REMOTE SENSING AND FISHERIES APPLICATIONS: AN OVERVIEW

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ABSTRACT

Satellite remote sensing enables measurement of oceanographic variables over large spatial scales, with increasingly small spatial resolution and rapid repeat sampling. The challenge for fisheries science is to develop methods that relate the spatio-temporal patterns of these variables to factors concerning the fishery, e.g. location of fishing grounds and prediction of recruitment. This overview has been written to provide a context for the Case Studies that follow in this volume and a broad introduction to the science underlying fisheries applications of remote sensing. The state of world fisheries is briefly presented. Ocean-viewing satellite sensors are described in terms of the geophysical variables measured and how they may relate to fisheries. Some examples of applications to date are outlined and potential future applications are discussed. The literature in this field is discussed, especially with regard to different approaches

to the use of satellite data in fisheries. Finally, a list of acronyms and links to internet resources is provided.

INTRODUCTION

The State of World Fisheries

EUROPE: Many demersal stocks have been intensively exploited over recent decades and some stocks *e.g.* North Sea Cod (Cook *et al*, 1997) are now considered to at critical levels of biomass. Smaller pelagic resources are generally less affected. Pollution has caused deterioration of some nearshore environments in the north Atlantic. Wild stocks of salmon in the Baltic sea are threatened by disease and competition from reared stocks. In the Mediterranean, most demersal stocks are also fully- or over-exploited. Elimination of overcapacity, adjustment of fishing effort and granting of premiums for permanent withdrawals of vessels are all part of the Common Fisheries Policy (CFP) of the European Union. Access to distant waters and other nations' EEZs has also been an active policy issue. Demand for fish is still increasing and will likely be met by increasing imports.

NEAR EAST & NORTH AFRICA: The Mediterranean Sea shows a steady increase in production over the entire time series of fisheries statistics, but rapid ecological change is suggested within the Mediterranean basins that may apply elsewhere in semi-enclosed and coastal seas. Such ecological changes are a result not only of fishing, but of other activities within adjacent land masses, particularly those which influence the runoff of nutrients. Other than anchovy, which has high value and has declined in a number of areas, most small pelagics can be considered moderately to underexploited, due to a generally low market demand. In the Persian/Arabian Gulf however, all commercial stocks are thought to be fully exploited. Throughout the area, fisheries are threatened by environmental degradation, mainly from oil spills, and industrial, urban and agricultural run-off. The Caspian sea is severely polluted and over-fishing has further reduced fish stocks. The Atlantic waters off Morocco seem capable of sustaining increased fishing effort, largely from foreign fleets, with commercially important levels of small and large pelagics, as well as cephalopods and octopods.

SOUTHERN AFRICA: The Benguela upwelling system supports productive and well established fisheries along much of the coastline of Angola, Namibia and South Africa. These fisheries have a general history of good management in recent decades, after periods of overexploitation in the 1950s and 1960s. Despite the level of management intervention, however, a number of fisheries are in a tenuous state, largely because of the susceptibility of stocks to environmental variability. The pelagic fisheries in the region are being affected by declines in sardine abundance in the north and anchovy abundance in the south, while the trawl fishery in Namibia and Angola is being affected by a decline in hake abundance in their waters.

SOUTH & SOUTHEAST ASIA: The fisheries of the Eastern Indian Ocean are characterised by increased fishing pressure, especially in inshore areas. Coastal areas off the east of India, the west of Thailand and the south coast of central Java are good examples of areas where fishing pressure has kept increasing, reflecting the often intense human population pressure at coasts. Most of the catch from coastal fisheries is used for local consumption. Shrimp and tuna are the main export commodities. Knowledge of fish stocks is generally poor and management actions have usually been taken on an *ad hoc* basis, in most cases without scientific support. Most fish stocks are approaching levels of full exploitation. Coastal species have generally been heavily exploited; offshore resources have been less intensively fished. Demand is expected to increase with the size of the human population, and marine fisheries offer few opportunities to increase supply.

EAST ASIA: All fished species are thought to be overfished and the catch of particularly valuable species has declined recently. Total marine production has decreased slightly, mainly due to the fall in Japanese pilchard (*Sardinops melanostictus*). This is thought not to be related to fishing, but rather caused by decadal scale changes in the marine environment (Kawasaki & Omori, 1995). Restricted exchange between the open ocean and the east Asian seas

apparently makes these fish particularly sensitive to environmental change, whether from human or natural causes. Consumption of seafood is increasing, despite these concerns.

SOUTH PACIFIC: In the South Pacific region there are three main types of fisheries: the industrial fisheries (mainly tunas); coastal fisheries for export (e.g. mother-of-pearl shells), and coastal fisheries for domestic consumption (FAO, 1997). Throughout the islands, little is known about the volumes of coastal fish catches and the status of stocks, as stock assessment is virtually non existent. Many inshore resources have declined as a result of overfishing and habitat degradation around urban or industrial areas. Overfishing of inshore and lagoon areas and sustainable fisheries are therefore major issues in social and economic policy in nearly every state and territory. Fish imports are forecast to contract and a small increase in exports, mainly of tuna, is expected. The impact of high seas fishing by foreign fleets is a matter of concern, and international bodies exist to monitor these fisheries.

NORTH AMERICA: In the Northwest Atlantic, while invertebrates such as lobster and scallop are at healthy levels, the demersal stocks that were the dominant resources of the past have collapsed due to a combination of heavy fishing and environmental effects, mainly the low water temperature of the Labrador current (FAO, 1997). In the United States, 80% of 191 commercial fish stocks are overexploited (Los Angeles Times, Aug. 1999). Regional fleets are characterised by high technology, and excess capacity is an important issue in both the USA and Canada. There has been a drive to reduce fishing effort by way of withdrawing permits and introducing early retirement plans for fishers. Loss or degradation of essential fish habitat is one of the most serious environmental issues and active research areas here.

LATIN AMERICA AND THE CARIBBEAN: Overfishing and El Niño effects brought about recruitment failure and induced the collapse of the fishery for Peruvian anchoveta (*Engraulis ringens*) in the last decade. Dramatic fluctuations at decadal scales in the Pacific basin have severely affected overall abundance and total production of small pelagics as well as other stocks. The anchoveta fishery is now gradually improving but the 2 main sub-stocks are reported to be fully exploited and require monitoring to avoid overfishing. Lloyd's register of shipping shows a 5 percent annual rate of increase in fleet capacity, which is of obvious concern. Degradation of coastal areas is believed to be further reducing fishing potential. In the Caribbean there is general concern for a number of species and stocks in the region. The pelagic fisheries of the area may be divided into large offshore pelagics with an oceanic distribution, large coastal pelagics with a regional distribution and smaller pelagics. The first group includes billfishes, tunas and swordfish, most of which are managed by the International Commission for Atlantic Tunas (ICCAT) and are considered to be fully or over-exploited. The status of the stocks of the more common locally distributed large pelagics, such as mackerel *Scomberomorus* species, blackfin tuna and common dolphinfish, is unknown. Fisheries for small pelagics, usually Carangids, are locally important providers of employment and food. The demersal fishes of the region also support important commercial fisheries. The main crustacean fisheries are those for spiny lobster and penaeid shrimps. This resource is generally considered to be overexploited in many countries and a more holistic and effective management strategy is required for the region.

Reinventing Fisheries Management

Judged by a dismal record, the methodology, data, institutions and policy goals for fisheries stand world-wide in need of reinventing.'(Pauly, Hart & Pitcher; 1998). This is a common cry in the fisheries literature but is yet to be translated into action. Institutional and socio-economic change need to be supported by well directed, statistically sound investigations of scientific questions relevant to a framework of coherent and transparent policy goals. These investigations should consider fisheries oceanography, fish biology and trophic interactions, identify and quantify uncertainty, and ultimately enable better decision making, thus preventing overfishing, over-capacity, resource depletion and species extinction.

The Role of Satellite Remote Sensing

'Better understanding of ecological responses through better upper-ocean monitoring on relevant scales is one area of shared concern between fisheries scientists and oceanographers.' (Sharp, 1995). Satellite remote sensing provides a unique suite of tools for

the environmental scientist and resource manager. As such it may well play a constructive role in the reinvention of fisheries management. Priorities in its use for marine fisheries will include:

1. Identification of spatio-temporal patterns in oceanography (*e.g*. Uddstrom & Oien, 1999);
2. Habitat identification and delimitation for key life-history stages, *e.g.* spawning/nursery grounds, feeding grounds, migration routes for juveniles/adults *etc.*;
3. Identification of degradation of the coastal zone and catchment areas, including pollution, sedimentation, clearance of mangroves, landfill, mining, oil exploration, *etc.*;
4. Dynamics of coastal flood plains, landuse, landcover and agricultural outputs.
5. Conservation engineering, *e.g.* coral reef protection, enhancement, classification, *etc*.;
6. Identification of sites and environmental monitoring for aquaculture;
7. Discriminating between the effects of human interference and natural events.

SATELLITE SENSORS FOR OCEANOGRAPHIC RESEARCH

A list of satellites carrying sensors relevant to fisheries research and applications is given in Table 1.

Visible and infrared radiometers

Advanced Very High Resolution Radiometer (AVHRR)

Band	Wavelength (µm)	Measures:
1	0.58–0.68	visible (green)
2	0.725–1.00	reflected infrared
3	3.55–3.93	reflected/thermal infrared
4	10.3–11.3	thermal infrared
5	11.5–12.5	thermal infrared

Table 2. Sensor characteristics for the AVHRR

The AVHRR is a scanning radiometer with five detectors in the visible and infrared wavelengths. The three channels within the infrared band detect the heat radiation from the sea surface and the sea surface temperature may then be calculated.

On account of the intervening atmosphere, the sea surface appears cooler from above by several degrees, for which a very accurate correction must be made.

AVHRRs have been flown on the NOAA suite of satellites since the mid-1970s. These polarorbiting satellites constantly circle the Earth in an almost north-south orbit, passing close to both poles. Always operating as a pair, these satellites ensure that data for any region of the Earth are no more than six hours old. Sensor characteristics for the AVHRR are given in Table 2.

Along Track Scanning Radiometer (ATSR)

The ATSR is an advanced imaging radiometer flown on the European satellites, ERS 1 & 2. The main objective for ATSR was to measure global SST with the high levels of accuracy required for climate research. In order to achieve this, ATSR-1 had three thermal infra-red channels matching those of the AVHRR plus a reflected infra-red channel in order to detect clouds by day. ATSR-2, launched in April 1995 on board ERS 2, has three extra channels which are being used to develop new applications of data obtained over land.

Atmospheric correction is achieved principally by viewing each part of the Earth at two angles. As the two views of the same scene are taken through different atmospheric path lengths, it is possible to calculate a correction for the effect of atmospheric absorption. The combination of radiometric sensitivity, stability and the dual-angle viewing geometry enables sea surface temperature to be measured over large areas to an accuracy of 0.2 - 0.3 Kelvin. There is an Advanced ATSR (AATSR) on ENVISAT.

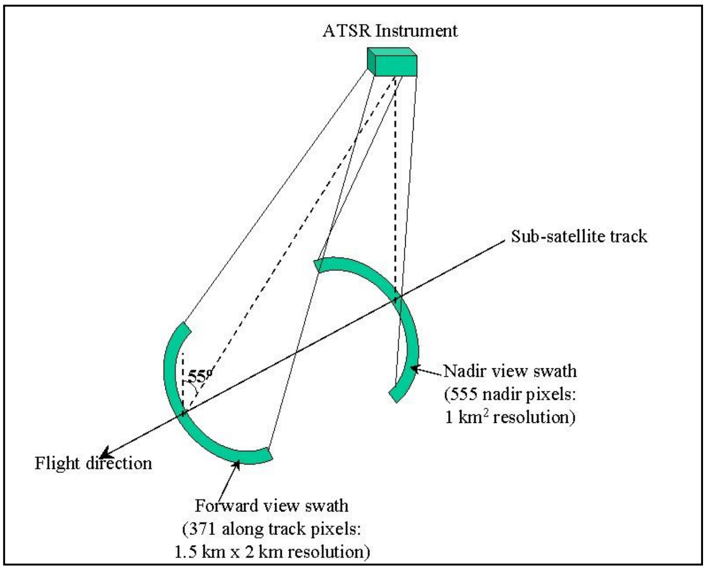


Figure 1. Viewing Geometry for ATSR & AATSR

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

SeaWiFS has 8 bands in the visible and near-infrared wavelengths (Table 3.) and is designed to measure ocean colour, a physical property largely determined by biological (photosynthetic) processes.

Table 3. Sensor characteristics for SeaWiFs

Wavelength [µm]	Colour:	Used to measure:
0.402-0.422	Violet	Dissolved organics
0.433-0.453	Blue	Chlorophyll
0.480-0.500	Blue/green	Chlorophyll / k490
0.500-0.520	Green	Chlorophyll
0.545-0.565	Green/yellow	Chlorophyll
0.660-0.680	Red	Aerosols
0.745-0.785	Near infrared	Aerosols
0.845-0.885	Near infrared	Aerosols

The sensor is a successor to the Coastal Zone Colour Scanner (CZCS), which operated from 1978 to 1986. The CZCS was a 'proof-ofconcept' mission, which established the feasibility of global monitoring of bio-optical variability, data that is critical for the study of oceanic primary production and global biogeochemistry.

SeaWiFS contains specific enhancements both in terms of its engineering capabilities and in the algorithms used for atmospheric correction and derivation of pigment concentrations. Whereas the CZCS calculated 'total photosynthetic pigment', SeaWiFS is able to distinguish different classes of pigment (*i.e.* chlorophyll-a versus carotenoid) and estimate concentrations of different classes of phytoplankton.

Correction for atmospheric effects is much more important for SeaWiFS data than for AVHRR infrared data because up to 90% of the visible radiation received by the sensor originates in the atmosphere rather than at the sea surface. SeaDAS, the software package for processing SeaWiFS data, calculates corrected radiances using a database of climatologies for ozone concentration, surface wind speed, atmospheric pressure and relative humidity. The main outputs are the normalised water-leaving radiances in bands 1-5, the atmospheric aerosol radiances in bands 6-8, the aerosol optical thickness in band 8, the coefficient of diffuse attenuation at 490 nm, chlorophyll *a* concentration and "CZCS-type" total pigment concentration

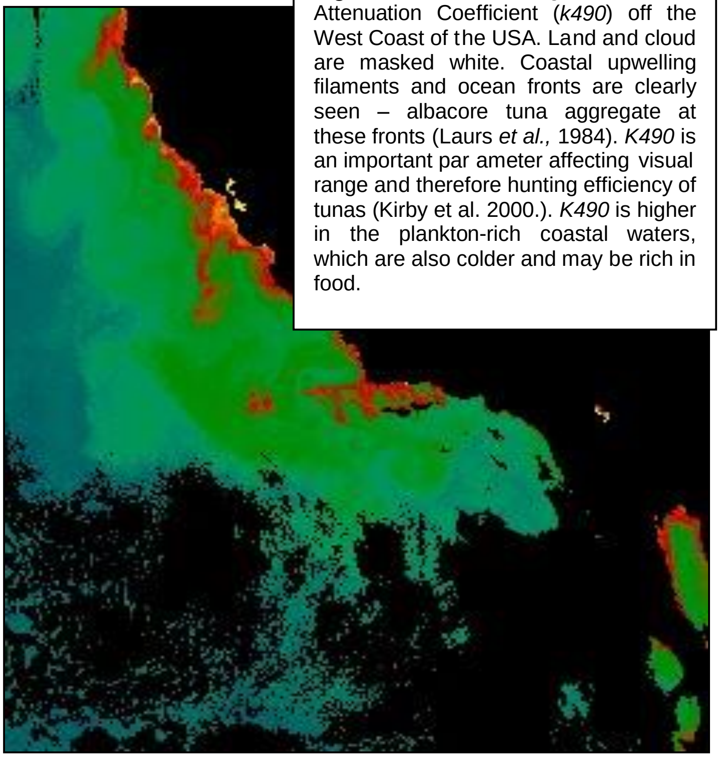


Figure 2. SeaW iFS Image of Di ffusion Attenuation Coefficient (*k490*) off the West Coast of the USA. Land and cloud are masked white. Coastal upwelling filaments and ocean fronts are clearly seen – albacore tuna aggregate at these fronts (Laurs *et al.,* 1984). *K490* is an important par ameter affecting visual range and therefore hunting efficiency of tunas (Kirby et al. 2000.). *K490* is higher in the plankton-rich coastal waters, which are also colder and may be rich in food.

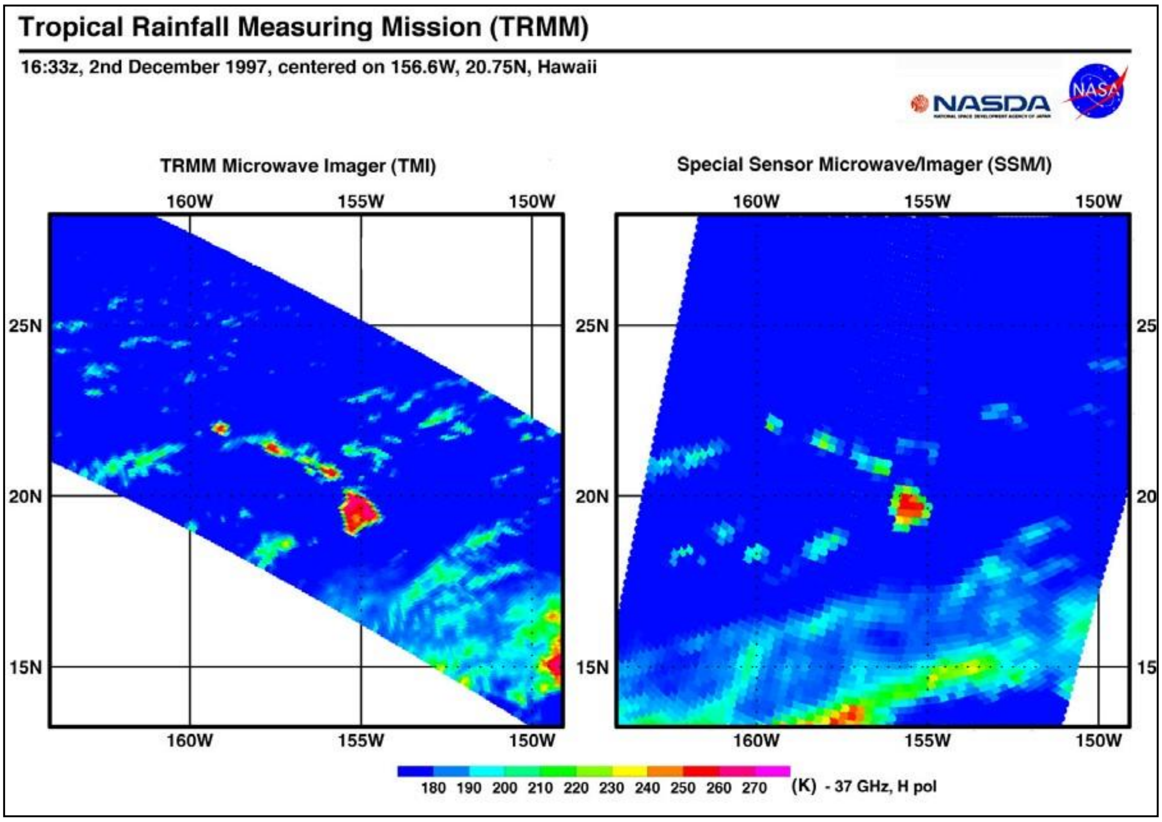
There will be various other ocean colour sensors in the near-future, thus minimising the repeat cycle between measurements of the same area. These will be flown on board satellites carrying other sensors, thus allowing coincident multi-sensor imaging.

Passive microwave radiometers

The measurement of sea-surface temperature by satellite microwave radiometers has been an elusive goal for many years. The important feature of microwave retrievals is that SST can be measured through clouds, a distinct advantage over traditional infrared SST observations that require a cloud-free field of view. Furthermore, microwave retrievals are not affected by aerosols and are insensitive to atmospheric water vapour, although they are sensitive to seasurface roughness.

Early radiometers were poorly calibrated and later radiometers lacked the low frequency channels needed to retrieve SST. At present there are passive microwave sensors capable of measuring SST, although their use by ocean scientists is not widespread, and ocean areas with persistent cloud coverage can now be viewed on a daily basis. The Special Sensor Microwave / Imager (SSM/I) is a seven-channel, four frequency system carried aboard Defence Meteorological Satellite Program (DMSP) satellites and measuring atmospheric, ocean and terrain microwave brightness temperatures. These data are used to derive geophysical parameters, notably: SST, land surface temperature, ocean surface wind speed, area covered by ice, age of ice, ice edge, precipitation, cloud liquid water, integrated water vapour, soil moisture and snow cover. In 1997, a well-calibrated radiometer with a 10.7 GHz channel was launched aboard the Tropical Rainfall Measuring Mission (TRMM) satellite, a joint program between NASA and NASDA. A primary function of the TRMM Microwave Imager (TMI) SST retrieval algorithm is the removal of surface roughness effects. A further passive microwave sensor (AMSR) will be launched on ADEOS 2.

Figure 3. Simultaneous images from the TMI & SSMI.
Note the greater spatial resolution of the TMI.



Active microwave radiometers *Radar altimeter (RA)*

Sea level, undisturbed by waves or tides etc., is an equipotential surface of the Earth's

Synthetic Aperture Radar (SAR)

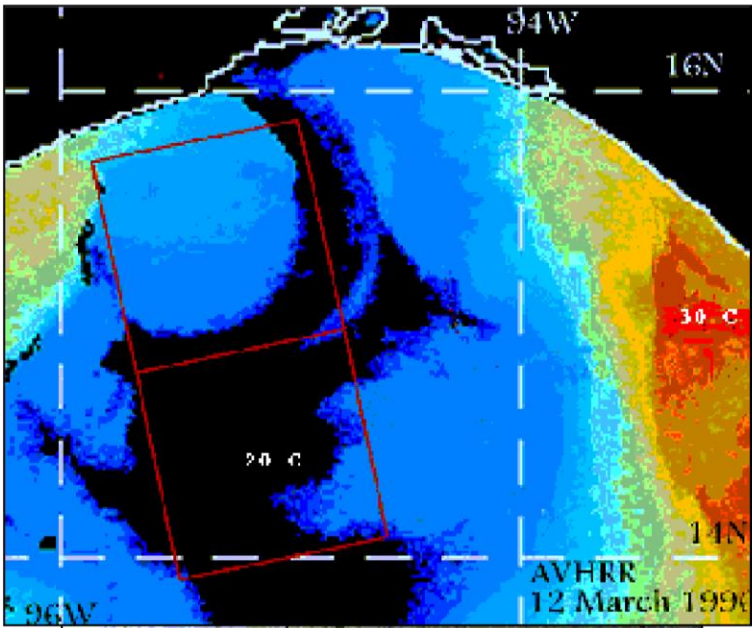
SAR obtains the spatial pattern of reflected microwave energy from an elliptical area or 'footprint' on the

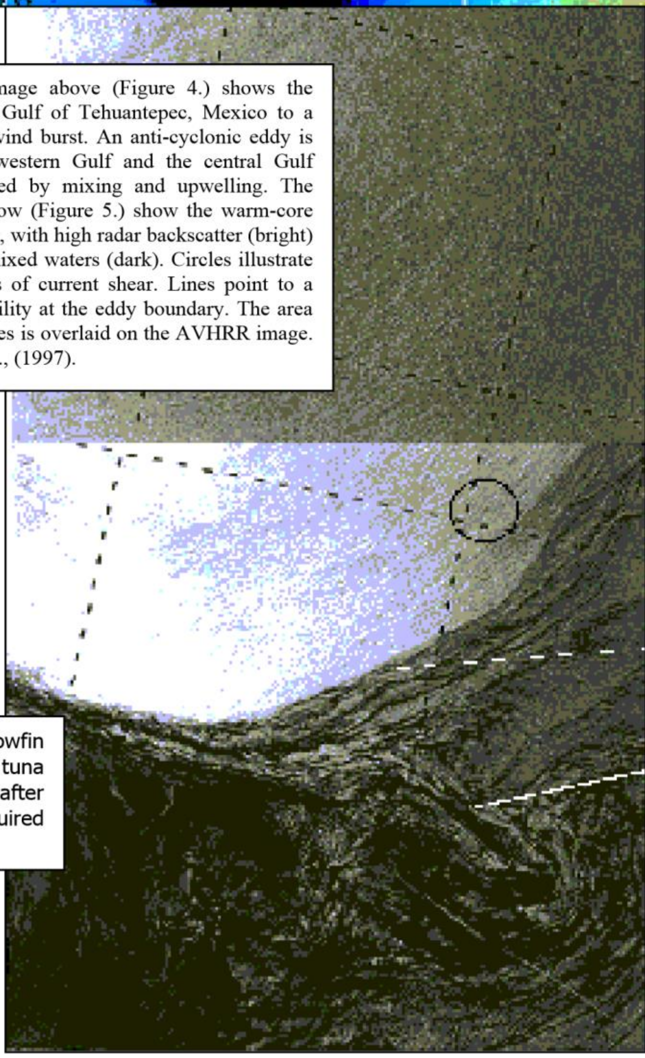
Earth's surface and imagery is built up from the time delay and strength of the returned signals. It is thought that resonance between the radar and surface capillary waves is the primary mechanism for backscattering radar pulses.

Capillary waves have wavelengths of less than 10 cm, and form in response to wind stress. The SAR directly images the spatial distribution of the Bragg-scale capillary waves, referred to as sea surface roughness.

This may be affected by longer gravity waves and other oceanographic and atmospheric features, such as: variable wind speed, changes in stratification in the atmospheric boundary layer, and variable currents associated with fronts, eddies, internal waves and bottom topography.

SARs are currently carried on RADARSAT and ERS-2. There will be an Advanced SAR (ASAR) on ENVISAT.





The AVHRR image above (Figure 4.) shows the response of the Gulf of Tehuantepec, Mexico to a cold, northerly wind burst. An anti-cyclonic eddy is formed in the western Gulf and the central Gulf waters are cooled by mixing and upwelling. The SAR frames below (Figure 5.) show the warm-core eddy 2 days later, with high radar backscatter (bright) and the colder mixed waters (dark). Circles illustrate concentric bands of current shear. Lines point to a baroclinic instability at the eddy boundary. The area of the SAR frames is overlaid on the AVHRR image. From Kirby *et al*., (1997).

The Gulf of Tehuantepec is an important area for yellowfin tuna fisheries. Blackburn (1962; 1963) describes how tuna abundance increases approximately 3 months after upwelling events; this lag is attributed to the time required for development of micronektonic food for the tunas.

gravitational field. Density differences within the solid earth distort the equipotential leading to departures from the standard ellipsoid. The real resulting equipotential surface is the Geoid. The permanent, time-averaged ocean currents cause the real sea surface to be different from the marine geoid by a few tens of centimetres. Satellite radar altimeters are designed to

measure this departure from the geoid by measuring the distance between the satellite and the nadir point to within a precision of a few centimetres. A short pulse of microwaves is transmitted vertically downwards, which illuminates a footprint on the sea surface of 2-12 km in width, depending on sea state. The echoes from these transmissions are received and the distance covered by the pulse is calculated using the time delay. Corrections are applied to account for refraction by the atmosphere and for the effect of sea state.

Sea surface height measurements may be used to monitor the permanent ocean circulation and the large scale temporal variations that may be exhibited. Mesoscale current systems may also be studied, and the RA is particularly useful for measuring the dynamic topography associated with meandering, vortex shedding and the migration of eddies. The geostrophic currents associated with these features may then be calculated from the sea surface slope. In addition to measuring sea level anomaly, RAs may also be used to deduce wave height, by measuring the slope of the return pulse, and to calculate wind speed, from the fraction of power returned to the sensor. RAs are presently flown on ERS-2, TOPEX/POSEIDON, and the GFO satellites and there is an RA on ENVISAT I.

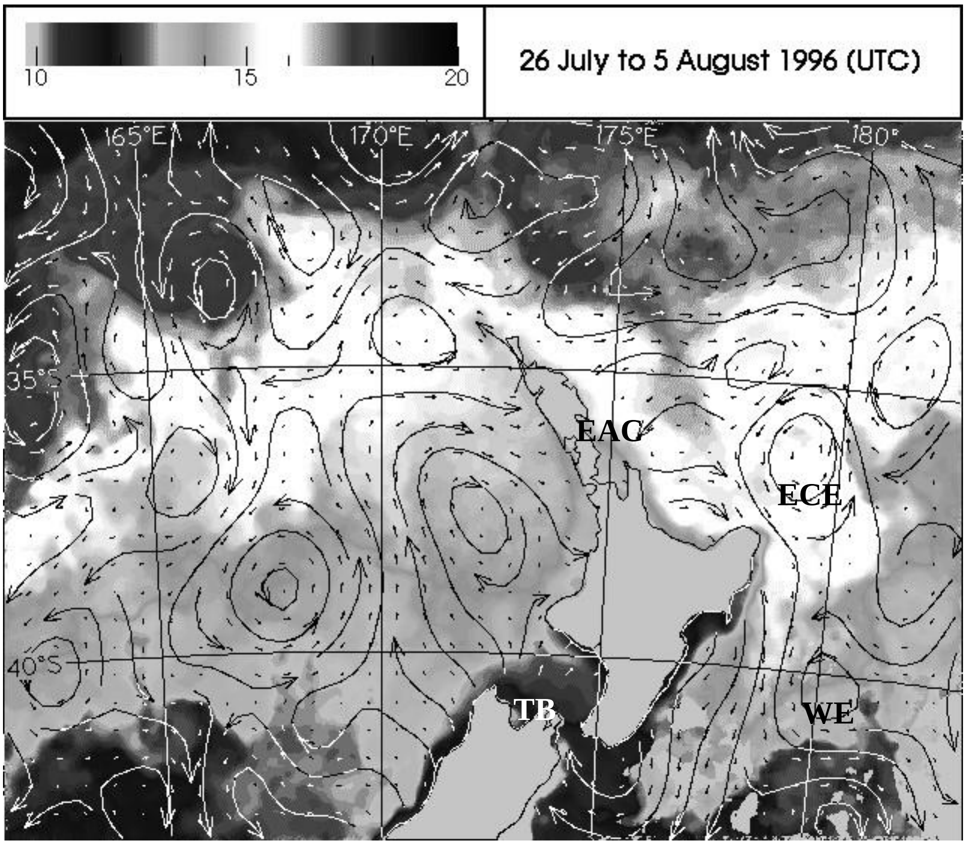
Figure 6 – Seasurface temperature and current anomaly composites for July 26 to August 5, 1996. Temperatures are a 10-day composite matching the 10-day Topex-Poseidon cycle from which the current patterns are deduced. These currents are indicated by streamlines. Their strength is measured by the small arrows: the longer the arrows the stronger the current.

SST data from the NIWA SST Archive

(1999)Udstrom & extractedOien and ,

coolocated with SSH by Andrew Laing, NIWA.

This image captures important oceanographic features around the North Island of New Zealand that are related to fisheries for tunas to the north (Bigeye occupy the warm waters of the East Auckland Current, EAC) and north-east (Southern Bluefin occupy cooler waters around the edge of the East Cape Eddy, ECE), and for squid to the south-west (found in cool upwelled waters in the Taranaki Bight, TB). In addition, the Wairapa Eddy (WE) off the east coast is thought to retain larvae, supporting coastal populations of rock lobster Jasus edwardsiii (Chiswell & Booth 1999)



Radar Scatterometers

Winds over the ocean modulate air-sea changes in heat, moisture, gases and particulates, regulating the crucial bond between atmosphere and ocean that establishes and maintains global and regional weather and climate. In the past, weather data could be acquired over land, but our only knowledge of surface winds over oceans came from reports from ships and buoys. Radar Scatterometers have their origin in early radar used in World War II. Measurements over oceans were corrupted by noise and it was not known at that time that this was the radar response to the winds over the oceans. Radar response was first related to wind in the late 1960’s. The first spacebourne scatterometer flew as part of the Skylab missions in the early 1970s. The Seasat-A Satellite Scatterometer (SASS) operated from June to October 1978 and proved that accurate wind velocity measurements could be made from space. A single-swath scatterometer flew on ERS-1 and the first dual-swath scatterometer to fly since Seasat was the NASA Scatterometer (NSCAT) on board ADEOS-1. Since the demise of ADEOS-1, QuikSCAT has been developed and launched by NASA as a quick recovery mission. The SeaWinds instrument on the QuikSCAT satellite is a specialised microwave radar that measures near-surface wind speed and direction under all weather and cloud conditions over the Earth's oceans. SeaWinds uses a rotating dish antenna with two spot beams that sweep in a circular pattern. The antenna radiates microwave pulses at a frequency of 13.4 GHz. The instrument will collect data over ocean, land, and ice in a continuous, 1800 km swath, covering 90% of the Earth's surface each day. A SeaWinds scatterometer will also be launched on ADEOS II.

Scatterometers are not yet widely used for fisheries research. However, the fact that much coastal upwelling is wind-driven, either directly or indirectly, and wind-generated turbulence, proportional to wind speed cubed (w^3), has significant influence on larval fish feeding success (Fiksen *et al*., 1998), survival and recruitment (Cury & Roy, 1989), may mean that more attention is given to these data in the future. Surface wind data are also needed to drive ocean circulation

models; the output of these models may then be used as input to models **FISHERIES OCEANOGRAPHY AND ECOLOGY**

Fisheries oceanography is concerned with the production and dynamics of fish populations in relation to the marine environment. The emphasis is on the identification of mechanisms controlling abundance and the exploration of factors affecting recruitment. Studies in fisheries

developed for the spatial dynamics of fish (Bertignac *et al*., 1998, Kirby *et al*., unpubl.).

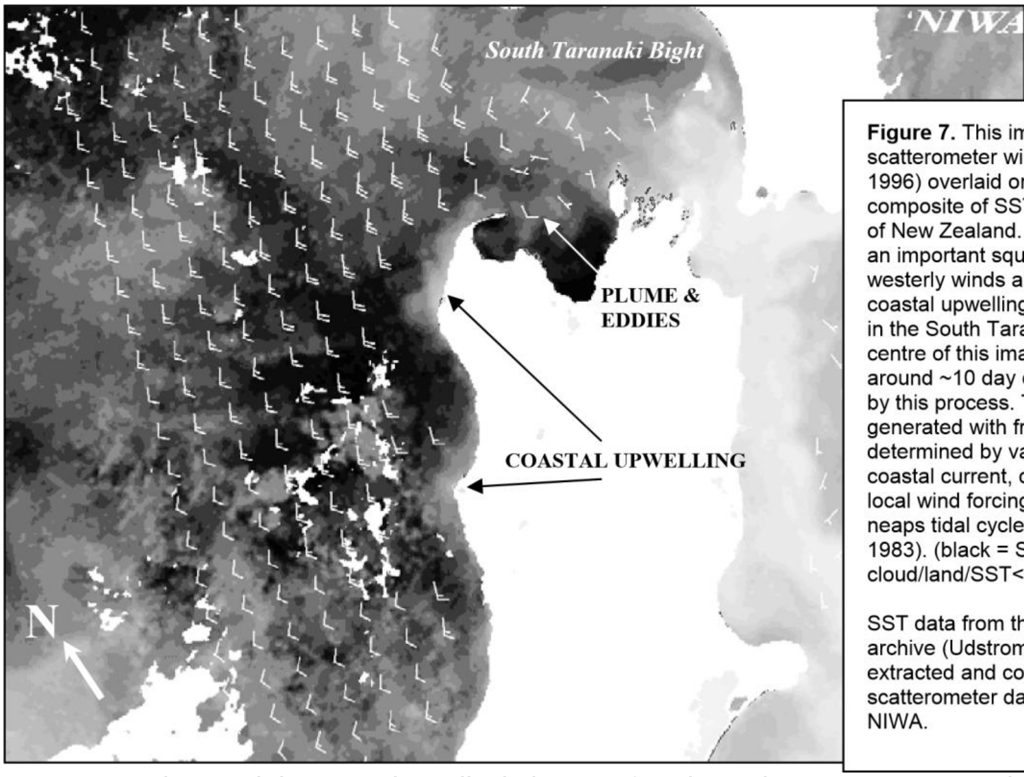


Figure 7. This image is of ERS scatterometer wind data (28 Feb. 1996) overlaid onto a 10-day composite of SST for the west coast of New Zealand. This area supports an important squid fishery. South-westerly winds are favourable to coastal upwelling, and squid fishing in the South Taranaki Bight (top-centre of this image) is often targeted around ~10 day old eddies spawned by this process. These eddies are generated with frequencies determined by variability in the coastal current, determined in turn by local wind forcing and the springs-neaps tidal cycle (Bowman *et al*, 1983). (black = SST > 20^{o} C; white = cloud/land/SST<15^{o} C).

SST data from the NIWA SST archive (Udstrom & Oien, 1999) extracted and collocated with scatterometer data by Andrew Laing, NIWA.

oceanography are inherently interdisciplinary, often involving meteorology, physical, chemical and biological oceanography, as well as fish biology and fisheries economics or social science. They seek to bring together important ideas from all schools of thought, accepting that oceanographic variability at various spatio-temporal scales may affect recruitment and spatial population dynamics, and seeking to understand how and why this occurs. Ecology is the branch of biology concerned with the relations between organisms and their environment. Fisheries Ecology may therefore be defined as the study of interactions between the biology of exploited fish populations and their aquatic environment. Depending on the time and space scales of interest, physiological, behavioural and evolutionary ecology may be important perspectives on fish population dynamics.

The challenge in fisheries oceanography is to identify the important physical characteristics of a particular environment and to then consider how these relate to obligate physiological processes and life-history characteristics of the species of interest. Temperature effects on egg and larval survival, and on metabolic rates and stress effects for adults are examples of important bio-physical interactions. Water mass dynamics may be important for nutrient enrichment, concentration of food and retention of larvae and adults in favourable habitats (Bakun, 1996). Different systems will have different dynamics, and biological processes, even within species, may be locally adapted. Thus there is a still a need for local study of 'pure' marine biology and physics, before an understanding of the whole system may emerge.

Clupeoids

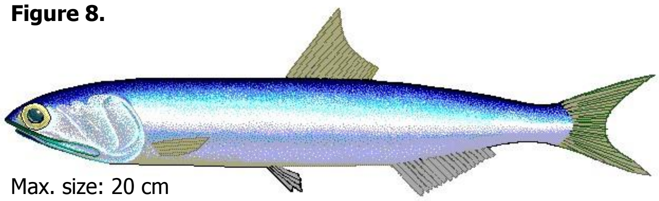
Clupeoid fishes (sardines, anchovies, herring) are found throughout the world's oceans and support commercially important fisheries in all the major eastern boundary upwelling zones. Single species tend to dominate the biomass of such systems, and represent the mid-trophic level 'wasp's waist' populations through which variability in the physical ocean-atmosphere system may affect the dynamics of whole ecosystems (Rice, 1995; Bakun, 1996). In these

classical Ekman-type upwelling systems, annual recruitment of clupeoids has been shown to increase with upwelling intensity until wind speed *w* approximates 5-6 $m.s^{-1}$, decreasing thereafter (Cury & Roy, 1989). A wind speed of 6 $m.s^{-1}$ corresponds to a w^3 index of 216 $m^3.s^3$, and pelagic spawning habitats for clupeoids are generally located where the seasonal average w^3 index is less than 250 m^3s^{-3} (Bakun, 1993).

Cole & McGlade (1998) give a general perspective on clupeoids and their environment. As might be expected, life history characteristics vary between species, although there are common aspects, including serial spawning and early age-at-maturity. Different species have different environmental 'preferences' for successful reproduction; this leads to a direct effect of physical variability on species dominance for any particular area. Fishing pressure adds a significant component to mortality, and by removal of size/age classes increases the vulnerability of the whole population to natural variations in recruitment success. At high levels of spawning stock biomass, density-dependent processes such as cannibalism may also become important, forcing an upper limit on population size.

Peruvian Anchoveta *Engraulis ringens* (Jenyns, 1842)

Figure 8.

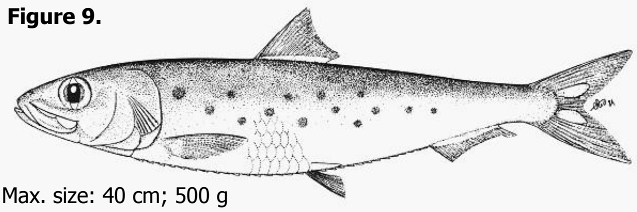


Max. size: 20 cm

The Peruvian anchoveta (Fig. 8) has a subtropical distribution along the western coast of South America, the extent of which depends on the coastal extent of the Peru Current. It is found mainly within 80 km of the coast, and forms huge schools, chiefly in surface waters. This fish is a filter-feeder, entirely dependent on the rich plankton of the Peru Current. In some studies, diatoms constituted as much as 98% of the diet. In turn, large populations of birds depend on this fish.

California pilchard *Sardinops caeruleus* (Girard, 1854)

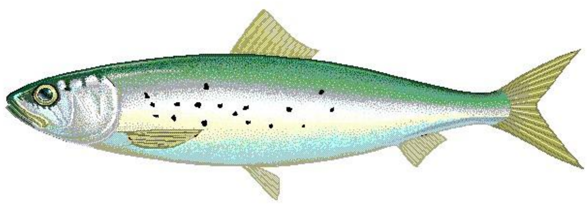
Figure 9.



Max. size: 40 cm; 500 g

The California pilchard (Fig. 9) is a temperate (60°N to 21°N) pelagic coastal species found from southeastern Alaska to Cabo San Lucas, and throughout the Gulf of California. It migrates northward between California and British Columbia in summer and back in autumn or winter. It forms large schools and filter feeds on zooplankton (chiefly small crustaceans) and phytoplankton.

South American pilchard *Sardinops sagax sagax* (Jenyns, 1842)



Max. size: 30.0 cm

The South American pilchard has a subtropical (1°S - 39°N) distribution, and is found in the Peru Current at temperatures from 16° to 23°C in summer and 10° to 18°C in winter. It forms large schools and feeds mainly on planktonic crustaceans.

Cephalopods

World fisheries for cephalopods target cuttlefish, octopods and squid. There is a large fishery for octopus off north-west Africa, but three quarters of the world cephalopod catch is squid. This comes mostly from two families, the flying squid, *Omnastrephidae*, and the inshore squid, *Loliginidae*. In addition to direct exploitation of stocks, commercially important fisheries operate

on other species for which cephalopods are a highly significant prey. Squid themselves prey on zooplankton and micro-nekton and will turn to cannibalism under competition (Karpov & Calliet, 1978). In general, stomach contents of squid reflect the local availability of different food types rather than individual preferences (Okutani, 1983). For many species of cephalopods, basic biological data is sparse, making population models difficult to derive. Fisheries models are also not well suited for short-lived species. However, it is apparent that cephalopods are important components of many marine ecosystems and future research will no doubt address these areas. The main, high biomass populations of omnastrephid squid are associated with the major, permanent western boundary currents of the world's oceans. These rapid current streams are fast-moving and unidirectional and long adult migrations may be necessary to close the habitat loop and return to preferred spawning grounds (*e.g. Illex argentinus*; Rodhouse *et al*, 1995). During these migrations, cannibalism may be essential to maintain the energy reserves of the survivors, in between encounters with patches of food; certainly the squid have to avoid the frontal zones where, even though food concentrations may be higher, the opposing current is likely to be greatest. Many adults are therefore lost due to predation, including cannibalism, and starvation, and the short (usually one year) life cycle may be the natural evolutionary response to such a high energy, high mortality way of life (Bakun & Csirke, 1998). This short life cycle also makes them particularly sensitive to environmental fluctuations, as anomalous temperatures or circulation patterns may have catastrophic consequences for spawning stock biomass, larval survival and recruitment into subsequent populations.

Many species of squid rise from near the seabed at night, descending back to avoid predation during the day (Lipinski & Wrzesinski, 1982). These strategies are exploited by fishing vessels such that bottom trawling is often a daytime activity and squid jigging is carried out at night. The squid fisheries in New Zealand waters are on two species of flying squid: the northern arrow squid, *Nototodarus gouldii* and the southern arrow squid, *Nototodarus sloanii*. The distribution of *N. gouldii* is predominantly confined to sub-tropical water and the distribution of *N. sloanii* is mainly restricted to the sub-tropical convergence zone and sub-Antarctic waters (Smith, 1985). There is a limited amount of mixing near the common boundaries of their distributions, but the two species are normally distinguished on the basis of location alone. This reflects the fact that the two species are most likely adapted to different water temperatures fitting these distributions (Smith *et al*., 1987).

Tunas

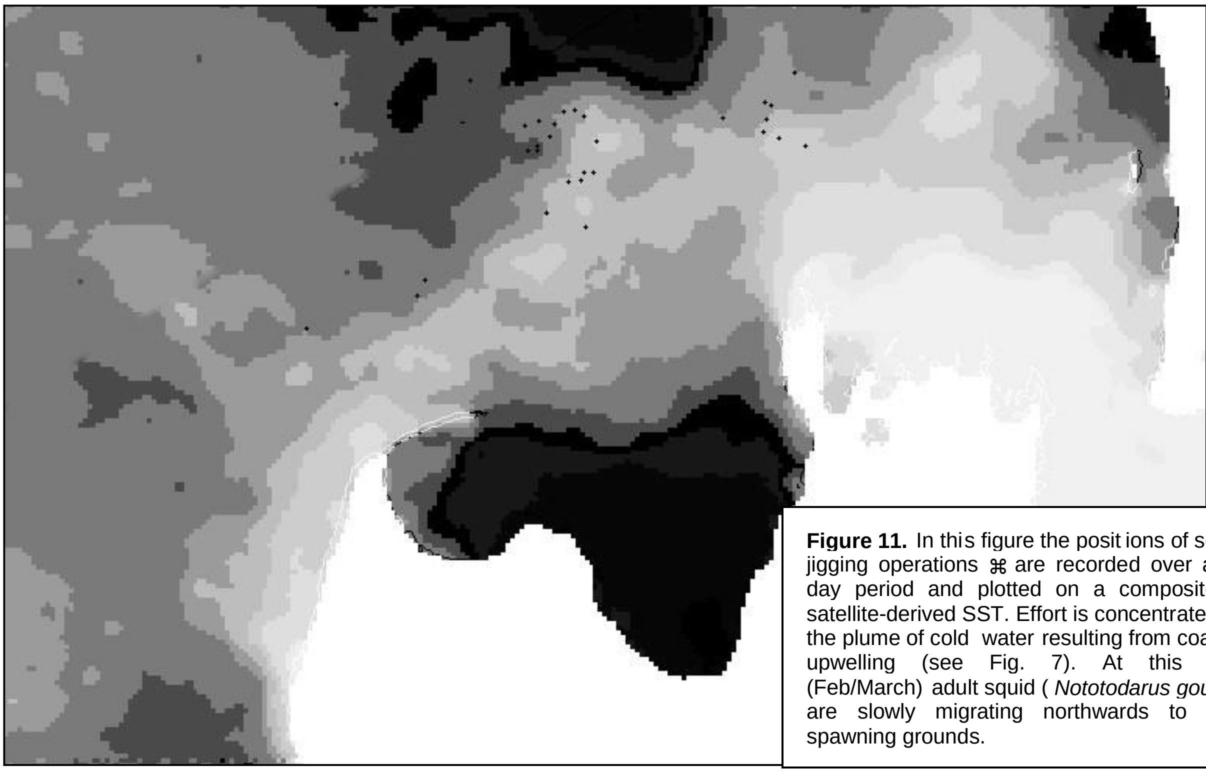


Figure 11. In this figure the positions of squid jigging operations ⌘ are recorded over a 10 day period and plotted on a composite of satellite-derived SST. Effort is concentrated on the plume of cold water resulting from coastal upwelling (see Fig. 7). At this time (Feb/March) adult squid (*Nototodarus gouldii*) are slowly migrating northwards to their spawning grounds.

Tunas (family *Scombridae*, subfamily *Scombrinae*, tribe *Thunnini*) (Klawe, 1977) are found in the surface waters of all the world's oceans, from 40ºN to 40ºS, by volume one of the largest habitats on the planet. They are often highly migratory (Nakamura, 1969) and are well adapted for sustained fast swimming. Tunas also support one of the world's largest commercial fisheries landing roughly 2-3 million tonnes per annum. They have reproductive and growth rates capable of sustaining this high level of fishing mortality, in addition to high natural mortality, even though they are apex predators living in a low energy environment, where food is widely scattered (Blackburn, 1965; Sund *et al*., 1981; Brill, 1996).

The genus *Thunnus* is sub-divided into two main groups, the tropical tunas or *Neothunnus* and the temperate tunas or Bluefin group (Gibbs & Collette, 1967; Collette, 1978). Tropical tunas are more closely associated with warmer latitudes and shallower depths, with ranges limited vertically by the thermocline and horizontally by coastlines and frontal boundaries with colder waters; temperate tunas have higher latitudinal ranges and forage in deeper waters. Tunas are thought to have a common origin as inshore tropical fishes, which through biochemical and morphological adaptations extended their ranges, making themselves less dependent on environmental fluctuations and reducing competition (Sharp *&* Pirages, 1978).

A defining characteristic of tunas is their ability to maintain muscle temperatures above ambient water temperature (Sharp & Vlymen, 1978). There may be several advantages to tunas of warm body temperatures and large thermal inertia. Foraging range may be increased in both horizontal and vertical dimensions, by the ability to maintain body temperature (Neill, Chang & Dizon, 1976; Graham & Deiner, 1978). This facility may also be useful when escaping from predators. Recent reviews (Brill, 1994; 1996) suggest that the high performance physiology of tunas, of which elevated body temperature is a result, has evolved to permit rapid somatic and gonadal growth, rapid digestion, and rapid recovery from exhaustive exercise, all of which are central to success in the pelagic environment.

Tunas are opportunistic and unselective visual predators, feeding on micro-nekton, including epipelagic fish, molluscs and crustaceans, and the larvae of these groups (Blackburn, 1965). The foraging behaviour of tunas includes both upward and downward vertical excursions within the surface waters and below the thermocline, as well as horizontal excursions within the same water mass or into and across frontal boundaries between water masses (Holland *et al*., 1990; Block *et al*., 1997; Brill *et al*., 1999). The extent of these movements outside the warm surface waters is limited by the acute reductions in water temperature that are experienced. Despite the mechanisms of heat conservation that are available to tunas, temperature limitation of foraging range is suggested by laboratory experiment (Dizon *et al*., 1977; Barkley *et al*., 1978; Brill *et al*., 1998) and apparent in field observations (Blackburn, 1965; Sund *et al*., 1981; Brill, 1994; Brill *et al*., 1999).

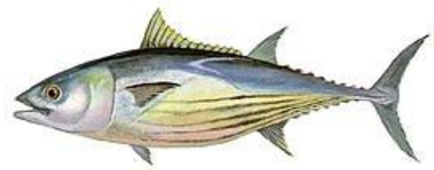
Blackburn (1965) noted that fronts are very important in the ecology of tunas and other pelagic animals, but that the reasons for this were rather poorly understood. Even now there are no datasets that allow a definitive assessment of trophic interactions at fronts, particularly with regard to the behaviour of tunas (Olson *et al*., 1994). Whilst it is generally accepted that tunas aggregate at fronts, presumably to feed (Laurs *et al*., 1984; Fielder *&* Bernard, 1987), field observations do not show for all cases that tunas and their prey are more abundant in or at fronts than in adjacent waters (Sund *et al*., 1981; Power *&* May, 1991).

The reasons why tunas may prefer to aggregate at fronts has been examined in a theoretical modelling exercise (Kirby *et al.,* 2000.). Stochastic dynamic programming (Mangel & Clark, 1988) was used to examine decision making and optimal foraging behaviour in relation to the environment. The results showed that temperature, turbidity, food abundance and food quality will all influence fish behaviour in the vicinity of fronts, as the fish has to trade off expected gains in food consumption from foraging excursions into cold waters, against the cardiac and metabolic stress that such activity causes.

Tropical tunas:

Skipjack *Katsuwonus pelamis* (Linnaeus, 1758)

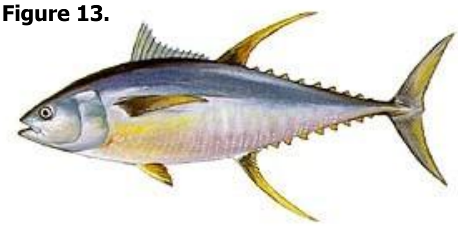
Figure 12.



max. size: 110 cm; max.weight: 35 kg

Skipjack (Fig. 12) are cosmopolitan in tropical and warmtemperate waters (15 - 30°C; 58°S - 47°N) although they are not found in the eastern Mediterranean Sea and the Black Sea. The species is highly mobile, but not necessarily highly migratory (Kearney, 1991). These fish are found in offshore waters, and their larvae are restricted to waters with surface temperatures of at least 25°C. Skipjack exhibit a strong tendency to school in surface waters, and are often found associated with birds, drifting objects, sharks and whales. They feed on fishes, crustaceans, cephalopods and molluscs, and cannibalism is common. In turn they are preyed upon by large pelagic fishes. They are usually fished by purse seine or by trolling.

Figure 13.



max. size: 280cm; max.weight: 200 kg

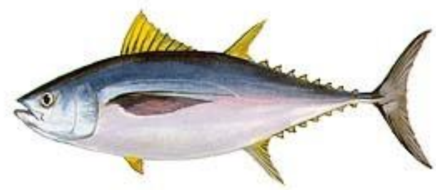
Yellowfin *Thunnus albacares* (Bonnaterre, 1788)

Yellowfin (Fig. 13) have a worldwide distribution in tropical and subtropical seas (15 - 31°C; 45°S - 45°N) but are absent from the Mediterranean. They are a highly migratory oceanic species. They school primarily by size, often in association with floating objects, and larger fish frequently school with porpoises. They are sensitive to low concentrations of oxygen and so are often limited to depths < 200 m. Peak spawning occurs in batches during summer.

Bigeye *Thunnus obesus* (Lowe, 1839)

Bigeye (Figure 14.) are found in tropical and subtropical waters of the Atlantic, Indian and Pacific oceans. Preferred water temperatures range from 13°-29°C, and are optimal between 17° and 22°C. Variation in occurrence is closely related to seasonal and climatic changes in surface temperature and thermocline depth. Juveniles and small adults school at the surface in mono-specific groups or mixed with other tunas, and may be associated with floating objects. Adults stay in deeper waters but may occasionally come to surface waters to thermoregulate. Bigeye are considered to be a Highly Migratory Species and vulnerable to overexploitation.

Figure 14.



max. size: 250 cm; max weight: 210 kg

Temperate tunas (Bluefin group)

Northern bluefin tuna *Thunnus thynnus* (Linnaeus, 1758)

Figure 15.

max. size: 458.0 cm; max.weight: 684 kg

Bluefin (Fig. 15) are highly migratory oceanic fish with a subtropical (70°S - 40°N) distribution. In the Western Atlantic they are found off Canada, and in the Gulf of Mexico (where they spawn) and in Caribbean Sea dowmn to Venezuela and Brazil. In the eastern Atlantic they are found from the Lofoten Islands off Norway to the Canary Islands, including the Mediterranean and the southern part of the Black Sea. They are also reported from Mauritania and there is a subpopulation off South Africa. They school by size, sometimes together with other tunas. They seasonally come closer to shore and can tolerate a wide range of temperatures. They are commercially cultured in Japan, and are utilised fresh for sashimi, but they are also canned.

Northern Bluefin in the Pacific is recognised as a sub-species, *Thunnus thynnus orientalis* Temminck & Schlegel (1844). Distribution in the North Pacific is from the Gulf of Alaska to southern California and Baja California and from Sakhalin Island in the southern Sea of Okhotsk south to northern Philippines. An epipelagic, usually oceanic fish that seasonally comes close to shore, the sub-species migrates between June and September in a northward direction along the coast of Baja California, Mexico and California. There are also some substantiated records

of this subspecies in the southern hemisphere: off Western Australia, New Zealand, in the eastern South Pacific (37°11'S, 114°41'W) and Gulf of Papua.

A single stock of Southern Bluefin Tuna (SBT) *Thunnus maccoyii* Castelnau (1872) inhabits the temperate and cold seas of the Southern Hemisphere, mainly between 30° and 50°S, but to nearly 60°S. It is a highly migratory and critically endangered species. By maturity, most southern bluefin tuna lead an oceanic, pelagic existence but during spawning, large fish (max. size: 245.0 cm; max. weight: 260 kg) migrate to tropical seas up to 10°S, off the north-west coast of Australia, where surface temperatures are between 20° and 30°C. 98% of the global catch is shipped to Japan and consumed as sashimi. Efforts to farm SBT caught by purseseine have been successfully developed in Australia, with production at 4700 tonnes in 1998. **Albacore *Thunnus alalunga* (Bonnaterre, 1788)**

Figure 16.

max. size: 130cm; max. weight: 45kg

Albacore (Fig. 16) are cosmopolitan in the tropical and temperate waters (45°S - 50°N) of all oceans, including the Mediterranean Sea, but are not found at the surface between 10°N and 10°S. A highly migratory epi- and mesopelagic species, they are abundant in surface waters of 15.6° to 19.4°C; deeper swimming, large albacore are found in waters of 13.5° to 25.2°C, although temperatures as low as 9.5°C may be tolerated for short periods. They form mixed schools,
which may be associated with floating objects, including sargassum weeds. Albacore meat is not of sashimi quality but forms the basis of commercial fisheries for canned tuna.

METHODS AND CASE STUDIES IN SPATIAL DATA ANALYSIS AND PREDICTION

"For some obscure reason, fisheries management has become wedded to biomass as the principal measure of resource status…(yet) the key (to sustainability) is to maintain the geographic distributions of each species" (Sharp, 1995).

That global fisheries are in crisis (Pitcher *et al.,* 1998) is largely due to inequities in space (Meaden, 2001). Clearly there is a need for tools to handle the spatial data that satellite remote sensing and other more traditional sea-going survey methods can provide. In this section I have provided some case studies that illustrate how satellite data have been used in fisheries science and I have discussed some relevant data analysis and prediction methods.

Case Studies

Satellite sea surface temperature (SST) data have been available to fishermen in the USA since the mid-1970s and maps of ocean thermal boundaries have been produced using data from the AVHRR sensors on board the NOAA series of satellites. In 1981 NASA and NOAA initiated a two-year fisheries demonstration program where a variety of remotely sensed and numerically simulated data types were collected as 'Fisheries-aid Charts' and faxed or radioed to participating vessels (Montgomery *et al*, 1986). These charts mapped and gave a 5-day outlook for critical SST for selected fish species; surface wind speed and direction, combined wave heights and direction, location of fronts, centres of low and high atmospheric pressure, coastal SSTs, and mixed layer depth. The study concluded that, "...conventional and satellite derived data of the marine environment can, when properly combined and correlated, offer the commercial fisherman tactical tools which can result in the selection of fishing strategies for more efficient and economical operations."

Japan has developed a Fisheries Information Service based on satellite technology (Yamanaka *et al*., 1988). The history of the forecasting service can be traced back to the mid1930's when the Japan Broadcasting Corporation broadcast a fisheries forecast once a week as part of the news report. The present day system divides the forecasting role into two temporal perspectives: short-term forecasting, which considers the immediate ocean physical state and likely effects on fish locations, and long-term forecasting which considers changes in catchability and total fisheries production through the monitoring and estimation of factors such as spawning, larval survival and recruitment. Long-term forecasting is carried out chiefly by the national fisheries research institutes in collaboration with local experimental stations. Short-term

forecasting is carried out by the Japan Fisheries Information Service Centre (JAFIC), a central Government agency, in collaboration with research institutes.

Short-term forecasting is based on the location of ocean fronts, a principle known locally as 'Kitahara's Law' (after Kitahara, 1922, in Yamanaka *et al.,* 1988) which supported the fishermen's premise that fish gather where two different seas converge. Where the warm Kurishio Current from the South Pacific meets the cold Oyashio current from the Kuril Islands, a fishery is supported which produces 15 % of world fish products (Tameishi *et al*., 1993). The predictive system which assists the exploitation of this fishery is based principally around preferred temperatures and temperature gradients for given fish species.

Once the analysis has been carried out, maps of fishing potential are then transmitted to vessels and other subscribers, including research institutes and fishing administrations. The system was applied to SST data from the NOAA satellites and tested against skipjack tuna (*Katsuwonus pelamis*) catch data. For the years 1982-85, fishing potential *F* was positive in 82% of productive fishing grounds and was negative for 94% of unproductive areas. The system may have been developed further since this time but details have not been published.

The tuna, swordfish and sardine fisheries off continental Portugal and the Azores are supported operationally by the University of Lisbon Oceanography Group (Santos & Fiúza, 1992). The operational support consists of the provision of SST charts based on satellite (AVHRR) observations and the annotation of these charts to include gradient analysis for the location of thermal fronts. The group is also investigating the relationships between fish aggregations and the distributions of oceanographic parameters. There is evidence that swordfish concentrate in warm, clear water at intermediate distances from the strong thermal front separating upwelled waters from the open ocean during periods of relaxation in coastal upwelling. Inter-annual variability in swordfish catch is inversely correlated with the strength of coastal upwelling. The reverse is true for bigeye and albacore tuna, which aggregate just seaward of upwelling filaments. The tunas are assumed to aggregate at the fronts in order to feed, as there is evidence that sardines are found in, “moderately cool, relatively ‘old’ upwelling waters,” on the inside of thermal fronts (Santos & Fiúza, 1992).

There has been considerable research into the physical and biological variability of the Upwelling Zone off the coast of North West Africa. There is year-round Ekman upwelling in the major part of this zone with seasonal upwelling to the South dependent on the extent of the northerly winds. This upwelling supports significant fishing grounds for tuna and for many other species of fish, cephalopods and crustacea. Until the 1960s the Spanish fleet was the only foreign fleet in the area but since that time it has been joined by other European and oriental fleets from over 25 countries (Clementé-Colón *et al.,* 1992).

This is certainly a promising area for the application of remote sensing for operational fisheries forecasting. International fleets already direct their effort towards waters that have been advected downstream of their point of origin at the surface, and satellite sensors of both SST and ocean colour could provide useful tools for tracking these waters (Clementé-Colón *et al.,* 1992). The highest Catch per unit effort (CPUE) for skipjack tuna is recorded at upwelling fronts (Ramos *et al.,* 1992). In the Canary Isles, the persistent eddies associated with the island wake behind Gran Canaria can constitute a thermal boundary for further northward movement of skipjack. The fishing ground is compressed by the cold core eddy towards the warmer island wake. As the SST is homogenised, the surface wake extinction determines the spreading of fishing locations around the island (Ramos *et al.,* 1991).

Scientists from the French ‘Scientific Research Institute for Development and Co-operation’ (ORSTOM), supporting French fleets from the South Pacific to the North Atlantic, have developed a variety of forecasting aids with which to assist and direct fishing effort. (Clementé-Colón *et al.,* 1992). In the Eastern Tropical Atlantic, the PREVI-PECHE model (Stretta, 1991) is used. The fishing potential of an area is calculated by comparing the evolution of temperature distribution with an ‘ideal thermal scenario’. SST on the day of catch is not thought to be the sole determinant of tuna distribution; instead the evolution of a water mass over time is considered, with regard to whether it is likely to support concentrations of tuna forage. The delay between the onset of upwelling and the presence of tuna forage has been estimated as about 4-6 weeks (Mendelsshon & Roy, 1986). A high concentration of tuna could therefore be

expected in an area where a decrease in SST at the start of the enrichment process is followed by a regular increase over this time period.

Long term forecasting requires relationships between ocean variables and fish life history characteristics to be identified at larger spatio-temporal scales. Apparent shifts in the distribution of Pacific skipjack tuna may be linked to large zonal displacements of the convergence zone marking the boundary of the western Pacific warm pool (Lehodey *et al*., 1997). These displacements occur during ENSO events and so it should be possible to predict, months in advance, the region of highest skipjack abundance. For the South Atlantic squid (*Illex argentinus*) links between recruitment variability and the environment have recently been examined (Waluda *et al.,* 1999). Correlation analyses show that when temperatures are colder in the spawning grounds of the northern Patagonian shelf during the period of hatching, better catches arise in the fishery in the following season. No significant correlation was obtained between squid catches and SST co-incident with the period of the fishery. Further analysis showed that cross-correlation exists between SST anomalies in the western Pacific and in the spawning grounds of the northern Patagonian shelf after a lag of 4.5 to 5 years. Therefore, not only can year class strength be predicted 8 months in advance from SSTs observed in the spawning grounds, but planning may be enabled some 6 years in advance based on these longer spatio-temporal correlations.

Geographical Information Systems (GIS)

A Geographical Information System (GIS) comprises of a collection of integrated computer hardware and software which together is used for inputting, storing, manipulating, analysing and presenting a variety of geographical data (Meaden & Do Chi, 1996). Some authors include the requirement for trained staff to the definition of a GIS and others add that its primary role is to aid decision making, but it should be recognised that different researchers, policy analysts and decision makers will have different requirements and will develop systems accordingly. The diversity of applications of GIS is seen in this volume, with examples of biological research and statistical modelling (Perez-Marrero *et al.,* Chapter 2) as well as fisheries management (Caddy & Carrocci, Chapter 5). In fact many of the computer-based spatial analyses presented here could be described as GIS (*e.g.* Barbieri *et al*., Chapter 1). What will determine the success or otherwise of a marine fisheries GIS is the extent to which the relevant data can be collected, co-located and displayed in such a way as to enhance understanding beyond that which existed before the exercise. GIS allow user-friendly display of co-registered spatial data. However, further analyses will be required before relationships between variables can be established. This may be possible within a GIS but until recently the capacity of commercial GIS software for complex statistical analysis has been limited. This situation is changing as additional modules for spatial statistical analysis are being created, often by outside research groups. GIS-type software created 'in-house' will obviously be as simple or as sophisticated as its programmers allow. At the National Institute of Water and Atmospheric Research (NIWA), New Zealand, systems originally developed for the analysis of meteorological data have been extended for SST and SSH data analysis, and are presently being used in the development of models for relative fisheries potential, through statistical analyses of CPUE and oceanographic variability. Various actual and potential applications of GIS in fisheries were discussed at the 'First International Symposium on GIS in Fishery Sciences' held from March 2-4, 1999 in Seattle. Many of the case studies presented there utilised remotely sensed data and statistical modelling, and the proceedings should provide a useful resource for researchers in this area.

Theoretical modelling of spatial dynamics

Most operational fisheries forecasting services have adopted a statistical approach to the use of satellite data in fisheries research. This approach seeks to correlate fish distributions with oceanographic features detectable from space and to then make predictions of the probability p of finding species i at position x,y based on the statistical relationships established. Statistical or empirical models are driven by data and for this reason they are specific to the location and the system studied. A good example of this approach is the Japanese Fisheries Information Service described above. It works for the Japanese fisheries because there is a substantial amount of historical data available for analysis and empirical relationships can be derived which have so far seemed to hold. The approach may be adopted in other areas but the statistical relationships that are found to be significant in the Japanese fisheries may not be of relevance elsewhere.

It is extremely difficult to find statistical relationships that hold in highly variable environments (Sharp, 1995). Furthermore, although they may describe relationships well or badly, they cannot be used to show causality (Sharp, 1995; Hilborn & Mangel, 1997). The researcher may use statistical methods to identify relationships between variables but the ultimate questions regarding *why* such relationships exist cannot be answered in this way. Causality may be established through knowledge of specific obligate physiological responses and consequent behavioural decisions in the context of the system as a whole (Sharp, 1995) as well as through research into the life history strategies of the species of interest. This theoretical approach has its emphasis on identifying mechanisms of interaction between organism and environment, allowing cause and effect relationships to be established and used to make predictions that may be better founded than those based on projection of past trends into the future. The level of detail required to develop such process-oriented models is usually high, and simplifications and assumptions have to be made in order to progress. Nevertheless, even simple models can provide a better understanding of the system under study than may be obtained by statistical analyses alone, as they also have explanatory power.

By using altimeter data to compute geostrophic surface currents, larval transport dynamics can be investigated (Polovina, 1999; Chiswell & Booth, 1999). By seeding the circulation with a passive tracer representing the larvae, Chiswell & Booth (1999) are able to conclude that an anticyclonic eddy is responsible for larval retention which may in turn be responsible for maintaining a population of rock lobster (*Jasus edwardsii*) off the New Zealand coast. They also conclude that geostrophic advection alone cannot explain the presence of lobsters at the coast and suggest that larvae may develop swimming capabilities at an earlier stage than has previously been demonstrated. Such a suggestion, whilst speculative, is at least a testable hypothesis generated from the falsification of the earlier advection-based hypothesis, which was enabled by the development of the theoretical model.

Spatially explicit modelling of fish population dynamics has been carried out by various scientists in various ways (*e.g.* Bertignac *et al*., 1998; Huse & Giske, 1998; Sibert *et al*., 1999). As yet the input of remotely sensed data to the models remains limited. The model of Bertignac *et al*. (1998), for the spatial population dynamics of Pacific skipack tuna (*Katsuwonus pelamis*) relies on earlier levels of modelling, covering general circulation (Blanke & Delecluse, 1993), biogeochemistry and new production (Stoens *et al*., 1998) and tuna forage production (Lehodey *et al*., 1998). Satellite data of different types are input at different levels. Weekly wind data from the ERS-1 Scatterometer are used to drive the circulation model; monthly climatological chlorophyll data from the CZCS are assimilated into the new production model. In this way the model as a whole is prognostic for tuna. In a different but complimentary approach the same input data have been used in a spatial lifehistory model also for Pacific Skipjack (Kirby *et al*. unpubl.) which uses adaptive methods to evolve movement and reproduction within the model (i.e. a neural network coupled with a genetic algorithm; Giske et al. 1998).

CONCLUSIONS

We have reached a respectable level in our use of remote sensing data for fisheries but there remains much challenging work to do. Integrated information systems (GIS) will continue to have management and research applications. These spatial databases will enable better understanding of the ecosystems in which fisheries operate. For statistical modelling to succeed it must be carried out in a way that is sensitive to the ecology of the species of interest. Statistical relationships that are useful for forecasting may only be obtained if life history stages that are vulnerable to or influenced by environmental effects are first identified.

There exist functional tools for modelling fish behaviour and life histories, based on proximate and ultimate models of their interactions with the physical oceanic environment (Giske *et al.*, 1998). These methods that have yet to be applied to fisheries forecasting using remote sensing but they clearly represent a possible way forward. Physical variables measurable from space represent habitat characteristics that may be very important for one or more life stage of fish. Value is added to oceanographic feature detection if we understand the mechanism through which such a feature interacts with the fish, as well as its statistical significance to past, present or future biomass or distribution. Spatially explicit methods for modelling whole life histories of fish (Fiksen *et al*., 1995; Huse & Giske, 1998; Huse, *in press*) should be coupled with state-of-the-art dynamical models, with particular attention paid to representation of trophic dynamics and bio-physical interactions. The use of theoretical modelling in relation to fish tagging studies

has been discussed in Kirby (2001). Satellite data can play several roles: forcing the dynamics, assimilation into primary productivity, feature detection and instantaneous habitat characterisation (*e.g.* by temperature, turbidity, wind and current).

Another important issue is that of technology transfer (Hammann & Cárdenas, 1996; Barbieri *et al*., Chapter 1) *i.e.* the problem of utilising space technology and remotely sensed data to support not just large-scale commercial fisheries but also artisanal, community-based fishing. Gary Sharp (http://faculty.csumb.edu/SharpGary/world/Phyllo1.html) describes the present day fishers of Scylla, Italy where: “These ancient/modern people continue to struggle with the sea, even today, as they have harvested the seasonal migrants, tunas and swordfish, each summer for at least two thousand years... using tall "antenna" towers from which the ships are guided, and from which they sight fish...” Contrary to his own feelings that: “It seems highly unlikely that The Internet will have a great immediate effect on traditional cultures;” I believe that as a low-cost global communications medium that is comparatively easy to set up and use, the internet could have a very significant impact. Developing nations and traditional communities will doubtless adapt this technology to their needs. The value of information for fishing and fisheries science is unquestioned and the Internet will be the primary tool in the new millennium for dissemination of this information. Whilst the cost of developing space technology has been borne by richer economies, it is possible for other nations to obtain and utilise these data for their own purposes. Ship-borne satellite-based communication systems will be available to commercial vessels but shore-based systems may also be established to support fishing communities in rural areas. The demand and utility of such services should be identified locally and international co-operation might bring about their implementation. Hopefully this module will show just what can be achieved by bringing together technology and an understanding of nature, and future applications will be developed that will harness such knowledge for the benefit of humanity without further detriment to our environment.

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References

*Essential and #Recommended reading

*Bakun, A. (1996) Patterns in the Ocean: Ocean Processes and Marine Population Dynamics. California Sea Grant. 323pp.

Bakun, A. (1993) The California Current, Benguela Current, and Southwestern Atlantic Shelf Ecosystems: A comparative approach to identifying factors regulating biomass yields. Pp. 199–224. *In* K. Sherman, M. Alexander and B. Gold (eds.).

Bakun, A. & J. Csirke (1998) Environmental processes and recruitment variability. *In* P.G. Rodhouse, E.G. Daw & R.K. O’Dor (eds.) Squid recruitment dynamics: The genus *Ilex* as a model, the commercial *Ilex* species and influences on variability. *FAO Fisheries Technical Paper* 376. 273pp.

Barkley, R.A., W.H. Neill & R.M. Gooding (1978) Skipjack tuna, *Katsuwonus pelamis*, habitat based on temperature and oxygen requirements. *Fish. Bull.* **76**(3): 653-662.

Bertignac, M., P. Lehodey & J. Hampton (1998) A spatial population dynamics simulation model of tropical tunas using a habitat index based on environmental parameters. *Fisheries Oceanography* **7:**3/4, 326–335.

Blackburn, M. (1962) *U.S. Fish. Wildl. Serv. Spec. Sci. Rep. Fish.,* No. 404, 28pp.

Blackburn, M. (1963) *F.A.O. Fish. Rep.,* No. 6, 3, pp.1557–1582.
#Blackburn, M. (1965) Oceanography and the ecology of tunas. *Oceanography and Marine Biology: An Annual Review* 3, 299–322.

Blanke, B. and Delecluse P. (1993) variability of the tropical Atlantic Ocean simulated by a general circulation model with two different mixed-layer physics. *Journal of Physical Oceanography* **23:** 1363–1388.

Block, B.A., J.E. Keen, B. Castillo, H. Dewar, E.V. Freund, D.J. Marcinek, R.W. Brill, & C. Farwell (1997) Environmental preferences of yellowfin tuna (*Thunnus albacares*) at the northern extent of its range. *Marine Biology* **130**: 119-132.

Bowman, M.J., S.M. Chiswell, P.L. Lapennas, R.A. Murtagh, B.A. Foster, V. Wilkinson & W. Battaerd (1983) Coastal upwelling, cyclogenesis and squid fishing near Cape Farewell, New Zealand. pp.279–310 *In* Gade, H.G., A. Edwards and H. Svendsen (eds.) *Coastal Oceanography*. NATO Conference Series IV:11. 582pp.

Brill, R.W. (1994) A review of temperature and oxygen tolerance studies of tunas pertinent to fisheries oceanography, movement models and stock assessments. *Fisheries Oceanography* **3:**3, 204–216.

Brill, R.W. (1996) Selective advantages conferred by the high performance physiology of tunas, billfishes and dolphin fish. *Comparative Biochemistry & Physiology.* **113A**: 3-15.

Brill, R.W., T.E. Lowe, & K.L. Cousins (1998) *How water temperature really limits the vertical movements of tunas and billfishes - it's the heart stupid!* American Fisheries Society, International Congress on Biology of Fish, Towson University, Baltimore, MD. URL: http://www.soest.hawaii.edu/PFRP/brill_afs.pdf

Brill, R.W., B.A. Block, C.H. Boggs, K.A. Bigelow, E.V. Freund & D.J. Marcinek (1999) Horizontal movements and depth distribution of large adult yellowfin tuna (*Thunnus albacares*) near the Hawaiian Islands recorded using ultrasonic telemetry: implications for the physiological ecology of pelagic fishes. *Marine Biology* **133:** 395-408

Chiswell, S.M. and J.D. Booth (1999) Rock lobster *Jasus edwardsii* larval retention by the Wairapa Eddy off New Zealand. *Marine Ecology Progress Series* **183**: 227–240.

Clemente-Colon, P., J.B. Zaitzeff & O. Llinas (1992) Satellite Upwelling Observations and Fisheries Resources of the North West African Regions. Proceedings of the International Symposium on Evaluation of Natural Resources with Remote Sensing Techniques. 7–9 October 1992, Rabat, Morocco.

Cole J. & J. McGlade (1998) Clupeoid population variability, the environment and satellite imagery in coastal upwelling systems. *Reviews in Fish Biology and Fisheries* **8**, 445-471.

Collette, B.B. (1978) Adaptations and Systematics of the Mackerels and Tunas. In: *The Physiological Ecology of Tunas*. G.D. Sharp and A.E. Dizon (Eds.) New York: Academic Press, pp. 7-40.

Cook, RM, A. Sinclair & G. Stefansson (1997) Potential collapse of North Sea cod stocks. *Nature* **385**, 521-522

#Cury, P. & C. Roy (1989) Optimal environmental window an pelagic fish recruitment success in upwelling areas. *Can. J. Fish. Aquat. Sci.* 51:1664–1673.

Dizon, A.E., W.H. Neill & J.J. Magnuson (1977) Rapid temperature compensation of volitional swimming speeds and lethal temperatures in tropical tunas (Scombridae). *Environmental Biology of Fishes* **2**: 83-92.

FAO (1997) Review of the state of world fishery resources: marine fisheries. FAO Fisheries Circular. No. 920. Rome, FAO. 1997. 173 p.

Fielder, P. & H. Bernard (1987) Tuna aggregation and feeding near fronts observed in satellite imagery. *Continental Shelf Research* **7**: 871-881.

Fiksen, Ø. (1998) Modelling the influence of light, turbulence and ontogeny on ingestion rates in larval cod and herring. *Fisheries Oceanography* **7:**3/4, 355-363.

Fiksen, Ø., J. Giske & D. Slagstad (1995) A spatially explicit fitness-based model of capelin migrations in the Barents Sea. *Fisheries Oceanography* **4:**3, 193–208.

Gibbs, R.H. & B.B. Collette (1967) Comparative anatomy and systematics of the tunas, genus *Thunnus. Fisheries Bulletin* **66**: 65-130.

Giske, J., G. Huse & Ø. Fiksen (1998) Modelling spatial dynamics of fish. *Reviews in Fish Biology & Fisheries* **8,** 57–91.

Graham, J.B. & D.R. Deiner (1978) Comparative Morphology of the Central Heat Exchangers in the Skipjacks *Katsuwonus* and *Euthynnus. In* .G.D. Sharp & A.E. Dizon (eds.) The Physiological Ecology of Tunas. Academic Press, New York. pp. 113–134.

Hammann M.G. & T. Cárdenas (1996) The utilisation of satellite data to support fishery activities in Africa's coastal waters. 1996 Seminar Series of the United Nations Space Applications Programme. Vol. 7

Hilborn, R. & M. Mangel (1997) The Ecological Detective: confronting models with data. Princeton University Press, Princeton, New Jersey, 315 pp.

Holland, K.N., Brill, R.W. and Chang, R.K.C. (1990) Horizontal and vertical movements of Yellowfin and Bigeye tuna associated with fish aggregating devices. *Fisheries Bulletin* **88**: 493-507.

Huse G. (*in press*) A spatial life history model of the Barents' Sea capelin. *Sarsia*

Huse G. & J. Giske (1998) Ecology in Mare Pentium: An individual-based spatio-temporal model for fish with adapted behaviour. *Fisheries Research* **37:**1–3, 163–178.

Karpov, K.A. & G.M. Calliet (1978) The feeding dynamics of *Loligo opalescens. In* C. Recksiek & H.W. Frey (eds.) Biological, oceanographic and acoustic aspects of market squid, *Loligo opalescens* Berry. *California Fish and Game Fisheries Bulletin No. 169.* 185 pp.

Kawasaki, T. and M. Omori (1995) Impacts of climate change on the Japanese fisheries. pp. 523–528 *In* R.J. Beamish (ed.). Climate Change and Northern Fish Populations. *Can. Spec. Pub. Fish. Aquat. Sci.* 121. 739pp.

Kearney, R.E. (1991) Extremes in fish biology, population dynamics and fisheries management: Pacific skipjack and southern bluefin tuna. *Reviews in Aquatic Science,* **4**(2 – 3):289–298.

#Kirby DS (2001) On the integrated study of tuna behaviour and spatial dynamics: tagging and modelling as complementary tools. In: Sibert JR, Nielsen J (eds) Electronic tagging and tracking in marine fisheries. Kluwer Academic Publishers, The Netherlands, 407–420

#Kirby, D.S., Ø. Fiksen and P.J.B. Hart. (2000) A dynamic optimisation model for the behaviour of tunas at ocean fronts. *Fisheries Oceanography* 9(4): 328–342

Kirby, D.S., E.D. Barton, E.G. Mitchelson-Jacob and A. Trasviña (1997) Synthetic Aperture Radar (SAR) Remote Sensing of Wind-driven Circulation in the Gulf of Tehuantepec, Mexico. *Proc. 3rd ERS Symp. on* **Space at the service of our Environment,** *Florence, Italy, 17-21 March 1997* (ESA SP-414, 3 Vols., May 1997)
URL: http://earth1.esrin.esa.it/florence/participants/data/kirby/index.html

Klawe, W.L. (1977) What is a tuna? *Mar. Fish. Rev.* **39**(11): 1-5.

#Laurs, R.M., Fielder, P.C. and Montgomery, D.R. (1984) Albacore tuna catch distributions relative to environmental features observed from satellites. *Deep Sea Research* **31**(9): 10851099.

Lehodey, P., M. Bertignac, J. Hampton, A. Lewis and J. Picaut (1997) El Niño Southern Oscillation and tuna in the western Pacific. *Nature* **389**: 715–718.

Lehodey, P., J.-M Andre, M. Bertignac, J. Hampton, A. Stoens, C. Menkes, L. Memery & N. Grima (1998) Predicting skipjack tuna forage distributions in the equatorial Pacific using a coupled dynamical bio-geochemical model. *Fisheries Oceanography* **7:** 3/4, 317–325.

Lipinski M. & O. Wrzesinski (1982) Some observations on the behaviour of squid (*Cephalopoda*: *Omnastrephidae*) during jigging operations. Proceedings of the International Squid Symposium, August 9–12, 1981, Boston, Massachusetts. pp137–144. New England Fisheries Development Foundation Inc., New York.

Mangel, M. & C.W. Clark (1988) Dynamic Modeling in Behavioural Ecology. *Monographs in Behaviour and Ecology*, J.R. Krebs & T. Clutton-Brock (eds.) Princeton University Press, New Jersey. 308 pp.

Meaden, G.J. (2001) GIS in fisheries science: foundations for the new millenium. Proceedings of the First International Symposium on GIS in Fishery Sciences, March 2–4, Seattle, Washington, USA.

Meaden, G.J. (1996) Geographical information systems: applications to marine fisheries. *FAO Fisheries Technical Paper* **356**, FAO, Rome. pp335.

Mendelsshon, R. & C. Roy (1986) Environmental influences on the F.I.S.M. tuna catches in the Gulf of Guinea. Proceedings of the ICCAT Conference on the International Skipjack Program. 21–29 June 1983, Islas Canarias, Spain.

Montgomery, D. R., R.E. Wittenberg-Fay & R. W. Austin (1986) The application of satellitederived ocean colour products to commercial fishing operations. *Marine Technology Society Journal* **20**: 72–86

Nakamura, H. (1969) Tuna distribution and migration. Fishing News Books Ltd., London.

Neill, W.H., R.K.C. Chang & A. Dizon (1976) Magnitude and ecological implications of thermal inertia in skipjack tuna, *Katsuwonus pelamis* (Linnaeus). *Environmental Biology of Fishes* **1**: 61-80.

Okutani, T. (1983) *Todarodes pacificus. In* Boyle, P.R. (ed.) Cephalopod life cycles, Vol. 1: Species accounts, pp.201–214. Academic Press, London.

Olson, D. B., G.L. Hitchcock, A.J. Mariano, C.J. Ashjian, G. Peng, R.W. Nero & G.P. Podestá (1994) Life on the edge: marine life and fronts. *Oceanography* **7:** 2, 52-60.

Pauly, D., P.J.B. Hart & T. Pitcher (1998) Speaking for themselves: new acts, new actors and a New Deal in a reinvented fisheries management. pp. 409–415 *In* T. Pitcher, P.J.B. Hart & D. Pauly (eds.). Reinventing Fisheries Management. Kluwer Academic Publishers Fish and Fisheries Series 23, 435pp

#Pitcher, T., P.J.B. Hart & D. Pauly (1998) Reinventing Fisheries Management. Kluwer Academic Publishers, Fish and Fisheries Series **23**, 435pp.

Polovina, J., P. Kleiber & D.R. Kobayashi (1999) Application of TOPEX-POSEIDON satellite altimetry to simulate transport dynamics of larvae of spiny lobster, *Panulirus marginatus*, in the Northwestern Hawaiian Islands, 1993–1996. *Fisheries Bulletin* **97**: 132–143.

Power, J.H. & L.N. May (1991) Satellite observed Sea-surface Temperatures and Yellowfin Tuna Catch and Effort in the Gulf of Mexico. *Fisheries Bulletin.* **89**(3): 429-439.

Ramos, A., P. Sangra, A. Hernandez-Guerra, & M. Canton (1991) Large and small scale relationships between skipjack tuna (*Katsuwonas pelamis* Linnaeus 1758) and oceanographic features observed from satellite imagery in the Canary Islands area. Proceedings of the ICES 79th Statutory Meeting.

Ramos, A., Canton, M., and A. Hernandez (1992) Large and small scale relationships between skipjack tuna (Katsuwonus pelamis) and oceanographic features observed from satellite imagery. Proceedings of the Evaluation of Natural Resources with Remote Sensing Techniques. 07-09 October, 1992, Rabat, Morocco.

Raver, D. Jr (1984) Fisherman's guide to fishes of the southeastern United States. NC State Museum of Natural History, Raleigh, NC

Rice, J. (1995) Food web theory, marine food webs, and what climate change may do to northern marine fish populations. pp. 561–568. *In* R.J. Beamish (ed.). Climate Change and Northern Fish Populations. *Can. Spec. Pub. Fish. Aquat. Sci.* 121. 739pp.

Rodhouse, P.G., J. Barton, E.M.C. Hatfield & C. Symon (1995) *Ilex argentinu*s: life cycle, population structure and fishery. ICES Marine Science Symposium 199:425–432.

Santos, A.M.P. & F.G. Fiuza (1992) Supporting the Portuguese fisheries with Satellites. Proceedings of the Central Symposium of the 'International Space Year' Conference. 30 March – 04 April 1992, Munich, Germany.

Sharp, G. URL: http://faculty.csumb.edu/SharpGary/world/Phyllo1.html

Sharp, G.D. & S.W. Pirages (1978) The Distribution of Red and White Swimming Muscles, Their Biochemistry, and the Biochemical Phylogeny of Selected Scombrid Fishes. *In* .G.D. Sharp & A.E. Dizon (eds.) The Physiological Ecology of Tunas. Academic Press, New York. pp. 41–78.

Sharp, G.D. & W.J. Vlymen (1978) The Relation between Heat Generation, Conservation and the Swimming Energetics of Tunas*. In* .G.D. Sharp & A.E. Dizon (eds.) The Physiological Ecology of Tunas. Academic Press, New York. pp. 213–232.

Sharp, G.D. (1995) It's about time: new beginnings and old good ideas in fisheries science. *Fisheries Oceanography* **4**,4: 324–341.

Sibert, J.R., J. Hampton, D.A. Fournier & P.J. Bills (1999) An advection-diffusion-reaction model for the estimation of fish movement parameters from tagging data, with application to skipjack tuna (*Katsuwonus pelamis*). *Canadian Journal of Fisheries & Aquatic Sciences*, **56:** 6, 925-938.

Smith, P.J. (1985) Distribution of two species of arrow squid (*Nototodarus*) around New Zealand. *Fisheries Research Division Occasional Publication No. 49.* 14pp.

Smith, P.J., R.H. Mattlin, M.A. Roeleveld & T. Okutani (1987) Arrow squids of the genus *Nototodarus* in New Zealand waters: systematics, biology and fisheries. *N.Z. Journal of Marine and Freshwater Research* **21**, 315–326.

Stoens A., C. Menkes, Y. Dandonneau & L. Memery (1998) New production in the equatorial Pacific: a coupled dynamical- biogeochemical model. *Fisheries Oceanography* **7:**3-4, 311-316.

Stretta, J.-M. (1991) Forecasting models for tuna fishery with aerospatial remote sensing. *International Journal of Remote Sensing* **12:** 4, 771–779.

#Sund, P.N., Blackburn, M. and Wiliams, F. (1981) Tunas and their environment in the Pacific Ocean: a review. *Oceanogr. Mar. Biol. Ann. Rev.* **19**: 443-512.

Tameishi, H., K. Saitoh, & T. Sugimoto (1993) Application of satellite imagery for Japanese fisheries. *In* Jones, Sugimori & Stewart (eds.) Satellite Remote Sensing of the Oceanic Environment Seibutsu Kenkyusha, Tokyo.

Uddstrom, M.J. & N.A. Oien (1999) On the use of high-resolution satellite data to describe the spatial and temporal variability of sea surface temperatures in the New Zealand region. *Journal of Geophysical Research* **104:**C9, 20,729–20,751.

Waluda, C.N., P.N. Tratham & P.G. Rodhouse 1999) Influence of oceanographic variability on recruitment in the *Illex argentinus* (Cephalopoda: Omnastrephidae) fishery in the South Atlantic. *Marine Ecology Progress Series* **183**: 159–167.

Yamanaka, I., S. Ito, K. Niwa, R. Tanake, Y. Yabuta, & S. Chikuni (1988) *The Fisheries Forecasting System in Japan for Coastal Pelagic Fish.* FAO Fisheries Technical Paper **301** FAO, Rome.

Table 1. Satellites carrying sensors relevant to fisheries research and application

Current Satellites *launch date 2002	Relevant Sensors
ERS 2	ATSR SAR RA
NOAA 12/14/15	AVHRR
TOPEX/POSEIDON	RA
ORBVIEW 2	SeaWiFS
ENVISAT	AATSR ASAR RA
EOS AM-1 (TERRA) & *PM1 (AQUA)	MODIS
*ADEOS II	AMSR GLI SeaWinds

APPENDIX I. LIST OF ACRONYMS

(A)ATSR	(Advanced) Along Track Scanning Radiometer
ADEOS	Advanced Earth Observation Satellite
AMSR	Advanced Microwave Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
(A)SAR	(Advanced) Synthetic Aperture Radar
BAS	British Antarctic Survey
CZCS	Coastal Zone Colour Scanner
DMSP	Defence Meteorological Satellite Program, USA.
ENVISAT	Environmental Satellite, Europe.
EOS	NASA Earth Observing System satellites EOS-AM (TERRA) and EOSPM AQUA
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESRI	Environmental Systems Research Institute, Inc. (manufacturers of ARCINFO & ARCVIEW GIS Software)
GFO	GEOSAT (Geodesy Satellite) Follow-On

GIS	Geographic Information System
GLI	Global Imager
JAFIC	Catch Per Unit Effort
MERIS	Medium Resolution Imaging Spectrometer
NASA	National Aeronautic and Space Administration, USA.
NASDA	National Space Development Agency, Japan.
NOAA	National Oceanic and Atmospheric Administration, USA.
RA	Radar Altimeter
RADARSAT	Radar Satellite
SeaWiFS	Sea-viewing Wide Field of view Sensor
SeaWinds	Wind Scatterometer
SSM/I	Special Sensor Microwave / Imager
SST	Sea Surface Temperature
TRMM	Tropical Rainfall Measuring Mission
TOPEX/POSEIDON	Topographical Experiment (POSEIDON satellite)

Appendix II. Useful Web Links

<u>Satellites and Sensors</u>

AVHRR

http://www.ngdc.noaa.gov/seg/globsys/avhrr.shtml	AVHRR Sensor Overview
http://podaac.jpl.nasa.gov/sst/	AVHRR Oceans Pathfinder Dataset

ATSR

http://earth.esa.int/ers/eeo4.80	ATSR Sensor Information, European Space Agency
http://www.atsr.rl.ac.uk/	ATSR Science Group, Rutherford Appleton Laboratory, UK
http://www.leos.le.ac.uk/home/	Earth Observation Science Group, University of Leicester, UK.

Ocean Colour Sensors

http://seawifs.gsfc.nasa.gov/SEAWIFS.html	SeaWiFS Project Homepage (includes CZCS information) Goddard Space Flight Centre, USA.
http://envisat.esa.int/	MERIS Sensor Information European Space Agency
http://eos-pm.gsfc.nasa.gov/ http://eos-am.gsfc.nasa.gov/	EOS satellite and MODIS sensor information

Other

http://www.ssmi.com/	SSM/I, TMI and QuikScat data
http://topex-www.jpl.nasa.gov/ http://podaac.jpl.nasa.gov/topex/	TOPEX-Poseidon information and data
http://www.asf.alaska.edu/user_serv/user_serv/sar_data_sources.html	List of SAR data providers

Institutions involved in Remote Sensing for Fisheries Applications

http://me-www.jrc.it/	Marine Environment Unit, Space Applications Institute, Joint Research Centre of the European Commission, Ispra, Italy.
http://www.fao.org/fi/	Fisheries Department, Food and Agriculture Organisation of the United Nations, Rome, Italy.
http://www.nrsc.no/	Nansen Environmental and Remote Sensing Centre, Bergen, Norway.
http://www.orstom.fr/	Scientific Research Institute for Development and Cooperation (ORSTOM), France.
http://www.spc.int/OceanFish/index.html	Secretariat of the Pacific Community, Oceanic Fisheries Programme, New Caledonia.
http://www.pml.ac.uk/	Centre for Coastal Marine Sciences, Plymouth Marine Laboratory, UK.
http://www.soest.hawaii.edu/PFRP/	Pelagic Fisheries Research Program*…and the…*
http://www.satlab.hawaii.edu/	Satellite Oceanography Laboratory*…at the…*School of Ocean and Earth Science and Technology , University of Hawaii, USA.