Flying at No Mechanical Energy Cost: Disclosing the Secret of Wandering Albatrosses

Gottfried Sachs, Johannes Traugott, Anna P. Nesterova, Giacomo Dell'Omo, Franz Kümmeth, Wolfgang Heidrich, Alexei L. Vyssotski., Francesco Bonadonna

Supporting Information

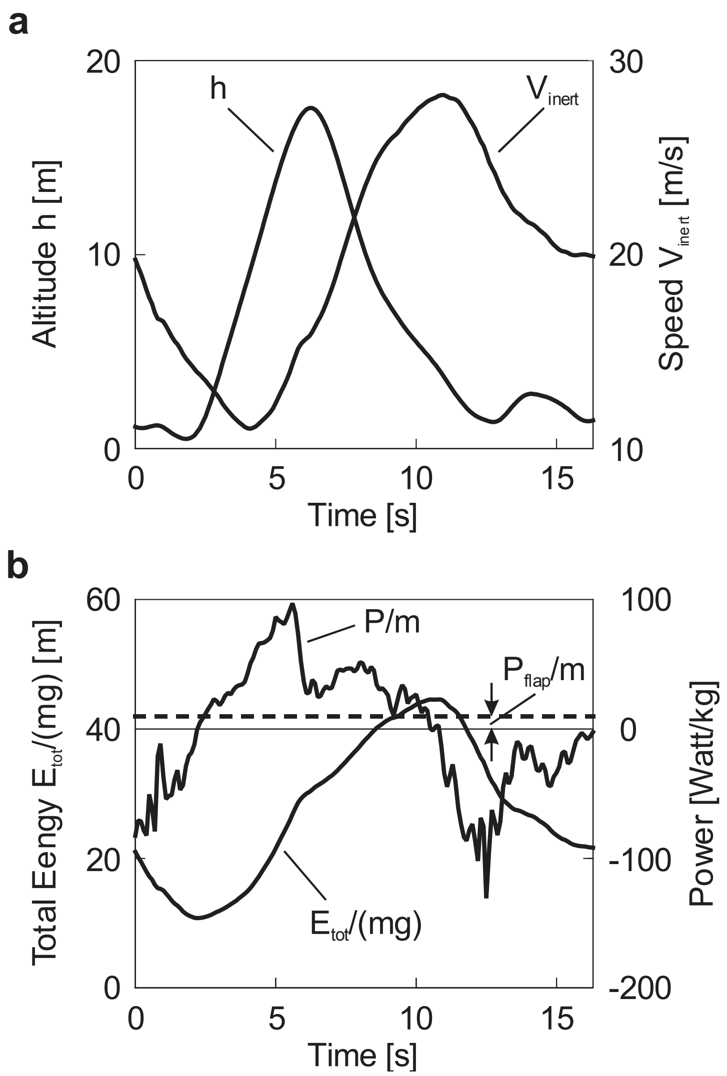

Figure S1. Dynamic soaring cycle 1. (**a**) Altitude h and inertial speed V_{inert}. The behaviour of the altitude and the speed correspond with that of Fig. 2 of the main manuscript, showing the repeatability in the flight pattern. This particularly holds for the cyclic characteristics of both quantities, for their magnitude during the dynamic soaring cycle and for the time lag of the speed relative to the altitude. (**b**) Total energy $E_{tot}/(mg)$ and mechanical power P/m and P_{flap}/m. The behaviour of the total energy also corresponds to Fig. 2. In particular, this holds for the energy gain phase which is associated with the upper altitude region. Furthermore, there is a large energy gain of about 350% relative to the beginning of the dynamic soaring cycle, similar to Fig. 2. As a result, the total energy characteristics confirm the repeatability in the energy gain mechanism in terms of an energy transfer from the wind to the bird. The mechanical power, (solid line), shows two parts as a characteristic feature of dynamic soaring: A part with a high positive power level, associated with the upper altitude region where the energy gain from the wind is achieved. The other part shows a negative power level associated with the lower altitude region where the energy loss occurs. The mechanical power level available in flapping flight (dashed line) is much smaller in magnitude than during of the dynamic soaring cycle. As a result, the large power values cannot be generated by flapping the wings. Instead, this is due to the effect of the wind in terms of the interaction between the moving air and the motion of the bird.

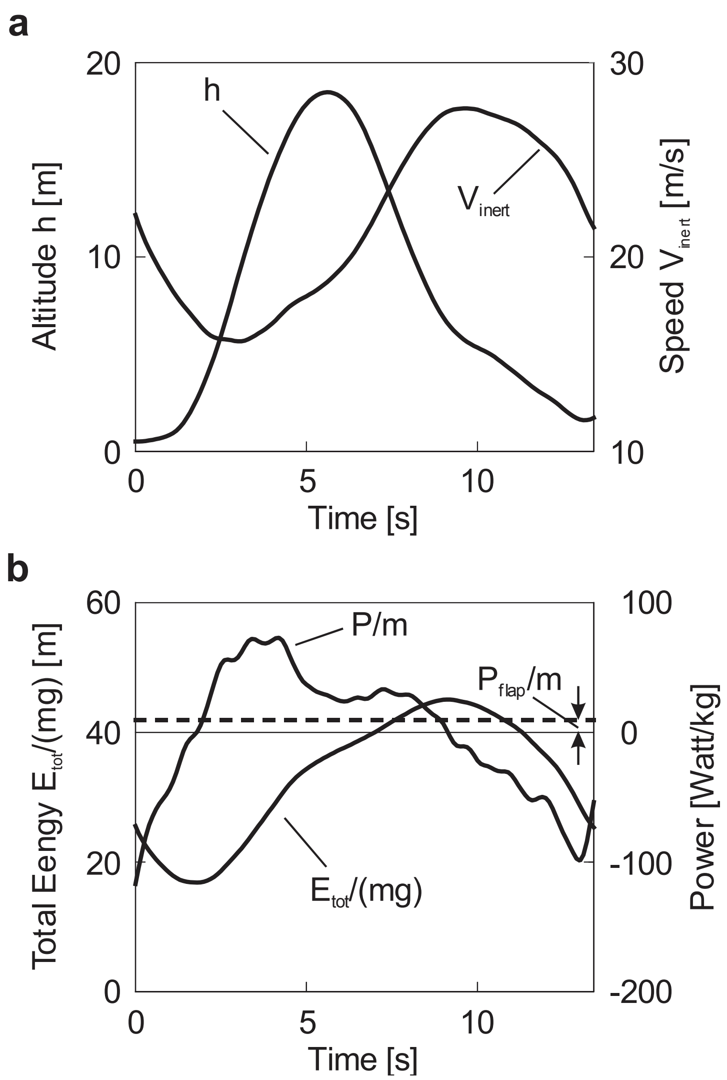

Figure S2. Dynamic soaring cycle 2. (**a**) Altitude $h$and inertial speed V_{inert}, (**b**) Total energy $E_{\mathrm{tot}}/(mg)$and mechanical power $P/m$and P_{flap}/m, In Figure S2, the same characteristics hold as in Figure S1.

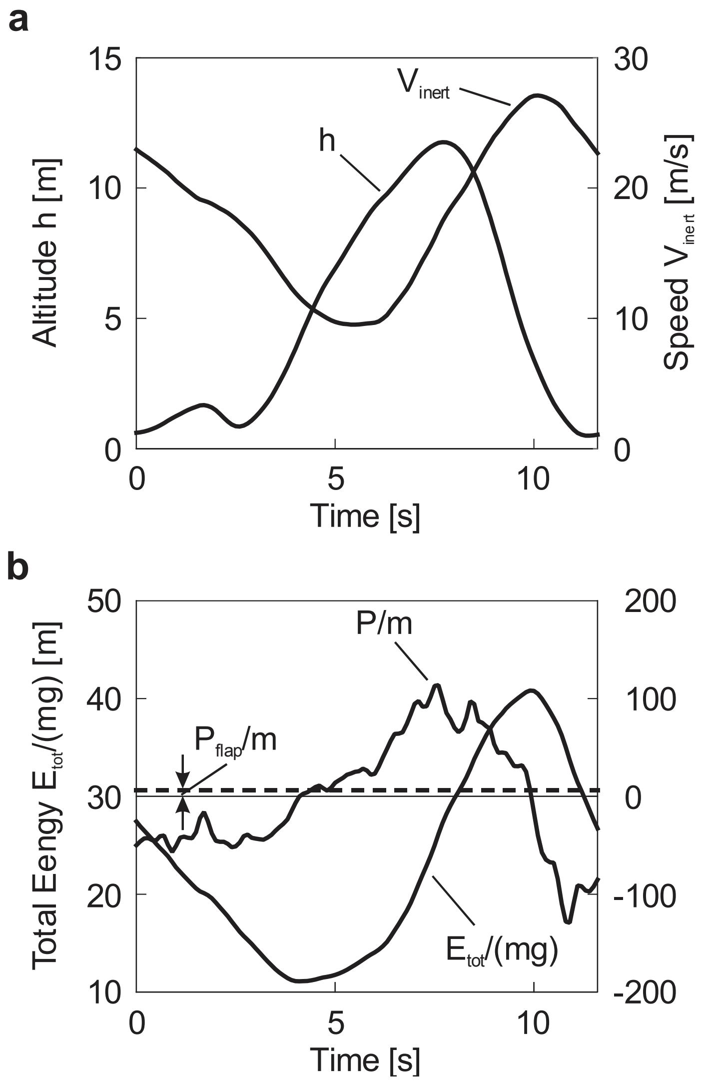

Figure S3. Dynamic soaring cycle 3. (**a**) Altitude h and inertial speed V_{inert}, (**b**) Total energy $E_{\mathrm{tot}}/(mg)$ and mechanical power P/m and P_{flap}/m, In Figure S3, the same characteristics hold as in Figure S1.

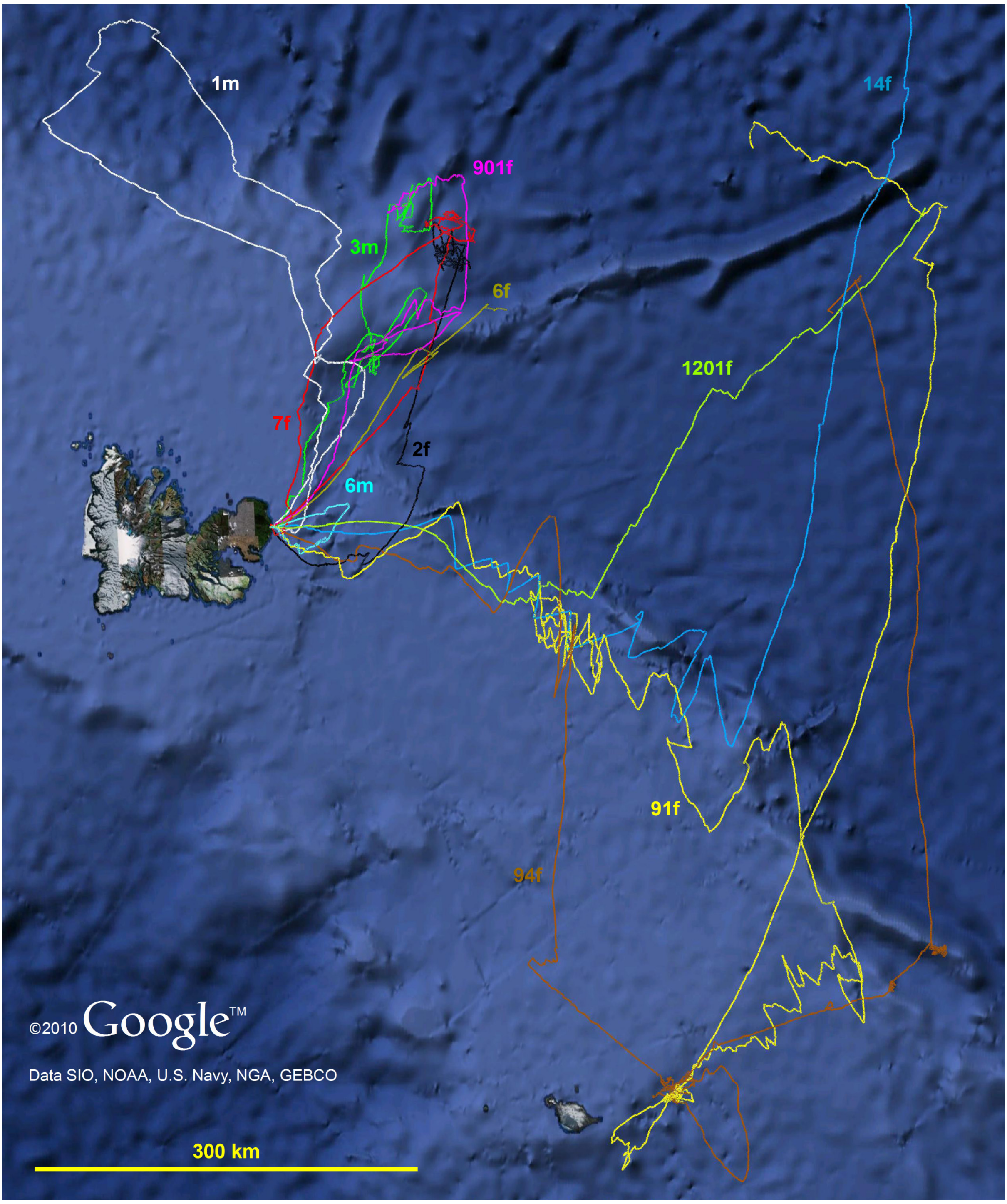

Figure S4. Albatrosses' long-distance flights. Individual paths (projected to the sea surface) of long-distance flights of 11 albatrosses are represented. Both males (1 m, 3 m, 6 m) and females (2f, 6f, 7f, 14f, 91f, 94f, 901f, 1201f) were tracked. Complete paths were recorded for 1 m, 6 m, and 7f individuals and information on the part of the paths is available for the other birds. The scope of the study was to obtain high resolution data, and not necessarily complete paths. Additional information on 14f path that was longer than others is provided in Fig. 1a. The recording times for the other five birds are short, and their paths are not presented. The image was generated in the Google Earth Pro software.

FUEL CONSUMPTION OF GASOLINE ENGINE PRODUCING THE SAME POWER AS A WANDERING ALBATROSS

Energy required by albatross

Mass: $m = 8.5\,\mathrm{kg}$

Drag-to-lift ratio: $C_\mathrm{D} / C_\mathrm{L} = 0.05$

Speed: $V = 70\,\mathrm{km/h}$

Energy required for $t_\mathrm{day} = 24\,\mathrm{h}$ flying: $E_\mathrm{day} = DVt_\mathrm{day} = (C_\mathrm{D} / C_\mathrm{L})mgVt_\mathrm{day}$

Thus: $E_\mathrm{day} = 7.0 \times 10^6\ \mathrm{J}$

Gasoline

Energy: 4.0 10^7 J/kg

Density: 0.75 kg/dm^3

Efficiency: 25 %

Effective gasoline energy per litre: $E_\mathrm{litre} = 7.5 \times 10^6\ \mathrm{J/dm^3}$

Fuel consumption per day

$m_\mathrm{fuel,day} = E_\mathrm{day} / E_\mathrm{litre}$

Thus: $m_\mathrm{fuel,day} = 0.93\,\mathrm{dm}^3$

INTERACTIVE 3-DIMENSIONAL VISUALIZATION OF DYNAMIC SOARING

A .kmz file for Google Earth can be downloaded by following the link below. The file enables interactive visualization of the dynamic soaring cycle discussed in the article. This manoeuvre was reconstructed with high precision and 10 Hz resolution by means of GPS raw data post-processing. The file also holds approximately eleven minutes of flight preceding and following this manoeuvre. These data come from the coarse 1 Hz online solution provided directly by the GPS module.

Instructions and hints for achieving the best visualization results

- Open the file (Wandering Albatross Dynamic Soaring.kmz) by double clicking (MS Windows) or simply by dragging and dropping to Google Earth.
- Google Earth *sidebar*
  If not already displayed when opening the file, activate the sidebar in the view menu. Enable or disable the various trajectory elements (described below) by clicking on the respective checkbox.
- Use of the *scroll wheel* of your mouse to navigate through the trajectory
  - Scroll the wheel for zooming
  - Press Ctrl and scroll for changing the map heading
  - *Press down the scroll wheel and move the mouse* for freely changing the camera angle.

Displayed elements

Click on the respective icons in the Google Earth map to display bubbles holding further information.

- **Dynamic soaring trajectory**
  Eleven minutes of dynamic soaring. The purple arrows integrated in the trajectory indicate the flight direction. The displayed position fixes are the coarse solution calculated online by the GPS module with a rate of 1 Hz.
- **Dynamic soaring cycle**
  Individual dynamic soaring manoeuvre as analysed in the article (Fig. 2a, 2b and 3). The 10 Hz position fixes come from GPS raw data post-processing.
- **Wind**
  Blue arrows indicating wind direction according to NASA QuickSCAT L3 wind data.
- **Labels**
  Display of additional information. Disable for unrestricted view using the respective sidebar checkbox.
- **Tour:** *Fly with the Albatross!*
  Google Earth 5.0 and higher. Double click on the sidebar checkbox next to the camera symbol to take off.
  If a previous version of Google Earth is installed on your machine, this element will not appear in the sidebar.

Download the file here:

http://www.fsd.mw.tum.de/images/stories/Daten/Mitarbeiter/Traugott/Wandering%20Albatross%20Dynamic%20Soaring.kmz

Details on the recorded long-distance flights of tracked wandering albatrosses are given in the table below (see also Figure S4). The trip parameters presented were calculated based on segment of the trip for which GPS data were available. Travel speed reflects overall speed including flying and resting on the water surface.

Table S1| Parameters of albatrosses' long distance flights.

№	Animal	Trip duration (days)	Path length (km)	Travel speed (km/h)	Flight duration (%)	Flight speed (km/h)
1	6m	0.82	173.7	8.84	26.20	53.30
2	1201f	0.93	659.6	29.62	47.02	76.12
3	901f	0.95	646.0	28.25	68.15	56.81
4	6f	0.99	316.6	13.38	23.98	61.31
5	1m	3.55	1115.7	13.09	24.71	64.29
6	7f	3.80	765.7	8.40	19.77	57.02
7	3m	4.16	842.5	8.43	22.96	54.10
8	2f	4.38	746.7	7.09	23.66	50.41
9	14f	6.02	4847.0	33.52	70.06	61.21
10	94f	6.38	2348.8	15.34	42.46	57.37
11	91f	6.47	3363.3	21.67	63.06	55.57
	Mean±STD	**3.50±2.27**	**1439±1471**	**17.06±9.61**	**39.27±19.81**	**58.86±6.96**