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Analyses of body condition in sei, Brydes and common minke whales in the western North Pacific with JARPN and JARPN II dataset

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INTERNATIONAL WHALING COMMISSION

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ABSTRACT

The annual trend in energy storage in sei *Balaenoptera borealis* and Bryde's *B. edeni* during the JARPN II period and common minke whales *B. acutorostrata* during the JARPN and JARPN II period were examined. Regression analyses showed that blubber thickness and half girth in sei whales have been increasing during 2002-2015. The increase per year is estimated at 0.109 ±0.038 SE cm for mid-lateral blubber thickness and 2.183 ±1.379 SE cm for axillary half-girth. The regression analyses also showed negative year effects on blubber thickness in common minke whale while Bryde's whale, year effects were not seen. The regression analyses also showed that sei and Bryde's whale have good body condition with larger body length and in later days. Some analyses also showed body condition and its seasonal increase differ among maturity stages. Meanwhile, prey species and surface water temperature where whale were caught were not selected as predictors. The reasons for increase body condition in sei and decrease body condition in minke whale are difficult to identify. However, increase trend of body condition in sei whales suggest the favourable food availability change for sei whale in the study area. The regression also showed decrease body condition in common minke whale using JARPN and JARPNII (both Offshore and Coastal components) suggesting unfavourable food availability change and difference between stocks, however the analysis for the minke whale leave to be improved.

KEYWORDS: MINKE WHALES, ENERGY STORAGE, ECOSYSTEM CHANGES, JARPN II, NORTH PACIFIC

INTRODUCTION

Marine mammals, such as whale and pinniped, stock energy by food intake into its blubber as lipids, and this increase and decrease in lipid content changes its thickness and mass (Lockyer, 1987; Víkingsson, 1995; Næss *et al*., 1998; Konishi, 2006; Field *et al*., 2007; Williams *et al*., 2007; Konishi *et al*., 2008; Christensen *et al*., 2013; Konishi and Walløe, in press). Therefore, the measurement of blubber thickness and girth have been used as body condition indices that can be used to monitor history of food intake, such as increase through the feeding season, local food availability and long-term change in relation to environmental change. Because precise measurements of blubber thickness, girth or fat weight need lethal sampling, these informative results have been reported and discussed in IWC-SC (IWC, 2015; Konishi *et al*., 2008; Christensen *et al*., 2013; Konishi and Walløe, in press). In previous IWC-SC, *"the Working Group to Address Multi-Species and Ecosystem Modelling Approaches" also considered that indices of body condition are potentially of importance to ecosystem modelling, because they can enable detection of changes over a shorter time period than changes in abundance* (IWC, 2012). Furthermore in the long-term continuous monitoring of food availability as indicated by stomach contents and of energy storage in the form of blubber thickness can contribute important information for the management and conservation under the mandates of both the IWC and CCAMLR of the krill fishery and of the predators that depend on krill for food in the Southern Ocean (Konishi *et al*., 2014). These previous studies and discussion in the Scientific Committee also motivated the adaptation of the examination of body condition trend in the North Pacific baleen whales off the Pacific coast of Japan.

This study is listed in the section *"Objective 1 Feeding ecology and ecosystem studies Sub-objective 7"* of JARPN II framework paper (Tamura *et al*., 2016: SC/F16/JR1). Although the body condition analyses was not included in the original JARPN II survey plan, this study is related to the understanding of the mechanism of feeding ecology and the role of a component of the ecosystem. Waters off the pacific coast of Japan have rich fishery ground where the Kuroshio and Oyashio Currents meet, and the current direction goes offshore carrying pelagic fish which is important prey for baleen whales (Konishi *et al*., 2009). JARPN and JARPNII surveys have examined the feeding ecology of sei *Balaenoptera borealis*, Bryde's *B.edeni* and minke whale *B. acutorostrata* with food and oceanographic environment occasionally, therefore linkage of this information to the nutritional study are useful for understanding the ecosystem study.

The purpose of this study is to examine the time trends of blubber thickness and what factors influence the energy storage of sei and Bryde's, and common minke whales in the western North Pacific. This study also aims to integrate a study using feeding ecology and biological data from stomach contents and measurements and geographical difference and oceanography from using sighting info data near sea surface temperature. The long-term dataset also includes dynamics of those data that will contribute to the ecosystem study. To conduct comprehensive analyses, data from JARPN and JARPN II including both offshore and coastal components are used for analyses in common minke whale.

METHODS

Survey area and Sampling

The research area of JARPN and JARPN II was the area between the Pacific coast of Japan and 170°E, and a latitudinal range between 35º N and 50° N (Figure 1), including a part of sub-areas 7, 8 and 9 established by the Scientific Committee of the International Whaling Commission (IWC, 1994). Whales used in this study were sampled during 2002–2015 for sei whales, during 2000-2013 for Bryde's whales from offshore component and during 1994-2015 from common minke whales from both offshore component and coastal component. Sampling was conducted from May to October in offshore component, April-May in coastal component in spring and September-November in coastal component in fall. The whales were sampled by sighting and sampling vessels (SSV) at offshore component and positions of the sampled whales found and sea surface temperature (SST) were also recorded. Then the whales were transported to a base research vessel (*Nisshin-Maru*) where they were examined by biologists. In coastal component, whales sampled by SSV were dissected at a land base station at Sanriku and Kushiro regions. All whales were measured, weighed, and their reproductive organs were examined to distinguish sexual maturity. Males of sei, Bryde's, and common minke whales, were defined as sexually mature by testis weights (larger side) of more than 1090 g, 560 g and 290 g, respectively (Bando *et al*., pers. comm., Institute of Cetacean Research, Toyomi 4-5, Chuo-ku, Tokyo 104-0055, Japan). Females were defined as sexually mature by the occurrence of at least one corpus luteum or albicans in their ovaries and the presence of foetus and mammary gland was observed to examine lactation. The category of sexual maturity and the number of sample sizes used in this study are listed in Table 1, 2, and 3.

Blubber thickness was measured to the nearest mm, by dissecting perpendicularly from skin to muscle without including connective tissue or black surface skin at the level of dorsal fin and umbilicus. Half girth was also measured at the level of axillary, umbilicus and anus. The measurement positions are shown in Figure 2. The lateral blubber for blubber thickness measurements has uniformity in thickness and is easy for precise measurement. Any tension in the blubber tissue was released by cutting through the blubber layer down to the muscle fascia around the measurement site. Fat weight of all the blubber including the ventral groove and visceral fat had been weighed in the first animal caught each day and one of the fine proxy for body condition (see Konishi *et al*., 2008; Konishi and Walløe, in press), however, fat weight was not used in this study because of the limited measurements for fat weight after 2010.

To examine the feeding activity when a whale was caught and its body condition, stomach content data including the main prey item in the forestomach was used. (see detail of stomach content treatment in Tamura *et al*., 2016: SC/F16/JR15). Stock structure of common minke whale in the Western North Pacific can be divided into two sub-population "J and O" by genetic definition. We also included the stock information at 75% confidential level (Pastene et al. JR38). Since the three baleen whales distribute through the different oceanographic waters and different feeding histories (see also Konishi *et al*., 2016: SC/F16/JR23), water temperature near surface "wtemp" was included as potential covariate.

Statistical analyses

All response (body condition indicators) and predictor variables are listed in Table 4. To make a biologically plausible full model, independent variables including continuous and categorical variables are included at first, then quadratic terms of continuous variables are also added to see any non-linear effects. If quadratic term is much better than non-quadratic term based on the *p*-values, the quadratic term was used in the full model. To consider potential interaction effects in the model fitting, variables of interaction term were selected based on the dendrogram of basic models. The dendrogram was illustrated using package "tree" 1.0 in R (Ripley, 2015), and selected variables which were likely to give strong effects on responsible variable were used to consist of interaction terms. The regression with a model with all two-way interaction terms were analysed and the interaction terms far from *p*-value (>= 0.1) were deleted. Then three-way interaction terms were composed by the combination of remaining two-way interaction variables and were added into the model (Crawley, 2005). We used this biologically plausible model with potential interaction terms for the step-wise procedure with 1) random effects to account for the sampling heterogeneity and 2) selection of fixed effects.

A statistical model is needed to account for the effects of date and location when making inferences about possible year trends (de la Mare, 2011). To account for the effects, we included random-effects terms in a fixed-effects model. One of the random effects is intercept of categorical year "YearCat" assuming that random slope and intercept in other variables among years. For fitting models that estimate the growth in blubber to be different in space and time, random effects of date "DateNum" divided by "LatCat" and "LongCat" were also tested if inclusion of these random effects bring better fit. These random effects accounted for samples from different dates at different places throughout the survey period by a single operation as used in JARPN and JARPN II cruise.

The step-wise procedure used in this study basically followed one used in Konishi and Walløe (in press) which were also recommended by the JARPA II review panel (IWC, 2014) for the study of body condition trend in Antarctic minke whale. To evaluate fitting of the models, the Bayesian information criterion (BIC) (Schwarz, 1978) was used. The use of Maximum Likelihood (ML) or Restricted Maximum Likelihood (REML) can be explained as follows (see also Zuur *et al*., 2009).

(1) The first step is to decide which random effects to include. The models should then be fitted using REML.

(2) The next step is to systematically try to eliminate some of the fixed effects. The models should then be fitted using maximum likelihood but order of elimination is started from three-way interaction term, two-way interaction term then other fixed-effects terms.

(3) When the best model has been identified in step (2), this model should be fitted using REML.

All statistical analyses were conducted in R environment version 3.2.2 (R Core Team, 2015) using package "lme4" version 1.110 (Bates *et al*., 2015) for mixed effects models, "LMERConvenienceFunctions" version 2.10 (Tremblay, 2015) for the above stepwise model selection (2) and (3) (Tremblay, 2011) was used. Packages "sjPlot" (Ludecke, 2015) and "ggplot2" (Wickham, 2009) were used to visualise modelling results.

RESULTS

Sei whale

Full models and selected best models with BT11, BT7, umbilicus Girth and axillary girth as response variables for sei whale were listed in Table 5, and dendrogram to select component of interaction term for each response variable were drawn in Figure 3, 4, 5, and 6. In the regression analyses for blubber thickness at the mid-lateral point below the dorsal fin (BT11) in sei whale, the best model selected by BIC included YearNum, BLm^2, DateNum, PreMaturity_Cat, Interaction terms of DateNum:BLm, YearNum:DateNum and DateNum:PreMaturity_Cat at the 5 % level and FirstS (t=-1.715) and wtemp(t=1.242) (Table 6) with paired correlation plots and diagnostic plots (see Appendix 1). The year effect indicates that the blubber thickness at the level of dorsal fin (BT11) significantly increased during 13 years (2002-2015) by 0.109 ± 0.038SE (cm/year). In other predictive effects, whales of large body length and later date have positive effects on BT11 at 5% level. BT11 also significantly differ among maturity stage, for example mature females have thicker blubber and pregnant and lactating females and mature males have thinner blubber than immature females. The main prey species, categorical term of latitude and longitude were not included in the best model, suggesting these variables do not have effects on the change of BT11. The three interaction terms were also included in the best model for BT11 and illustrated as representative of interaction terms. The year effects depend on the value of date (Figure 7). BT11 also significantly increased with BLm and DateNum while the effects of DateNum depend on the effects of BLm (Figure 8) and maturity stage (PreMaturity_Cat; Figure 9). There were significant difference of BT11 among maturity stage (PreMaturity_Cat). The best model for BT11 also included random intercept of year as categorical (1|YearCat).

In the regression analyses for blubber thickness at the mid-lateral point at the level of umbilicus (BT7) in sei whale(Table 7), the best model selected by BIC included BLm, DateNum, latitude, weight of first stomach and maturity stage with an interaction of body length and latitude. Random intercept of year (1|YearCat), body length and date were included as well as in BT11. However "YearNum" was not selected in the best model. Diagnostic plots for the best model are shown in Appendix 1.

In the best models with umbilicus and axillary girth, body length, date and maturity stage in the same manner as blubber thickness (Table 8 and 9). The weight of forestomach content was only significant in umbilicus girth but not in axillary half-girth, while significant increase of girth with year (2.183 ± 1.379SE cm) was found in axillary half-girth. Diagnostic plots for the best model are shown in Appendix 1.

In the analyses using BT7 and umbilicus girth, the both best models did not include year effect while negative and positive effect of stomach content weight “FirstS” were included at 5% level, respectively.

Bryde’s whale

Full models and selected best models with BT11, BT7, umbilicus Girth and axillary girth as response variables for Bryde’s whale were listed in Table 10. Dendrograms to select component of interaction term for each response variable were drawn in Figure 10, 11, 12, and 13. In the regression analyses for Bryde’s whale, the best models selected by BIC included BLm, DateNum and PreMaturity_Cat at the 5 % level (Table 11, 12, 13 and 14), showing larger animals in later days are thicker in blubber thickness and wider in girth. No interaction terms were selected in any best models without year and body length in axillary girth, suggesting year effect differs in relation to body length. Significant year effect was only found in response variable of axillary half-girth, showing increase of the coefficient 3.848 ± 1.824SE cm per year during 2000-2013. Random intercept of categorical year “YearCat” were included into all four best models for Bryde’s whale. Other diagnostic plots for the best model are shown in Appendix 1.

Common minke whale

Common minke whales were sampled from JARPA period and followed by JARPNII offshore and in two coastal regions. To examine the long-term trend since 1994, data with consistency throughout the years were used for the analyses. Therefore, some independent variables, such as water temperature “wtemp” and feeding information were not included in a full model. Stock structure of common minke whales in the Western North Pacific can be divided into two sub-populations: “J and O” by genetic definition. This stock information (Pastene *et al.*, 2016: SC/F16JR38) was included as one of the independent variables in a full model.

Full models and selected best models with BT11, BT7, umbilicus Girth and axillary girth as response variables for common minke whale were listed in Table 15. Dendrogram to select component of interaction term for each response variable were drawn in Figure 14, 15, 16, and 17. In the regression analyses for common whale using BT11, the number of fixed effects are selected more than other whales and the best models selected by BIC included BLm, DateNum, F_lat, F_long, Maturity state (PreMaturity_Cat), LatCat, stock information (OJ75) and three interaction terms(Table 16, 17, 18 and 19). These terms are also significant at the 5 % level. Negative year effect was only included and significant at 5 % level in BT11 -0.051 ±0.015 cm per year. Year effect was included using BT7 but was not significant (t = -1.640). The date and body effects were included in all best models, however the coefficients totally differ among body condition indices including negative and positive values, suggesting no common effects were found for these variables. Other diagnostic plots for the best model are shown in Appendix 1.

To conduct integrated analyses from JARPN II survey, we included prey information from the stomach content analyses taken in JARPN II for sei and Bryde’s whales, however main prey species (MainPreyS) were not selected throughout the analyses and water temperature was not included or not significant at most of best models.

DISCUSSION

Sei whale

In the regression analyses for sei whales, the best models using BT11 and axillary girth show that the positive year effects at 5% level, indicating that food environment for sei whale has been becoming favourable during JARPN II period. In the regression analyses using other two response variable, that is BT7 and umbilicus half-girth, year was not included in the best model, suggesting the sensitivity of the body condition for energy intake differ among blubber thickness and girth measurement position and these positions are less sensitive than BT11. Blubber thicknesses at BT7 and umbilicus birth are both near internal organs and these measurement areas could possibly be affected by other factor such as stomach fullness and pregnancy. BT11 is a more posterior area from umbilicus level and likely to be a good indicator. Positive effects of body length and date on body condition are biologically reasonable and similar results were reported in the Antarctic minke whale and common minke whale in Atlantic waters (Konishi *et al.*, 2008; Konishi and Walløe, in press; Christensen *et al.*, 2013).

In the analyses using BT11, quadratic body length (BLm^2) was selected and its coefficient is positive value, indicating small animals tend to have thicker blubber in the early period of lifetime when they are thinner and again gain thicker blubber in relation to their growth. This may suggest fatting in the period of lactating remained in the small animals. The inclusion of interaction terms also demonstrated that change in blubber thickness accordance with date change in relation to growth and year. The regression analyses also showed the difference of increase in blubber thickness in accordance with date among maturity stage. Interestingly only mature females have negative correlation with date while other maturity stages showed increase with days. The exact interpretation for this needs further behavioural difference among maturity stages, especially non-pregnant mature females.

From the analyses using BT7 and umbilicus girth, negative and positive effects of stomach content were detected, respectively. This possibly suggests that these two measurement points related to umbilicus position are somewhat less sensitive than other anterior and posterior levels of the body, such as BT11 and axillary position in sei whales. Sei whales sometimes feed and stock full of pelagic fish in the forestomach exceeding 500kg although the amount of copepod or euphausiids prey is usually decent in JARPN II. The effects of food intake on the stomach need to be studied further, however the interpretation from the results using BT11 and axillary girth will likely be more precise when we see the yearly trend as we mentioned above.

Bryde's whale

In the regression analyses for Bryde's whale, Year effect was not included in the best model without a case for axillary half-girth. In the best model using axillary half-girth, the coefficient of body length is a distant value. This large coefficient was caused by inclusion of interaction of YearNum and BLm. When we exclude this interaction, the coefficient of BLm becomes 20.000 ± 0.853SE cm while year effect becomes negative -5.901 ± 1.130SE cm. Therefore we could not conclude the results for axillary girth so far. Eventually we did not find any trends of energy storage during 2002-2013 period in Bryde's whale in the survey area.

In all analyses, positive effects of body length and date on body condition are included and significant at 5% level, suggesting the model could capture the increase of energy deposit during feeding season and change in body length. Maturity state is also an important effect on body condition and pregnant females have better body condition than immature females.

Common minke whale

Data source from common minke whales has different situation compared to other two whale species. In the results from analyses for common minke whales, we tried to conduct analyses using integrated datasets including previous JARPN data and two different components in JARPN II. Among the analyses with these data pooled, we did not find consistent trends among four body condition indices. In this study, we used data from both JARPN since 2003 in Sanriku, 1994 to 1999 and JARPN II since 2000 to 2013 including coastal components since 2002. In the future study, stratified analyses for each dataset sharing common features are needed to catch exact yearly trends and biological features in addition to testing different types of independent variables. From the regression analyses, minke whales have thicker blubber at higher latitude and in western regions, in "O-stock", and are different between latitude stratum at BT11.

For the purpose of integrating analyses using stomach content and oceanography, we included main prey species and surface water temperature into a full model. Unfortunately, these variables were not included or were included but not statistically significant in the best models for all whale species and body condition indices without exception. In the trend analyses, this study showed that sei whales substantially increase in blubber thickness and half girth. Although this interpretation is difficult from only our results, the feeding habits have been drastically changed with decreasing the occurrence of Japanese anchovy since early 2000s (Konishi *et al*., 2016: SC/F16/JR23). The change of feeding habits was not seen in Bryde's whales because of high dependency on euphausiids (Konishi *et al*., 2016: SC/F16/JR23). The results of this study did not show the relationship between prey species as snap shot and body condition, however the amount of food intake and difference of prey species, such as calorie and feeding efficiency, are important research for future energetic study. The body condition analysis also needs to be developed for management purposes.

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Table 1. Number of sei whale samples used in the analyses.

	Year														
Maturity stage	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Male immature	3	6	11	6	16	15	10	12	14	11	11	15	10	10	150
Male mature	12	16	27	40	29	30	33	33	28	40	31	28	25	15	387
Female immature	3	4	11	14	11	15	16	9	10	12	10	6	9	14	144
Female mature	2	2	5	4	5	4	2	9	8	7	7	17	6	11	89
Pregnant	17	15	25	28	24	15	32	32	35	15	35	30	28	26	357
Pregnant lactating		3	5	1	7	1	1	1	4	2	1	2	5	4	37
Total	37	47	85	94	92	80	95	97	99	87	96	98	83	80	1170

Table 2. Number of Bryde's whale samples used in the analyses.

	Year														
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Male immature		13	17	10	5	10	8	13	6	9	5	10	5	3	114
Male mature		4	7	9	14	11	13	10	23	8	19	10	6	9	143
Female immature	5	12	11	9	7	12	7	5	4	14	4	11	4	3	108
Female mature	5	2	3	7	2	6	9	6	7	7	6	8	8	4	80
Pregnant	9	10	10	10	21	7	11	15	9	9	15	11	10	7	154
Pregnant lactating	1	9	1	4		4		1		2			1	1	24
Total	20	50	49	49	49	50	48	50	49	49	49	50	34	27	623

Table 3. Number of common minke whale samples used in the analyses.

	Year																						
Maturity Stage	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Male immature	1	2	11	16	15	12	10	15	24	25	21	46	47	44	43	56	44	33	69	29	31	9	603
Male mature	17	89	52	71	74	59	25	78	93	89	102	93	89	88	60	37	26	49	38	32	20		1281
Female immature	2	2	5	7	6	13	1	4	20	21	12	45	40	54	43	56	45	33	56	27	22		514
Female mature	0	0	2	0	1	1	1	0	2	1	2	3	1	0	3	1	0	6	2	3	0	0	29
Pregnant	1	7	7	6	4	14	3	3	7	13	6	17	8	11	12	4	2	5	9	3	4	1	147
Pregnant lactating														1	1								2
Total	21	100	77	100	100	99	40	100	146	149	143	204	185	198	162	154	117	126	174	94	77	10	2576

Table 4 Names of variables and terms used in the regression analyses.

Response variable	BT11	Blubber thickness at mid-lateral point on the vertical axis of the dorsal fin (in cm)
(with sample size)	BT7	Blubber thickness at a mid-lateral position on the vertical axis of the umbilicus (in cm)
	UmbilicusGirth	Half girth at the level of the umbilicus (in cm)
	AxillaryGirth	Half girth at the level of the axilla (in cm)
	FatWeight	Weight of subcutaneous fat (blubber) + weight of intestinal fat (in metric tons)
Explanatory variable	YearNum	Year as a continuous variable
(continuous)	BLm	Body length (in m)
	DateNum	Date number (1 April = day 1)
	LongNum	Longitude in degrees E
	LatNum	Latitude in degrees N
	LtimeNum	Local time of day
	wtemp	Near surface water temperature (°C)
Explanatory variable	YearCat	Year as a categorical variable
(categorical)	LatCat	Latitude divided into 5 intervals
	LongCat	Longitude divided into 5 sectors
	PreMaturity_Cat	Maturity stage based on theobservation of internal organs
	OJ75	Stock difinition by genetic infromation for common minke whales with confidence level at 75% (Pastene *et al*., JR39)
Interaction and	A:B	Interaction between A and B
random effects	(1|YearCat)	Random effects of year on the model Intercept (assuming randomness of slope and intercept among years)
	(DateNum|LatCat)	Random effects of DateNum partitioned by LatCat
	(DateNum|LongCat	Random effects of DateNum partitioned by LongCat

Table 5 The full model and best model for each response variable.

Response	model type	The response variables of each model
BT11	Full model	YearNum + BLm^2 + DateNum + F_lat + F_long + FirstS + wtemp + LatCat + LongCat + PreMaturity_Cat + MainPreyS + BLm:DateNum + BLm:YearNum + BLm:PreMaturity_Cat + DateNum:YearNum + DateNum:PreMaturity_Cat + YearNum:PreMaturity_Cat + DateNum:BLm:PreMaturity_Cat + DateNum:BLm:YearNum
	Best model	YearNum + BLm^2 + DateNum + FirstS + wtemp + PreMaturity_Cat + (1 | YearCat) + DateNum:BLm + YearNum:DateNum + DateNum:PreMaturity_Cat
BT7	Full model	YearNum + BLm + DateNum + F_lat + F_long + FirstS + wtemp + LatCat + LongCat + PreMaturity_Cat + MainPreyS + BLm:PreMaturity_Cat + BLm:F_lat + F_lat:PreMaturity_Cat+ BLm:F_lat:PreMaturity_Cat
	Best model	BLm + DateNum + F_lat + FirstS + wtemp + PreMaturity_Cat + BLm:F_lat + (1 | YearCat)
Umbilicus Girth	Full model	YearNum + BLm + DateNum + F_lat + F_long + FirstS + wtemp + LatCat + LongCat + PreMaturity_Cat + MainPreyS + BLm:PreMaturity_Cat + (1|YearCat)
	Best model	BLm + DateNum + FirstS + wtemp + PreMaturity_Cat + (1 | YearCat)
Axillary Girth	Full model	YearNum + BLm + DateNum + F_lat + F_long + FirstS + wtemp + LatCat + LongCat + PreMaturity_Cat + MainPreyS + BLm:PreMaturity_Cat + BLm:YearNum + YearNum:PreMaturity_Cat
	Best model	YearNum + BLm + DateNum + FirstS + wtemp + PreMaturity_Cat + YearNum:BLm + (1 | YearCat)

Term (A:B) means interaction of “A” and “B”.

Table 6. Summary for the best model using BT11 of sei whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	0.04214	0.2053
Residual		0.74552	0.8634
Number of obs: 1152, groups: YearCat, 14			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	−219.300	75.470	−2.906
YearNum	0.109	0.038	2.908
I(BLm^2)	0.022	0.005	4.831
DateNum	1.876	0.652	2.875
FirstS	−0.001	0.000	−1.715
wtemp	−0.015	0.012	−1.242
PreMaturity_Cat[T.F_mat]	1.490	0.479	3.113
PreMaturity_Cat[T.F_preg]	0.692	0.406	1.705
PreMaturity_Cat[T.F_preglac]	−1.842	0.754	−2.444
PreMaturity_Cat[T.M_immat]	−0.227	0.367	−0.617
PreMaturity_Cat[T.M_mat]	−0.835	0.347	−2.408
DateNum:BLm	−0.003	0.001	−3.151
YearNum:DateNum	−0.001	0.000	−2.787
DateNum:PreMaturity_Cat[T.F_mat]	−0.013	0.004	−2.893
DateNum:PreMaturity_Cat[T.F_preg]	0.006	0.004	1.646
DateNum:PreMaturity_Cat[T.F_preglac]	0.005	0.007	0.748
DateNum:PreMaturity_Cat[T.M_immat]	−0.001	0.003	−0.215
DateNum:PreMaturity_Cat[T.M_mat]	0.006	0.003	1.853

Table 7 Summary for the best model using BT7 of sei whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	0.0375	0.1936
Residual		0.381	0.6172
Number of obs: 1153, groups: YearCat, 14			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	−14.550	4.044	−3.597
BLm	1.179	0.292	4.033
DateNum	0.007	0.002	4.414
F_lat	0.395	0.098	4.026
FirstS	−0.001	0.000	−2.546
wtemp	0.004	0.011	0.393
PreMaturity_CatF_mat	0.044	0.099	0.444
PreMaturity_CatF_preg	0.822	0.081	10.119
PreMaturity_CatF_preglac	−0.649	0.128	−5.093
PreMaturity_CatM_immat	−0.265	0.073	−3.609
PreMaturity_CatM_mat	−0.052	0.069	−0.749
BLm:F_lat	−0.026	0.007	−3.688

Table 8 Summary for the best model using umbilicus girth of sei whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	19.68	4.437
Residual		166.89	12.919
Number of obs: 1145, groups: YearCat, 14			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	15.823	7.893	2.000
BLm	17.469	0.552	31.670
DateNum	0.169	0.018	9.410
FirstS	0.010	0.005	2.090
wtemp	0.156	0.177	0.880
PreMaturity_CatF_mat	−2.057	2.075	−0.990
PreMaturity_CatF_preg	19.503	1.699	11.480
PreMaturity_CatF_preglac	−16.341	2.698	−6.060
PreMaturity_CatM_immat	−5.238	1.539	−3.400
PreMaturity_CatM_mat	−4.524	1.450	−3.120

Table 9 Summary for the best model using axillary girth of sei whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	35.69	5.974
Residual		185.46	13.618
Number of obs: 1133, groups: YearCat, 14			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	−4397.000	2769.000	−1.588
YearNum	2.183	1.379	1.584
BLm	726.400	192.000	3.784
DateNum	0.141	0.019	7.258
FirstS	0.003	0.005	0.638
wtemp	−0.071	0.188	−0.381
PreMaturity_CatF_mat	−0.256	2.233	−0.115
PreMaturity_CatF_preg	15.720	1.809	8.689
PreMaturity_CatF_preglac	−12.710	2.825	−4.499
PreMaturity_CatM_immat	−4.704	1.640	−2.868
PreMaturity_CatM_mat	−4.101	1.542	−2.659
YearNum:BLm	−0.351	0.096	−3.671

Table 10 Summary of the full and best models for each response variable in Bryde's whale.

Response	model type	The independent variables of each model
BT11	Full model	YearNum + BLm + DateNum + F_lat + F_long + FirstS + wtemp + LatCat + LongCat + PreMaturity_Cat + MainPreyS + PreMaturity_Cat:F_long + (1|YearCat)
	Best model	BLm + DateNum + FirstS + wtemp + PreMaturity_Cat + (1 | YearCat)
BT7	Full model	YearNum + BLm + DateNum + F_lat + F_long + FirstS + wtemp + LatCat + LongCat + PreMaturity_Cat + MainPreyS + BLm:F_long + PreMaturity_Cat:F_long + YearNum:F_long + BLm:F_long:YearNum + (1|YearCat) + (DateNum|LatCat)
	Best model	BLm + DateNum + FirstS + PreMaturity_Cat + (1 | YearCat) + (DateNum | LatCat)
Umbilicus Girth	Full model	YearNum + BLm + DateNum + F_lat + F_long + FirstS + wtemp + LatCat + LongCat + PreMaturity_Cat + MainPreyS +BLm:PreMaturity_Cat + PreMaturity_Cat:YearNum+ (1|YearCat)
	Best model	BLm + DateNum + FirstS + wtemp + PreMaturity_Cat + (1 | YearCat)
Axillary Girth	Full model	YearNum + BLm + DateNum + F_lat + F_long + FirstS + $wtemp^2$ + LatCat + LongCat + PreMaturity_Cat + MainPreyS + YearNum:BLm + (1|YearCat)
	Best model	YearNum + BLm + FirstS + I(wtemp^2) + PreMaturity_Cat + (1 | YearCat) + YearNum:BLm

Table 11 Summary for the best model using BT11 of Bryde's whales as the response variable.

Random effects				
Groups	Name	Variance	Std.Dev.	
YearCat	(Intercept)	0.082	0.286	
Residual	0.6625	0.814		
Fixed effects				
	Estimate	Std.Error	t-value	
(Intercept)	1.346	0.927	1.452	
BLm	0.117	0.049	2.409	
DateNum	0.008	0.003	2.97	
FirstS	0.000	0.000	−0.284	
wtemp	0.040	0.022	1.813	
PreMaturity_Cat[T.F_immat]	0.262	0.596	0.44	
PreMaturity_Cat[T.F_mat]	0.321	0.590	0.544	
PreMaturity_Cat[T.F_preg]	1.221	0.585	2.086	
PreMaturity_Cat[T.F_preglac]	−0.040	0.618	−0.065	
PreMaturity_Cat[T.M_immat]	−0.014	0.596	−0.023	
PreMaturity_Cat[T.M_mat]	−0.080	0.586	−0.136	

Table 12 Summary for the best model using BT7 of Bryde's whales as the response variable.

Random effects:				
Groups	Name	Variance	Std.Dev.	Corr
YearCat	(Intercept)	0.085	0.292	
LatCat	(Intercept)	0.033	0.182	
	DateNum	0.000	0.001	−1
Residual		0.383	0.618	
Number of obs: 506, groups: YearCat, 14; LatCat, 5				
Fixed effects:				
	Estimate	Std. Error	t value	
(Intercept)	2.221	0.677	3.282	
BLm	0.084	0.037	2.247	
DateNum	0.009	0.002	4.648	
FirstS	0.000	0.000	0.052	
PreMaturity_Cat[T.F_immat]	−0.352	0.456	−0.772	
PreMaturity_Cat[T.F_mat]	−0.065	0.450	−0.143	
PreMaturity_Cat[T.F_preg]	0.414	0.446	0.929	
PreMaturity_Cat[T.F_preglac]	−0.431	0.471	−0.914	
PreMaturity_Cat[T.M_immat]	−0.504	0.456	−1.107	
PreMaturity_Cat[T.M_mat]	−0.192	0.447	−0.431	

Table 13 Summary for the best model using umbilicus girth of Bryde's whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	43.110	6.566
Residual		168.470	12.979
Number of obs: 505, groups: YearCat, 14			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	−18.268	14.875	−1.228
BLm	16.199	0.774	20.940
DateNum	0.125	0.045	2.780
FirstS	0.010	0.007	1.475
wtemp	0.591	0.353	1.671
PreMaturity_Cat[T.F_immat]	31.588	9.514	3.320
PreMaturity_Cat[T.F_mat]	37.977	9.429	4.028
PreMaturity_Cat[T.F_preg]	49.735	9.346	5.322
PreMaturity_Cat[T.F_preglac]	31.900	9.879	3.229
PreMaturity_Cat[T.M_immat]	31.123	9.514	3.271
PreMaturity_Cat[T.M_mat]	31.902	9.351	3.412

Table 14 Summary for the best model using axillary girth of Bryde's whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	269.500	16.420
Residual		189.100	13.750
Number of obs: 503, groups: YearCat, 14			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	−7739.000	3658.000	−2.115
YearNum	3.848	1.824	2.110
BLm	1649.000	242.300	6.805
FirstS	0.008	0.007	1.097
I(wtemp^2)	0.020	0.008	2.494
PreMaturity_Cat[T.F_immat]	31.230	10.090	3.097
PreMaturity_Cat[T.F_mat]	40.810	10.000	4.081
PreMaturity_Cat[T.F_preg]	47.580	9.911	4.800
PreMaturity_Cat[T.F_preglac]	32.590	10.500	3.104
PreMaturity_Cat[T.M_immat]	29.890	10.090	2.963
PreMaturity_Cat[T.M_mat]	34.650	9.919	3.494
YearNum:BLm	−0.812	0.121	−6.722

Table 15 Summary of the full and best models for each response variable in common minke whale from JARPN and JARPN II period (1994-2015).

Response	model type	The independent variables of each model
BT11	Full model	YearNum + BLm + DateNum + F_lat + F_long + PreMaturity_Cat + LatCat + LongCat + OJ75 + BLm:DateNum + BLm:LongCat + BLm:DateNum + BLm:LongCat + YearNum:DateNum + F_long:LongCat + BLm:DateNum:LongCat + BLm:DateNum:F_long + BLm:DateNum:YearNum + BLm:LongCat:DateNum + YearNum:DateNum:F_long + YearNum:DateNum:LongCat + BLm:LongCat:YearNum + (1|YearCat)
	Best model	YearNum + BLm + DateNum + F_lat + F_long + PreMaturity_Cat + LatCat + OJ75 + BLm:DateNum + YearNum:DateNum + YearNum:BLm:DateNum + (1 | YearCat)
BT7	Full model	YearNum + BLm^2 + DateNum + F_lat + F_long + PreMaturity_Cat + LatCat + LongCat + OJ75 + PreMaturity_Cat + BLm:PreMaturity_Cat + BLm:DateNum + BLm:LongCat + YearNum:DateNum + F_long:DateNum + F_long:LongCat + BLm:DateNum:LongCat + BLm:DateNum:F_long + BLm:DateNum:YearNum + BLm:LongCat:DateNum + YearNum:DateNum:F_long + YearNum:DateNum:LongCat + BLm:LongCat:YearNum + (1|YearCat)
	Best model	YearNum + BLm^2 + DateNum + PreMaturity_Cat + OJ75 + DateNum:BLm + YearNum:DateNum + (1 | YearCat)
Umbilicus Girth	Full model	YearNum + BLm + DateNum + F_lat + F_long + PreMaturity_Cat + LatCat + LongCat + OJ75 + PreMaturity_Cat + BLm:PreMaturity_Cat +BLm:DateNum + PreMaturity_Cat:DateNum + BLm:DateNum:PreMaturity_Cat + (1 | YearCat)
	Best model	YearNum + BLm + DateNum + F_long + PreMaturity_Cat + LatCat + OJ75 + YearNum:BLm + (1 | YearCat)
Axillary Girth	Full model	YearNum + BLm + DateNum + F_lat + F_long + LatCat + LongCat + OJ75 + PreMaturity_Cat + BLm:PreMaturity_Cat + (1|YearCat)
	Best model	YearNum + BLm + DateNum + OJ75 + PreMaturity_Cat + BLm:PreMaturity_Cat + (1 | YearCat)

Table 16 Summary for the best model using BT11 of common minke whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	0.066	0.258
Residual		0.404	0.636
Number of obs: 2104, groups: YearCat, 20			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	106.600	29.110	3.661
YearNum	−0.051	0.015	−3.537
BLm	−0.284	0.040	−7.130
DateNum	0.212	0.406	0.522
F_lat	0.083	0.029	2.855
F_long	−0.015	0.003	−4.903
PreMaturity_Cat[T.F_immat]	−0.193	0.108	−1.789
PreMaturity_Cat[T.F_mat]	0.427	0.166	2.571
PreMaturity_Cat[T.F_preg]	0.863	0.104	8.310
PreMaturity_Cat[T.F_preglac]	0.135	0.462	0.292
PreMaturity_Cat[T.M_immat]	−0.281	0.104	−2.700
PreMaturity_Cat[T.M_mat]	−0.067	0.086	−0.781
LatCat[T.2]	−0.321	0.086	−3.738
LatCat[T.3]	−0.416	0.131	−3.165
LatCat[T.4]	−0.601	0.196	−3.063
LatCat[T.5]	−0.225	0.271	−0.828
OJ75[T.O]	0.304	0.047	6.449
BLm:DateNum	−0.210	0.056	−3.783
YearNum:DateNum	0.000	0.000	−0.569
YearNum:BLm:DateNum	0.000	0.000	3.849

Table 17 Summary for the best model using BT7 of common minke whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	0.049	0.222
Residual		0.257	0.507
Number of obs: 2104, groups: YearCat, 20			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	42.280	23.760	1.779
YearNum	−0.019	0.012	−1.640
I(BLm^2)	−0.020	0.002	−8.344
DateNum	−0.592	0.142	−4.169
PreMaturity_Cat[T.F_immat]	−0.165	0.087	−1.905
PreMaturity_Cat[T.F_mat]	0.512	0.132	3.884
PreMaturity_Cat[T.F_preg]	0.759	0.082	9.243
PreMaturity_Cat[T.F_preglac]	0.035	0.366	0.094
PreMaturity_Cat[T.M_immat]	−0.262	0.084	−3.105
PreMaturity_Cat[T.M_mat]	−0.080	0.068	−1.165
OJ75[T.O]	0.285	0.037	7.718
DateNum:BLm	0.003	0.000	15.188
YearNum:DateNum	0.000	0.000	4.064

Table 18 Summary for the best model using umbilicus girth of common minke whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	26.040	5.103
Residual		94.790	9.736
Number of obs: 2379, groups: YearCat, 20			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	64.300	6.353	10.121
BLm	19.000	0.670	28.374
DateNum	−0.258	0.021	−12.334
F_long	−0.142	0.035	−4.053
PreMaturity_Cat[T.F_mat]	92.146	32.389	2.845
PreMaturity_Cat[T.F_preg]	49.438	16.304	3.032
PreMaturity_Cat[T.F_preglac]	155.338	374.253	0.415
PreMaturity_Cat[T.M_immat]	−6.927	4.486	−1.544
PreMaturity_Cat[T.M_mat]	70.176	7.531	9.319
OJ75[T.O]	−0.913	0.636	−1.434
BLm:PreMaturity_Cat[T.F_mat]	−12.027	4.100	−2.933
BLm:PreMaturity_Cat[T.F_preg]	−5.262	2.111	−2.493
BLm:PreMaturity_Cat[T.F_preglac]	−21.790	51.154	−0.426
BLm:PreMaturity_Cat[T.M_immat]	1.316	0.807	1.630
BLm:PreMaturity_Cat[T.M_mat]	−9.578	1.089	−8.796
BLm:DateNum	0.048	0.003	14.190

Table 19 Summary for the best model using axillary girth of common minke whales as the response variable

Random effects:			
Groups	Name	Variance	Std.Dev.
YearCat	(Intercept)	9.341	3.056
Residual		91.176	9.549
Number of obs: 2360, groups: YearCat, 20			
Fixed effects:			
	Estimate	Std. Error	t value
(Intercept)	7.870	3.340	2.360
BLm	24.446	0.585	41.810
DateNum	0.021	0.004	5.060
OJ75[T.O]	0.312	0.622	0.500
PreMaturity_Cat[T.F_mat]	0.576	31.713	0.020
PreMaturity_Cat[T.F_preg]	40.416	15.982	2.530
PreMaturity_Cat[T.F_preglac]	126.855	366.992	0.350
PreMaturity_Cat[T.M_immat]	−3.182	4.413	−0.720
PreMaturity_Cat[T.M_mat]	53.589	7.393	7.250
BLm:PreMaturity_Cat[T.F_mat]	0.139	4.013	0.030
BLm:PreMaturity_Cat[T.F_preg]	−4.078	2.070	−1.970
BLm:PreMaturity_Cat[T.F_preglac]	−16.579	50.162	−0.330
BLm:PreMaturity_Cat[T.M_immat]	0.492	0.793	0.620
BLm:PreMaturity_Cat[T.M_mat]	−7.241	1.067	−6.780

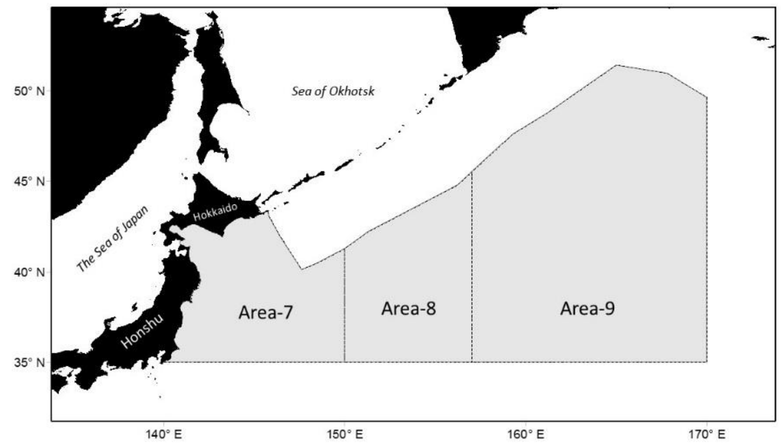

Figure 1. Map of JARPN II research area (grey highlighted). Areas 7, 8 and 9 are defined by IWC (1994).

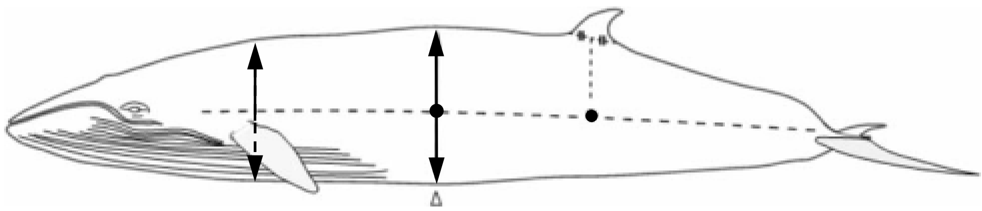

Figure 2. Position of blubber thickness and half girth measurements. Closed circles: Lateral points for blubber thickness measurements. Open triangle: position of the umbilicus. Arrows: half girth at the levels of the axilla and the umbilicus. (Cited from Konishi and Walløe, in press)

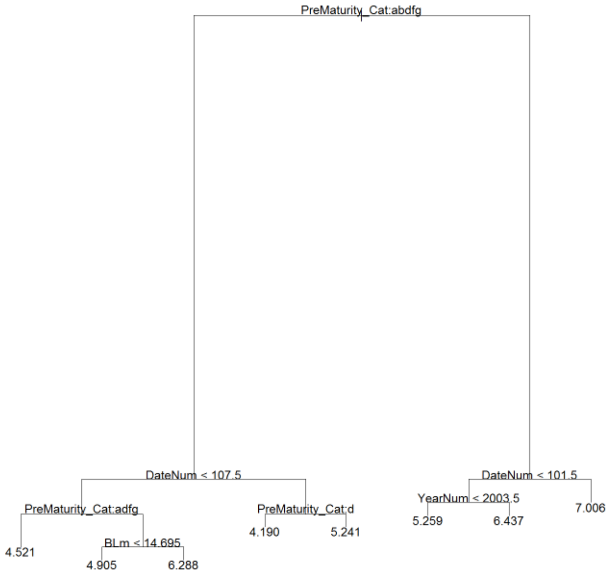

Figure 3. Dendrogram of only fixed effects model for BT11 in sei whale.

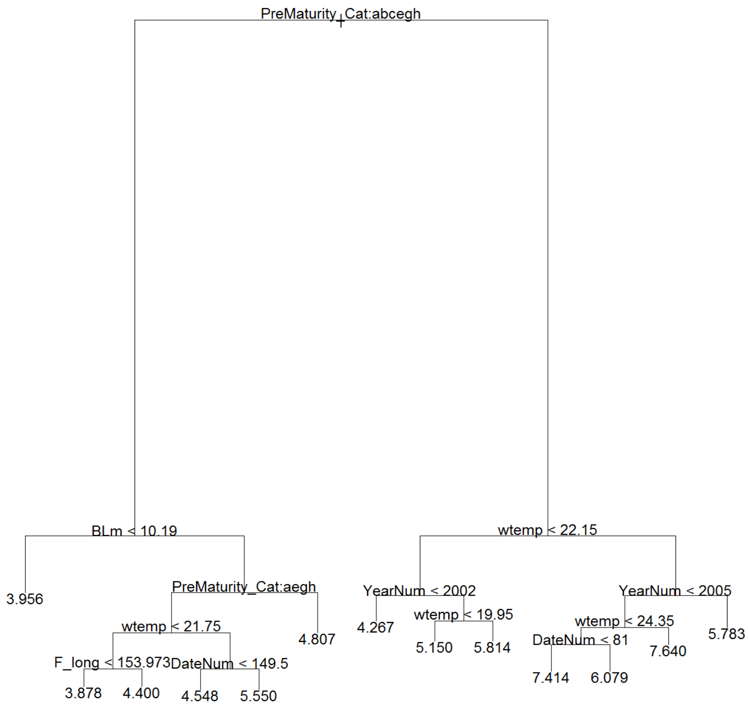

Figure 4. Dendrogram of only fixed effects model for BT7 in sei whale.

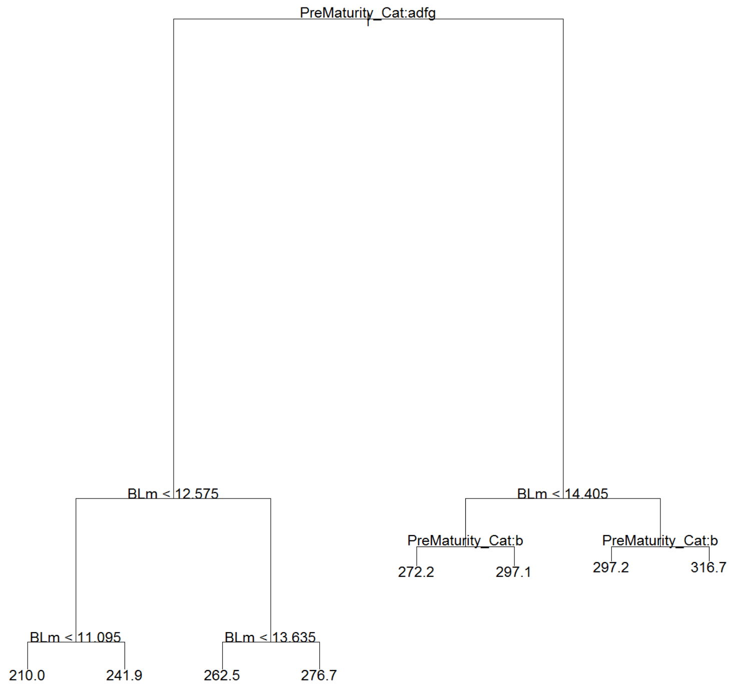

Figure 5. Dendrogram of the basic model for umbilicus girth in sei whale.

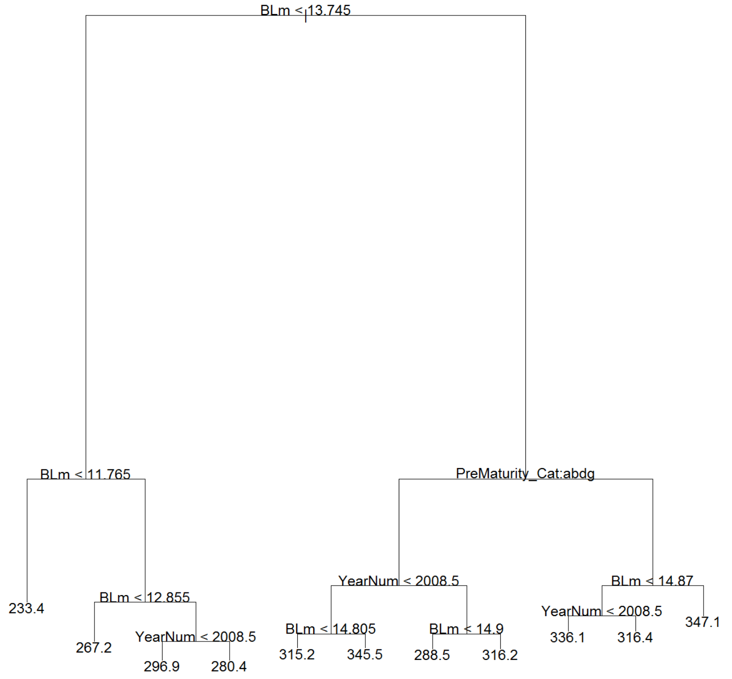

Figure 6. Dendrogram of the basic model for axillary girth in sei whale.

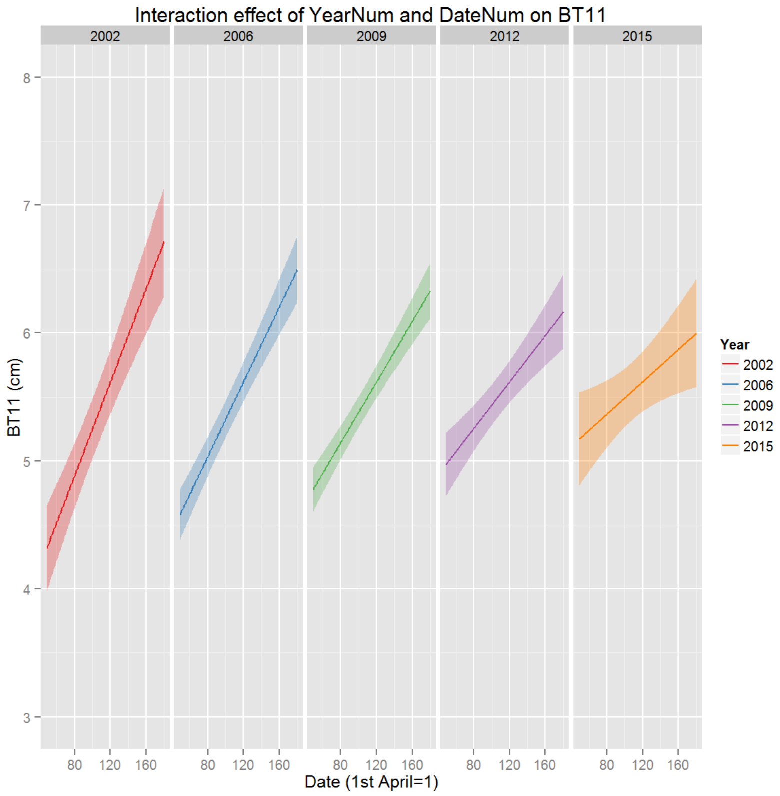

Figure 7. Interaction effect of YearNum and DateNum on BT11 in sei whale.

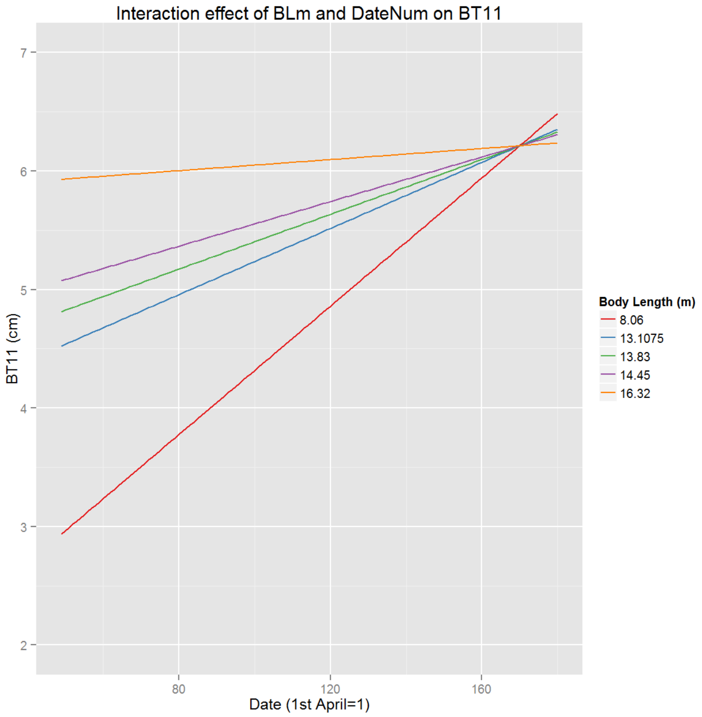

Figure 8. Interaction effect of BLm and DateNum on BT11 in sei whale. Body length was defined by 0,25,50,75,100 percentile.

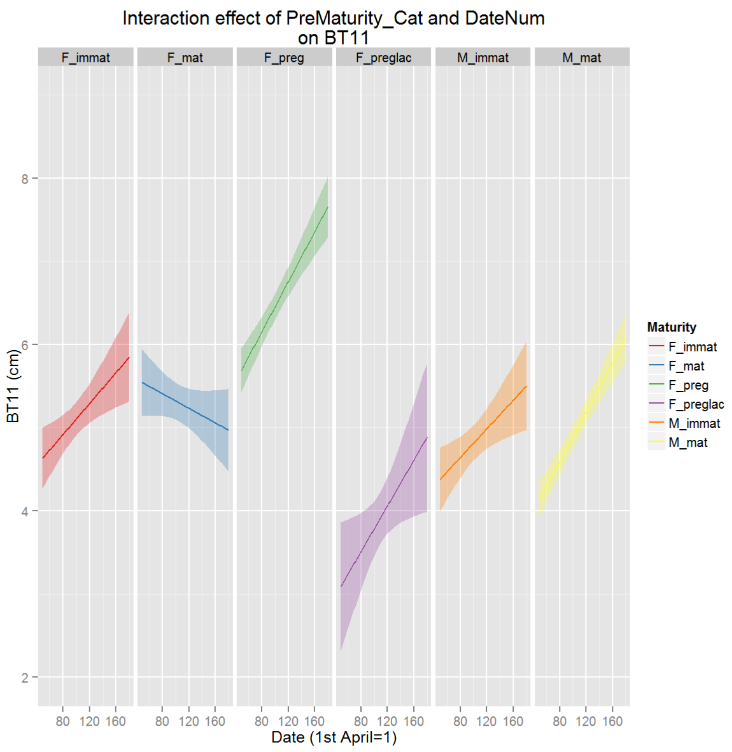

Figure 9. Interaction effect of PreMaturity_Cat and DateNum in the best model for BT11 (PreMaturity_Cat and DateNum) in sei whale. (F: female, M: male, immat: immature, mat: mature, preg: pregnant, preglac: pregnant and lactating).

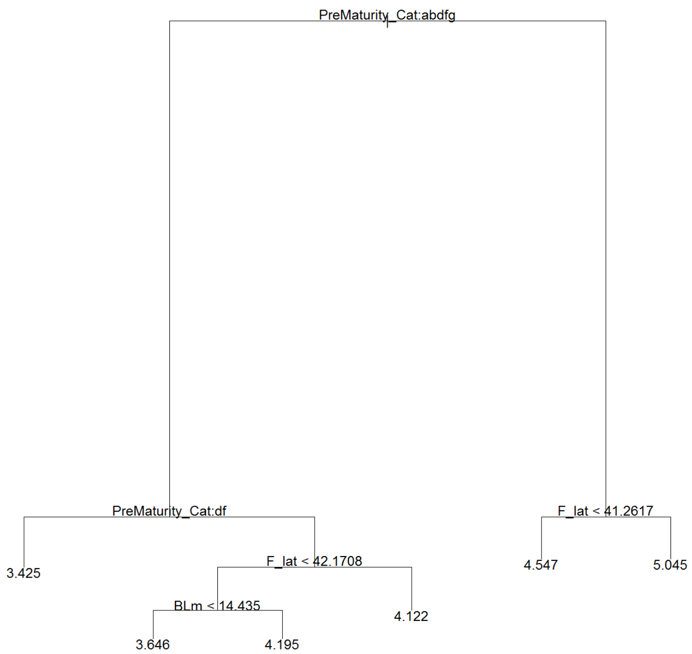

Figure 10. Dendrogram of only fixed effects model for BT11 in Bryde's whale.

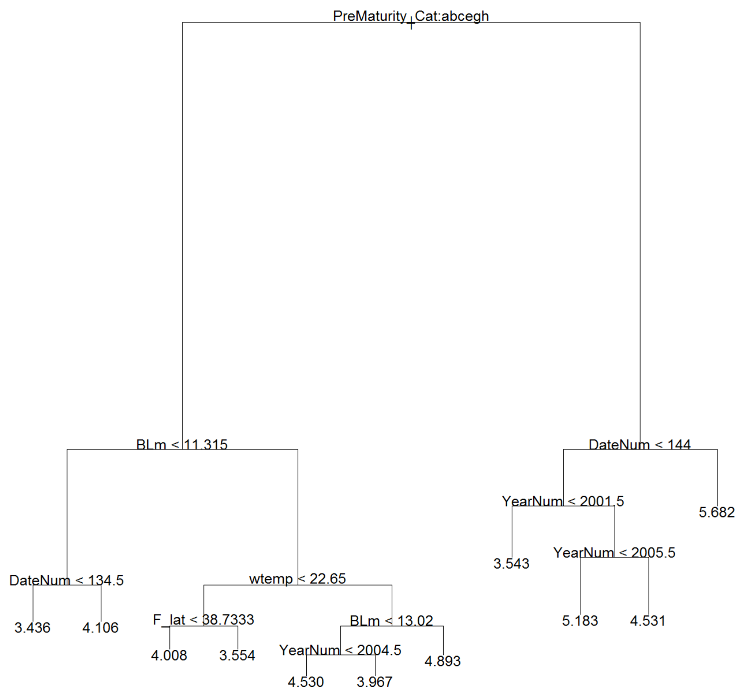

Figure 11. Dendrogram of only fixed effects model for BT7 in Bryde's whale.

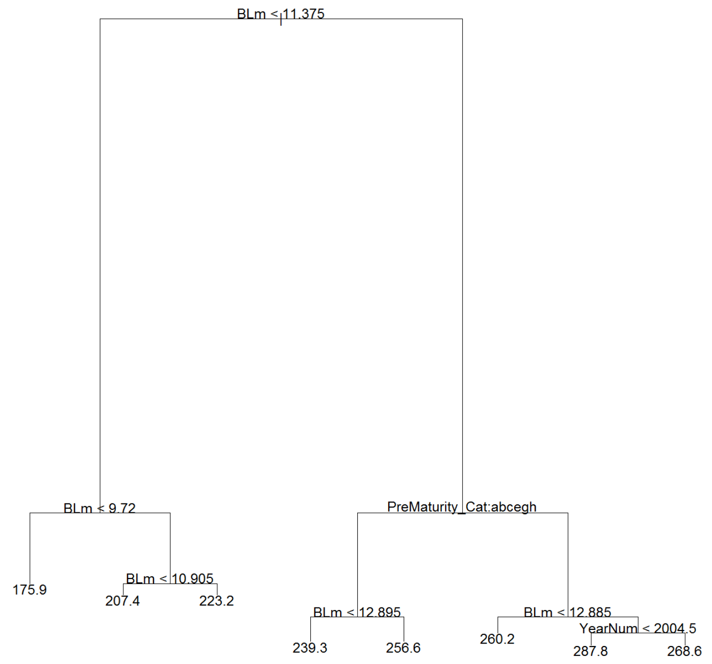

Figure 12. Dendrogram of only fixed effects model for umbilicus girth in Bryde's whale.

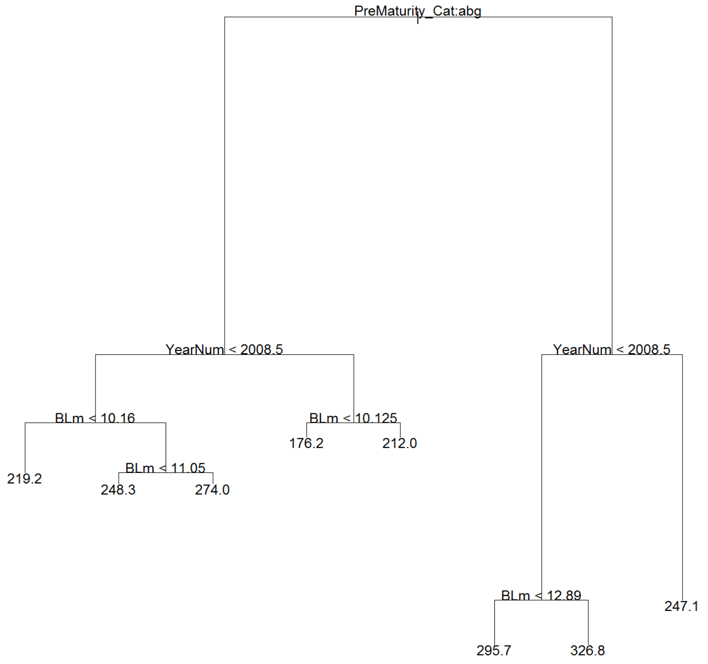

Figure 13. Dendrogram of only fixed effects model for axillary girth in Bryde's whale.

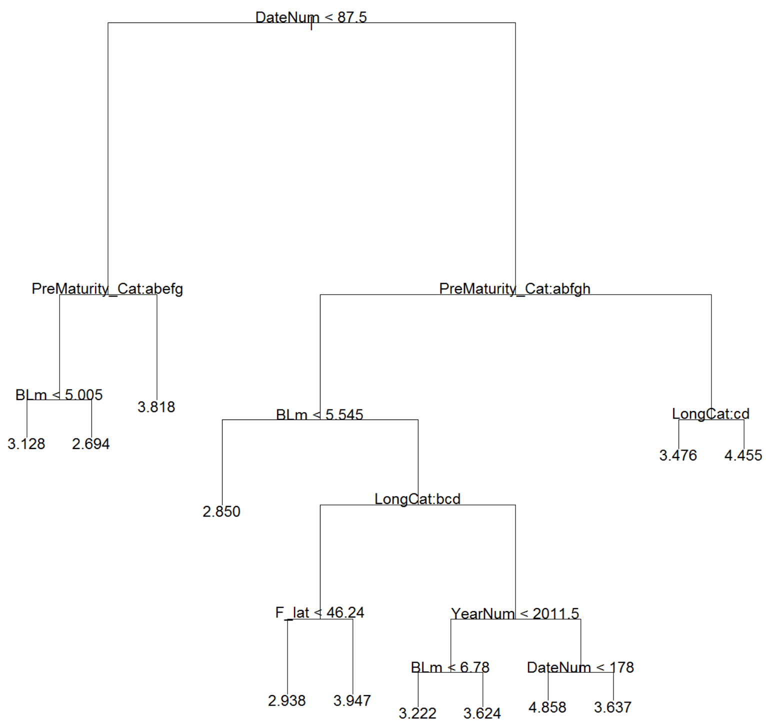

Figure 14. Dendrogram of only fixed effects model for BT11 in common minke whale.

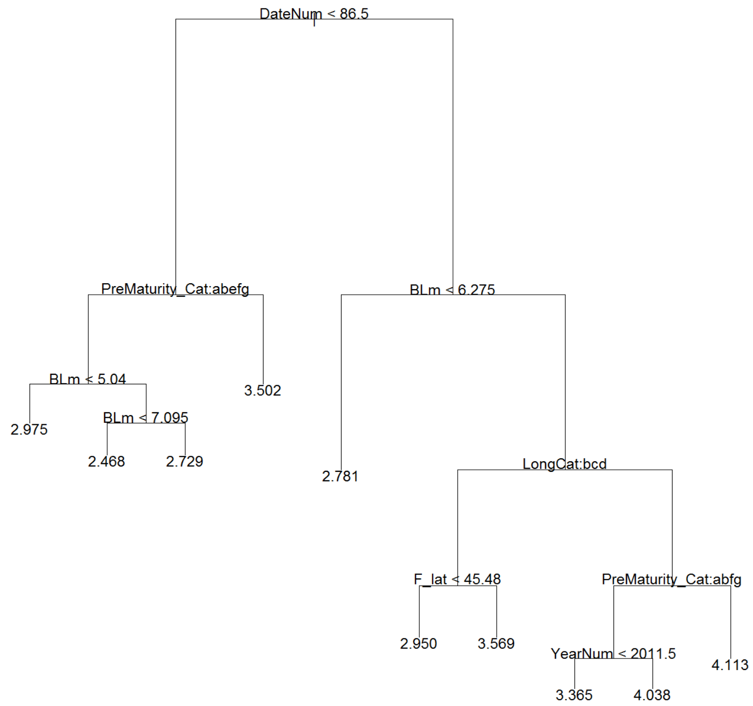

Figure 15. Dendrogram of only fixed effects model for BT7 in common minke whale.

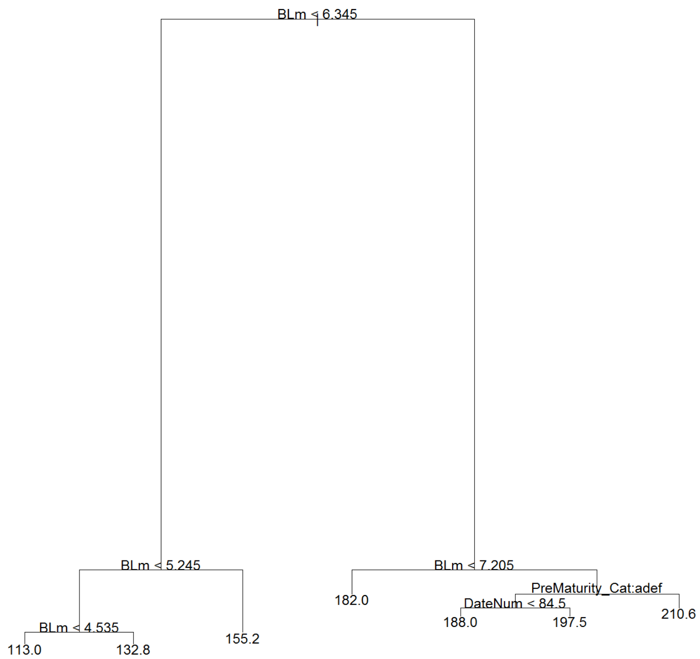

Figure 16. Dendrogram of only fixed effects model for umbilicus girth in common minke whale.

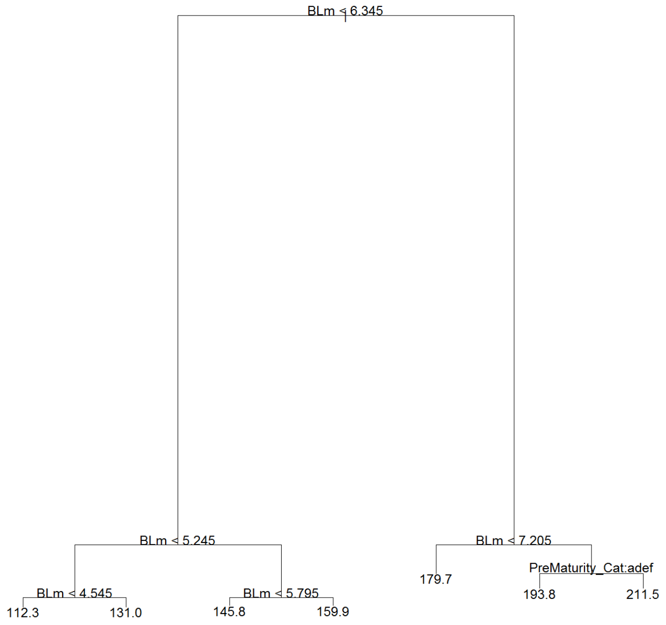

Figure 17. Dendrogram of only fixed effects model for axillary girth in common minke whale.

APPENDIX 1

SCATTER PLOTS AND DIAGNOSTIC PLOTS FOR THE BEST MODELS IN SC/F16/JR27

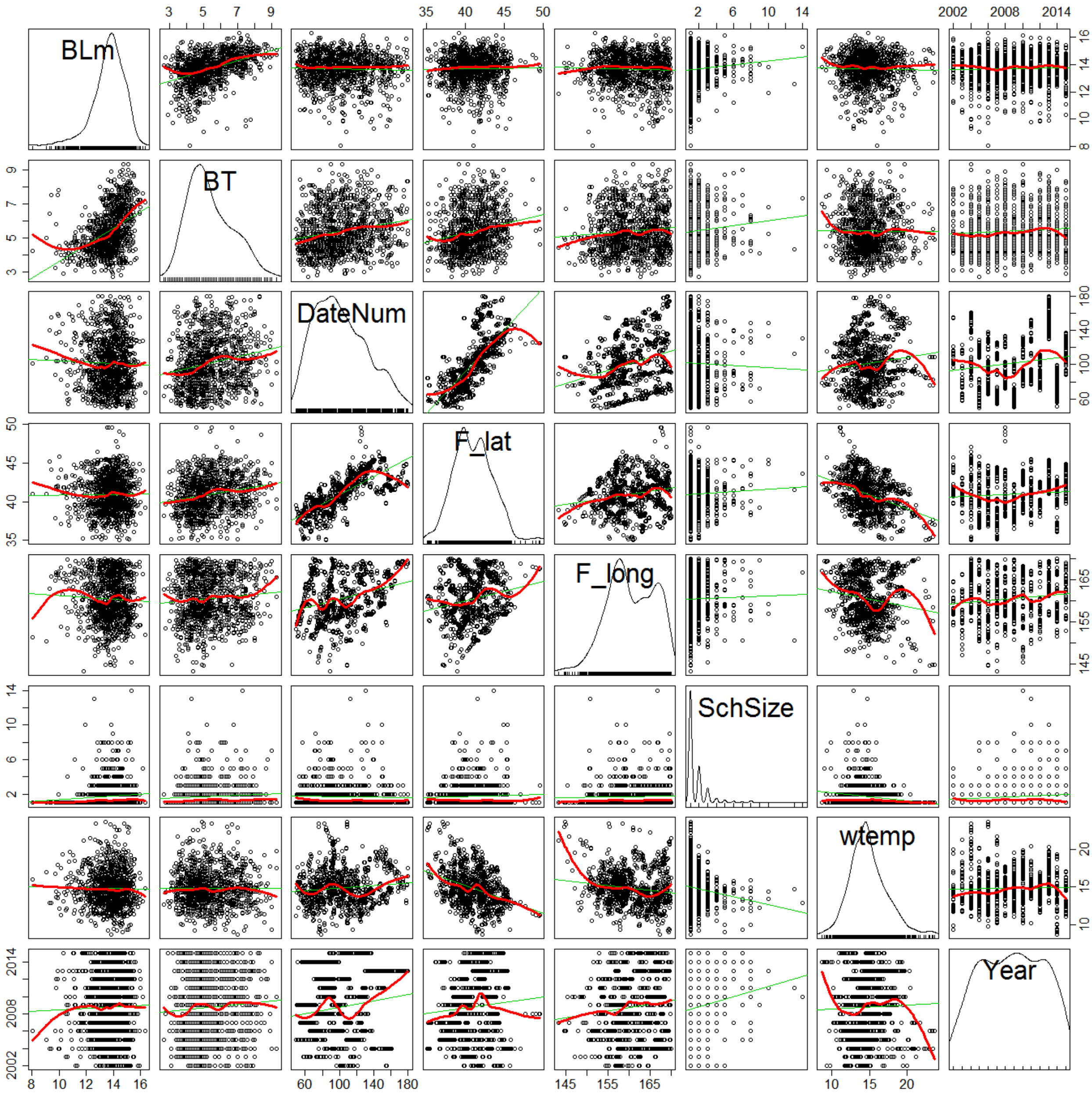

Figure 1. Scatter plots of predictor variables in sei whales sampled in JAPPN II cruise.

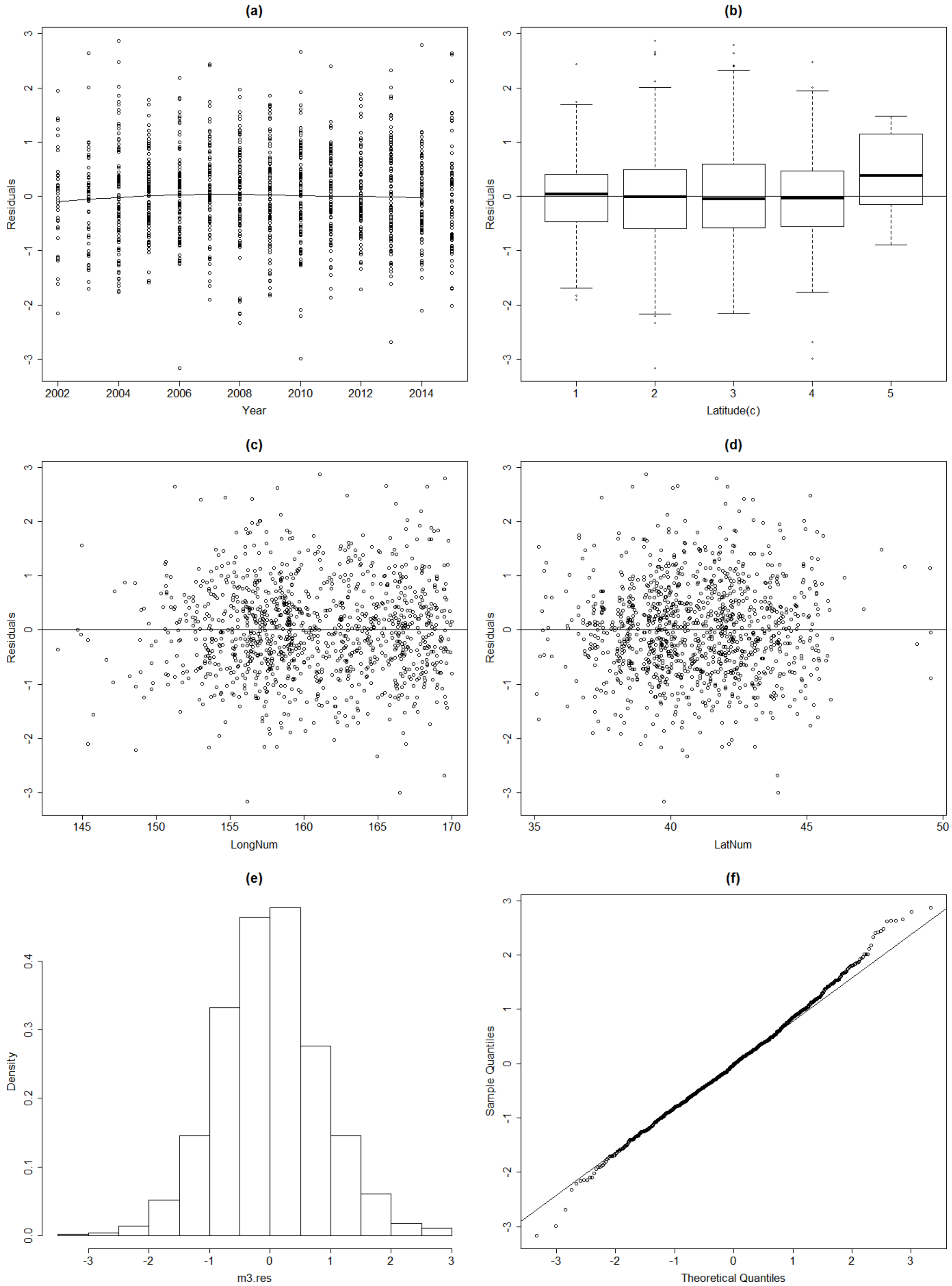

Figure 2. Diagnostic plots of the best model in BT11 of sei whale.

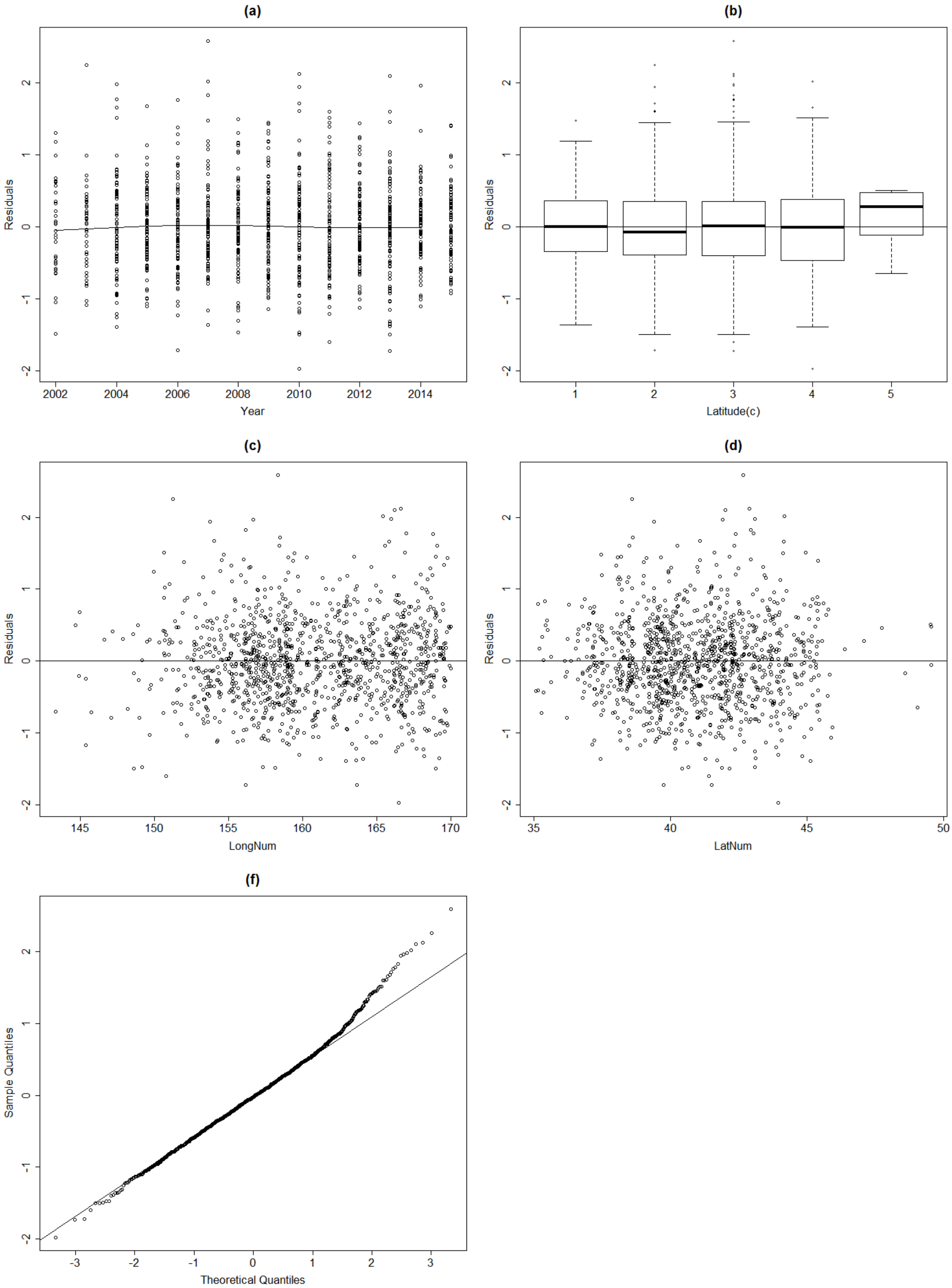

Figure 3. Diagnostic plots of the best model for BT7 in sei whale.

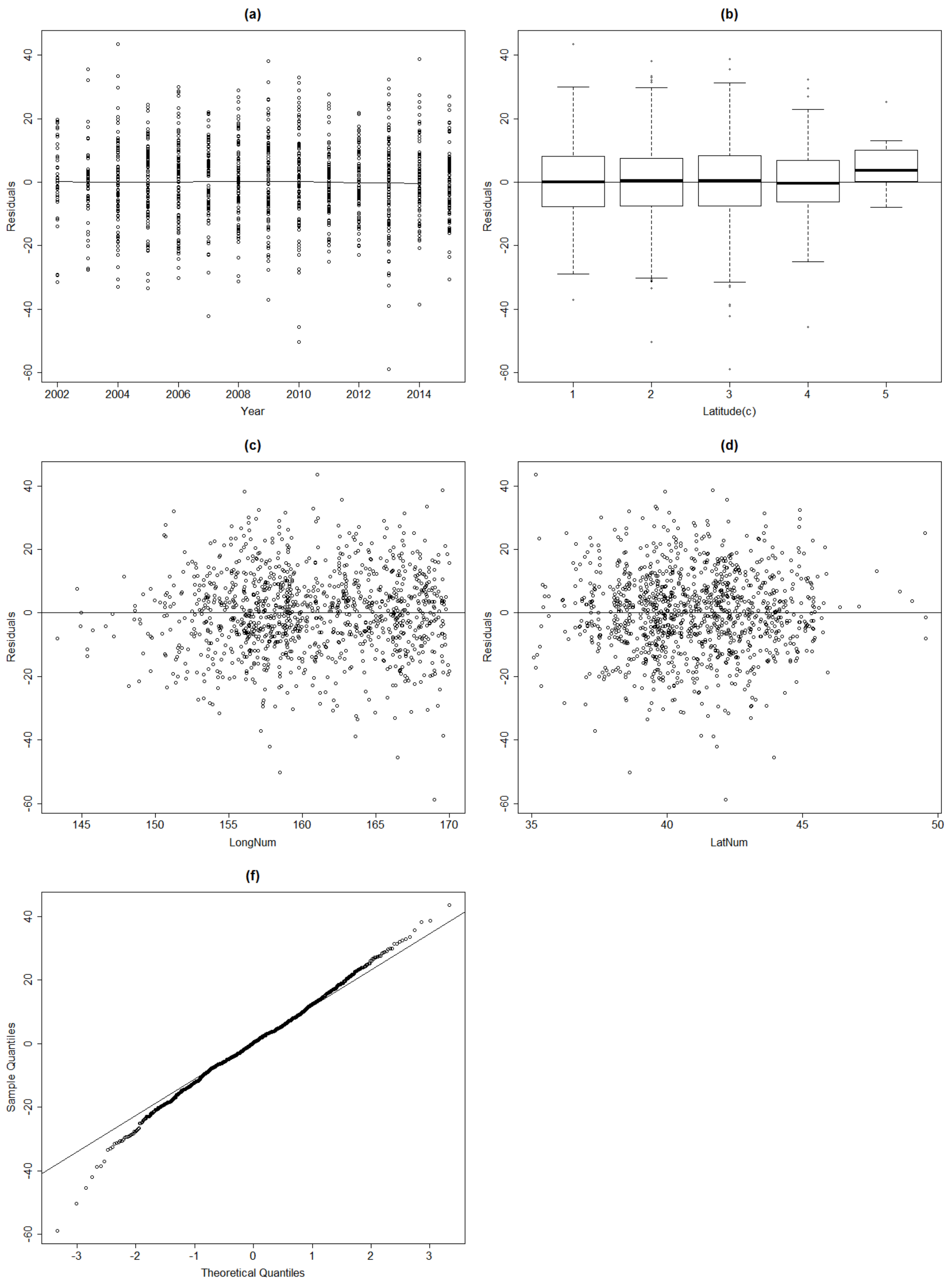

Figure 4. Diagnostic plots of the best model for umbilicus girth in sei whale.

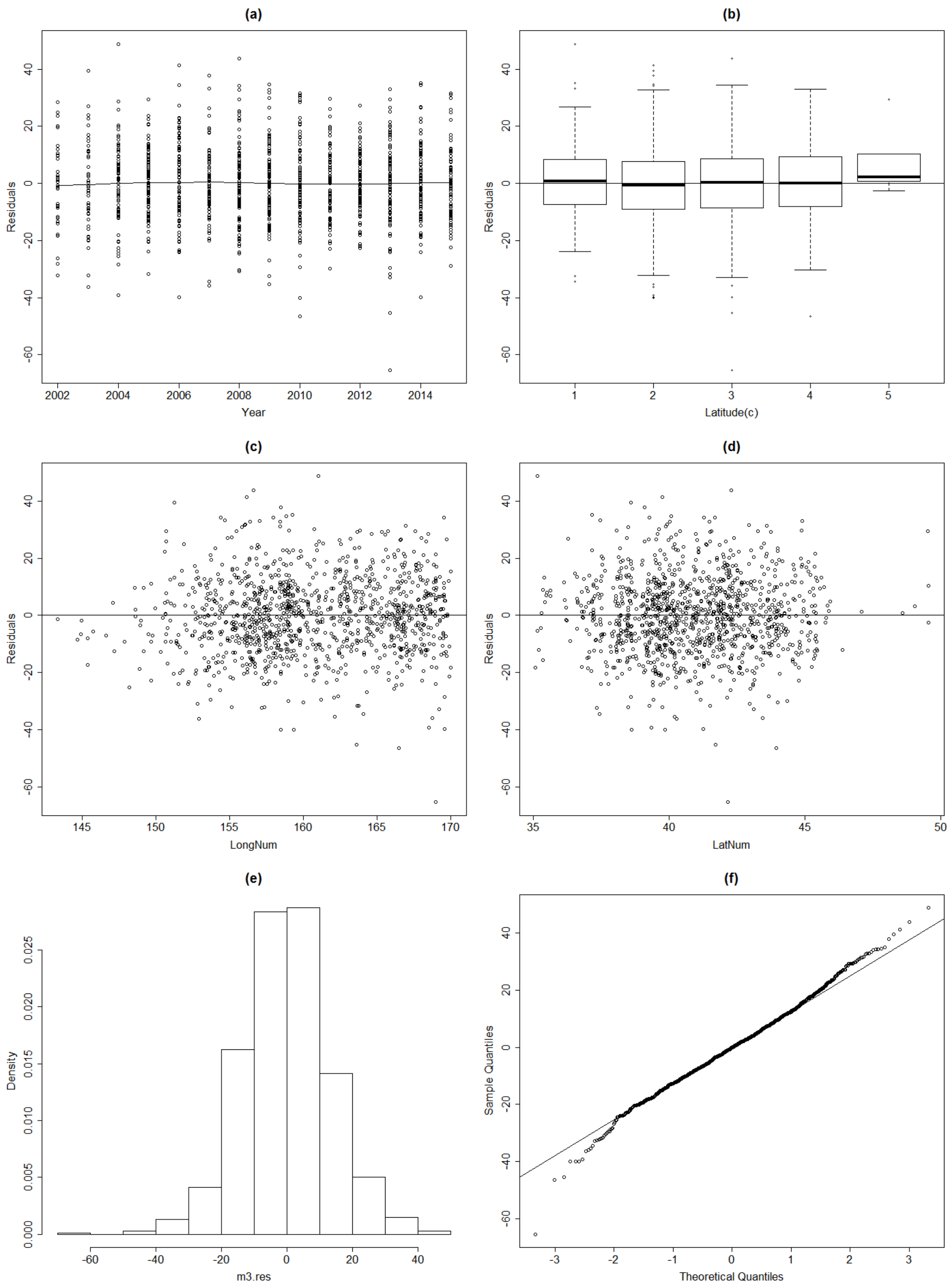

Figure 5 Diagnostic plots of the best model for axillary girth in sei whale.

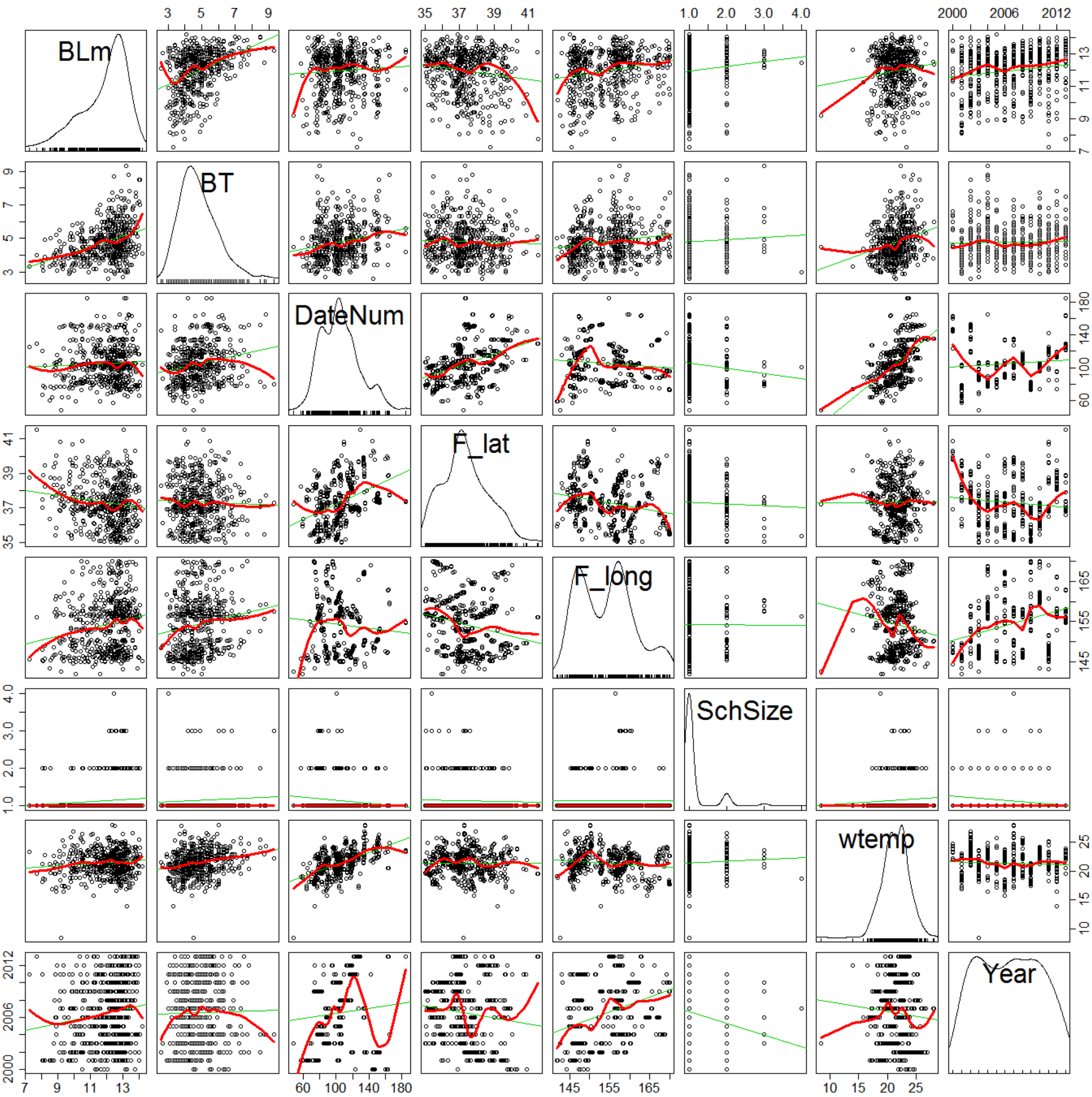

Figure 6. Scatter plots of predictor variables in Bryde's whales sampled in JAPPN II cruise.

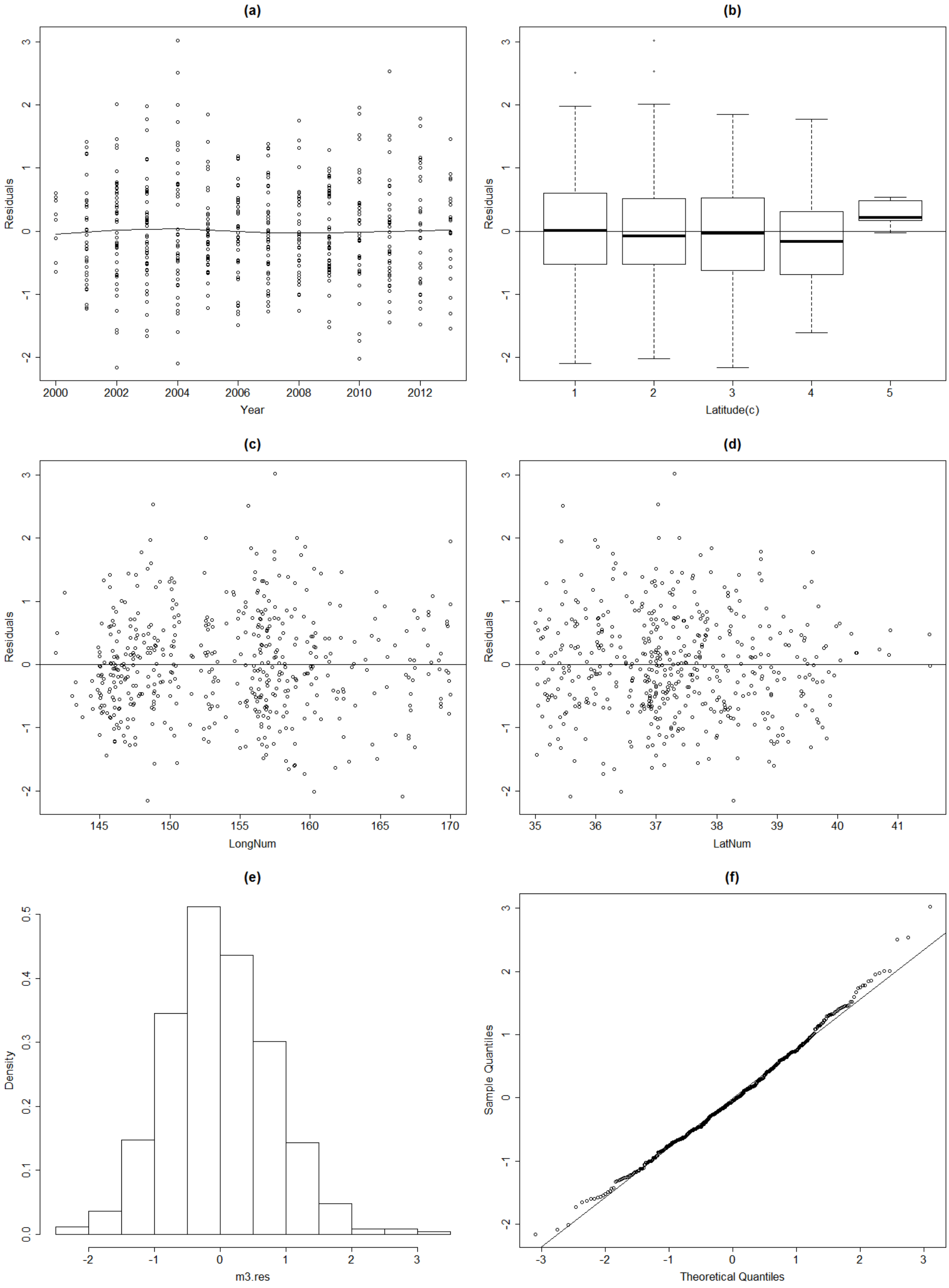

Figure 7. Diagnostic plots of the best model for BT11 in Bryde's whale.

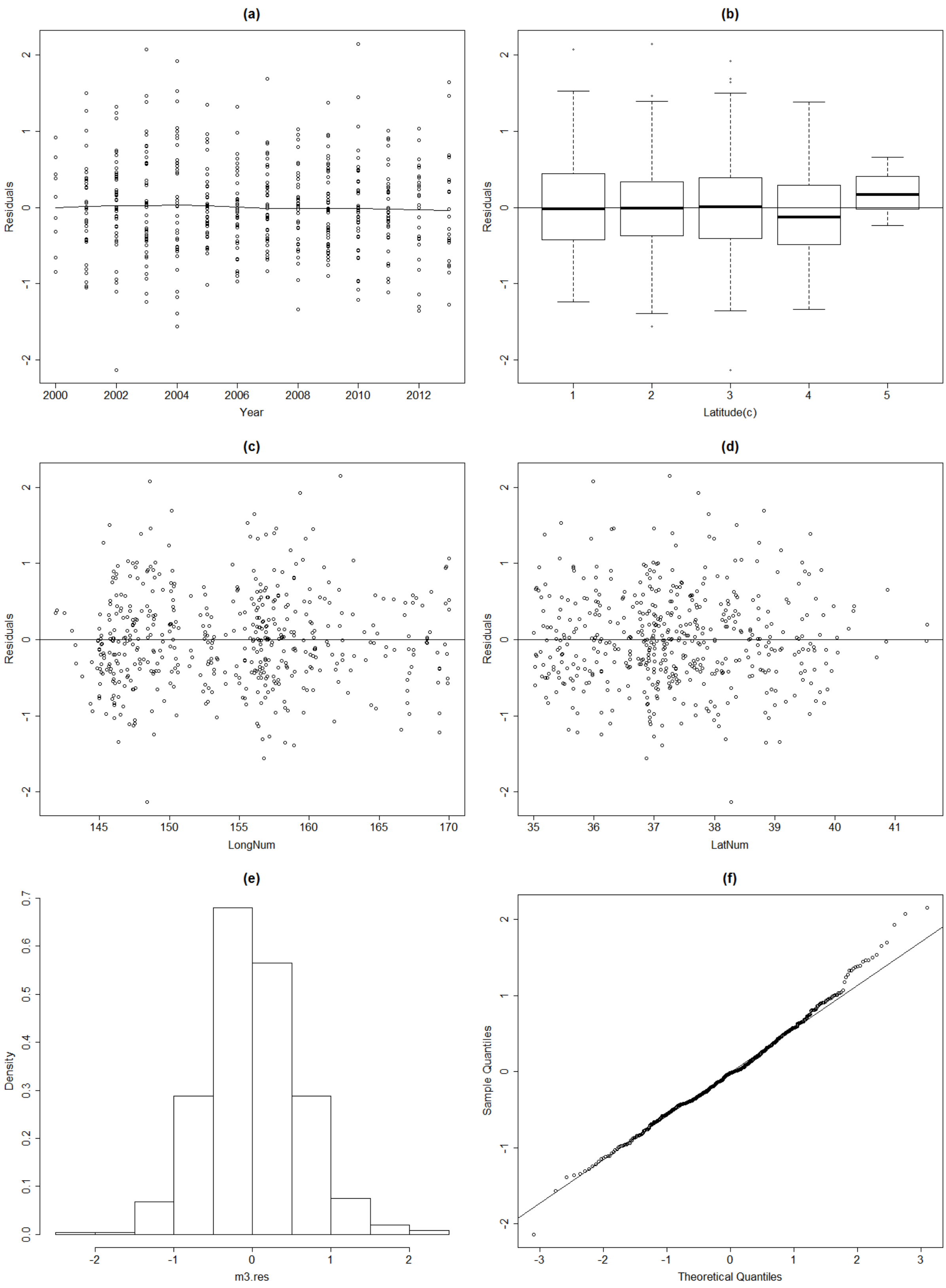

Figure 8. Diagnostic plots of the best model for BT7 in Bryde's whale.

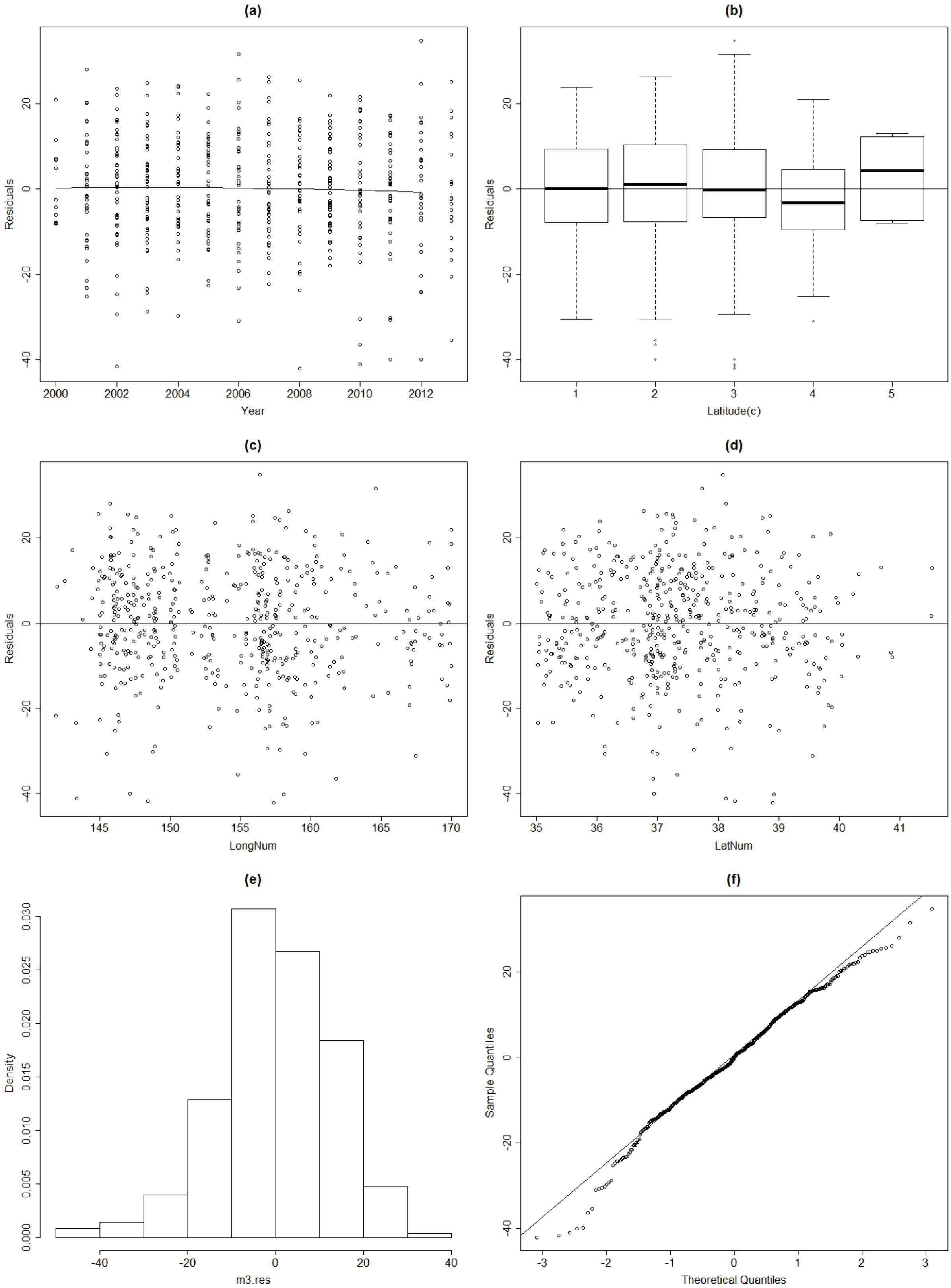

Figure 9. Diagnostic plots of the best model for umbilicus girth in Bryde's whale.

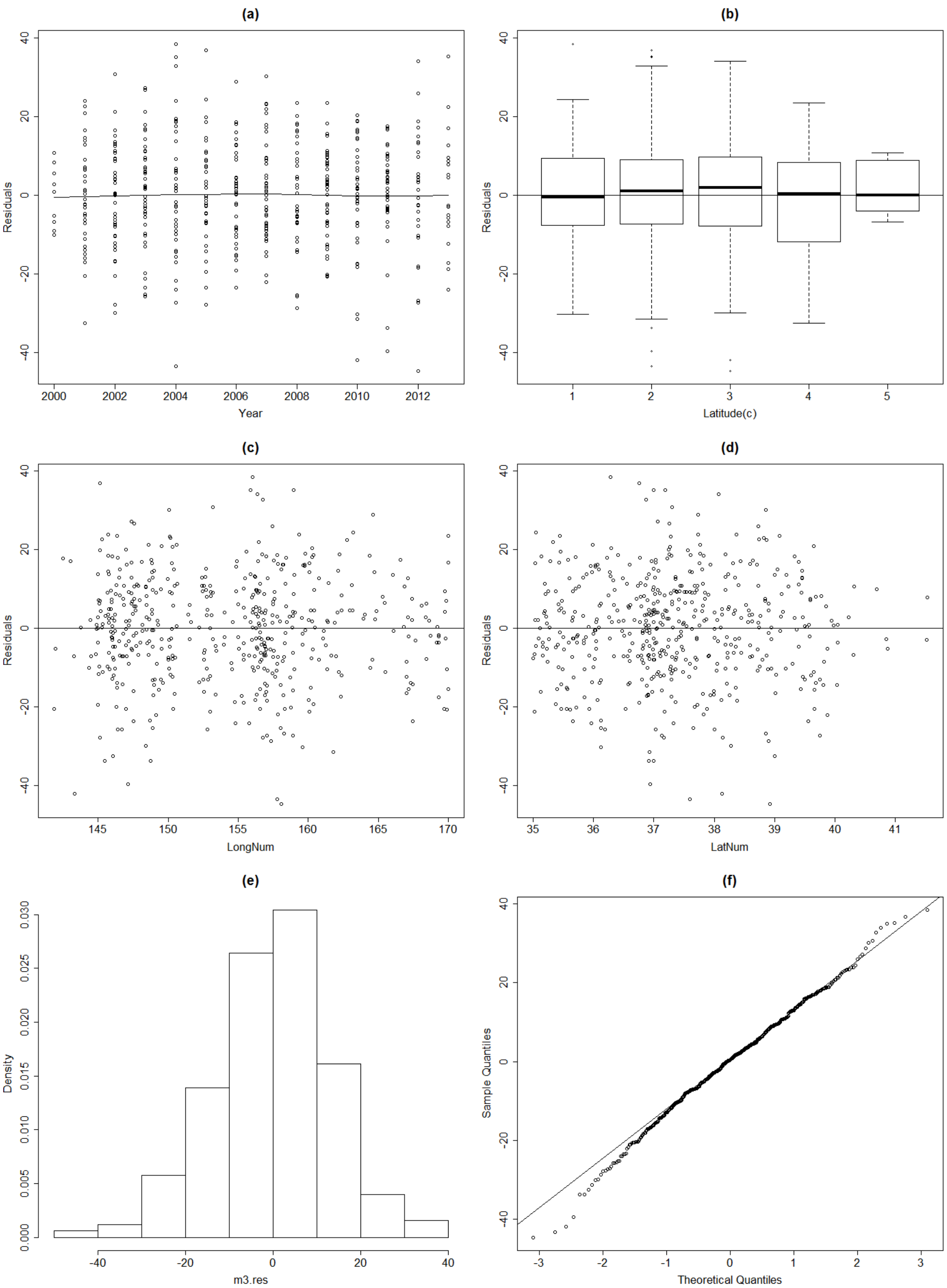

Figure 10. Diagnostic plots of the best model for axillary girth in Bryde's whale.

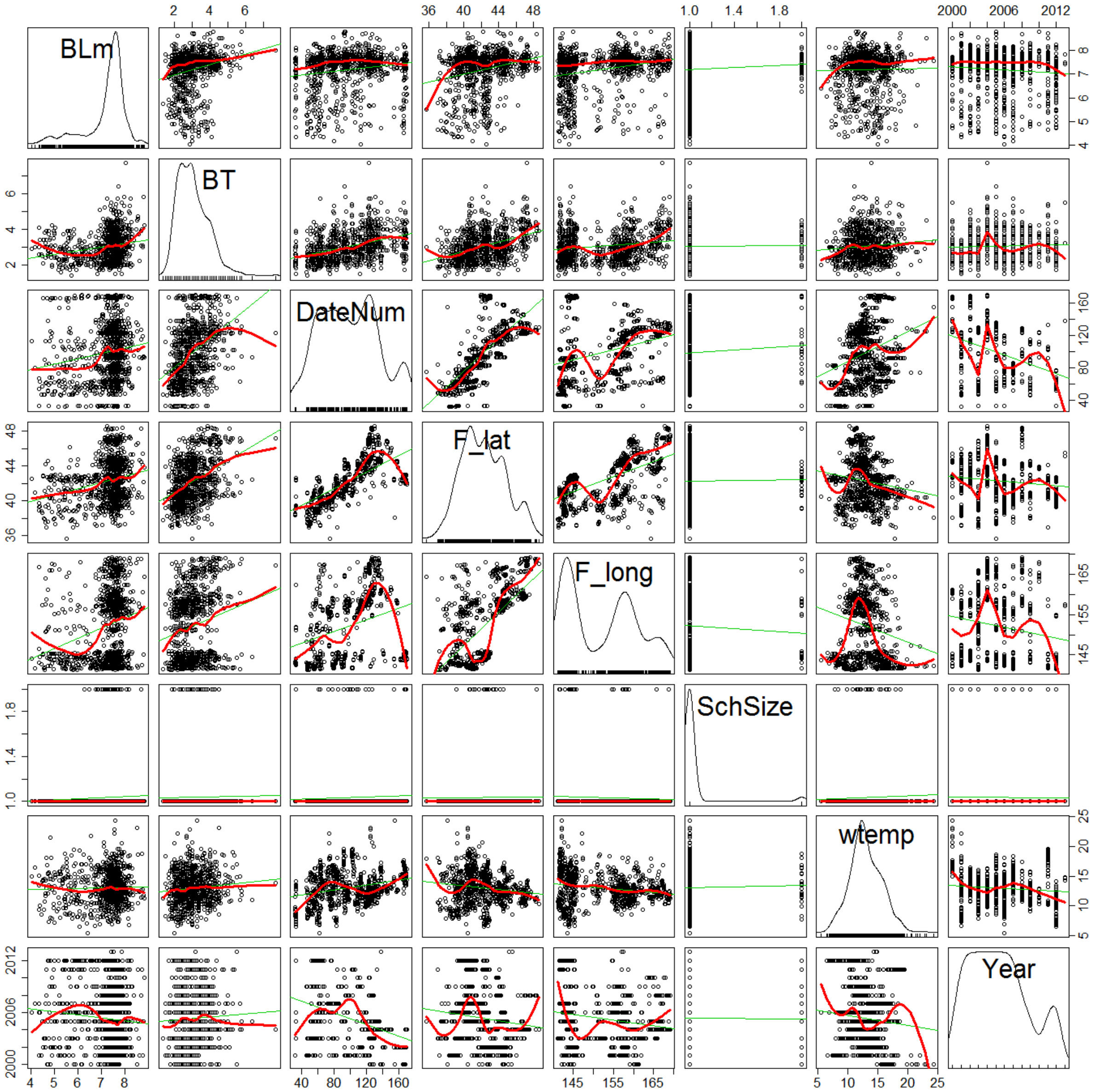

Figure 11. Scatter plots of predictor variables in common minke whales sampled in JARPN and JAPPN II cruise.

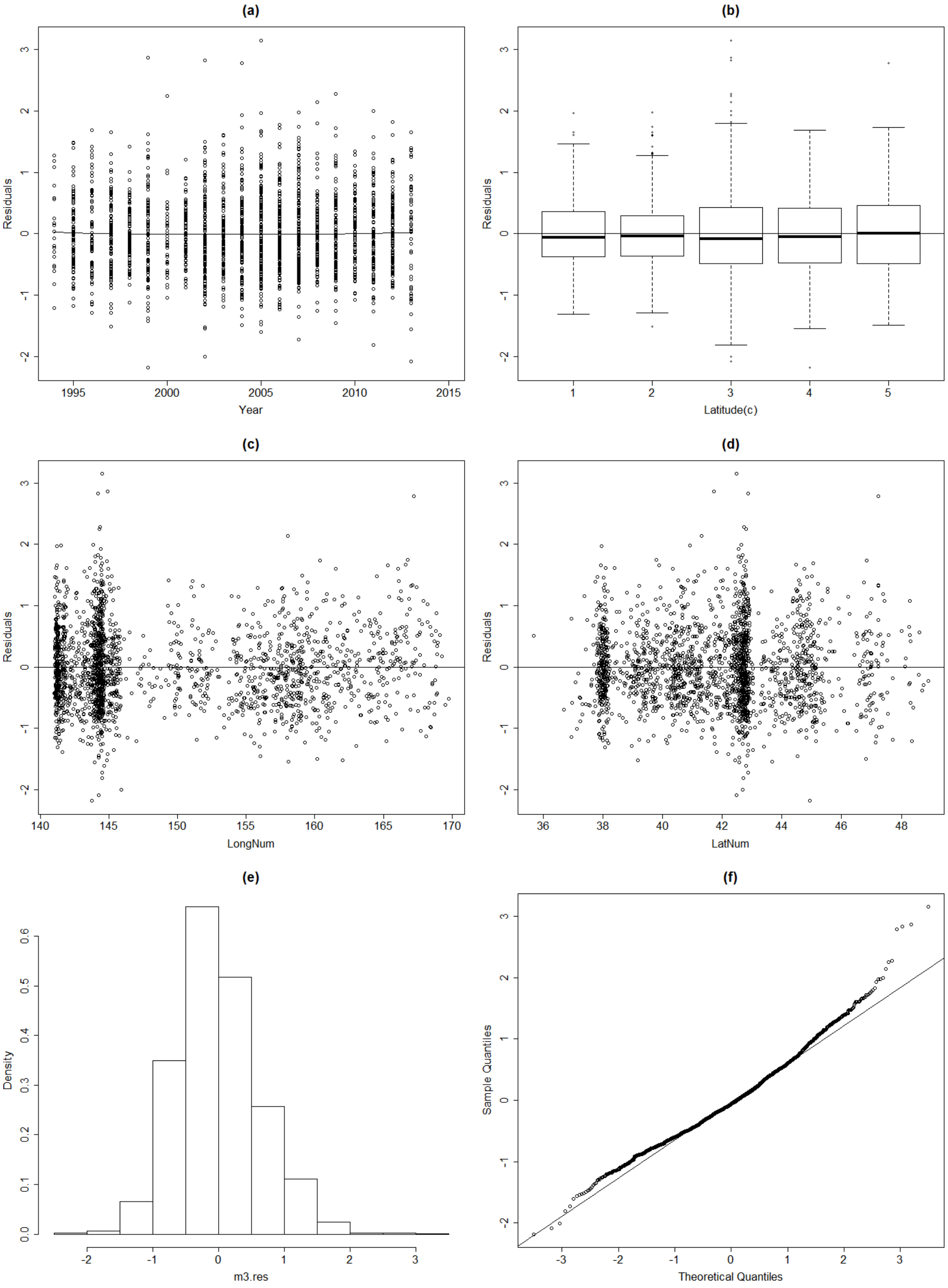

Figure 12. Diagnostic plots of the best model for BT11 in common minke whale.

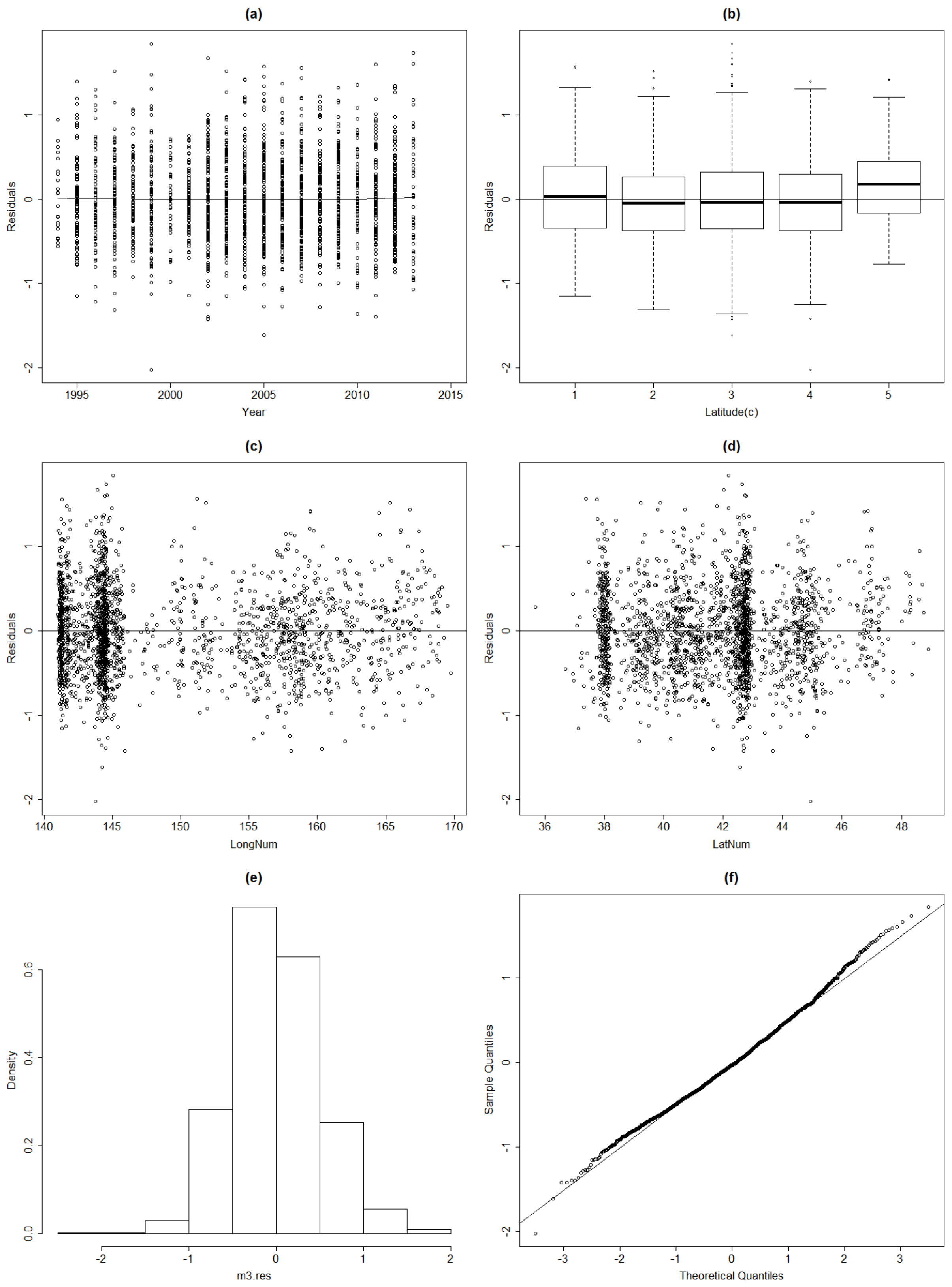

Figure 13. Diagnostic plots of the best model for BT7 in common minke whale.

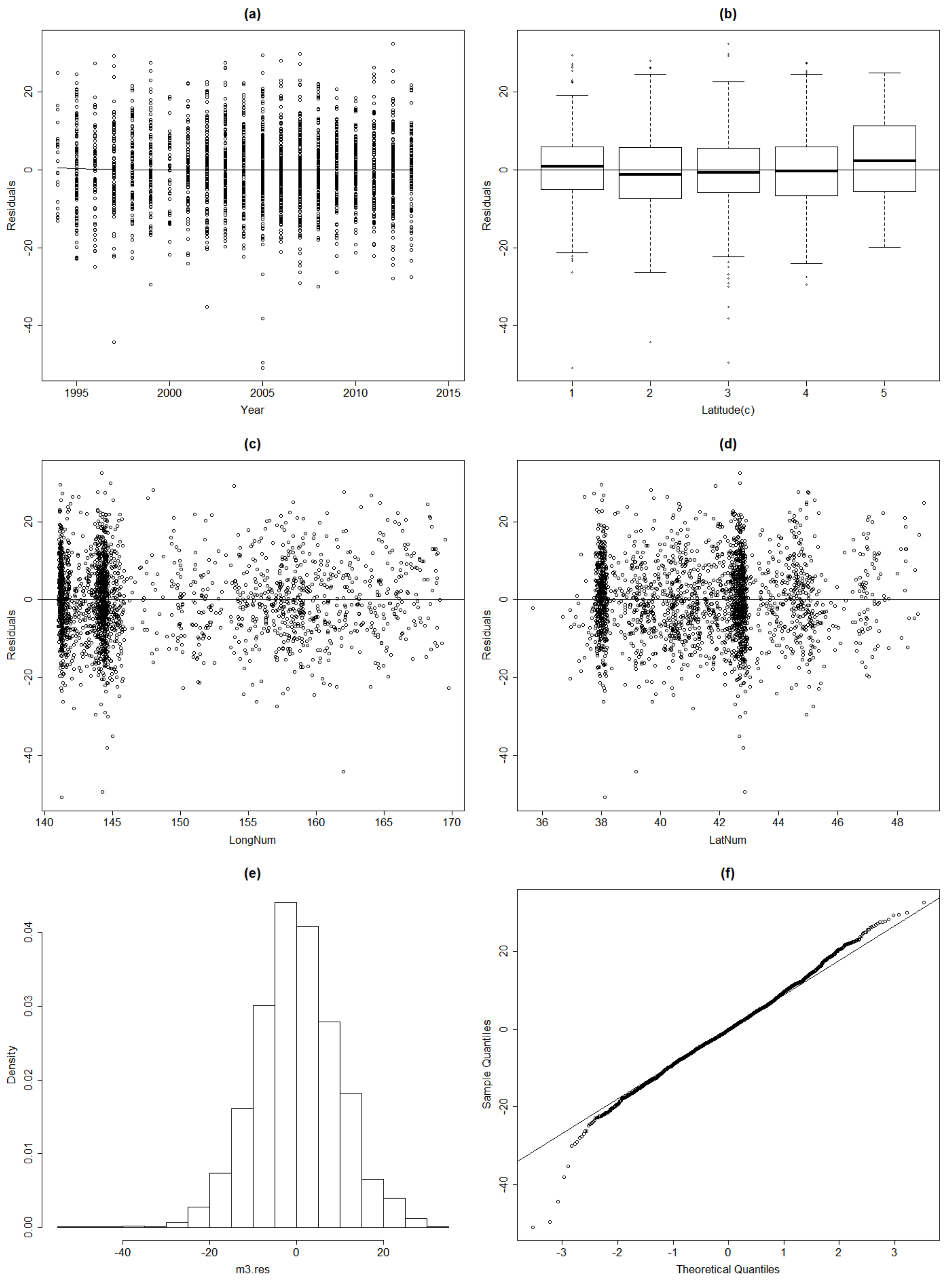

Figure 14. Diagnostic plots of the best model for umbilicus girth in common minke whale.

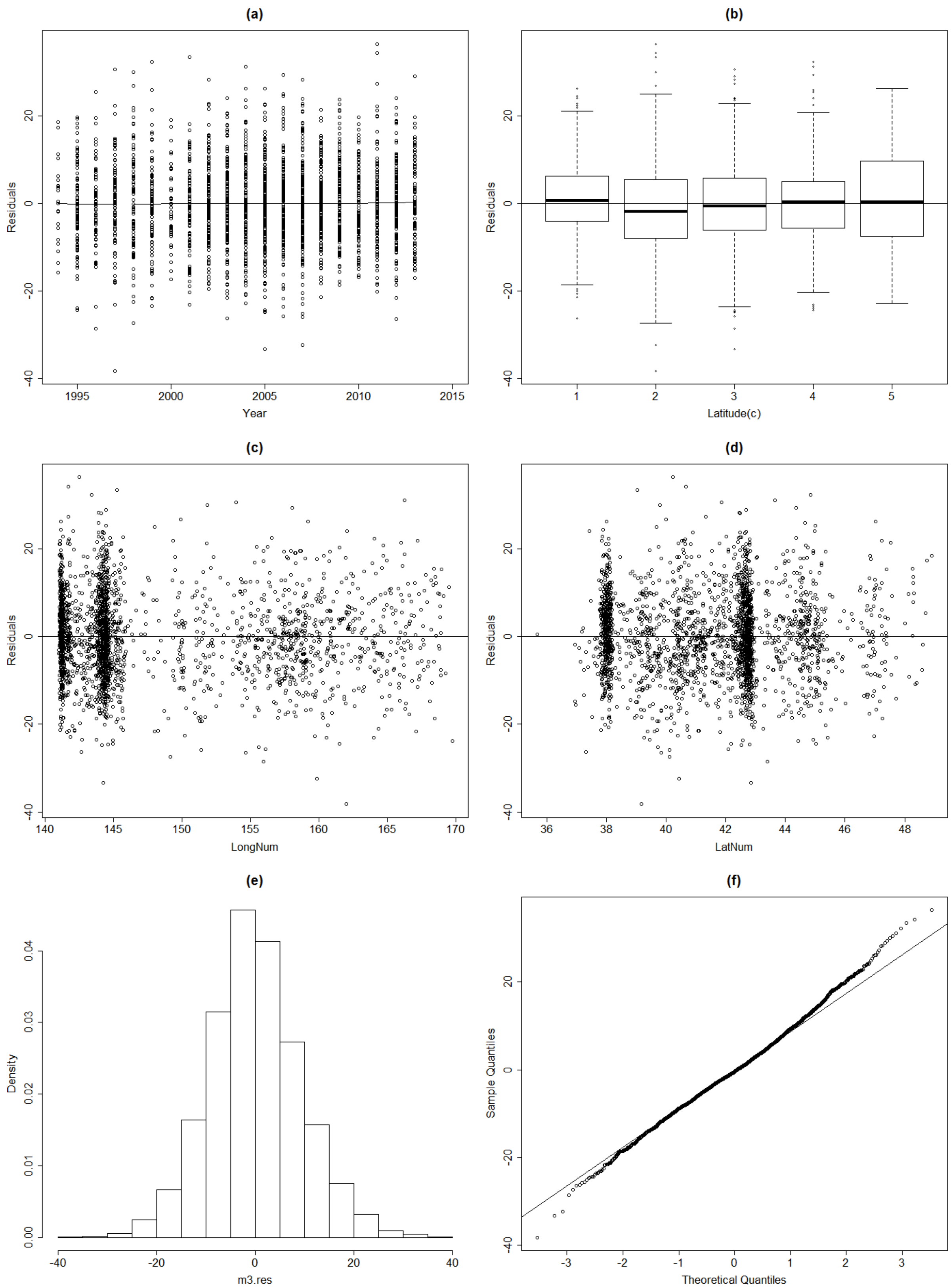

Figure 15. Diagnostic plots of the best model for axillary girth in common minke whale.