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Research Article

Reducing uncertainty and bias in acoustic biomass estimations of southern blue whiting (*Micromesistius australis*) in the southeastern Pacific: transducer motion effects upon acoustic attenuation

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ABSTRACT. We evaluated the loss of sensitivity due to the motion experienced by a hull-mounted transducer and its effects upon the estimated biomass of southern blue whiting (*Micromesistius australis*) in an acoustic survey conducted in the southeastern Pacific, off the Chilean coast, during the austral winter of 2009. Vessel motion data (pitch and roll) were registered *in situ* using a digital clinometer and used to correct the nautical area scattering coefficients (NASC) in elementary sampling units of 926 m distance by 10 m depth. These NASC correction factors ($NASC_{CF}$) were calculated using Dunford's algorithm for circular transducers. We found high variability in $NASC_{CF}$, which averaged 12%, and ranged between 0 and 50%. $NASC_{CF}$ variability was explained significantly by the mean depth of the integrated stratum (33%), the weather condition, as measured by Beaufort's scale (5%), and the vessel course relative to wind direction (2%). The empirical model we used to explain $NASC_{CF}$ variability may be suitable for correcting bias due to transducer motion in other, past and future, fisheries acoustic surveys targeting mid-water species under rough weather conditions.

Keywords: NASC correction factor, transducer motion, pitch and roll, fisheries acoustics, southern blue whiting, *Micromesistius australis,* echo integration, Chile.

Reduciendo el sesgo e incertidumbre de las estimaciones hidroacústicas de biomasa de merluza de tres aletas (*Micromesistius australis*) en el Pacífico suroriental: efectos del movimiento del transductor sobre la atenuación acústica

RESUMEN. Se evaluó la pérdida de sensibilidad producida por el movimiento de un transductor montado en el casco y sus efectos sobre la abundancia y biomasa estimada de merluza de tres aletas (*Micromesistius australis*) en un estudio acústico realizado en el Pacífico suroriental, frente a la costa de Chile, durante el invierno austral de 2009. Los datos de movimiento del barco (cabeceo y balanceo) fueron registrados *in situ* utilizando un clinómetro digital y luego utilizados para estimar la pérdida teórica de sensibilidad del transductor y, finalmente, traducir esta pérdida en factores de corrección del coeficiente de dispersión por área náutica (*NASC*) calculados para intervalos básicos de muestreo de 926 m de distancia por 10 m de profundidad. Los factores de corrección del NASC ($NASC_{CF}$) fueron calculados utilizando el algoritmo de Dunford para transductores circulares. Los valores estimados del $NASC_{CF}$ presentaron gran variabilidad, con promedio de 12% y rango entre 0 y 50%. La variabilidad del $NASC_{CF}$ fue explicada significativamente por la profundidad del estrato integrado (33%), la condición climática medida por la escala de Beaufort (5%) y por el curso del barco en relación con la dirección del viento (2%). El modelo empírico construido para explicar la variabilidad observada posee un potencial uso predictivo para corregir el sesgo debido al movimiento del transductor en otras evaluaciones acústicas, pasadas y futuras, de recursos mesopelágicos y demersales bajo condiciones meteorológicas difíciles.

Palabras clave: factor de corrección del NASC, movimiento del transductor, acústica pesquera, merluza de tres aletas, *Micromesistius australis,* ecointegración, Chile.

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INTRODUCTION

Southern blue whiting *Micromesistius australis* is a very important fishery resource, exploited in the Pacific, Atlantic and Southern Oceans. Two main spawning/nursery grounds are known: one in the southwestern Atlantic Ocean, southwest of the Falkland (Malvinas) Islands; and other in the SE Pacific Ocean, off the Chilean coast and south of the Taitao Peninsula (Niklitschek *et al*., 2010). Southern blue whiting spawning aggregations in the south-eastern Pacific Ocean concentrate between latitude 47ºS and 51ºS during the austral winter (Lillo *et al*., 1994), at which time acoustics surveys have been conducted by the Chilean goverment on a yearly basis, since 2000. The typical weather conditions in this area are characterized by strong winds, with Beaufort forces (BF) typically between 4 and 5, although BF 6 is not rare in this area. These weather conditions are far from ideal and can affect both precision (interannual variability) and accuracy (bias) of biomass estimates (Simmonds *et al*., 1988), mainly due to signal attenuation caused by the enhanced surface bubble layer (Dalen & Løvik, 1981) and sensitivity attenuation produced by the transducer motion (Stanton, 1982).

Attenuation due to the air bubble surface layer is proportional to its thickness and becomes significant as this layer extends below the transducer (Dalen & Løvik, 1981; Novarini & Bruno, 1982). While an attenuation of 3 dB has been reported for a 38 kHz echosounder at a wind speed of 40 km h^{-1} (Dalen & Løvik, 1981), the magnitude of this source of attenuation is affected by wind force and waves height. It depends also upon transducer frequency and positioning, hull hydrodynamics, and vessel-speed (Dalen & Løvik, 1981; Simmonds & MacLennan, 2005; Welcome, 2009). This problem has been tackled either by using semi-empirical correction algorithms (Berg *et al*., 1983; Bruno & Novarini, 1983), or by protruding (Ona & Traynor, 1990) or towing (Kloser, 1996; Dalen *et al*., 2003) the transducers below the bubble layer.

Attenuation of the transducer sensitivity due to transducer motion can generate errors whose magnitude tends to be even greater than the surface bubble layer, particularly when narrow beam angles are used. This attenuation is caused by the interaction between the decreasing sensitivity of the transducer away from the main axis, and the angular separation between transmitted and received pings experienced by the transducer as it changes its orientation with time (Stanton, 1982). Transducer effects upon sensitivity attenuation are greater in un-stabilised hull mounted transducers, which mimic vessel movements (Kloser, 1996). Overall, these effects increase with waves height and wind force, and are also affected by the relative difference between vessel course and wind direction (Simmonds *et al*., 1988). Because of the later, it is possible to reduce transducer motion effects by changing transect orientation and/or vessel course within each survey. Besides weather-related factors, the magnitude of the bias caused by a given motion level is affected also by target depth and beam width, being greater for deeper shoals and narrower beams (Stanton, 1982; Simmonds & MacLennan, 2005).

Stanton (1982) proposed a theoretical algorithm suitable for quantifying and correcting the theoretical bias produced by different degrees of angular motion in circular transducers of several beam-widths. Furusawa & Sawada (1991) discussed this problem for sinusoidal transducer motion and its effects upon quantifying single fish echoes, concluding that bias in target strength was not significant for targets shallower than 50 m. Dunford (2005) simplified Stanton (1982)'s algorithms and produced a single relationship to estimate correction factors for a wide range of circular transducers. Empirical correction methods for transducer motion have been also developed to reduce bias in fisheries acoustic surveys. One of these methods is based upon observed variability among adjacent seabed echoes (Boyer *et al*., 2004), while the other uses motion information derived from repeated echoes produced by single targets (Furusawa & Amakasu, 2010). Nonetheless, no published comparisons between empirical and theoretical effects of transducer motion upon transducer sensitivity are available.

Within a single survey, sensitivity losses due to transducer motion increase variability among transects and produce an overall under-estimation of NASC values (Simmonds *et al*., 1988). Thus, these losses both increase uncertainty and reduce accuracy in biomass estimates. As weather-related effects are expected to vary among surveys (years), time series become affected by an increase uncertainty caused by variable levels of bias. Despite these issues and the existence of theoretical and empirical approaches for estimating and correct for transducer movement effects, they have been frequently neglected in fisheries acoustic surveys. It is possible, however, that the required corrections were acceptably small in many situations, e.g. when the targets are shallow or when the transducer motion is minimal (Dunford, 2005). Nonetheless even small levels of additional uncertainty may be enough to obscure true abundance changes in the population with time. Reported NASC correction factors for transducer motion effects are very variable. For instance, while Niklitschek *et al*. (2007) reported NASC correction factors due to transducer motion between 3 and 6% for orange roughy (*Hoplostethus atlanticus*) in different seamounts around the Juan Fernandez Archipelago (350-850 m, optimal weather conditions), Kloser *et al*. (2001) reported signal losses due to transducer motion and aeration of equivalent to NASC correction factors between 47 and 104% for the same species (600-1000 m, variable weather conditions).

The aims of this research were to evaluate the effects of transducer motion upon acoustic signal attenuation in a particular southern blue whiting acoustics survey and to evaluate the relative contribution of weather conditions (Beaufort scale), wind direction relative to vessel course and mean depth stratum to the magnitude of these effects.

MATERIALS AND METHODS

Acoustic data were collected in a survey oriented to estimate southern blue whiting abundance and biomass, carried out on August 18th and 29th 2009, aboard the trawler fishing vessel "Friosur 8" (54.0 m length, 10.5 m width, 7.0 m depth, Deutz engine 2240 HP and 885 ton of GRT**)**. The study area corresponded to the main spawning grounds of southern blue whiting in the southeastern Pacific, between latitudes 47ºS and 51ºS off the Chilean coast (Fig. 1). The acoustic survey design was composed of 49 parallel transects orientated in a west–east direction, with an inter-transect distance of 9.26 km (5 nm), covering a total surface area of 5,982 km^2. The vessel was equipped with a Simrad EK60 echosounder and a 38 kHz hull-mounted ES38B split-beam transducer. The echosounder was calibrated using a 60 mm diameter copper sphere, according to standard procedures (Foote *et al*., 1987). The survey was conducted using a maximum ping rate (1480 ms-1 nominal sound speed), with a pulse duration of 1024 ms, and a transmitting power of 2000 W. Vessel pitch and roll movements were registered at a rate of 3 datum/sec using a digital clinometer (Honeywell HMR-3000), connected directly to the Simrad EK60 computer.

Data collection

The acoustic data were logged with Echolog® software version 3.00.81 and stored as individual raw data files (EK6 format) per transect. Vessel motion (pitch and roll) data were stored in comma separated text files, and then merged with acoustic data by matching the motion and ping times (ms). Weather conditions measured as Beaufort's scale and wind direction (degrees) were registered every hour during

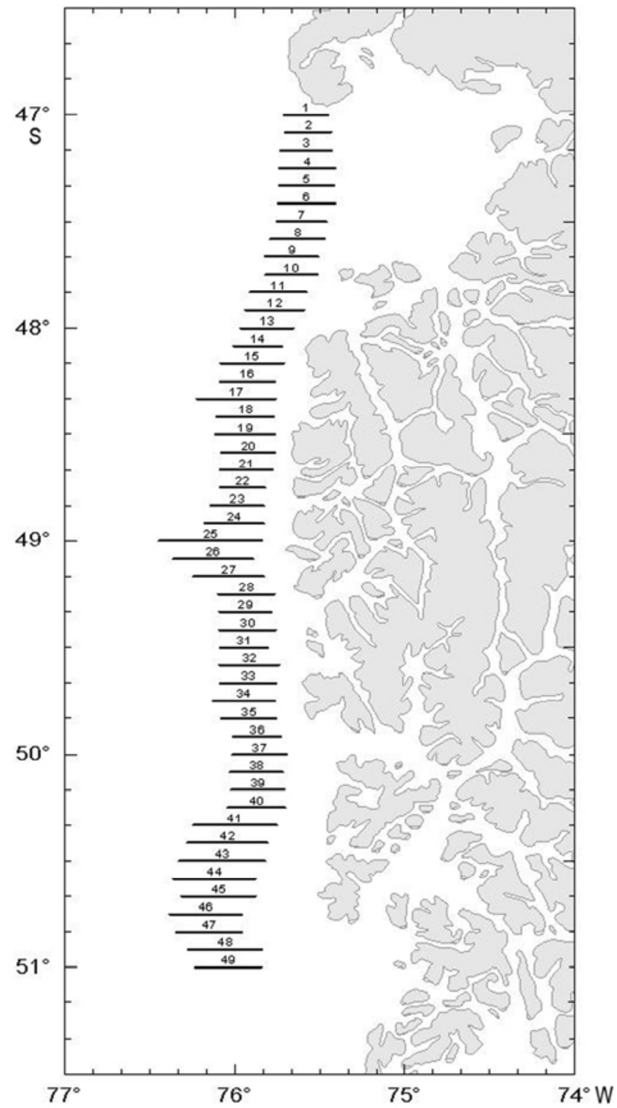

Figure 1. Study area and nominal positioning of acoustic transects.

Figura 1. Área de estudio y distribución nominal de las transectas de evaluación acústica.

the cruise period by a bridge officer, according to the international Beaufort scale accepted by the Chilean Merchant Marine (Table 1). Thus, we computed two weather variables per transect: mean Beaufort scale and mean wind direction relative to the vessel course.

During the survey period (11 days, Table 1), we had two days with very good weather (BF 0-3), seven days with BF 4-5, and two days with very bad conditions (BF > 5). Under BF 4-5, wind speed ranged between 11 and 21 knots and waves height between 1 and 3 m. These are normal survey conditions in the southeastern Pacific, off southern Chile. We carried out three transects under BF > 6, although the third transect was discarded and repeated under better

Table 1. Beaufort force occurrence during survey period. Beaufort scale adopted from Log book of sea and bridge of the National Merchant Marine (Chile).

Tabla 1. Ocurrencia de fuerza Beaufort durante el período del crucero. Escala Beaufort adoptada de la bitácora de puente y mar de la Marina Mercante Nacional de Chile.

Beaufort scale (force)	Wind speed (knots)	Wave heigth (m)	Frecuency (%)	Number of days
0	1 <	0	3.1	0.3
1	1 - 3	≤ 0.5	1.5	0.2
2	4 - 6	0.5	5.3	0.6
3	7 - 10	0.5 - 1	9.2	1.0
4	11 - 16	1 - 2	34.4	3.8
5	17 - 21	2 - 3	28.2	3.1
6	22 - 27	3 - 4	13.0	1.4
7	28 - 33	4 - 5	1.5	0.2
8	34 - 40	6 - 7	2.3	0.3
9	41 - 47	7 - 9	1.5	0.2
10	48 - 55	9 - 12	0.0	0.0
11	56 - 65	12 - 14	0.0	0.0
12	> 65	> 14	0.0	0.0

weather conditions. Acoustic and pitch and roll data were also logged during some BF 7-8 periods, but the quality of these acoustic data was too poor to estimate the biomass. During BF 9 (41-47 knots wind speed, 7-10 m wave height), acoustic data was considered useless and excluded from all analyses.

In order to simplify the modelling and interpretation of the data, wind direction relative to the vessel course was categorized into three classes: bow (wind by bow, 315º to 44º); stern (wind by stern, 135º to 224º); and side (wind from both port and starboard, 45°-134° or 225°-314°).

Data processing

Acoustic data was processed and corrected ping by ping using Dunford (2005)'s method, implemented in the "Motion correction" routine that is a part of the virtual variable operator of the Echoview® software version 4.60.58 (Myriax, 2008). This operator compensates volume backscattering coefficient (S_V) values by the theoretical loss in transducer sensitivity due to different orientation between transmitted pulse and received one. The motion correction operator corrects backscatter values, but does not correct the geometry of the data. Hence, the output virtual variable has the same data type and geometry as the input acoustic variable. As a result of this correction process, we obtained two echograms: an original (uncorrected) echogram and a corrected virtual echogram for each transect.

In both corrected and uncorrected echograms, bottom and near-field exclusion lines were created at 1 m above the bottom and 3 m below the transducer surface. Single transect echograms were divided into elementary sampling units (ESUs) of 926 m (0.5 nmi) distance by 10 m depth, after excluding any record deeper than 600 m (Fig. 2). Echograms were then analyzed using standard echo integration methods (Simmonds & MacLennan, 2005), exporting the resulting NASC values and the mean depth for each integrated cell (depth stratum), regardless of fish presence or density. NASC correction factors were calculated as:

$$NASC_{cf} = \left(\frac{NASC_c - NASC_u}{NASC_u} \right)$$

where $NASC_c$ and $NASC_u$ corresponded to the corrected and uncorrected values of NASC.

Statistical models

A generalized linear models (GLMs) approach (Nelder & Wedderburn, 1972; McCullagh & Nelder, 1989) was used in order to test hypotheses on the relationship between the estimated NASC correction factor ($NASC_{CF}$) and the explanatory variables: Beaufort force, relative wind direction and mean stratum depth. The GLMs generalize the traditional assumptions from linear regression and allow model errors to follow any statistical distribution belonging

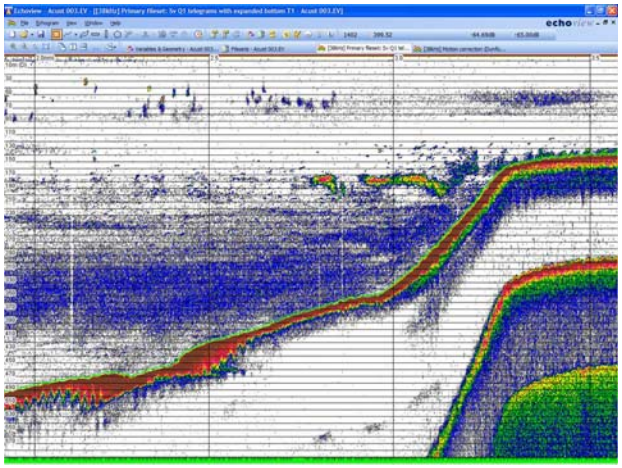

Figure 2. Sample echogram from the 2009 southern blue whiting survey. It is possible to observe integration cells of 926 m (horizontal) by 10 m (vertical).

Figura 2. Ejemplo de ecograma de la evaluación acústica de merluza de tres aletas en el 2009. Es posible apreciar celdas de integración de 926 m (horizontal) por 10 m (vertical).

to the exponential family. In this case, we considered and tested both normal and gamma distributions of the model errors (see below). GLMs use a variety of link functions to relate the linear predictor with the expected value of the response variable ($NASC_{CF}$), following the general expression:

$$g\ (\mu i) = \eta i$$

where

$$\eta i = \beta_1\text{Depth} + \beta_2\text{BF} + \beta_3\text{Wind cat. (stern)} + \beta_4\text{Wind cat. (side)} + \textit{Interactions}$$

u is the expected NASC value, n_i is the linear predictor and g is the link function. The explanatory variables corresponded to Depth = mean depth of the integrated cell, BF = Beaufort force, and two dichotomic variables (0/1) used to represent wind categories (Wind cat.(stern) = stern wind, Wind cat.(side) = side wind)).

Since $NASC_{CF}$, the response variable, was constrained by construction to be greater than 0, errors distributions were expected to depart from a normal distribution. Therefore a gamma distribution with a natural logarithmic link function was tested as a suitable alternative. Under this model, the vector of expected values for the correction factor becomes equivalent to:

$$E(NASC_{cf}) = exp(\eta)$$

A deviance analysis (Faraway, 2006; Zuur *et al*., 2007) was used to determine the contribution from each explanatory variable in explaining observed variability in NASC_{CF}. Explanatory variables were added to the model using a forward selection procedure based upon's Akaike (1973)'s Information Criteria (AIC) obtained from specific GLM models fit for each predictive variable (Venables & Ripley, 2002). Significance of added explanatory variables was tested using a (Type I) F-test (Fox, 2008). Suitability of competing error distribution models (normal and gamma) was evaluated by comparing the AIC values from each final GLM selected model. All analyses were implemented using the language and environment for statistical computation and graphics R (R Development Core Team, 2009), and its extension packages "statmod" (Smyth *et al.*, 2011) and "car" (Fox & Weisberg, 2011).

RESULTS

NASC correction factors at various condition

$NASC_{CF}$ showed a mean value of 0.12 and high variability, ranging between 0 and 1.5. $NASC_{CF}$ tended to increase with depth stratum (Fig. 3a) and Beaufort force (Fig. 3b). While the lowest $NASC_{CF}$ were calculated under stern-wind conditions, the highest ones appeared under side-wind conditions (Fig. 3c).

Statistical modeling

Residuals analysis (Fig. 4) indicated that the gamma distribution produced a better fit to the model errors than the normal distribution. This was reflected by a lower Akaike's information criterion for the full gamma model than for the normal model (Table 2). The absence of evident trends and extreme residual values indicated a nearly constant variance for both models (Fig. 4), particularly for the gamma one. As a result, all subsequent results in this section make reference to the gamma model.

The full GLM explained 41% of the total deviance. All explanatory variables and their interactions were found to have significant effects with the only exception of the interaction between depth stratum and BF. The linear effect of stratum depth was the most significant explanatory variable, contributing 80% of the explained deviance (Table 2). It was followed in importance by the linear effects of BF (13%) and wind category (6%). Although, simple interactions were also significant, they contributed to less than 1% of the explained deviance. Model coefficients for BF and depth stratum indicated a positive (log-linear) relationship between these covariates and the $NASC_{CF}$ (Table 3). The largest wind effect coefficient corresponded to

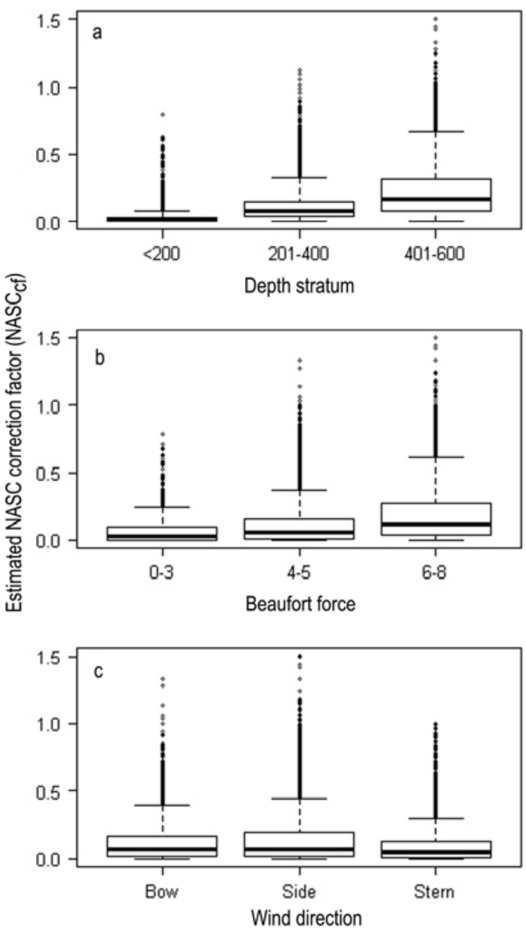

Figure 3. Box-plot of NASC correction factors computed for integration cells at different conditions regarding a) target depth strata, b) Beaufort force and c) wind direction relative to the vessel course (bow = 315-44°, sides = 45-134°/225-314, stern = 135-224°). Boxes limited by the first and the third quartiles. Whiskers project 1.5 times the interquartile range above and below the box.

Figura 3. Diagrama de cajas que representa los valores calculados del factor de corrección del NASC según a) estrato de profundidad del pez, b) fuerza Beaufort y c) dirección relativa del viento respecto al curso de barco (por popa = 315/44º, por lado = 45-134º/225-314º, por proa = 135/224º). Límites de las cajas representan percentiles 25 y 75. Los bigotes proyectan 1,5 veces el rango intercuartil por sobre y bajo las cajas.

the side-wind category, which predicted the largest $NASC_{CF}$ values. The smallest coefficient within wind categories corresponded to the stern-wind category (Table 3).

Model predictions yielded relatively low (<5%) coefficients of variation (CV) for most scenarios particularly for BF 3-5 Beaufort values. These were intermediate values that had a higher number of observations. The largest CV in predicted $NASC_{CF}$ (CV ~7%) corresponded to the Beaufort 0/stern-wind scenario (Table 4). This increased uncertainty was related to the lack of observations fulfilling these two conditions simultaneously. Data dispersion around predicted values tended to increase with depth and BF (Fig. 5).

Model predictions showed a consistent effect of wind conditions upon $NASC_{CF}$, regardless of depth (Fig. 5). Predicted $NASC_{CF}$ for strata shallower than 300 m insonified at BF < 3 ranged between 0.02 and 0.04 (2 and 4%, respectively), but increased up to 0.37 at 600 m (Table 4). For BF between 4 and 6, predicted $NASC_{CF}$ ranged between 0.08 and 0.13 at 300 m, increasing up to 0.76 at 600 m.

DISCUSSION

This research presents a first assessment of the magnitude of transducer motion effects upon uncertainty and bias in echointegration-based acoustic estimates of fish abundance and biomass in the southeastern Pacific off the Chilean Patagonian coast. Here, we have focused on a mesopelagic fish, southern blue whiting, under weather conditions that can be considered representative of this area during the winter. Our results show that neglecting $NASC_{CF}$ has had significant effects upon both uncertainty and bias of abundance and biomass estimates. An over-estimation of uncertainty had resulted from failing to apply single $NASC_{CF}$ values that ranged between 0 and 1.5 among ESUs. An overall under-estimation of total abundance and biomass estimates had also been produced by the joint omission of these $NASC_{CF}$ values, which exhibited an overall mean of 0.12 (12%).

Our results indicate that depth stratum had the highest effect upon $NASC_{CF}$, followed by Beaufort condition and wind category. As weather conditions and wind direction are highly variable between years, transducer motion will not only be a source of uncertainty and bias within years, but also a relevant source of random variability between years, which could make it impossible to detect small true changes or trends in stock size. Thus, it is likely that stock assessment procedures would benefit both from applying transducer motion $NASC_{CF}$ in future surveys on a regular basis, and from conducting a retrospective correction of transducer motion effects upon past acoustic estimates. This may not only be the case of southern blue whiting but also for other stocks assessed in the same area and season, such as southern

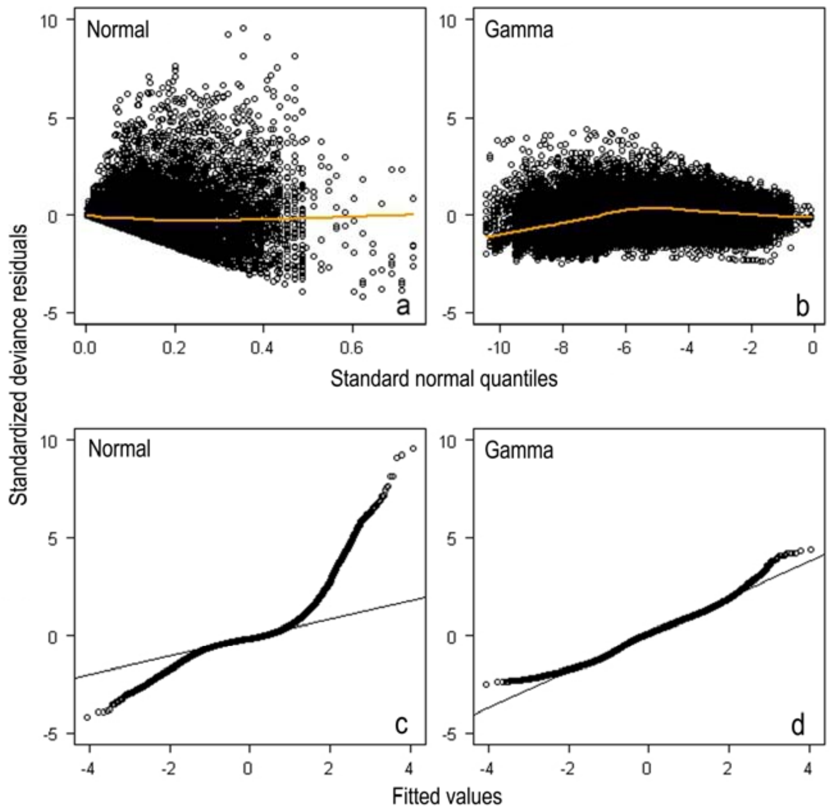

Figure 4. a-b) Residuals plotted against fitted values, and c-d) sorted residuals against standardized quantiles for normal and gamma GLM models used to explain variability in NASC correction factor.

Figura 4. a-b) Gráfico de valores residuales sobre valores ajustados, y c-d) residuales ordenados sobre quantiles estandarizados de las distribuciones normal y gamma, utilizado para explicar la variabilidad en el factor de corrección del NASC.

hake *Merluccius australis* and Patagonian grenadier *Macruronus magellanicus*.

While recording vessel or transducer motion directly on a routine basis is the most adequate procedure for estimating $NASC_{CF}$ in future surveys, using our empirical GLM as a linear predictive model offers an option for hind-casting and applying $NASC_{CF}$ values to past surveys. This would require, to ignore the added uncertainty and potential bias derived from differences in size, shape and power among survey vessels. The accuracy and precision of coefficients and the structure of the model could be, however, improved with time by incorporating new information from other vessels and surveys. It is necessary to acknowledge that Beaufort is a semi-quantitative scale of ordered categories, based upon standardized criteria. Depending upon vessel instru-mentation, some or all these criteria, are subject to the expert judgment of bridge officers. Although this observational procedure introduces additional uncertainty to the model, the fact that BF data is routinely recorded by all vessels, increases the feasibility of applying the model to past and future acoustic surveys where vessel motion is unavailable.

GLM model predictions exhibited higher accuracy and precision for BF between 3 and 5. Fortunately, this range represents the most common scenario at which acoustic surveys are conducted in this area. $NASC_{CF}$ predictions for BF > 5 tended to ander-estimate observed values, reducing the possibility of over-compensating abundance or biomass estimations. Nonetheless, we do not recommend applying our GLM model beyond BF 6. Moreover, as transducer motion, surface bubble layer thickness and the proportion of missing pings increase substantially above this threshold, we suggest that conducting and/or using data from surveys above this limit should be avoided. Particularly, those based upon conven-tional hull mounted transducers.

While fish depth is, obviously, beyond human control, there is room to reduce weather and wind effects by adjusting survey timing and vessel course. For instance, surveying at BF 2-3, under stern-wind, would constrain $NASC_{CF}$ to a range between 1.01-1.03

Table 2. Residual deviance analysis yielded by forward selection procedures conducted to select explanatory variables adequate to explain observed variability in $NASC_{CF}$. Data obtained from a single southern blue whiting acoustic survey, conducted in winter 2009. Results are presented for two candidate error models: normal and gamma. df: degrees of freedom, AIC: Akaike's information criterion after adding each explanatory variable.

Tabla 2. Análisis de devianza residual correspondiente a un procedimiento de selección progresiva de variables adecuadas para explicar la variabilidad en los valores del $NASC_{CF}$. Datos procedentes de una prospección hidroacústica de merluza de tres aletas, realizada en invierno 2009. Se presentan resultados para dos modelos candidatos de distribución de los errores (normal y gamma). df: grados de libertad, AIC: criterio de información de Akaike luego de incorporar cada nueva variable.

	df	Deviance			AIC	*P*-value
		Residual	Delta	% Expl.		
Normal model						
1	1	485,0	-	-	-16.270	-
Depth	1	347,9	137,1	66,02	-22.669	< 0.01
Beaufort	1	294,0	53,9	25,97	-25.913	< 0.01
Wind category	2	281,0	13,0	6,26	-26.780	< 0.01
Depth:Beaufort	1	280,9	0,1	0,05	-26.785	< 0.01
Depth:Wind category	2	280,8	0,1	0,05	-26.788	0,035
Beaufort:Wind category	2	277,3	3,4	1,66	-27.022	< 0.01
Total deviance explained: 42.81%						
Gamma model						
1	1	46.151,3	-	-	-50.516	-
Depth	1	30.968,2	15.183,2	80,19	-60.257	< 0.01
Beaufort	1	28.487,6	2.480,6	13,10	-62.221	< 0.01
Wind category	2	27.358,6	1.129,0	5,96	-63.160	< 0.01
Depth:Beaufort	1	27.354,0	4,6	0,02	-63.162	0,065
Depth:Wind category	2	27.311,4	42,6	0,23	-63.195	< 0.01
Beaufort:Wind category	2	27.217,0	94,4	0,50	-63.271	< 0.01
Total deviance explained: 41.03%						

Table 3. Estimates and standard errors of GLM parameters for each factor, covariate, and significant interactions, used to explain variability in observed NASC correction factor. Coefficients correspond to the gamma error distribution model.

Tabla 3. Valores estimados y errores estándar de los parámetros del modelo GLM para cada factor, covariable e interacción significativa, usados para explicar la variabilidad en los valores observados del factor de corrección del NASC. Los coeficientes corresponden al modelo de distribución gamma.

	Estimate	Standard error
Intercept	-5,20200	0,044920
Depth	0,00583	0,000088
Beaufort	0,23840	0,010370
Wind category:side	0,47280	0,057120
Wind category:stern	-0,82280	0,085790
Depth:Wind category:side	-0,00040	0,000120
Depth:Wind category:stern	0,00021	0,000118
Beaufort:Wind category:side	-0,04639	0,012080
Beaufort:Wind category:stern	0,07162	0,018360

Table 4. Predicted NASC correction factors and their coefficients of variation (CV, in parentheses) by Beaufort force, mean depth of integration stratum and wind category.

Tabla 4. Valores estimados del factor de corrección del NASC y sus respectivos coeficientes de variación (CV, entre paréntesis) para diferentes categorías de fuerza Beaufort, profundidad media del estrato de integración categoría del viento.

Depth (m)	Wind category	Beaufort scale					
		0	2	3	4	5	6
100	Stern	0,0044	0,0082	0,0112	0,0153	0,0208	0,0284
		(7.2)	(4.4)	(3.1)	(2.2)	(2.2)	(3.0)
	Side	0,0152	0,0223	0,0270	0,0328	0,0397	0,0481
		(3.2)	(2.3)	(2.1)	(2.0)	(2.1)	(2.4)
	Bow	0,0099	0,0159	0,0202	0,0256	0,0325	0,0412
		(4.2)	(2.7)	(2.3)	(2.4)	(2.8)	(3.6)
200	Stern	0,0081	0,0150	0,0205	0,0280	0,0381	0,0520
		(7.1)	(4.2)	(2.9)	(1.8)	(1.7)	(2.6)
	Side	0,0261	0,0384	0,0465	0,0563	0,0683	0,0827
		(3.0)	(2.0)	(1.7)	(1.6)	(1.7)	(2.0)
	Bow	0,0177	0,0284	0,0361	0,0458	0,0582	0,0738
		(4.0)	(2.3)	(1.8)	(1.8)	(2.4)	(3.2)
300	Stern	0,0148	0,0275	0,0375	0,0511	0,0697	0,0951
		(7.2)	(4.2)	(2.9)	(1.7)	(1.5)	(2.5)
	Side	0,0450	0,0660	0,0800	0,0969	0,1174	0,1422
		(3.0)	(2.0)	(1.6)	(1.5)	(1.5)	(1.8)
	Bow	0,0316	0,0509	0,0647	0,0821	0,1042	0,1322
		(4.0)	(2.3)	(1.7)	(1.6)	(2.1)	(3.0)
400	Stern	0,0271	0,0503	0,0686	0,0935	0,1275	0,1739
		(7.3)	(4.4)	(3.0)	(1.9)	(1.7)	(2.5)
	Side	0,0773	0,1135	0,1376	0,1667	0,2019	0,2447
		(3.2)	(2.3)	(1.9)	(1.8)	(1.8)	(2.0)
	Bow	0,0566	0,0912	0,1158	0,1470	0,1865	0,2367
		(4.2)	(2.5)	(2.0)	(1.9)	(2.3)	(3.0)
500	Stern	0,0495	0,0920	0,1255	0,1711	0,2333	0,3180
		(7.5)	(4.7)	(3.4)	(2.4)	(2.2)	(2.8)
	Side	0,1330	0,1953	0,2366	0,2867	0,3473	0,4208
		(3.6)	(2.8)	(2.5)	(2.3)	(2.3)	(2.5)
	Bow	0,1014	0,1634	0,2074	0,2632	0,3341	0,4240
		(4.6)	(3.0)	(2.5)	(2.4)	(2.7)	(3.3)
600	Stern	0,0906	0,1683	0,2295	0,3129	0,4266	0,5817
		(7.8)	(5.1)	(3.9)	(3.0)	(2.8)	(3.3)
	Side	0,2288	0,3359	0,4069	0,4931	0,5974	0,7239
		(4.1)	(3.4)	(3.1)	(3.0)	(3.0)	(3.1)
	Bow	0,1817	0,2926	0,3714	0,4714	0,5983	0,7593
		(5.1)	(3.7)	(3.3)	(3.1)	(3.3)	(3.8)

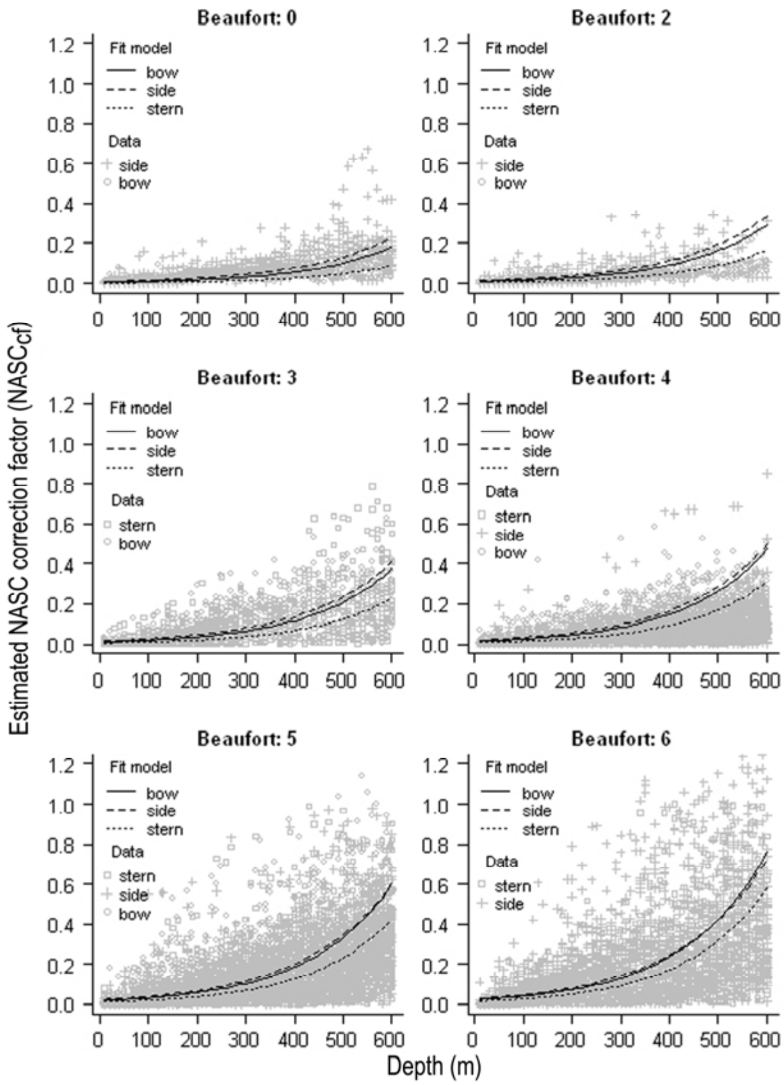

Figure 5. Observed and predicted values for the NASC correction factor at six Beaufort force values and three wind categories (bow, side and stern).

Figura 5. Valores observados y estimados para el factor de corrección de los NASC para seis categorías de fuerza Beaufort y tres categorías de viento (por proa, por el lado y por popa).

(1-3%). Thus, besides highlighting the potential magnitude of transducer motion effects and providing a predictive model for estimating $NASC_{CF}$ when transducer motion data are unavailable, we believe our results are useful for developing practical field guidelines that may define operational criteria for modifying transect orientation or interrupting acoustic surveys based upon BF and wind direction.

Finally, it is necessary to emphasize that although this work is focused on the acoustic attenuation effects of transducer motion, under relatively rough weather conditions, these may be similar or even smaller than those related to the surface bubble layer (Simmonds *et al*., 1988; Simmonds & MacLennan, 2005). While there are not theoretical models suitable for assessing surface bubble layer effects, there are empirical models (Dalen & Løvik, 1981) that may be used as a basis for assessing their magnitude in acoustic surveys being conducted in the southeastern Pacific off southern Chile. This should be a target for future research in order to keep reducing bias and uncertainty in acoustic surveys for southern blue whiting and other important stocks present in the same area.

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