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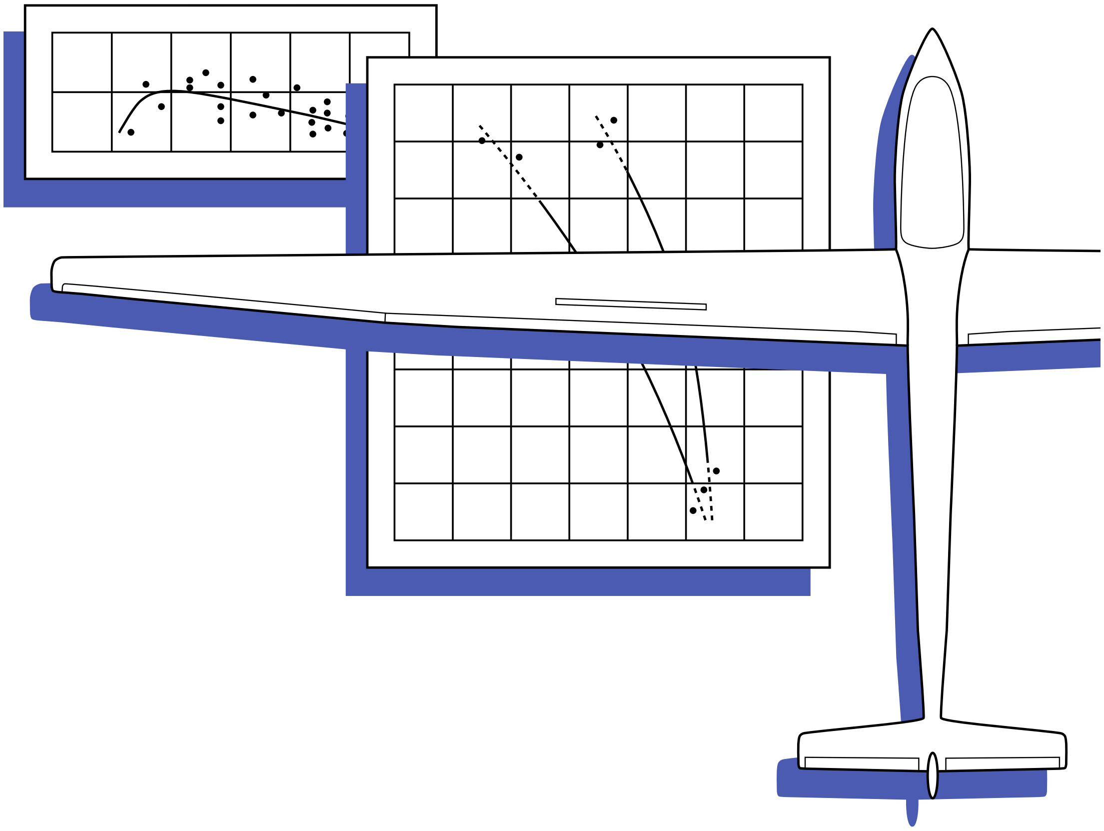

- **Call for Papers, OSTIV Congress XXXIV**
- **Frigate birds track atmospheric conditions over months-long transoceanic flights and perform flights inside clouds**

Organisation Scientifique et Technique Internationale du Vol à Voile (OSTIV)
International Scientific and Technical Organization for Soaring
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Technical Soaring (*TS*) documents recent advances in the science, technology and operations of motorless aviation.
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An index of *Technical Soaring* (Vol. 1 through Vol. 34) is at `soaringweb.org/Soaring_Index/Technical_Soaring`. Issues are indexed by author, subject and issue. Additional information on *TS* and information on OSTIV Publications can be found on the OSTIV website in a searchable Publications Index.

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Technical Soaring (*TS*) documents recent advances in the science, technology and operations of motorless aviation. *TS* welcomes original contributions from all sources.

General Requirements Manuscripts must be unclassified and cleared for public release. The work must not infringe on copyrights, and must not have been published or be under consideration for publication elsewhere. Authors must sign and submit a copyright form at time of submission. The form is available at `www.ostiv.org`.

Language All manuscripts submitted to *TS* must be in English. Submissions requiring extensive editing may be returned to author for proofreading and correction prior to review.

Layout Submit manuscripts in single-column, double spaced layout with all figures and tables at end, one per page.

Electronic submissions are preferred. Most data file formats are acceptable, with PDF preferred. Submit one file containing the complete paper including all figures, tables, and captions. Paper submissions will also be accepted — contact Editor for submission details.

Length There is no fixed length limit. At the discretion of the EIC, manuscripts may be returned to the author for reduction in length.

Structure Organize papers as needed in sections, subsections, and subsubsections.

Title A title block is required with author name(s), affiliation(s), location, and contact info (email address preferred).

Abstract All papers require a summary-type abstract consisting of a single, self-contained paragraph. Suggest 100 to 150 words. Acronyms may be introduced in the abstract, but do not cite references, figures, tables, or footnotes.

Nomenclature If the paper uses more than a few symbols, list and define them in a separate table. Otherwise, explain them in the text where first used. Define acronyms in the text following first use.

Introduction An Introduction is required that states the purpose of the work and its significance with respect to prior literature, and allows the paper to be understood without undue reference to other sources.

Conclusions The Conclusions section should review the main points of the paper. Do not simply replicate the abstract. Do not introduce new material or cite references, figures, or tables in the Conclusions section.

Acknowledgments Inclusion of support and/or sponsorship acknowledgments is strongly encouraged.

Citations Cite with bibliographic reference numbers in brackets (e.g. "[7]"). Do not cite Internet URLs unless the website itself is the subject of discussion.

References All references listed in the References section must be cited in the text. List references in order of first citation in the text. Any format is acceptable as long as all citation data are provided. At a minimum, all types of entries require title, year and manner of publication. Provide full names of all authors. Do not list Internet URLs as sources.

Captions All figures and tables require captions. Do not use the caption to explain line styles and symbols — use a legend instead.

Color Color graphics are acceptable. Avoid using color to distinguish data sets in figures — instead, use line styles, symbol shapes and fill patterns.

Footnotes Use footnotes sparingly. Do not footnote to cite literature.

Numbering All figures, tables, footnotes and references must be referenced in the text and are numbered sequentially in order of first reference. Equations are numbered only if they are referenced by number in the text. Number every page.

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Peer Review Manuscripts will be peer-reviewed before being accepted for publication. Authors are welcome to suggest names of reviewers and to contact the Editor or the assigned Associate Editor at any time for updates on the status of their review.

Charges *Technical Soaring* does not require a publication page-charge.

From the Editor

Publication Date

This issue is the first of Volume 41 of *TS*, corresponding to January-March 2017. For the record, the issue was published in October, 2017.

OSTIV Congress XXXIV

OSTIV Congress XXXIV will be held in conjunction with the 35th World Gliding Championships in Příbram, Czech Republic, 28 July to 3 August, 2018. The call for abstracts appears in this issue. We encourage everybody to attend and present their latest work.

About this issue

The main article of this issue is about transoceanic flights of frigate birds. Unknown to me was their ability to soar in clouds up to 4000 m! which enhances gliding distances substantially. I think it is a very interesting article and it really is worth it to be published in *Technical Soaring*.

The XXXIII Congress of the OSTIV was held in Benalla, Australia, from 8 to 13 January, 2017. The Congress addressed all scientific and technical aspects of soaring flight. We are grateful to Rolf Radespiel, president of OSTIV, for a short report about the congress following the editor's notes.

Thanks also to Murray Stimson, who wrote for *Technical Soaring* a summary of the discussion that developed during the 'Future of the Open Class' panel session. You will find it after Rolf's report.

Very Respectfully,

Arne Seitz
Editor-in-Chief, *Technical Soaring*
`ts-editor@ostiv.org`

XXXIII OSTIV Congress Report

By Rolf Radespiel, OSTIV President

The XXXIII OSTIV Congress was held at the same time as the recent World Gliding Championships in Australia, during January 2017. This conjunction of soaring science and gliding contest has a long tradition. It offers great opportunities for exchanging new ideas between sailplane developers, research scientists and contest practitioners.

The OSTIV Congress was hosted by the Gliding Federation of Australia in Benalla, Victoria. A joint Opening Ceremony of OSTIV and the World Gliding Championships on Sunday, January 8, was the beginning of a successful Congress week. The program consisted of 16 scientific and technical sessions held during the mornings and afternoons, whereas three evenings featured outreach sessions advertised for public attendance. The Congress took place at the Benalla Performing Arts Centre near the clubhouse at Benalla Airfield. This conference venue proved to be excellent in its quality of rooms, facilities and technical infrastructure. Access to the site of Championship operations was well organized and easy. Congress delegates and their partners

Congress delegates following presentations (left) and session chair Götz Bramesfeld with presenter Kai Rohde-Brandenburger (right)

were also taken on a wonderful all-day bus tour full of attractions such as a warbird restoration business in Wangaratta, a picnic on Mount Buffalo, a wine tasting and more. OSTIV is very thankful to the Gliding Federation of Australia for its great hospitality.

Preparing the Congress and running it throughout the week took endless hours of work by the Organizing Team, consisting of Murray Stimson and Stuart Smith, both from Australia, and Britta Schlenker and Rolf Radespiel, Germany.

A great number of organizational and industrial sponsors covered the cost of venue rental, refreshments during breaks, congress advertisements, booklet printing and bus rental for the Congress excursion. OSTIV is much obliged to its sponsors who made it possible to offer free access to the Congress and give special support to participating students.

The Call for Abstracts issued by OSTIV generated response by engineers and scientists from 11 countries worldwide. The received extended abstracts were reviewed, and they were published as a proceeding booklet, see `http://ostiv.org/index.php`. A varied program was generated this way. For their efforts in recruiting high-quality contributions OSTIV acknowledges the members of the Program Committee:

Zafer Aslan, Turkey; Mark Maughmer, USA; Lukáš Popelka, Czech Republic; Götz Bramesfeld, Canada; Judah Milgram, USA; Rolf Radespiel, Germany; Helmut Fendt, Germany; Ian Oldaker, Canada; Gerard Robertson, New Zealand.

As many as 55 international delegates registered at Congress Office to attend the technical and scientific sessions. They saw 45 presentations covering recent trends in sailplane development, training and safety, and meteorology. Noteworthy are comprehensive Congress Sessions in the fields of

- Laminar Boundary Layers and Transition
- Aerodynamic Configuration Design
- Electric Propulsion
- Gust Loads of Sailplanes
- Sailplane Performance
- Sailplane Safety
- Mountain Wave Flying
- Atmospheric Convection.

This list demonstrates the span of activity within OSTIV. The extended abstracts are available on the OSTIV website. As might be expected, many of the papers represent ongoing work, with updates being presented at future OSTIV Congresses.

The OSTIV-MacCready Award for the best scientific student contributions to the Congress was given to the joint contribution of Nilkan Akataş and Serhan Yeşilköy, 'Investigation of the Vegetation Effects on Convection by Using COSMO-CLM'. Maike Fröhner received the OSTIV-Mertens Award on the best technical student contribution for 'Measurement and Simulation of Potential Electromagnetic Interference Sources in Small Aircraft'. The two honored student contributions will soon appear as full papers in the OSTIV Journal Technical Soaring. The joint OSTIV-GFA Prize for the best presentation of the Congress went to Stuart Smith and Murray G. Stimson for 'Comparative Statistical Analysis of Fatal Spin Accidents for Training Gliders'.

To expand awareness of its activities, OSTIV held outreach sessions, covering:

- FES technology development, presented by Luka Žnidaršič
- Presentation by Martin Volck on 'Initiative ProSegelflieger', which aims at advancing crashworthiness of gliders in order to avoid fatal injuries due to crashes
- Panel discussion on the future of the Open Class, with the panel consisting of Oliver Binder, Loek Boermans, Tilo Holighaus, Uys Jonker, and Gerhard Waibel
- Presentation by Morgan Sandercock on the 'First year in Argentina with the Perlan 2 glider'.

One mission of OSTIV is to acknowledge major technical developments by awarding prizes. The OSTIV Congress is certainly the best opportunity for presenting the accomplishments of the award winners to the public. The OSTIV Prize for 2017 was awarded to Stefan Gehrmann, Axel Lange, and Luka Žnidaršič for their pioneering works on electric propulsion in sailplanes.

In 1992 Stefan Gehrmann started studies on electric propulsion systems and found that the new ultra-light sailplane Silent could be a suitable basis for such an electric motor-glider. In 1997 this concept was first flown under the AE-1 designation. After type certification in 1999 under national micro-light regulation the AE-1 became the first serial-produced electric powered sailplane available to the public. Stefan Gehrmann and his company have remained in the business to the present day, developing and producing electric components for different products and projects, with Solar Impulse probably being the largest example. Stefan Gehrmann therefore is honored for making electric propulsion available to customers with his AE-1.

Axel Lange started his path toward electrically powered sailplanes as an engineer in the Glaser-Dirks sailplane company. It soon became obvious to him that electric propulsion would be a suitable alternative to using combustion engines. Axel Lange took his chance to start a new business based on his ideas about electric systems. After founding Lange Flugzeugbau, he developed the Antares 20E as his first own product, combining a completely new electric propulsion system with other state-of-the-art elements like modern structures, excellent crash-worthiness and optimized aerodynamics. It took several years to complete type certification for the Antares 20E in 2006. Today this sailplane has become a familiar sight at glider airfields with more than 60 examples produced. The propulsion system now has also been installed into the Arcus E sailplane from Schempp-Hirth

Entrance to congress venue decorated with new OSTIV logo (left) and award of the OSTIV Prize 2017 to Luka Žnidaršič (co-recipients: Stefan Gehrmann and Axel Lange) during opening ceremony of OSTIV Congress (right)

Flugzeugbau, making this the first two-seated electrically powered sailplane available on the market. Therefore, Axel Lange is honored for type-certifying an electrically powered sailplane according to sailplane standards and for opening up serial production of such a system.

Luka Žnidaršič was also fascinated about the possibilities of electric propulsion, being an excellent sailplane pilot and working in his company with electric drives and generators. However, he aimed for a much smaller and more affordable system than those available on the market. By developing a compact electric motor, which fits into the nose of a typical sailplane, and combining this with propeller blades folding to the sides of the cockpit, he created a simple and error-proof propulsion system for a self-sustainer in 2009. He called this system Front Electric Sustainer and under the acronym FES this system is now integrated into several sailplanes produced by different manufacturers. At the time of presenting this award, models of sailplanes from JSC Sportinė Aviacija IR KO (LAK-17B FES), Alisport (Silent FES), Schempp-Hirth Flugzeugbau (Ventus-2cxaFES and Discus-2cFES) and HPH (HPH 304 S FES) have been equipped with the FES system. Accordingly, Luka Žnidaršič is honored for developing a simple electrically powered propulsion system which is comparatively easy and safe to operate, and can be used for a wide range of sailplanes.

The Board of OSTIV congratulates Stefan Gehrmann, Axel Lange and Luka Žnidaršič on their outstanding achievements.

Future of the Open Class

By Murray Stimson, Australia

The exciting future of Open Class could see gliders achieving 100:1 glide angle at airspeeds near 150kn, according to some of the worlds leading authorities on glider design. Gathered in Benalla, Australia for the 33rd OSTIV Congress and the World Gliding Championships 2017, these designers and manufacturers were giving a sneak preview of some of their dreams and goals under active research and development. Open Class, only restricted by a mass limit of 850kg, is the class where the most advanced concepts are first tested in the cauldron of competition. Balancing against these dreams is the practical reality that all manufacturers need to build, certify and sell enough aircraft to get a return on investment.

Five of the leading figures in sailplane design and manufacture participated in a panel Q&A session with the moderators and then the audience. Rolf Radespiel (President of OSTIV and Professor of Fluid Mechanics at Braunschweig, Germany) and Mark Maughmer (Professor of Aerospace Engineering at Penn State University, PA, USA) moderated the session. The great tradition of Open Class at Alexander Schleicher company was represented by Gerhard Waibel, famous designer starting with the D-36 in 1962 continuing through to his recent collaboration with Dick Butler on the Concordia glider in 2014. Renowned CEO's of Schempp-Hirth company, Tilo Holighaus, and for Jonkers Sailplanes, Uys Jonkers, both gave their views quite freely. Oliver Binder represented Walter Binder Flugzeugbau having brought two examples of the new EB-29R Open Class gliders to the WGC 2017 for the German Team. Not least, Loek Boermans, aerodynamics researcher at TU Delft, Netherlands, has had a major role in the aerodynamic design of many gliders across several different manufacturers (including Concordia) and won the prestigious FAI Lillienthal Medal in 2015 after 19 years as the president of OSTIV. There could hardly be a better qualified or more experienced panel on this topic.

Limitations and technical compromises abound in Open Class even when there are few regulatory limits. Certification to the crashworthiness requirements of a 9g impact is already a limiting factor and there were comments by a number of panelists that the mass of 850kg should not be raised further, as crashworthiness would otherwise be compromised. Aeroelastic tailoring has for many years held the promise of controlling the nose-down twist of the outer sections of a slender wing at high speed. That control may not be far in our future judging by research now underway, resulting in lower drag at high speed. Flutter margin is another limitation that practically limits the span and aspect ratio, particularly for Open Class gliders. But the strength of the carbon fibres themselves was described as a key design parameter that might soon be addressed by new fibres in development for the wider aerospace industry. The key benefits of new fibres would be to allow even thinner wing profiles and lighter wing panels for easier rigging!

But for the holy grail of drag reduction and the 100:1 glide ratio, Loek Boermans and Gerhard Waibel are firmly convinced that laminar flow control via suction is the key by reducing profile drag at higher speeds by as much as a third to a half. “With a drag polar so flat across the speed range, there would be no point flying between thermals slower than maximum permissible speed” concluded Gerhard Waibel. Wind-tunnel models are almost ready to study the effects of ingesting the near-wall boundary layer inside the wing through fine holes and then exhausting it rearward, providing a significant drag reduction. Whilst net thrust by blowing is now technically outside the regulations, there’s nothing to say such gliders could not form their own class in the future, “blowing away” the competition with astonishing performance.

Keeping the sport a pure expression of gliding pleasure could see some proposed developments not included on Open Class gliders. Some gliders in the class already sport self-launching piston engines in the fuselage behind the cockpit. But the current developments for Front-Electric Sustainer (FES) or even mid-fuselage electric motors is unlikely to reach Open Class anytime soon, according to some panelists. Current endurance for battery power is insufficient to compete with combustion engines, and the power insufficient to drag a heavy glider aloft. All of the motor options were seen to take away from the intent of Open Class: to maximize the gliding performance across the whole soaring day with the longest tasks possible. As Gerhard Waibel said: ”We must remember that adding an engine amputates the light weight end of the aircraft performance envelope and electric propulsion even more as the current batteries are the highest weight propulsion solution”. The panelists agreed that future open-class competitions should exploit the unique features of these superb sailplanes by sending the competitors out early in the day for as large tasks as possible, thereby eliminating tactics games and gaggles before the start line.

Major advances and substantial investments will still continue to drive performance ever upwards. Loek Boermans was happy to share for the first time in public that he is collaborating on a new Open Class sailplane. The new design will be heavier, fly by wire, and with a spanwise scheduled flap system that will be continuously and automatically moving. Wing loading will go up and it will use autoclave-cured structure. We can only dream of the soaring distances and speeds possible with one of these new Open Class super ships.

The Future of the Open Class panel; left to right, Mark Maughmer, Tilo Holighaus, Uys Jonker, Gerhard Waibel, Loek Boermans, Oliver Binder; Rolf Radespiel as moderator.

www.ostiv.org

Call for Abstracts

XXXIV OSTIV Congress, Příbram, Czech Republic

28 July–3 August, 2018

The XXXIV Congress of the International Scientific and Technical Organisation for Soaring Flight (Organisation Scientific et Technique Internationale du Vol à Voile, OSTIV) will be held at the site of the 34th FAI World Gliding Championships in the Open, 18m and 15m Classes, Příbram, Czech Republic from 28 July to 3 August, 2018. The Congress addresses all scientific and technical aspects of soaring flight including motorgliding, hang gliding, paragliding, ultralight sailplanes and aeromodeling.

Opportunity for presentation and discussion is given in the following categories:

Scientific Sessions: Meteorology, Climatology and Atmospheric Physics as related to soaring flight.

Technical Sessions: Aerodynamics, Structures, Materials, Design, Maintenance and Sailplane development.

Training and Safety Sessions: Training and Safety, Coaching, Health and Physiology.

Joint Sessions: Scientific and technical topics, reviews or news, presented in an informative and entertaining way for the broader interest of the World Gliding Championships and OSTIV.

Topics on instrumentation, electronics, statistics and other system technologies will be included in the sessions for which the application of the technology is most relevant.

Typical and Suggested Topics

Scientific Sessions

- Meteorology:
  - Meteorological data acquisition and service for gliding operations
  - Weather forecasting for soaring flight
- Climatology:
  - Climates that support soaring flight
  - Climate-change and soaring
- Atmospheric Physics:
  - Mesoscale and small convective, baroclinic or orographically induced phenomena
  - New observations; measurements or analysis of convergence lines, cellular patterns, shear structures, standing and moving waves, short period cycles, turbulence, boundary layer in complex terrain
  - Analytical techniques of delineating thermal and mesoscale structures from routine or experimental ground or flight data, or from remote sensors
  - Modeling of thermals, mesoscale or microscale structures

Technical Sessions

The technical sessions will cover all aspects of design, development and operation of sailplanes, motorgliders, ultralights and solar- or human-powered aircraft. Topics may include, but are not limited to:

- Airworthiness, structural concepts, new materials, fatigue, crashworthiness, manufacturing processes
- Aerodynamics and flight mechanics
- Trajectory optimization
- Stability and control
- Airframe vibration and flutter
- Propulsion systems
- Design integration and optimization
- New developments in flight testing
- Airworthiness requirements
- Cockpit instruments, including navigation instruments (GPS etc.)
- Autonomous soaring

Training and Safety Sessions

Training and Safety sessions will be held on subjects covering disciplines such as

- Flight training, theory and analysis of techniques and results, psychology, objectives, training facilities and material
- Human and medical factors in aircraft design and operation
- Piloting techniques
- Flight operation in controlled airspace
- Safety devices

Joint Sessions

Joint Sessions cover topics of general interest in the field of gliding such as

- Soaring history
- General philosophy of competition classes
- Documentation of badge and record flights
- Common interests with other air sports like hang gliding, paragliding, microlights and ultralights
- Human-powered flight; Solar-powered flight

Deadline for Abstracts and Summaries

The deadline for the Abstracts — maximum two A4 pages including figures — is **31 January, 2018**. Letters of acceptance will be mailed by **28 February, 2018**. Final four-page summaries of your contribution will be included in the conference booklet and are due by **1 June, 2018**. Full papers are not required but presenters are encouraged to prepare full papers for submission to *Technical Soaring* (`www.ostiv.org/publications.html`), OSTIV's refereed international journal (ISSN 0744-8996).

Please use the form below to send a copy of your Abstract to the OSTIV Secretariat, clearly marked for either the Scientific, Technical, Training and Safety, or Joint session.

Oral presentations at the Congress will be limited to 30 minutes.

There is **no registration fee** for the Congress!

If you would like to attend the Congress, please complete the form below and send it to the OSTIV Secretariat at `admin@ostiv.org`. Further information about OSTIV and the Congress can be obtained from the Secretariat or from the OSTIV website, `www.ostiv.org`.

Best Student Papers Awards

Awards of EUR 200 will be presented to the students delivering the best presentations in the Scientific and Technical Sections. To be eligible, presenters must be the first author and submit an abstract and four-page summary by the aforementioned deadlines, as well as a manuscript to *Technical Soaring* prior to the Congress. Students who are unable to attend the Congress may designate a representative to present the work on their behalf.

Call for nominations OSTIV Plaque / Klemperer Award

During the Opening Ceremony of OSTIV Congresses the OSTIV Plaque and Klemperer Award may be presented to the person who has made the most noteworthy scientific and/or technical contribution to soaring flight in recent years. All Active and Individual OSTIV Members can send in nominations. In making such nominations, particular attention should be given to recent contributions to soaring flight by the nominee, although earlier outstanding work also will be taken into account. Nominations should include details of the nominee's contributions and a short biography. All nominations for the OSTIV Plaque / Klemperer Award must be received by R. Radespiel, OSTIV President, c/o TU Braunschweig, Institute of Fluid Mechanics, Hermann-Blenk Str. 37, D-38108 Braunschweig, Germany, `president@ostiv.org` by **31 January, 2018**.

Note of interest / Pre-Registration Form and Extended Abstract, XXXIV OSTIV Congress, 28 July–3 August, 2018

Please send this pre-registration form to `admin@ostiv.org` no later than 31 January, 2018

☐ Please, send general information about OSTIV

☐ Please, put my name on the mailing list for further information about the XXXIV OSTIV Congress

☐ I wish to attend the XXXIV OSTIV Congress.

☐ I wish to present at the XXXIV OSTIV Congress in the:

- ☐ Scientific Session
- ☐ Technical Session
- ☐ Training and Safety Session
- ☐ Joint Session

Name: ....

Affiliation: ....

Postal Address: ....

....

Phone: ....

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E-mail: ....

Title of presentation: ....

Abstract (maximum 2 pages):

Frigate birds track atmospheric conditions over months-long transoceanic flights and perform flights inside clouds

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Abstract

Understanding how animals respond to atmospheric conditions across space is critical for understanding the evolution of flight strategies and long-distance migrations. We studied the three-dimensional movements and energetics of great frigate birds (Fregata minor) and showed that they can stay aloft for months during transoceanic flights. To do this, birds track the edge of the doldrums to take advantage of favorable winds and strong convection. Locally, they use a roller-coaster flight, relying on thermals and wind to soar within a 50- to 600-meter altitude band under cumulus clouds and then glide over kilometers at low energy costs. To deal with the local scarcity of clouds and gain longer gliding distances, birds regularly soar inside cumulus clouds to use their strong updraft, and they can reach altitudes of 4000 meters, where freezing conditions occur.

Introduction

The movement of animals is driven by processes that act across multiple spatial and temporal scales. Long-distance movements such as the migrations of birds have evolved in response to large-scale environmental gradients [1]. In particular, atmospheric conditions play a large role in determining the efficiency of migratory routes, whose consistency over years has allowed evolutionary processes to act at population levels [2]. At smaller time and spatial scales, long range movements have to constantly be adjusted to local conditions, in particular to minimize energy expenditure [3, 4]. These long movements or migrations can be done over inhospitable areas as different as deserts, high mountains or oceans, which come with specific environmental constraints to which birds need to behaviorally and physiologically adapt their flight strategies [5, 6]. How these long restless flights can be energetically achieved has attracted much interest, but remains largely unknown because of the inherent difficulties of studying such behaviors in situ.

Biologists have long been attracted to locomotor extremes because they provide clear examples from which information about structure-function relationships can be drawn [7]. Among birds, frigate birds are extreme in many aspects of their life history, including having the lowest wing loading, with a specialized capacity for soaring flight [8]. They are also unusual seabirds because their feathers are not waterproof and their legs are small, so they are unable to land on the sea surface even though they feed exclusively at sea. They deal with these conflicting constraints by staying aloft for days when they are foraging from their nest when breeding [9]. Probably as a consequence of these extreme attributes, frigate birds have the longest period of parental care in birds, suggesting a long period of learning to acquire flight and foraging abilities in early life [10]. Their ability to remain airborne continuously for days is probably possible because of the capability of frigate birds to use thermals over the sea as a main energy source for soaring [11, 12].

We asked how frigate birds can perform long migrations over oceans without landing and whether oceanic thermals are reliable enough in space and time to allow birds to stay airborne over long periods. To address these questions, we investigated the movement of frigate birds at several spatial scales with regard to

(i) how frigate birds make use of large-scale weather systems to perform long-range movements, and

This article is reprinted with some modification from Weimerskirch et al., "Frigate birds track atmospheric conditions over months-long transoceanic flights" Science 01 Jul 2016: Vol. 353, Issue 6294, pp. 74-78. DOI: 10.1126/science.aaf4374. Reprinted with permission from AAAS.

(ii) how flight dynamics and energetics at a finer scale contribute to these long ranges.

Transoceanic flights of frigate birds

We studied the three-dimensional movements and energetics of frigate birds on Europa Island (Fig. 1) between 2011 and 2015 [13]. To study large scale migratory movements, 24 adults and 25 juvenile birds were equipped with solar-powered Argos transmitters [13]. To study the relationship between heart rate, activity (flapping frequency), and behavior (ascent rates and horizontal speed), 11 adult females were equipped with external custom-designed loggers measuring triaxial acceleration and electrocardiography and a Global Positioning System (GPS) device [13]. To study movements, activity, and ambient temperature, 37 adult females and males were equipped with solar powered GPS accelerometers, whose data were recovered regularly by an automatic recording station [13].

During the southwest Indian monsoon from June to October, strong trade winds occur in the southern Indian Ocean and cross the equator to form southwest winds in the northern Indian Ocean [14] (Fig. 1). During this season, adult frigate birds finishing the breeding season left Europa and migrated northward to take advantage of the southerly winds. They settled on roosting sites in the Seychelles from where they foraged for months. Some adults performed long looping movements around the equator, where a belt of converging air and wind occurs, with no wind in the center, named the doldrums zone by ancient mariners (Fig. 1). On successive loops, adults closely followed the edges of the doldrums, which oscillate longitudinally (Fig. 1, A and B). Birds stayed continuously on the wing for periods lasting up to 48 days and traveled on average 420 $\pm$ 220 km daily.

Young frigate birds left their birthplace at the same time as adults, but independently of their parents. They crossed the equator and turned eastward to enter into a circular transoceanic movement into the wind belt around the doldrums (Fig. 1, C and D). During these dispersive movements, juvenile birds stayed continuously aloft for flights lasting up to 2.1 months (average maximum time spent aloft, 41.2 $\pm$ 15.1 days, n = 8 birds). They travelled on average 450 $\pm$ 220 km daily. They episodically stopped on isolated islands such as Chagos, islets off Indonesia, or on islets of the Seychelles archipelago for very short rests (8 hrs to 48 hrs) before continuing their large-scale wandering movement tracking the edge of the doldrums (Fig. 1C). They flew at altitudes ranging between the sea surface and 3000 m, but mainly between 0 and 600 m.

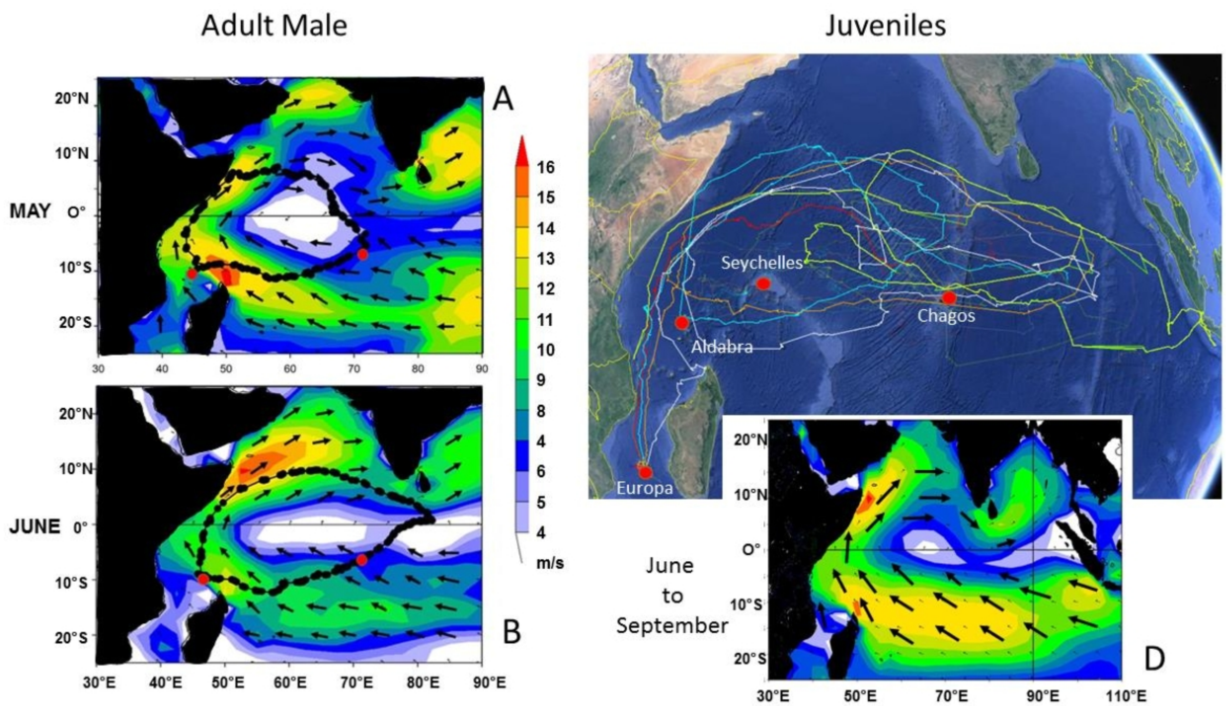

Fig. 1: Movements of adult and juvenile frigate birds in relation to wind conditions in the Indian Ocean.
(Left) Two successive clockwise movements from Aldabra Island (Seychelles) of an adult male great frigate bird (no. 138502) in relation to wind strength (in meters per second, color scale) and direction (arrows). (A) In May 2015, a 24-day foraging trip around the doldrums (shown by the absence of wind, in white),with 1 day of rest in Chagos. (B) In June 2015, a28-day foraging trip,with a 36-hour rest in Chagos. (C) Movements between June and September 2015 of six young frigate birds fledged from Europa Island, moving around the doldrums zone. (D) Climatology of wind speed and direction (average values over 4 months) in June to September 2015, showing the average position of the doldrums (white) on the equator.

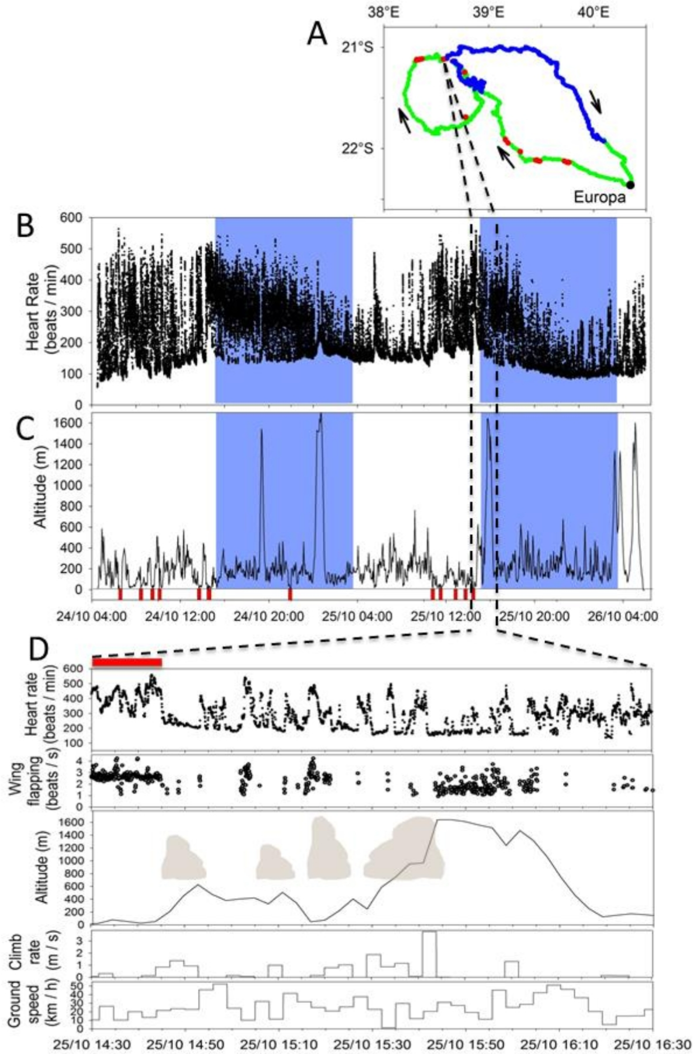

Fig. 2: Movement, changes in altitude, heart rate, and flight parameters during a 2-day trip at sea.

(A) 1130-km-long movement from Europa during the daytime (green) and night (blue) with foraging bouts in red, with recorded (B) heart rate and (C) altitude. Shaded blue areas represent nighttime, and red blocks represent foraging bouts. (D) A 2-hour period during the trip at sea, with an active foraging phase followed by a traveling phase, showing the changes in altitude and corresponding heart rate, wing flapping rate, climb rate, and ground speed. On the altitude panel, the predicted presence of cumulus clouds is indicated (gray).

To understand how frigate birds are able to stay aloft for such long periods, we studied their flight dynamics and energetics during 2- to 15-day foraging trips from Europa. Breeding frigate birds travelled on average 410 ± 142 km per day (n=18 birds), mainly during the daytime, traveling over shorter distances at night (Fig. 2). Two clear behavioral modes were identified during movements at sea. Traveling occurred with high ground speeds and low wing beat frequencies (82 ± 9% of travelling time with no or rare wing beats),with birds remaining at altitudes ranging from 30 m to 2000 m, reaching up to 4120 m. Foraging can only occur when birds descend close to the sea surface (altitudes 0 to 30 m), and during these periods they are very active, flapping during 75 ± 18% of the foraging phase (Fig. 2). Active foraging occurred only episodically (10 ± 7% of time at sea), indicating rare feeding opportunities, mainly during the day (86.4% of bouts of active foraging occurred during the daytime).

When in flight at sea, heart rate was on average 203 ± 84 beats min^{-1} but varied extensively (Fig. 2), occasionally attaining values as low as when resting on the nest (71 ± 25 beats min^{-1}, range 57 to 215). Heart rate and dynamic body acceleration were generally well correlated [13]; therefore, we used dynamic body acceleration, measured on all individuals, as the main proxy for energy expenditure. Whereas active foraging is very costly for frigate birds, requiring high dynamic body acceleration and heart rates, traveling periods have a remarkably low energy expenditure, with few wing beats (Fig. 2), suggesting that overall field metabolic rate during months at sea is likely to be exceptionally low [13]. Excluding periods of active foraging close to the surface, dynamic body acceleration was the lowest at altitudes between 300 and 600 m, indicating an optimal altitude for traveling at low cost.

Traveling at low cost is achieved by successive climbs,mainly through soaring with no or few wing flaps and low heart rate, and descents, by gliding (Figs. 2 and 3). A close examination of flight paths shows that when soaring, birds move with the wind, using circling movements to soar (Fig. 3C) in thermals below cumulus clouds where rising air creates updrafts [15]. Because of the strong trade winds, they drift with the wind while climbing (Fig. 3), resulting in wind-drift circling soaring. Conversely, when gliding, they preferentially fly with side winds and achieve the highest ground speeds (Figs. 2 and 3). The resulting movement is a complex zig-zagging, roller-coaster movement, with an average altitude gain of 59.1 ± 43.8 m per kilometer covered (ground distance); i.e., 15.4 ± 3.0 km climbed daily. These vertical movements take place generally up to 600 m to 700 m, corresponding to the base of the cumulus clouds that is relatively constant throughout the trade wind zone [16].

However, birds regularly climbed up to altitudes higher than 700 m. Climbing to high altitudes can be separated into a phase of slow climb up to the base of the cumulus clouds at 600 m to 700 m, followed by a more rapid climb to 1600 m (Fig. 2D) or higher. This second phase of the ascent is performed without flapping the wings (Fig. 2D); i.e., in pure soaring flight. Ascent to high altitude can only take place inside cumulus clouds, where updrafts reach 5 m/s and are strong enough to provide large climb rates [15]. During the gliding phase made outside the clouds, the minimum sink rate was 23.6 ± 19.1 m of ground distance covered per meter lost between 500 m to 700 m altitudes, compared to 14.3 ± 11.7 m at higher altitudes ($F_{1,7}$ = 8.4, P = 0.045).

Our study shows that frigate birds can remain almost indefinitely on the wing by tracking, at a basin-wide scale, the wind

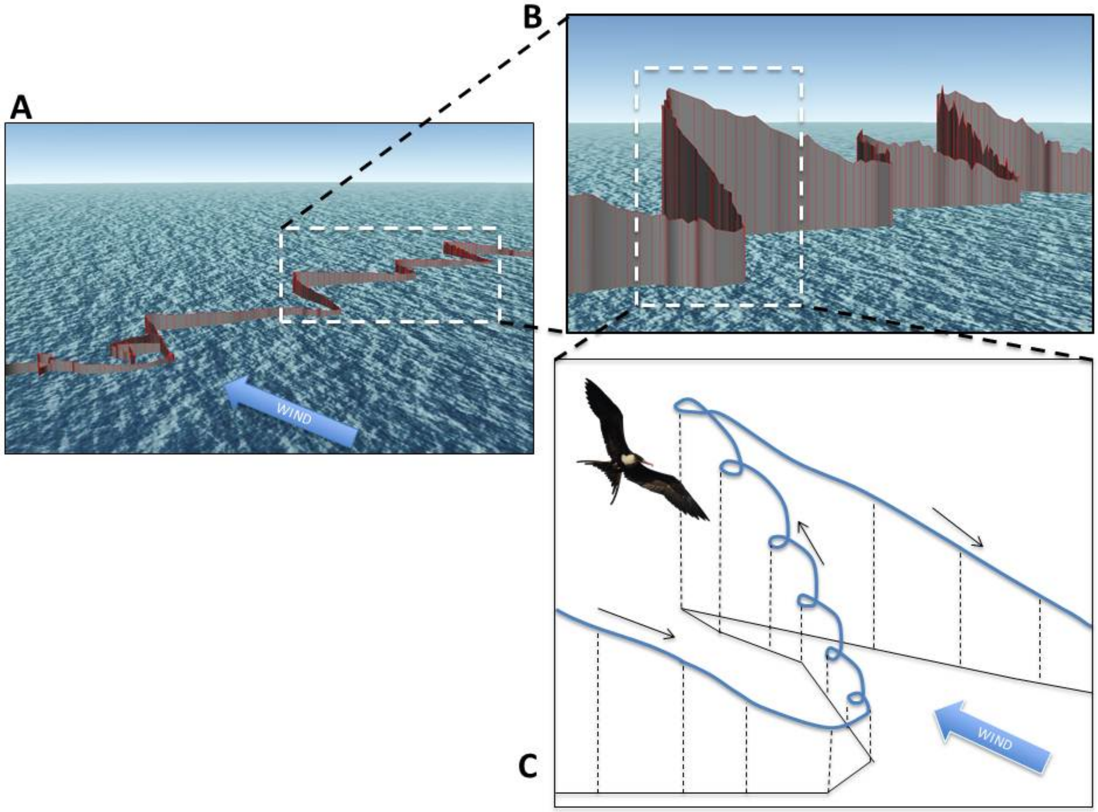

Fig. 3: Three-dimensional movement of a frigate bird at three scales.
(A) Section of a track of a frigate bird traveling with side winds. (B) Enlargement showing the movement alternating gliding and soaring, resulting in a zig-zag and roller-coaster movement. (C) Detailed schematic representation of a single cycle of soaring and gliding, illustrating the climb by circling, with a resulting drift due to wind, followed by the descent.

belt around the doldrums, an atmospheric feature whose location is predictable. Locally, they display a specific flight strategy based on an energy-efficient use of convection and wind. By using wind-drift circling soaring and long periods of gliding, frigate birds are able to simultaneously use convection and wind as energy sources and move over extensive distances at low energy costs. They favor altitudes between 50 m and 600 m, where atmospheric conditions are optimal for low-cost flight; i.e., steady winds and updrafts from convection under clouds (Fig. 4). These altitudes are also convenient to spot feeding opportunities from long distances away during the daytime; birds then descend close to the surface to forage actively when feeding opportunities have been detected [9].

Although birds are not thought to carry out intentional, sustained cloud climbs [17, 18], our study shows the ability of frigate birds to frequently ascend to very high altitudes inside clouds. At an altitude of 4000 m, air temperatures are negative and air density and oxygen availability are almost half of those at sea level [17], suggesting that this tropical bird encounters extreme conditions at such altitudes. Cumulus clouds and cloud fields are considered to be randomly distributed in space in the trade wind zone [16]. In these conditions, climbing higher than 1000 m presents a fundamental advantage by allowing frigate birds to cover much longer distances by gliding to reach the next updraft under clouds. Therefore, when clouds are sparsely distributed, birds can adjust their gliding distance by climbing higher to avoid the risk of switching to costly flapping flight. Juvenile individuals are able to master the flight strategy of adults as soon as they become independent. When they leave their birthplace, they all head north to reach the equator and circle the entire Indian Ocean. This stereotyped movement suggests a genetically encoded behavior that brings young individuals directly to a predictable, favorable, and large-scale atmospheric feature located thousands of kilometers from their birthplace.

Great frigate birds are the only birds other than swifts [19] to be able to stay aloft for months. Long periods in continuous flight are interrupted by very short periods of rest on land, suggesting that frigate birds might sleep while airborne [20]. Periods of low activity (no flapping) occur mainly during soaring episodes and may allow sleep. However, periods of completely motionless (no flapping at all) flight, potentially corresponding to periods of sleep, are relatively short, (2 min, never exceeding

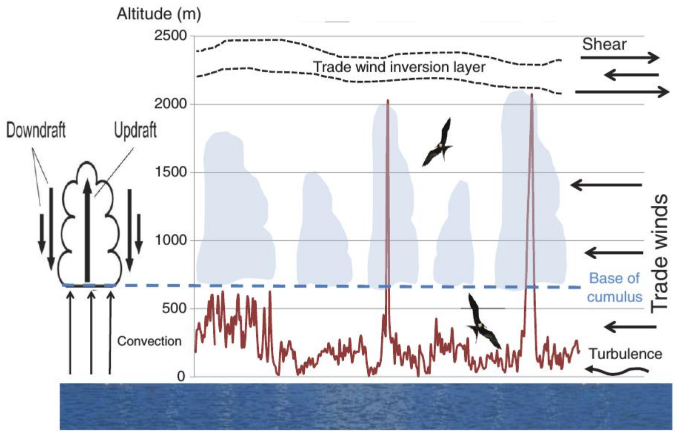

Fig. 4: Altitudinal movement of a frigate bird in relation to potential atmospheric conditions.
The traveling flight is performed between 30 and 600 to 700 m altitude in a band with regular winds, avoiding the turbulence close to the surface. The bird occasionally climbs to 2000 m within cumulus clouds that form by convection, whose base is at 600 to 700 m and whose vertical extension is limited by the inversion layer where strong shear occurs. A schematic presentation of the updrafts and down drafts characteristic of cumulus clouds is shown at left [24]

12 min). Animals such as frigate birds may have evolved the ability to dispense with sleep when ecological demands favor wakefulness such as during extended flights [21], but studies are needed to determine how they sleep during much longer-lasting flights.

Frigate birds clearly encounter several atmospheric challenges during their movements at sea, such as low temperatures, low air density and oxygen levels during high climbs, and the unpredictable distribution of cumulus clouds at small scale, together with the presence of powerful cyclones in their optimal range. This dependence on atmospheric systems could make them particularly sensitive to future climate changes, along with some other seabirds [22]. Climate models for the tropical ocean forecast an increase in the intensity of tropical storms and of convections around the equator, where the doldrums and strong convections occur [23]. More variable atmospheric conditions in the future may become too challenging for a species that already seems to encounter extreme conditions during its lifetime movements.

Flights of frigate birds inside clouds

The unique ability of frigate birds to fly inside clouds raises questions about the mechanical energy balance, possible energy advantages or the control of flight. Such questions are of great interest with regard to soaring and gliding in general, including application to piloted sailplanes. Some of those aspects will be dealt with in the following treatment.

An issue is whether or not frigate birds are able to perform regularly flights inside clouds. Exemplary results are presented in Fig. 5 where a number of flights inside trade cumulus clouds are shown. The maximum altitude achieved in each of the flights inside a cloud is well above the cloud base the altitude of which is about 600 m to 700 m in the trade wind zones [25]. There is one flight where an altitude higher than 4000 m was reached. Furthermore, the bird performs flights inside clouds during daytime as well as at night. The results presented in Fig. 5 suggest that frigate birds intentionally and regularly perform flights inside clouds.

Ascending flights inside clouds to high altitudes such as 4000 m is a unique ability of frigate birds when compared with all other seabirds. That ability provides an unparalleled possibility to cover large distances at little or even no mechanical energy cost. This is graphically addressed in Fig. 6 where flight scenarios for covering the distance between two trade cumulus clouds 80 km away from each other are shown. Two flight modes denoted by 1 and 2 are considered. For both flight modes, the maximum distance achievable in gliding flight plays an essential role. The maximum gliding distance is generally given by the relation [26]

$$x_{max} = (L/D)_{max} \cdot h,$$

where $(L/D)_{max}$ is the maximum lift-to-drag ratio of the bird and h is the altitude at the beginning of the glide. For the problem under consideration, it is assumed that

$$(L/D)_{max} = 20.$$

Flight mode 1 which is graphically addressed in the upper part of Fig. 6 applies to the altitude region below cumulus clouds where the bird climbs by circling soaring in an updraft until the cloud base at h = 600 m is reached. From that altitude, the bird can glide over a track length of x_{max} = 12 km at no mechanical energy cost. Subsequently, the bird can no longer climb by soaring in rising air as there are no more updrafts available. Thus, the bird has to perform a flight involving continuous flapping for

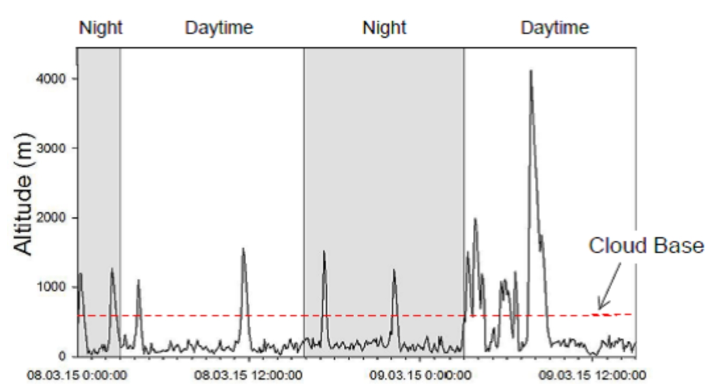

Fig. 5: Flight inside clouds during daytime and night.
The altitude profile recorded during a 2.5-day foraging movement of a frigate bird is presented. There are ascending flights inside clouds at daytime as well as at night, showing altitudes at top of climbs well beyond the cloud base. The highest altitude reached is 4120 m.

the remaining 68 km to the adjacent cumulus cloud. As a result, there is a correspondingly large mechanical energy cost for the major part of the distance between the two clouds.

Flight mode 2 which is graphically addressed in the lower part of Fig. 6 shows an ascending flight inside the first cloud using an updraft for circling soaring up to h = 4000 m and a subsequent glide. From h = 4000 m, the bird glides over a track length of x_{max} = 80 km, thus covering the 80 km to the next cumulus cloud in gliding flight, without any flapping. In this scenario, birds can travel the entire distance between the two clouds without a mechanical energy cost. As a result, the possibility of flying inside cumulus clouds to increase the achievable altitude yields a considerable energy advantage compared with flight mode 1.

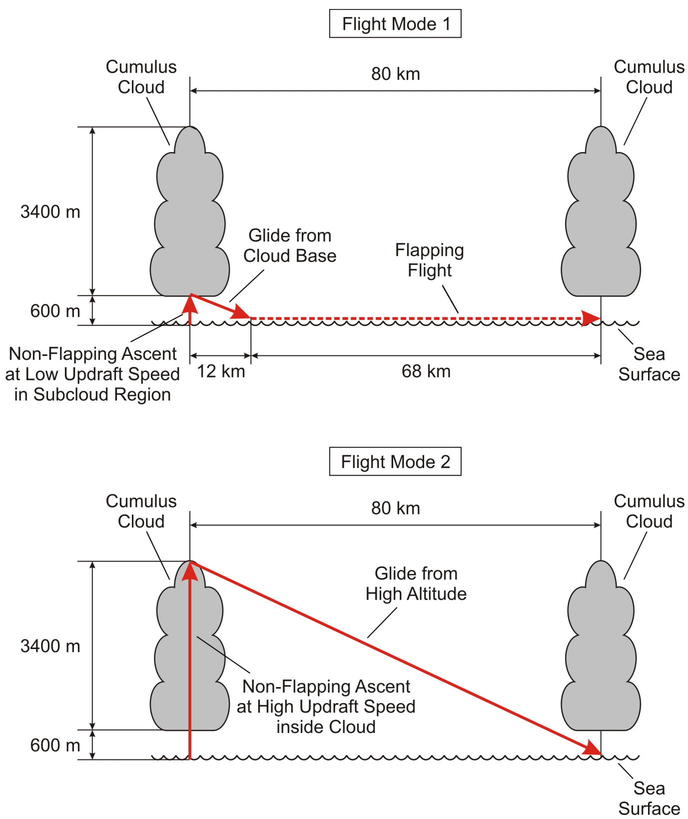

Fig. 6: Distances achievable in glides following ascent below the cloud base and an ascent inside a cloud.

Flight mode 1 is made up of 3 sections. The first section is a circling ascent in an updraft in the altitude region below the cumulus cloud base. In the second section, the bird glides from the cloud base to the sea surface over a ground distance of 12 km. The third section consists of a horizontal flight using flapping until the next cumulus cloud is reached. The remaining distance to reach the adjacent cumulus cloud by means of flapping flight is much longer than the distance covered in gliding flight.

Flight mode 2 comprises 2 sections. The first section is a circling ascent in an updraft inside the cumulus cloud. In the present case a high altitude of 4000 m is supposed to be reached, corresponding with measurement results presented in Fig. 1. The second section shows a glide from the highest altitude to the sea surface. The track distance achieved in gliding flight is 80 km which means the whole distance between the two clouds is covered in gliding flight so that there is no mechanical energy cost.

Flight mode 2 is an issue in the case of widely spaced clouds. Oceanic trade cumuli involve irregular groups or clusters of about 10 km to 50 km across and separated by somewhat wider clear areas [27]. Thus, there can be large differences in the distances between clouds which a frigate bird has to cover when flying from one cloud (or cloud group) to the other. This means that flight mode 2 yields a significant energetic advantage for the travelling of frigate birds.

How frigate birds manage to control and perform flights inside clouds is of great interest. For dealing with that aspect, a closer look at flights inside clouds is provided in Fig. 7 which shows — on a small-scale basis — the altitude profile of ascents of a frigate bird inside a trade cumulus cloud and below the cloud. Climb rates in ascents below the clouds are around 0.5 m/s. That is a relatively small climb rate which corresponds with the low updraft speeds existing in the altitude region below trade cumulus clouds [27]. By contrast, the climb performance of flights inside the cumulus cloud is higher. In Fig. 7, a climb rate of 3.3 m/s was achieved by the bird, a 6-fold increase compared with a 0.5 m/s climb rate below the cloud. The large climb rate is due to the high updraft speed existing inside the cumulus cloud. The fact that such high updraft speeds are possible in trade cumulus cloud has been confirmed by direct measurement [15].

Furthermore, the results presented in Fig. 7 show that the ascents are of consistent and steady nature. This suggests that the bird is capable of performing such flights in a controlled and stabilized manner which would allow them to conduct the flights inside clouds regularly and consistently.

The fact that frigate birds have the ability to fly inside clouds is all the more noteworthy, as there are severe and adverse environmental conditions. One of those conditions is the lack of visibility in clouds, with no visual cues for an orientation in space. In aircraft, gyroscopic type instruments provide the required information for spatial orientation in clouds. However, no biological sense organ providing analogous information is known in birds [17]. Accordingly, it is assumed that sustained, controlled flight in clouds is not possible for birds [17, 18, 28, 29]. Further to demanding environmental conditions, the air inside trade cumulus clouds shows increased turbulence levels [15]. Turbulence means that birds are exposed to effects disturbing their motion, potentially leading to deviations from the desired flight path. The disturbing effects are stronger with a higher turbulence level. Combined effects of lack of visibility and high turbulence can result in an even more demanding environmental condition.

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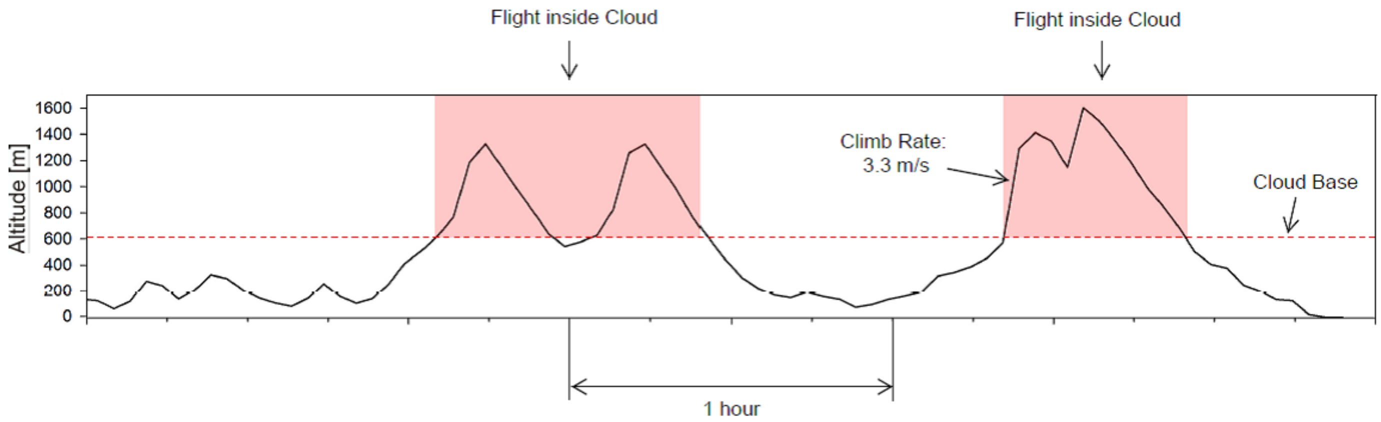

Fig. 7: Climb performance achieved with ascending flights inside cloud and below cloud.
The altitude profile recorded during the flight of a frigate bird below and inside clouds is shown on a small-scale basis. The climb rate achieved in the altitude region below the cloud base is around 0.5 m/s, while climb rates of a bird ascending inside a cumulus cloud can be much higher. In the presented case, a climb rate of 3.3 m/s was achieved.

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