# Agreement on the Conservation of Albatrosses and Petrels

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# Climate change induced wind trends affect albatross distribution and life history traits

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# Climate change induced wind trends affect albatross distribution and life history traits

(Climate change induced wind reinforcement has modified the distribution and improved foraging pattern and condition of wandering albatrosses in the southern ocean)

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In the Southern Ocean, westerly winds have increased in intensity and moved poleward. Using unique long term demographic and foraging records, we show that breeding wandering albatrosses have increased their travel rates and flight speeds, whereas their foraging range has shifted poleward, in conjunction with wind changes. As a consequence, the duration of foraging trips has decreased, breeding success has improved and birds have increased in mass by more than one kg. The consequences of climate change have so far been positive, with important implications for the conservation of the species, but are likely to become negative with the predicted further trends in southern westerlies regime under climate change scenarios. This study illustrates the importance of including foraging performances in mecanistic models to be able to link environmental and population parameters, and thus to be able to make robust prediction about future climate change effects.

It is now well established that climate change is affecting living species by modifying their physiology, phenology, distribution or abundance (*1, 2*). For example in highly mobile vertebrates such as birds, shifts in distribution related to climate change are often the consequences of spatial rearrangement of food availability (*3*). However, the mechanisms underlying these distributional shifts and their proximate causes are still poorly known (*4*), often due to the paucity of detailed long term data (*5*). Thus, there is an urgent need for more empirical data from longitudinal studies of populations to assess responses to changing environmental conditions (*6*). In particular, the ability of individuals to extract resources from

the environment (i.e. foraging performance) is a central parameter linking environmental conditions to population processes (*7*). Yet, long term data on individual foraging performance are rare and this limits our understanding on the mechanisms underlying the link between environmental and population parameters, ultimately reducing our ability to make predictions on future changes.

The vast majority of studies on the effects of current changing environments on species biology have been developed in terrestrial ecosystems and generally temperature and rainfall are the main environmental factors considered, potentially overlooking other key climatic variables. Wind is a major component of climate and changes in oceanic wind regimes and strength have already occurred (*8*); they are expected to continue in the future, especially to increase over many parts of the oceans (*9*). To our knowledge, there is no empirical evidence of the effect of wind changes on the species in terms of physiology, distribution or abundance, although it is likely to impact at least the lower trophic levels (*10*). In particular, changes in wind regime may directly affect the movement or distribution of highly wind-dependent species, such as migratory land birds (*11*) or pelagic seabirds (*12-14*). Thus, future changes in global oceanic wind fields may be a further conservation concern for already threatened pelagic seabirds such as albatrosses and petrels. These species are large wide ranging predators relying extensively on wind to operate large scale movements during breeding (*12, 15*) and wind is essential for their low cost efficient foraging movements (*12*). As central place foragers, the persistence of colony locations is probably partly dependent upon changes in wind patterns within the foraging range of populations.

Over the past 50 years Southern Hemisphere westerlies have shifted poleward and increased in intensity, possibly in relation to ozone depletion and warming from rising concentrations of atmospheric $CO_2$ (*16*). These changes in the strongest time-mean oceanic winds in the world are related to a shift of the Southern Annular Mode (SAM, the normalised difference in the zonal mean sea-level pressure between 40° S and 65° S) into a positive phase (*17*). Positive SAM results in a strengthening of the westerly winds well marked in the Indian Ocean (*18*), with the strongest effects occurring during the austral summer (*19*). Based on these pieces of evidence, we might expect that changes in wind conditions could have impacted the distribution and foraging performance of flying seabirds and consequently their life history traits.

In this study, we use several long term data sets to investigate whether changes in wind conditions over the Southern Ocean have influenced the foraging ecology and life history traits of the wandering albatross (*Diomedea exulans*), one of the most wide ranging

flying seabird. Our aim was to assess whether the foraging performance of albatrosses changed over the last decades in relation to wind conditions and to understand their possible consequences on life history (i.e. breeding performance and condition). We use data collected over the past decades on the duration of foraging trips and breeding success (1966-2010), as well as foraging performance (tracking studies) and body mass (1989-2010) of breeders from Crozet Islands, located in the windiest area of the Southern Ocean. During the incubation in January-February (austral summer), wandering albatrosses forage at the longest distances from the colony[20]. It is during this period that 80% of the breeding failures occur [20]. We therefore concentrate on this period critical for the breeding success of the species.

In January-February Crozet wandering albatrosses foraged from sub-tropical to Antarctic waters at a maximum range of more than 3500km (Fig. 1 upper panels). Although both sexes overlap in the latitudinal band of 40-50°S, males prefer colder waters at the latitude of Crozet or to the south (down to 60°S), whereas females favour warmer waters to the north as far as 30°S (Fig. 1 lower panels). Thus, males foraged to a larger extent in the central westerlies flow and encountered on average stronger winds than females (Fig. 1).

In the foraging range of Crozet wandering albatrosses, as a result of the shift of the global SAM index into a positive phase (Fig. 2a), wind speeds have increased in the centre of the westerly flow (Fig. 1), as well as locally at Crozet (Fig 2b). No significant changes occurred in subtropical waters exploited by females (30-40°S), whereas wind speed increased in sub-Antarctic waters, especially south of Crozet (Appendix 1; Fig. 1). When decomposing wind into its two components, zonal wind – component west to east, and meridional wind - from north to south (Fig. 1), the most striking changes have occurred for the latter. The meridional component has strongly increased and shifted poleward, whereas these trends were not as strong for the zonal component (Fig. 1, Fig. 2c,d).

Foraging parameters estimated from tracking data have changed over the past 20 years in parallel to these changes in wind conditions. The northern range (the most northerly latitude attained during a foraging trip) of wandering albatrosses was strongly influenced by meridional winds and shifted extensively poleward in females and to a smaller extent in males (Table 1, Fig. 3), whereas there was no significant trend over time for the southern range (Table 1). Concurrently, there was a significant decrease in the maximum distance from the colony (Table 1, foraging range).

As shown by earlier studies (12, 15), wind strongly influenced albatross flight speed. We found that it was the meridional component that best explained the increase in average flight speed during a foraging trip (Table 1). Flight speeds increased until 2008, the last value

of the time series (2010) was characterised by very low winds, comparable to those in the early 1990s (Fig. 2, 3). Travel speed (daily distance covered) increased over the past 20 years in both sexes, in relation to wind speed whereas total distance covered did not changed over years (Table 1, Fig. 3). Females spent a higher proportion of the overall foraging time in flight than males over the study period (Fig. 3). Thus, the increase in the daily distance covered observed in the two sexes was due, for females to an increase in flight speed with a concomitant shift in distribution poleward into more windy conditions, while for males it was due to shorter time periods spent sitting on the water.

Even though the total distance covered did not increased over years, as a result of higher travel and flight speeds, the duration of foraging trips decreased over the past 20 years and this trend was related to increasing meridional winds (Table 1). This decrease in the duration of trips was confirmed over a longer period (during the past 4 decades; in 1970, 1989, 1999 and 2008) from an independent large dataset (i.e. duration of foraging trips during incubation shifts monitored visually). The mean duration of foraging trips was similar between sexes, it was highly variable (2-35 days) and decreased by 22% between 1970 and 2008 (from $12.4 \pm 6.8$ to $9.7 \pm 5.5$ days, Appendix Fig. 1, Mixed ANOVA, year effect $F_{3,724} = 11.3$, $P < 0.001$). Finally, the angle between flight direction between two locations and wind direction shifted by 10° shift from 1989 to 2010, with birds tending to use to a larger extent tail winds in the 1990s than in the 2000s (Fig. 4).

The breeding success of wandering albatrosses was high ($76.0 \pm 6.5\%$; Fig. 5a) and has increased over the past 40 years. Breeding success is the result of failures that mainly occur during incubation ($81.7 \pm 9.1\%$ of total failures, n= 18 years). Failures during incubation were explained by the duration of foraging trip (Generalized Linear Models, $F_{1,310} = 5.7$, $P = 0.018$), the probability of breeding failure increasing with the duration of foraging trips. In parallel, the body mass of incubating males and females increased significantly over the past 20 years by one kg, i.e. by 10-12% of the body mass ($F_{8, 519} = 12.3$, $P < 0.0001$ and $F_{8,498} = 17.2$, $P < 0.0001$, respectively, Fig. 5b). This increase in body mass was not related to changes in body size (no change in the length of the beak length over the same period; males $F_{9,424} = 1.5$, $P = 0.143$, females $F_{9,402} = 1.46$, $P = 0.158$).

Long term series are crucial to understand ecological processes generally occurring over multiple years, and their importance is increasingly recognised (*5*). Here, we combined classical long term data on demographic and phenotypic parameters with a unique long term tracking database of foraging movements, to better understand the links underlying the response of a marine vertebrate to environmental changes. The study stresses the importance

of wind, a climatic factor that has so far not been considered in studies on effect of climate changes on marine animals.

Wandering albatrosses appeared so far to be favoured by climatic changes occurring in the Southern Ocean, with higher wind speed allowing more rapid movements. In wandering albatrosses the probability to encounter and capture prey is related to the daily distances individuals are able to cover (*21*). In the 2000s birds move quicker than in the 1990s and thus are able to cover similar distances and probabilities to capture prey during shorter bouts at sea. Simultaneously, tracked birds have shifted their range southward (Fig. 3), a trend also documented for wandering albatrosses observed from line transects in the south-western Indian Ocean over the past 30 years (*22*). Since males and females share equally incubation duties (*20*), the reduction of foraging time has concurrently resulted in shorter incubation shifts and thus lower probability of breeding failure. Our results indicate that the decrease in durations of foraging trips and fasts on the nest is likely to be the reason for the increase in breeding success.

Females appeared to have been more impacted by wind changes than males. They have shifted poleward their northern range to a larger extent than males. This southward shift of the northern range allows also females to fly at higher speeds in windier areas, as well as in less distant waters from the colonies, and thus to further reduce foraging time. In the 1990s, females had significantly lower rates of mass gain during a foraging trip than males – 61% (*20*), whereas in 2011 the difference between sexes was no more significant – 25% (unpublished data).

One of the most spectacular and unexpected changes over the past 20 years in the ecology of wandering albatrosses is the increase of both males and females by more than one kg in body mass, i.e. more than 10%,. Such an increase is considerable even for a species with a large body size, and has considerable implications for flight performances (*23, 24*). The increase in mass for a similar structural size results in an increase in wing loading (*23*). An increase of one kg for a wandering albatross results in an increase of 0.6 m s$^{-1}$ of the most efficient gliding speed per unit distance flown (*24*). Thus, increased mass, with no concurrent change in size, should be favourable for species using dynamic soaring, under increasing wind strength (*23*), i.e. the situation that is presently experienced by wandering albatrosses. Therefore, increased mass could be viewed as an adaptive response to environmental changes, and increased flight speed may be the result of the combined effects of increased wind speeds encountered and increased body mass.

Physically increase in mass, being not the result of larger size, likely corresponds to an increase in body stores, rather than food in the stomach since during incubation albatrosses return to the nest with an empty stomach. It could be the result of the shorter fasts of birds on the nest. If not adaptive, mass increase may alternatively be the result of improved prey availability and abundance, e.g. through enhanced production and consequently prey abundance in the Southern Ocean system due to environmental changes. Unfortunately in the Southern Ocean there is no long term information on changes in availability or abundance of squids, the major prey of wandering albatrosses, and this hypothesis remains to be confirmed.

The shift to positive values of the SAM during the past half century is projected to continue, creating more upwelling favourable conditions in the Southern Ocean (IPCC AR4 Fig 10.17). Westerlies are predicted to continue to move poleward and increase in intensity and by 2080, winds speed, as well as meridional and zonal winds should be higher south of Crozet, but lower north, with a reversing of zonal and meridional wind at the extremes of the range of wandering albatrosses (Fig. 6). The present positive effect of climate change through improving travel speed, decreasing trip duration and improving body condition may not last in the coming decades. Indeed we can expect that travel and flight speeds may not respond linearly to the increase in wind speed and too strong winds are probably less optimal for dynamic soaring flights (*25*). In addition the position of the Crozet islands with regard to wind conditions may not be as favourable as it is presently if the westerlies flow continues to move southward away from the colonies. The trend observed during the past 20 years in the change in angle between flight track and wind conditions results in a progressive shift in the use of tail to side winds (Fig. 4). Because of the constraints of central place foraging, this trend is possibly related to the position of Crozet with regard to the poleward shifting westerly flow. If this trends continues towards side and head winds, costs of foraging should increase with increasing head winds (*12*), making the position of Crozet less optimal with regard to the westerly flow. Similarly to wandering albatrosses the movements of many other species of albatrosses and petrels are strongly constrained by wind conditions (*12, 26*), and species richness of Procellariiformes is positively associated to wind speed (*14*). Thus, future research should consider wind fields as an important driver of the distribution and migration of these oceanic species.

Finally, the observed southward shift of the northern range of wandering albatrosses (this study, (*22*) ) may have also significant consequences in terms of conservation. Indeed wandering albatrosses, as many other albatrosses and petrels, remain nowadays threatened by longline fisheries (*27*). In particular, the population size of wandering albatrosses has

decreased as a result of adult mortality in the Indian Ocean, especially females, due to longline fishing targeting tuna in subtropical waters (*27, 28*). If the range of breeding females moves southward due to environmental changes, they will be less likely to overlap with tuna longliners, whose effort has not shifted southward during the past 50 years (*29*). Therefore, past climate changes have affected the foraging efficiency and foraging range of wandering albatrosses, improving ultimately breeding success and reducing mortality risks respectively. These positive effects are likely not to last in the future, since foraging efficiency will be reduced by the occurrence of less favourable winds for the Crozet population. This study has allowed a better understanding of the mechanisms explaining the links between environmental changes and population parameters. It illustrates the importance of long term records of foraging parameters, but also the complexity of these linksand thus the difficulty to make robust predictions if mechanisms involved are not well understood.

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Table 1 – Estimated parameters (and SE) of retained models of the stepwise procedure using the Akaike Information Criteria (AIC) scores to explain foraging parameters of wandering albatrosses.

| Parameter | Final model | Sex | P- value | Year Estimate (±SE) | P- value | Wind Speed (WS) Estimate (±SE) | P- value | Meridional Wind (MW) Estimate (±SE) | P- value | AIC |
|---|---|---|---|---|---|---|---|---|---|---|
| Trip duration | ~ year + MW + Sex:year | | | -0.029 ± 0.087 | 0.017 | | | +0.615±0.195 | 0.002 | 512.4 |
| Total distance covered | ~ WS | | | | | -465±169 | 0.007 | | | 2674.9 |
| Maximum range | ~ year + WS | | | -19.7±8.0 | 0.025 | -136.2±40 | 0.001 | | | 2297.7 |
| Travel speed | ~ sex + year + WS | F > M | 0.004 | 0.128±0.029 | <0.001 | 0.271±0.138 | 0.052 | | | 296.3 |
| Flight speed | ~ MW | | | | | | | -0.207±0.09 | 0.023 | 196.1 |
| % time on water | ~ sex + year + MW + sex:MW | M > F | <0.001 | -0.741±0.219 | <0.001 | | | 2.10±0.751 | 0.007 | 492.5 |
| Northern range | ~ sex + MW | F > M | <0.001 | | | | | 0.221±0.162 | 0.013 | 451.6 |
| Southern range | ~ sex + WS | F > M | <0.001 | | | 0.623±0.249 | 0.013 | | | 504.1 |

Legends of figures

Figure 1 – Foraging trips of breeding male and female wandering albatrosses during incubation period (January-February 1989-2010; lower panels), and frequency distribution according to latitude of locations of males and females, and changes according to latitudes during two periods (1990-1995 and 2000-2005) in wind speed (S wind), zonal and meridional winds. Green dots (upper panels) and dotted line (lower panels) indicate position of Crozet Islands

Figure 2 – Changes over time a) in the Southern Annular Mode (SAM) , as well as in wind parameters in January-February at the Crozet islands (from 1989 to 2010) such as b) average speed ($y = 0.0572 * year – 105.1$, $r^2 = 0.34$, $P = 0.0034$; top right), c) zonal component; west-east, positive values indicate westerly flow, negative values easterly flow ($y = 0.0447 * year + 86.8$, $r^2 = 0.23$, $P = 0.032$) and d) meridional component; north-south, positive values indicate southerly winds, negative values northerly wind ($y = -0.0485 * year - 89.8$, $r^2 = 0.23$, $P = 0.030$) (bottom).

Figure 3 – Changes between 1989 and 2010 in four foraging parameters of males and females Crozet wandering albatrosses. Continuous lines indicate when trends over time are significant. (Dotes lines indicate significant trends over years significant when the atypical 2010 year is excluded from analysis).

Figure 4 – Percentage of flight tracks between locations where albatrosses were flying with various wind conditions from tail (0°) to head winds. In the 1990s birds preferentially fly with tail to side winds and a significant shift occurred in the 2000s, with birds using in a larger extent side and tail winds (Kolmogorov-Smirnov, $D = 0.11$, $p = 0.0039$).

Figure 5 – a) Changes in breeding success over the past 40 years ($R^2 = 0.30$, $P = 0.0003$). For the period 1988-2009 only, $R^2 = 0.19$, $P = 0.048$. b) Changes over the past 20 years in the mass of breeding wandering albatrosses in January-February.

Figure 6 - Wind speeds, zonal and meridional components averaged over the longitude 40°E and 60°E between 30° and 70°S of latitude predicted by the simulations of the inmcm3 model for 2000s and 2080s.

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Fig. 1

Fig 2



a)

b)

$y=0.043-76.0,$
$r^2=0.285, P=0.013$

c)

$y=0.029-51.2,$
$r^2=0.100, P=0.158$

d)

$y=-0.043-83.9,$
$r^2=0.258, P=0.022$

Fig. 3

Fig. 4



Angle between flight track and wind direction (°)
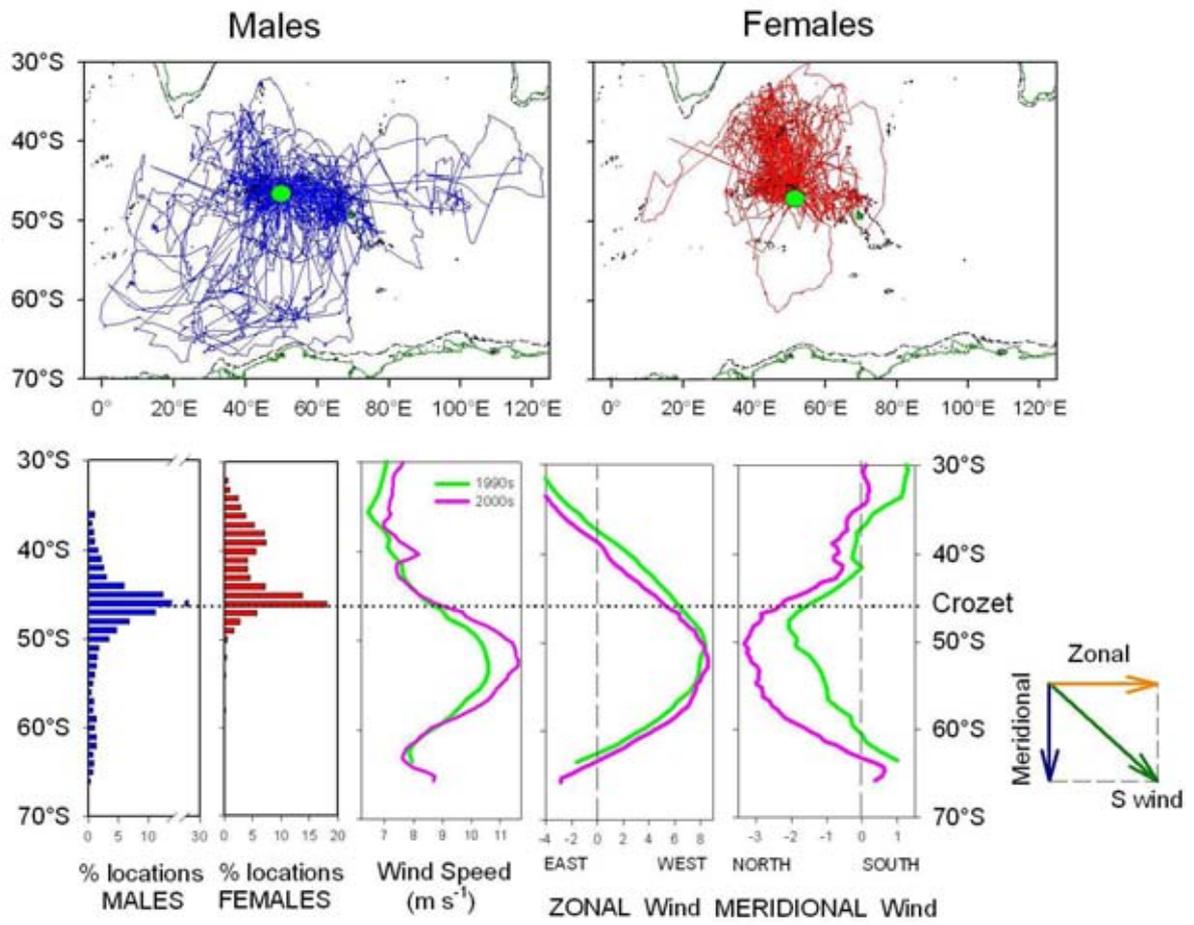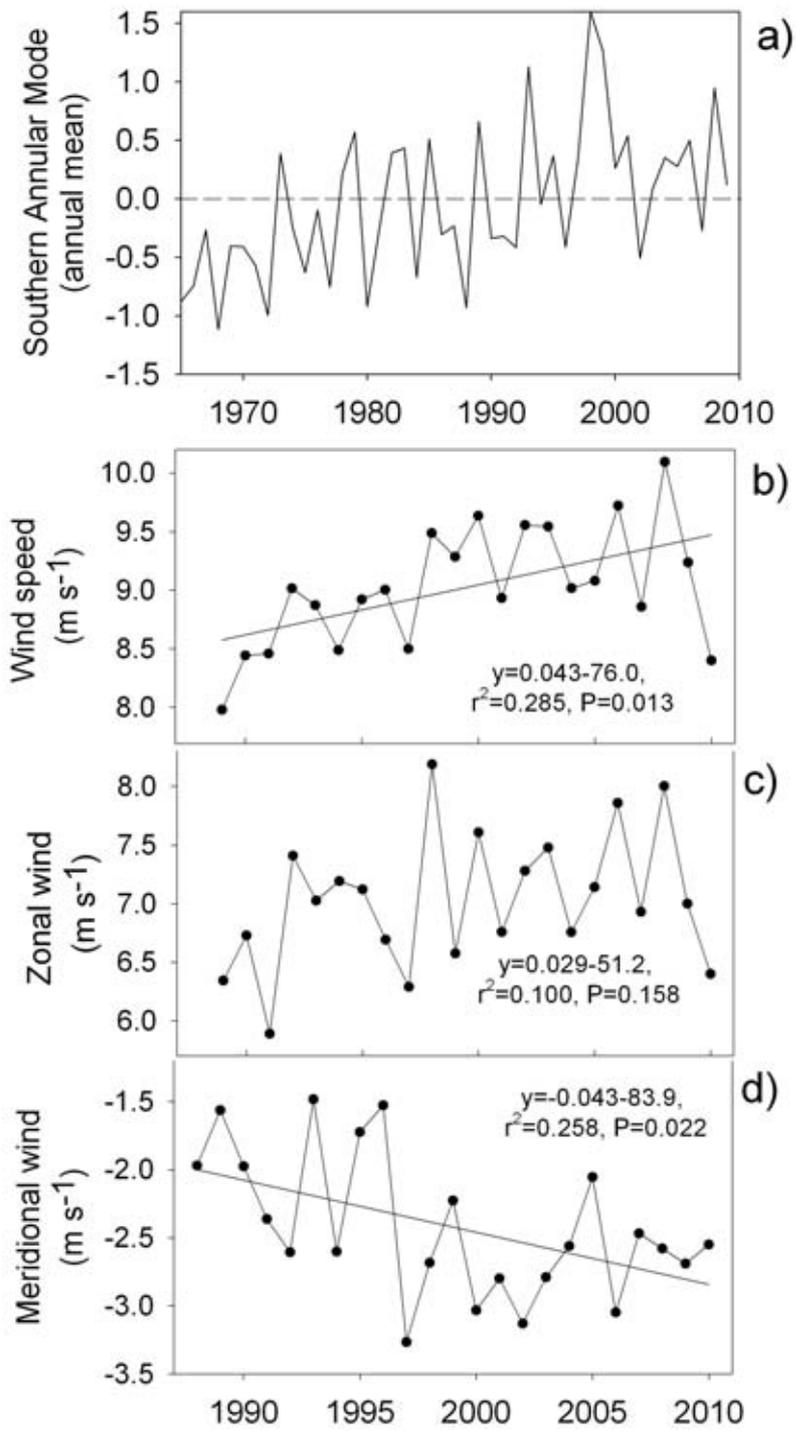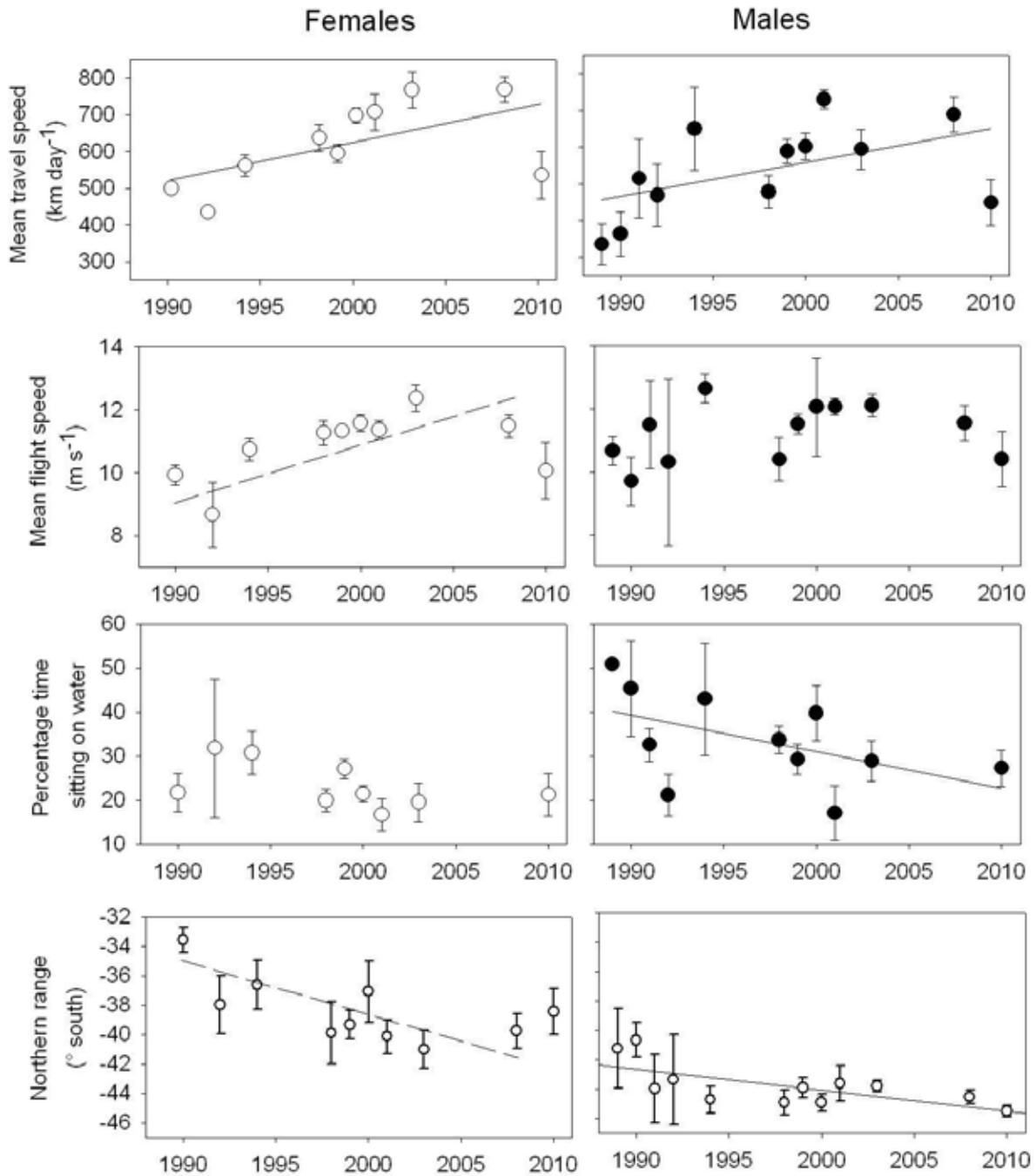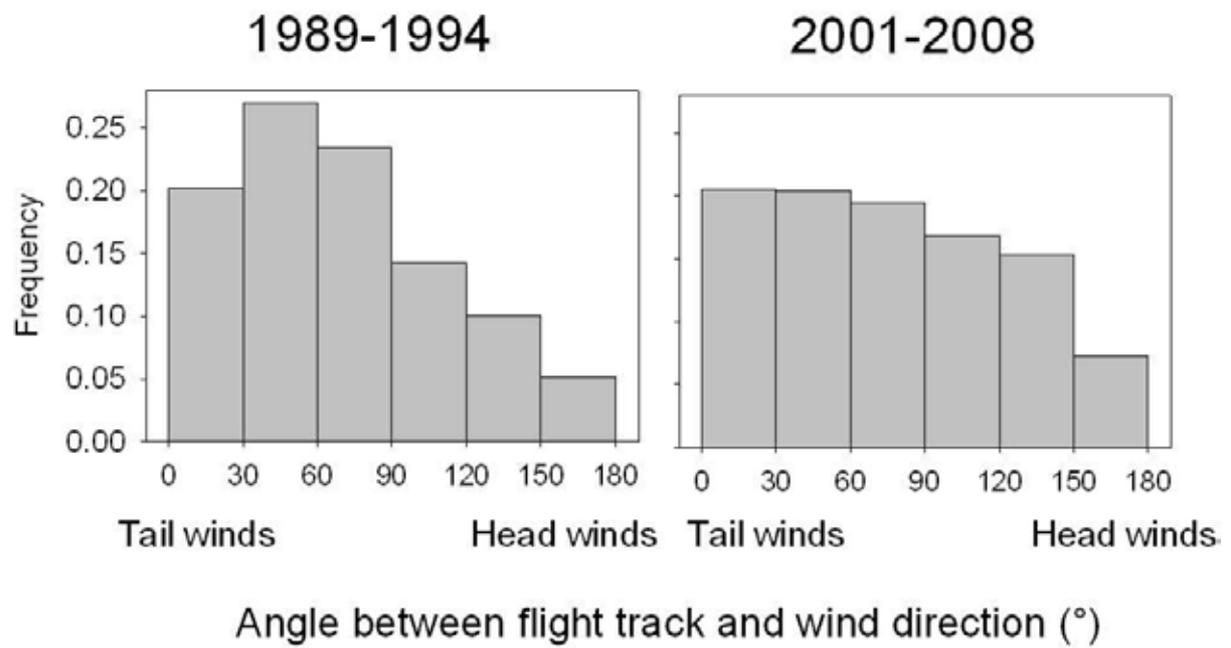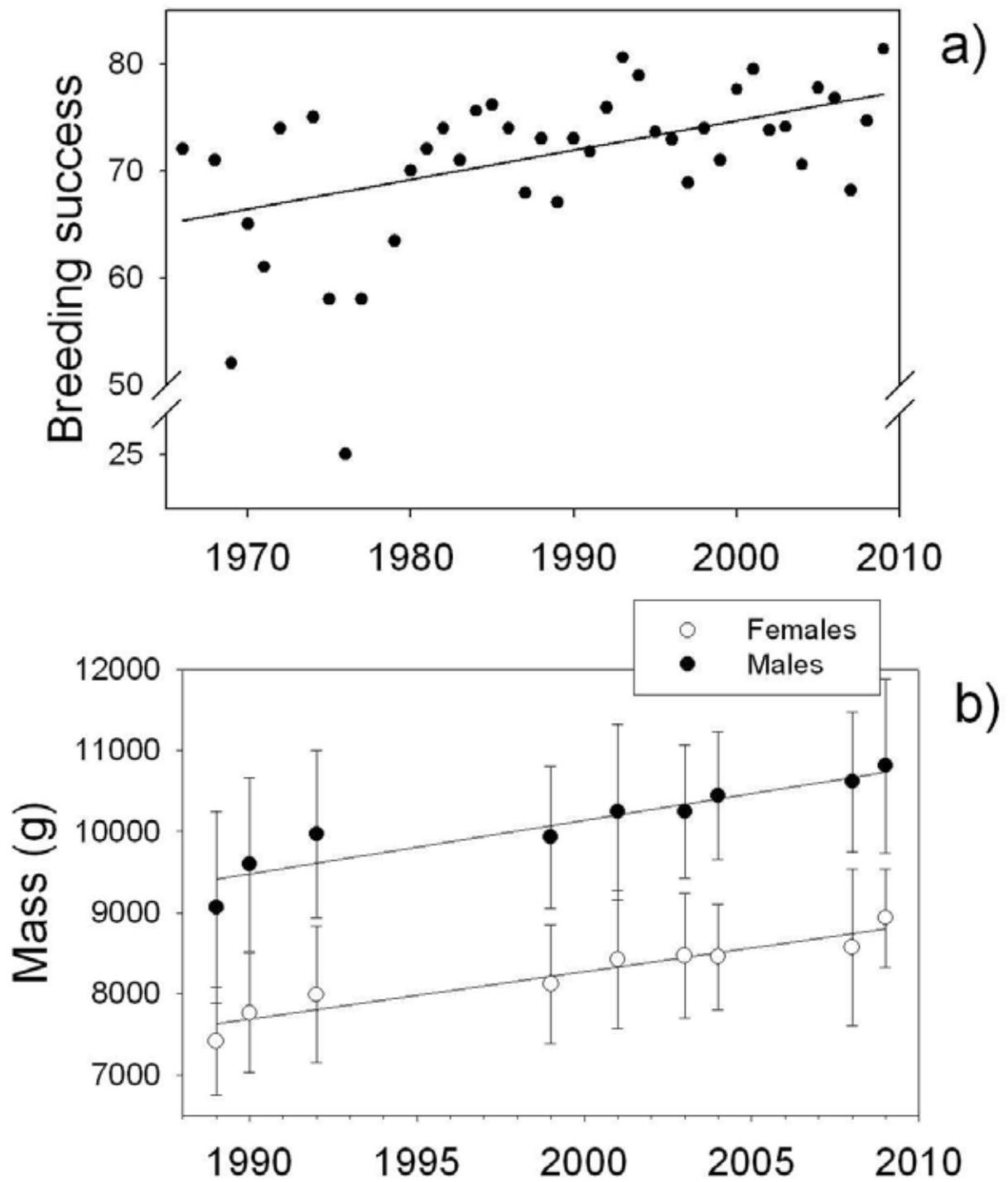
Figure 5

Figure 6
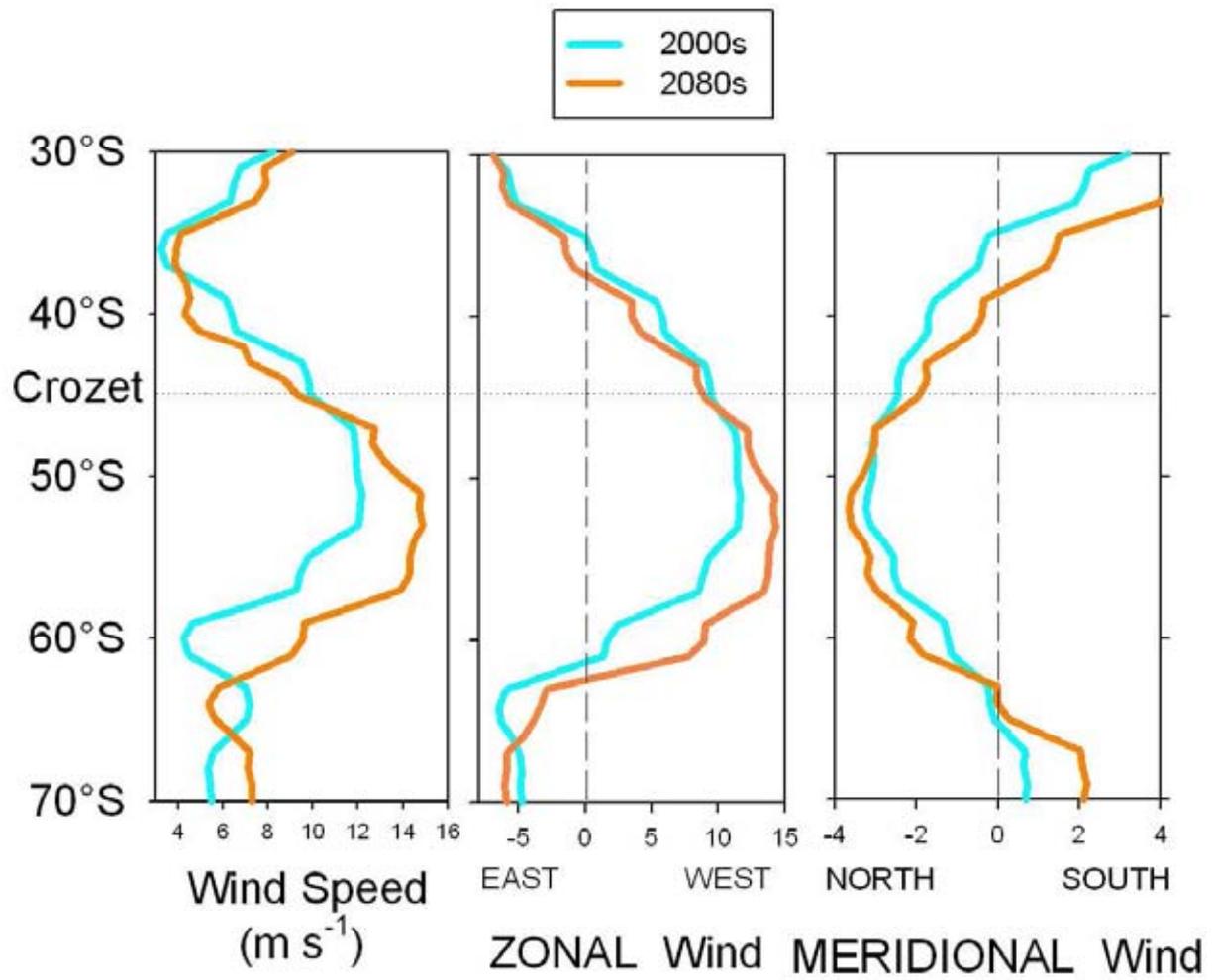
**Supporting Online Material**


**METHODS**


We confirm that all work followed approval by an ethics committee and conforms to the legal requirements of the country in which it was carried out, including those relating to conservation and welfare.


**Field and methodological procedures**


We studied wandering albatrosses foraging trips, incubation shifts, body mass and biometry of adults and breeding success on the population of Possession Island, Crozet islands (46°S, 52°E). On this island, the entire population (350 pairs today) is monitored annually since 1960 for population size, breeding success and demographic parameters from mark-capture-recapture of individuals [28]. Between 1989 and 2010 a total of 210 albatrosses of known sex and age were equipped during the incubation period, just before taking off for the sea, with Argos PTT Satellite Transmitters powered with battery and working in continuous mode (1989-2003), duty-cycled GPS/Argos satellite transmitters solar panel (2008) and GPS (2010). Details of equipment and analysis of data are given in [12]. The total mass of devices was far below the recommended 3% threshold [30] and the same procedure has been used during the last 20 years. Analyses of foraging parameters were performed on complete foraging trips (93% of trips). We used all Argos locations (classes A, B, 0, 1 to 3) but, in order to filter unrealistic positions, we removed those with an estimated speed above 25 m s$^{-1}$. We re-sampled all the data similarly to have one location per hour, except for duty-cycled PTTs for which we did not interpolated locations, hence only some parameters were estimated for these data.

At the individual level, we calculate different foraging parameters using scripts developed within the R environment (R Development Core Team 2010): trip duration (d), total distance covered (km), travel speed (km d$^{-1}$), flight speed (m s$^{-1}$), percentage of time on the water, maximum range (km), both northern and southern range (°S), bearing at departure and the shape of trip. Travel speed (distance covered per day) was calculated from the total distance covered divided by the duration of the foraging trip. To identify different behaviours such as flying or sitting on the water, we used a threshold of 5 ms$^{-1}$ considering higher speeds

as flying bird . Foraging trip sections with speeds higher than 5 ms$^{-1}$ were used to calculate flight speeds, whereas sections with speeds below 5 ms$^{-1}$ were used to estimate the proportion of time spent on the water. We calculated maximum range as the most distant point from the colony, whereas the maximum northern and southern ranges were estimated as the minimum and maximum latitude reached. Some of these parameters (e.g. proportion of time spent on the water, total distance covered) were not calculated for birds equipped with duty cycled PTTs. Bearing at departure were estimated as the overall direction during the first 6h after departure from the colony. We considered three types of shape of foraging trips, looping trips either clock-wise or anti-clockwise, or twisted trips following [12]. We found no evidence that males or females changed the general heading at departure or the bearing of the maximum range between the first and second decade of the study (Circular statistics, Watson two test, U2<0.0001 in all cases), nor that the shape of the foraging trips (clockwise, anticlockwise or twisted loops [12], $\chi^2_{10}$=1.4, P=0.451) changed over time.

At the population level, we considered only breeding birds of known sex captured in January and February to study changes in body mass and structural measurement. Birds were weighted with a spring balance to the nearest 50g either while incubating or when returning or leaving for a foraging trip [20]. Culmen length was measured with a caliper to the nearest 0.1 mm. The duration of foraging trips was estimated from daily checks of nests in 1970, 1989, 1999 and 2008. Nest failures, due to nest abandonment generally, were studied in 1989 and 1999 and related to the duration of the preceding complete foraging trips of the two members of the pair.

Daily and monthly wind data from ERS1, ERS2 et Quickscat were obtained from CERSAT web portal (http://www.ifremer.fr/cersat), the Southern Hemisphere Annular Mode Index from http://www.antarctica.ac.uk/met/gjma/sam.html).

**Modelling procedures**

We analysed the influence of wind fields (speed, zonal and meridional components) on the foraging parameters of wandering albatrosses considering the effect of sex, age classes (7-17 years, 18-30, older than 30 years), and year, as well as their interaction. Since the size of the loggers varied according to years, we have investigated whether loggers mass could have influenced foraging parameters. Since wind speed, zonal and meridional components are correlated; they were included separately in the model. Since wind components increased over time, we used the residuals of the relationship between time (year) and wind components as a

measure of wind conditions encountered. Because in some cases several trips of the same individual were recorded, either the same year, or during different years we selected randomly one trip per individual. The model building procedure was defined a priori to address hypotheses about sex and age specific, temporal and wind-related patterns in foraging parameters during foraging trips. We considered trip duration, total distance covered, maximum range, travel speed, flight speed, percentage of time on the water and both northern and southern ranges. We used a stepwise procedure (Step in R 2.6.1 (cran.r-project.org), at each step, variables were retained only if they decreased (improved) the Akaike Information Criteria (AIC) scores. Retained models are listed in Table 1. Sex and meridional wind influenced strongly several foraging parameters, as well as the wind speed to a lesser extent (Table 1). No significant effect of age classes and logger mass was found and none of the foraging parameters were influenced by zonal winds.

Finally, we tested whether breeding success ('success' or 'failure') was influenced by the duration of foraging trips, sex and their interaction by using a Generalized Linear Model (GLM) with a binomial distribution and a logit link.

Statistical analyses were performed using Statistica 8 (StatSoft Inc.) and R 2.6.1 (cran.r-project.org). Unless otherwise indicated, the results are expressed as means ± SD and all reported P-value are two-tailed.

**Future trends of oceanic wind fields**

We obtained future trends of oceanic wind fields from the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset conducted in support of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) (https://esgcet.llnl.gov:8443/home/publicHomePage.do). We used climate models forced with the ''business as usual'' scenario (A1b). Under this scenario, $CO_2$ levels double from the pre-industrial level of 360 parts per million (ppm) to 720 ppm by 2100.

Regarding IPCC climate model selection, we used the root mean squared error (RMSE) estimation for selecting the model that best match the statistical properties of wind speed with those of the satellite observations [31]. Simulations and observations were compared for the available time window, from 2001 to 2010, during the incubation period (January-February) of wandering albatrosses. Given the differing spatial resolution of each climate model, we interpolated wind fields of each climate model onto a 1°×1° grid using inverse weighting distance method. Moreover, the original 0.25° remotely sensed wind speed

was also aggregated to match the $1°\times1°$ grid. We used wind speed averaged over a sector between the longitude 40°E and 60°E along from subtropical to Antarctic latitudes. RMSE comparison yielded that the simulations of the model inmcm3_0 better approximates observations (lower RMSE values. Thus, we used only this model for considering future trends of wind speed, as well as the zonal and meridional components during 2000s and 2080s. Wind values for each decade are the mean value between the first and fifth year (e.g. 2000s represents the average from 2001 to 2005).

Table S1

Mean wind speed and both zonal (west-east, positive values indicate westerly flow, negative values easterly flow) and meridional components (north-south, positive values indicate southerly winds, negative values northerly wind) over 5° latitudinal bands in the foraging range of Crozet wandering albatrosses averaged over 40°-70°E. Regression coefficient for trends over the period 1989-2008 indicated only when significant, otherwise NS: no significant. Wind directions indicated by arrows, ▲ south, ▼ north, ►west and ◄ east.

| Latitudinal Band | Wind Speed (m s$^{-1}$) | | Zonal Wind | | | Meridional Wind | | |
|---|---|---|---|---|---|---|---|---|
| | Mean (± SD) | Trend | Direction | Mean | Trend | Direct. | Mean | Trend |
| 26°-30 °S | 8.0 | (NS) | ◄ | -5.7 | (NS) | ▲ | +0.1 | (NS) |
| 31°-35 °S | 7.1 | (NS) | ◄ | -3.1 | (NS) | ▼ | -0.2 | (NS) |
| 36°-40 °S | 7.5 | (NS) | ► | +1.0 | (NS) | ▼ | -0.8 | (NS) |
| 41°-45 °S | 8.2 | (r=+0.441, P=0.026) | ► | +4.5 | (NS) | ▼ | -1.5 | (r=-0.419, P=0.033 |
| 46°-50 °S | 9.6 | (r=+0.698, P<0.001) | ► | +7.1 | (r=+0.485, P=0.016) | ▼ | -2.5 | (r=-0.481, P=0.017 |
| 51°-55 °S | 10.3 | (r=+0.404, P=0.039) | ► | +7.5 | (NS) | ▼ | -2.6 | (r=-0.330, P=0.078 |
| 56°-60 °S | 9.6 | (NS) | ► | +6.4 | (NS) | ▼ | -2.1 | (NS) |

Fig. S1 Frequency distribution of the duration of foraging trips of Crozet wandering albatrosses at 10 years intervals. The vertical line indicates the average value that decreased by 3 days over the past 40 years and