 2007; Burmeister and Saint-Marie, 2010; Dawe et al., 2012). In many animals, thermal sensitivity is likely to be enhanced at large body sizes (Komoroske et al., 2014) as metabolic rates slow, however in the present study, both large commercial and juvenile snow crab were influenced by the extended period of warm waters within CFA 4X.

Thermal conditions have been suggested previously to have resulted in a contraction of snow crab distribution in the Eastern Bering Sea (EBS) in the late 1970's and early 1980's (Orensanz et al., 2004). This contraction was believed to be caused by near-bottom mean summer temperature increases of 2 °C (2 → 4 °C). This temperature shift was more gradual and less dramatic than observed in 4X in 2012 which supports potential localized mortality of snow crab in CFA 4X rather than emigration. In the EBS case, an increase in potential predators in these newly vacated southern habitats, coupled with a migration of spawning females to "up-current" locations, created an "environmental ratchet" hindering re-establishment of the snow crab populations into these traditional grounds. Conversely, CFA 4X is located down-current of very productive crab populations which promises potentially persistent larval drift from these other areas with no documented increase in predation. This optimism is tempered by the more specific habitat preferences of juvenile instars of snow crab (Dionne et al., 2003) as compared to adult snow crab in 4X; environmental conditions may have to be ideal rather than just suitable.

Re-establishment of a commercially-viable snow crab population in 4X was likely bolstered by immigration from abundant eastward snow crab populations. Tagging studies of snow crab on the Scotian Shelf have documented movements of > 250 km by commercial size male crab (Cook et al., 2014). The revitalization and re-colonization of 4X by commercial size snow crab since the 2012 warming event has led to fishable biomasses only for the area adjacent to the more thermally stable CFA24. Furthermore, the lack of juvenile snow crab in recruiting size classes (80–95 mm) post 2012 in CFA4X suggests adult snow crab are moving into the area rather than recruiting to the commercial population from remaining resident crab.

In summary, we have provided evidence to suggest warming thermal conditions observed in NAFO division 4X, in the southernmost Atlantic snow crab population has resulted in the signficant decrease in abundance of a resident population. This loss had significant impact on the commercial biomass and resulted in several years of unexpected, low commercial catches. The positive impact of adjacent snow crab populations likely provided a source of commercially exploitable biomass through immigration which has allowed the continuation of the fishery in CFA4X.

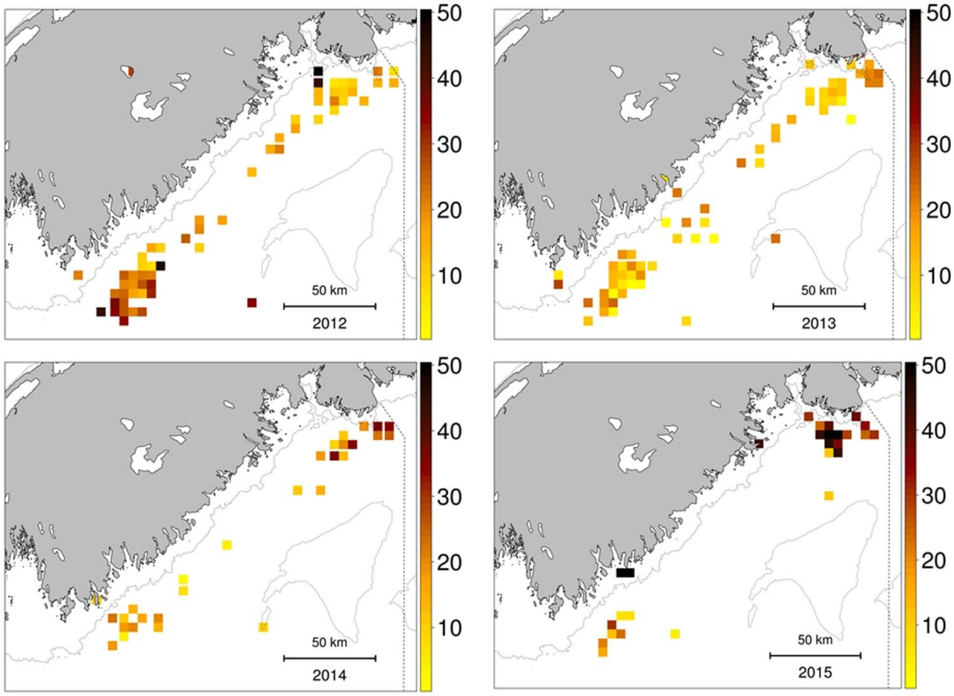

Fig. 9. Spatial distribution of commercial catch rates in kilograms per trap haul aggregated by 10 km^2 grid obtained from fisheries logbook information for CFA 4X.

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