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A1–BORNE BY THE FLOW: THE BEHAVIOUR PHYSIOLOGY AND ECOLOGY OF ENVIRONMENTAL TRANSPORT

Organised by J. Metcalfe and T. Alerstam

A1.1–Adaptive aspects and costs of migration in the monarch butterfly

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The annual migratory cycle of the monarch butterfly in North America involves 3 to 5 generations and evolved with the *Asclepias* milkweed flora that serve as larval foodplants. West of the Rocky Mountains, the butterflies migrate to overwinter in groves of trees near sea level along the central Pacific Coast. The larger population east of the Rocky Mountains migrates to high altitude *Abies religiosa* fir forests in the Transverse Neovolcanic Belt of central Mexico. Beginning in August newly emerged adults have repressed gonads, become gregarious, ride tailwinds and migrate southwesterly for up to 2000 miles. At dusk they bivouac in trees. When overtaken by high-pressure fronts, they suspend migratory flying and nectar from the Asteraceae, building lipid reserves that will sustain them for five months. Upon reaching twelve separate massifs, they coalesce on the fir boughs, forming 0.2 to 5.0 hectare colonies with 65 million monarchs per hectare. Overwintering at 3200 m elevation on mountains subject to polar cold fronts is possible because the fir trees function as an umbrella and blanket. The dense clusters reduce radiational heat loss and wetting, thereby protecting the monarchs from freezing. The ability of the butterflies to form such dense aggregations was probably made possible because monarch caterpillars sequester bitter and emetic cardiac glycosides from milkweeds, resulting in the adults being unpalatable to avian and mouse predators. My presentation will discuss the interactions and conflicting aspects of these remarkable behaviors, all now severely endangered because of ever-increasing forest exploitation in Mexico.

A1.2–Energetic cost of transport in avian flight: an inter- and intra-specific comparison

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Avian flight has been studied for long, but many aspects are still matter of debate.

Data on energetic costs of flight (P) has been collected by direct measurements in various species. The interspecific correlation between P and body mass (M) has been described in allometric regressions as P proportional to M ($P \sim M^{coefficient}$). The coefficient ranges from 0.7 to 1.

Aerodynamic models simulate flight mechanics drawing conclusions about the energetic costs of flight, and predict a similar relation of P to M.

However, individuals fly at different body mass, too: migratory birds, for example, increase mass for migration. In a first study on this topic, Kvist et al. (2001)[1] found in knots a coefficient of 0.35.

We investigated the flight costs of barn swallows with naturally fluctuating body mass. In contrast to knots the mean coefficient is higher (0.65), although it differs among individuals from 0.05 to 1.

Kvist proposed that changes in flight muscle efficiency are responsible for the lower coefficient. However, this mechanism is debated and has yet to be confirmed experimentally.To investigate the adaptive flexibility of muscle efficiency we are running experiments to compare the energetic flight costs of birds with naturally varying body mass to birds with artificially increased mass. If changes in muscle efficiency were flexible, birds would be expected to respond to a naturally increased body mass but not to an artificial one.

We will present the different regressions of inter-specific, intra-specific and intra-individual flight costs and will discuss possible explanations.

1 Nature 41: 730–732

PII: S1095-6433(03)00034-5

A1.3–Influence of oceanographic factors on long-distance movements of leatherback sea turtles (*Dermochelys coriacea*)

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The long-distance movements of pelagic turtles are becoming known thanks to satellite telemetry, but the factors determining their courses have rarely been investigated. The leatherback turtle (*Dermochelys coriacea*) displays the most extensive movements among sea turtles, wandering over large oceanic areas while feeding on macroplankton. The leatherback postnesting movements so far reconstructed are fairly complex, showing an alternation of straight transfers, sometimes along migratory corridors common to different individuals, and shorter circuitous segments, assumed to be related to the turtles' feeding activity. We have studied the postnesting movements of three leatherbacks tracked by satellite in the Southwest Indian Ocean, in relation to the effects of oceanographic factors of the areas crossed. The area is dominated by the intense Agulhas Current, which moves along the African coast in SW direction forming a number of intense eddies and rings. By superimposing the turtle tracks on contemporaneous remote-sensing images of sea surface temperatures, sea height anomalies and chlorophyll content, we found that current-related features largely determined the shape of the reconstructed routes. After an initial offshore movement made in the absence of strong currents, turtles moved along straight routes when in the core of the Current, or executed loops within eddies circling in a sense always in accordance with the rotation of the water masses. Large parts of the turtle routes were strikingly similar to those of surface drifters tracked in the same region. This strategy of moving with currents allows turtles to exploit resources over large areas with minimal effort.

A1.4–Water loss in flying birds. The respiratory pathway

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Bird flight is an energetically demanding mode of locomotion. Metabolic rates can be as high as ten times BMR. These high oxygen demands can be met by either increasing the oxygen extraction rate or lung ventilation. Other authors (Bernstein 1976[1]; Torre-Bueno 1977[2]) have shown that oxygen extraction rate does not change with flight. Therefore it is hypothesized that increased lung ventilation is responsible for covering the higher demands of oxygen during flight. This can be achieved by increasing respiratory frequency or tidal volume.
However, during long flights both energetic and water balance demands have to be met. Excretion, cutaneous and respiratory evaporation are balanced only by metabolic water production. Respiratory water loss is a major factor in this equation. Increased lung ventilation due to energetic demands does not only lead to a higher oxygen uptake but also increases respiratory evaporation.
Respiratory water loss during flight has never been measured directly. By recording tracheal air flow as well as exhaled air temperature in a starling flying at different speeds in a wind tunnel, we found that the tidal volume doubled during flight and that breathing frequency increased by the factor 3.5. This results in a minute volume 7.5 times higher than the resting value. Despite differences in flight speed, respiratory frequencies and mean tidal volumes do not differ between experimental flights.
Our measurements of respiratory frequency, tidal volume and exhaled air temperature enable us to determine respiratory water loss quantitatively for the first time.
[1]Resp. Physiol. 26:371–382
[2]Respir. Function in birds, Ed. J. Piper, Springer

A1.5–Effects of temperature on myocardium activity of European sea bass (*Dicentrarchus labrax*) and dover sole (*Solea solea*) at cellular and tissue level

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The aim of the present study was to examine the effects of water temperature on the heart contractility of two teleosts (sea bass *Dicentrarchus labrax* and dover sole *Solea solea*). Four groups of sea bass and soles were acclimated during four weeks respectively to 10, 15, 20, 25 °C and to 6, 12, 18, 24 °C. First, calcium responses of isolated ventricular cardiomyocytes were measured by laser cytofluorimetry after stimulations with hyperpotassic and caffeine solutions. Secondly, myocardium contractility was examined via measurements of isometric force, contraction and relaxation kinetics in ventricular strips electrically stimulated at frequencies ranging from 0.2 to 2.5 Hz. Over the temperature range tested, the amplitude of the calcium responses following cellular hyperpotassic stimulation was increased by approximately 50 % in both species. Ventricular strips force,

contraction and relaxation kinetics also significantly increased with acclimation temperature in both species. Moreover, the force–frequency relationship was positive between 0.2 and 1.2 Hz at 18–25 °C. Total calcium stores of sarcoplasmic reticulum (SR) were quantitatively more important in both species at 24–25 °C. Experiments realized using ryanodine revealed that more than 50% of calcium available for myocardium contraction originated from SR in sole acclimated to high temperature. Unlike sole, more than 50% of calcium available for myocardium contraction originated from SR in sea bass acclimated to 10–15 °C.

A1.6–The concept of energy height in animal locomotion: separating mechanics from physiology

C.J. Pennycuick, Biology, University of Bristol

From a given starting height, representing a store of potential energy, a glider can fly a distance determined by its glide ratio, representing the gradient on which it comes down. Likewise a store of fuel energy can be represented as a virtual 'energy height', from which a bird can 'descend' on a gradient determined mainly by its aerodynamical attributes. The physiology of converting energy into work is taken into account when calculating the energy height, while the descent gradient is determined by the mechanics of locomotion. This principle can be applied to running and swimming, as well as to flight. An animal's fuel energy height is independent of its body mass, and represents what the animal can do with its stored energy, rather than the energy itself. This applies to other activities, besides locomotion, that require stored energy. For example, it would appear that a bird that nests early in the high arctic must arrive on the breeding grounds at a fuel energy height approximately 80 km, if incubation is to be completed before significant food becomes available. The required energy height is mass-independent, and applies equally to large geese or small waders. Likewise, a full moult requires approximately 650 km of energy height in a bird of any size, although in this case most birds acquire the energy concurrently with the moult, rather than storing all of it in advance.

A1.7–Selective migratory flight initiation by passerines: effect of weather and winds

Susanne Åkesson – Animal Ecology, University of Lund

Birds in flight are strongly influenced by winds, and therefore the migratory takeoff is likely to be selected when favourable flight conditions are met. We have used radio-telemetry to study orientation and migratory flight initiation in relation to wind and air pressure in nocturnal passerine migrants in autumn at Ottenby and Falsterbo Bird Observatories in south Sweden. At Falsterbo the majority of the reed warblers studied departed in the expected migratory direction towards south of southwest, while a low number of the birds took off in reverse directions between north and east. Flight directions at departure correlated with wind directions at both sites. This was particularly prominent at higher wind speeds, and at Falsterbo it did not occur at all at wind speeds below 4 m/s. Birds departing in the expected migratory direction compensated completely for wind drift. The reed warblers preferred to depart during nights with tailwinds and when air pressure was increasing suggesting that reed warblers are sensitive to winds and air pressure and select favourable wind conditions for their migratory flights. Since air pressure as well as velocity and direction of the wind are correlated with the passage of cyclones, a combination of these weather variables is presumably important for the birds' decision to migrate.

A1.8–Fuel use by trout muscle during glycogen resynthesis: influence of age and metabolic state

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Exercise to exhaustion causes a decrease in muscle glycogen in trout white muscle. In order to recover sprint performance, fish must resynthesize muscle glycogen and clear the associated lactate load. Most studies to date have indicated that this can be a lengthy process, requiring up to 8–12 h in adults ($\sim$200 g) and more than 24 h in juveniles ($\sim$5 g). However, these studies were carried out on fasting fish, in which substrate may be limiting. We fed both juvenile and adult fish after exercise and found that feeding accelerated muscle glycogen resynthesis in both juveniles (complete at 6 h) and adults (complete at 4 h). These results suggested that exogenous substrates play an important role in fueling muscle glycogen resynthesis. We used an in vitro muscle slice preparation and radiolabelled substrates to examine fuel use during periods of glycogen synthesis. In adults, glycerol made the greatest contribution to the glycogen pool (2.8%) while lactate incorporation was minimal ($<$1%). Muscle preferred to oxidize lactate (313 nmol/g) over glycerol (3 nmol/g) or palmitic acid (52 nmol/g). In juveniles, a different pattern emerged; lactate (5.5%), glycerol (2.2%) and glucose (1.5%) were all incorporated into the glycogen pool. Palmitic acid was the preferred oxidative fuel of juveniles (150 nmol/g over glycerol (50 nmol/g), lactate (15 nmol/g) or glucose (2 nmol/g). These differences likely reflect the more aerobic nature of juvenile muscle, and suggests muscle metabolism, and perhaps regulation, changes with development.

A1.9–Spending the night in the wind: roosting behaviour of common swifts

J. Backman, Animal Ecology, Lund University

In the summer, some Common Swifts spend the night on their wings. From tracking radar observations, we know that swifts prefer to orient into the wind direction during these nocturnal flights. The angular concentration into the wind direction increases with an increase in wind speed. The reason for this behaviour is probably to avoid excessive wind drift and minimize the distance of the compensatory return flight the following morning. Swifts do not primarily select flight altitude with favourable wind speeds, nor do they alter the flight speed with variations in wind speed. A more detailed analysis of the orientation behaviour in the swifts reveals that that the angle between the heading and the wind direction varies in a regular, periodic way. This 'oscillatory orientation' is observed at both low and high wind speeds and there is no typical frequency of these changes in heading.

A1.10–Hydrostatic pressure sensing in crustacea and fish

Fraser, P.J. Zoology Department, School of Biological Sciences, University of Aberdeen

Depth regulation may be mediated through hydrostatic pressure detectors in a variety of fish and crustacea. The identity of the sensor involved remained elusive until small changes in hydrostatic pressure were found to alter resting and stimulus evoked neural activity in angular acceleration afferents belonging to the balancing systems of crabs. The mechanism utilizes differential compression of tissue and cuticular components leading to small strains in the order of a few nanometers which act directly on mechanoreceptor neurones linked to the thread hairs. Positive going and negative going responses have been found and mapped to the two directional classes of thread hairs. Recently angular acceleration afferents from the vestibular system of the dogfish have also been found to respond to hydrostatic pressure, with positive going responses affecting resting and angular acceleration derived activity. Sensitivities of these systems are approximately 5–10 mbar. Ability to regulate depth is likely to be a key requirement of a tidal transport system. The sensitivity and mechanisms involved would also allow small tidally derived pressure changes to be sensed at any depth in the sea, allowing tidal synchrony at depth.

A1.11–Habitat selection of juvenile banana prawns, *Penaeus merguiensis*: testing the roles of habitat structure, predators, light phase and prawn size

J.J. Meager, Queensland University of Technology; I. Williamson, Queensland University of Technology; N.R. Loneragan, CSIRO; D.J. Vance, CSIRO

Juvenile banana prawns, *Penaeus* (*Fenneropenaeus*) *merguiensis* use mangrove-lined estuaries as nurseries and move into mangrove forests during each flood tide. It is thought that the structural complexity of mangrove forests provides habitat and protection from predation. The roles of fish predators, light phase, habitat structure and prawn size on the microhabitat preferences of juvenile *P. merguiensis* were tested in laboratory experiments in a tank (1.8 m diameter) divided into four habitats: bare substrata, leaf litter, mangrove pneumatophores and mangrove woody debris. The locations and behaviour of 10 prawns were monitored over 135 minutes and the experiment was repeated five times with different prawns for each prawn size class (3–6 mm, 6–10 mm and 10–14 mm carapace length), and during light and dark phases. This procedure was then repeated for each predator, ariid catfish (*Arius graeffei* – a slow moving tactile-chemosensory predator) and barramundi (*Lates calcarifer* – a fast, visual predator).Juvenile *P. merguiensis* of each size class selected for vertical structure (mangrove debris and pneumatophores) over microhabitats with little vertical structure (leaf-litter and bare substrata), in both light and dark conditions and in the presence or absence of predators. When *L. calcarifer* were present, the preference by prawns for the mangrove debris microhabitat increased significantly. This was attributed to an increase in the predation risk in the other microhabitats, as *L. calcarifer* rarely pursued prey amongst the heterogeneous vertical structure of mangrove debris, compared to the less complex structures of the other microhabitats.

A1.12–Environmental transport in fish: necessity or nicety?

G.P. Arnold, Lowestoft

Most of the several hundred species that sustain the world's major commercial fisheries follow extensive migration circuits that are undertaken annually for feeding and reproduction and are generally contained within oceanic gyres. Eggs and early larvae are carried passively by residual currents and in many species the adults compensate for this displacement by homing to well-defined spawning areas situated upstream of the nursery grounds used by the juvenile fish. In some instances migrating adults also appear to follow oceanic

gyres and there is a prima facie case that compensation occurs by environmental transport. On the continental shelves, where tidal currents are dominant, demersal fish appear to make use of transporting currents when this is energetically advantageous, but adopt other mechanisms of migration when it is not. On the European shelf, for example, adult plaice use selective tidal stream transport when their spawning migrations traverse areas of fast tidal streams and they can save energy by swimming downstream in the same direction as the tidal current. In areas with slower and less directional currents, however, they migrate independently of the tidal streams. Most oceanic migrants (e.g. tuna) are much larger than their counterparts on the continental shelves and live in an environment where currents are generally much slower. It seems probable, therefore, that the facultative use of environmental transport is a general phenomenon, which applies as much in the open ocean as in shelf seas, although direct evidence to support the hypothesis is so far limited.

A1.13–The importance of wind in bird migration

T. Alerstam, Dept Animal Ecology, Lund University

Wind is expected to be a factor of supreme importance for several different aspects of bird migration. Wind has been suggested to affect the evolution of large-scale geographic migration patterns, promoting migration routes along which the birds can benefit from frequently occurring following winds. Furthermore, birds are expected to exploit the winds by selecting occasions and altitudes providing wind assistance for their flights (or providing minimum wind resistance if opposing winds cannot be avoided) and by orienting relative to wind so as to allow wind drift or compensate for the wind drift, whichever is most favourable depending on wind patterns and distances to the destination. Although these aspects have been investigated during several decades there still remain important open questions about the birds' responses to wind, about the existence of differences in such responses between different categories of migrants and about the adaptive values of the responses. Vertical and horizontal winds make up the main source of energy for bird migration by soaring flight, mainly thermal soaring migration over land and dynamic soaring and sweeping flight over the sea. Recent studies by satellite tracking have demonstrated that soaring migrants, especially the seabirds, attain the highest performance with respect to total speed of migration among birds (and presumably among all organisms).

A1.14–Age-dependent wind drift in migrating raptors

K. Thorup, Zoological Museum, University of Copenhagen; T. Alerstam, Animal Ecology, Lund University; M. Hake, Grimsö Wildlife Research Station, Swedish University of Agricultural Sciences; N. Kjellén, Animal Ecology, Lund University

Despite many years of research we still have only little knowledge of migratory birds' behaviour in relation to wind drift, as a highly complex and partly contradictory picture has been reported. In most cases drift vs. compensatory behaviour has been studied using radar, in which case, however, the proximate goal is not known for individuals followed, making drift/compensation assessment difficult. In this study we analyse satellite tracking data on two long-distance migratory raptor species, to determine the degree of compensation. For these birds we use the course variation of separate movements between position readings of individual birds for which the ultimate goal is known. It is thus possible to calculate the forward and perpendicular components of each movement. The relationships between both forward and perpendicular movement and the corresponding wind component show strong positive correlations. For juveniles the relationship is about equal for both forward and perpendicular movement, which suggests full wind drift. Adults show a similar relationship in forward winds but are markedly less affected than juveniles by side winds. This suggests that adults compensate for the main part of crosswind displacement, whereas juveniles are fully drifted.

A1.15–When to go with the flow: the energetics of plaice migration in the North Sea, part II

Metcalfe J.D. & E. Hunter CEFAS, Lowestoft

Early tracking experiments in the southern North Sea showed that plaice selectively exploit the tidal streams to aid their spawning migration. However, I was unclear whether this behaviour is primarily an energy-saving strategy, or a transport mechanism by which fish that are unable to navigate over long distances can be carried reliably between feeding and spawning grounds. Because selective tidal stream transport requires that fish remain stationary on the sea-bed during the 'non-transporting' tide, energetic calculations predict that this behaviour is beneficial only when the current speed exceeds a critical, size-dependent, value. Since 1993 we have been using used electronic data storage tags to monitor the patterns of vertical movements of plaice in various locations in the North Sea with a range of tidal stream speeds. We show that plaice use selective tidal stream transport only in areas where the tidal streams

are suitably fast, and that individuals can switch from directed swimming to selective tidal stream transport as they move from areas with slow tidal stream speeds to areas with faster tidal stream speeds. Our results confirm that this behaviour is primarily an energy saving strategy.

A1.16–Species-specific swimming performance: relation with muscle energy stores and pH

G. De Boeck, R. Blust, Biology, University of Antwerp, Belgium

The disruption of longitudinal connectivity by man-made obstacles may threaten the fish fauna of local rivers to various extents. Obstacles impede migrations between habitats that are vital for populations, and they may restrict the gene flow between populations, thereby reducing the effective size and genetic diversity of populations and increasing the risk of local extinction. To assess the capacity of indigenous fishes to clear physical barriers, our research assessed the swimming capacities of several local fish species as criticical swimming speeds. Their capacity to recover from the prolonged swimming exercise was determined with a second critical swimming speed measurement after a recovery period. In order to estimate the impact of the swimming activities on the total energy budget of the fish, the swimming experiments are combined with simultaneous measurements of aerobic and anaerobic energy consumption. Energy stores (lipids, proteins and carbohydrates), lactic acid and muscle pH are determined before and after the exercise, and possible relationships between these factors are examined.

A1.17–Adaptive variation of airspeed in relation to wind, altitude and climb rate by migrating birds in the Arctic

Anders Hedenström, Thomas Alerstam, Martin Green, Animal Ecology, Lund University; Gudmundur A. Gudmundsson, Icelandic Institute of Natural History

Power of flapping flight in birds follows a U-shaped function of speed through the air. From this and the assumption of limited power available from flight muscles, the birds' airspeed in relation to external factors such as wind can be predicted. These predictions are derived from flight mechanical theory and optimality criteria concerning migration or transport flight economy. Using tracking radar we measured flight speeds of migrating birds at 12 sites along the Northwest Passage in arctic Canada. We analysed variation in airspeed (V_a) in relation to the wind effect ($V_g - V_a$, V_g is groundspeed), vertical speed (V_z), altitude (z) and the compensation for side wind ($1/\cos\alpha$, α is the angle between track and heading). We found significant effects on the variation in V_a for all four variables, revealed by multiple regression analysis, but the total variation explained was relatively small suggesting that other factors might be involved. The sign of the regression coefficients were as predicted, except for the effect of side wind where we found a negative relationship between V_a and $1/\cos\alpha$, possibly because our sample included an unknown mixture of species.

We also compiled information from the literature on the effects of the four variables on V_a. Adjustment of V_a in relation to the wind effect seems nearly omnipresent among birds, while the effects of vertical speed and altitude have been reported surprisingly few times. An increased V_a with increasing α (and $1/\cos\alpha$) has not been found yet, perhaps due to the lack of critical observation conditions.

A1.18–Stream transport in the oceanic journeys of marine turtles

P. Luschi, Department of Ethology, Ecology and Evolution, University of Pisa, Italy

Sea turtles move widely between disparate habitats during most of their lifecycle, often travelling in open-sea unsheltered areas, where sea currents and related features are likely to affect their movement patterns. Indeed, recent research work has shown that the oceanic journeys of turtles are often highly dependent on oceanographic processes. The developmental migrations of hatchlings can range over entire ocean basins, and are driven by large-scale current systems, which offer turtles a safe and suitable feeding habitat. Pelagic-stage juveniles have also been shown, through satellite telemetry, to move over large areas, sometimes swimming against currents. The open-sea movements of juvenile loggerhead turtles (*Caretta caretta*) in the Mediterranean Sea have been found to be dependent on oceanographic factors such as sea surface temperature and mesoscale features. In adult turtles, satellite tracking results allow two main patterns of movement to be distinguished. Pelagic-feeding turtles, like leatherbacks (*Dermochelys coriacea*), display complex and circuitous routes undirected toward a target area, that are largely shaped by major oceanographic features. A similar dependence on oceanographic processes has also been recorded in the oceanic wanderings of two loggerheads in the Indian Ocean. In these cases, turtles have been found to be transported for hundreds of km by the flow of major currents. Other species, such as the green turtle (*Chelonia mydas*), migrate between fixed breeding and feeding areas, that are reached with well-oriented, straightforward routes. In these cases, currents may drift turtles from the intended target, thus challenging their navigational abilities.

A1.19–Torn by the flow: tidal stream mediation of metapopulation structure in North Sea plaice

Ewan Hunter, J.D. Metcalfe, G.P. Arnold (CEFAS) & J.D. Reynolds (University of East Anglia

Between December 1993 and September 1999, we released 752 mature female plaice tagged with electronic data storage tags to test the hypothesis that variation in the migratory behaviour among plaice (*Pleuronectes platessa*) in the North Sea could be explained by large-scale differences in the speed and directions of the tidal streams, which the fish use as a transport mechanism. The experiment yielded 20 403 days of data from 145 plaice, with individual records of depth and temperature of up to 512 days. The position of each fish was determined at intervals throughout the liberty period using the tidal location method. Three geographically discrete feeding aggregations were located in warm, thermally mixed water in the eastern and western North Sea, and in deeper, cold, thermally stratified water to the north during summer. These dispersed over the southern North Sea and Eastern English Channel to spawn during winter. The results re-affirmed the major role of the tidal streams in the southern North Sea in structuring plaice dispersion, both by providing transport and guidance, and by delimiting the extent of distribution due to thermal stratification during the summer. Northern North Sea plaice also migrated south, but did not use the tidal stream currents to migrate. Our results confirm the prediction therefore, that large-scale variation in migration behaviour can be explained in part by the tidal guidance and transport mechanisms available.

A1.20–Opercular differential pressure as a predictor of metabolic oxygen demand in starry flounder (*Platichthys stellatus*)

A.Z. Dalla Valle, University of Milan, R. Rivas-Diaz CNRS-IFREMER

Our current inability to assess accurately energy expenditure in free-swimming fish has been a limitation for biologists attempting to estimate the various components of fish's energy budget. The laboratory determination of activity energetics with subsequent field extrapolation is highly error prone since, within the confines of the laboratory, behaviour and activity patterns may differ from those under natural condition.

In recent years different tools have been tested in order to improve our to ability to predict fish energetic demand.

As a new approach, we investigated the feasibility of using a differential pressure sensor connected to an acoustic telemetry device to monitor opercular activity (ventilation rate and amplitude) as a correlate oxygen consumption. Four starry flounders (*Platichthys stellatus*) were fitted with a miniature differential pressure sensor mounted close to the operculum.A cannula was connected to the sensor and inserted under the operculum, inside the branchial cavity. Measurement of oxygen consumption and opercular activity were carried out over 24 hours periods and a full range of metabolic activity, from the post surgery stress (high metabolic rate) to resting metabolic rate the following day. Relationships between differential pressure changes (rate and amplitude) were highly correlate with oxygen consumption($r^2 = 0.74$ and 0.60 respectively). The results indicate that monitoring opercular activity offers an alternative method for measuring aerobic metabolism in free ranging fish in nature.

A1.21–A comparison of swimming energetics and aerobic capacity of adult migrating pink (*Oncorhynchus gorbuscha*) and sockeye salmon (*O. nerka*) in relation to water temperature

M.J. MacNutt, Zoology, University of British Columbia; S. G. Hinch, Forest Sciences, UBC; A.P. Farrell, Biological Sciences, Simon Fraser University

Pacific salmon rely solely on body reserves to fuel the spawning migration, develop gonads and successfully spawn. All fish die after spawning. Inappropriate allocation of energy could limit the amount available for gamete production and reduce reproductive fitness. To assess the physiological limitations of migrating Pacific salmon, swimming performance and energetics of pink (*Oncorhynchus gorbuscha*) and sockeye (*O. nerka*) were examined. These species are believed to be the weakest and strongest swimmers, respectively, of the Pacific salmon species. Two large mobile Brett-type respirometers were used to evaluate critical swimming speed (Ucrit), oxygen consumption (Mo2), cost of transport (COT), tail beat frequency (TBF) and recovery ability of sockeye from the early Stuart stock and pink from the Seton/Thompson stocks. Both groups of fish are the longest distance migrants of their species in British Columbia. Fish performed modified repeat ramp-Ucrit tests at temperatures ranging from 9–22C. Contrary to expectations, sockeye did not perform better

than pinks. No significant differences were found between species in Ucrit, resting or active Mo2, TBF-swimming speed relationships or COT. Sockeye swimming performance and metabolic rates showed typical relationships with temperature, with optimal performance at 15–16C. However, no temperature relationships or optima were evident for pink salmon. Strong spawning site fidelity and genetic homogeneity exists within stocks of sockeye but not in pinks, suggesting that pink salmon are more flexible in spawning timing and locations. We speculate that the temperature-independence of pink swimming performance and metabolism may ensure successful migration of pink salmon under diverse river conditions.

A1.22–It pays to be choosy: waders migrating from Europe to Siberia fly on days with favourable winds and decrease travel costs substantially

M. Green, Animal Ecology, University of Lund, and T. Piersma, Marine Ecology, Royal Netherlands Institue of Sea Research (NIOZ)

Migration intensities, measured by radar, and individual departure decisions, recorded by radio-telemetry, of arctic-breeding waders were analysed in relation to winds during spring migration. The gains in terms of total flight time of selective departures were evaluated by the construction of travel schemes based on wind data and recorded bird behaviour along the >4000 km long non-stop flight between spring staging and breeding areas. Average daily migration intensity was positively associated with tailwind assistance at the start of the flight as well as during passage over southern Sweden, a few hours after departure. Migration intensity was negatively associated with total estimated flight time. Tailwinds at departure and overall flight time was significantly better (stronger and shorter, respectively) during days when radio-tagged bar-tailed godwits departed on the long flight than during days when none departed. By selecting favourable departure conditions the waders had high probabilities of encountering very good winds for at least the first half of the journey, translating into large savings in overall flight time. Total reduction in flight time for the distance between Western Europe and arctic Russia was estimated to be about 25% compared to a flight in calm situations. Such large savings help to explain why arctic-breeding waders manage very long non-stop flights.

A1.23–Effect of fuel exposure on the physiological and ecological performance of juvenile common sole (*Solea solea*)

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Experiments were conducted to determine the effects of petroleum hydrocarbon on the cardiovascular performance of the common sole (*Solea solea*). Fish acclimated to 6 and 15 °C were exposed to fuel #2/water ratios of 0 (control), 1/2000, 1/1000 and 1/200 for 5 days. Total polycyclic aromatic hydrocarbons concentrations (PAH) were measured in water, muscle and liver. The effects of pacing frequency and adrenergic stimulation on index of pumping capacity (contraction frequency $\times$ relative tension) in ventricular muscle strips were examined. For each force frequency trial, the pacing frequencies tested ranged between 0.2 to 2.5 Hz. Correlations between tissues or water PAH concentrations and index of pumping capacity were established. It was concluded that following fuel exposure, maximum cardiac performance was reduced by approximately 20% in highly contaminated fish ($\geq 1/1000$). A comparison between the control and fuel-exposed fish at 6 and 15 °C showed that adrenaline improves the performance of cardiovascular system in lesser contaminated fish but not in highly contaminated fish. We found that temperature modulates the effect of fuel on cardiovascular performance. For instance the deleterious effect of fuel exposure on index of pumping capacity observed in 6 °C—acclimated fish was not observed in 15 °C—acclimated fish.

A1.24–Effect of acclimation temperature on the swimming performance of the sea bass (*Dicentrarchus labrax*)

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Temperature has been implicated as an important factor in regulating the seasonal movements (migrations) of numerous fish species. The proposed investigation aims at elucidating the ways in which the environment sets

the limits (scope) within which internal bioenergetic processes, particularly those related to swimming, take place. Sea bass of both sexes (147.16 ± 2.68 g) were thermoacclimated and swam at 7, 11, 14, 18, 22, 26, and 30 °C in a thermoregulated Brett-type swimming respirometer. At each acclimation temperature a relationship between oxygen consumption and swimming speed was fitted by the least squares ($MO_2 = a + bU^c$) and the optimal swimming speed was calculated ($U_{op} = (a/(c-1)b)^{1/c}$) as well as the active and standard metabolic rates. We found that U_{opt} was increased twofold over the temperature range 7–30 °C i.e., from 0.32 to 0.61 cm sec^{-1}. A relationship between U_{opt} and temperature was fitted using a linear regression ($U_{opt} = 0.0116T + 0.2866$; $r^2 = 0.75$). When the seven temperature trials were compared, a strong relationship between the extent of sea bass' aerobic metabolic scope and their sustainable swimming speed was observed ($U_{max} = 0.001AMR + 0.5051$, $r^2 = 0.9656$). The relationship between swimming speed and net cost of transport was not influenced by acclimation temperature. In order to investigate the effect of acclimation temperature on the relationship between aerobic metabolism and swimming performance we designed the following model: $MO_2 = 168.6(1 - EXP(-0.0077T^{1.65})) + 366.07U^{2.44}$.

A1.25–Subdivision of the North Sea plaice population: evidence from electronic tags

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Migration is widespread among marine fishes, yet little is known about variation in the migration of individuals within localities. Here we present the results of electronic plaice tagging experiments conducted over a period 6 years, which illustrate the temporal subdivision of the North Sea population into discrete feeding aggregations during the summer months, which disperse onto mixed spawning areas during the winter spawning period. Our results illustrate how variation in the behaviour of North Sea plaice is linked to variation in the physical environment, most notably in the tidal stream currents. The results have revealed features of spatial dynamics not previously observed from a century of conventional tagging experiments and illustrate how the study of individual fish can successfully define the migratory characteristics of populations.