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Model-based estimation of commercial- sized snow crab (*Chionoecetes opilio*) abundance in the southern Gulf of St. Lawrence, 1980-2012, using data from two bottom trawl surveys

H.P. Benoît[1] and N. Cadigan[2]

[1] Fisheries and Oceans Canada
Gulf Fisheries Centre
343 Université Avenue, P.O. Box 5030
Moncton, NB E1C 9B6

[2] Centre for Fisheries Ecosystem Research
Fisheries and Marine Institute of Memorial University of Newfoundland
P.O. Box 4920
St. John's, NL A1C 5R3

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The assessment for snow crab in the southern Gulf of St. Lawrence (sGSL) has been founded on a dedicated fishery-independent bottom-trawl survey conducted annually since 1988 (henceforth called the crab survey, CS). The sampling frame for this survey increased gradually during much of the intervening period and there has been no accounting to date for possible changes in catchability in the survey resulting from three gear or vessel changes that have occurred since the survey's inception. In the absence of robust methods to account for changes in the survey sampling frame and vessels/gear, long-term indices of sGSL snow crab abundance from the crab survey risk conflating true changes in abundance and apparent changes caused by modifications in the sampling protocols. Another research vessel (RV) bottom-trawl survey of the sGSL, initially focused on demersal fish (henceforth called the RV survey), has collected information on snow crab catches in survey sets since 1980. The RV survey provides synoptic estimates of snow crab abundance and distribution for a consistently sampled area of the sGSL that largely overlaps with, and is larger than, the area covered by the crab survey. Furthermore, with the exception of a single year (2003), specific data exist to estimate correction factors required to produce a standardized series for the RV survey in the face of vessel, gear and protocol changes that have occurred since 1980.

In this document, we present a model-based estimation framework that integrates data from the two surveys to produce an annual standardized index of commercial-sized sGSL snow crab abundance for 1980 to the present. The basic model is conceptually simple and assumes that crab density varies randomly with a constant mean within geographic strata and that trawl catches are basically Negative Binomial random variables. The model uses data from paired trawling at specific sites and joint fishing in common strata to estimate relative catchabilities for different RV survey vessels used since 1980 and for day vs. night to adjust for a shift from day-only to 24hr fishing that occurred in 1985. Likewise, the model exploits information from joint fishing in common strata to estimate the relative catchabilities of the vessels and gears used in the crab survey since 1988, by treating the RV survey as a standardized series. A similar logic is also applied to estimate the relative catchability of the RV survey vessel used in 2003. Because the relative catchabilities are estimated in a common model, associated uncertainties are reflected in the estimated abundance index. The model appears to fit the observations reasonably well, though discrepancies for the RV survey in certain strata and years require further investigation. Additional work aimed at simplifying the model and testing model robustness via simulation is also required. While the results presented in this document should be considered as preliminary, they indicate a strong potential for this approach which synthesizes important sources of data on snow crab abundance and distribution and which generates a standardized index whose duration is twice that of the series presently used in the assessment.

Estimation fondée sur un modèle de l'abondance des crabes des neiges (*Chionoecetes opilio*) de taille commerciale dans le sud du golfe du Saint-Laurent de 1980 à 2012 au moyen de données provenant de deux relevés au chalut de fond

RÉSUMÉ

L'évaluation du crabe des neiges dans le sud du golfe du Saint-Laurent (sGSL) repose sur un relevé au chalut de fond indépendant de la pêche, effectué annuellement depuis 1988 (dorénavant appelé le relevé du crabe [RC]). Le cadre d'échantillonnage de ce relevé a été élargi graduellement pendant une grande partie de la période concernée et jusqu'à maintenant, on n'a pas tenu compte des changements possibles de la capturabilité résultant de trois modifications d'engins ou de navires survenues depuis le début du relevé. En l'absence de méthodes rigoureuses pour tenir compte des modifications du cadre d'échantillonnage du relevé et des changements d'engins et de navires, les indices à long terme de l'abondance du crabe des neiges dans le sGSL du relevé risquent de combiner les véritables changements de l'abondance et les changements apparents découlant de la modification des protocoles d'échantillonnage. Un autre relevé au chalut de fond par navires de recherche (NR) (dorénavant appelé le relevé par NR) dans le sGSL visait initialement les poissons démersaux, et a permis de recueillir de l'information sur les prises de crabe des neiges dans le cadre des relevés menés depuis 1980. Le relevé par NR fournit des estimations synoptiques de l'abondance et de la répartition du crabe des neiges dans une zone faisant l'objet d'échantillonnages uniformes dans le sGSL, qui chevauche en grande partie la zone visée par le relevé du crabe et est plus grande que celle-ci. Par ailleurs, à l'exception d'une seule année (2003), il existe des données précises permettant d'estimer les facteurs de correction requis pour produire une série normalisée du relevé par NR malgré les modifications des navires, des engins et des protocoles survenues depuis 1980.

Dans le présent document, nous présentons un cadre d'estimation fondé sur un modèle qui intègre les données des deux relevés en vue de produire un indice annuel normalisé de l'abondance des crabes des neiges de taille commerciale dans le sGSL de 1980 à aujourd'hui. Le modèle de base est simple sur le plan conceptuel et suppose que la densité du crabe varie de façon aléatoire selon une moyenne constante dans chacune des strates géographiques et que les prises au chalut sont fondamentalement des variables binomiales négatives aléatoires. Le modèle utilise les données des relevés au chalut à deux bateaux effectués dans des sites communs précis et les données des opérations conjointes de pêche dans des strates communes pour estimer les capturabilités relatives des différents NR utilisés depuis 1980 pour effectuer les relevés, et utilise des données de jour et des données de nuit afin de tenir compte du changement survenu en 1985, où l'on est passé de la pêche de jour uniquement à la pêche 24 heures sur 24. De même, le modèle exploite l'information provenant des opérations conjointes de pêche dans les strates communes pour estimer les capturabilités relatives des navires et des engins utilisés dans le cadre du relevé du crabe depuis 1988 en traitant le relevé du NR comme une série normalisée. Une logique similaire est aussi appliquée pour estimer la capturabilité relative du NR utilisé pour effectuer le relevé en 2003. Comme les capturabilités relatives sont estimées dans un modèle commun, les incertitudes connexes sont reflétées dans l'indice d'abondance estimé. Le modèle semble correspondre raisonnablement bien aux observations, bien que quelques écarts dans certaines strates et certaines années du relevé du NR nécessitent davantage d’investigations. D'autres travaux devront être réalisés pour simplifier le modèle et vérifier sa robustesse par simulation. Bien que les résultats présentés dans ce document doivent être considérés comme préliminaires, ils démontrent que cette approche, qui résume les sources importantes de données sur l'abondance et la répartition du crabe des neiges et qui produit un indice normalisé dont la durée est le double de celle de la série actuellement utilisée dans l'évaluation, risque d'être fort utile.

1. INTRODUCTION

The assessment for snow crab in the southern Gulf of St. Lawrence (sGSL) has been founded on a dedicated fishery-independent bottom-trawl survey conducted annually since 1988 (henceforth called the crab survey). Two key features of this survey affect its reliability in providing an annual standardized relative index of abundance over the stock area for the entire period from 1988 to the present. First, the survey sampling frame has changed and generally increased over time, even as recently as 2006. The survey area was considerably smaller than the stock area in all years prior to 1997 and consequently the data for those years are presently not considered as part of the standardized stock-abundance series for the survey (DFO 2012). Second, there are presently no adjustments made for possible changes in catchability resulting from a change in the configuration of the fishing gear used after 1990, and from changes in survey vessels that occurred after 1998 and 2002. Comparative fishing between the former and replacement vessels/gears to estimate their relative fishing efficiency (e.g., Pelletier 1998; Cadigan and Dowden 2010) was not undertaken prior to these changes. In the absence of robust methods to account for survey sampling frame and vessel/gear changes, long-term indices of sGSL snow crab abundance from the crab survey risk conflating true changes in abundance and apparent changes caused by modifications in the sampling protocols.

Another standardized research vessel (RV) bottom-trawl survey of the southern Gulf (henceforth called the RV survey) has been conducted each September since 1971 and has principally been used for assessments and scientific research dedicated to marine fish (e.g., Hurlbut et al. 2010; Benoît and Swain 2008). Catches of snow crab in this survey have been recorded since 1980 (Tremblay 1997) and since 2001 the carapace size composition of those catches has also been recorded. The summary statistics from the RV survey of sGSL snow crab relative abundance, distribution and size composition are comparable to those from the snow crab survey (Benoît 2012, 2013). The RV survey provides synoptic estimates of snow crab abundance and distribution for an area of the southern Gulf of St. Lawrence that is larger than the area covered by the crab survey and that has been consistently sampled over time. Furthermore, data from comparative fishing are available to produce conversion factors for three vessel changes (one of which also included a change in fishing gear) and a change from daylight only to 24 hr fishing that have occurred over the history of the RV survey (Benoît and Swain 2003a,b; Benoît 2006; this document). Such conversions factors are applied during analysis to maintain the standardized nature of the indices.

In this document, we present a framework for model-based estimation of a relative abundance index for commercial-sized (95+ mm carapace width) snow crab in the sGSL that incorporates data from both the crab and RV surveys. Combining the surveys in this manner has a number of advantages. First, the standardized nature of the RV survey allows it to be used effectively as a baseline against which to estimate the relative efficiencies of the various crab survey vessels and two gear configurations. Conversely, the ten year span of the most recent crab survey vessel allows for the estimation of the relative efficiency of the CCGS W. Templeman which was used in the RV survey exclusively in 2003 and for which the relative efficiency compared to the present RV survey vessel (CCGS Teleost) cannot otherwise be determined because of an absence of comparative fishing for both vessels using the RV survey Western IIA trawl. Second, a standardized series for the stock area can be extended back to 1980. Third, including the RV survey data in the snow crab assessment increases the number of sampled stations for the 2000s by almost 50%, which should increase the precision of the estimates, with positive consequences to the risk assessment used to inform management decision making (Hébert et al. 2011). Fourth, the chosen model incorporates information from comparative fishing experiments and for diel effects on catchability for RV survey vessels, allowing for the estimation of relative efficiencies within a common model. This is advantageous because the associated uncertainties due to changes in vessels and gears are accounted for in standard errors and confidence intervals for abundance and biomass indices. Uncertainty about changes in survey catchability can be large, and it is desirable to account for this uncertainty when estimating trends in stock size.

2. METHODS

2.1 BACKGROUND AND DATA

2.1.1 The September multi-species RV survey

The RV survey has been conducted each September since 1971. It follows a random-stratified design, with strata defined on the basis of depth and area (Fig. 1). Hurlbut and Clay (1990) provide more details on the survey methodology. A common group of strata has been sampled annually since 1971, covering most of the southern Gulf of St. Lawrence (Northwest Atlantic Fishery Organization area 4T). Three inshore strata (strata 401, 402 and 403) added to the survey in 1984 are excluded from the present analyses in order to maintain a constant survey domain for the analyses. Even if these strata were included in an analysis spanning only 1984 onwards, they would contribute very little to the estimates of crab abundance because the majority of survey sets in the strata have caught no snow crab, and the few that did (6 of 271 sets) caught few crabs (Fig. 2). The target fishing procedure for the RV survey is a 30-min. tow at 3.5 knots. The number of valid fishing sets completed annually has varied from approximately 70 during the early 1980s to 175 or more during much of the 1990s and 2000s. Note that there are a small number of strata in which there was no sampling in certain years, namely stratum 421 in 1983 and 1988, and strata 438 and 439 in 2003, though the model employed here can address these gaps (described below).

Catches of snow crab (total numbers and mass per tow) have been recorded in the survey since 1980 (Tremblay 1997). Since 2001, captured crabs have also been measured and sexed, though maturity determination only began in 2012 (Benoît 2013). For the period 1980-2000, commercial-sized crab (males ≥95 mm) numbers are inferred using total catch numbers and an empirical relationship between the mean catch mass (mass/number) and the proportion of commercial-sized males in a tow (details below). For 2001 onwards, commercial-sized catch numbers are directly available from the RV data.

In most years prior to 1991, there was a small proportion of sets for which catch numbers were recorded but mass was not because the mass was <1 kg (Table 1). In practice, catches close to 1 kg would have been rounded up to that value, so the absence of a mass value indicates even lighter catches. Consequently in these cases, we assumed that the catch of large snow crab (≥95 mm) was nil in these sets given the typical mass of large crabs (>500 g; see Fig. 2 in Cadigan 2012). This assumption may cause a slight underestimation of commercial-sized crab abundance during 1980-1990, though the magnitude of this bias is likely to be small because the proportion of affected sets is small and the number of large crabs implied by the low catch weights is also small. In most years prior to 2001 there was a small proportion of sets for which snow crab catch mass was recorded, but not catch numbers (Table 1). In these instances, we used the stratum and year specific averages of mean catch mass per crab for sets with both catch and mass observations to infer catch numbers.

Fishing during the RV survey was carried out by the E.E. Prince from 1971 to 1985 using a Yankee-36 trawl. Since then, a number of different vessels have been used, each fishing a Western IIA trawl: the Lady Hammond (1985-1991), the CCGS Alfred Needler (1992-2002 and 2004-2005), the CCGS Wilfred Templeman (2003), and the CCGS Teleost (2004-present). Details on the trawls and vessels used in the RV survey can be found in Benoît (2012).

Comparative fishing experiments, involving side-by-side fishing by the former and replacement vessels at a large number of sites, were undertaken prior to each vessel change (Fig. 3a,b; for details see Benoît and Swain 2003a; Benoît 2006), except for the use of the CCGS Wilfred Templeman in 2003. These experiments provide information on the relative catchability of vessels and fishing gears. Two of the comparative fishing experiments took place during the regular surveys: (1) the E.E. Prince fishing the Yankee-36 and the Lady Hammond fishing the Western IIA done in 1985, and (2) the CCGS Alfred Needler and the CCGS Teleost done in 2004 and 2005. In contrast, the experiment involving the Lady Hammond and the CCGS Alfred Needler took place in August 1992, just prior to the annual survey. The data from that experiment are used here to estimate the relative catchability of the two vessels, but these data are not included otherwise in estimating the abundance index. Given the limited movements of snow crab between August and September, and the fact that the crab survey spans these months, these data probably should be included in future estimates and would simplify the estimation model a little. There is no comparative fishing data for the CCGS Wilfred Templeman fishing the Western IIA to inform us about its fishing efficiency relative to the other RV survey vessels. However, contrasts with snow crab catches in the snow crab survey lead to estimates of relative efficiency (details below).

Fishing in the RV survey was restricted to daylight hours (07:00-19:00) from 1971 to 1984 but has been conducted 24 hours per day since 1985. Because fishing efficiency can vary by time of day as a result of species and size specific diel behaviours such as hiding and trawl avoidance, the effect of time of day needs to be accounted for in analyses of the RV survey that predate 1984 (e.g., Benoît and Swain 2003b). Two approaches have been used to estimate relative catchability of various species in the RV survey. The first approach is a comparison of catches in paired day and night fishing sets taken at a common location, and the second approach uses a generalized linear model to estimate relative catchability, while controlling for differences in abundance between strata (details in Benoît and Swain 2003b). The two approaches produce very similar results. Data for the first approach were collected in 1988, 1998, 1999 and 2000 during the regular RV survey (Fig. 3b), while the second approach utilizes all the survey data. Here we estimate the relative catchability of large crabs in the RV survey for day (07:00-19:00) relative to night simultaneously using both types of information (details below). Previous analyses using only the second approach applied to data for 2001-2002 found that crabs with a carapace width >100 mm were more catchable at night (Benoît and Swain 2003b)

2.1.2 The snow crab survey

The snow crab survey has been conducted annually since 1988, though survey coverage was very limited in 1996. The survey has generally been conducted following the commercial fishery, often beginning in July and ending in late September or early October, though the start and duration have varied between years. The survey follows a systematic random sampling design in which stations were largely fixed once chosen, and fishing only takes place during daylight hours (with a few exceptions). The survey gear is a Nephrops trawl (20 m Bigouden trawl net) and the target fishing procedure at each site is a 4-6 minute tow at an average speed of approximately 2 knots. Trawl mounted sensors are used to quantify the swept area of tows, which is used to standardize the catches.

Three chartered vessels have been used to conduct the survey since 1988: the side trawler Emy-Serge for 1988-1998, and the stern trawlers, Den C Martin for 1999-2002 and Marco-Michel for 2003-2012. There has not been any comparative fishing between these vessels to estimate their relative fishing efficiency. In addition to the change in vessels, the survey gear was modified after 1990 by taking a chain that was normally attached to the trawl footgear and wrapping it around the footgear to increase fishing efficiency and gear-handling safety, based on the advice of experienced harvesters. There has been no comparative fishing with respect to the gear modifications and possible effects on fishing efficiency.

The snow crab survey sampling frame has changed considerably from 1988-present (Fig. 4). With the notable exception of 1996, the area covered generally increased over time though the area was largely constant from 1997-2005 and from 2006-present. Because of gaps in survey coverage with respect to the target area for the sGSL snow crab assessment, only snow crab survey data since 1997 are considered as part of the existing standardized time series for the stock assessment (DFO 2012). Hence, nine years of survey data for 1988-1996 are not used in the stock assessment.

Each individual crab captured in the snow crab survey is sampled to obtain data on the following characteristics: chelae height in males, the abdomen widths for females, and the carapace widths for both sexes. Here we consider only the catches of commercial sized-males.

The approach we present in this document models the survey catches of commercial snow crab as a function of the strata used in the RV survey. Sets from the snow crab survey were attributed to the strata based on their respective geographic positions using the 'point.in.polygon' function in the 'sp' package for R (Bivand et al. 2008)

2.1.3 Defining the area for estimation

The snow crab survey sampling frame, including the one that is presently used, is almost completely circumscribed by the RV survey domain. The exception is a small area in Gaspé Bay (Fig. 5, area in red) that has been sampled by the crab survey in most years of that survey and in which commercial snow crab fishing takes place (Hébert et al. 2011). It was therefore important that that area be included in the estimation domain for the snow crab index. Because there have never been any RV survey sets in that area, the easiest way to make inferences for it, even in years without crab survey sampling there, was to merge that area with an existing RV survey stratum. Because it is contiguous with stratum 417 and is composed of similar water depths (i.e., in line with the homogeneity assumption for the strata), the area was merged with stratum 417 and the area of that stratum was adjusted accordingly, increasing it by 29%. The RV survey sampling frame for strata 415-439, including the annex to stratum 417 was then taken as the estimation domain for our analyses.

A very small number of snow crab survey sets fell within a few miles of the estimation domain boundaries. These sets were attributed to the most proximate stratum. However there were three snow crab survey sets from 1988-2012 in the eastern portion of the area that were considered to be too far from the boundaries to be included (Fig. 5, blue circles).

2.2 ANALYSIS

2.2.1 Estimating the proportion of large male crabs in an RV survey set

The RV survey data prior to 2001 cannot be used directly to estimate the abundance of large male crabs because only the total catch (in numbers and mass) of crabs was recorded in this period. The RV survey data for 2001-2012 provide the information required to estimate a relationship between the mean mass in a set, defined as the ratio of catch mass and numbers, and the proportion of the catch comprised of males ≥95 mm in that set (Fig. 6). This relationship was applied to RV survey catches for the years prior to 2001 to infer the proportion of large males in survey sets based on the observed mean mass.

A series of binomial generalized linear models based on either the logit or the probit model, and including various degrees of polynomials of mean mass, were fit to these data. These models were compared using Akaike's Information Criterion (AIC) to select the best one for the data. Annual histograms of standardized residuals from the selected model were examined for possible difference in residual distributions between years. Furthermore, generalized additive models (GAMs; Hastie and Tibshirani 1990) were fit to standardized residuals for each year from 2001-2012 to look for patterns as a function of mean mass that would suggest interannual differences in the shape of the relationship between mean mass and the proportion of large males in a set.

2.2.2 Exploratory analyses of the diel effects on relative catchability

Exploratory analyses were undertaken using GAMs to see whether the day/night dichotomy proposed above was reasonable for the RV survey data. The observed catch of crabs was modelled as a smooth function of the time of day (decimal hours) using a cyclic cubic regression spline (Wood 2006) and a function of a stratum-year factor (Benoît and Swain 2003b). An offset term was included to account for differences in tow distance between sets and to account for the predicted proportion of large males for years prior to 2001. Data were assumed to follow a quasi-Poisson distribution and analyses were conducted separately by vessel. The optimal level of smoothing was determined using generalized cross-validation.

Similar analyses were undertaken for catches of commercial male crabs in the snow crab survey. With a few exceptions, fishing sets in that survey are only made during daylight hours. Though changes in catchability due to the time of the day are likely to be minimized as a result of that protocol, analyses were undertaken nonetheless to look for evidence for a diel effect on catchability in the survey during the daylight sampling hours. Given that the snow crab survey takes place over a protracted period of weeks during summer and early autumn, adjustments for the length of daylight were required for the analysis. Sunrise and sunset times were calculated for each snow crab survey tow based on its geographic position and date using the approach of Teets (2003), implemented in the ‘suncalc’ function of the R package ‘RAtmosphere’ (Biavati, 2012). A relative time, RTi, for each SCS tow i was calculated as:

$$RT_i = (T_i - T_{SUNRISE\,i}) \Big/ (T_{SUNSET\,i} - T_{SUNRISE\,i})$$

where T_i is the time of day for set *i*, and $T_{SUNRISEi}$ and $T_{SUNSETi}$ are respectively the sunrise and sunset times for the date and location of set *i* (all times expressed as decimal hours). The effect of RT_i on the catch of commercial male snow crab, y_i, was examined using a GAM like the one described above for the RV survey, but using regular cubic regression splines. The analysis was carried out in blocks of years proper to each vessel used in the snow crab survey. Only values of RT_i ranging from [-0.2, 1.2] were retained for analysis, as other values were uncommon in the data (Fig. 7).

2.2.3 Abundance index estimation model

The basic model is conceptually simple and assumes that crab density is stochastically constant within strata; that is, density varies randomly within a stratum with a constant mean. Density is assumed to be independent from site to site within strata. Otherwise no assumptions are made. That is, crab densities are modeled separately for each stratum and for each year. An index of stock size will be based on the common strata size-weighted average of the strata densities (described below). This model and index estimator is similar to that described in Cadigan (2011) where additional motivations for the approach are given. Trawl catches are assumed to be Negative Binomial (NB) random variables. This count-data distribution is often considered to be suitable for modeling trawl catches (e.g. Cadigan 2011). Let *R* be a random variable for a survey catch. In addition to stratum and year, other important factors for snow crab are survey vessel and associated fishing protocols (denoted as *v*), day or night (denoted as *d* = 0 or 1, respectively), and site *i* in a stratum. In some years there are repeat samples at some sites in the RV survey due to comparative fishing or other reasons, and these repeat samples are indicated with a *j* subscript. At most sites there is only one tow but there have been as many as 10 tows at a site (Table 2).

Let R_{syvij} denote the catch from the j'th tow at site i for survey vessel v in stratum s and year y. Let λ_{syij} denote stock density at site i,j in stratum s and year y. The motivation for the i,j subscripts will be described shortly. The catch depends on trawl catchability (q) and the density of snow crab at the site. This density is assumed to be the product of a fixed (i.e. not random) stratum and year effect (λ_{sy}), a random site effect (γ_{syi}) and a random repeat tow effect (γ_{syij}) at site i; that is, $\lambda_{syij} = \lambda_{sy}\gamma_{syi}\gamma_{syij}$. The random effects are assumed to have means equal to one, $E(\gamma_{syi}) = E(\gamma_{syij}) = 1$, and $E(\lambda_{syij}) = \lambda_{sy}$. Fixed effects parameters (e.g λ_{sy}), denoted collectively as the parameter vector θ, are estimated via maximum likelihood (MLE) based on the marginal likelihood, $L(\theta)$, in which random effects, denoted collectively as γ, are "integrated out". The marginal likelihood is:

$$L(\theta) = \int\int\int_{\gamma} f_{\theta}(data \mid \theta, \gamma) g_{\theta}(\gamma) \partial\gamma \qquad (1)$$

where $f_{\theta}(data \mid \theta, \gamma)$ is the joint probability mass function (pmf) of the survey data conditional on γ and $g_{\theta}(\gamma)$ is the joint probability density function (pdf) for γ. The γ's are not required for inferences about trends in stock size.

Conditional on λ_{syij}, R_{syvij} is assumed to be Poisson distributed with mean $q_{vdy}\lambda_{syij} = \mu_{syvij}$. The survey catchability parameters (q's) are described later. The γ_{syij}'s are assumed to be independent and identically distributed (iid) Gamma random variables with mean 1 and variance $1/k_p$. A gamma random variable is strictly positive and seems appropriate for modeling variation in species density. The p notation indicates pair because most repeat tows are due to paired vessel comparisons. It is well known (e.g., Cadigan 2011) that if $R_{syvij}|\gamma_{syi}\gamma_{syij} \sim \text{Poisson}(\mu_{syvij})$ then the marginal distribution (with respect to γ_{syij}) of $R_{syvij}|\gamma_{syi} \sim$ NB with mean $\mu_{syvi} = q_{vdy}\lambda_{sy}\gamma_{syi}$ and variance $\mu_{syvi} + \mu_{syvi}^2 / k_p$. The pmf is:

$$\Pr(R_{syvij} = y \mid \gamma_{syi}) = \frac{\Gamma(y + k_p)}{\Gamma(y+1)\Gamma(k_p)} \left(\frac{\mu_{syvi}}{\mu_{syvi} + k_p} \right)^{y} \left(\frac{k_p}{\mu_{syvi} + k_p} \right)^{k_p}.$$

However, the marginal distribution (with respect to γ_{syi}) of R_{syvij} is not NB. If the γ_{syi}'s are iid Gamma random variables with mean 1 and variance $1/k$ then the marginal distribution of R_{si} is

$$\Pr(R_{syvij} = y) = \int\int \Pr(R_{syvij} = y \mid \gamma_{syi}, \gamma_{syij}) \Pr(\gamma_{syi}) \Pr(\gamma_{syij}) \partial\gamma_{syi} \partial\gamma_{syij}$$

$$= \frac{k^k k_p^{kp} \mu_s^y \Gamma(k+y)}{\Gamma(k)\Gamma(k_p)} \int_0^{\infty} \frac{e^{-k_p t} t^{y+k_p-1}}{(\mu_{sy} t + k)^{y+k}} \partial t \qquad (2)$$

The ∂t integral in equation (2) does not have a closed form but this can be evaluated numerically. Note that we expect the between-site variability of crab density to be greater than the within-site variability during repeat tows; that is, $Var(\gamma_{syi}) > Var(\gamma_{syij}) \Rightarrow k < k_p$. It is not difficult to show that $E(R_{syvij}) = \mu_{syv}$ and $Var(R_{syvij}) = \mu_{syv} + \mu_{syv}^2 / k_c$, where $k_c = kk_p/(1 + k + k_p)$.

Note that the over-dispersion, $1/k_c$, is the sum of the site and pair over-dispersion plus their product, $1/k_c = 1/k + 1/k_p + 1/kk_p$. To simplify estimation, the marginal distribution R_{syvij} is approximated as NB with over-dispersion parameter k_c.

Repeat tows at a site have marginal correlation because there is a common γ_{syi} random effect in their distribution. Consider the situation where there is only a pair of tows at a site. The marginal probability of the pair R_{syvi1}, R_{syvi2} is the integral of two NB probabilities:

$$\Pr(R_{syvi1} = y_1, R_{syvi2} = y2) =$$

$$\frac{\Gamma(y_1 + k_p)\Gamma(y_2 + k_p)k^k}{\Gamma(y_1 + 1)\Gamma(y_2 + 1)\Gamma(k)\Gamma^2(k_p)} \int \left(\frac{\mu_{syv1}t}{\mu_{syv1}t + k_p} \right)^{y_1} \left(\frac{k_p}{\mu_{syv1}t + k_p} \right)^{k_p} \left(\frac{\mu_{syv2}t}{\mu_{syv2}t + k_p} \right)^{y_2} \left(\frac{k_p}{\mu_{syv2}t + k_p} \right)^{k_p} t^{k-1} e^{-kt} \partial t. \quad (3)$$

The ∂t integral in equation (3) does not have a closed form but this can be evaluated numerically. Note that the means for R_{syvij} may depend on j because of vessel effects or day/night effects (see below). The marginal variance of R_{syvij} is $Var(R_{syvij}) = \mu_{syvj} + \mu_{syvj}^2 / k_c$ and $Cov(R_{syvi1}, R_{syvi2}) = \mu_{syv1}\mu_{syv2} / k_c$ indicating positive correlation of paired tows. The distribution of three or more tows at a site can be derived similarly to the distribution of a pair. Unlike the single tow case, the marginal distribution of repeat tows cannot be approximated using an NB pmf.

The maximum likelihood method was used to estimate fixed parameters θ and to provide the snow crab abundance index. Note that in the current implementation of the model only the first two repeat tows at a site are used in the likelihood, but this included the vast majority of the data (Table 2). There are very few sites with three or more tows and data from two tows at these sites are still used in the likelihood.

The mean $\mu_{syvj} = q_{vyj}\lambda_{sy}$ is a product of catchability (q) and density (λ). The λ_{sy}'s are treated as fixed parameters. There are great many of these, one for each of 24 strata and 33 years, plus some additional strata effects for comparative fishing tows from August 1992 that were not part of the RV survey. Note that these August 1992 tows contribute information about q but not information about λ for the index. There are a total of 805 λ_{sy} parameters; however, λ_{sy} was fixed at a small value (e^{-10}), for any stratum in which all survey catches were zeros. The MLE of λ_{sy} tends towards zero in this case, but λ must be greater than zero and a lower bound of e^{-10} was used. This reduced the number of λ_{sy} parameters to estimate from 805 to 669.

The catchability parameters depend on vessel and day/night tows. Catchability is modeled as a product of a vessel-specific day/night effect (δ_{vj}) and vessel effects (q_v). Let

$$\delta_{vj} = \begin{cases} 1, & j \text{ is a day tow} \\ \delta_{v,} & j \text{ is a night tow} \end{cases}$$

There was not strong evidence that the day/night effect was vessel dependent (details later), so this parameter was further assumed to be the same for all surveys and vessels (i.e, δ_j). Vessel effects are defined as:

$$
q_v = \begin{cases}
1, & v = Teleost, & 2004-2012, \\
q_{WT\to T}, & v = Wilfred\ Templeman, & 2003, \\
q_{AN\to T}, & v = Alfred\ \ Needler, & 1992-2005, \mathit{not}\ 2003, \\
q_{LH\to AN}\, q_{AN\to T}, & v = Lady\ Hammond, & 1985-1992, \\
q_{EP\to LH}\, q_{LH\to AN}\, q_{AN\to T}, & v = EE\ \ Prince, & 1980-1985, \\
q_{SCS1\to T}, & gear\ used\ in\ SCS1, & 1988-1990, \\
q_{SCS2\to T}, & gear\ used\ in\ SCS2, & 1991-1998, \\
q_{SCS3\to T}, & v\ in\ SCS3, & 1999-2002, \\
q_{SCS4\to T}, & v\ in\ SCS4, & 2003-2012.
\end{cases}
$$

The notation $q_{a\to b}$ indicates the catchability of vessel *a* relative to vessel *b*. The catchability of the CCGS Teleost is fixed at one and CCGS Teleost is the reference vessel. There was no direct comparative fishing between the EE Prince or the Lady Hammond and the CCGS Teleost and these conversions were inferred stepwise, e.g. $q_{EP\to T} = q_{EP\to LH}\, q_{LH\to AN}\, q_{AN\to T}$. Hence, in addition to the stratum density parameters, there are 8 vessel q parameters, 1 day/night δ parameter, and two NB over-dispersion parameters (k and k_p).

Catches should be standardized for variations in tow distance. The usual approach is to adjust catches to some nominal tow distance d_o. If d_j is the actual tow distance for the *j*'th tow then conceptually the strategy is to adjust R to the nominal tow distance d_o; that is, $R^* = Rd_o/d_j$. However, it is usually better to not adjust data and the standardization is applied to the model:

$$
\mathrm{E}(R_{syvij}) = \mu_{syvij} = q_v \delta_{vj} \lambda_{sy} \frac{d_{syvij}}{d_0}
$$

Further adjustments were made to account for subsampling of catches (ratio) and to standardize λ to number per km^2. The swept area of a standard CCGS Teleost tow is 0.0405028 km^2. Hence, the model for expected catch was:

$$
\log(\mu_{syvj}) = \beta_0 + \log(q_v) + \log(\lambda_{sy}) + \log(\delta_{vj}) + Z_{syvij} \qquad (4)
$$

where Z_{syvij} = log(d_{syvij}/d_o) + log($ratios_{yvij}$) + log(0.0405028). Z is often referred to as an offset. Adjustment of total RV survey catches prior to 2001 to correspond to catches of commercial-sized males were also incorporated this way. Rather than multiplying catches by the proportion of commercial-sized males, this proportion was divided into E(R); that is, the offsets for RV survey total catches prior to 2001 were Z_{syvij} = log(d_{syvij}/d_o) + log($ratio_{syvij}$) + log(0.0405028) – log(proportion large males).

The estimated proportion of large males sometimes varied substantially among sets in a stratum. If the proportion was very small for sets with low catch weights then the offset could be large. If there were other larger catches in a stratum then the few sets with large offsets produced large predicted catches when observed catches were near zero. The only way to get predictions closer to observations was if λ_{sy} was estimated to be close to zero, but this resulted in poor fits to the sets with larger catches. With the NB model, because the variance increases with the square of the mean, over-predicting a small catch is a smaller error (i.e. the variance is high in this case) than under-predicting a large catch (i.e. the variance is low in this case).

This situation leads to estimation problems. As a remedy, a catch-weighted average proportion for each stratum was used. With this approach the mean total catch divided by the average proportion is identical to the average of the estimated catch of large males obtained by applying tow-specific proportions to the total catches. That is, if there are n_s catches in some stratum s and if $\bar{p}_s = \sum_{i=1}^{n_s} r_i p_i \Big/ \sum_{i=1}^{n_s} r_i$ then $\bar{r}_s \bar{p}_s = \sum_{i=1}^{n_s} r_i p_i \Big/ n_s$.

AD Model Builder (Fournier et al. 2012) was used to implement the model. The joint pmf (equation 3) for the likelihood function of repeat survey catches was computed using the numerical integration function adromb(). The pmf for single catches was based on the NB approximation with over-dispersion parameter k_c. The stock size index is defined as:

$$\lambda_y = \frac{\sum_{s \in S} W_s \lambda_{sy}}{\sum_{s \in S} W_s}$$

where W_s is the size of stratum s and S is the set of all strata. A nice feature of ADMB is that it can be used to automatically provide standard errors for λ_y and these standard errors include uncertainty due to changes in survey protocols (i.e. vessels and gears). Stratum 421 was not sampled in 1983 and 1988, and therefore λ_{sy} was assigned a small value, e^{-10}, in those years. The median catch in this stratum for all other years combined was 0 so this assumption seems reasonable.

3. RESULTS

3.1 ESTIMATING THE PROPORTION OF LARGE MALE CRABS IN AN RV SURVEY SET

Based on AIC, the best model relating the proportion of large males and the mean mass in a set was a probit model with a third degree polynomial of mean mass (Table 3). The model fit the data very well (Fig. 6). The distribution of standardized residuals and patterns as a function of fitted values confirm the adequacy of the model overall (Fig. 8). Furthermore, similarity between years in the distribution of residuals (Fig. 9) and the absence of convincing patterns in residuals as a function of catch mass for individual years (Fig. 10) suggest that a single model is appropriate for all years, 2001-2012. Because this period includes years of high and low crab abundance characterized by difference in the size composition of the stock (Hébert et al. 2011), it appears that neither size composition, nor possible effects of density dependence on individual crab weights, affect the relationship. Consequently, we assumed that the model was appropriate for estimating the proportion of large crabs in RV survey catches prior to 2001.

3.2 EXPLORATORY ANALYSES OF THE DIEL EFFECTS ON RELATIVE CATCHABILITY

The results of the GAM analyses suggest that although the diel effect on the catches of large crabs appears to be continuous in time, the divisions used to separate day and night are not unreasonable (Fig. 11). Treating the effect of time as dichotomous (day vs night) greatly simplifies the estimation of abundance and was therefore used in the estimation model. The consequence is that variation in crab catches in the RV survey due to the effect of the time of day will not be fully accounted for. However the bias resulting from the switch in 1984 from daylight only to 24 hr fishing is addressed. The results presented in Figure 11 also confirm the great similarity in the diel effect across survey vessels, a result that has previously been noted for snow crab and numerous other fish and invertebrate taxa captured in the RV survey (Benoît and Swain 2003b). Likewise, results from a NB model version with vessel-specific diel effects also suggested that there were no differences between vessels in relative day/night catchability (not shown). Consequently to simplify the methods a common diel effect was estimated for the RV survey in the population estimation model presented here.

In contrast to the RV survey, no evidence was found for the effect of the time of day (expressed as relative time) on commercial crab catches in the snow crab survey (Fig. 12). Spline functions for the effect of relative time were not statistically significant for the years 1990-1998 and 1999-2002 (Table 4). The results were marginally statistically significant for 2003-2012 (p=0.044), which likely reflects the large sample size in the analysis, given the subtlety of the effect (Fig. 12).

3.3 MODEL RESULTS

Estimates of snow crab abundance (number per km^2) have varied since 1980 but are currently at about the average for the series (Table 5; Fig. 13). Abundance appears to have cycled between periods of relatively high levels in the early 1980s, early 1990s, mid 2000s and most recently 2011-2012, and intervening periods of low levels. Estimated peak abundances during the early 1980s and 1990s are greater than the peak abundance of the mid 2000s, though confidence intervals for the estimates overlap.

Estimates have very good precision since about 1991, with CV's close to 0.1 during this period (Table 5; Fig. 13). Estimates prior to 1991 are less precise, particularly during 1980-1984. This seems to be primarily driven by the relatively low number of tows in these years (see Table 1). The CV's when calibration parameters were simply fixed at their estimated values (Table 5) were not much smaller in 1980-1984 so this is not the source of the higher CV's in this period. The increase in CV due to uncertainty about calibration parameters ranged from a low of 6.2% in 1981 to a high of 65.8% in 1990. The median increase was 18.3%.

Other model parameter estimates (Table 6; Fig. 14) seemed reasonable or were consistent with literature values or expectations. For catchability parameters that were not derived at least in part by comparative fishing results (i.e., $q_{SCS1\to T}, q_{SCS2\to T}, q_{SCS3\to T}, q_{SCS4\to T}, q_{WT\to T}$), fits to stratum-year mean catches in the two surveys were good (e.g., Appendix A Figures 1 and 2). The *q*'s for the four snow crab survey periods were much larger than the Teleost *q*. This makes sense because the gear used in the snow crab survey is more efficient at catching crabs given that it is meant to dig into sediment, whereas the RV survey gear uses a much larger rockhopper footgear meant to ride over the bottom. The relative *q*'s for the snow crab survey also make sense based on a priori expectations that the estimates would be lowest for the period in which the less efficient configuration of the gear was used (SCS1). The estimates of $q_{EP\to LH}$ and $q_{LH\to AN}$ reported in Benoît and Swain (2003a) for size-aggregated crab catches were 0.475 and 1.10, respectively. These values are reasonably similar to the values in Table 6. Benoît (2006) estimated of $q_{AN\to T}$ to be 0.973 which is also very close to the value in Table 6. Both approaches indicate that the catchability of the CCGS Alfred Needler is not significantly different than the CCGS Teleost for snow crab in 4T. It is likewise for the Lady Hammond and CCGS Alfred Needler. The *δ* estimate in Table 6 indicates that adult snow crabs are more catchable at night, which is the same conclusion in Benoît and Swain (2003b). Finally, $k \ll k_p \Rightarrow Var(\gamma_{syi}) \gg Var(\gamma_{syij})$ as expected; that is, the within-site over-dispersion is much smaller than the between-site over-dispersion. Hence, the calibration and over-dispersion results seem reasonable.

The NB variance model provided a good description of how the variance in the raw residuals increased with the mean (Fig. 15). These raw residual standard deviations were computed for bins of size 50 defined by sorted predicted values. The NB predictions of the standard deviations were based on the bin mean predicted values and the estimate of k_c. However, there is some suggestion (Fig. 16) that k_c may be survey vessel/gear dependent. In particular, the snow crab survey may have less over-dispersion overall than the RV survey, and this makes sense because of the higher gear efficiency in the snow crab survey.

There were no major time trends in residuals (Figs.17 and 18) indicating major differences in survey trends. There is a close correspondence between stratum-average catches and model predictions for the snow crab survey (Fig. 19) and, to a lesser extent, the RV survey (Fig. 20). Average RV catches usually correspond closely but there were some strata and years where there were large differences (i.e. strata 424, 427, 436, 437). The possible causes of these discrepancies are the subject of ongoing study.

Maps of model residuals do not suggest any strong spatial heterogeneity for either survey across the years (Fig. 21). Annual variograms for the residuals for the snow crab survey suggest that the spatial distribution of residuals is essentially random in many years. In other years, with the exception of 1989 and 1998, the range of influence is nonetheless small (<25 km) and the nugget effect is relatively large suggesting only minor spatial clustering. Likewise for the RV survey, variograms for 1988-2012 suggest no or minor spatial clustering, depending on the year. Note that there are generally few set pairs at small distances in the RV survey and the shape of the variograms over the 0-25 km range may not be well defined in most years. Annual variograms for 1980-1987 are quite variable owing to the lower sampling intensity in the RV survey in those years.

4. DISCUSSION

4.1 GENERAL

The model provides a useful method for integrating the available data on snow crab abundance in the sGSL, making the best use of data that are costly to obtain. The model draws strength from both the RV and crab surveys to estimate relative catchability parameters that would otherwise be difficult to estimate (SCS1-SCS4 and $q_{WT \to T}$). Furthermore, the model provides a useful framework in which to efficiently estimate relative catchability coefficients for the RV survey for vessels and for a diel effect by drawing simultaneously on information from samples that are paired/grouped at the site level and at the stratum level. By estimating these parameters within a common modeling framework, their associated uncertainty is reflected in the estimated abundance index uncertainty.

4.2 NEXT STEPS

Though the results presented here suggest that the approach for integrating the survey data is promising, the results to date should only be viewed as preliminary. Additional work to strengthen and validate the model includes the following:

- The present model provides estimates of commercial male crab abundance. However, the precautionary approach framework for the stock and harvest decisions are based on biomass. The mean mass of commercial male crabs can be incorporated in the estimation to produce a biomass estimate. The best approach for estimating and incorporating the mean mass, particularly for years in which there are no observations to inform us of the mass of individuals, has yet to be determined.
- Ideally, the uncertainty of the model estimates should reflect uncertainty from all sources included in the estimation. Uncertainty associated with the prediction of the proportion of large males in an RV survey set for 1980-2000 is currently not accounted for in the final estimates. Possible approaches include Monte Carlo simulations and the estimation of the relationship between large males and mean weight within the same likelihood framework as the rest of the estimation model.

- The model involves a large number of parameters (e.g., the strata effects) to estimate. More parsimonious models that could produce better inferences about trends in stock size need to be explored, such as a main effects model (strata and year) with correlated random effects to account for stock distribution shifts. At a minimum, inclusion of the August 1992 RV comparative fishing data in the abundance estimates should be considered, which would reduce model complexity slightly.
- The efficacy of the model should be simulation tested (e.g., Cadigan 2011)
- A model variant including values of the NB parameter k specific to each survey should be evaluated to determine whether count variance is survey dependent. In the present model, sites are defined based on stratum, year and location.
- The large estimate of k_p suggests that this source of Poisson-overdispersion (i.e. $1/k_p$ is small) may not be important. If this is the case then the statistical model and analysis may be simplified – in particular the marginal likelihood may have a closed form solution.
- A model variant in which day/night is also used to define sites should be explored further. Such a model uses slightly more data because there are fewer sites with > 2 sets. Preliminary results suggest that estimates are very similar in most years (compare Figures 13 and 22), though differences in estimates greater than 10% occur in some years (e.g., 1987-1990).

4.3 PERSPECTIVES AND RECOMMENDATIONS

The approach presented here constitutes the best available science concerning the relative fishing efficiency of the vessels (or gear configurations) used to conduct the snow crab survey. Once the model has been thoroughly reviewed and simulation tested, we recommend that the estimated relative catchability coefficients be used in analyses involving the snow crab survey data for commercial-sized male crabs. We also recommend that the approach or a related one be considered to estimate similar relative catchabilities for other sizes, stages or groups of snow crabs in the snow crab survey.

The approach presented provides a synthesis of the available data on snow crab abundance and distribution in the southern Gulf. Once the model has been thoroughly reviewed and simulation tested, it will produce a standardized time series of estimated commercial stock abundance that is twice the duration of the presently accepted one. This longer term perspective on stock dynamics and productivity with respect to exploitation will provide a better basis on which to model stock dynamics and derive reference points. Serious consideration of this approach as part of the basis for the provision of science advice should be given at, or perhaps prior to, the next scheduled assessment framework for this stock.

The utility of our approach is likely not limited to snow crab in the sGSL. Given that catches of fish are recorded in the snow crab survey, we recommend the approach be evaluated to determine whether it can provide reliable relative abundance indices for fish. These indices are presently derived using only the RV survey and a Sentinel bottom-trawl survey. In particular, we believe that our approach might be useful for estimating standardized catches in 2003, the year (i.e., 2003) in which the CCGS Wilfred Templeman was used and in which certain strata were not sampled. Presently, data from 2003 are excluded from stock assessments for sGSL fish.

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7 TABLES

Table 1. Summary of the number of sets from the RV and crab surveys used to estimate the abundance index. The summary for the RV survey sets is further broken down to indicate the number of sets for which both catch mass and numbers were recorded and sets for which values of only one of the two variables was recorded.

	RV survey				*Crab survey*
Year	Valid sets	Numbers and Mass	Numbers only	Mass only	Valid sets
1980	70	47	2	21	
1981	70	57	13	0	
1982	65	47	17	1	
1983	67	48	14	5	
1984	102	85	12	5	
1985	209	162	41	6	
1986	164	156	0	8	
1987	152	128	13	11	
1988	147	121	19	7	154
1989	166	143	14	9	155
1990	141	134	6	1	212
1991	188	184	0	4	215
1992	162	154	0	8	233
1993	183	176	0	7	208
1994	154	150	0	4	259
1995	175	168	0	7	260
1996	194	189	0	5	72
1997	202	185	0	17	259
1998	192	145	0	47	261
1999	180	175	0	5	277
2000	182	181	0	1	280
2001	141	141	0	0	290
2002	173	173	0	0	319
2003	78	78	0	0	317
2004	212	212	0	0	347
2005	231	231	0	0	355
2006	165	165	0	0	354
2007	163	163	0	0	355
2008	177	177	0	0	355
2009	148	148	0	0	355
2010	137	137	0	0	354
2011	126	126	0	0	353
2012	142	142	0	0	321

Table 2. Frequency distribution of the number tows done at a common site within the same year for the RV and Snow crab surveys combined. Sites are defined separately for the RV and Snow crab surveys.

Number of tows	Frequency
1	11,263
2	372
3	15
4	4
8	1
9	1
10	1

Table 3. Results of the probit analysis relating the proportion of large male crabs and the mean mass of crabs in a set, using the RV survey data for 2001-2012. MeanWt is the mean mass of crabs, while MeanWt2 and MeanWt3 are the mean mass squared and cubed, respectively.

Coefficients	Estimate	Std. Error	z value	P-value
(Intercept)	-3.01029	0.05857	-51.397	< 2e-16
MeanWt	13.60908	0.77637	17.529	< 2e-16
MeanWt2	-18.19219	3.03271	-5.999	1.99e-09
MeanWt3	10.91325	3.51737	3.103	0.00192
Null deviance: 11876.4 on 1429 degrees of freedom				
Residual deviance: 1710.4 on 1426 degrees of freedom				
AIC: 4815.2				

Table 4. Summary of the results of GAM analyses of the effect of hour relative to sunrise and sunset (RT) on the catches of commercial male snow crab in the snow crab survey. Analyses were undertaken for three separate blocks of years that are defined by the vessels used in the snow crab survey. ϕ is the estimated value of the over dispersion parameter, n is the sample size, and edf is the estimated degrees of freedom for the spline function estimated by generalized cross validation. The F-statistic and the P-value are for the effect of RT, while the deviance explained is for the whole model.

Years	ϕ	*n*	*edf*	*F*	*P-value*	*Deviance explained*
1990-1998	9.06	1906	1.315	1.45	0.224	33.2%
1999-2002	5.52	1153	4.912	0.69	0.659	21.7%
2003-2012	5.25	2781	1.001	4.05	0.044	35.1%

Table 5. Estimates of 4T snow crab abundance (number per km^2), with 95% confidence intervals. CV are coefficients of variation when vessel and diel calibration parameters were fixed at their estimates and did not contribute to standard errors.*

Year	*Estimate*	*CV*	*Lower*	*Upper*	*CV**
1980	89.512	0.37	43.286	185.115	0.34
1981	100.110	0.42	43.840	228.573	0.40
1982	180.530	0.36	88.773	367.132	0.33
1983	187.300	0.38	88.697	395.508	0.35
1984	83.037	0.29	46.803	147.326	0.26
1985	47.834	0.15	35.352	64.718	0.11
1986	64.854	0.20	44.218	95.114	0.17
1987	64.320	0.17	45.896	90.146	0.14
1988	68.627	0.26	41.259	114.151	0.24
1989	81.100	0.15	59.979	109.661	0.10
1990	216.690	0.14	164.110	286.135	0.09
1991	135.230	0.12	107.791	169.662	0.07
1992	133.880	0.11	107.847	166.215	0.08
1993	168.800	0.12	134.463	211.900	0.09
1994	199.500	0.12	158.942	250.400	0.08
1995	132.790	0.11	106.521	165.547	0.08
1996	53.709	0.14	40.566	71.113	0.12
1997	72.458	0.11	58.823	89.252	0.07
1998	86.989	0.11	70.195	107.804	0.08
1999	56.065	0.11	44.844	70.093	0.07
2000	50.665	0.11	40.545	63.307	0.08
2001	58.096	0.12	45.604	74.010	0.08
2002	74.199	0.12	59.015	93.280	0.08
2003	143.200	0.11	115.695	177.229	0.08
2004	147.450	0.09	122.894	176.916	0.08
2005	133.690	0.09	112.102	159.428	0.08
2006	116.760	0.09	98.049	139.035	0.08
2007	98.127	0.08	83.428	115.425	0.07
2008	83.746	0.08	71.252	98.433	0.07
2009	52.628	0.09	43.926	63.061	0.08
2010	53.255	0.09	44.687	63.467	0.08
2011	101.180	0.09	85.395	119.882	0.07
2012	110.810	0.09	92.931	132.124	0.08

Table 6. Estimates of some snow crab model parameters, with 95% confidence intervals. The negative loglikelihood = 34357.1.

Year	*Estimate*	*CV*	*Lower*	*Upper*
$q_{AN \to T}$	1.012	0.07	0.881	1.163
$q_{LH \to AN}$	1.147	0.07	0.995	1.323
$q_{EP \to LH}$	0.404	0.10	0.333	0.490
$q_{WT \to T}$	0.621	0.22	0.406	0.949
$q_{SCS1 \to T}$	12.771	0.15	9.586	17.014
$q_{SCS2 \to T}$	23.387	0.09	19.562	27.961
$q_{SCS3 \to T}$	30.380	0.11	24.621	37.487
$q_{SCS4 \to T}$	17.404	0.06	15.552	19.477
δ (day/night)	1.267	0.04	1.176	1.367
K	0.617	0.02	0.597	0.637
k_p	10.312	0.07	9.065	11.730

8. FIGURES

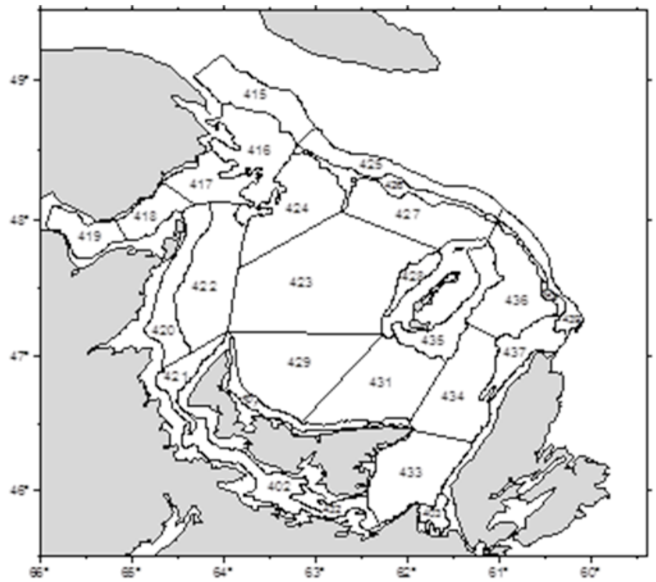


Figure. 1. Stratum boundaries for the southern Gulf of St. Lawrence September RV survey.

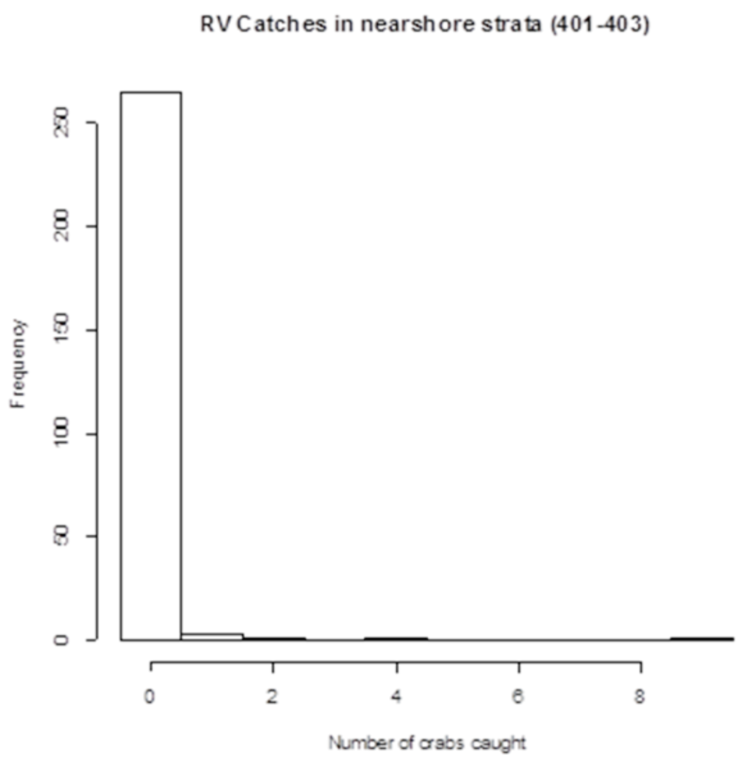
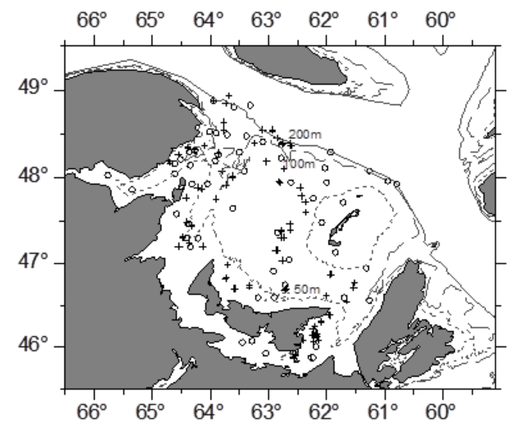
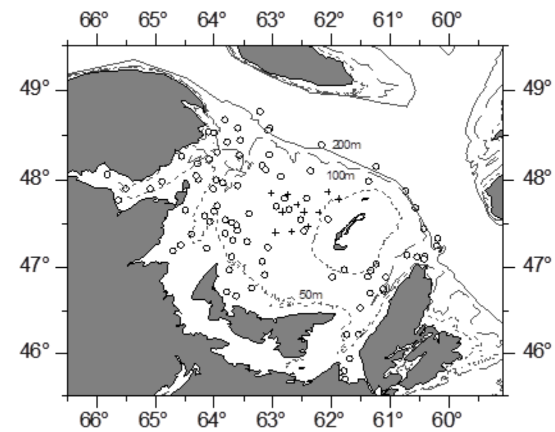


Figure. 2. Histogram of frequency of snow crab catches (by number, all sizes) in strata 401, 402 and 403 for 1984-2012.

A) Vessel comparisons, 1985 & 1992



B) Vessel comparisons, 2004-2005



C) Day/night comparisons, 1988 & 1998-2000

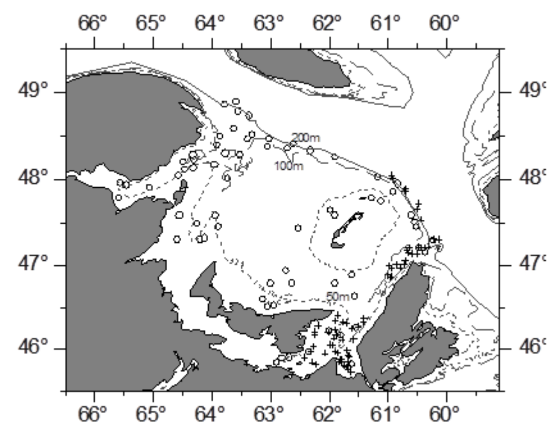


Figure 3. Location of paired fishing sets used to estimate the relative catchability of vessels and relative diel catchability. A) Location of the 1985 (o) and 1992 (+) comparative fishing sites (from Benoît and Swain 2003a). B) Location of fishing sets in the 2004 (+) and 2005 (o) comparative fishing experiments (from Benoît 2006). C) Location of fishing stations for day/night repeat sets, sampled in 1988 by the “Lady Hammond” (o) and sampled by the “Alfred Needler” in 1998-2000 (+) (from Benoît and Swain 2003b).

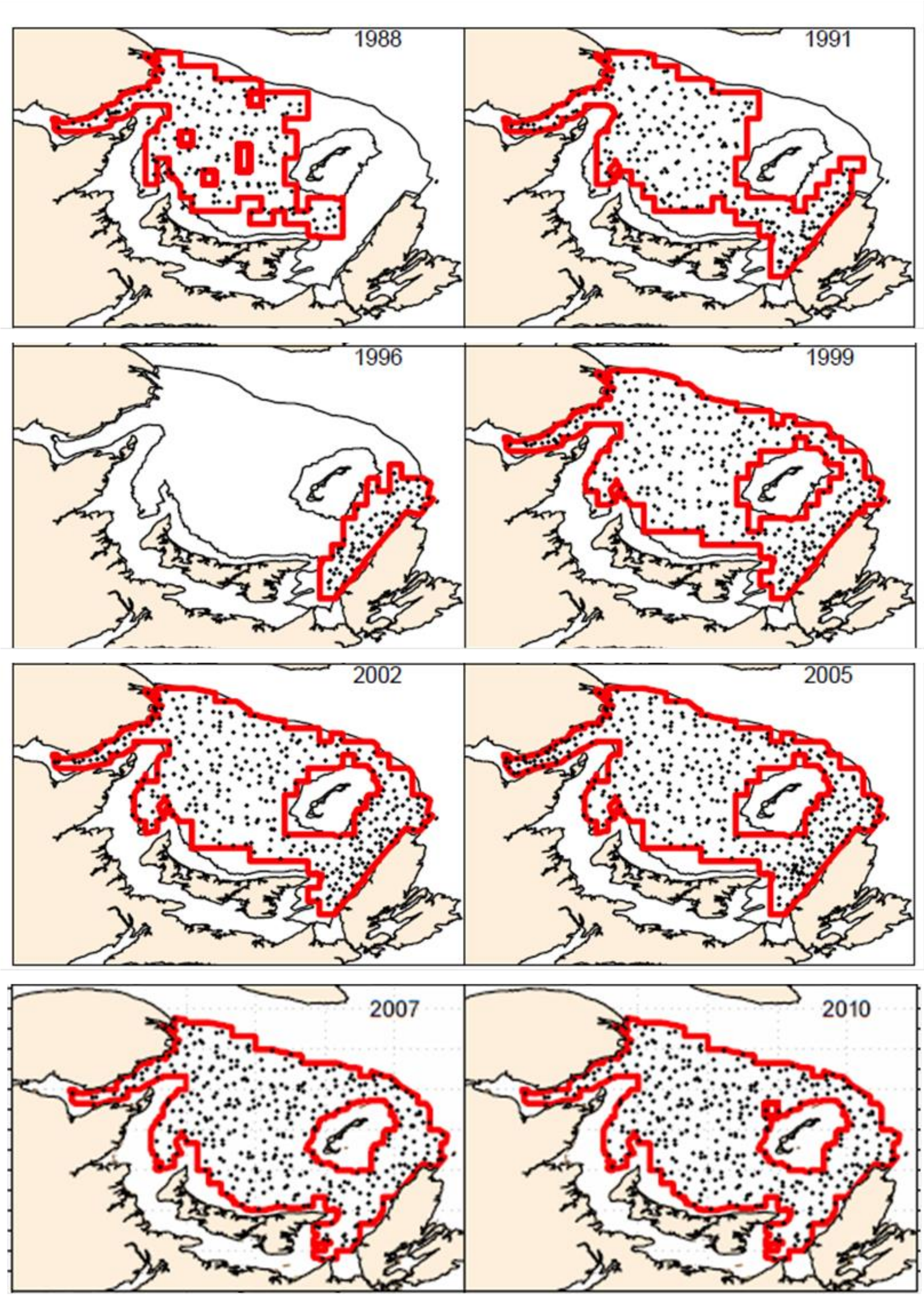


Figure 4. Examples of the differences between years in the areas covered by the snow crab survey (E. Wade[1] DFO unpubl. report). The black dots represent individual survey sets, while the red polygon roughly defines the survey area for each year. Note that survey area was relatively constant for the years 1997-2005 and 2006-present.

[1] Fisheries and Oceans Canada, Gulf Fisheries Centre, 343 Université Avenue, Moncton NB E1C 9B6.

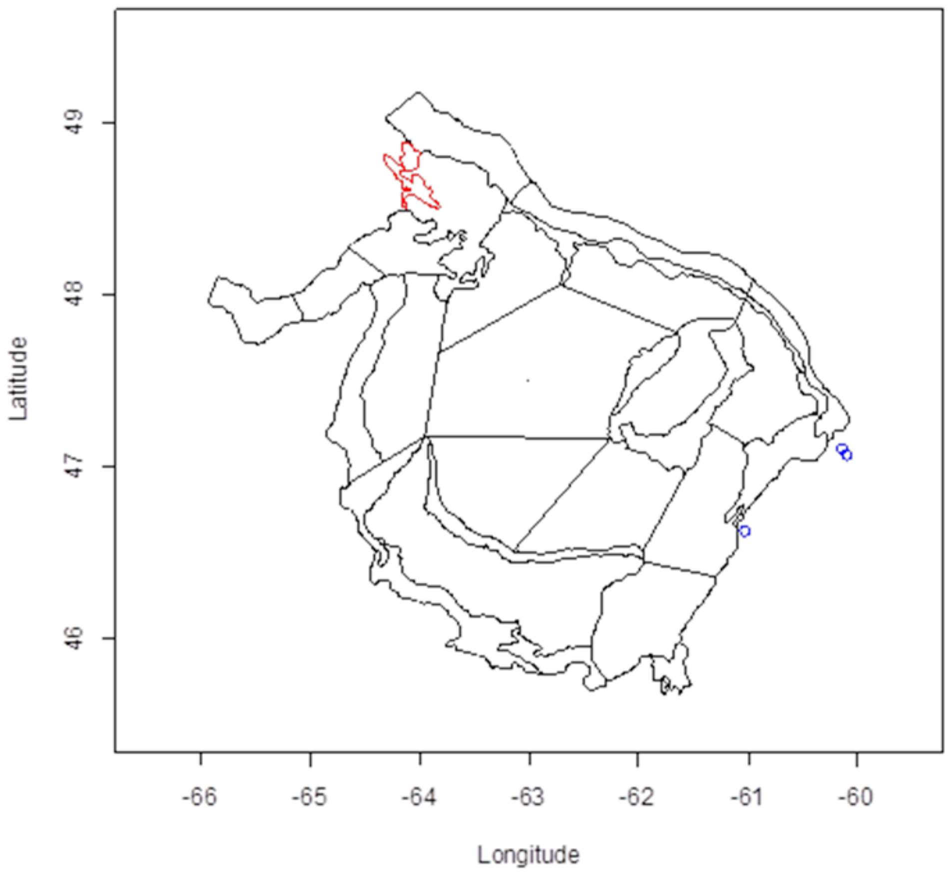


Figure 5. Location of the stratum boundaries for the regular RV survey (black lines) and boundaries for the area of the snow crab survey sampling frame that was added to stratum 417 for the analyses (red lines). Also shown are the locations of the three snow crab survey sets (blue circles) in the eastern portion of the area that were excluded from the analysis because they fell outside the defined estimation domain.

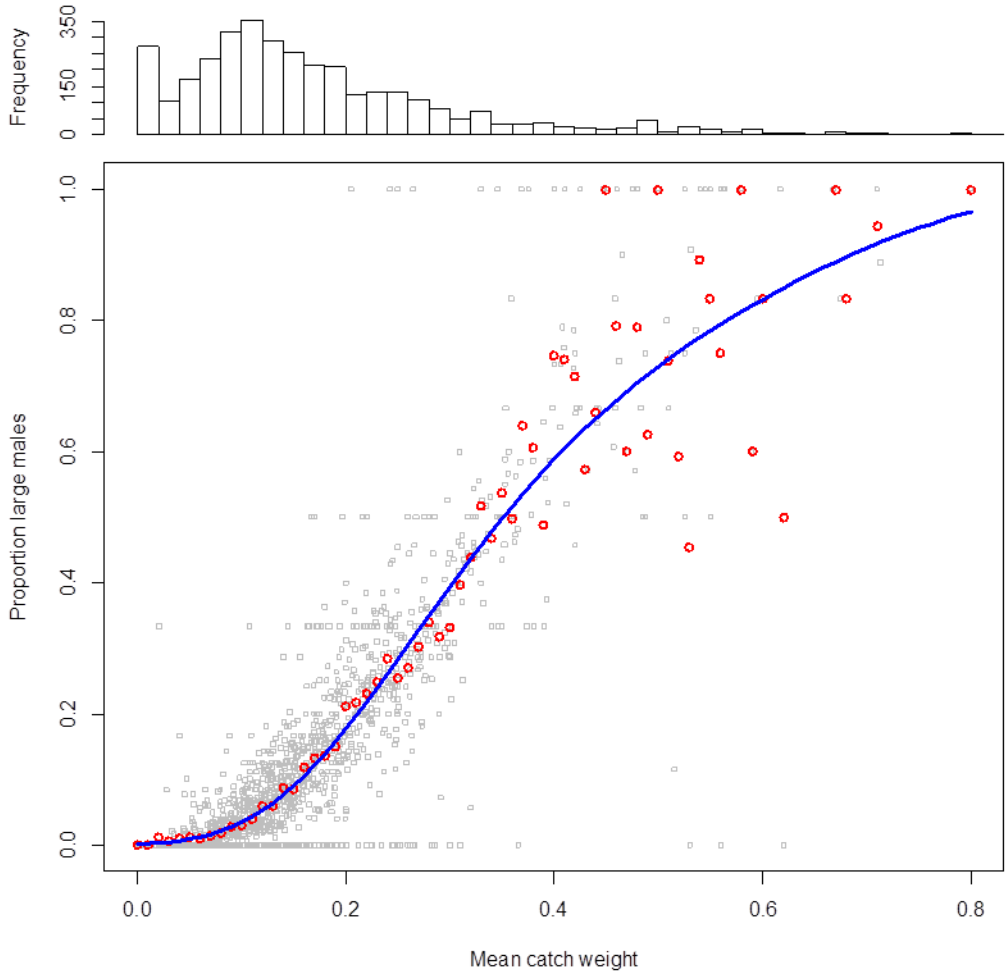


Figure 6. Main panel: proportion, by numbers, of the catch in a RV survey set that is comprised of large males (≥ 95 mm carapace width), as a function of the mean mass of individuals in the set. Grey squares represent values for individual RV survey sets (2001-2012), red circles represent the average proportion summarized in mean mass bins of 0.01 kg, and the blue line is the fit of the best model. Top panel: frequency histogram distribution of the mean mass of individual set catches for RV survey sets from 1980 to 2000 for which inferences are required.

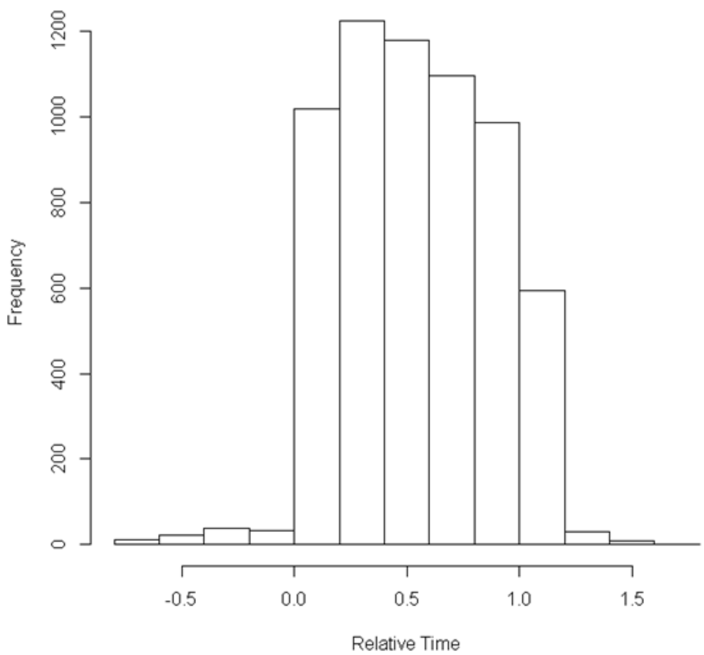


Figure 7. Frequency histogram by bins of relative time (RT) for tows in the snow crab survey from 1990-2012.

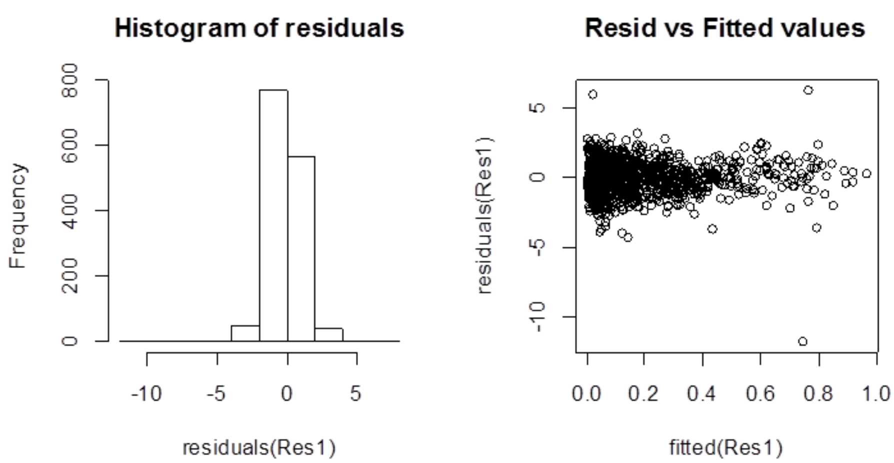


Figure 8. Summary of patterns in the standardized residuals from the probit model for the proportion of large males in a set.

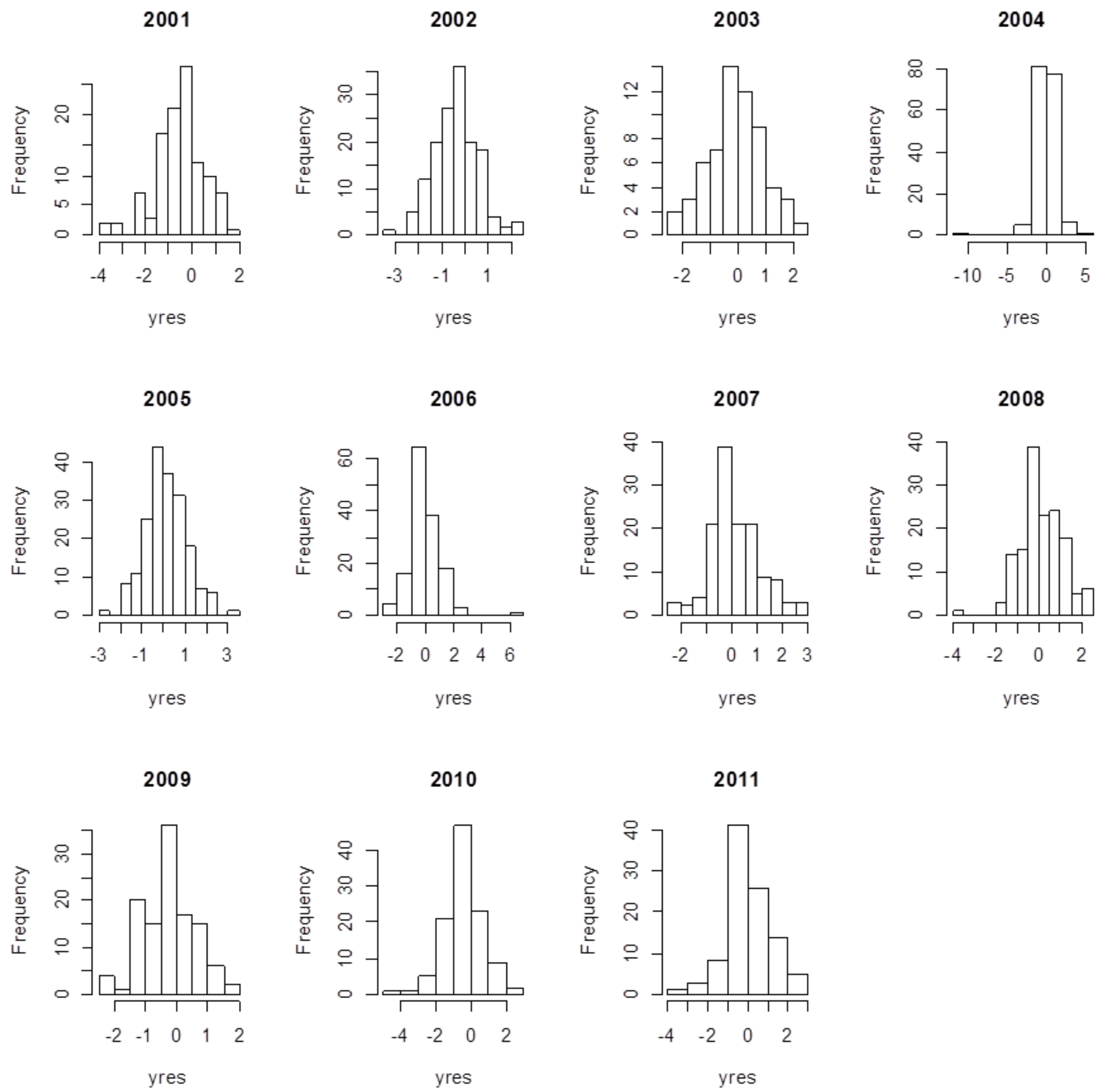


Figure 9. Annual histograms of standardized residuals from the probit analysis of the proportion of large male crabs as a function of mean crab mass in an RV survey set.

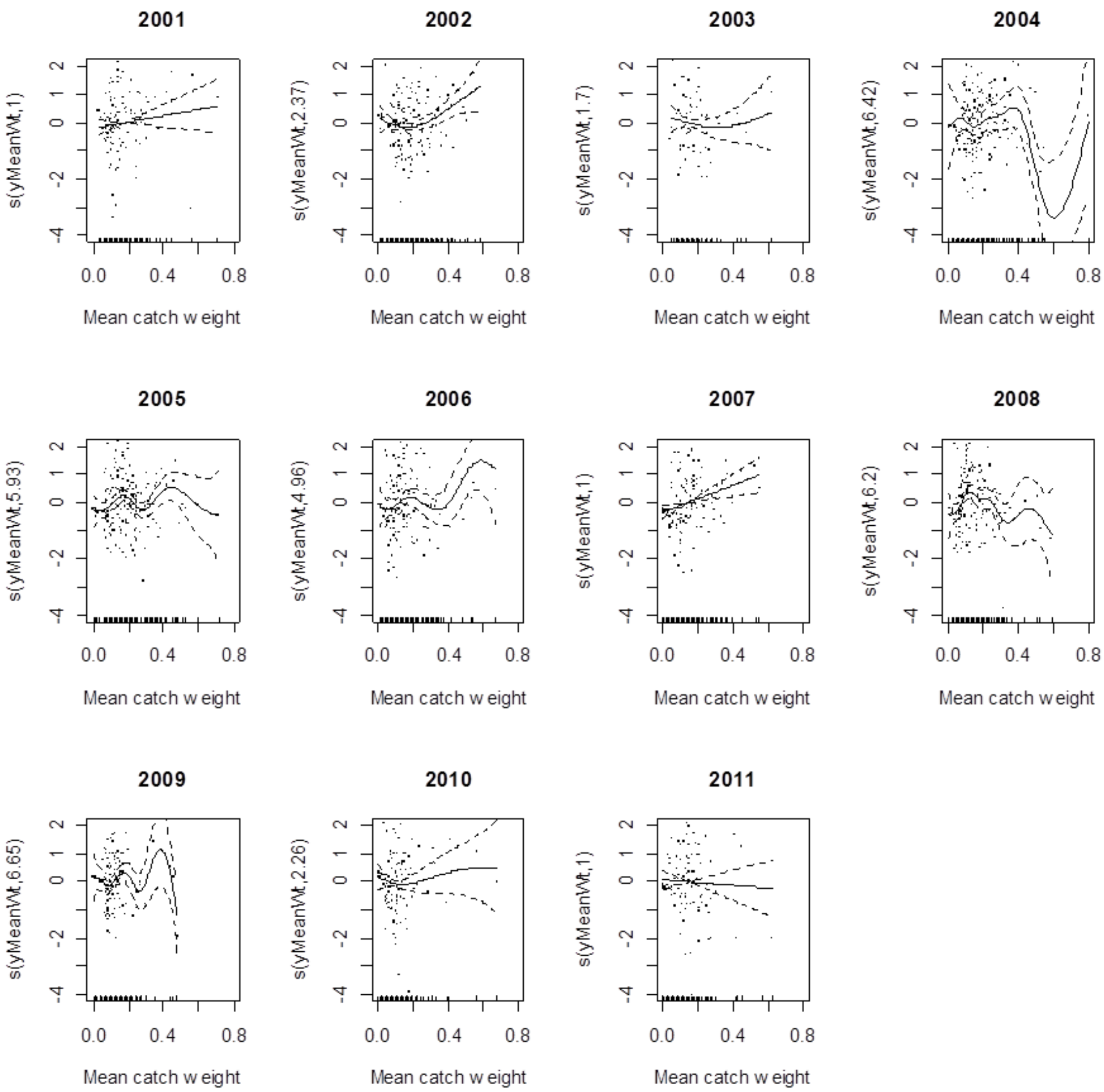


Figure 10. Results of individual GAM fits to probit model standardized residuals for individual years. In each panel, individual residuals are shown as dots, while the model fit and associated 95% confidence intervals are shown using solid and dashed lines respectively. The optimal degrees of freedom used for the smoothing was estimated using generalized cross validation (Wood 2006), and is indicated in the y-axis label for each plot.

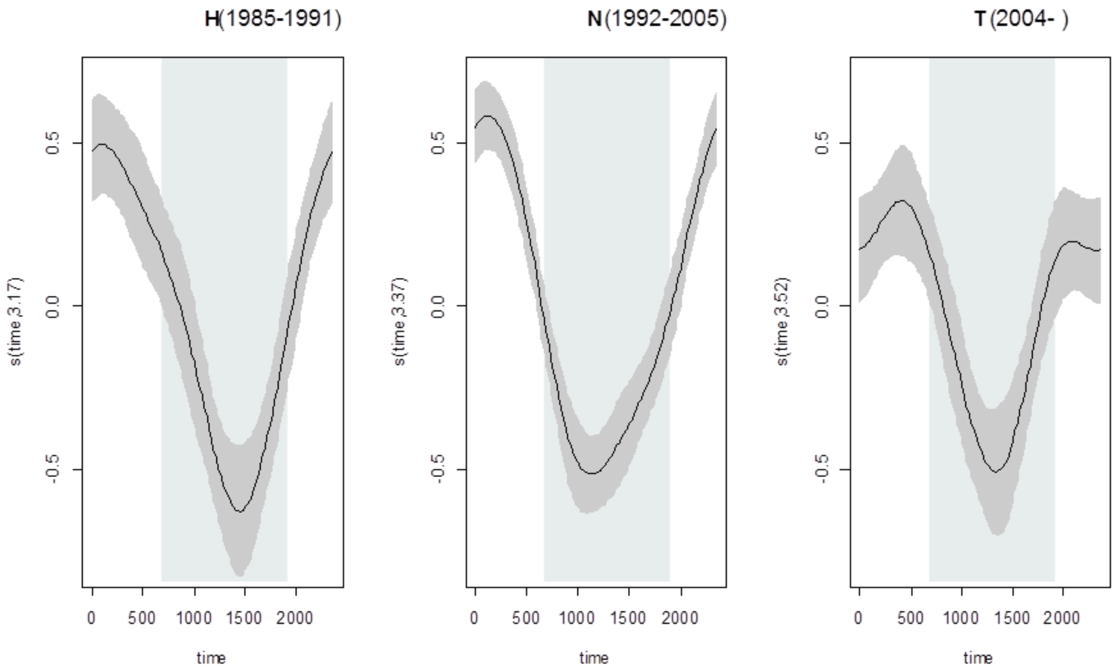


Figure 11. Cyclic cubic regression spline function predictions (with 95% confidence band in grey) of the effect of the time of day on catches of large male snow crab in analyses conducted separately by vessel (H- Lady Hammond, N- Alfred Needler, T-Teleost). The optimal degrees of freedom used for the smoothing estimated using generalized cross validation are indicated in the y-axis label for each plot The blue shaded area in each panel covers the hours considered as daytime.

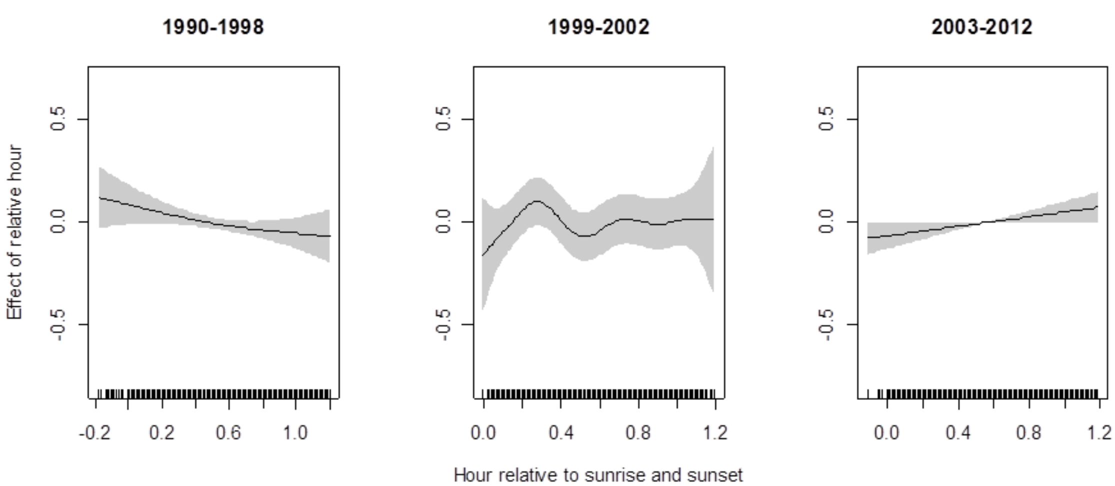


Figure 12. Predictions (with 95% confidence band in grey) from the GAM analyses of the effect of hour relative to sunrise and sunset (RT) on the catches of commercial male snow crab in the snow crab survey. Results are presented for three blocks of years that are defined by the vessels used in the snow crab survey.

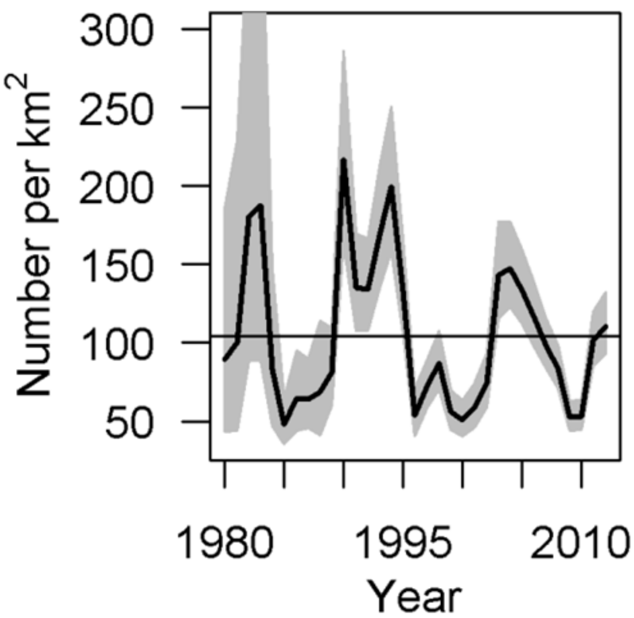


Figure 13. Estimates of 4T snow crab abundance (number per km²) for 1980 to 2012. The shaded region indicates 95% confidence intervals. The horizontal line indicates the series average over the years.

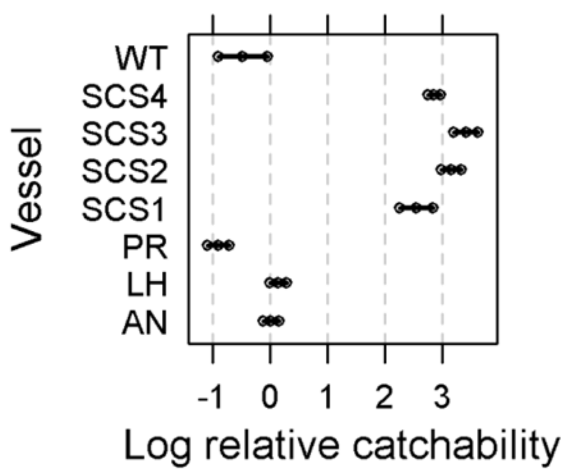


Figure 14. Estimates (middle points) of survey vessel/gear catchabilities, expressed as log(q), with 95% confidence intervals. WT is CCGS Wilfred Templeman → CCGS Teleost, PR is EE Prince → Lady Hammond, LH is Lady Hammond → CCGS Alfred Needler, and AN is CCGS Alfred Needler → CCGS Teleost. The entries SCS are for the catchability of the snow crab survey vessel/gear, relative to the Teleost: SCS1 – Snow crab survey gear for 1988-1990, SCS2 – vessel for 1991-1998, SCS3 – vessel for 1999-2002, and SCS4 – vessel for 2003-2012.

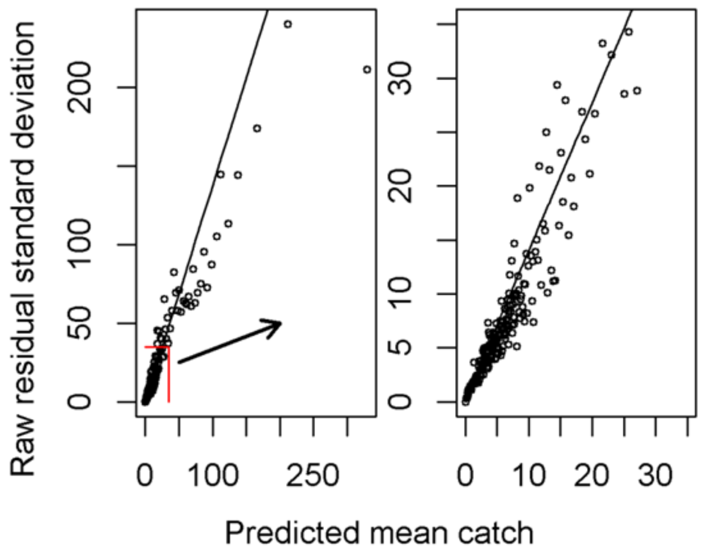


*Figure 15. Standard deviations (sd's) of the binned raw residuals. The solid line is the NB prediction of the raw residuals (predicted * (1 + predicted/k) / 2).*

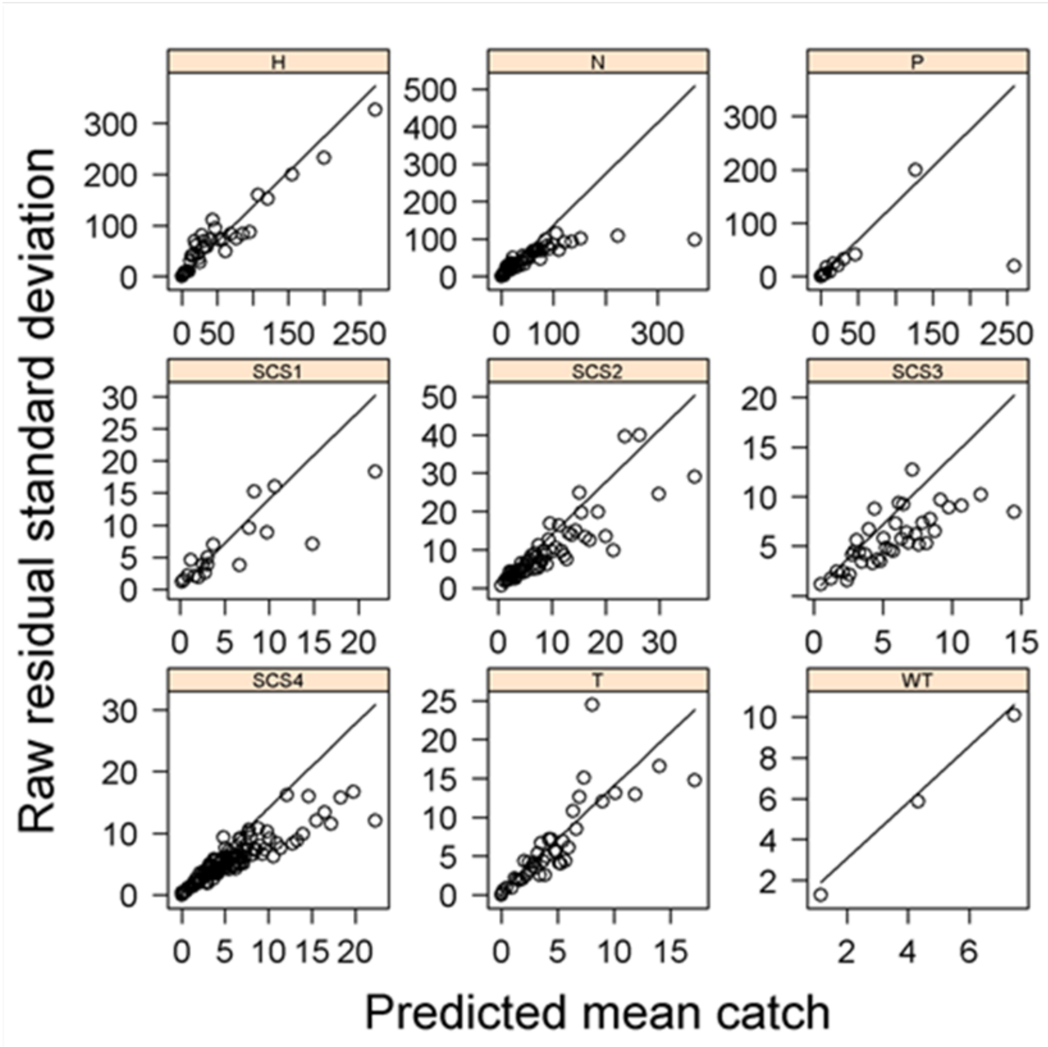


*Figure 16. Standard deviations (sd's) of the binned raw residuals for survey vessel/gears. The solid line is the NB prediction of the raw residual sd (predicted * (1 + predicted/k) /2). WT - CCGS Wilfred Templeman, T - CCGS Teleost, P - EE Prince, H – Lady Hammond, N – CCGS Alfred Needler. SCS1 – Snow crab survey gear for 1988-1990, SCS2 – vessel for 1991-1998, SCS3 – vessel for 1999-2002, and SCS4 – vessel for 2003-2012.*

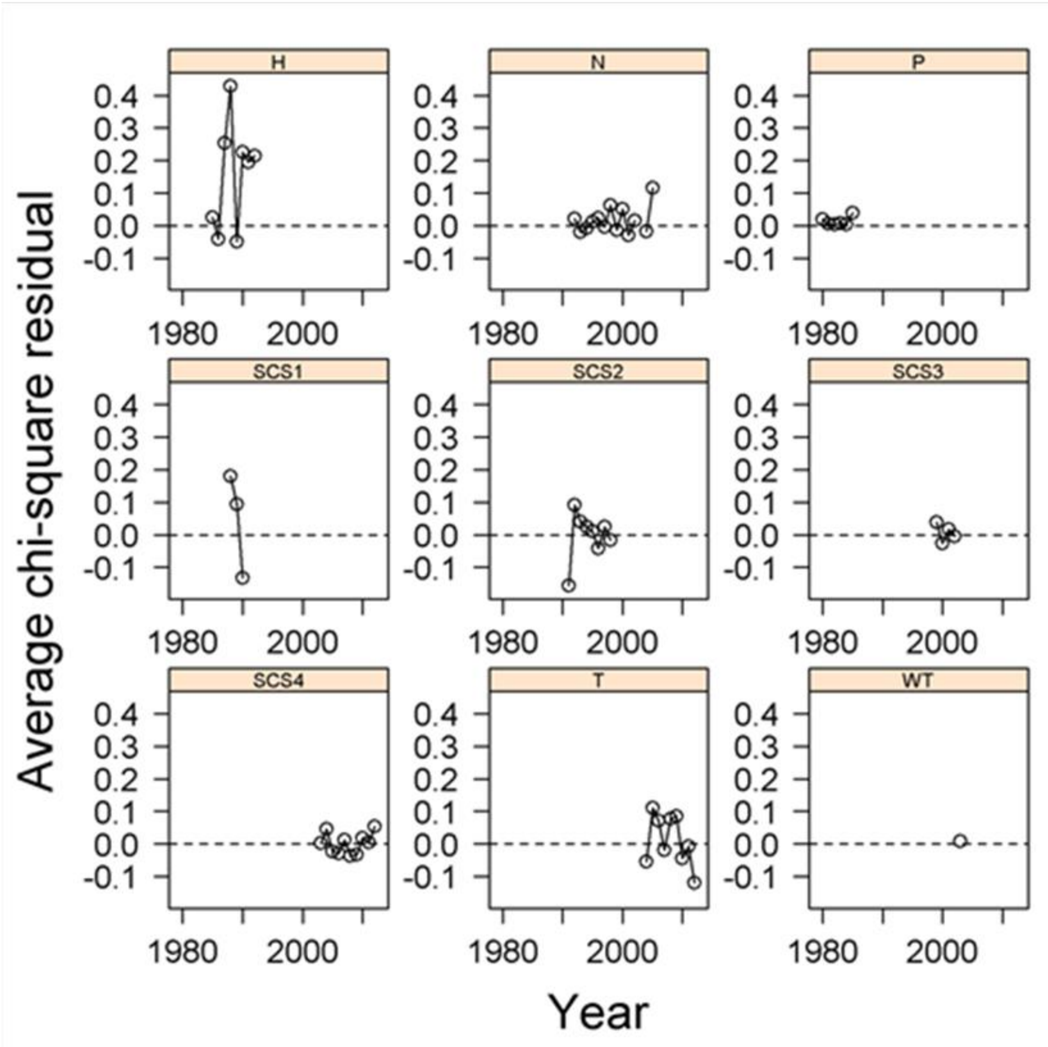


Figure 17. Average residuals for survey vessel/gears. A dashed reference line at 0 is shown. WT - CCGS Wilfred Templeman, T - CCGS Teleost, P - EE Prince, H – Lady Hammond, N – CCGS Alfred Needler. SCS1 – Snow crab survey gear for 1988-1990, SCS2 – vessel for 1991-1998, SCS3 – vessel for 1999-2002, and SCS4 – vessel for 2003-2012.

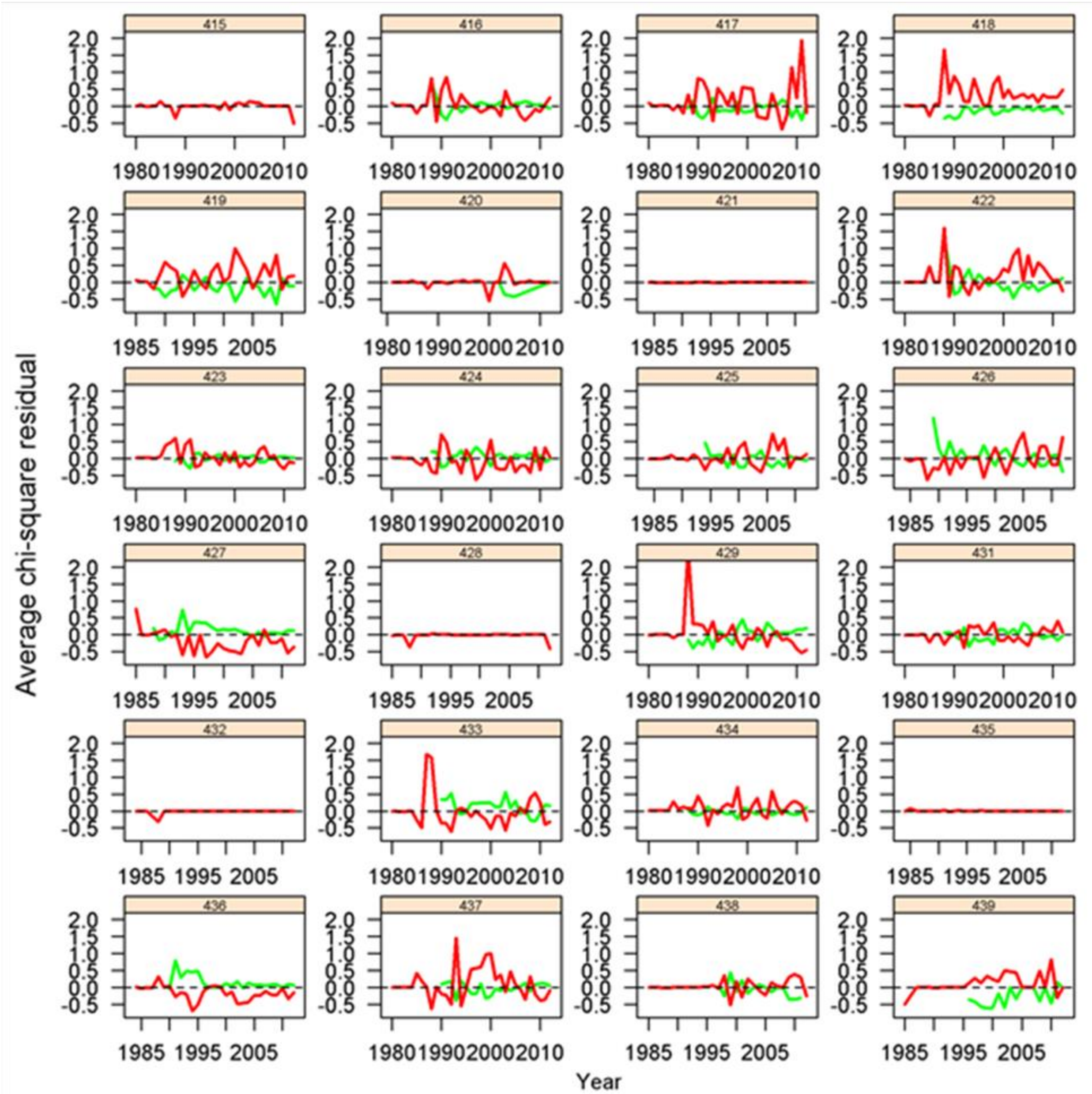


Figure 18. Annual stratum-average chi-square residuals for the RV survey (red) and the snow crab survey (green). A dashed reference line at 0 is show. Stratum number is listed at the top of each panel. Only averages based on more than two observations are shown.

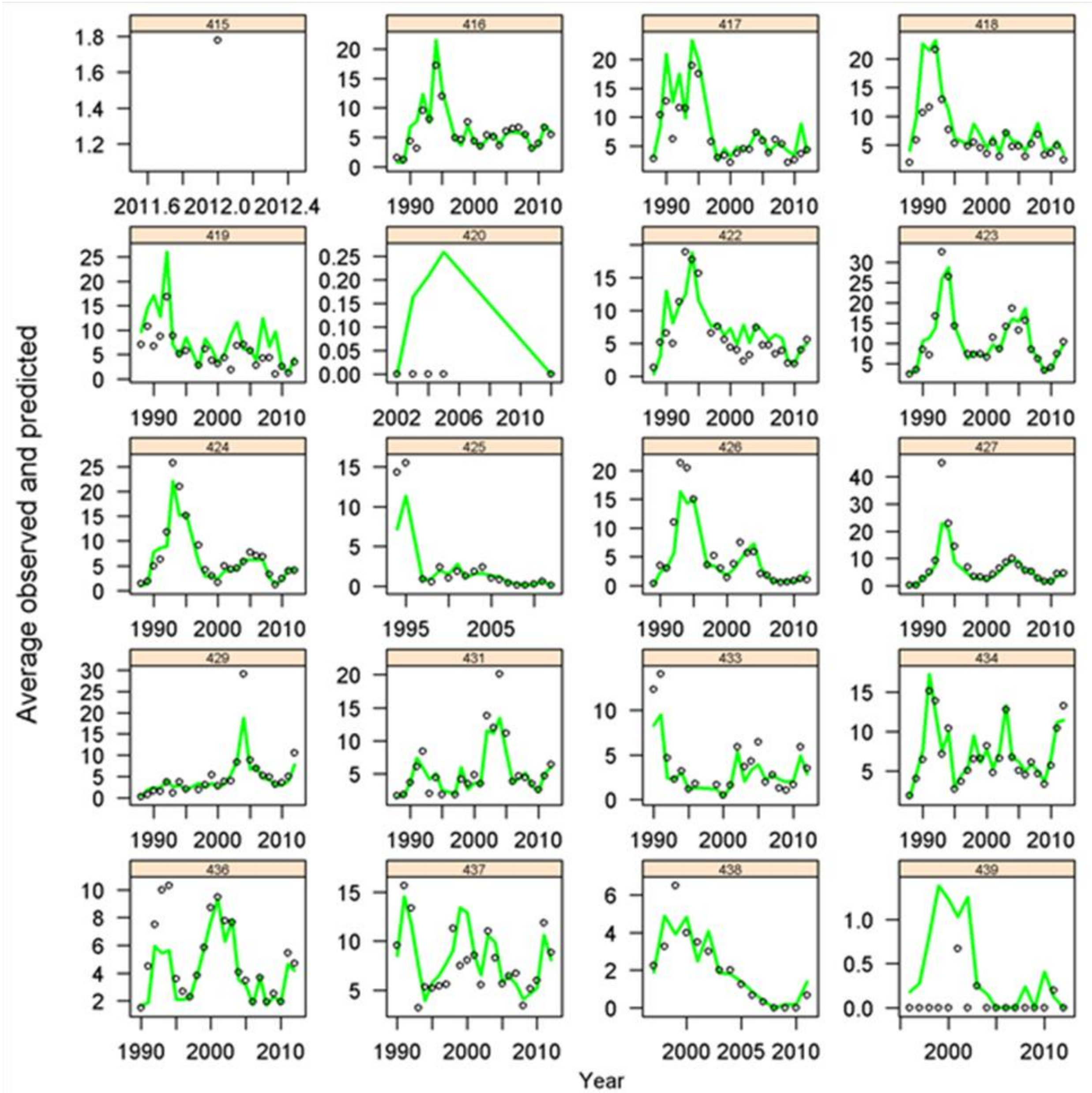


Figure 19. Annual stratum-average observed (points) versus predicted (lines) snow crab survey catches. Stratum number is listed at the top of each panel. Only averages based on more than two observations are shown.

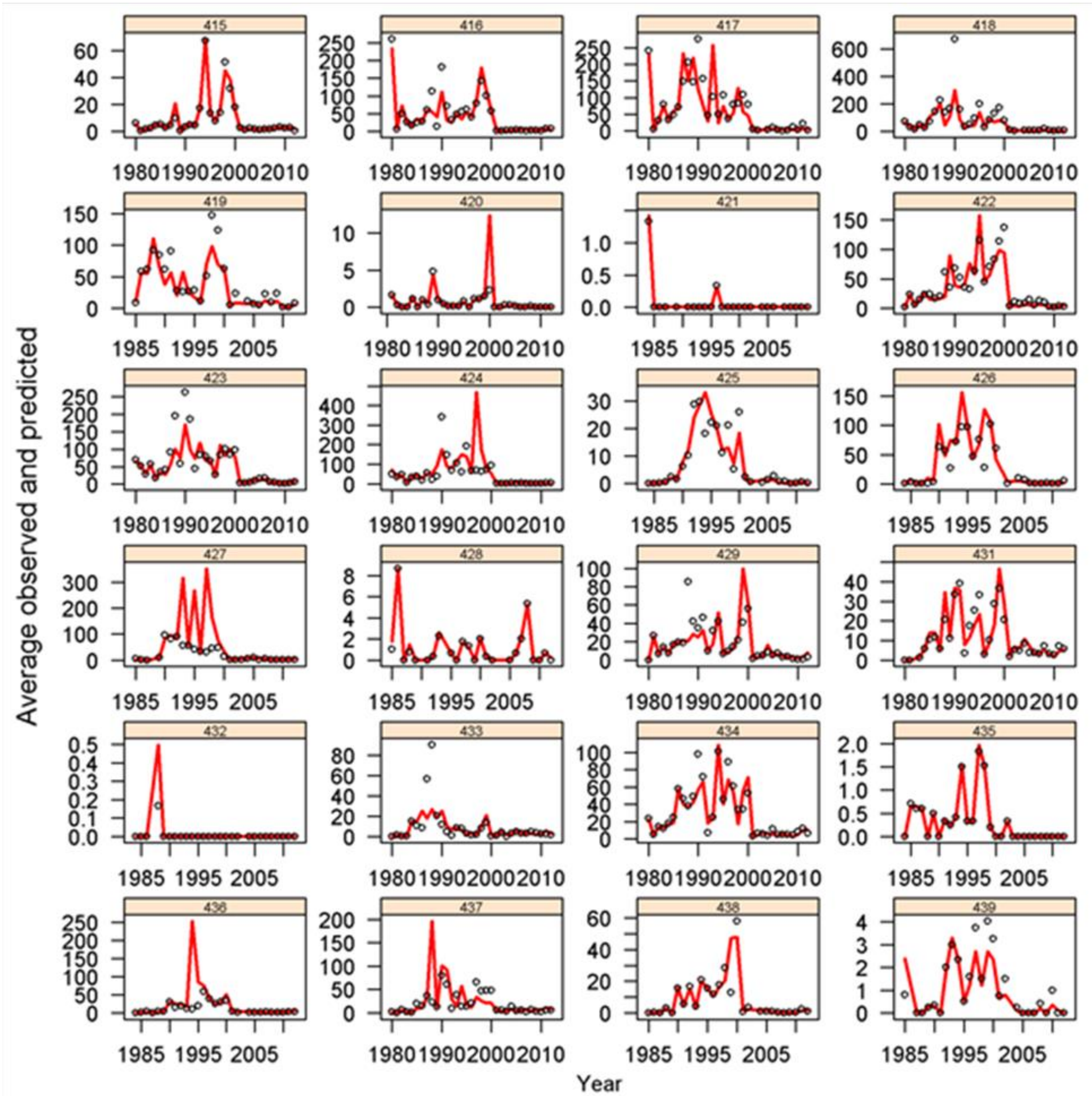


Figure 20. Annual stratum-average observed (points) versus predicted (lines) RV survey catches. Stratum number is listed at the top of each panel. Only averages based on more than two observations are shown. Note that both the observed and predicted values do not reflect adjustments for the estimated proportion of large males during the period 1980-2000.

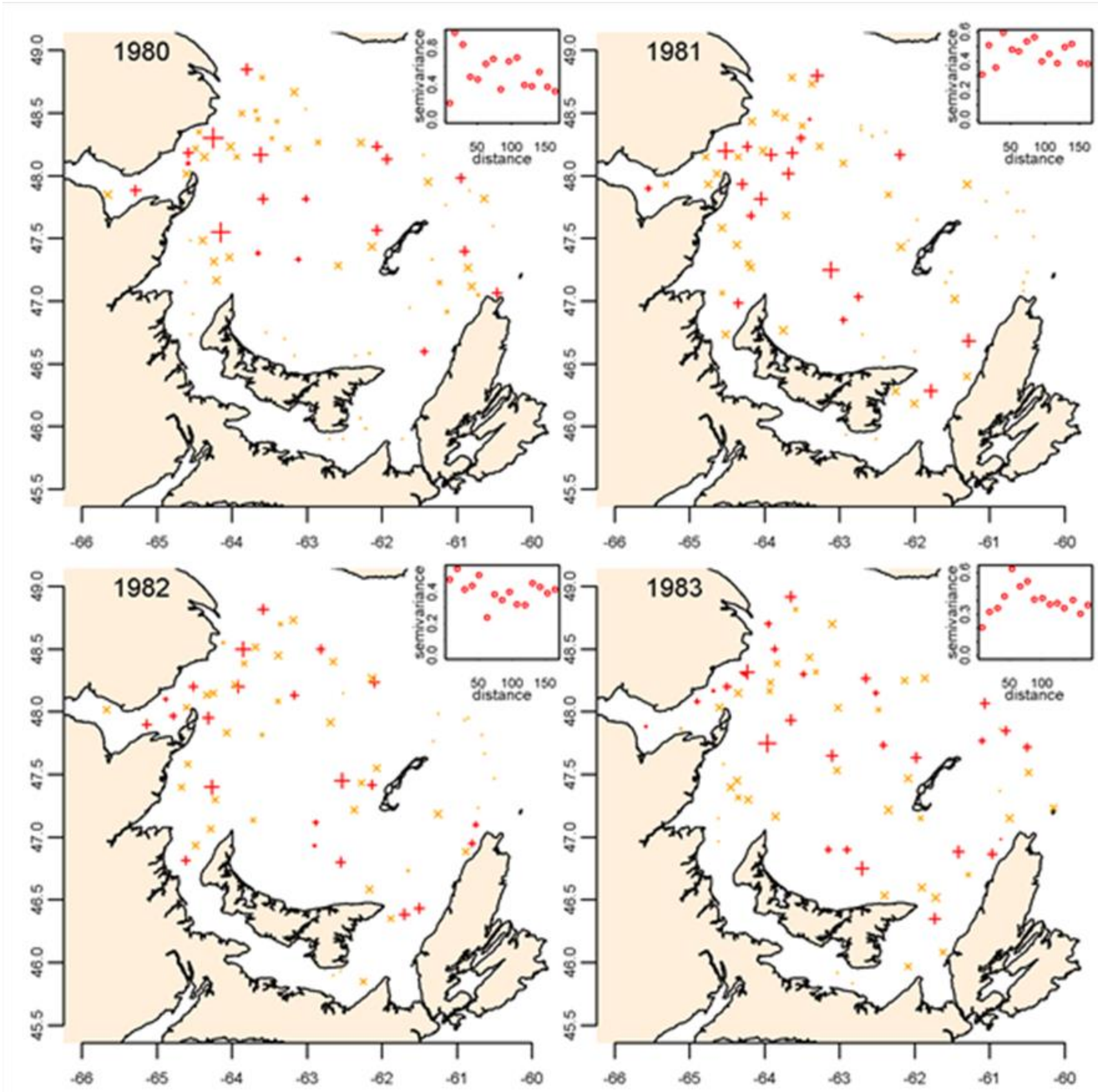


Figure 21. Annual (1980 to 2012) maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 1980 to 1983 are shown.

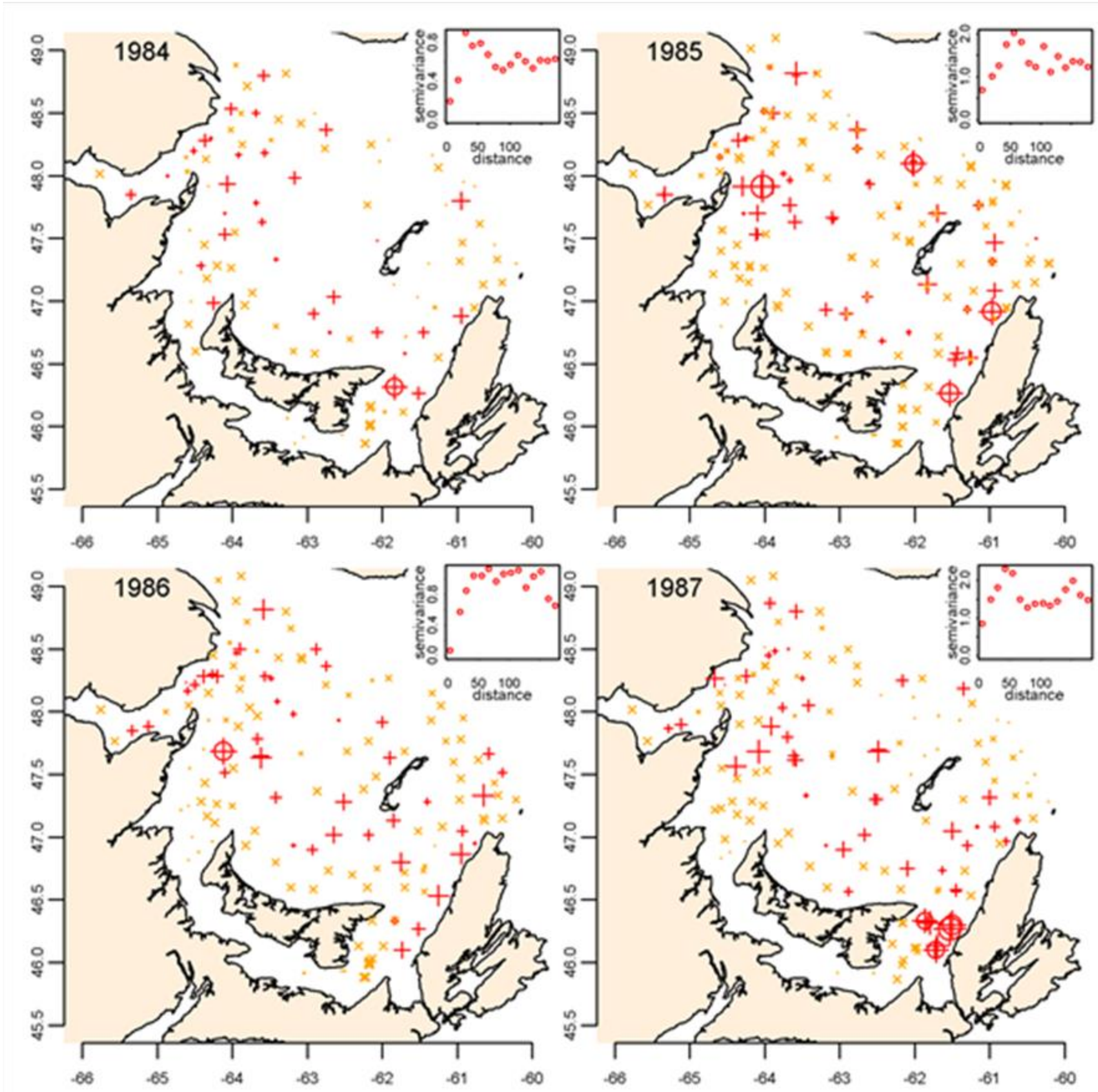


Figure 21 (continued). Annual maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 1984 to 1987 are shown.

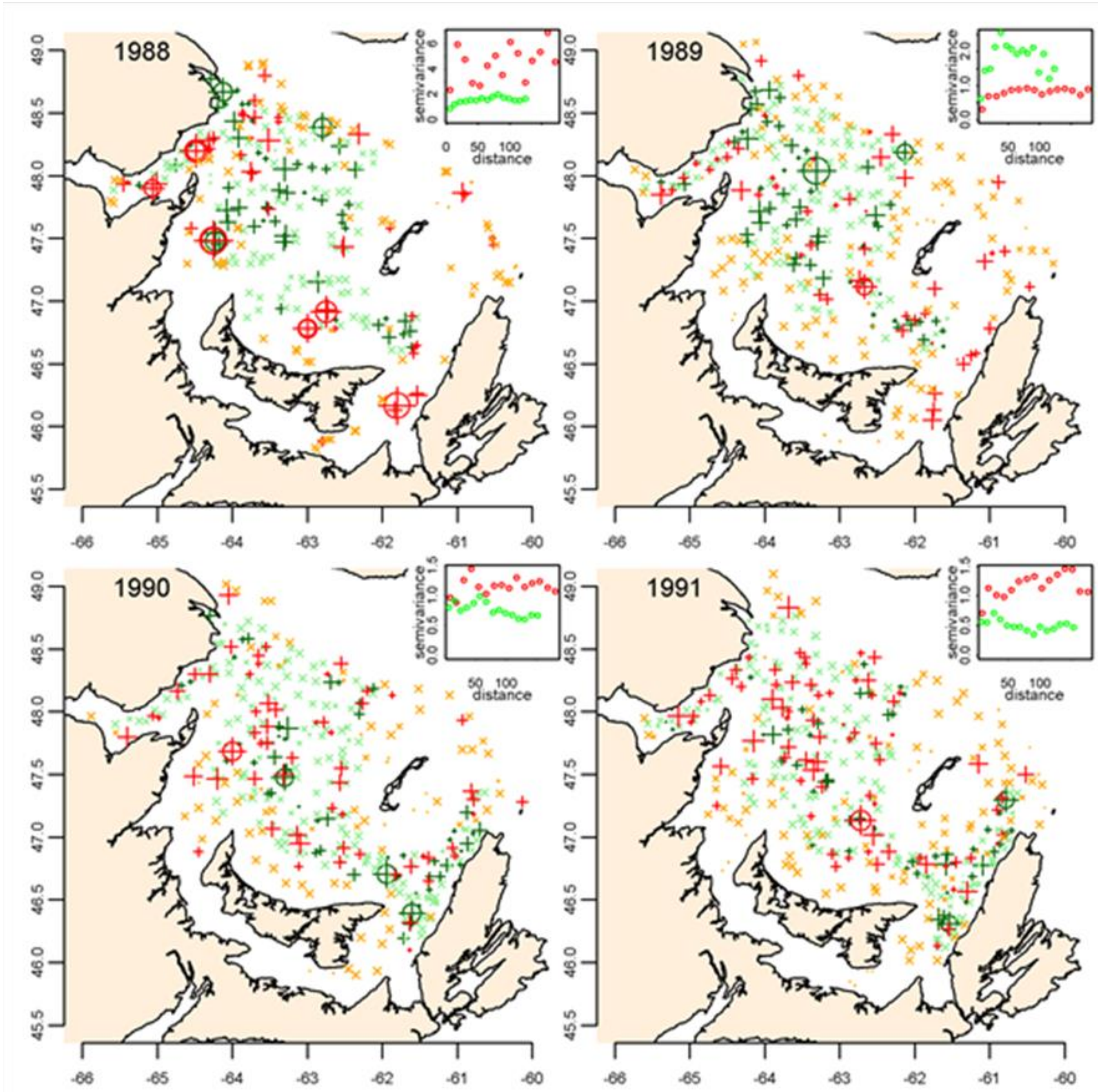


Figure 21 (continued). Annual maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 1988 to 1991 are shown.

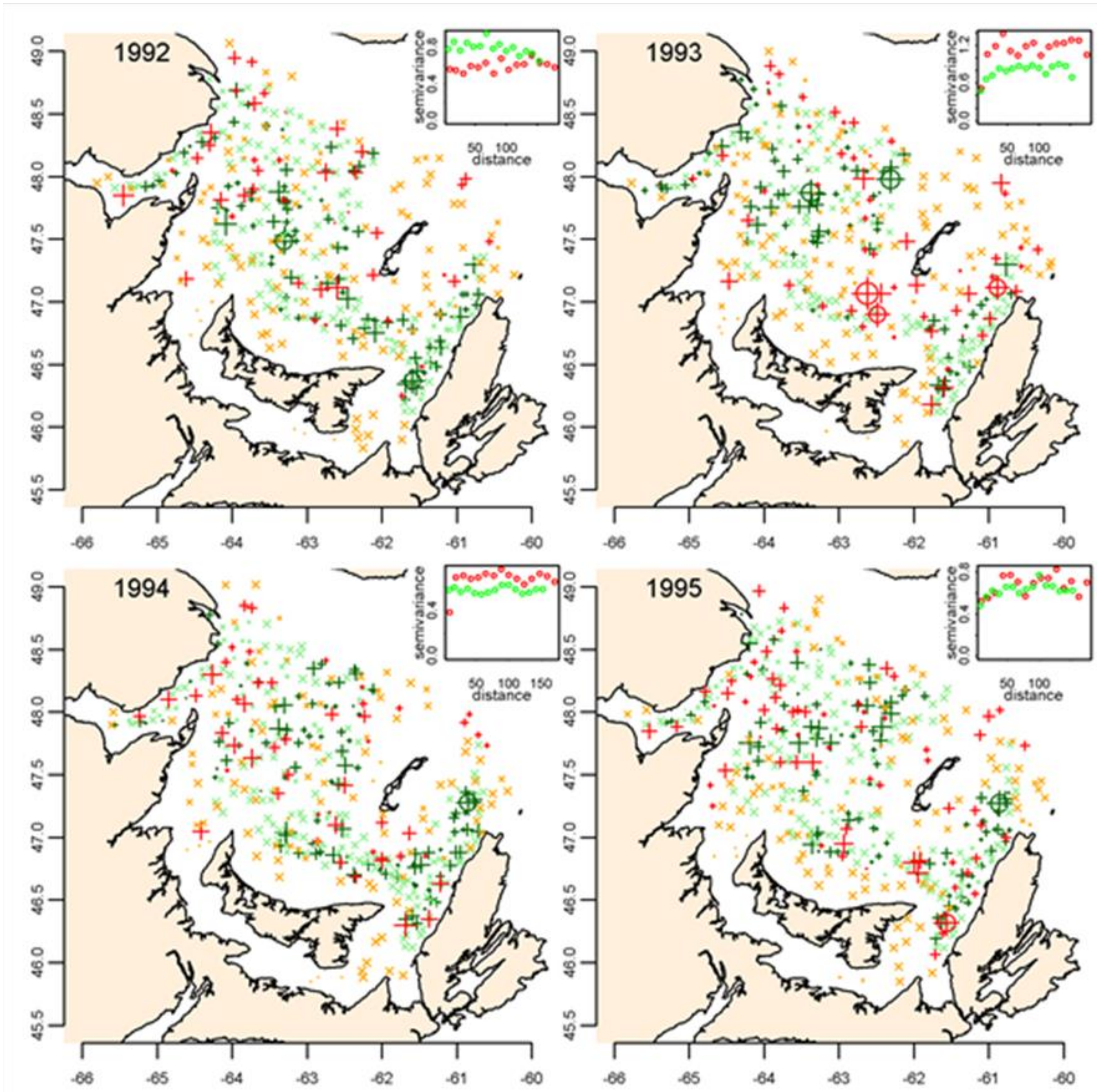


Figure 21 (continued). Annual maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 1992 to 1995 are shown.

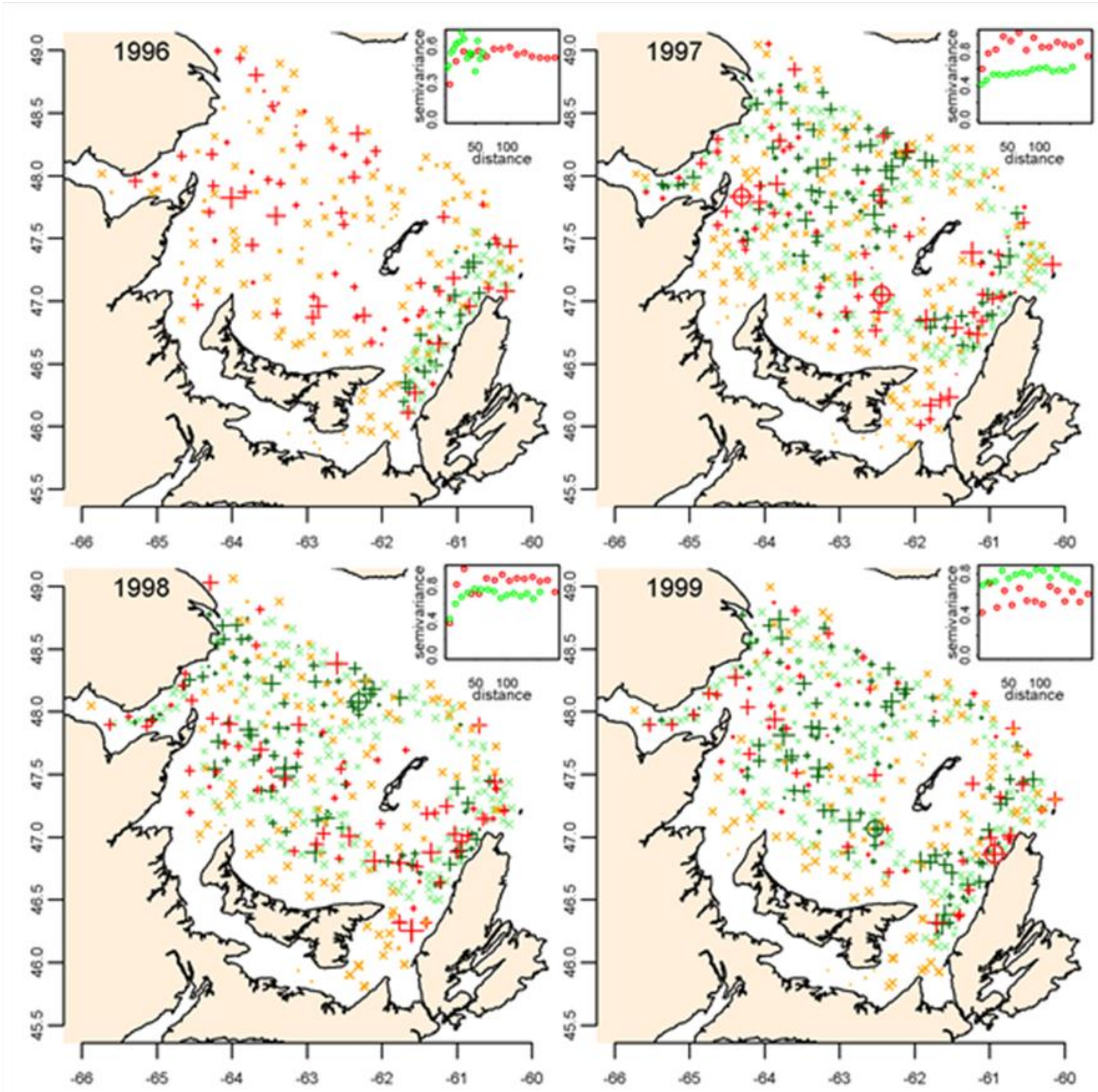


Figure 21 (continued). Annual maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 1996 to 1999 are shown.

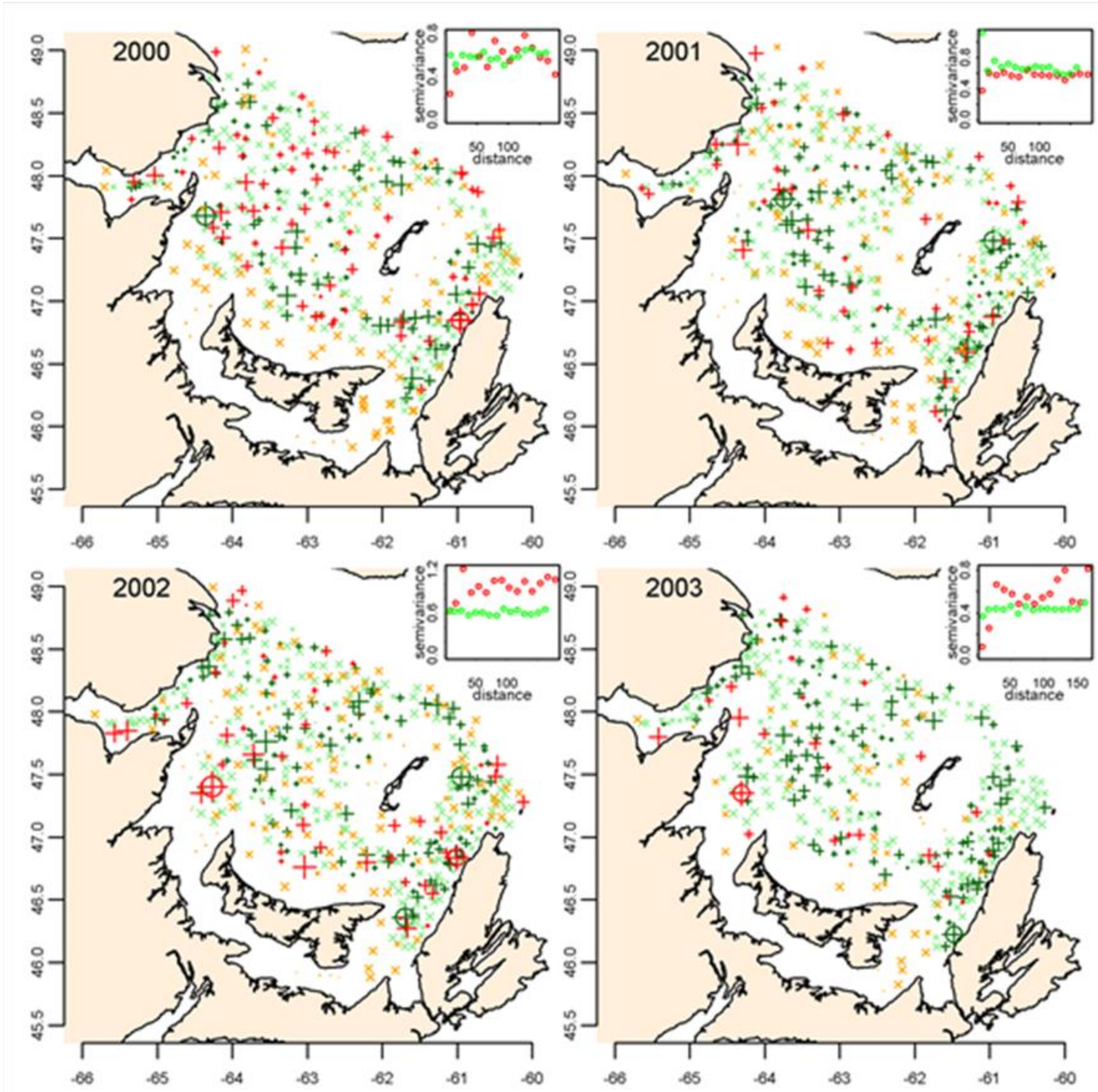


Figure 21 (continued). Annual maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 2000 to 2003 are shown.

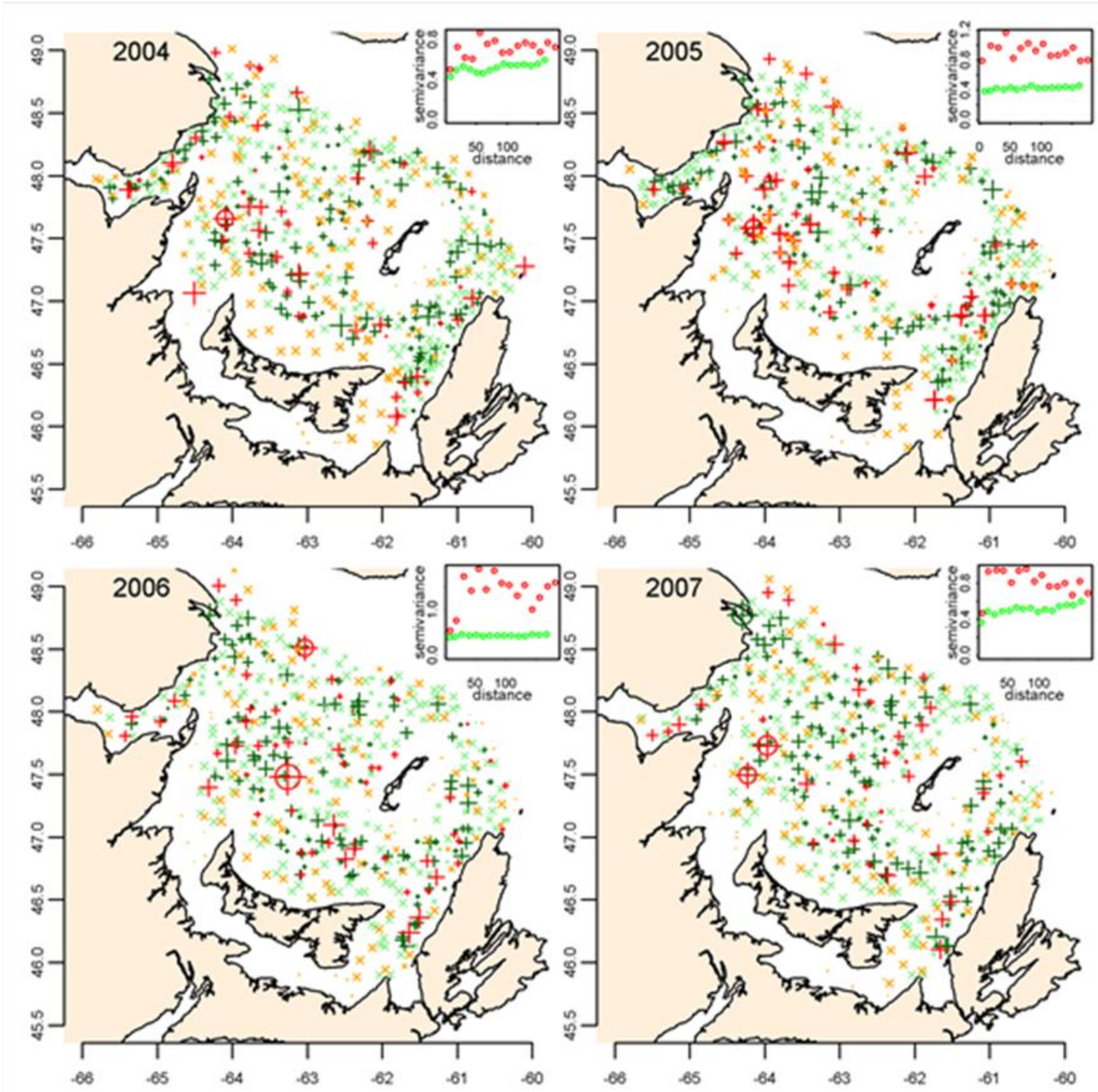


Figure 21 (continued). Annual maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 2004 to 2007 are shown.

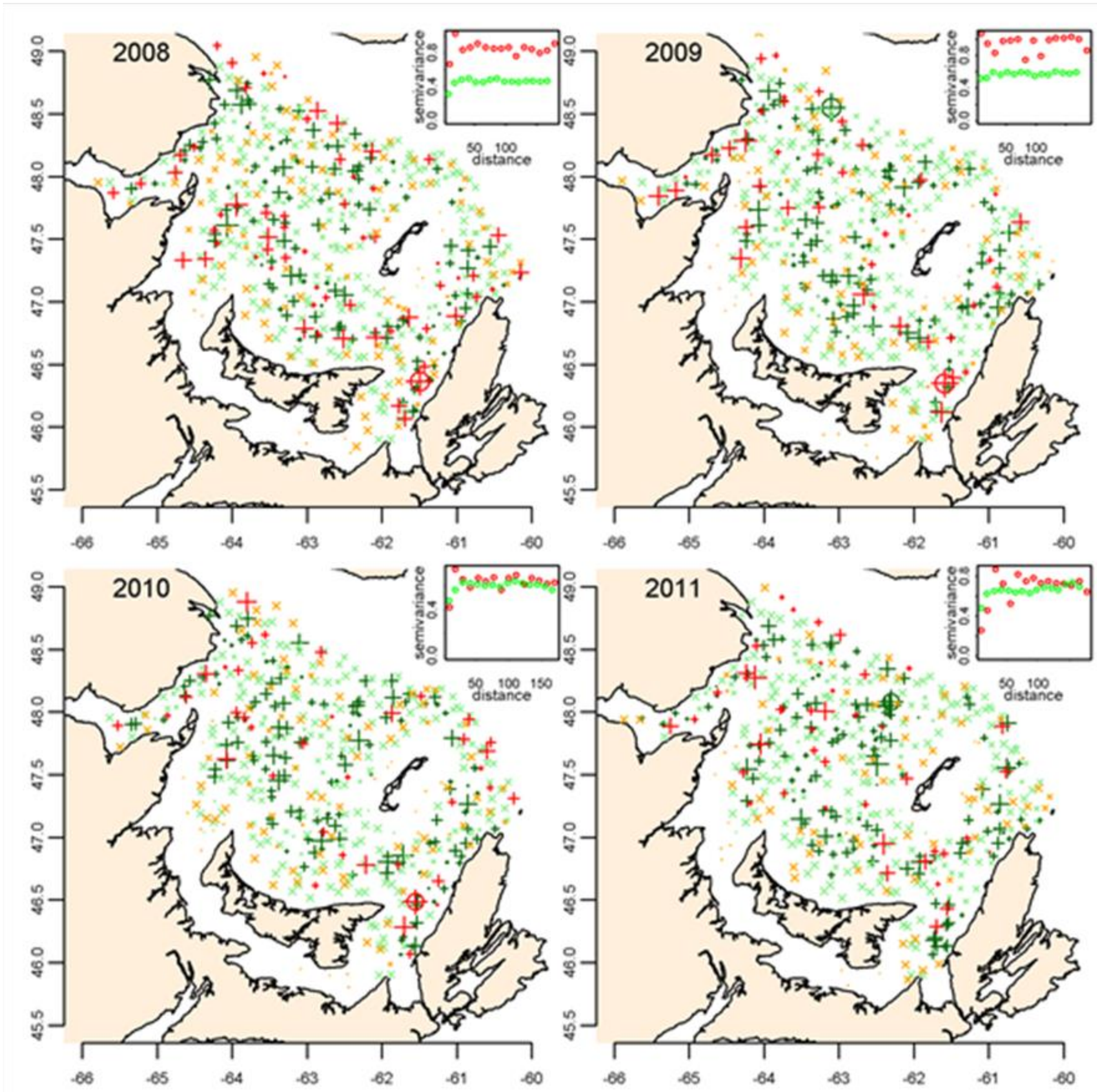


Figure 21 (continued). Annual maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 2008 to 2011 are shown.

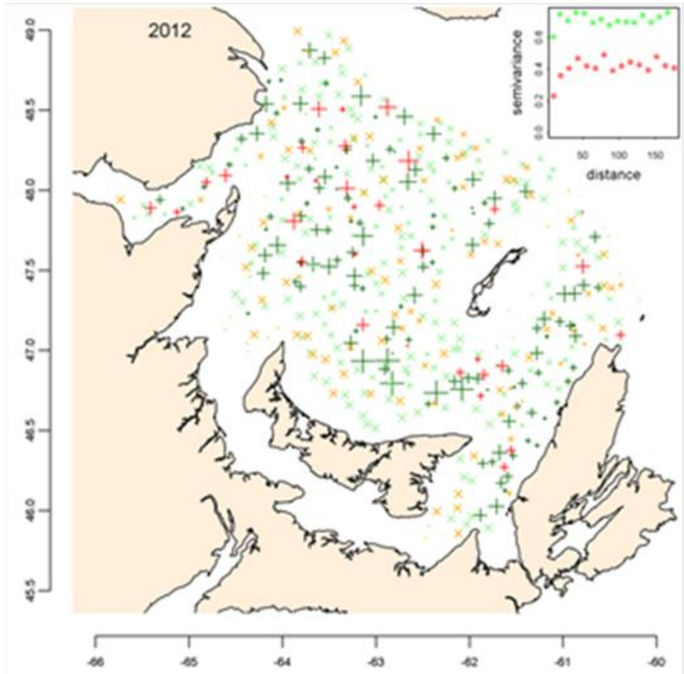


Figure 21 (continued). Annual maps of model residuals: snow crab survey positive (+) and negative residuals (x), and RV survey positive (+) and negative residuals (x), with circles indicating residual absolute values >4. The inset in each map is the annual survey-specific empirical variogram for the model residuals (RV survey in red, snow crab survey in green). In this figure, 2012 is shown.

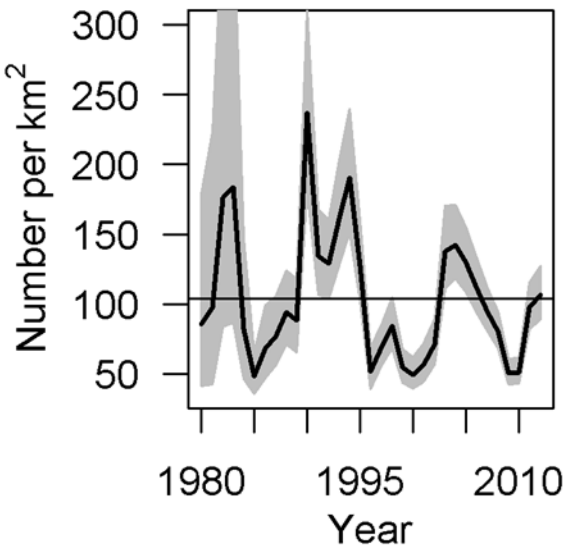
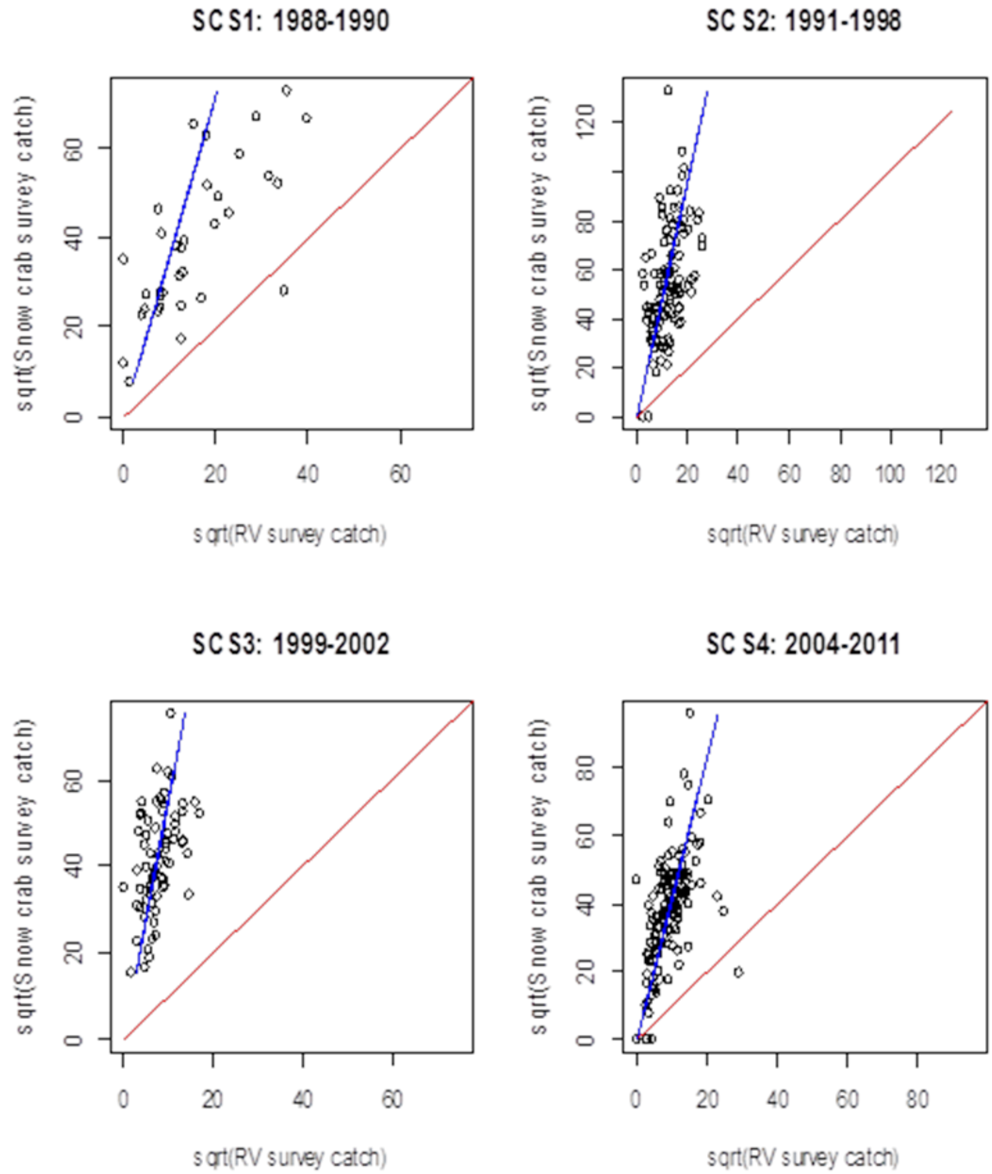
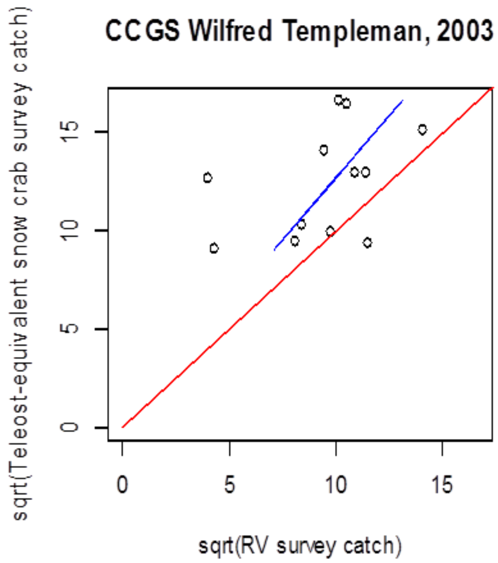


Figure 22. Estimates of 4T snow crab abundance (number per km²), based on a model in which day/night is used in the definition of a site in addition to using stratum, year and location. The shaded region indicates 95% confidence intervals. The horizontal line indicates the series average.

APPENDIX A



Appendix A Figure 1. Biplots of stratum-year mean standardized catches in the RV survey (x-axis) and in the crab survey (y-axis) for the four time periods of the snow crab survey for which relative catchability coefficients were estimated (note the square root transformation). 1:1 lines are shown in red, while the respective model estimate of relative catchability are indicated in blue.



Appendix A Figure 2. Biplot of the stratum-year mean standardized catches in 2003 by the Wilfred Templeman in the RV survey (x-axis) and in the crab survey for catches adjusted to Teleost equivalents using $q_{scsa\rightarrow T}$ (y-axis) (note the square root transformation). The 1:1 line is shown in red while the model estimate of the catchability of the CCGS Wilfred Templeman relative to the CCGS Teleost, $q_{WT\rightarrow T}$, is indicated in blue.