

**Statistical Modeling of the Red Sea Chlorophyll  
Concentration and Application to the ERSEM  
Ecological Model**

Thesis by  
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In Partial Fulfillment of the Requirements

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Kingdom of Saudi Arabia

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# TABLE OF CONTENTS

<b>Examination Committee Approval</b>	<b>2</b>
<b>Copyright</b>	<b>3</b>
<b>List of Figures</b>	<b>11</b>
<b>List of Tables</b>	<b>13</b>
<b>1 Introduction and Motivation</b>	<b>15</b>
1.1 Phytoplankton and the Red Sea Biology: Importance, Impact, Large-Scale Features, and Applications . . . . .	16
1.1.1 The Importance of Phytoplankton . . . . .	16
1.1.2 Red Sea Large-Scale Phytoplankton Dynamics . . . . .	16
1.2 Remotely-Sensed Chlorophyll Data: Relevance and Challenges for the Red Sea . . . . .	16
1.2.1 Measuring Chlorophyll Concentration . . . . .	16
1.2.2 Limitation of Remotely-Sensed Chlorophyll Data . . . . .	16
1.3 Modeling Chlorophyll: Data-Driven and Physics-Driven Approaches and Applications . . . . .	16
1.3.1 Why Modeling Chlorophyll? . . . . .	16
1.3.2 Data-Driven Approaches . . . . .	16
1.3.3 Deterministic Models . . . . .	16
1.3.4 Ecological Models . . . . .	16
1.3.5 Data Assimilation . . . . .	16
1.4 Thesis Objectives . . . . .	16
<b>2 Research Plan</b>	<b>17</b>
2.1 Task 1: Dataset Building and Exploration . . . . .	18
2.1.1 Motivation . . . . .	18
2.1.2 Open Questions . . . . .	18
2.1.3 Method . . . . .	18

2.1.4	Expected Outcomes . . . . .	18
2.1.5	Accomplished Word and Preliminary Results . . . . .	18
2.2	Task 2: Forecasting Chlorophyll Concentration in Regional Aggregates	18
2.2.1	Motivation . . . . .	18
2.2.2	Open Questions . . . . .	18
2.2.3	Method . . . . .	18
2.2.4	Expected Outcomes . . . . .	18
2.2.5	Accomplished Word and Preliminary Results . . . . .	18
2.3	Task 3: Global Geostatistical Model for Chlorophyll Forecasting . . .	18
2.3.1	Motivation . . . . .	18
2.3.2	Open Questions . . . . .	18
2.3.3	Method . . . . .	18
2.3.4	Expected Outcomes . . . . .	18
2.3.5	Accomplished Word and Preliminary Results . . . . .	18
2.4	Task 4: Local Geostatistical Model for Forecasting . . . . .	18
2.4.1	Motivation . . . . .	18
2.4.2	Open Questions . . . . .	18
2.4.3	Method . . . . .	18
2.4.4	Expected Outcomes . . . . .	18
2.4.5	Accomplished Word and Preliminary Results . . . . .	18
2.5	Task 5: Assimilation of 1D Ecological Models and Comparison to Sta- tistical Models . . . . .	18
2.5.1	Motivation . . . . .	18
2.5.2	Open Questions . . . . .	18
2.5.3	Method . . . . .	18
2.5.4	Expected Outcomes . . . . .	18
2.5.5	Accomplished Word and Preliminary Results . . . . .	18
2.6	Task 6: Improving an Ecological Model Data Assimilation Scheme through Statistical Predictive Models . . . . .	18
2.6.1	Motivation . . . . .	18
2.6.2	Open Questions . . . . .	18
2.6.3	Method . . . . .	18
2.6.4	Expected Outcomes . . . . .	18
2.6.5	Accomplished Word and Preliminary Results . . . . .	18











# LIST OF FIGURES



# LIST OF TABLES





# Chapter 1

## Introduction and Motivation

### 1.1 Phytoplankton and the Red Sea Biology: Importance, Impact, Large-Scale Features, and Applications

#### 1.1.1 The Importance of Phytoplankton

#### 1.1.2 Red Sea Large-Scale Phytoplankton Dynamics

### 1.2 Remotely-Sensed Chlorophyll Data: Relevance and Challenges for the Red Sea

#### 1.2.1 Measuring Chlorophyll Concentration

#### 1.2.2 Limitation of Remotely-Sensed Chlorophyll Data

### 1.3 Modeling Chlorophyll: Data-Driven and Physics-Driven Approaches and Applications

#### 1.3.1 Why Modeling Chlorophyll?





# Chapter 2

## Research Plan

### 2.1 Task 1: Dataset Building and Exploration

#### 2.1.1 Motivation

#### 2.1.2 Open Questions

#### 2.1.3 Method

#### 2.1.4 Expected Outcomes

#### 2.1.5 Accomplished Work and Preliminary Results

### 2.2 Task 2: Forecasting Chlorophyll Concentration in Regional Aggregates

#### 2.2.1 Motivation

#### 2.2.2 Open Questions

#### 2.2.3 Method

#### 2.2.4 Expected Outcomes

#### 2.2.5 Accomplished Work and Preliminary Results

# REFERENCES

- [Abualnaja et al., 2015] Abualnaja, Y., Papadopoulos, V. P., Josey, S. A., Hoteit, I., Kontoyiannis, H., and Raitsos, D. E. (2015). Impacts of climate modes on air-sea heat exchange in the red sea. *Journal of Climate*, page 150106132132005.
- [Acker et al., 2008] Acker, J., Leptoukh, G., Shen, S., Zhu, T., and Kempler, S. (2008). Remotely-sensed chlorophyll a observations of the northern red sea indicate seasonal variability and influence of coastal reefs. *Journal of Marine Systems*, 69(3-4):191–204.
- [Alvera-Azcarate et al., 2007] Alvera-Azcarate, A., Barth, A., Beckers, J. M., and Weisberg, R. H. (2007). Multivariate reconstruction of missing data in sea surface temperature, chlorophyll, and wind satellite fields. *Journal of Geophysical Research-Oceans*, 112(C3).
- [Anderson, 2005] Anderson, T. R. (2005). Plankton functional type modelling: running before we can walk? *Journal of Plankton Research*.
- [Beckers and Rixen, 2003] Beckers, J. M. and Rixen, M. (2003). EOF calculations and data filling from incomplete oceanographic datasets. *Journal of Atmospheric and Oceanic Technology*, 20(12):1839–1856.
- [Brewin et al., 2013] Brewin, R. J. W., Raitsos, D. E., Pradhan, Y., and Hoteit, I. (2013). Comparison of chlorophyll in the Red Sea derived from MODIS-Aqua and in vivo fluorescence. *Remote Sensing of Environment*, 136:218–224.
- [Brown et al., 2000] Brown, P. E., Karesen, K. F., Roberts, G. O., and Tonellato, S. (2000). Blur-generated non-separable space-time models. *Journal of the Royal Statistical Society Series B-Statistical Methodology*, 62:847–860.
- [Butenschon and Zavatarelli, 2012] Butenschon, M. and Zavatarelli, M. (2012). A comparison of different versions of the SEEK Filter for assimilation of biogeochemical data in numerical models of marine ecosystem dynamics. *Ocean Modelling*, 54-55:37–54.

- [Camps-Valls et al., 2006] Camps-Valls, G., Gomez-Chova, L., Munoz-Mari, J., Vila-Frances, J., Amoros-Lopez, J., and Calpe-Maravilla, J. (2006). Retrieval of oceanic chlorophyll concentration with relevance vector machines. *Remote Sensing of Environment*, 105(1):23–33.
- [Ciavatta et al., 2014] Ciavatta, S., Torres, R., Martinez-Vicente, V., Smyth, T., Dall’Olmo, G., Polimene, L., and Allen, J. I. (2014). Assimilation of remotely-sensed optical properties to improve marine biogeochemistry modelling. *Progress in Oceanography*, 127:74–95.
- [Ciavatta et al., 2011] Ciavatta, S., Torres, R., Saux-Picart, S., and Allen, J. I. (2011). Can ocean color assimilation improve biogeochemical hindcasts in shelf seas? *Journal of Geophysical Research-Oceans*, 116.
- [Cressie and Huang, 1999] Cressie, N. and Huang, H.-C. (1999). Classes of nonseparable, spatio-temporal stationary covariance functions. *Journal of the American Statistical Association*, 94(448):1330–1339.
- [Fontana et al., 2013] Fontana, C., Brasseur, P., and Brankart, J. M. (2013). Toward a multivariate reanalysis of the North Atlantic Ocean biogeochemistry during 1998-2006 based on the assimilation of SeaWiFS chlorophyll data. *Ocean Science*, 9(1):37–56.
- [Gneiting, 2002] Gneiting, T. (2002). Nonseparable, stationary covariance functions for spacetime data. *Journal of the American Statistical Association*, 97(458):590–600.
- [Gneiting et al., 2007] Gneiting, T., Genton, M. G., and Guttorp, P. (2007). Geostatistical space-time models, stationarity, separability, and full symmetry. *Statistical Methods for Spatio-Temporal Systems*, 107:151–175.
- [Gneiting and Guttorp, 2010] Gneiting, T. and Guttorp, P. (2010). Continuous parameter spatio-temporal processes. *Handbook of Spatial Statistics*, 97:427–436.
- [Gokaraju et al., 2011] Gokaraju, B., Durbha, S. S., King, R. L., and Younan, N. H. (2011). A machine learning based spatio-temporal data mining approach for detection of harmful algal blooms in the Gulf of Mexico. *Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 4(3):710–720.

- [Handcock and Wallis, 1994] Handcock, M. S. and Wallis, J. R. (1994). An approach to statistical spatial-temporal modeling of meteorological fields. *Journal of the American Statistical Association*, 89(426):368–378.
- [Hohn et al., 1993] Hohn, M. E., Liebhold, A. M., and Gribko, L. S. (1993). Geostatistical model for forecasting spatial dynamics of defoliation caused by the gypsy moth (lepidoptera: Lymantriidae). *Environmental Entomology*, 22(5):1066–1075.
- [Jeong et al., 2006] Jeong, K. S., Kim, D. K., and Joo, G. J. (2006). River phytoplankton prediction model by artificial neural network: Model performance and selection of input variables to predict time-series phytoplankton proliferations in a regulated river system. *Ecological Informatics*, 1(3):235–245.
- [Kim et al., 2014] Kim, Y. H., Im, J., Ha, H. K., Choi, J. K., and Ha, S. (2014). Machine learning approaches to coastal water quality monitoring using GOCI satellite data. *Geoscience & Remote Sensing*, 51(2):158–174.
- [Korres et al., 2012] Korres, G., Triantafyllou, G., Petihakis, G., Raitzos, D. E., Hoteit, I., Pollani, A., Colella, S., and Tsiaras, K. (2012). A data assimilation tool for the Pagasitikos Gulf ecosystem dynamics: Methods and benefits. *Journal of Marine Systems*, 94:S102–S117.
- [Lee et al., 2003] Lee, J. H. W., Huang, Y., Dickman, M., and Jayawardena, A. W. (2003). Neural network modelling of coastal algal blooms. *Ecological Modelling*, 159(2-3):179–201.
- [Mann and Lazier, 2006] Mann, K. H. and Lazier, J. R. N. (2006). *Dynamics of marine ecosystems: Biological-Physical Interactions in the Oceans*. Blackwell Publishing.
- [Miles and He, 2010] Miles, T. N. and He, R. (2010). Temporal and spatial variability of Chl-a and SST on the South Atlantic Bight: Revisiting with cloud-free reconstructions of MODIS satellite imagery. *Continental Shelf Research*, 30(18):1951–1962.
- [Mulia et al., 2013] Mulia, I. E., Tay, H., Roopsekhar, K., and Tkalich, P. (2013). Hybrid ANN-GA model for predicting turbidity and chlorophyll-a concentrations. *Journal of Hydro-Environment Research*, 7(4):279–299.
- [North et al., 2011] North, G. R., Wang, J., and Genton, M. G. (2011). Correlation models for temperature fields. *Journal of Climate*, 24(22):5850–5862.

- [Pal, 2014] Pal, R. (2014). *An introduction to phytoplanktons : diversity and ecology*. Springer, New York.
- [Pettersson and Pozdniakov, 2013] Pettersson, L. H. and Pozdniakov, D. V. (2013). *Monitoring of harmful algal blooms*. Springer-Praxis books in geophysical sciences. Springer, published in association with Praxis Publishing, Chichester, UK.
- [Racault et al., 2015] Racault, M. F., Raitsos, D. E., Berumen, M. L., Brewin, R. J., Platt, T., Sathyendranath, S., and Hoteit, I. (2015). Phytoplankton phenology indices in coral reef ecosystems: application to ocean-colour observations in the red sea. *Submitted*.
- [Raitsos et al., 2011] Raitsos, D. E., Hoteit, I., Prihartato, P. K., Chronis, T., Triantafyllou, G., and Abualnaja, Y. (2011). Abrupt warming of the red sea. *Geophysical Research Letters*, 38(14).
- [Raitsos et al., 2013] Raitsos, D. E., Pradhan, Y., Brewin, R. J., Stenchikov, G., and Hoteit, I. (2013). Remote sensing the phytoplankton seasonal succession of the Red Sea. *PLoS One*, 8(6).
- [Richlen et al., 2010] Richlen, M. L., Morton, S. L., Jamali, E. A., Rajan, A., and Anderson, D. M. (2010). The catastrophic 2008-2009 red tide in the arabian gulf region, with observations on the identification and phylogeny of the fish-killing dinoflagellate *cochlo dinium polykrikoides*. *Harmful Algae*, 9(2):163–172.
- [Robinson, 2010] Robinson, I. S. (2010). *Discovering the ocean from space : the unique applications of satellite oceanography*. Springer praxis series geophysical sciences 4110. Springer, New York, 1st edition.
- [Sirjacobs et al., 2011] Sirjacobs, D., Alvera-Azcrate, A., Barth, A., Lacroix, G., Park, Y., Nechad, B., Ruddick, K., and Beckers, J.-M. (2011). Cloud filling of ocean colour and sea surface temperature remote sensing products over the southern north sea by the data interpolating empirical orthogonal functions methodology. *Journal of Sea Research*, 65(1):114–130.
- [Stein, 2005] Stein, M. L. (2005). Spacetime covariance functions. *Journal of the American Statistical Association*, 100(469):310–321.
- [Steinmetz et al., 2011] Steinmetz, F., Deschamps, P. Y., and Ramon, D. (2011). Atmospheric correction in presence of sun glint: application to meris. *Optics Express*, 19(10):9783–9800.

- [Taylor et al., 2013] Taylor, M. H., Losch, M., Wenzel, M., and Schroter, J. (2013). On the sensitivity of field reconstruction and prediction using empirical orthogonal functions derived from gappy data. *Journal of Climate*, 26(22):9194–9205.
- [Tett and Barton, 1995] Tett, P. and Barton, E. D. (1995). Why are there about 5000 species of phytoplankton in the sea. *Journal of Plankton Research*, 17(8):1693–1704.
- [Triantafyllou et al., 2013] Triantafyllou, G., Hoteit, I., Luo, X., Tsiaras, K., and Petihakis, G. (2013). Assessing a robust ensemble-based Kalman filter for efficient ecosystem data assimilation of the Cretan Sea. *Journal of Marine Systems*, 125:90–100.
- [Triantafyllou et al., 2014] Triantafyllou, G., Yao, F., Petihakis, G., Tsiaras, K. P., Raitsos, D. E., and Hoteit, I. (2014). Exploring the red sea seasonal ecosystem functioning using a three-dimensional biophysical model. *Journal of Geophysical Research: Oceans*, 119(3):1791–1811.
- [Waite and Mueter, 2013] Waite, J. N. and Mueter, F. J. (2013). Spatial and temporal variability of chlorophyll-a concentrations in the coastal Gulf of Alaska, 1998–2011, using cloud-free reconstructions of SeaWiFS and MODIS-Aqua data. *Progress in Oceanography*, 116:179–192.
- [Wang and Yang, 2013] Wang, H. and Yang, X. (2013). Prediction and elucidation of algal dynamic variation in Gonghu Bay by using artificial neural networks and canonical correlation analysis.
- [Weikert, 1987] Weikert, H. (1987). *Plankton and the pelagic environment*, pages 90–111. Pergamon Press, Oxford.
- [Wu et al., 2014] Wu, N. C., Huang, J. C., Schmalz, B., and Fohrer, N. (2014). Modeling daily chlorophyll a dynamics in a german lowland river using artificial neural networks and multiple linear regression approaches. *Limnology*, 15(1):47–56.
- [Yao et al., 2014] Yao, F. C., Hoteit, I., Pratt, L. J., Bower, A. S., Kohl, A., Gopalakrishnan, G., and Rivas, D. (2014). Seasonal overturning circulation in the red sea: 2. winter circulation. *Journal of Geophysical Research-Oceans*, 119(4):2263–2289.
- [Zhai and Bower, 2013] Zhai, P. and Bower, A. (2013). The response of the red sea to a strong wind jet near the tokar gap in summer. *Journal of Geophysical Research-Oceans*, 118(1):422–434.

- [Zhan et al., 2014] Zhan, P., Subramanian, A. C., Yao, F. C., and Hoteit, I. (2014). Eddies in the red sea: A statistical and dynamical study. *Journal of Geophysical Research-Oceans*, 119(6):3909–3925.



# APPENDICES

## A Appendix A Title

Detailed experimental procedures, data tables, computer programs, etc. may be placed in appendices. This may be particularly appropriate if the dissertation or thesis includes several published papers.



## **B    Appendix B Title**

Your content goes here.



## C Papers Submitted and Under Preparation

- Author 1 Name, Author 2 Name, and Author 3 Name, “Article Title”, *Submitted to Conference/Journal Name*, further attributes.
- Author 1 Name, Author 2 Name, and Author 3 Name, “Article Title”, *Submitted to Conference/Journal Name*, Mon. Year.