Supplement 1 - Background information on TRIWAQ model

The abiotic environmental variables were determined by running hind cast simulations with a series of nested models: (1) the Dutch Continental Shelf model (Gerritsen *et al*. 1995), covering the North Sea and continental shelf between Brest (France) and Ålesund (Norway), (2) Zuno, covering the southern part of the North Sea and (3) Kuststrook Model, covering the Dutch coast up to 75 km offshore (Alkyon 2001a, Alkyon 2001b). These models are part of the set of standard model schematizations, used by the Dutch government to assess the effects of human interventions on the water system and in operational forecasting. They use a finite difference solver for the depth-averaged shallow water equations called WAQUA (Rijkswaterstaat/RIKZ 1997, Rijkswaterstaat/RIKZ 2001, Rijkswaterstaat/RIKZ 2006). For the Voordelta, the southern half of the Kuststrook Model was run as a separate model with 10 equidistant terrain-following sigma layers, using the three-dimensional version of the WAQUA solver called TRIWAQ. The resolution of this model varies between 250 and 400 meter in the area of interest. The extent of this domain is given in Figure S1.

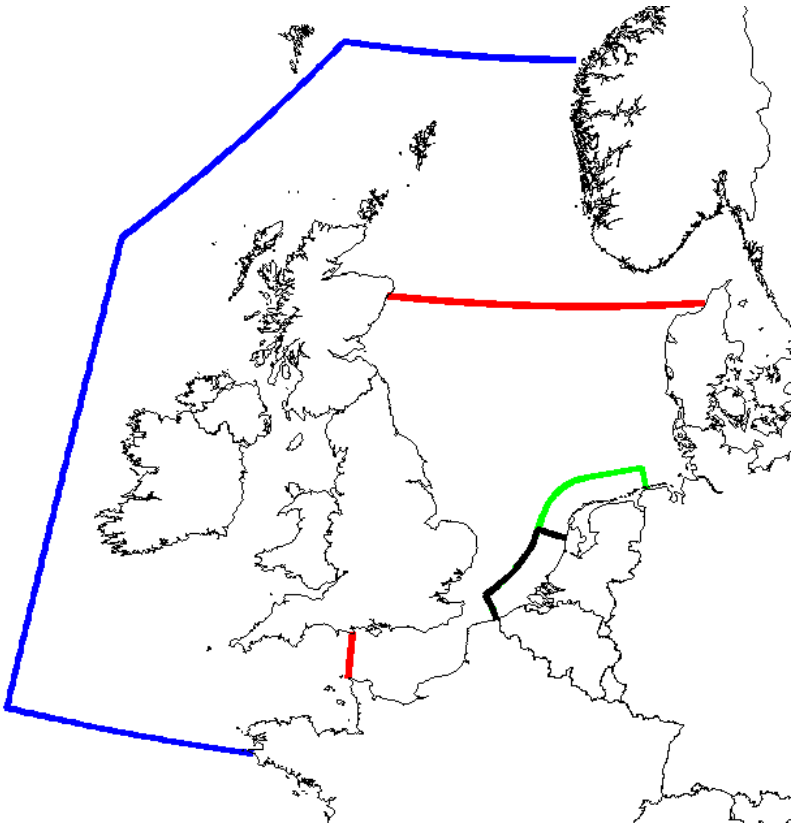

Figure S1. *The extent of each model domain, the Dutch Continental Shelf model (blue), the Zuno model (red), the Kuststrook model (green) and the 3D Voordelta model (black).*

The three 2D models (models 1-3) include transport of salinity, whereas in the 3D model (model 4), the transport of temperature is included as well. The results of the latter model were used to derive the abiotic environmental variables in the Voordelta. Astronomical tidal constituents were applied on the outer boundaries of the Dutch Continental Shelf model. All known freshwater river discharges were prescribed in all models based on actual discharge data or monthly averaged data in case actual data was not available. HIRLAM wind and pressure fields from the Royal Dutch Meteorological Institute (KNMI) provided the atmospheric forcing, in combination with the wind drag relation of Charnock (1955). The temperature model in TRIWAQ to describe the water-atmosphere interaction is based on the relation of De Goede (de Kok *et al*. 2001). The (short wave) solar radiation, based on

relative position of the sun, air temperature, relative humidity and cloud cover, and (long wave) radiation from the earth and the heat losses due to evaporation and convection, are computed by this model. Besides the atmospheric forcing, boundary conditions for temperature were based on temperature measurements at sea and in the rivers. The water density is derived from the equation of state relation by Eckart (1958), using the computed salinity and a constant temperature in the three 2D domains and both computed salinity and temperature in the 3D model. The hind cast simulations have been carried out for the period May 2004 to December 2015.

Comparisons between model results and measurements are presented in Figures S2 (water levels during a storm period) and S3 (salinity during a period with high Haringvliet discharge).

Over the whole 9.5 year hind cast period, the accuracy of the model results turned out to be very good: for the water levels a mean deviation of 5 cm and a root-mean-square error of 8 cm, for the water temperature a mean deviation of -0.5 °C and a root-mean-square error of 0.5 °C and for the salinity a mean deviation of 0.5 PSU and a root-mean-square error of 1.5 PSU. Unfortunately, no flow velocity measurements were available.

The hydrodynamic parameters (water levels, flow velocities, salinity and temperature) for all computational cells in the Voordelta have been stored with a half hour interval in a large database for further processing. Focus has been on temporal and spatial variations of monthly averages of those parameters and frequency of occurrence of extreme events (i.e. storms, periods with high or low river discharges or high or low temperatures, etc.).

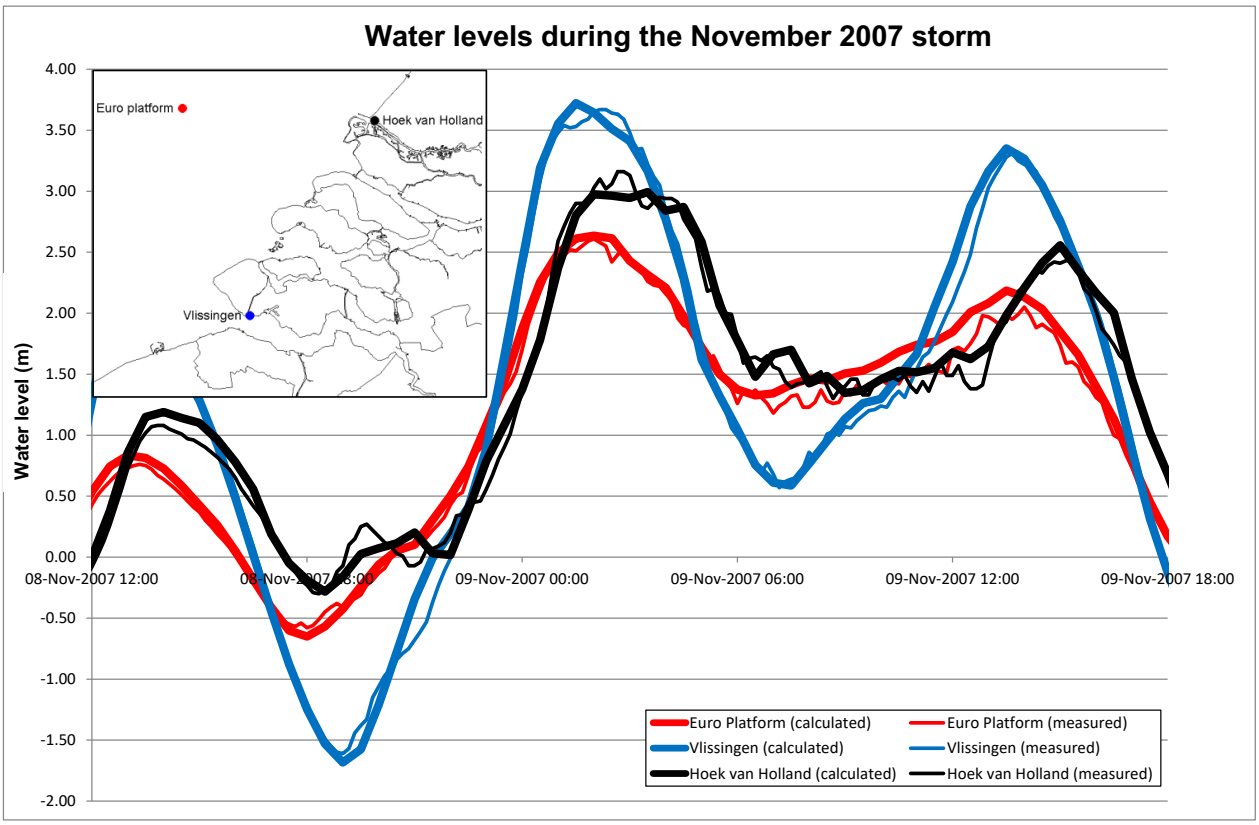

Figure S2. *Comparison between calculated and measured water levels during the November 2007 storm in the three stations shown in the insert.*

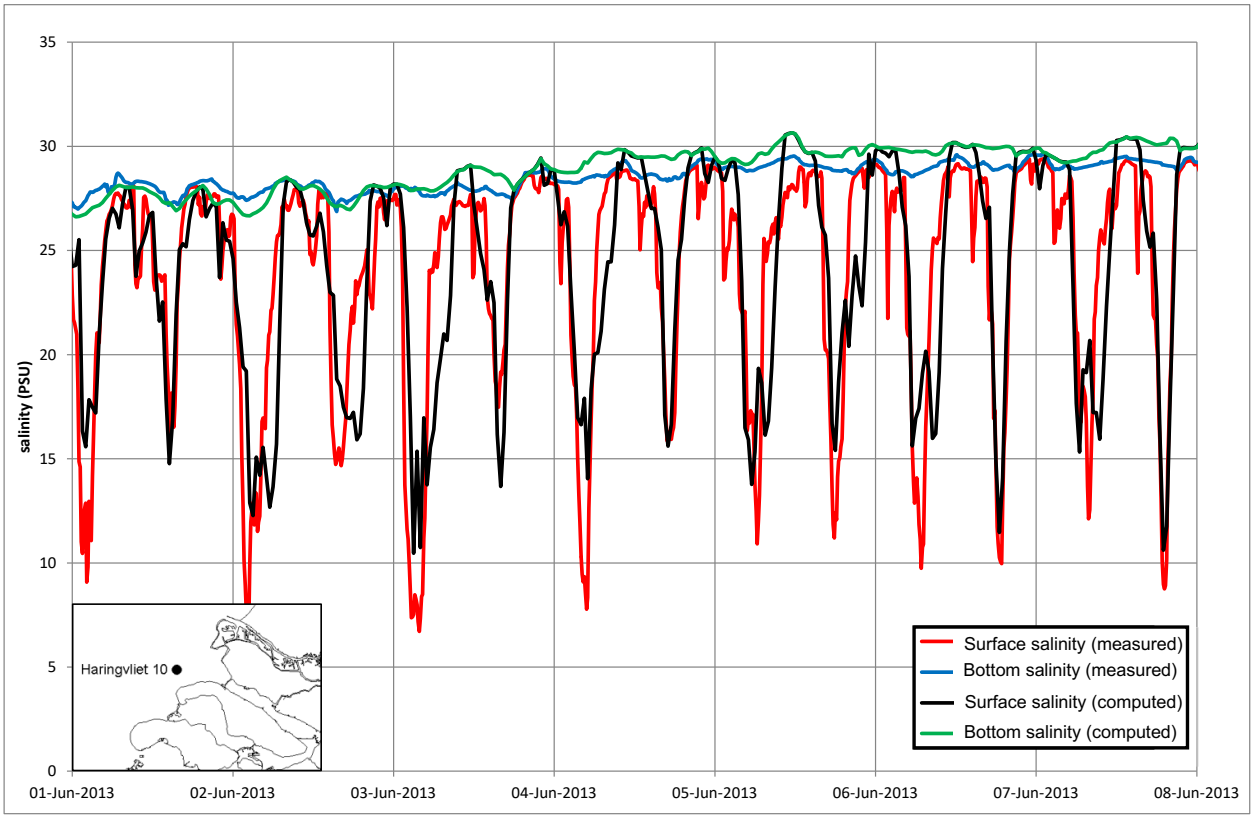

Figure S3. *Comparison between calculated and measured surface and bottom salinity during the first week of June 2013 in station Haringvliet 10, about 14 km offshore from the Haringvliet sluices, shown in the insert.*

References:

Alkyon (2001a) Herstel 1:3 koppeling binnen modellentrein, fase 1 – roostergeneratie, Report A705R2r1 (in Dutch), April 2001.

Alkyon (2001b) Herstel 1:3 koppeling binnen modellentrein, fase 2 – modelbouw en afregeling, Report A705R3r3 (in Dutch), October 2001

Charnock H (1955) Wind stress on a water surface. Quart J Roy Meteorol Soc 81:639–640.

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Gerritsen H, De Vries JW, Phillippart ME (1995) The Dutch Continental Shelf Model. In: Schrefler BA (ed) Proceedings of the International Conference on Computer Modelling in Ocean Engineering 331–338. Balkema, Rotterdam

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De Kok JM, De Valk C, Van Kester JHTM, De Goede E, Uittenbogaard RE (2001) Salinity and temperature stratification in the Rhine Plume. Estuar Coast Shelf Sci 53:467–475.

Supplement 2 - Variability in environmental conditions at seasonal, diurnal and tidal scales

To illustrate the variability of environmental covariates used in the HMM, TRIWAQ predictions were extracted for the period between 24 May and 16 July 2017, at six example locations (Figure S4). These six locations were selected at positions were Sandwich Terns either regularly foraged (locations 1-4) or where only very few tracks of Sandwich Terns occurred (locations 5-6). Variability of environmental covariates used in the HMM is shown in Figure S5.

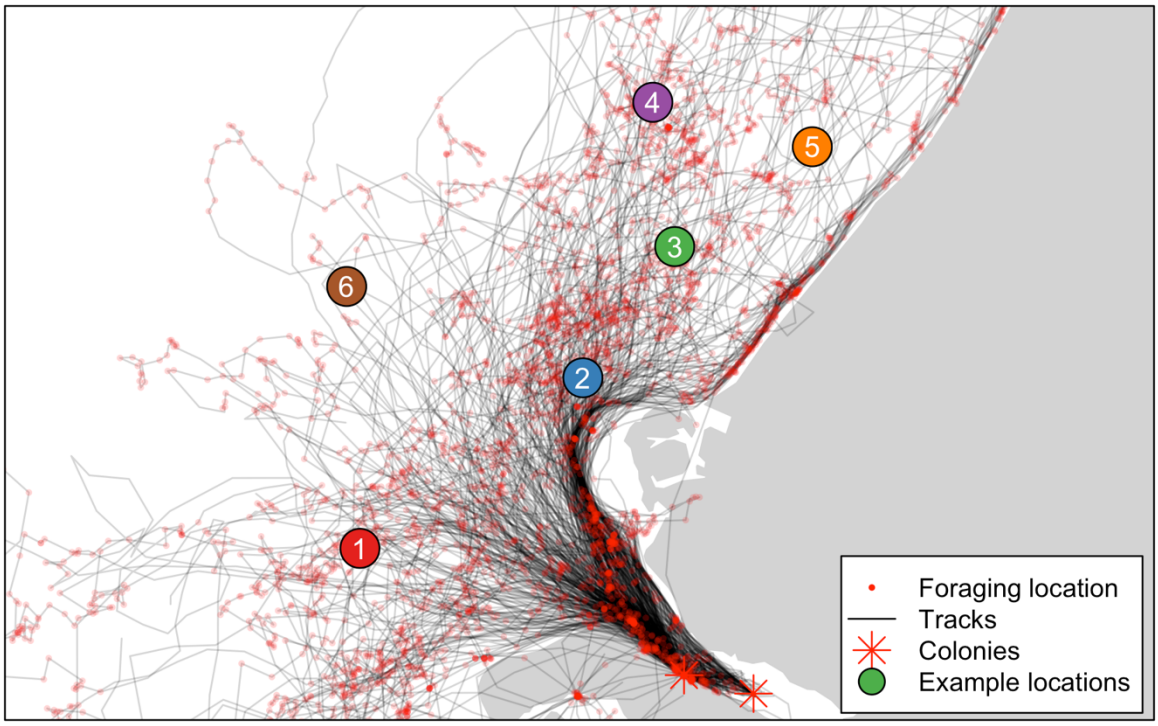
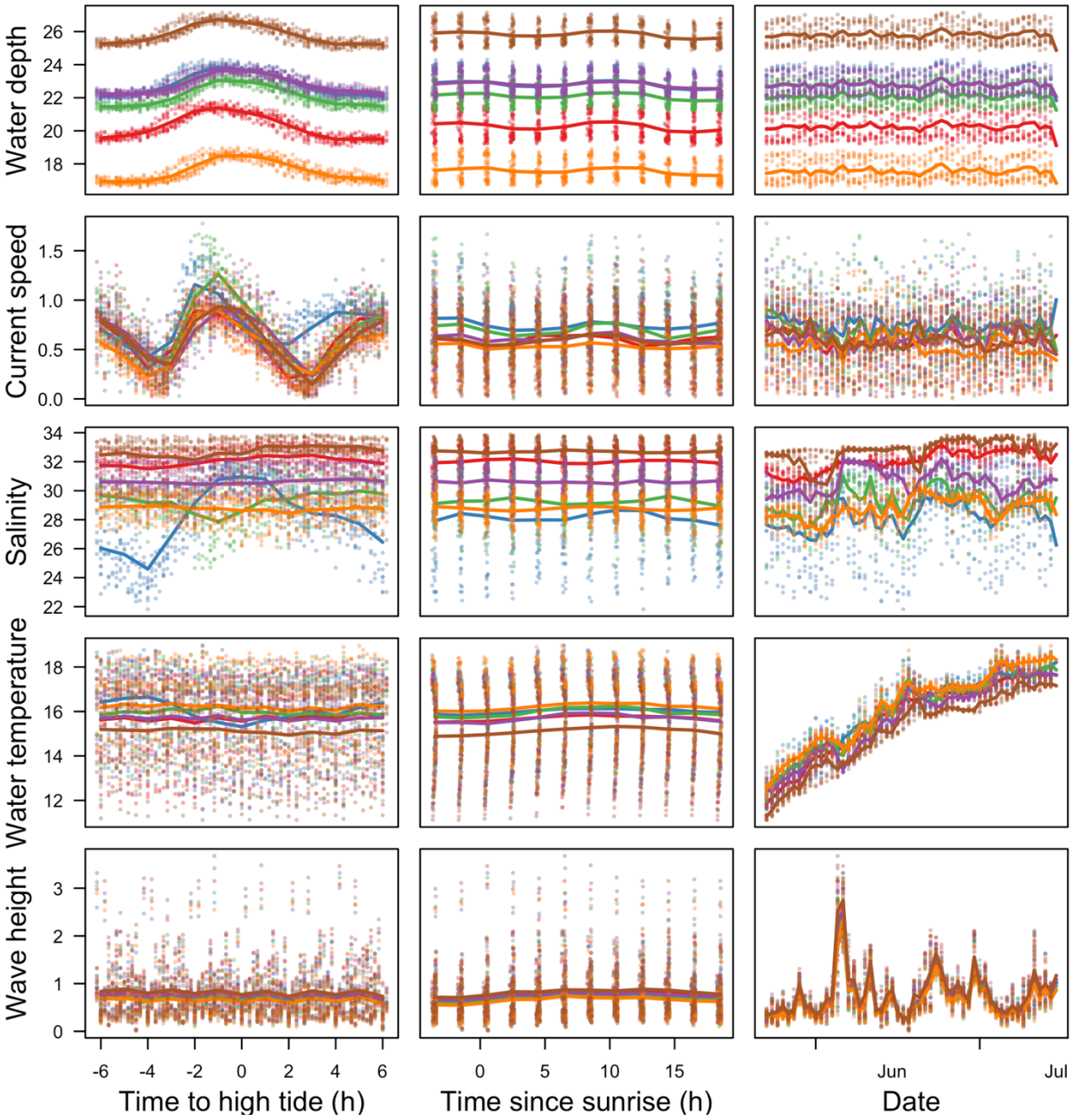


Figure S4: *Example locations where TRIWAQ predictions have been extracted to illustrate the temporal variability of environmental conditions.*


Water depth
26
24
22
20
18
Current speed
1.5
1.0
0.5
0.0
Salinity
34
32
30
28
26
24
22
Water temperature
18
16
14
12
Wave height
3
2
1
0
-6
-4
-2
0
2
4
6
Time to high tide (h)
0
5
10
15
Time since sunrise (h)
Jun
Jul
Date

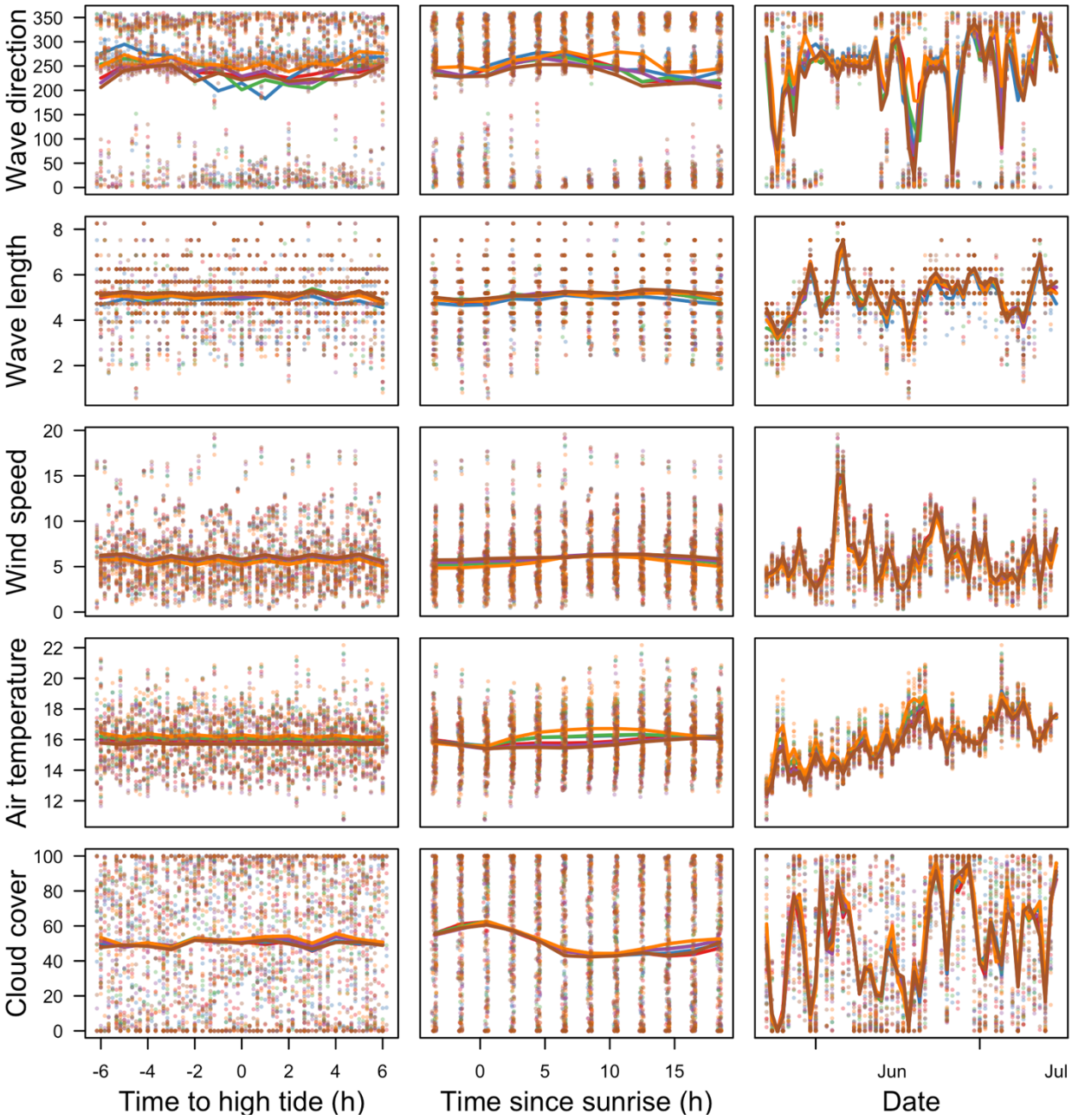


Figure S5: *Variability of environmental variables from the TRIWAQ model at six example locations. Colours correspond to the colours of the different locations in Figure S4. Points are all raw measurements per time unit (10 min interval for 'Time to high tide', 2 hr interval for 'Time since sunrise', day interval for 'Date'), lines represent average values per time interval.*

Supplement 3 - Area use across the tidal cycle, day and season

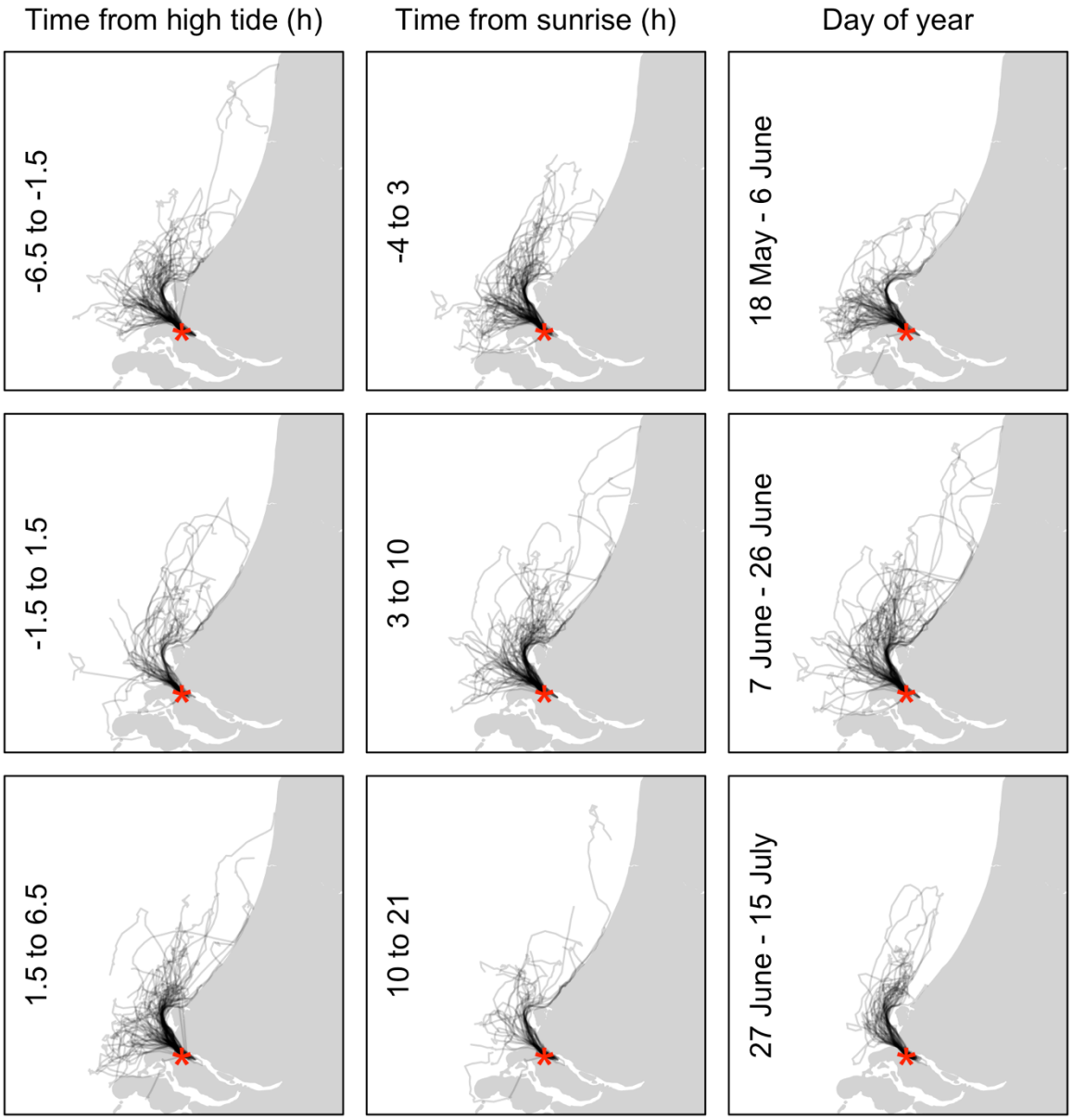


Figure S6: *Area use relative to (a) high tide, (b) sunrise and (c) day of year. Grey lines show foraging trips; red dots show positions classified as foraging by the HMM. The red star indicates the Scheelhoek/Slijkplaat colony.*