# CONTENTS

iv

Declaration	i
Abstract	ii
Acknowledgements	iii
Contents	iv
List of Tables	vi
List of Figures	vii
List of Abbreviations	xii

#### INTRODUCTION 1

- BACKGROUND 1.1
- SIGNIFICANCE OF THE STUDY 1.2
- STATEMENT OF THE PROBLEM 1.3
- PURPOSE AND OBJECTIVES 1.4

#### LITERATURE REVIEW 2

-

2.1	OCEANOGRAPHY OF THE INDIAN OCEAN	9
	2.1.1 Physical Properties of sea water	10
	2.1.2 Physical Processes in the Ocean	12
	2.1.3 Biological Processes in the Ocean	14
2.2	FISHERIES IN THE INDIAN OCEAN	18
	2.2.1 Tuna Fishery in the Indian Ocean	18

1

4

5

6

9

		2.2.2	Tuna Production in the Indian Ocean	22
		2.2.3	Tuna Management in The Indian Ocean	27
	2.3	OCEA	28	
		2.3.1	Satellites and Sensors	29
		2.3.2	Advantages and limitations of Remote Sensing	36
	2.4	REM	39	
		2.4.1	Predictions of Fishing Grounds	41
		2.4.2	Predictions of Fishing Depth	45
		2.4.3	Fisheries Management	46
3	STUDY AREA			49
	3.1	PHYS	SICAL ENVIRONMENT	49
	3.2	2 OCEANOGRAPHIC ENVIRONMENT		
		3.2.1	Salinity and Temperature	51
		3.2.2	Upwelling	54
		3.2.3	Mixed Layer Properties	54
	3.3	3.3 TUNA FISHERY IN THE STUDY AREA		
		3.3.1	Sri Lanka's Tuna Fishery	56
		3.3.2	Sri Lanka's Tuna Production	59

#### MATERIALS AND METHODS 61 4 DATA USED 61 4.1 4.1.1 Satellite Data 61 4.1.2 Argo Float Data 71 4.1.3 Fishery Data 74 DATA PROCESSING AND ANALYSES 4.2 76 4.2.1 Satellite Data Processing 76 4.2.2 Fishery Data Processing 77 4.2.3 Fishery and Satellite Data Matching 78

V

				, 0
		4.2.4	Statistical Analyses	79
		4.2.5	Processing of Temperature Vertical Profiles	82
		4.2.6	Modeling of Temperature Vertical Profiles	82
		4.2.7	Model Outputs and Satellite Data Matching	84
	4.3	DETE	ERMINATION OF POTENTIAL FISHING GROUNDS	85
		4.3.1	Fuzzy Logic System	85
		4.3.2	Image Classification	87
5	<b>RESULTS AND DISCUSSION</b>			92
	5.1	VARI	ABILITY OF CATCH DATA	92
		5.1.1	Spatial and Temporal Variability of Catch Rates	92
		5.1.2	Catch Variability on Sea Surface Temperature	96
		5.1.3	Catch Variability on Sea Surface Chlorophyll	97
		5.1.4	Catch Variability on Sea Surface Height	98
	5.2	HABI	TAT PREFERENCES OF YELLOWFIN TUNA	98
	5.3	POTE	NTIAL FISHING GROUNDS	104
		5.3.1	Fishing Grounds Forecast	104
		5.3.2	Validation of Fishing Grounds	108
	5.4	YELL	OWFIN TUNA AGGREGATING DEPTHS	115
		5.3.1	The Sigmoid Model Results	115
		5.3.2	Calculation of Parameters for the Sigmoid Model	121
		5.3.3	Fishing depth Predictions	131
6	CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK			136
	6.1	CONC	CLUSIONS	136
	6.2	RECO	MMENDATIONS FOR FUTURE WORK	137
	APP	ENDICI	ES	147

148

A International Publication-1 **B** International Publication-2 C Fishery Database

158

166

# LIST OF TABLES

vi

Caption

Page No.

Table 2.1AMSR-E performance characteristics.

- Table 2.2 The spectral bandwidth ( $\mu$ m) and Field of View (IFoV) of the AVHRR, Source: World Data Center.
- Table 2.3Temporal coverage of NOAA-AVHRR sensor.
- Table 2.4MODIS sensor specifications of Band 8-16 used for ocean color, phyto-<br/>plankton and biogeochemistry.
- Table 2.5 Details about MODIS ocean products (NASA, b).
- Table 2.6The mission goals Topex/Poseidon are carrying six science instruments that<br/>are divided into 4 operational and 2 experimental sensors.33
- Table 3.1
   Summary of offshore and high seas fishing fleets operated by Sri Lanka in 2012.

32

33

34

35

57

75

99

Table 4.1Logbook data sheet printed on calendar days to record daily operational fish-<br/>ery data and information.

Table 5.1 Monthly variation of SST, SSC, SSH for Yellowfin tuna abundance.

- Table 5.2Single predictor GAM fits for Yellowfin tuna fishing grounds. The percent-<br/>age of deviance and the generalized cross validation score is given for each<br/>predictor.100
- Table 5.3Significance of the smooth terms included in the GAM for Yellowfin tunaoccurrence in fishing grounds.100
- Table 5.4Deviance and GCV scores of Yellowfin tuna CPUE of fishing grounds explained in GAM with variables added.100
- Table 5.5 Construction of GLM as each variable is added, residual deviance, the approximate AIC and F-statistic for Yellowfin tuna availability in the fishing

grounds.

Table 5.6Set of coefficients (slop and offset) in the linear relationships as shown inFigure 5.23, 5.23 and 5.25 corresponding to each latitude intervals.122

# LIST OF FIGURES

vii





## Figure 2.1 The Indian Ocean

- Figure 2.2 Schematic representation of upwelling process due to surface wind stress and Ekman transport.
- Figure 2.3 Marine Phytoplanton and Zoopnlankton.
- Figure 2.4 Distribution of Tropical and Temperate tunas in the world oceans.
- Figure 2.5 Target speicies of tuna by Sri Lanka offshore/high seas fishry, Skipjack tuna (*Katsuwonus pelamis*), Yellowfin tuna (*Thunnus albacares*) and Bigeye tuna (*Thunnus obesus*) from top to bottom in relative sizes.
- Figure 2.6 Purse seine (PS) fishing effort form 1980-2010 in geographical areas shown above. Source: (IOTC, 2009).
- Figure 2.7 Increased effort on log-schools of Yellowfin tuna by purse seine fishing gear. Source: (IOTC, 2009).

12

16

19

20

21

22

22

24

24

25

- Figure 2.8 Yellowfin tuna (left) and Bigeye tuna (right) catches by gear types in 2011. Source: (IOTC, 2009).
- Figure 2.9 Annual catches of Skipjack tuna by gear type from 1955 to 2007. Source: (IOTC, 2009).
- Figure 2.10 Mean of annual total catches of Skipjack tuna by gear operating in the Indian Ocean over the period of 2008. Source: (IOTC, 2009).
- Figure 2.11 Annual catches of Yellowfin tuna by gear type from 1955 to 2007. Source: (IOTC, 2009).
- Figure 2.12 Mean of annual total catches of Yellowfin tuna by gear operating in the Indian Ocean over the period of 2008. Source: (IOTC, 2009).
- Figure 2.13 Annual catches of Bigeye tuna by gear type from 1955 to 2007. Source: (IOTC, 2009).

26

50

25

Figure 2.14 Mean of annual total catches of Bigeye tuna by gear operating in the Indian Ocean over the period 2008. Source: (IOTC, 2009).

Figure 3.1 A schematic representation of identified current branches during the Southwest Monsoon (May-September). Source: (Schott *et al.*, 2002)

### viii

- A schematic representation of identified current branches showing reversal Figure 3.2 current pattern during the Northeast monsoon from December to March. Source: (Schott et al., 2002)
- Sea surface currents overlay on sea surface height in the Bay of Bengal from Figure 3.3 Jan-Dec 2008. Source: (Office of Naval Research)

52

58

51

- Figure 3.4 Sea surface salinity variation in the Bay of Bengal from Jan-Dec 2008.
- Source: (Office of Naval Research) 53
- Figure 3.5 Sri Lankan Longline fishing fleets, over 40 feet long; Picture taken from a fishery harbor at Negombo-Sri Lanka.
- Figure 3.7 Total fishery production of Sri Lanka showing its catch trends of large pelagic fish from 1997-2008 (Source: PELAGOS database, NARA). 59
- Monthly average sea surface temperature generated using daily AMSR-AVHRR Figure 4.1 microwave-infrared blended data products from Jan-June 2008. 63
- Figure 4.2 Monthly average sea surface temperature generated using daily AMSR-AVHRR microwave-infrared blended data products from Jul-Dec 2008. 64
- Monthly average sea surface chlorophyll<sub>a</sub> generated using daily Terra/Aqua Figure 4.3 MODIS data products from Jan-Jun 2008. 66
- Monthly average sea surface chlorophyll<sub>a</sub> generated using daily Terra/Aqua Figure 4.4 MODIS data products from Jul-Dec 2008.
- Monthly average sea surface height generated using daily Topex/Poseidon Figure 4.5 data products from Jan-Jun 2008.
- Monthly average sea surface height generated using daily Topex/Poseidon Figure 4.6 data products from Jul-Dec 2008.
- Float structure showing its components of 3-subsystems including the mea-Figure 4.7 suring sensors. (source: http://imos.org.au/instrument.html).
- Maps showing the distribution of Argo floats and the observed temperature Figure 4.8 veertical profiles during the period from 2007-2009.
- Figure 4.9 Schematic illustration of 3-day time series data generation of SSC.
- Figure 4.10 Flow chart showing the main steps of data processing and analyses.
- Figure 4.11 Sketch diagram showing temperature vertical profile of the ocean, illustrating upper mixed surface waters, the thermocline and deep layer.

69

70

72

73

77

79

83

Figure 4.12 Flow chart showing data processing, analyses and prediction of temperature vertical profiles.

Figure 4.13 The fuzzyfication with membership function of the three variables to generate potential fishing grounds.

86

85

#### ix

Figure 4.14 The function to evaluate the combined probability image to classify highest potential fishing grounds.

Figure 4.15 The fuzzy membership functions of the three fuzzy sets of oceanographic parameters in each month (Jan-April).

Figure 4.16 The fuzzy membership functions of the three fuzzy sets of oceanographic parameters in each month (May-Aug).

88

89

90

91

93

94

95

Figure 4.17 The fuzzy membership functions of the three fuzzy sets of oceanographic parameters in each month (Sep-Dec).

- Figure 5.1 Geographical locations of Yellowfin tuna fishing activities of the 3-year dataset (2006-2008).
- Figure 5.2 Favorable SST isotherm on monthly average temperature image with superimposed of Yellowfin tuna catch rates (dots). This shows the space-time variability is more effective in predicting fishing grounds on SST images.
- Figure 5.3 Temporal variability of (a) Yellofin tuna catch rates, (b) AMSR-AVHRR SST, (c) MODIS SSC and (d) AVISO SSH extracted from fishing grounds during the 3-year period (2006-2008).
- Figure 5.4 (a) Box and whisker plot of SST ranges of Yellowfin tuna caught (b) Scatter plot of CPUE against SST and (c) Frequency of SST of Yellowfin tuna caught by Sri Lankan longliners.
- Figure 5.5 (a) Box and whisker plot of SSC ranges of Yellowfin tuna caught (b) Scatter plot of CPUE against SSC and (c) frequency distribution SSC of Yellowfin tuna caught by Sri Lankan longlines.
- Figure 5.6 (a) Box and whisker plot of SSH ranges of Yellowfin tuna caught (b) Scatter plot of CPUE against SSH and (c) Frequency distribution SSH of Yellowfin tuna caught by Sri Lankan longliners.
- Figure 5.7 Empirical cumulative distribution frequencies for (a) AMSR-AVHRR SST,
  (b) MODIS SSC and (c) AVISO SSH as weighted by Yellowfin tuna catch during the period 2006-2008.
- Figure 5.8 Generalized additive model (GAM) derived effect of oceanographic variables (a) AMSR-AVHRR SST, (b) MODIS SSC, and (c) AVISO SSH on Yellowfin tuna catch rates. Tick marks (rug) at abscissa axis represent the observed data points. Solid-line is the explaining function and dashed-line

97

99

101

indicates the 95% confidence interval, equivalent to two standard deviations  $(\pm 2S.D.)$  102

Figure 5.9 Potential Probability maps for Yellowfin tuna fishing grounds generated using monthly averaged SST, SSC and SSH from Jan-Jun 2008. 106

### Х

110

111

118

Figure 5.10 Potential Probability maps for Yellowfin tuna fishing grounds generated using monthly averaged SST, SSC and SSH from Jul-Dec 2008. 107

Figure 5.11 Catch overlay (black circles) on predicted potential fishing grounds in Jan. 2008 on left and on right showing the catch rates against predicted fishing potentials.

Figure 5.12 Catch overlay (black circles) on predicted potential fishing grounds in March

- 2008 on left and on right showing the catch rates against predicted fishing 110 potentials.
- Figure 5.13 Catch overlay (black circles) on predicted potential fishing grounds in April 2008 on left and on right showing the catch rates against predicted fishing potentials.
- Figure 5.14 Catch overlay (black circles) on predicted potential fishing grounds in May 2008 on left and on right showing the catch rates against predicted fishing 111 potentials.
- Figure 5.15 Catch overlay (green circles) on weekly predicted potential fishing grounds 112 on May 2008.
- Figure 5.16 Deviation of Tuna catches (black circles) on predicted potential fishing grounds during SW monsoon peaks (June 2008) on left and on right showing the catch rates against predicted fishing potentials. 113

Figure 5.17 Deviation of Tuna catches (black circles) on predicted potential fishing grounds during SW monsoon peaks (July 2008) on left and on right showing the catch rates against predicted fishing potentials. 113

- Figure 5.18 Deviation of Tuna catches (black circles) on predicted potential fishing grounds during NE monsoon peaks (October 2008) on left and on right showing the 114 catch rates against predicted fishing potentials.
- Figure 5.19 Less deviation of Tuna catches (black circles) on predicted potential fishing grounds during NE monsoon (November 2008) on left and on right showing 114 the catch rates against predicted fishing potentials.
- Figure 5.20 Histograms of the thermocline dephs  $(Z_{tc})$ , hermocline temperatures  $(T_{tc})$ , and mixed layer temperatures  $(T_{max})$  calculated using the Argo temperature 116 profiles from 2007-2009.
- Figure 5.21 Relationship between mixed layer temperature  $(T_{max})$  obtained from Argo 116 and SST measured by satellites.

Figure 5.22 Sigmoid Model fits (solid line) to the average temperature profile measured by Argo floats (dots) in six locations on January 2008. Horizontal and vertical dotted lines show the thermocline depth and its temperature. Date and location of the profiles is shown on the upper left corner.

## xi

Figure 5.23 Linear model fits showing the relationships, (a) A vs  $T_{max}$ , (b)  $\rho$  vs A and (c)  $\lambda$  vs A of the profiles between latitude 14-17. 119

Figure 5.24 Linear model fits showing the relationships, (a) A vs  $T_{max}$ , (b)  $\rho$  vs A and (c)  $\lambda$  vs A of the profiles between latitude 10-13. 120

Figure 5.25 Relationship between SSH and thermocline depths ( $Z_{tc}$ ) calculated by Sigmoid model fitting to the Argo temperature profiles. 123

Figure 5.26 Based on the Table 5.6, linear model fits to (a) slopeA, (c) slopep, (e) slope $\lambda$ , (g) slope $Z_{tc} * offset\lambda$  with respect to latitudes, and (b) of fsetA, (d) of f set  $\rho$ , (f) of f set  $\lambda$  and (h) of f set  $Z_{tc}$  with respect to their slopes. 124

- Figure 5.27 Temperature vertical profiles predicted (solid line) and observed (circles) in four locations on 16.09.2007. 129
- Figure 5.28 Temperature vertical profiles predicted (solid line) and observed (circles) in four locations on 01.06.2008 and 11.06.2008. 130
- Figure 5.29 Thermocline depth (m) predictions made by the predictive algorithm using monthly SST and SSH from Jan.-June. 2008. 132
- Figure 5.30 Thermocline depth (m) predictions made by the predictive algorithm using monthly SST and SSH from Jul.-Dec. 2008. 133
- Figure 5.31 20°C Isotherm depth (m) predictions made by the predictive algorithm using monthly SST and SSH from Jan.-June. 2008. 134

Figure 5.32 20°C Isotherm depth (m) predictions made by the predictive algorithm using 135 monthly SST and SSH from Jul.-Dec. 2008.