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An application of satellite-derived sea surface temperatures to southern bluefin tuna and albacore off Tasmania, Australia*

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SUMMARY: This paper examines the relationship between thermal features from satellite imagery and reported catches of tuna off eastern Tasmania. The satellite data is in the form of sea surface temperature (SST) obtained from a National Oceanic and Atmospheric Administration (NOAA) satellite using an Advanced Very High Resolution Radiometer (AVHRR) sensor. The fishery data is the catch of southern bluefin tuna and albacore for the Japanese longline tuna fishery off the Tasmanian coast. The winter fishing seasons for May to July 1991 and 1992 are considered in detail. The study focuses on the relationship between southern bluefin tuna and albacore and the occurrence of warm core eddies and thermal fronts. In 1991 a persistent mesoscale eddy was observed using the NOAA-11/AVHRR infrared data. In 1992 there was no similar eddy structure but a strong thermal front occurred. Southern bluefin tuna and albacore catches tend to occur at the location of the eddy and thermal fronts. An algorithm that identifies the edges of thermal fronts proved to be a good predictor of the location of productive fishing areas.

Key words: Satellite remote sensing, sea surface temperatures, fisheries, southern bluefin tuna, albacore, eddies, thermal fronts and edge detection.

RESUMEN: UNA APLICACIÓN DE LA TEMPERATURA SUPERFICIAL DEL MAR OBTENIDA VÍA SATÉLITE AL ATÚN DEL SUR Y A LA ABACORA DE TASMANIA, AUSTRALIA. – En este trabajo se examina la relación entre las características térmicas obtenidas a partir de imágenes de satélite y las capturas de atún en este de Tasmania. La información procedente de los satélites es en forma de datos de temperatura de la superficie del mar (SST) obtenida a partir de un satélite de la National Oceanic and Atmospheric Administration (NOAA) usando un sensor radiómetro avanzado de muy alta resolución (AVHRR). Los datos de pesca corresponden a las capturas de palangreros japoneses de atún del sur y albacora en en aguas de Tasmania, se consideran en detalle las estaciones de pesca invernal de Mayo a Julio de 1991 y 1992. El estudio se centra en la relación entre el atún del sur y la albacora y la ocurrencia de remolinos cálidos y frentes térmicos. En 1991 se observó un persistente remolino mesoescalar usando los datos infrarrojos del NOAA-11/AVHRR. En 1992 no se observó un remolino similar pero sí un fuerte frente térmico. Las capturas de atún del sur y albacora tienden a tener lugar en donde se sitúan el remolino y los frentes térmicos. Un algoritmo que identifica los límites del frente térmico probó ser un buen método de predecir la localización de áreas de pesca productiva.

Palabras clave: Sensores remotos, temperatura superficial del mar, pesquerías, atún del sur, albacora, remolinos, frentes térmicos y detección de límites.

INTRODUCTION

Remote sensing of the ocean is playing an increasingly important role in fishery research and fishing operations. Satellites provide a unique view of the ocean by covering large areas synoptically and are particularly useful in historically data-poor areas. However, NOAA-11/AVHRR satellite measurements are limited to the surface or near-surface layers in cloud-free areas. Therefore, satellite data complement conventional shipboard observations and the best research approach requires close coor-

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dination of the two sources of information. In this way, the evolving capabilities of satellite remote sensing are providing a powerful tool to enhance the efficient use of living marine resources.

The promise of remote sensing techniques for fisheries research, management, and exploitation has been recognised since the early 1960s when the first visible and infrared images of the earth's surface were obtained from orbit. FIUZA (1990) has recently reviewed oceanographic, meteorological, chemical and biological parameters of interest for fisheries research and fishing operations, as well as the pertinent capabilities of satellite remote sensors. LAURS and BRUCKS (1985) review fisheries applications of satellite oceanic remote sensing in USA. Examples of recent and potential uses of satellite imagery in eastern North Pacific Ocean fisheries are given in FIEDLER *et al.* (1985). YAMANAKA (1982) describes the utilisation of satellite imagery in Japanese fisheries. GOWER (1982) gives an overview of the different kinds of remote sensing data relevant to fisheries science and oceanography and MONTGOMERY (1981) discusses the utility of satellite imagery to ocean industries, including fisheries.

MAUL *et al.* (1984) used satellite imagery to compare SST with Atlantic bluefin tuna (*Thunnus thynnus thynnus*) catches reported by the Japanese longline fishery that operated in the Gulf of Mexico during 1979 and 1980. Satellite infrared imagery using NOAA satellite was used by LASKER *et al.* (1981) for describing ocean processes in relation to spawning of the northern anchovy *Engraulis mordax*. The distribution and availability of albacore catches off the west coast of the United States have been related to SST oceanic fronts seen in AVHRR infrared imagery by LAURS *et al.* (1984). These authors speculated that the distribution of albacore in these waters was related to feeding activity.

The water temperature is a major environmental factor determining the distribution and abundance of marine organisms. Some fish respond to extremely small changes in temperature. However, the way in which fish are physiologically affected by changes in temperature and how they respond to these changes are undoubtedly complex and varied. Although some fish show temperature preferences, free-swimming fish in their search for food may be found in waters where temperatures are marginally acceptable (BREAKER 1981). Based on the dependence of fish on temperature regimes, LASKER *et al.* (1981) linked the location of spawning grounds of certain species with the temperature regimes in oceanic waters. According to LYNE *et al.* (1992) the association of fish schools with preferred SST is a well known phenomenon that is exploited by fishermen. Large and commercially important pelagic fish such as tuna are thought to respond to increased food concentrations or other favourable conditions by aggregating in frontal regions (ALVERSON 1961, BREADSELY 1969, FIEDLER and BERNARD 1987, KLIMLEY and BUTLER 1988, LAURS *et al.* 1984, MAUL *et al.* 1984). Fishermen off the north west coast of the USA and Canada have long believed that fishing near thermal or colour fronts increase fishing success, and sometimes they refer to favourable waters as "tuna water" (ALVERSON 1961). The expression "tuna water" refers to the typical deep blue oceanic water having surface temperature equal to or greater than 14.4°C (58°F). Thermal fronts are often detectable using the AVHRR aboard NOAA series of satellites to determine SST from which horizontal SST gradients may be derived. SSTs change rapidly across fronts resulting in higher SST gradient values than in areas away from the fronts.

Oceanic fronts or "siome" as they are referred to by Japanese fishermen are very important as indicators of fishing localities (UDA 1959). An oceanic front is loosely defined as a boundary separating two water masses. Temperature and salinity may change across an oceanic front. In some cases, temperature and salinity change in such a way that little or no change in density occurs. Since temperature is important in determining the density of sea water, thermal discontinuities are usually accompanied by discontinuities in density. Infrared satellite images often indicate thermal gradients or fronts.

South-eastern Tasmania is subjected to considerable periods of strong westerly winds. The westerly winds characteristically blow with a pattern of a few days of strong winds followed by a few days of calm as the atmospheric highs and lows pass over Tasmania. Periods of increased winds in south-eastern Tasmanian coastal waters lead to subsequent increase in phytoplankton biomass. CLEMENTSON *et al.* (1989) showed that periods of increased westerly wind stress interacted strongly with the seasonal stratification of the water column and caused increased mixing. This led to periodic incursions of nitrate into south-eastern Tasmanian surface waters in summer during windy years. There is a close link between climate and the fisheries in these waters (HARRIS *et al.* 1991) similar to that found in many other parts of the world (CUSHING 1982). The oceanic circulation off Tasmania is further complicated by the influence of the East Australian Current and the Leeuwin Current.

The purpose of this paper is to investigate the dependence of the fish catch on the oceanic thermal structure. We utilised satellite imagery to compare SST with southern bluefin tuna (*Thunnus maccoyii*) and albacore catches reported by the Japanese longline fishery that operated in eastern Tasmanian waters during 1991 and 1992. The southern bluefin tuna and albacore fishery in this region began in early 1950s (SHINGU 1978) and takes place each year from May to July (winter) and from October to December (summer).

METHODS

There are four primary components to the study

*acquisition, validation and summarisation of the seasonal and spatial patterns in the longline fishery catch and effort data,
*development of satellite images and description of the seasonal and spatial patterns in SST,
*investigation of any associations between the two data sets and
*development of an edge detection algorithm.

Data on longline sets were acquired from the Japanese longline logbook records compiled by the Bureau of Resource Sciences for 1991 and from the observer data for 1992. These records include date, location, number of hooks, total weight of the fish catch, and number of fish caught. Catch records without valid latitude and longitude coordinates were deleted. Data such as time of day and duration of set, bait used, sizes of fish caught, or whether the reported geographic coordinates represented the location of the beginning or end of the set, were not available for our analyses. The location is usually the noon position of the ship, so only gives a general indication of the location of the catch. The total number of sets available for analysis was approximately 9000. The median longline length deployed was 28 miles, although some sets were recorded as over 60 miles long. Effort is generally referred as the total number of hooks used. The number of hooks per set varied between 2760 and 9000 with a median of approximately 3000.

Sea-surface temperatures are monitored at CSIRO's Hobart Remote Sensing Centre, which receives the high resolution picture transmission signals measured by the AVHRR instrument aboard NOAA polar-orbiting satellites. The data from daily satellite passes are archived and maintained on cartridges at this Hobart centre. Although the NOAA-11 AVHRR covers the Tasmanian region twice a day, the number of good, cloud-free images is usually limited to one or two per week, sometimes one or two per month. During 1991 and 1992 there were four NOAA polar-orbiting satellites NOAA-9, -10, -11 or -12 and each would have passed over the study area twice daily, only the data from NOAA-11 has been used in this study.

Figure 1 shows the areal coverage for the NOAA satellite from CSIRO's Hobart Remote Sensing Centre.

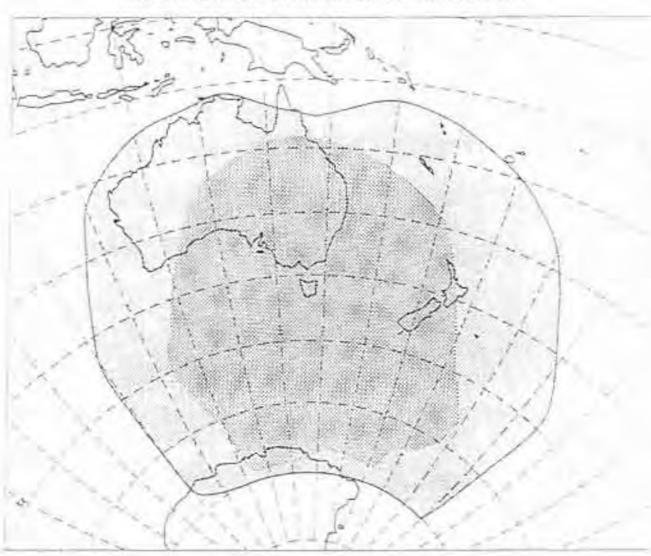

FIG. 1. – Areal coverage for the NOAA satellite from CSIRO's Hobart Remote Sensing Centre.

The AVHRR measures thermal infrared radiant energy in three wavelength bands (channels 3, 4 and 5 listed in Table 1). SSTs were estimated from the AVHRR thermal infra-red channels 4 and 5 using the split-window algorithms proposed by McCLAIN *et al.* (1985). The estimates are accurate to about 0.5°C.

TABLE 1. – Characteristics of the NOAA-11/AVHRR satellite.

Sensor	Channel	Description	Band Width (μ metres)
AVHRR	1	Visible	0.58-0.68
	2	Near infra-red	0.725-1.1
	3	Middle infra-red	3.55-3.93
	4	Thermal infra-red	10.3-11.3
	5	Thermal infra-red	11.5-12.5
Spatial Resolution 1.1km x 1.1km	Scene Coverage 2700 km (Swath)	Frequency Everyday	Measur. SST, sea ice

A large amount of satellite data off eastern and southern Tasmania was processed to identify oceanographic features for the fishing seasons during 1991 and 1992. In selecting images for analysis, an effort was made to exclude those containing significant cloud cover. This selection was made either by CSIRO personnel while compiling their image archive, or during retrieving the SSTs from AVHRR data and examination of images at the Hobart centre. Altogether a total of 10 images acquired during May-July for 1991 and 1992 (7 images for 1991 and 3 images for 1992) were included in the analysis. An algorithm has been developed which identifies that the edges of fronts proved to be a good predictor of the location of productive fishing areas.

RESULTS

The imagery received during the winter of 1991, show the SST field off eastern Tasmania to be dominated by a circular shaped, warm core, mesoscale eddy with an approximate diameter of 120 km (Figure 2). As a consequence of cloud cover the feature is incompletely seen on the image of 11 May 1991 but it can be clearly observed on the image of 30 May. The SST increased from 14°C at the edge of the eddy to 17°C inside the eddy. In black and white images warm waters are shown in light shades and cooler waters in darker shades. As seen from the series of satellite images in Figure 2, the eddy travelled southwards in the following months and filaments of warm water were observed at its outer edge. These filaments can be clearly seen on the image of 24 June 1991. By 3 August 1991, the eddy had weakened and the temperature at the centre of the eddy had decreased to about 15°C. During the period of the study from May to July 1991, the eddy moved about 85 km southwards. Similar warm core eddies form a major part of the circulation and water mass structure further north off the southeast coast of Australia.

According to NILSSON and CRESSWELL (1981) these eddies apparently form when a meander of the southward flowing East Australian Current breaks off into a closed ring structure. This warm core eddy probably originated in this way and travelled further south to a position off eastern Tasmania. The warm-core eddies of the east Australian current are mainly shallow cone-shaped lenses of coral sea water (about 250 km in diameter) that pinch off from meanders of the East Australian Current and drift southwards into the cooler Tasman sea. During their life span of 6-12 months, these eddies demonstrate strong surface currents 2-4 km wide along the run and central isothermal layers up to 300 m deep. East Australian Current eddies show a variety of hydrodynamic behaviour patterns (CRESSWELL and GOLDING 1980, NILSSON and CRESSWELL 1981). They may remain as an independent body of water, be reabsorbed into the parent current or escape to the south and decay.

A number of East Australian Current eddies have been studied with respect to their physical dynamics (NILSSON and CRESSWELL 1981, BOLAND and CHURCH 1981) and biological properties (BRANDT 1981, BRANDT 1983, JEFFREY and HALLEGRAEFF 1980, TRANTER *et al.* 1983). Nutrient enrichment may occur at eddy margins and at the eddy centre due to the strong current shear and transport of nutrients upwards along isopycnals (TRANTER *et al.* 1983).

Figure 2 also shows a few strong thermal oceanic fronts. The identification of oceanic fronts in infra-red satellite imagery is not always straightforward. First, areas which are cloud covered must be identified. Cloud covered areas are usually masked out on SST images using one or two together with an infra-red band. SSTs within the study area have characteristic patterns which are often different from the patterns associated with clouds. Once cloud-free areas have been identified, frontal structures are usually

FIG. 2. – Series of SST images off eastern Tasmania from May to August 1991.Clouds are white, land is black and water temperatures are shown in a temperature bar scale at the top of each image.

quite easy to identify in a properly enhanced image.

The Japanese longline fishery operated in oceanic waters off Tasmania with the main fishing period May to July and a secondary period from October to December. Usually 10-20 sets were recorded each day with very few days having no sets reported. The southern bluefin tuna and albacore catch data for the Japanese longline fishery in oceanic waters off eastern Tasmania were graphed as circles on maps with the same scales as the satellite images. The radii of the circles are directly proportional to the catch sizes. The superposition of the satellite images of SST and albacore and southern bluefin tuna catches show that commercial concentrations of albacore and southern bluefin tuna are associated with warm core eddies and strong thermal fronts during the study period for 1991 and 1992.

Winter catch off eastern Tasmania

Our results have shown that commercial concentrations of albacore and southern bluefin tuna are associated with oceanic boundaries marked by SST fronts detectable from satellites. The satellite images and concurrent albacore and southern bluefin tuna catch data show that the distribution and availability of catch data are related to eddies and oceanic fronts.

Figure 3 shows the positions of the Japanese longline fishing vessels operating off eastern Tasmania on 1 July 1992 with the southern bluefin tuna catches for the month of July 1992 superimposed. Crosses represent the ships positions on 1 July 1992, while the circles represent the total southern bluefin tuna catches for the month of July. Unfortunately ship positions were available for two days only. We conclude that, whereas fishing is conducted over a wide area, the catches have been obtained in only a few locations. In some areas no fish have been caught even though considerable effort has occurred. The SST and fish catches during the 1991 and 1992 fishing seasons will now be discussed in detail.

Southern bluefin tuna is a highly migratory and slow-growing species, estimated to live as long as 20 years, attain a weight of 200 kg and a length of

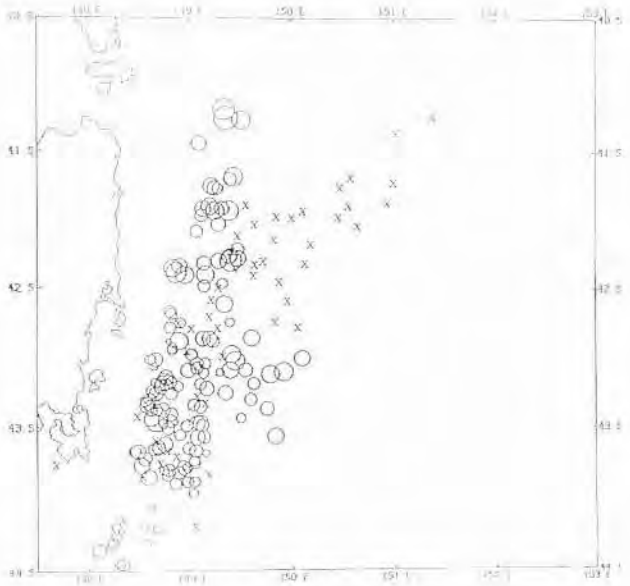

FIG. 3. – Superposition of the Japanese longline fishing vessels (crosses) on 1 July 1992 and the southern bluefin tuna (circles) catches for the month of July 1992.

200 cm (SHINGU 1978). It is found only in the southern hemisphere.

Albacore is also a migratory oceanic tuna that is an important target species for jig fishing, live bait and recreational fishing. Albacore are distributed from about 45°N to 50°S in all tropical, subtropical and temperate oceans (COLLETTE and NAUEN 1983). Albacore are usually taken as a by-catch on Japanese fishing vessels longline for southern bluefin, yellowfin and bigeye tunas. Locations of albacore catches are very similar to those for southern bluefin tuna as shown by the Figure 4 in which southern bluefin tuna and albacore catches for June 1991 are superimposed. Circles represent the southern bluefin tuna catches and the crosses represent the albacore catches. Furthermore, when the oceanic fronts are diffuse and widely spread there is likely to be a corresponding spread in the distribution of albacore.

Figure 5 shows the SST infrared image off eastern Tasmania during May 1991. It is a composite of two satellite images taken on 15 and 16 May 1991.

These images have been composited mainly to remove the cloud contaminated pixels. The image shows the presence of the warm core eddy discussed above. The superposition of this satellite image of SST and southern bluefin tuna catch positions for the month of May 1991 shows that commercial concentrations of southern bluefin tuna were associated with this warm core eddy. It is observed that most

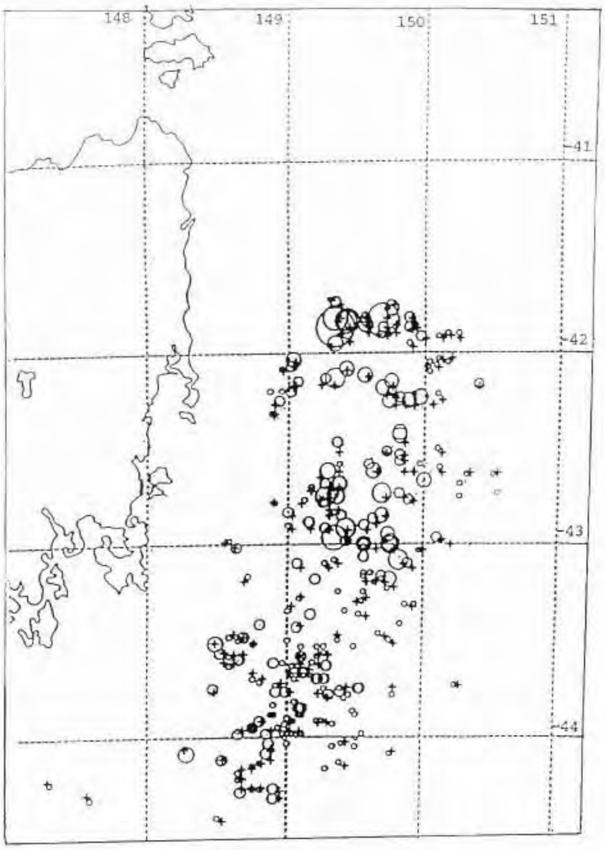

FIG. 4. – Superposition of southern bluefin tuna (circles) and albacore (crosses) catches for June 1991.

southern bluefin tuna were caught in and around the eddy. The temperature at the edge of an eddy is 14°C and inside the eddy it is 17°C.

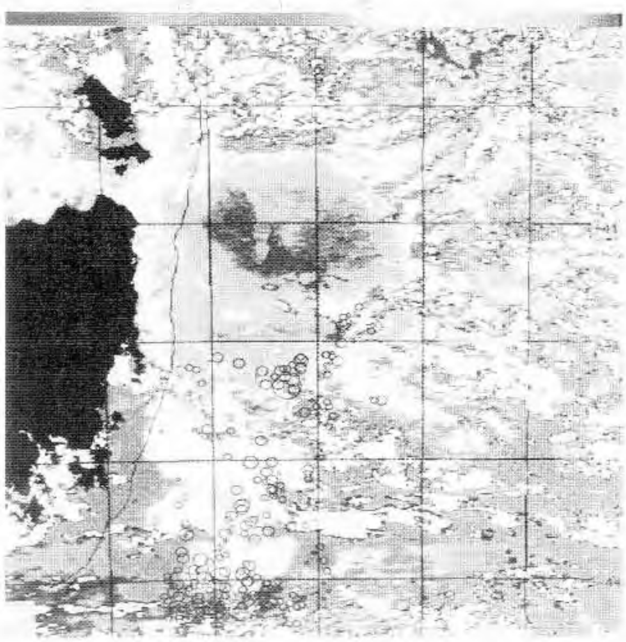

FIG. 5. – Southern bluefin tuna catches for May 1991 superimposed on the composited SST image.

Figure 6 shows the satellite derived SST image of 24 June 1991. During the month the warm-core eddy has moved southward to a location 42°S-43°S and 149°E-150°E and filaments of warm water have formed at its outer edge. The temperature increases from 12°C outside the eddies to 14°C at its edge to 17°C at its centre. Southern bluefin tuna catches are observed to be concentrated along the front surrounding the mesoscale eddy. Some catches are also observed along the filaments extending from the eddy. There is a predominance of high catches around the perimeter of the eddy.

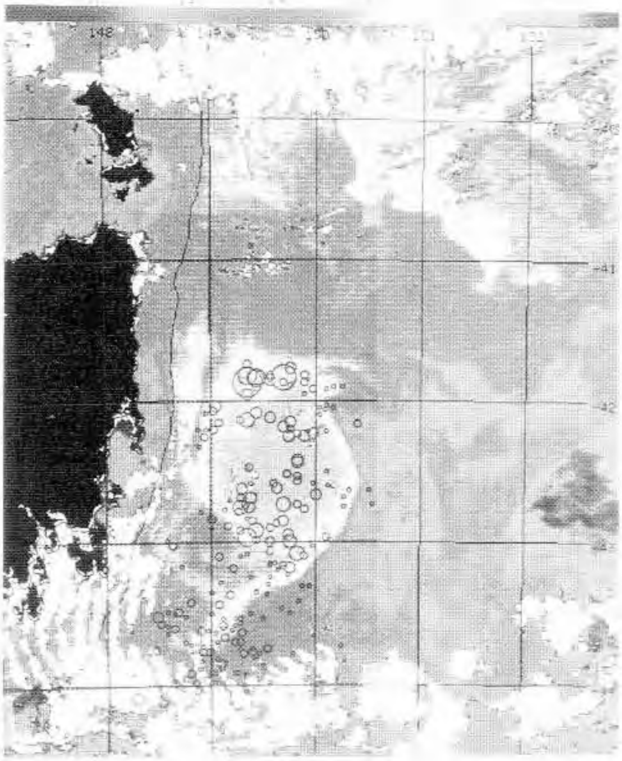

FIG. 6. – Southern bluefin tuna catches for June 1991 superimposed on the SST image of 24 June 1991.

Figure 7 represents the satellite derived SST image for 13 July 1991 with southern bluefin tuna catch overlaid. The eddy has moved farther southwards but is not completely seen because of clouds. Southern bluefin tuna catches in July are less than the previous month, indicating the end of the fishing season. A large proportion of the catch occurs in and around the weakening eddy structure.

Figure 8 shows the SST image with southern bluefin tuna catch for May 1992. The image is a composite of four passes from 7 May to 30 May 1992. It shows thermal fronts but no eddy as occurred during the same period in 1991. The superposition of the southern bluefin tuna catch data for the

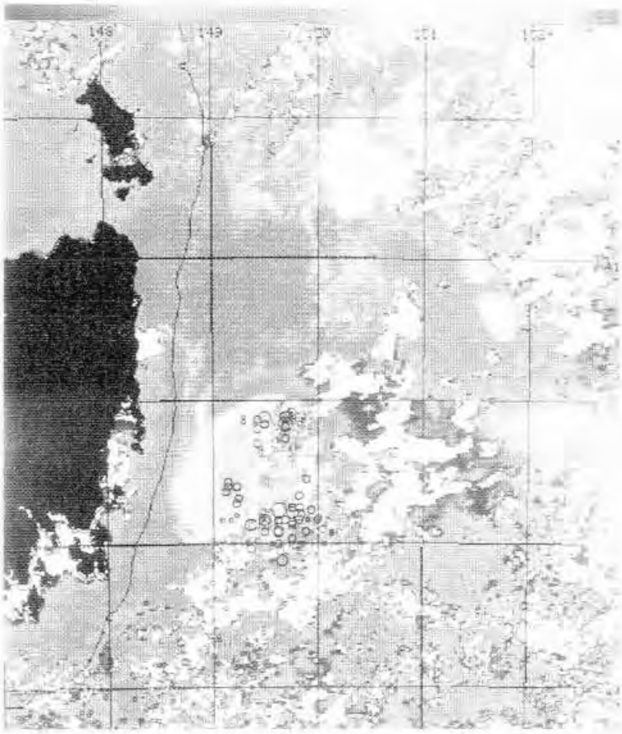

FIG. 7. – Southern bluefin tuna catches for July 1991 superimposed on the SST image of 13 July 1991.

month of May 1992 shows most of the catches are favouring sites along strong thermal fronts with some of the large catches occurring in warmer waters.

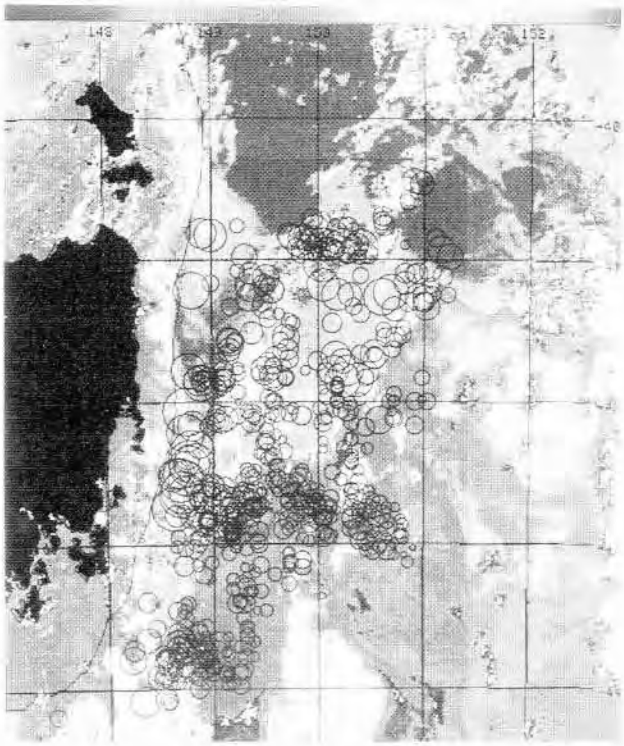

FIG. 8. – Southern bluefin tuna catches for May 1992 superimposed on the composited SST image.

Figure 9 shows the satellite image of 2 June 1992 and the southern bluefin tuna catches for the month of June 1992. Here approximately two thirds of the southern bluefin tuna catches are associated with the oceanic fronts with a temperature of 15°C.

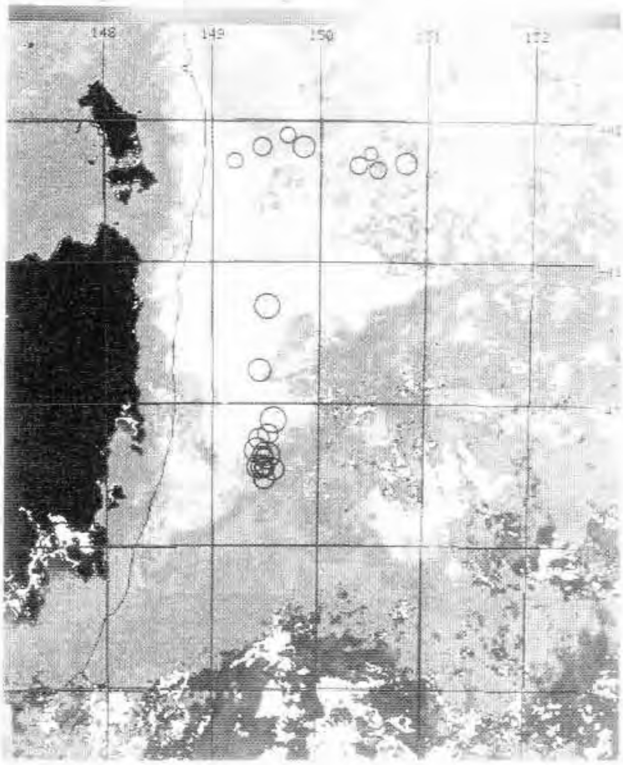

FIG. 9. – Southern bluefin tuna catches for June 1992 superimposed on the SST image of 2 June 1992

During July 1992 frontal structures were poorly developed and water mass boundaries less distinct. Southern bluefin tuna catches for the month of July were distributed over a large range of latitude and longitude (Figure 10). Overall southern bluefin tuna catches in 1992 were less than in 1991.

The distribution of southern bluefin tuna catch rates from the Japanese longline fishery in eastern Tasmania waters during the winter period from May to July 1991 appear to have been closely associated with eddies and thermal fronts. Although catches were generally poor during 1992, there were relatively high catches in the thermal frontal regions. Most of 1992 southern bluefin tuna catches were concentrated at the thermal boundaries/fronts. In both the years, southern bluefin tuna preferred warmer temperatures in these regions during winter periods with temperatures ranging from 12°C to 16°C. The gradients appear to be weaker in 1992 than in 1991. One localised area at latitude 40°S had strong gradients but the fish catch was not concentrated in this area.

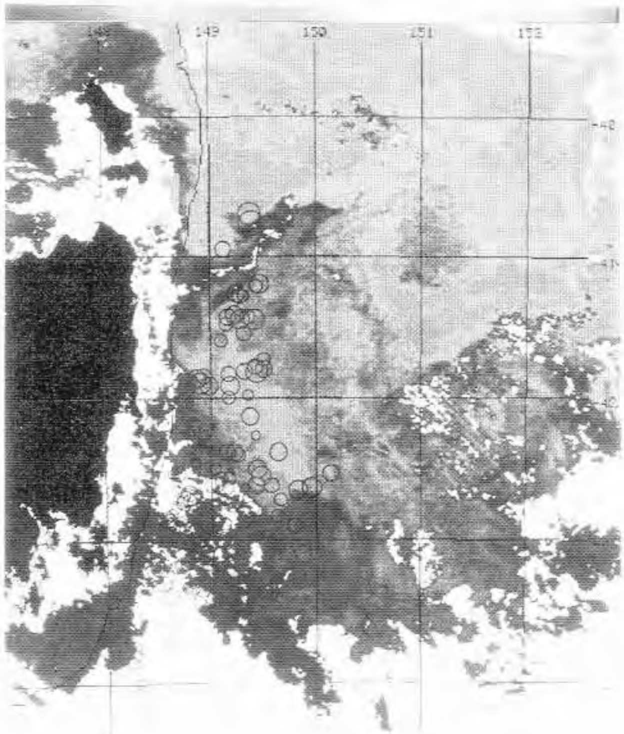

FIG. 10. – Southern bluefin tuna catches for July 1992 superimposed on the SST image of 16 July 1992.

Similar to southern bluefin tuna, albacore are associated with eddies and thermal fronts indicating that southern bluefin tuna and albacore have a preference for water with warmer surface temperatures in this region off eastern Tasmania during the winter fishing season. Percentages of southern bluefin tuna and albacore catches for 1991 made inside (including the edge) and outside the eddy are shown in Table 2. It indicates that most of the catches are inside the eddy or on its edges.

TABLE 2. – The number and percentage of southern bluefin tuna (SBT) and albacore caught inside and outside the eddy.

Species	Inside eddy	Outside eddy
SBT May 1991	439 (73%)	162 (27%)
Albacore May 1991	260 (79%)	70 (21%)
SBT June 1991	313 (76%)	100 (24%)
Albacore June 1991	305 (78%)	80 (22%)
SBT July 1991	145 (64%)	82 (36%)
Albacore July 1991	189 (67%)	94 (33%)
Total	1649 (74%)	588 (26%)

Gradient Analysis

Analysis of the gradients of satellite-derived SST data have been used to describe the position of an eddy and the front at each cloud-free location. For fishery applications valuable information that may be derived from a SST image is locating the edges surrounding various objects and features of interest. Generally, edges are qualitatively identified as sharp changes in the brightness value between adjacent pixels. An algorithm has been developed to quantify the position of these edges using a gradient enhancement technique. Similar approaches have been done by VAN WOERT (1982) and SIMPSON (1992). The edge enhancement operation described here delineates these edges and thereby makes outlines of features of the image more conspicuous and easier to analyse.

The position and strength of edges of eddies and fronts have been numerically estimated from SST gradients. These gradients were computed using the two-dimensional centred finite difference equation using the Unix shareware program POPI. The gradient of image A at point (x,y) is defined as

$$B(x,y)=abs(A(x-5,y)-A(x+5,y))+abs(A(x,y-5)-A(x,y+5))$$

where x and y are the current pixel cartesian coordinates (x,y),

A(x,y) = value of the original input image A,
B(x,y) = value of the output image B,
abs = absolute value.

Cloud and land contaminated values have been removed. Figure 11 shows the eddy edges and fronts calculated by our gradient method for the image of 24 June 1991. Albacore catches for the month of June 1991 are superimposed. The calculated positions of the edges of the fronts and eddy are good predictors of the best sites for the fish catch.

Table 2 summaries the results of investigations for both southern bluefin tuna and albacore catches in number of fish for May, June and July 1991 off eastern Tasmania. The catches have been classified visually as belonging to the eddy if the centre of the catch circle is within the length of the longline of the eddy structure or otherwise as being outside the eddy. The fish catch in and around the eddy is between 70% and 80% of the total catch in May and June but falls to between 60% and 70% in July when total fish catch is also smaller. These percentages are achieved even though the area of the eddy and of the thermal fronts is approximately 10% of the water area of the image.

FIG. 11. – Eddy edges and fronts calculated by the gradient method for the image of 24 June 1991 with the albacore catches for the month of June 1991 superimposed.

CONCLUSIONS

This paper has discussed the application of remote sensed SST data to describe large-scale general ocean circulation for the purpose of predicting the location of the best sites for fishing effort. Examples of the aggregation of southern bluefin tuna and albacore associated with oceanic fronts and eddies have been given.

SST patterns were different for the fishing seasons for similar periods in 1991 and 1992. During winter 1991 an abundance of albacore and southern bluefin tuna occurred in the eddy field off eastern Tasmania between latitudes 42°S and 43°S and longitudes 149°E and 150°E. The eddy persisted for several months in this area and much of the fish catch was located in and around the eddy. During the 1992 season no eddy formed but similar concentrations of fish catches occurred at the thermal fronts. Some catches were observed along the filaments of these thermal structures. The numerical algorithm proved useful in determining the position of the thermal gradients likely to be habited by the tuna.

Knowledge of the dynamics of the oceanic structures is greatly enhanced by the use of satellite sensed SST data. The use of this technology is essential to the ongoing description of the eddies and fronts and determining their influence on fish abundance. The major problem for the satellite data is the presence of cloud cover.

REFERENCES

ALVERSON, D. L. – 1961. Ocean temperatures and their relation to albacore tuna (Thunnus germo) distribution in waters off the coast of Oregon, Washington and British Columbia. *Journal Fisheries Research Board Canada*, 18, 1145-1152.

BOLAND, F. M., and J. A. CHURCH. – 1981. The East Australian Current 1978. *Deep-Sea Research*, 28, 937-957.

BRANDT, S. B. – 1981. Effects of a warm-core eddy on fish distributions in the Tasman Sea off east Australia. *Marine Ecology Progress Series*, 6, 19-33.

BRANDT, S. B. – 1983. Temporal and spatial patterns of lanternfish (family Myctophidae) communities associated with a warm-core eddy. *Marine Biology*, 74, 231-244.

BREADSELY, G. L. J. – 1969. Distribution and apparent relative abundance of yellowfin tuna (Thunnnus albacares) in the eastern tropical Atlantic in relation to oceanographic features. *Bulletin Marine Science*, 19, 48-56.

BREAKER, L. – 1981. The application of satellite remote sensing to west coast fisheries. *Journal of the Marine Technological Society*, 15, 32-40.

CLEMENTSON, L. A., G. P. HARRIS, F. B. GRIFFITHS and D. W. RIMMER. – 1989. Seasonal and interannual variability in chemical and biological observations in Storm Bay Tasmania. *Australian Journal of Marine and Freshwater Research*, 40, 25-38.

COLLETTE, B. B., and C. E. NAUEN. – 1983. *Scombirds of the world: an annotated and illustrated catalogue of tunas, mackerels, bonitos and related species known to date* (Technical Report No. 125). FAO.

CRESSWELL, G. R. and T. J. GOLDING. – 1980. Observations of a south-flowing current in the southeastern Indian Ocean. *Deep-Sea Research*, 27A, 449-466.

CUSHING, D. H. – 1982. *Climate and fisheries*. London: Academic Press.

FIEDLER, P. C. and H. J. BERNARD. – 1987. Tuna aggregation and feeding near fronts observed in satellite imagery. *Continental Shelf Research*, 7(8), 871-881.

FIEDLER, P. C., G. B. SMITH and R. M. LAURS. – 1985. Fisheries applications of satellite data in the eastern north Pacific. *Marine Fisheries Review*, 46, 1-13.

FIUZA, A. F. G. – 1990. Application of satellite remote sensing to fisheries. *Operations research and management in fishing*. In A. G. Rodrigues (Eds.), pp. 257-279. Klumer Academic Publishers.

GODFREY, J. S., D. J. VAUDREY and S. D. HAHN. – 1986. Observations of a shelf edge current south of Australia, winter 1982. *Journal of Physical Oceanography*, 16, 668-679.

GOWER, J. F. R. – 1982. General overview of the nature and use of satellite remote sensing data for fisheries application. NAFO *Science Council Studies*, 4, 7-19.

HARRIS, G. P., F. B. GRIFFITHS, L. A. CLEMENTSON, V. LYNE and H. VAN der DOE. – 1991). Seasonal and interannual variability in physical processes, nutrient cycling and the structure of the food chain in Tasmanian shelf waters. *Journal of Plankton Research*, 13, 109-131.

JEFFREY, S. W., and G. M. HALLEGRAEFF. – 1980. Studies of phytoplankton species and photosynthetic pigments in a warm-core eddy of the East Australian Current. I. Summer populations. *Marine Ecology Progress Series*, 3, 285-294.

KLIMLEY, A. P., and S. B. BUTLER. – 1988. Immigration and emigration of a pelagic fish assemblages to seamounts in the Gulf of California related to water mass movements using satellite imagery. *Marine Ecology Progress Series*, 49, 11-20.

LASKER, R., J. PELAEZ and R. M. LAURS. – 1981. The use of satellite infrared imagery for describing ocean processes in relation to spawning of the northern anchovy (Engraulis mordax). *Remote Sensing of Environment*, 11, 439-453.

LAURS, R. M., and J. T. BRUCKS. – 1985. Living marine resources applications. *Advances in Geophysics*, 27, 419-452.

LAURS, R. M., P. C. FIEDLER and D. R. MONTGOMERY. – 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. *Deep-Sea Research*, 31, 1085-1099.

LYNE, V. D., F. B. GRIFFITHS, G. P. HARRIS, J. S. PARSLOW and S. H CLIFT. – 1992. Detecting surface schools of fish with a SLAR: Real-time target detectability and enhancement. *International Journal of Remote Sensing*, 13, 1927-1941.

MCCLAIN, E.P., W.G. PICHEL and C.C. WALTON. – 1985. Comparitive performance of AVHRR based multichannel sea surface temperatures. *Journal of Geophysical Research*, 90(C6), 11,587-11,601.

MAUL, G. A., F. WILLIAMS, M. ROFFER and F. M. SOUSA. – 1984. Remotely sensed oceanographic patterns and variability of bluefin tuna catch in the Gulf of Mexico. *Oceanologica Acta*, 7, 469-479.

MONTGOMERY, D. R. – 1981. Commercial applications of satellite oceanography. *Oceanus*, 24, 56-65.

NILSSON, C. S., and G. R. CRESSWELL. – 1981. The formation and evolution of East Australian Current warm-core eddies. *Progress Oceanography*, 9, 133-183.

SHINGU, C. – 1978. *Ecology and stock of southern bluefin* Research Report No. 131. CSIRO, Division of Fisheries and Oceanography.

SIMPSON, J.J. – 1992. Remote sensing and geographical information systems: Their past, present and future use in global marine fisheries. *Fisheries Oceanography*, 1(3), 238-280.

TRANTER, D. J., G. S. LEECH and D. AIREY. – 1983. Edge enrichment in an ocean eddy. *Australian Journal of Marine and Freshwater Research*, 34, 665-680.

UDA, M. – 1959. Water mass boundaries 'Siome'. Frontal theory in oceanography. *Fisheries Research Board Canada*, 51, 10-20.

VAN WOERT, M. – 1982. The subtropical front: Satellite observations during fronts 80. *Journal of Geophysical Research*, 87(C17), 9523-9536.

YAMANAKA, I. – 1982. Application of satellite remote sensing to fishery studies in Japan. NAFO *Science Council Studies*, 4, 41-50.