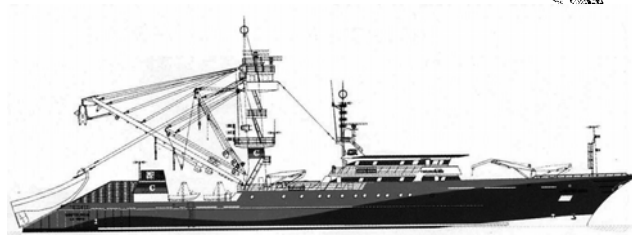
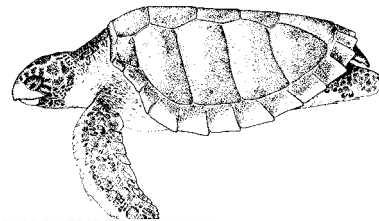
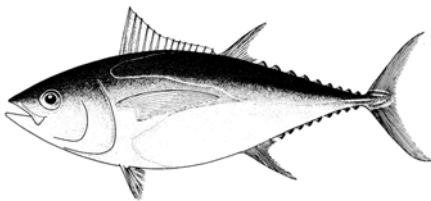


Individual/Agent-based Modelling of Fishes, Fishers, and Turtles



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Introduction to Individual/Agent-based Modelling

“The essence of the individual-based approach is the derivation of the properties of ecological systems from the properties of the individuals constituting those systems.” Łomnicki 1992

The purpose of this paper is to present a brief review of individual/agent-based modelling and its actual and potential applications to fisheries in the Western and Central Pacific Ocean (WCPO). ‘Agent-based’ and ‘Individual-based’ are really synonyms for the same kind of modelling approach that has developed in different disciplines; ‘Individual based’ is more commonly used in ecology, whereas ‘agent based’ is often found in other fields such as economics. Individual/agent-based models have, at least in principle, the potential to determine to what extent individual properties and elements of individual performance are essential for generating characteristic features of overall system dynamics (Fahse et al. 1998). According to Kaiser (1979) I/ABMs are needed because (1) individual properties cannot be fully taken into account in state variable models and (2) because we want to understand how individual properties determine the system’s properties. This emphasis on understanding the system, not just recreating a faithful simulation of its aggregate properties, is where I/ABMs can be particularly useful through the definition of model agents. The computational agents depicted in I/ABMs might well be individual animals, plants or people, but they may also be higher-level units such as fish schools, fishing vessels or institutions; the approach is relevant to simulation modelling of any scenario involving information-based and state- and/or environment-dependent decision making. This paper presents some background discussion and an outline of present projects developing A/IBMs and suggests some directions for future research. Finally, we present a case study towards the development of a rule-based A/IBM for bigeye tuna based on some preliminary analysis of archival tag data.

Individual-based Modelling in Ecology

Individual-based models (IBMs) abound in ecology but the term has acquired a double meaning. It is sometimes used for equation-based models of physiological processes occurring at the organismal level (e.g. digestion, growth) but these models in themselves are quite distinct from those that define autonomous computational agents with varying/evolving characteristics and interactions. Ecologists have to look at supposed A/IBMs with a critical eye because of this confusion. Uchmanski & Grimm (1996) recommended that these differential equation based ecological models that consider organismal-level physiological processes and/or behaviour of individuals without representing individual agents explicitly be called ‘individual-oriented’ models. ‘Individual/agent-based’ more clearly denotes computational models comprised of autonomous agents. Detailed physiological models may be incorporated as sub-models in ecological I/ABMs (e.g. Kirby et al. 2000, 2003) but it is also possible to build I/ABMs without physiological detail. These models are often ‘rule based’ in design, based on empirical observations of behaviour in relation to internal/external variables. The rules may be implemented discretely (IF *condition* THEN *action*) or in the form of continuous equations denoting habitat preference; the latter may also be used in models for spatial dynamics which are not individual-based (e.g. Bertignac 1998, Lehodey 2004).

In ocean ecology, the distinction between individual-based and biomass-based models is comparable to the distinction between Eulerian and Lagrangian methods for analysing fluid flow, the difference being best illustrated by considering the data collected by anchored versus drifting buoys: the former are fixed in space and measure changing conditions and fluxes; in the latter, the displacement of the ‘particle’ is of primary interest, as are its changing characteristics. In ecological modelling, an I/ABM emphasises a moving reference frame, tracking the changing characteristics of individual agents as they move through time and space, whether drifting with ocean currents (e.g. Allain et al. submitted) or conducting directed movement (e.g. Kirby et al 2000, 2003).

Many IBMs for pelagic organisms focus on planktonic early life history stages (e.g. krill, anchovy) and do not explicitly model behaviour, the spatial distribution of individuals is determined firstly by ocean circulation, and then by natural mortality (usually starvation and predation). These factors are

important for nektonic stages too, but modelling is complicated by the fact that organisms can move quicker than currents – this element of choice brings the topic into the realm of behavioural ecology, a field that is rich in empirical studies, theoretical paradigms and practical techniques.

The main difference between classical state variable models and I/ABMs lies in the different notions of theory and generality. Theoretical population ecology has traditionally tried to formulate both general questions and general answers—a notion of theory evidently adopted from physics. Notions of population regulation and negative feedback derive from the field of cybernetics, the theoretical study of communication and control. Both foundations omit any reference to the basic unit of natural selection in ecological systems: individuals. Their explanatory power is therefore limited. The notion of ecological systems as being fundamentally self-organized through the emergent properties of interacting individuals under selection pressure leads to a deeper understanding and integration of ecological principles. Individual-based modelling acknowledges that answers may not be very general, i.e. each population, community, etc. may have its own peculiarities which are essential to understanding their dynamics.

One of the main reasons for developing individual-based models is to investigate individual variability and its potential significance for population dynamics (Huston et al. 1988; Grimm 1999). Fahse et al. (1998) present a protocol for extracting the basic parameters of population dynamics (e.g. equilibrium population size, intrinsic rate of increase) from an IBM. The protocol makes use of the fact that processes on behavioral and population timescales can be treated separately. The IBM is reduced to pure behavior (i.e. birth and death are deactivated) and the behavioral model then used to calculate population parameters by comparison with the full model.

Another reason is that the quantitative integration of knowledge, originally established by other researchers at different times, allows the identification of data gaps and weak links, while sensitivity analysis reveals redundant complexity. There are also computational ‘tricks’ that may be used to develop ‘efficient’ I/ABMs, e.g. integration of fine-scale events such as state-dependent swimming speed and multiple feeding bouts over a larger timestep, and the use of ‘super-individuals’ to scale model population to realistic biomass (Kirby et al. 2003).

Agent-based Modelling in Socio-economics

Agent-based computational economics seeks to apply the modelling paradigm to economic systems that are ill-suited for classical deterministic analysis, such as decentralised market economies, organisational behaviour and the behaviour of individual traders. These systems are inherently similar to ecological systems defined on an individual basis: a number of individuals/agents are defined by certain characteristics that differ or may be shared, and which may change during the course of the simulation, through simple time evolution or through interactions with other.

Niedringhaus (2000) presents an Air Carrier Service Evolution Model (ACSEM), an agent-based model to explore the evolution of the airline industry and its interactions with the National Airspace System. ACSEM models decisions such as markets, fleet mix, schedules, fares and responses to delays, congestion and missed connections. The I/ABM paradigm makes it feasible to model such a web of interactions with multiple feedback loops and to construct management rules.

In a paper on strategic defense planning, Davis (2002) makes some very pertinent points relevant to modelling fish behaviour & spatial dynamics. Regarding rule-based models he states that: “A central problem is that the rules and models one thinks to write are often rather ‘brittle’. They may represent normal processes and reasoning well, but not adaptation to new capabilities and circumstances...Models used to evaluate alternative strategies must usually include behaviour and adaptation...many modellers dislike dealing with ‘soft factors’ such as ... behaviour. But the soft factors, such as the ... ability to learn and adapt, often dominate the problem!” Computational methods exist that allow both adaptive learning (within generation) and evolution (between generations) to be implemented in I/ABMs (see Giske et al. 1998, Strand et al. 2002). The I/ABMs developed by Davis illustrate the utility of the approach: “As one might expect from agent-based approaches, behaviors are sometimes ‘emergent’, in the sense that sensible and striking aggregate-level behavior was not dictated by the model, but rather a consequence of events and lower-level interactions...The key to success is finding appropriate approximations and in allowing...for different approximations in different regions of the problem space. Not only parameter values, but even model structure, may need to be quite different in those different regions.”

The application of this kind of thinking to fisheries science was recently illustrated in a paper presented at the 4th World Fisheries Congress by Beth Fulton, Keith Sainsbury and colleagues from CSIRO Marine Research (Fulton et al. submitted). They described a model used for the multiple-use management of the entire regional ecosystem of the Northwest of Australia. The model is a spatially explicit agent-based biophysical simulation model. It employs a mix of classical dynamic models and individual-based model structures and formulations and considers the links between the ecosystem functioning and cumulative impacts of human activities, such as fishing, conservation, coastal development and the extraction of oil and gas. The selective inclusion of biophysical and anthropogenic model components has been highly successful in guiding multi-sector reconciliation. Another recent, simple and powerful application of I/ABMs in fisheries science is given by Gaertner & Dreyfus-Leon (2004). They use an I/ABM to simulate information exchange among fishing vessels when fishing in areas of different environmental heterogeneity. They illustrate that the CPUE vs. abundance relationship becomes increasingly non-linear for cooperative fishing fleets in heterogeneous environments. The study illustrates that hyperstability, a feature commonly observed in schooling fisheries, can be largely attributed to information exchange among vessels.

I/ABM projects within the Oceanic Fisheries Programme:

I/ABM research within the OFP is focussed on: rule-based models based on data from archival tags; theoretical models for tuna behaviour; and the development of population/basin-scale I/ABMs. The SEAPODYM model developed by Lehodey (2004) requires the parameterisation of fish behaviour in relation to environmental variability, which may be more accurately achieved by developing rule-based I/ABMs based on archival tag data (see below). The physiology-based model of Kirby et al. (2003) is also under development, with the original model being separated into a ‘simple’ behaviour only model, parameterised as for SEAPODYM, to allow the development of quantitative methods for comparing the Lagrangian and Eulerian approaches. At the same time, the complexity of the ‘full’ model is being retained in studies investigating the adaptive dynamics of the model. The transferability of the model to other oceanic top predators is also being investigated.

Patrick Lehodey and David Kirby are funded by the European Community through the Pacific Region Coastal and Oceanic Fisheries (PROCFish) Project. We are also involved in two PFRP-funded projects with an I/ABM component: the first project, entitled *Mixed Resolution Models for Individual to Population Scale Spatial Dynamics*, funds Gwenael Allain to work on I/ABM development and Inna Senina to work on numerical solutions to advection-diffusion-reaction equations on a mixed resolution grid. The second project, entitled *Comparing sea turtle distributions and fisheries interactions in the Atlantic and Pacific*, is focussed on population assessments, to be carried out by Selina Heppell, Oregon State University, but will also investigate dispersal scenarios for hatchlings and the development of foraging models to study interactions with fishing gear; this latter component will be carried out by OFP in collaboration with Molly Lutcavage, University of New Hampshire.

Potential projects extending the I/ABM paradigm in application to WCPO tuna fisheries

The different I/ABMs briefly described here demonstrate the diversity of potential applications as well as the commonality of certain aspects among seemingly disparate disciplines. Of themselves, the airline industry or strategic defence planning are of little relevance to WCPO tuna fisheries, but the methods used and problems encountered in studies of these topics are illustrative. The study of effort dynamics by Gaertner & Dreyfus-Leon (2004) is relatively simply achieved in an I/ABM framework and has important ramifications for tuna fisheries. Their study used synthetic data with well known statistical properties; it would be most useful to carry out the work for data collected from real fisheries. Such a study would necessitate collaboration among relevant agencies and the support of industry, particularly with regard to the degree of information sharing. The use of coupled models for Management Strategy Evaluation as demonstrated by Fulton et al. (2004) illustrates the very real potential for I/ABMs to be used in a management context and future work might explore the potential application of this approach in WCPO tuna fisheries. This kind of work is already under development under the PFRP Mixed Resolution Models project, but more attention would need to be paid to modelling interactions of stakeholders and quantifying uncertainty.

Case study: Preliminary analysis of archival tag data

Archival tag records from two bigeye tuna tagged in the Coral Sea under a joint CSIRO/SPC project have been examined and compared with sea-surface temperature predicted by a physical-biogeochemical model developed by the Earth Systems Science Interdisciplinary Centre (ESSIC), University of Maryland (Christian & Murtugudde 2004; Christian et al. 2002a,b) and forage biomass predicted by the Spatial Ecosystem And Population Dynamics Model (SEAPODYM) developed by the SPC Oceanic Fisheries Programme (Lehodey 1998, 2004). Both in situ data and ocean model output were explored on common time/space scales to investigate interactions between fish movement and ocean variability. The data will be used to develop rule-based A/IBMs and to validate more theoretical A/IBMs (e.g. Kirby et al. 2003) under the PFRP project 'Mixed Resolution Models for Individual to Population Scale Spatial Dynamics'.

Since October 1999, more than 180 archival tags have been deployed on bigeye tuna in the Coral Sea; so far 17 have been recovered. Light records were processed by CSIRO using Wildlife Computers 'Global Position Estimator' software to estimate longitude and latitude. Most probable horizontal movements were then estimated from the geolocation data using Kalman filter analysis (Kftrack R Package by J. Sibert and A. Nielsen; Sibert et al. 2003). Two individual tag records clearly exhibit eastward migration to New Caledonian waters (Fig. 1 and Leroy 2003) at the same period of the year (Oct–Apr). The monthly evolution of predicted sea surface temperature and forage biomass from Jan 1999 to Dec 2002 in the area delimited by the supposed migration route (148°E–165°E, 16°S–22°S; Fig. 1) suggest that this is a time of seasonal warming and peak biomass of epipelagic and migrant mesopelagic forage. Figs 2 & 3 show finer-scale examination of tag records and model data along the tracks of the two individuals. Fig. 3 shows general coherence between predicted monthly temperature and temperatures recorded by archival tags; discrepancies can be attributed both to model and geolocation errors. Fig. 3 shows that distinct types of vertical behaviour recorded by archival tags (top) correspond to differences in the predicted forage biomass (bottom) in the areas frequented by tuna, suggesting that bigeye remain at the surface when forage is abundant there and exhibit classic day/night diving behaviour when food is limited at the surface.

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Fig. 1 : Migration route of two bigeye tunas and seasonal evolution of environmental variables. Top: Black dots and dashed lines denote most probable tracks for 2 bigeye tagged in Oct 1999 and 2001 in the Coral Sea. Dashed rectangle: area defined for the extraction of environmental variables. Bottom: Monthly SST and biomass of three forage components (epipelagic, migrant mesopelagic, deep mesopelagic) from Jan 1999 to Dec 2002. White dots: months when tunas recorded in the area

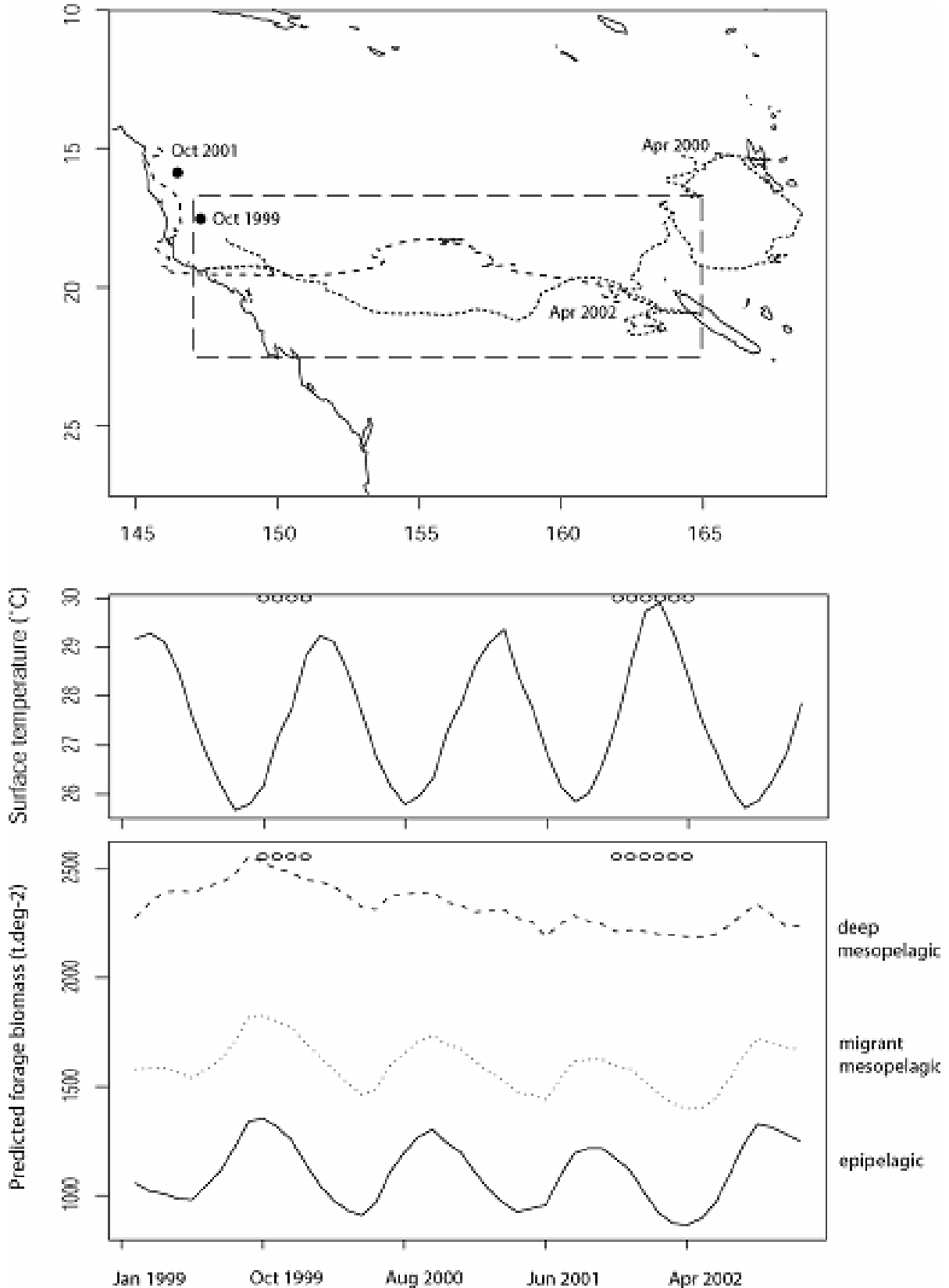


Fig 2 : Comparison of temperature recorded by an archival tag along the track of a bigeye tuna and temperature estimated by ESSIC model. Top: Most probable track of bigeye tuna 353 from Oct 1999 (black dot: tag location) to Apr 2000 (dashed lines). Dotted rectangles: areas defined for extraction of monthly temperature estimates. Bottom: monthly temperature estimates at the surface, 200 m and 400 m (black dots) and temperature recorded for the same months in the rectangle areas by archival tag 353 at corresponding depth ranges (<10m, 195–205 m, 395–405 m)

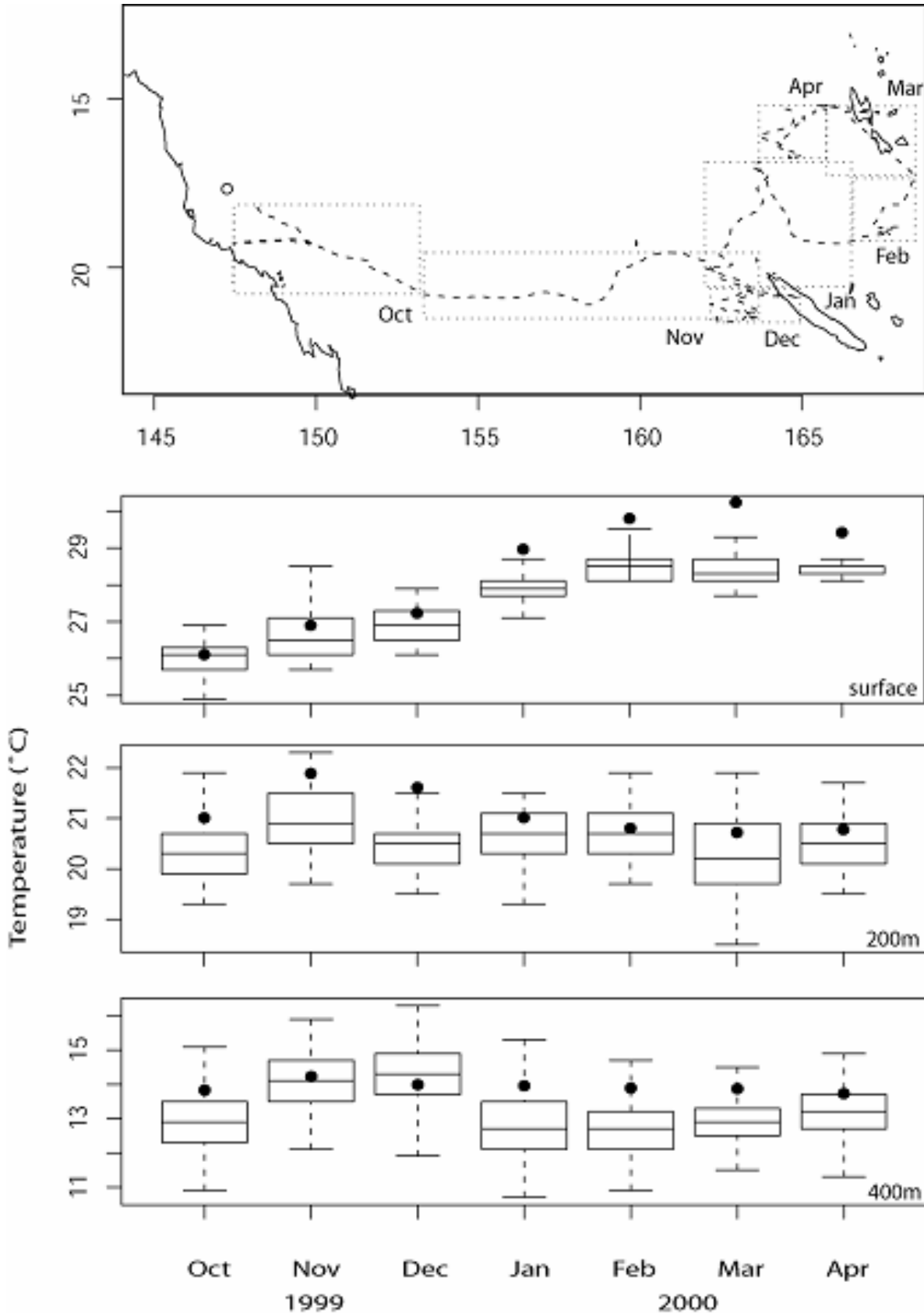


Fig. 3: Vertical behaviour of a bigeye tuna cf. forage biomass. Top: Typical vertical behaviour of bigeye tuna 213 recorded by archival tag in Nov 2001 (left) and Feb 2002 (right). Middle: Most probable track from Oct 2001 (black dot: tag location) to Apr 2002 (dashed lines). Dotted rectangles correspond to areas defined for the extraction of monthly temperature estimates. Bottom: Predicted biomass of three forage components (epipelagic, migrant mesopelagic, deep mesopelagic)

