Daudt *et al.* (2025) https://doi.org/10.1016/j.ecss.2025.109405

Estuarine, Coastal and Shelf Science

Supplementary material

Changing species occurrences in seasonal seabird assemblages at the Subtropical Frontal Zone

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Briefly, in this supplementary material you will find:

- List of detailed software used in the analyses;
- Table S1: Summary table of effort;
- Table S2: Species recorded, distribution status, and breeding period;
- Fig. S1: Sea surface salinity against distance along the transect;
- Fig. S2: Summary plot on distribution of water masses across the transect;
- Fig. S3: Boxplot with overall species richness and relative abundance by season;
- Table S3: Summary table with BIC values for each GLLVM, used to select the best model;
- Fig. S4: Residual plot for the best GLLVM 'null' model;
- Fig. S5: Residual plot for the best GLLVM model with 'predictors';
- Fig. S6: Residual plot for the GLMM model;
- Fig. S7: El Niño-Southern Ocillation (ENSO) summary plots;
- List of references related to *this* document.

Detailed list of software

We used R 4.2.0 (R Core Team, 2022) and the following set of packages: 'renv' 1.0.3 (Ushey and Wickham, 2023), 'plyr' 1.8.8 (Wickham, 2011), 'dplyr' 1.1.2 (Wickham et al., 2023a), 'tidyr' (Wickham et al., 2023b), 'janitor' 2.2.0 (Firke, 2023), 'stringr' 1.5.1 (Wickham, 2023b), 'forcats' 1.0.0 (Wickham, 2023a), 'ggplot2' 3.4.4 (Wickham, 2016), 'patchwork' 1.1.2 (Pedersen, 2022), 'RColorBrewer' 1.1-3 (Neuwirth, 2022), and 'gllvm' 2.0.2 (Niku et al., 2019, 2025). Packages dependencies are all listed under a 'renv.lock' file in the repository.

The code is archived at the Open Science Framework (see Daudt et al., 2024), where you will find all code and data under, and a detailed walk-through on the analyses.

Table S1. Survey effort by season, summarised by the number of voyages, years sampled, species and minimum number of individuals recorded. Seabirds were recorded along the Munida transect, off the Otago Peninsula, Aotearoa New Zealand, 2015–2023.

Season	No. voyages	No. years sampled	No. species	Min. no. individuals
Summer	14	9	40	46149
Autumn	7	7	37	5604
Winter	10	7	33	4209
Spring	5	5	35	13063

Table S2. Analysed species, their Māori, English and scientific names, breeding period (months) and distribution status (following Williams et al. 2006; see footnote for abbreviations). Some species did not have a 'Distribution' classification by Williams et al. (2006), so we manually input these, which are shown in parenthesis.

Te reo Māori name	Common English name	Scientific name	Breeding	Distribution[1]
–	Antarctic fulmar	*Fulmarus glacialoides*	Oct–Mar	(D–SO)
Karoro	Black-backed gull	*Larus dominicanus*	Oct–Feb	(S)
Takahikare-rangi	Black-bellied storm petrel	*Fregetta tropica*	Dec–May	M–SWP
Tarāpuka	Black-billed gull	*Chroicocephalus bulleri*	Sep–Feb	(S)
Toroa	Black-browed mollymawk	*Thalassarche melanophris*	Sep–Apr	D–SO
Tarapirohe	Black-fronted tern	*Chlidonias albostriatus*	Oct–Feb	(S)
Pararā	Broad-billed prion	*Pachyptila vittata*	Aug–Jan	D–SWP, SO
Toroa	Buller's mollymawk	*Thalassarche bulleri*	Dec–Oct	M–EP
Rako	Buller's shearwater	*Ardenna bulleri*	Sep–May	M–NP, EP
Toroa	Campbell albatross	*Thalassarche impavida*	Sep–Apr	M–TS/A, SWP
Karetai hurukoko	Cape petrel	*Daption capense*	Nov–Mar	D–SWP, SO
Tītī	Cook's petrel	*Pterodroma cookii*	Oct–May	M–NP, EP
Kuaka	Common diving petrel	*Pelecanoides urinatrix*	Aug–Feb	D–SWP
Tītī wainui	Fairy prion	*Pachyptila turtur*	Oct–Mar	D–SWP, SO
Reoreo	Grey-backed storm petrel	*Garrodia nereis*	Sep–Mar	D–SO
Ōi	Grey-faced petrel	*Pterodroma gouldi*	Jun–Jan	D–SP
Kuia	Grey petrel	*Procellaria cinerea*	Apr–Dec	D–SO
Kaikōura tītī/	Hutton's/	*Puffinus huttoni/*	Oct–Apr/	
Pakahā	Fluttering shearwater	*Puffinus gavia*	Sep–Feb	M–TS/A[2]
Toroa pango	Light-mantled albatross	*Phoebetria palpebrata*	Oct–Jun	D–SO
Kōrure	Mottled petrel	*Pterodroma inexpectata*	Dec–Jun	M–NP
Pāngurunguru	Northern giant petrel	*Macronectes halli*	Aug–Feb	D–SO
Toroa	Northern royal albatross	*Diomedea sanfordi*	All year	M–SA, SO
Matapo	Otago shag	*Leucocarbo chalconotus*	Sep–Mar	(S)
Tarāpunga	Red-billed gull	*Chroicocephalus novaehollandiae*	Oct–Feb	(S)
Toroa	Salvin's mollymawk	*Thalassarche salvini*	Aug–Apr	M–EP, SA, SO
–	Soft-plumaged petrel	*Pterodroma mollis*	Dec–May	D–SO
Tītī	Sooty shearwater	*Ardenna grisea*	Nov–May	M–NP, EP
Pāngurunguru	Southern giant petrel	*Macronectes giganteus*	Jul–May	(D–SO)
Toroa	Southern royal albatross	*Diomedea epomophora*	All year	M–SA, SO
Kawau tikitiki	Spotted shag	*Phalacrocorax punctatus*	All year	(S)
Toroa	Wandering albatross	*Diomedea exulans*	All year	D–SO
–	Westland petrel	*Procellaria westlandica*	May–Dec	M–EP
Toroa	White-capped mollymawk	*Thalassarche steadi*	Nov–Aug	M–SA, SO
Karetai kauae mā	White-chinned petrel	*Procellaria aequinoctialis*	Nov–May	D–SO
Takahikare-moana	White-faced storm petrel	*Pelagodroma marina (maoriana)*	Oct–Mar	M–EP
Tara	White-fronted tern	*Sterna striata*	Oct–Mar	(S)
–	White-headed petrel	*Pterodroma lessonii*	Nov–May	D–SO
–	Wilson's storm petrel	*Oceanites oceanicus*	Dec–Apr	(M–NP)
Hoiho	Yellow-eyed penguin	*Megadyptes antipodes*	Sep–Mar	S

[1]Distribution are coded as migratory (M), dispersive (D), or sedentary (S), followed by their geographic range North Pacific (NP), South Pacific (SP), eastern Pacific (EP), South Atlantic (SA), circum-polar southern ocean (SO), Tasman Sea/Australian coast (TS/A), and southwest Pacific (SWP). Sedentary species remain within New Zealand territory year-round.

[2]Williams et al. (2006) classified both species as migratory, but note that fluttering shearwaters mostly remain in New Zealand (as sedentary residents) although some individuals may, indeed, migrate to TS/A (see Berg et al. 2019).

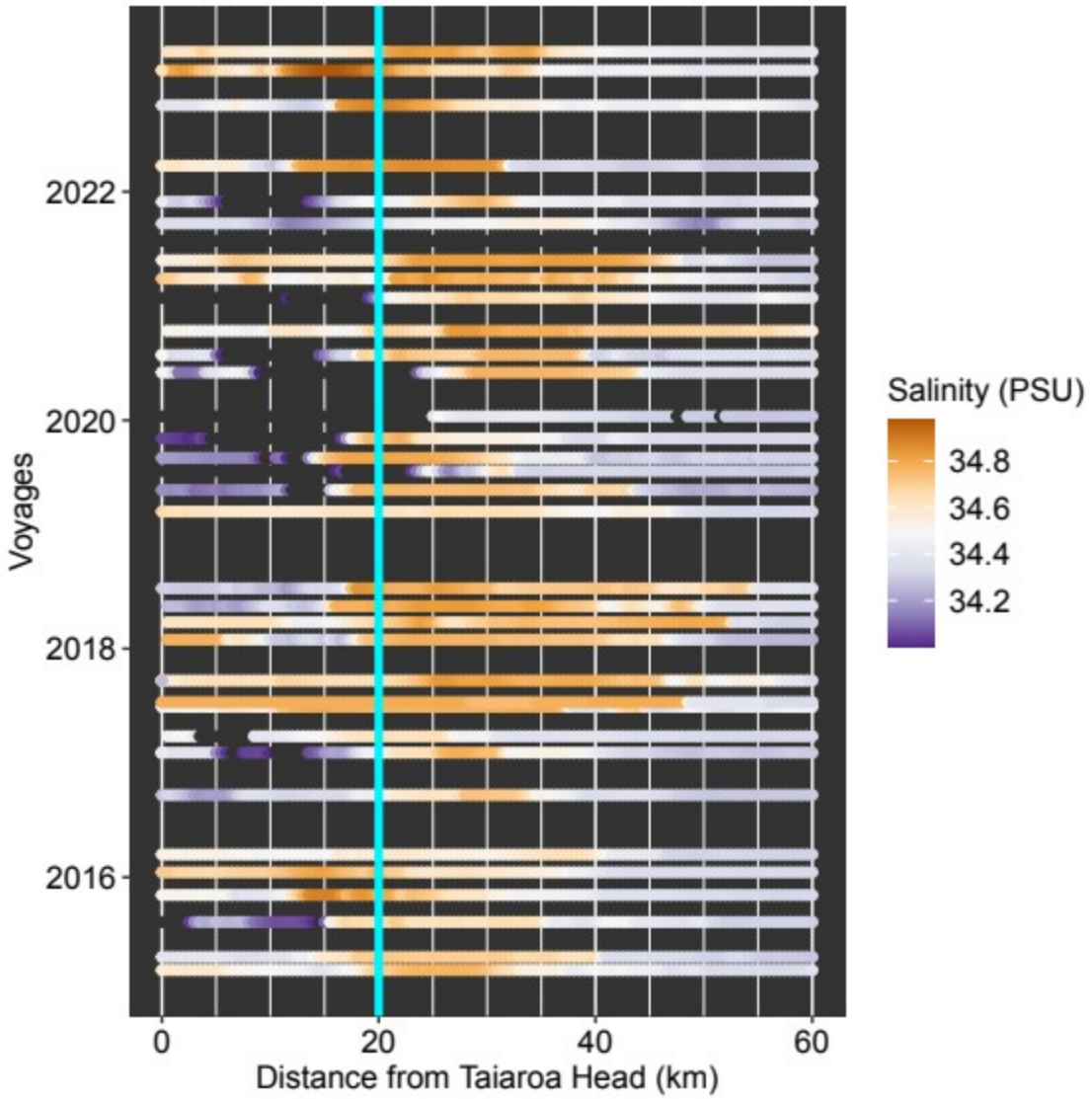

Fig. S1. Sea surface salinity against distance along the transect. Salinity measurements are colour-coded based on their value (note: values below 34 PSU are in dark grey). For each 5 km segment of the transect (measurements in between the vertical white lines on the background), salinity was averaged, and then classified into water masses according to their average and distance from the coast (see main text for cut-offs). The cyan line at the 20 km off the coast represents the offshore limit for the Neritic Water.

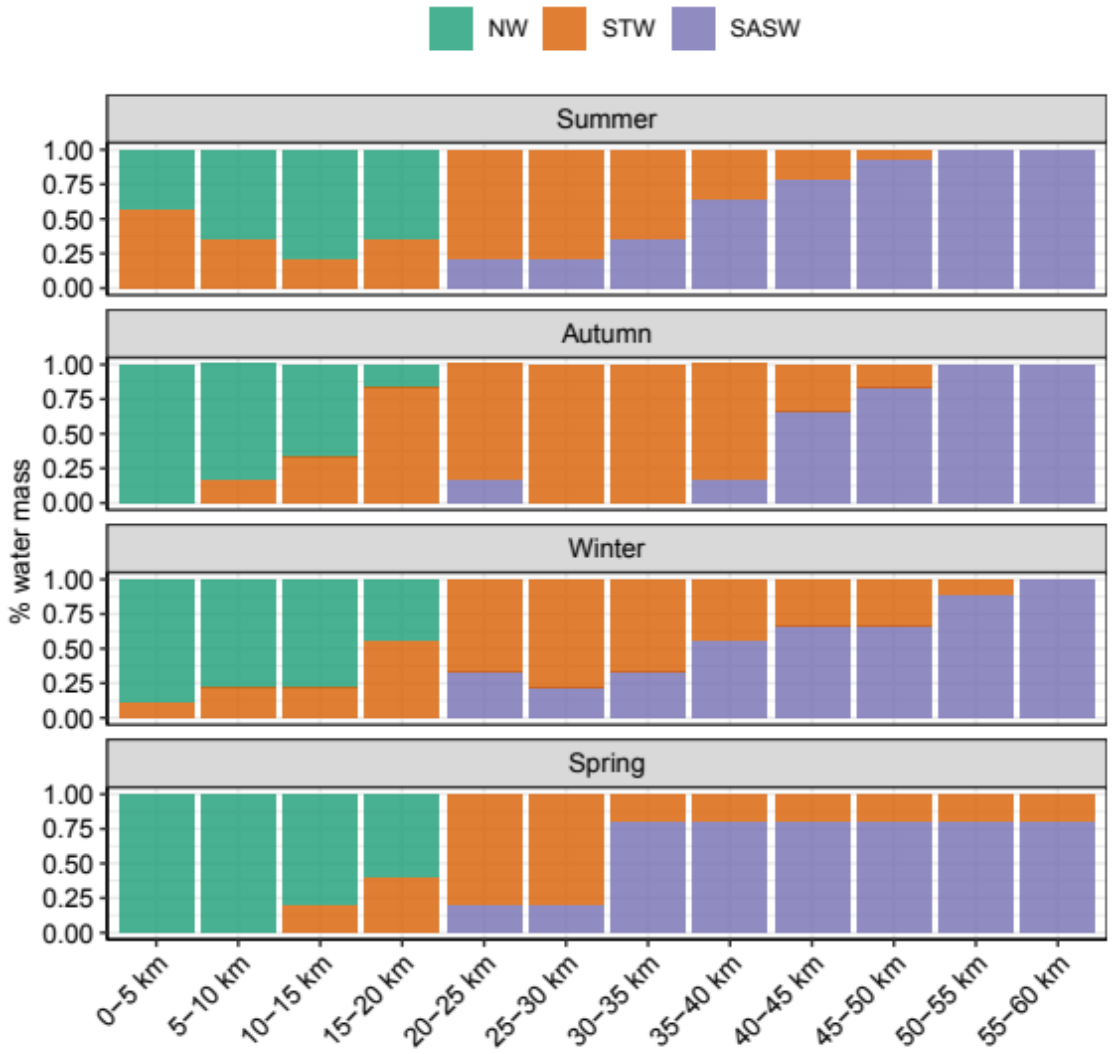

Fig. S2. Percentage of times a specific water mass was present during seabird surveys in each 5-km segment along the Munida transect, off the Otago Peninsula, Aotearoa/New Zealand, 2015–2023. Note this is a summary based on *in situ* data from the *sampled* days, and not using a continuous time series based on remote sensing.

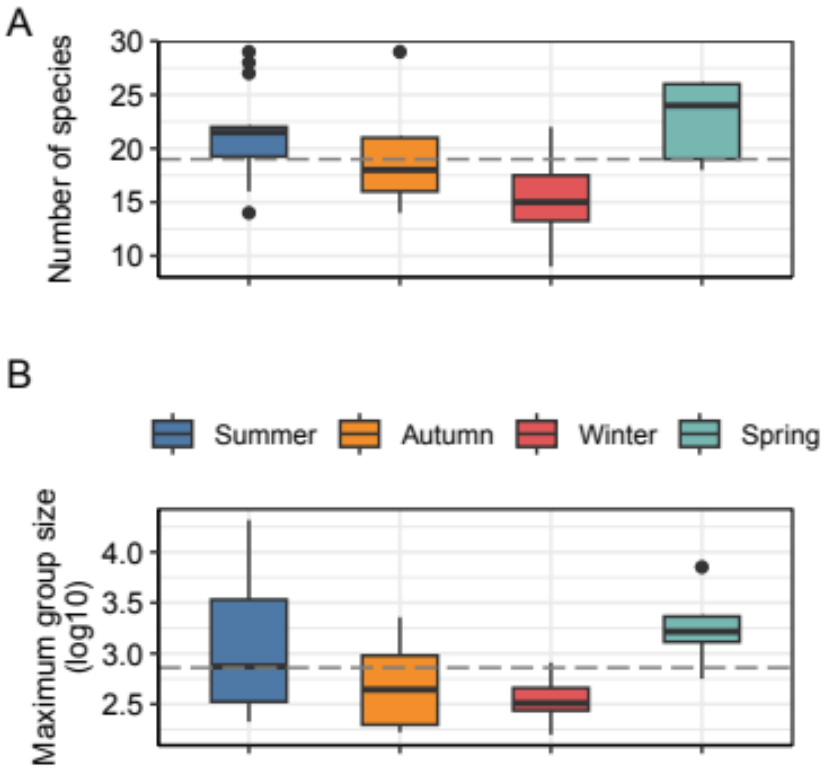

Fig. S3. Boxplot of the overall species richness (A) and log10-transformed sum of maximum group sizes (B) of seabirds for each voyage by season, observed along the Munida transect, off the Otago Peninsula, Aotearoa/New Zealand, 2015–2023.

Table S3. Summary Bayesian Information Criteria (BIC) values used to select the best GLLVM model; (a) null model (selecting only the number of latent variables [LVs]); (b) full model (selecting the best number of LVs); (c) selecting predictors. BIC highlighted in bold indicates the chosen model.

Model	Latent variables	BIC
(a) Null		
~ 1	LV 1	17490.18
~ 1	LV 2	**17349.96**
(b) With predictors (full)		
~ DistanceFromCoast + Season + WaterMass	LV 0	15510.87
~ DistanceFromCoast + Season + WaterMass	LV 1	**15209.21**
~ DistanceFromCoast + Season + WaterMass	LV 2	15287.40
(c) With predictors (covariate selection)		
~ DistanceFromCoast + Season + WaterMass	LV 1	15209.21
~ Season + WaterMass	LV 1	15175.35
~ DistanceFromCoast + WaterMass	LV 1	15205.31
~ DistanceFromCoast + Season	LV 1	**14609.29***
~ Season	LV 1	14793.81
~ DistanceFromCoast	LV 1	**14607.23**
~ WaterMass	LV 1	15094.94

*This was the chosen model (see main text for reasoning).

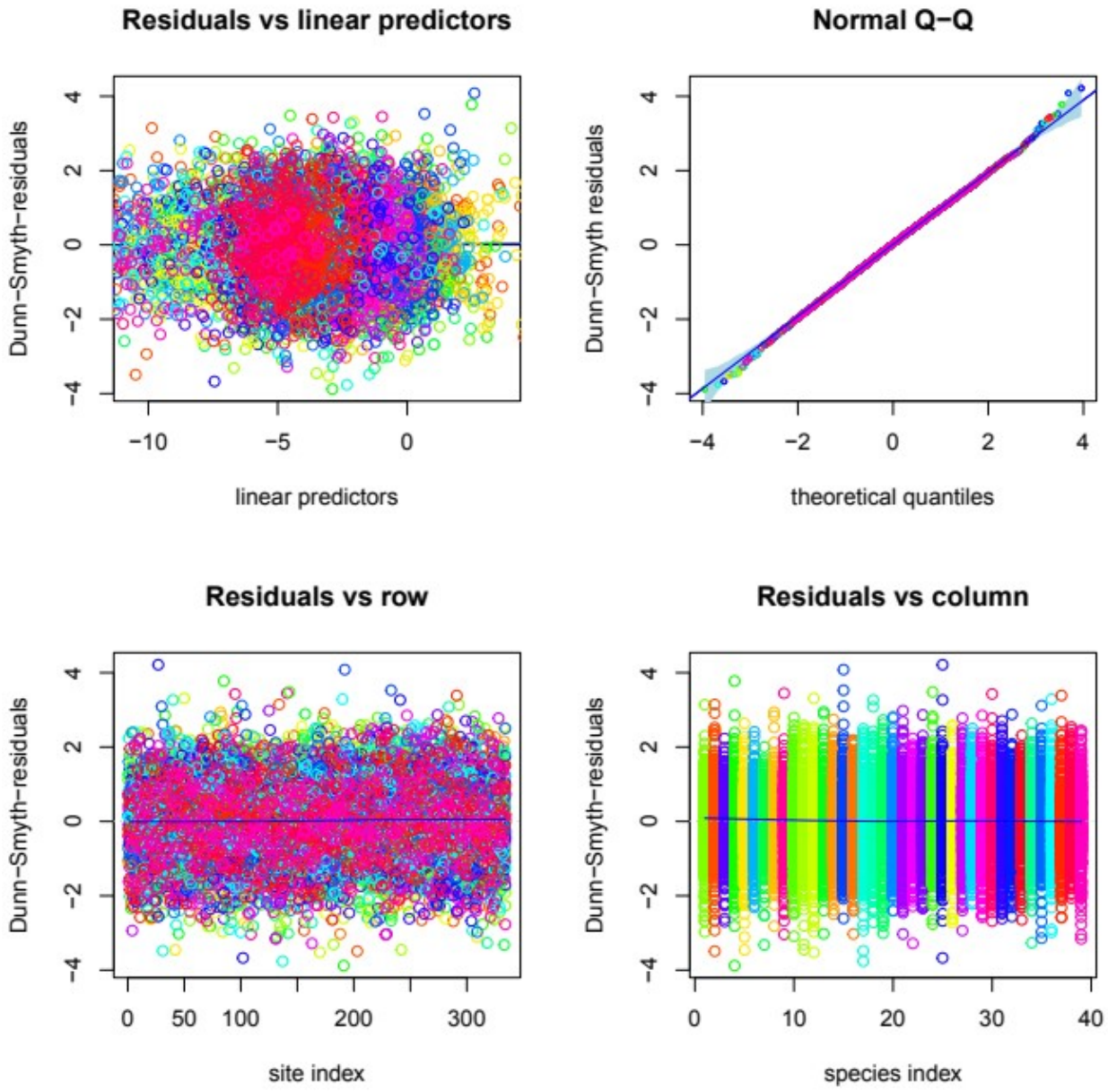

Fig. S4. Residual plot for the chosen GLLVM null model.

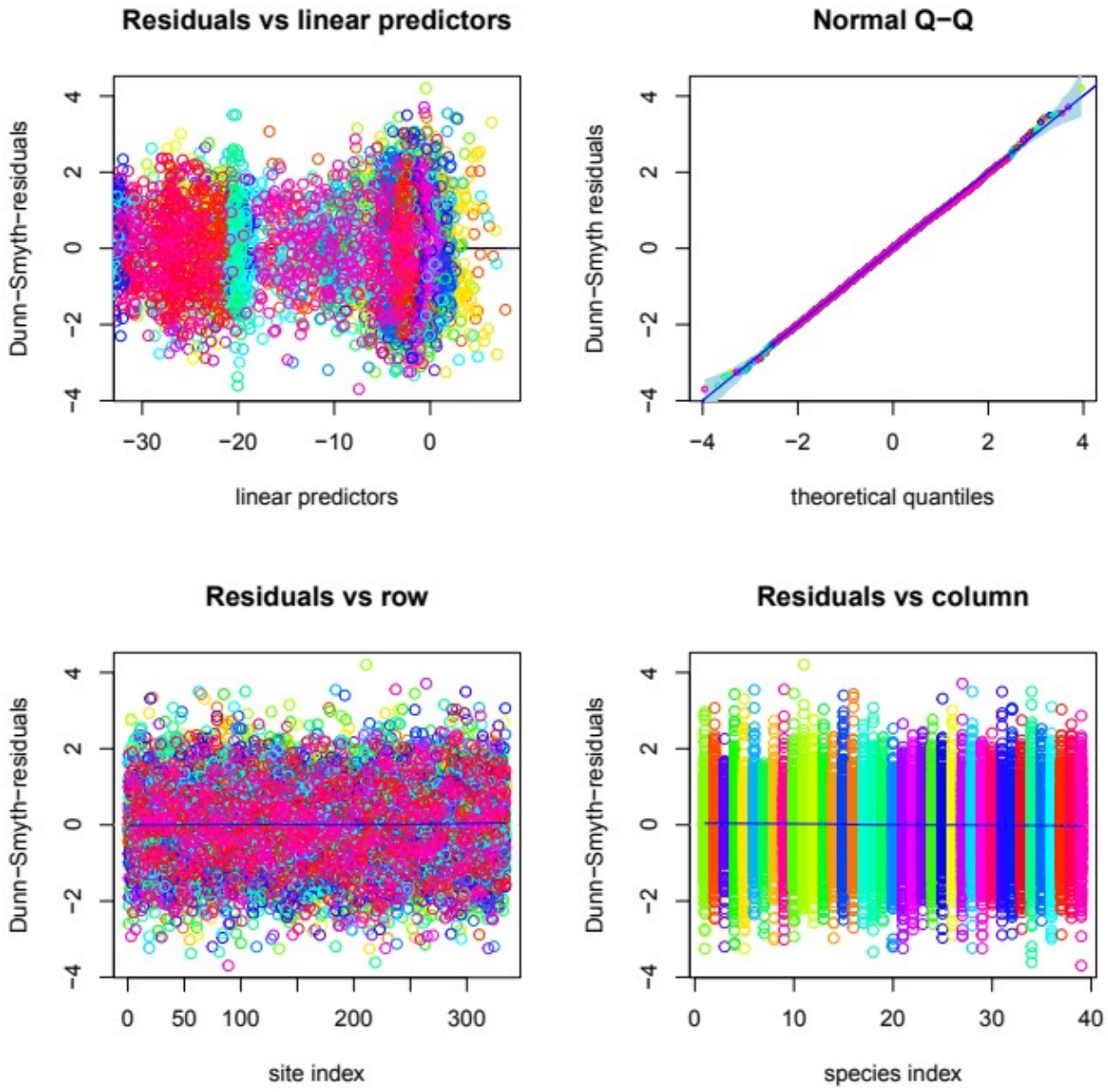

Fig. S5. Residual plot for the chosen GLLVM model with predictors.

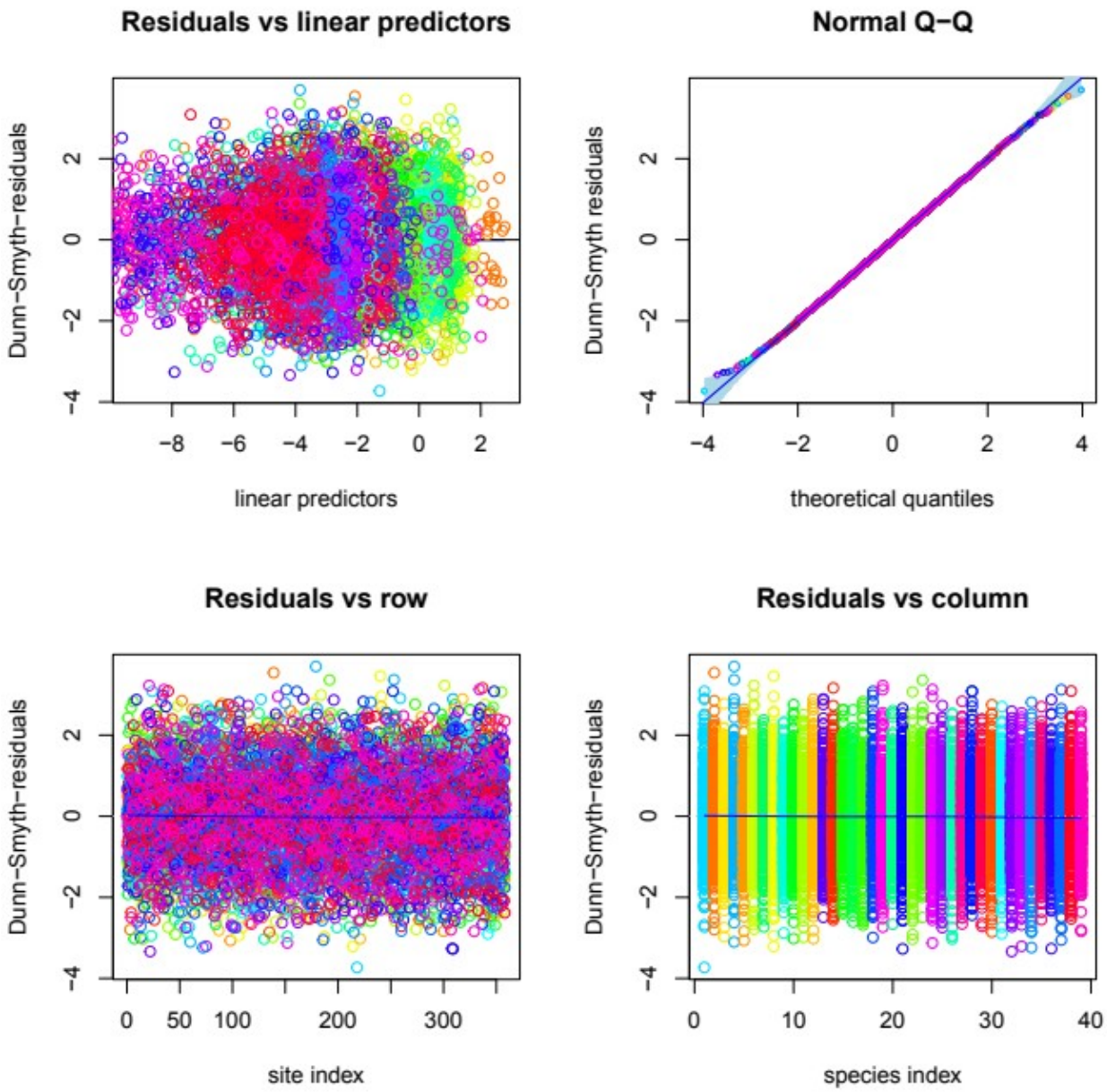

Fig. S6. Residual plot for the Binomial GLMM model.

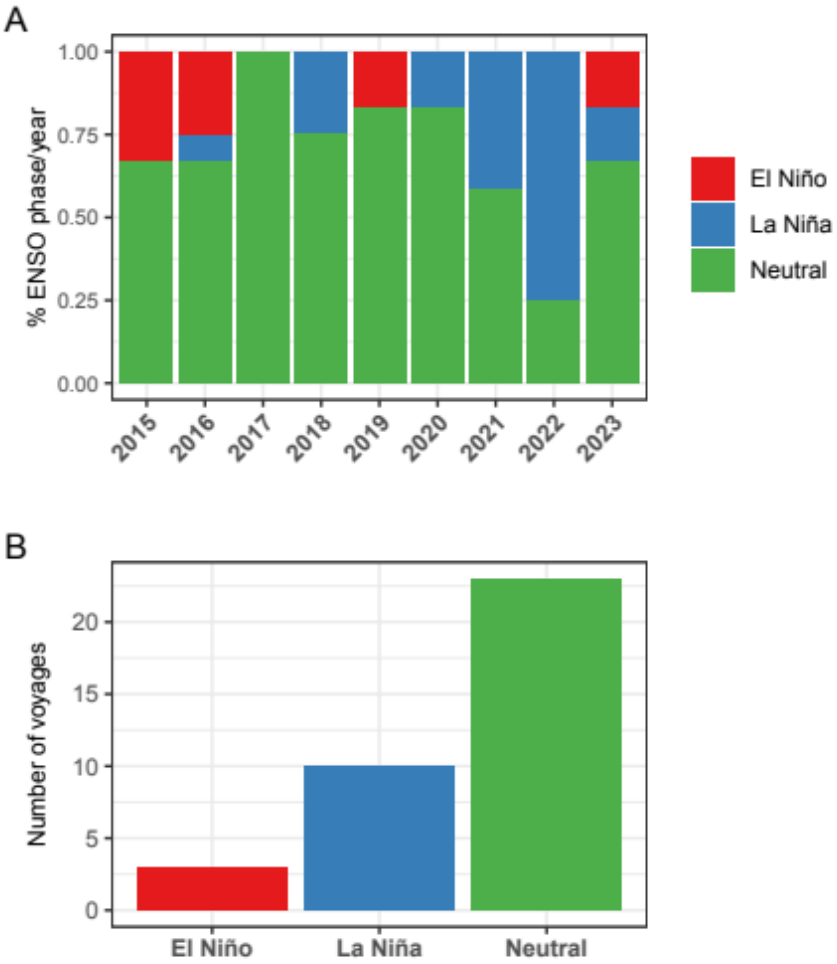

Fig. S7. Summary of El Niño-Southern Oscillation (ENSO) phases during the period of seabird surveys, 2015–2023; (A) stacked plot with the proportion (%) of months in each ENSO phase by year; (B) number of voyages in each ENSO phase.

The ENSO phase was classified as *La Niña* if the Southern Oscillation Index (SOI) was ≥1, *El Niño* if SOI ≤-1, and otherwise as *Neutral*. The SOI values are from NOAA/NCEI (https://www.ncei.noaa.gov/access/monitoring/enso/soi), accessed on the 17th July 2024.

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