Phytoplankton ecology and production of the Red Sea off Jiddah, Saudi Arabia

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PHYTOPLANKTON ECOLOGY AND PRODUCTION OF THE RED SEA
OFF JIDDAH, SAUDI ARABIA
VOLUME 1

by
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College of Oceanography
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A Thesis
Presented to
The Faculty of Science
of
The Open University
(In Two Volumes)

In partial fulfilment of requirements
for the degree of
Doctor of Philosophy
October, 1981

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IN THE NAME OF GOD

MOST MERCIFUL, MOST BENEFICENT

BLESSINGS OF ALLAH MAY BE UPON

OUR MESSENGER MOHAMMED

AND HIS COMPANIONS AND HIS UMMAH
Attention:

Members of Senate, The Open University
Dr. M.E. Varley, Department of Biology, The Open University.

As required according to "Schedule M to the General Regulations", and "Rules relating to the Submission of Dissertations and Theses for Higher Degrees", (Pages 45-46, Postgraduate Prospectus and Student Handbook 1982, Section Ph.D.12).

I hereby declare and state that no part of the material contained in my thesis entitled

"Phytoplankton Ecology and Production of the Red Sea off Jiddah, Saudi Arabia",

which I have submitted to The Open University in partial fulfilment of the Ph.D. degree, has been submitted by me to this or any other University for any degree. In addition, no part of this thesis has been, or will be submitted by any other candidate to any other University for any degree.

I further declare that none of the material contained in my thesis is yet published, but that preparations for publication are being made.
The Red Sea, being a landlocked, semi-enclosed body of water located in an arid zone where evaporation is far in excess of precipitation and run-off, offers a unique ecosystem from the tropical region. During 1977-78 off Jiddah, physical, chemical and biological data were collected at an eutrophicated inshore Sharm station and a relatively unpolluted offshore station. The prevailing high temperatures, high salinity and lack of land drainage resulted in highly stratified dense waters with little or no vertical admixture. There was not always an abundant supply of nutrients in these waters but, due to monsoonal activity, domes of high phosphate, silicates, nitrates and ammonia were noticed both in the offshore and inshore waters. Biological production, measured as phytoplankton cell numbers, chlorophyll a and primary production, also increased usually with a time-lag between the nutrients and production. Depending on the monsoonal currents, periodic recruitment and exchange of Red Sea component, Mediterranean component,
Nile estuarine component and Indo-Pacific components of phytoplankton takes place. The annual phytoplankton cycle follows a bimodal pattern with the peaks of production coinciding with the activity of the monsoons.

The magnitude of production was higher in the offshore waters and the production in the study area was higher than in several temperate and tropical waters. The high carbon assimilation ratios suggest a high efficiency of photosynthesis characteristic of sun-adapted phytoplankton. Based on the photosynthetic production, it is speculated that a rich fishery potential exists in the Red Sea.
ACKNOWLEDGMENTS AND DEDICATIONS

To acknowledge all those who made it possible for me to complete this work would be impossible, and they know themselves well.

The spirit of my departed father, to whom perfection and aspiration to the best was the goal of a lifetime dedicated to the betterment of mankind, was always and will remain a motivating force.

To Shaikh Muhammed Mutawalli Sharawi, whose guidance and example-setting will always be a most enriching and determining factor in my life.

To Dr. Abdullah Nasseef, whose friendship is more real than many brotherhoods.

To Dr. Naieem Dewidar, whose supervision and constant help and understanding made it possible for me to bring this work to light.

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To all my associates, colleagues and friends at King Abdulaziz University, to whom I owe a great deal of success in my practical life which is consequently reflected in this work. Especially to the man who knows the Red Sea better than the palm of his own hand, Mohammed Sayeed, who was with me from the first day and who, along with his colleagues, helped a great deal in collecting the data, maintaining the boats and made sure I was always in the right location.

To Angela and Rosemary, without whose unfailing dedication, hard work and sleepless nights I could not have come through with this.

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF TABLES</th>
<th>vi</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xii</td>
</tr>
<tr>
<td>PREFACE AND SUMMARY</td>
<td>xiii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>DESCRIPTION OF STUDY AREA</td>
<td>7</td>
</tr>
<tr>
<td>Geography and Location</td>
<td>7</td>
</tr>
<tr>
<td>Climatic Conditions</td>
<td>8</td>
</tr>
<tr>
<td>Circulation Pattern in the Red Sea</td>
<td>9</td>
</tr>
<tr>
<td>Land-drainage and Pollutants in the Jiddah area</td>
<td>10</td>
</tr>
<tr>
<td>MATERIALS AND METHODS</td>
<td>14</td>
</tr>
<tr>
<td>Sampling Programme</td>
<td>14</td>
</tr>
<tr>
<td>Physico-Chemical Methods</td>
<td>16</td>
</tr>
<tr>
<td>1. Temperature</td>
<td>16</td>
</tr>
<tr>
<td>2. Salinity</td>
<td>17</td>
</tr>
<tr>
<td>3. In situ Density (σt)</td>
<td>17</td>
</tr>
<tr>
<td>4. Sea Water Transparency</td>
<td>17</td>
</tr>
<tr>
<td>5. Dissolved Oxygen</td>
<td>18</td>
</tr>
<tr>
<td>6. Oxygen Saturation</td>
<td>18</td>
</tr>
<tr>
<td>7. pH</td>
<td>18</td>
</tr>
<tr>
<td>8. Alkalinity and Total Carbon Dioxide</td>
<td>19</td>
</tr>
<tr>
<td>9. Soluble Reactive Phosphorus (SRP)</td>
<td>19</td>
</tr>
</tbody>
</table>
Table of Contents. Continued.

10. Reactive Silicate (SiO$_2$) ............. 19
11. Nitrite (NO$_2$) ..................... 19
12. Ammonia (NH$_3$) ................... 19

Biological Methods ..................... 21
1. Qualitative and Quantitative Examination of Phytoplankton ............. 21
2. Species Diversity Index ............. 22
3. Photosynthetic Pigments ............. 22
4. Carbon Assimilation ................. 24

Statistical Methods .................... 26

RESULTS .................................. 28

Physico-Chemical Data ................. 28
1. Temperature ......................... 28
2. Salinity ............................. 30
3. Density Structure .................... 32
4. Transparency ......................... 35
5. Dissolved Oxygen ..................... 36
6. Soluble Reactive Phosphorus ........ 38
7. Silicate ............................. 40
8. Nitrite ............................... 42
9. Ammonia ............................. 44
10. Relationships between Salinity, Silicate and Phosphate ............... 45

Biological Data ......................... 46
1. Seasonal Composition of The Major Groups of Phytoplankton and Diversity Indices .. 46
Table of Contents. Continued.

2. Quantitative Abundance of Phytoplankton ........ 49
3. Seasonal Species Composition ...................... 53
4. Phytoplankton Pigments ............................ 62
5. Primary Production ................................ 65
6. Carbon Assimilation Ratios (mgC mgChla\(^{-1}\) hr\(^{-1}\)) .... 68
7. Inter-relationships of Physico-Chemical and Biological Data .... 70

DISCUSSION ............................................. 71
The Physico-Chemical Environment ..................... 71
Phytoplankton Ecology ................................ 81
1. Biogeography of Phytoplankton ....................... 82
2. Phytoplankton Succession ........................... 90
3. Factors influencing Phytoplankton Production ......... 91
4. Magnitude of Phytoplankton Biomass and Cell Densities .... 96
5. Magnitude of Primary Production ................... 97
6. Duration Range and Amplitude of Primary Production .... 99
7. Annual Phytoplankton Cycle and Production Estimates for the Red Sea .... 100

SUMMARY AND CONCLUSIONS ............................ 105
REFERENCES ............................................ 110
TABLES .................................................... 122
FIGURES .................................................. 148
Table of Contents. Continued.

<table>
<thead>
<tr>
<th>APPENDICES</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 10 (Repeated)</td>
<td>150</td>
</tr>
<tr>
<td>Figure 11 (Repeated)</td>
<td>151</td>
</tr>
<tr>
<td>Figures 6 to 9 and 13 to 24 TRANSPARENCIES</td>
<td>REAR POCKET</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Climatic data at Jiddah based on observations for the period 1966-1976</td>
<td>122</td>
</tr>
<tr>
<td>2. Maxima and minima of physico-chemical variables at the Sharm and offshore stations</td>
<td>123</td>
</tr>
<tr>
<td>3. Seasonal phytoplankton abundances (cells l⁻¹) and percentage composition of major groups at the Sharm station</td>
<td>123</td>
</tr>
<tr>
<td>4. Seasonal phytoplankton abundances (cells l⁻¹) and percentage composition of major groups at the offshore station</td>
<td>127</td>
</tr>
<tr>
<td>5. Maximum and minimum values of biological variables and parameters at the Sharm and offshore station</td>
<td>130</td>
</tr>
<tr>
<td>6. Correlation matrix (Pearson's r) of chemical and biological variables and parameters at the Sharm station (n ≥64; P &lt;0.05; * not significant)</td>
<td>131</td>
</tr>
<tr>
<td>7. Correlation matrix (Pearson's r) of chemical and biological variables and parameters at the offshore station (n ≥65; P &lt;0.05; * not significant)</td>
<td>132</td>
</tr>
<tr>
<td>8. Comparison of inorganic phosphate values (μg-at l⁻¹) from some selected regions</td>
<td>133</td>
</tr>
<tr>
<td>9. Comparison of silicate values (μg-t l⁻¹) from some selected regions</td>
<td>134</td>
</tr>
<tr>
<td>10. Comparison of nitrite values (μg-t l⁻¹) from some selected regions</td>
<td>135</td>
</tr>
<tr>
<td>11. Comparison of ammonia values (μg-t l⁻¹) from some selected regions</td>
<td>136</td>
</tr>
<tr>
<td>12. Composition of phytoplankton blooms in the Red Sea</td>
<td>137</td>
</tr>
<tr>
<td>13. Comparison of abundance of phytoplankton cell numbers from selected regions (cell nos l⁻¹)</td>
<td>138</td>
</tr>
<tr>
<td>14. Comparison of chlorophyll a (μg l⁻¹) from selected regions</td>
<td>140</td>
</tr>
</tbody>
</table>
List of Tables. Continued

<table>
<thead>
<tr>
<th>Table Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Comparison of primary production ((C_{14} \text{ method})) from selected regions</td>
<td>141</td>
</tr>
<tr>
<td>16</td>
<td>Comparison of carbon assimilation ratios ((\text{mg C mg Chl} \ a^{-1} \ \text{hr}^{-1})) from selected regions</td>
<td>143</td>
</tr>
<tr>
<td>17</td>
<td>Comparison of duration, range and amplitude of primary production during major phytoplankton blooms in selected regions</td>
<td>145</td>
</tr>
<tr>
<td>18</td>
<td>Period of occurrence of phytoplankton blooms in the Red Sea area</td>
<td>147</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The Red Sea showing major geographic features</td>
<td>148</td>
</tr>
<tr>
<td>2.</td>
<td>Study area showing location of inshore (Sharm) and offshore stations</td>
<td>149</td>
</tr>
<tr>
<td>3.</td>
<td>Showing the major coastal features of the City of Jiddah</td>
<td>150</td>
</tr>
<tr>
<td>4.</td>
<td>Lithography and sediment types around Sharm-Obhur</td>
<td>151</td>
</tr>
<tr>
<td>5.</td>
<td>Monthly mean wind velocities (nautical miles per 24 hrs) for the Red Sea area. Compass vectors indicate frequency of direction and sum to 100%</td>
<td>152</td>
</tr>
<tr>
<td>6.</td>
<td>Seasonal temperature distribution at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10)</td>
<td>153</td>
</tr>
<tr>
<td>7.</td>
<td>Seasonal temperature distribution at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11)</td>
<td>154</td>
</tr>
<tr>
<td>8.</td>
<td>Seasonal salinity (°/o) distribution at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10)</td>
<td>155</td>
</tr>
<tr>
<td>9.</td>
<td>Seasonal salinity (°/o) distribution at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11)</td>
<td>156</td>
</tr>
<tr>
<td>10.</td>
<td>Seasonal density (ct) distribution at the Sharm station</td>
<td>157</td>
</tr>
<tr>
<td>11.</td>
<td>Seasonal density (ct) distribution at the offshore station</td>
<td>158</td>
</tr>
<tr>
<td>12.</td>
<td>Seasonal changes in Secchi disc visibility at the Sharm and offshore stations</td>
<td>159</td>
</tr>
<tr>
<td>13.</td>
<td>Seasonal distribution of dissolved oxygen at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10)</td>
<td>160</td>
</tr>
</tbody>
</table>
List of Figures. Continued.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>14. Seasonal distribution of percent (°/₀) oxygen saturation at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10)</td>
<td>161</td>
</tr>
<tr>
<td>15. Seasonal distribution of dissolved oxygen at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11)</td>
<td>162</td>
</tr>
<tr>
<td>16. Seasonal distribution of percent (°/₀) oxygen saturation at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11)</td>
<td>163</td>
</tr>
<tr>
<td>17. Seasonal distribution of soluble reactive phosphorus (PO₄-P) at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10)</td>
<td>164</td>
</tr>
<tr>
<td>18. Seasonal distribution of soluble reactive phosphorus (PO₄-P) at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY FIGURE 11)</td>
<td>165</td>
</tr>
<tr>
<td>19. Seasonal distribution of reactive silicate (SiO₂) at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10)</td>
<td>166</td>
</tr>
<tr>
<td>20. Seasonal distribution of reactive silicate (SiO₂) at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11)</td>
<td>167</td>
</tr>
<tr>
<td>21. Seasonal distribution of nitrite (NO₂) at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10)</td>
<td>168</td>
</tr>
<tr>
<td>22. Seasonal distribution of nitrite (NO₂) at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11)</td>
<td>169</td>
</tr>
<tr>
<td>23. Seasonal distribution of ammonia (NH₄) at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10)</td>
<td>170</td>
</tr>
<tr>
<td>24. Seasonal distribution of ammonia (NH₄) at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11)</td>
<td>171</td>
</tr>
<tr>
<td>25. Salinity (°/₀) - reactive silicate (Si) relationships and water masses in the study area</td>
<td>172</td>
</tr>
</tbody>
</table>
List of Figures. Continued.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>26. Seasonal distribution of reactive silicate: soluble reactive phosphorus ratios at the Sharm station</td>
<td>173</td>
</tr>
<tr>
<td>27. Seasonal distribution of reactive silicate: soluble reactive phosphorus ratios at the offshore station</td>
<td>174</td>
</tr>
<tr>
<td>28. Seasonal composition of the phytoplankton by major groups at the Sharm station</td>
<td>175</td>
</tr>
<tr>
<td>29. Seasonal variation in diversity indices of the phytoplankton community at the Sharm station, for surface (0) and 30 m depths, and total water column</td>
<td>176</td>
</tr>
<tr>
<td>30. Seasonal composition of the phytoplankton by major groups at the offshore station</td>
<td>177</td>
</tr>
<tr>
<td>31. Seasonal variation in diversity indices of the phytoplankton community at the offshore station, for surface (0), 100 m and 200 m depths, and total water column</td>
<td>178</td>
</tr>
<tr>
<td>32. Seasonal abundances of phytoplankton cells by major groups at the Sharm station</td>
<td>179</td>
</tr>
<tr>
<td>33. Examples of vertical distributions of the major phytoplankton groups at the Sharm station</td>
<td>180</td>
</tr>
<tr>
<td>34. Seasonal abundances of phytoplankton cells by major groups at the offshore station</td>
<td>181</td>
</tr>
<tr>
<td>35. Examples of vertical distributions of the major phytoplankton groups at the offshore station</td>
<td>182</td>
</tr>
<tr>
<td>36. Seasonal profiles of chlorophyll a concentration at the Sharm station</td>
<td>183</td>
</tr>
<tr>
<td>37. Seasonal profiles of chlorophyll b concentration at the Sharm station</td>
<td>184</td>
</tr>
<tr>
<td>38. Seasonal profiles of chlorophyll a concentration at the offshore station</td>
<td>185</td>
</tr>
<tr>
<td>39. Seasonal profiles of chlorophyll b concentration at the offshore station</td>
<td>186</td>
</tr>
<tr>
<td>40. Seasonal variations in vertical profiles of carbon fixation (primary production rate) at the Sharm station</td>
<td>187</td>
</tr>
</tbody>
</table>
### List of Figures. Continued.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>41. Seasonal variations in vertical profiles of carbon fixation (primary production rate) at the offshore station</td>
<td>188</td>
</tr>
<tr>
<td>42. Integral primary production rates at the Sharm and offshore stations</td>
<td>189</td>
</tr>
<tr>
<td>43. Carbon assimilation ratios (mgC mg Chla$^{-1}$ hr$^{-1}$) at the Sharm station</td>
<td>190</td>
</tr>
<tr>
<td>44. Carbon assimilation ratios (mgC mg Chla$^{-1}$ hr$^{-1}$) at the offshore station</td>
<td>191</td>
</tr>
</tbody>
</table>
# LIST OF APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>VOLUME TWO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix</td>
<td>Page</td>
</tr>
<tr>
<td>1A. PHYSICAL, CHEMICAL AND BIOLOGICAL DATA</td>
<td>1</td>
</tr>
<tr>
<td>Sharm station</td>
<td></td>
</tr>
<tr>
<td>1B. PHYSICAL, CHEMICAL AND BIOLOGICAL DATA</td>
<td>8</td>
</tr>
<tr>
<td>offshore station</td>
<td></td>
</tr>
<tr>
<td>2. PHYTOPLANKTON SPECIES RECORDED IN THE REGION OF JIDDAH, 1977-1978 Sharm station - Abundance in cells/l (Van Dorn bottle collections)</td>
<td>15</td>
</tr>
<tr>
<td>3. PHYTOPLANKTON SPECIES RECORDED IN THE REGION OF JIDDAH, 1977-1978 offshore station - Abundance in cells/l (Van Dorn bottle collections)</td>
<td>49</td>
</tr>
<tr>
<td>4. PHYTOPLANKTON SPECIES RECORDED IN THE REGION OF JIDDAH, 1977-1978 (Van Dorn bottle collections and plankton hauls) Sharm Station</td>
<td>86</td>
</tr>
<tr>
<td>5. PHYTOPLANKTON SPECIES RECORDED IN THE REGION OF JIDDAH, 1977-1978 (Van Dorn bottle collections and plankton hauls) offshore station</td>
<td>106</td>
</tr>
<tr>
<td>7. ADDITIONS TO THE PHYTOPLANKTON TAXONOMIC LIST FOR THE RED SEA FROM THE PRESENT STUDY</td>
<td>138</td>
</tr>
<tr>
<td>8. REFERENCES USED IN COMPILING THE PHYTOPLANKTON SPECIES LIST IN THE REGION OF JIDDAH 1977-78</td>
<td>143</td>
</tr>
<tr>
<td>9. DIVERSITY INDICES FOR DIATOMS AND DINOFLAGELLATES IN THE REGION OF JIDDAH (Sharm station) DURING THE PERIOD NOVEMBER 1977 TO OCTOBER 1978</td>
<td>146</td>
</tr>
<tr>
<td>10. DIVERSITY INDICES FOR DIATOMS AND DINOFLAGELLATES IN THE REGION OF JIDDAH (offshore station) DURING THE PERIOD NOVEMBER 1977 TO OCTOBER 1978</td>
<td>148</td>
</tr>
</tbody>
</table>
PREFACE AND SUMMARY

Although the Red Sea has been important to the Arabs in their commerce since medieval times its oceanographic significance remained unrecognized until the Austrian Expedition Pola in 1895. Modern oceanography in the Red Sea region is in its infancy even today. Systematic investigations on the hydrography, plankton production and fishery production extended over a long period are not available.

In the last decade, the threat of increasing oil pollution, industrial and urban effluents and other manmade perturbations to the coastal marine ecosystems was recognized, and several marine science activities were initiated in the Red Sea area. At Jiddah, Saudi Arabia, King Abdulaziz University added an "Institute of Marine Sciences".

The present study was carried out during 1977-1978, while at King Abdulaziz University. Observations were made on a regular basis at two stations: an inshore station which receives pollutants, and an offshore station which is relatively unpolluted.

The results of this study are presented in this thesis and can be summarised as follows:
After a general introduction, a brief account of the study area is given, including a description of circulation patterns in the Red Sea. Methodology employed in this study is also presented. Data on temperature, salinity, density, transparency, dissolved oxygen, inorganic phosphate, silicate, nitrite and ammonia are presented and discussed. The semi-enclosed nature of the Red Sea, in an arid zone where the evaporation is far in excess of precipitation and run-off, is reflected in the hydographical conditions of the Red Sea. Nutrients such as phosphates, silicates and nitrites appear to be at a low level which could be attributed either to lack of input through rainfall and land drainage, or to rapid utilization by phytoplankton, or both.

Based on their abundances, four categories of phytoplankton were recognised: (a) those common in the inshore and offshore waters during the major bloom, (b) those common during the minor bloom, (c) those common to the major and minor bloom, and (d) those restricted to either of the blooms.

Based on the biogeography of 163 phytoplankton taxa, 10 floral elements were recognised in the study area. Succession patterns of the major phytoplankton groups: diatoms, dinoflagellates, and blue-green algae are discussed. Statistical correlations between physical, chemical and biological data are also presented and discussed.

A comparison of the magnitude of phytoplankton biomass, determined as cell numbers and chlorophyll a, with other temperate and tropical seas is made; the values obtained in
this study compare favourably with those reported from other tropical waters.

Primary production data (carbon-14 method) showed a bimodal peak distribution with a two month time lag between the inshore and offshore waters. Primary production and carbon assimilation rates in the study area compare favourably with some of the high values from tropical and temperate waters.

Based on the duration, range and amplitude of primary production, it is concluded that Red Sea waters resemble some of the other productive tropical seas.

Employing several conversion factors and assumed transfer coefficients, the primary production from the whole Red Sea has been converted to tertiary production. The calculated potential annual tertiary production from the Red Sea is between about 5-9 x 10^6 tons of fish which is higher than the fish landings reported by FAO.

In the light of the present data, the possible scope of future investigations in the Red Sea area is briefly discussed.
INTRODUCTION

Biological oceanographic studies on phytoplankton and primary organic production have been much more extensive in temperate and sub-Artic seas than in tropical waters. Ryther (1963), Platt and Subba Rao (1973), Parsons and Takahashi (1973), Fogg (1975), Cushing (1978), and Dunbar (1979) have presented excellent reviews on this subject. Recent investigations of Ryther et al. (1966), Ryther and Menzel (1965), El-Sayed and Turner (1977) and Qasim (1977) have shown that contrary to earlier beliefs, the magnitude of primary production in tropical and sub-tropical waters can be as high as that of temperate and sub-Artic seas. Conclusions drawn from temperate and sub-Artic waters cannot be uncritically applied to tropical seas; there is a clear need at this time to examine differences and similarities between temperate and tropical systems.

One interesting sub-tropical area which has received relatively little biological attention is the Red Sea. Hydrographic investigations in the Red Sea were first carried out by the Austrian Expedition Pola in 1895 and subsequently a number of expeditions carried out investigations. Although the physical and chemical oceanography of the Red Sea has been extensively reviewed by Morcos (1970), biological oceanography has received far less attention.
Marine biological studies in the Red Sea area date back to 1895 when the Pola expedition collected information on planktonic crustacea such as the Copepoda, Ostracoda and Amphipoda (see Halim 1969). Other zooplankton groups, including the Euphausiacea, Mysidacea, Sergestidae, Tomopteridae, Chaetognatha and planktonic larvae were also studied by Ammiraglio Magnaghi (1923-24). The German Deep Sea Expedition Valdivia and the John Murray Expedition (1933-34) have also collected information on microplankton, medusae and copepoda. The review of Halim (1969) gives details on the species distribution of zooplankton; he concluded that, contrary to the general impression, the variety and abundance of the standing crop of zooplankton in the Red Sea is high. Halim (1969) is of the opinion that, during the northeast monsoon the largest number of species are transported into the Red Sea from the Gulf of Aden, and during hot summer months the epipelagic species sink to deeper levels.

Ponomareva (1968) observed that out of 22 species of euphausids of the Indian Ocean, 10 are present in the Red Sea, and most of them are transported from the Gulf of Aden. The pteropod fauna (Frontier 1963) and pelagic tunicate fauna (Fenaux 1973) appear to be rich in the Red Sea and Gulf of Aden when compared to the Persian Gulf. In general, there is a predominance of the tropical Indo-Pacific zooplankters in the Red Sea. Cohen (1973) and Steinitz (1973) concluded that the Red Sea has a large element of Indo-Pacific fish fauna with distinct areas of endemism; the percentage of
endemic species increases in a northerly direction. The fish fauna of the Red Sea is richer than that of the Persian Gulf.

Fishelson (1973a, 1973b) reviewed the earlier work on the coral reef tables in the Red Sea. In the Gulf of Aqaba and the Gulf of Suez along the shallow sub-tidal region, fringing type corals predominate and two species of *Millepora* (*M. dichotoma* and *M. platyphyla*) constitute about 40% of the total reef formers. Fishelson (1973a) postulated that a high level of species diversity is maintained by prevention of overcrowding due to desiccation during periods of extreme low water, and by the regeneration capacity of the corals. The frequent oil spills and phosphate dust that stimulate the growth of the algae, seem to cause a high mortality of the corals in the Gulf of Aqaba (Fishelson 1973b).

Distribution of the majority of species in the coral reef communities seems to be determined by the light intensity (Schuhmacher 1973) on the coasts of Eilat, Dahab, Sharm el Sheikh and Aqaba on the Jordanian coast. Loya (1972) also observed a depth-dependent species ensemble of various corals.

Biomass of the zoobenthos is about 50g m$^{-2}$ in the southern part of the Red Sea and consists predominantly of seston feeders (60 to 90%) such as flat urchins, holothurians, bivalves and amphipods, while the detritus feeders (e.g. polychaetes such as Maldanidae), contribute only about 5g m$^{-2}$, (Neyman and Kondritskiy 1974). Such an oligotrophic zoobenthos was attributed to the prevailing high temperatures (>11°C) at the bottom. In the Red Sea region there are three
main fisheries of economic value: pelagic or midwater fisheries consisting of sardines, anchovy, mackerel and barracuda; demersal or bottom fisheries consisting of a great variety of species; and the shrimp fishery represented by species of Penaeus, (Botros 1971). The total annual catch is about $5.3 \times 10^5$ metric tons (FAO 1978) whereas the annual potential yield of the demersal fishery alone is considered to be at least $6.0 \times 10^5$ metric tons (Gulland 1970).

The review by Halim (1969) showed that phytoplankton studies in the Red Sea were mostly qualitative in nature. There was a paucity of diatoms during the warm season (March - May) and a maximum of 62 species was recorded during the winter months (November-February). There were only 13 species recorded south of 20°N. Dinoflagellates were in greater abundance than diatoms except in February, and consisted of 20 tropical species several of which were strictly Indo-Pacific. Discoloration of Red Sea waters by Trichodesmium erythraeum has also been mentioned.

Other phytoplankton studies available were made in the vicinity of the Suez Canal. Dowidar (1974) recorded 273 species and grouped them into Mediterranean, tropical and Indo-Pacific species; about 90% of the Suez Bay species are common to the Mediterranean. In Lake Maruit, a eutrophic lake in Egypt, Aleem and Samaan (1969) recorded 64 taxa and a high magnitude of phytoplankton production. Recently Spanier et al. (1979) observed in the Gulf of Elat (Aqaba) a greater biomass and productivity during the winter (December-March) than during the rest of the year (April-November), when production and biomass were poor. Primary
production increased towards the coral reefs and Red Sea proper.

In the Gulf of Aden, the trophic layer (the layer with the largest quantity of algae) reached to about 25 m and occurred during November to February; the quantity of algae depended on the depth of the thermocline (Savich 1971). Thus a period of maximum growth of phytoplankton between November and March appears to be a common feature of the studies of Halim (1969), Spanier et al. (1979) and Savich (1971).

The Red Sea provides a unique area of study in the tropics because of: (a) partial isolation from the open ocean which puts it in the category of landlocked seas; (b) absence of river flow and only scant rainfall; (c) evaporation loss, in excess of 210 cm yr\(^{-1}\) which is made up by inflow of waters through the Straits of Bab-el-Mandeb; (d) variable wind-driven and monsoon currents.

Due to oil pollution, increases in industrial and organic effluents and speculative or urban development of the coastal areas, marine ecosystems of the Red Sea area are seriously threatened (UNESCO 1976). It must be remembered that for a proper development and management of the resources and environment of the Red Sea, a sound knowledge of the physical, chemical and biological oceanographic aspects of the area is necessary.

Although several marine science activities were initiated
in recent years, a multi-disciplinary programme for studying the Red Sea is almost non-existent. The marine biological station at Ghardaga, Egypt has been reopened as the "Institute of Oceanography and Fisheries, Ghardaga, Red Sea, Egypt". Sudan established an "Institute of Oceanography" in 1971 at Port Sudan and a marine biological station belonging to the University of Khartum at Swakin in 1973. At the University of Jordan, Amman, a marine science programme was started in 1973. At Jiddah, Saudi Arabia, King Abdulaziz University added an "Institute of Marine Sciences". The Arab League Educational, Cultural and Scientific Organisation (ALESCO) in 1974 recognised the need to have a cooperative regional programme for "Environmental Studies of the Red Sea" and it is hoped that this area will be intensively studied.

The present study was carried out while at the Institute of Marine Sciences, recently started by the King Abdulaziz University, and the present thesis, though preliminary, constitutes the first of its kind from this geographical region. This study was undertaken to investigate:

a) the physico-chemical and planktological cycles at an inshore station (Sharm station) and an offshore station,
b) whether any qualitative and quantitative differences in the phytoplankton exist at these two stations,
c) how the magnitude of primary production at these two stations is governed by physico-chemical factors,
d) whether any local effect of pollution can be discerned, and
e) the potential fisheries production of the Red Sea as estimated from its primary production.
DESCRIPTION OF STUDY AREA

Geography and Location

The Red Sea (Figure 1) extends southeastwards from Suez for 1932 km to the straits of Bab-el-Mandeb, which connects with the Gulf of Aden and the Indian Ocean via a 100 m deep sill. It is 306 km wide at its maximum breadth in the southern sector, has a surface area of 440,000 km$^2$, a mean depth of 524 m, and a maximum depth of 2920 m.

The reef-studded shelves of the Red Sea are less than 50 m deep and drop off abruptly to about 500 m deep. The distances from the shore to the 200 m and 500 m depth contours are about 2 km and 5 km respectively. A narrow central trough with depths more than 1500 m is a salient feature. An island, El-Ketaah which is about 10 km off Sharm-Obhor is formed from a submarine pinnacle rising from depths exceeding 700 m. Such submerged elevations are common and support heavy algal and coral growth.

The area of study is shown in Figure 2; it includes both the neritic and oceanic provinces of the central Red Sea in the vicinity of the city of Jiddah. The city is located between latitudes 21°15'N and 21°45'N and extends for about 35 km along the coast from Petramean in the south (Figure 3) to Sharm-Obhor in the north. The coast-line is fringed by almost continuous flats of reefs which at certain places,
particularly in the south, have developed into small shallow lagoons (see Figure 3). The depth of water over the reefs varies between a few centimeters and two meters, and causes navigational hazards. In the shallow coastal areas calcareous rocks and thick coral formations predominate; moving away from the coast, the bottom is mostly covered with muddy sand or mud deposits (Figure 4).

Climatic Conditions

During June, July and August, the southwest monsoon season, the winds are generally NNW and NW, and are directed towards the Gulf of Aden (Table 1). During this period, winds are usually weak. During the northeast monsoon season (October-May), the winds are northerly and are stronger.

Air temperatures range between a low of 28.5°C during January to a high of 37.5°C during July. The temperature steadily increased during January through July, and from August onward decreased gradually. The difference between the mean daily minimum temperature and mean daily maximum is about 10°C (Table 1).

There is very little precipitation at Jiddah and it is restricted to the period October to May. During the southwest monsoon, precipitation is almost nil.

There is a high level of radiant energy available throughout the year (Table 1), peaking in June and being lowest in December. Neumann (1952) calculated an annual evaporation of 211 cm from the Daedalus reef area (25°N, 35°E) of the Red Sea.
Circulation Pattern in the Red Sea

Geometric features, tides, monsoon winds, change in density of the waters, evaporation and cooling are some of the factors influencing the circulation pattern in the Red Sea. Morcos (1970) presented a detailed discussion on this subject and what follows is a brief summary of the salient features of circulation in the Red Sea. In a narrow rectangular basin like the Red Sea, when winds blow the surface water will be driven at an angle of 45° to the right of the wind direction (because the area is located in the northern hemisphere) and an "Ekman spiral" develops. This has two components, one in the direction of the wind and the other to the right of the direction of the wind. Because of its narrowness, in the Red Sea, the first component will gain momentum while due to the latter, piling up of water continues. During the two reversing monsoons, contrasting features in circulation are noticed as follows.

During the summer months, May through September, when north northwest winds blow along the axis of the Red Sea, surface waters are transported along the African coast with greater frequency and increased velocity. Seasonal changes in the wind patterns for the southern Red Sea area are summarised in Figure 5.

Along the African coast, surface water gets piled up while water from depths moves upwards in an easterly direction; this causes upwelling along the Arabian coast. As the surface waters are driven towards the south, an outflow from the Red Sea into the Indian Ocean takes place.
Over the sill at the straits of Bab-el-Mandeb. However, because of the narrow sill, some of the water accumulated at the sill sinks and a bottom current develops and moves upwards in the northern part of the Red Sea. Newmann and McGill (1962), based on a more recent study, concluded that during early summer the water outflowing over the sill originates in the surface layer as a result of evaporation and cooling. They further reported an inflow of a third intermediate layer of waters in between the outflowing surface waters and northerly bottom current.

During winter, when the south southeast winds blow over the southern half of the Red Sea, surface waters are transported along the Arabian coast during December through to February. Their frequency and velocity are both high during the winter months. As the waters are piling up on the Arabian coast, sub-surface deep waters upwell on the African coast, a reversal of summer conditions. As the south southeast winds affect only the southern half of the Red Sea, at about 20°N two circulations converge, causing the surface water to sink. This sinking in turn causes an upward movement of water just north of the sill.

Land-drainage and Pollutants in the Jiddah area.

Five sources of land-drainage and pollutants can be identified:
(a) oil pollution,
(b) domestic wastes and sewage (city of Jiddah),
(c) domestic wastes and sewage (Sharm-Obhor area),
(d) fish wastes,
(e) de-salination plant inputs.

(a) Figure 3 shows the location of the oil refinery at Petramean in the southernmost region of Jiddah. Petroleum oil and oil products which leak during loading and unloading operations and through washing of the oil tankers are the chief pollutants.

(b) To the north of the Petramean area lies the Islamic seaport, which contributes to oil pollution through marine transportation. Additionally, during the pilgrimage season several thousands of pilgrims arrive by sea and stay in the City of Pilgrims. Domestic sewage and wastes are directly discharged into nearshore waters, causing heavy pollution in this area. A preliminary survey showed that the inshore waters contained as high as $88 \times 10^3$ coliform bacteria per ml of sea water during the pilgrimage season.

(c) Sharm-Obhor is a creek about 10 km long, located about 30 km north of Jiddah. Its breadth ranges between $<200$ m and $>800$ m. It has a maximum depth of 55 m near the mouth where it joins the Red Sea, and its average depth in the middle is about 30 m. The shores near its mouth are mostly rocky, with thick coral formations (Figure 4). In the central and northeastern regions, gently sloping beaches with scattered coral formations predominate. The Obhor area is a popular summer resort for the people of Jiddah, and in recent years many hotels and houses have been built on either side of the Sharm to accommodate the increasing population. Effluents which include domestic wastes and sewage are discharged directly into the Sharm without any treatment and these are
a source of eutrophication. Like the Islamic seaport, the waters of the Sharm are highly polluted and contain large numbers of coliform bacteria.

(d) To the north of the City of Pilgrims, the main fishing harbour and fish market of Jiddah are located (Figure 3). Fish wastes, decaying fish, and the sewage of metropolitan Jiddah are directly discharged into nearshore waters, which results in organic enrichment.

(e) To meet an ever-increasing demand for fresh water, the supply authorities have established a de-salination plant at about 20 km to the north of Jiddah (Figure 2). The de-salination plants Jiddah I and Jiddah II have the following characteristics:

<table>
<thead>
<tr>
<th></th>
<th>Jiddah I</th>
<th>Jiddah II</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Length of valve for pumping sea water</td>
<td>Artificial 85 meters gulf on shore</td>
<td></td>
</tr>
<tr>
<td>2. Depth of pumping valve (m)</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>3. Daily quantity of water pumped (m tons)</td>
<td>$0.40 \times 10^6$</td>
<td>$0.74 \times 10^6$</td>
</tr>
<tr>
<td>4. Salt content of sea water (%)</td>
<td>39 - 40</td>
<td>39 - 40</td>
</tr>
<tr>
<td>5. Sea water temperature (°C)</td>
<td>24 - 32</td>
<td>24 - 32</td>
</tr>
<tr>
<td>6. Quantity of blow down water/day (m tons)</td>
<td>$0.02 \times 10^6$</td>
<td>$0.69 \times 10^6$</td>
</tr>
<tr>
<td>7. Salt content of blow down water (%)</td>
<td>44.6</td>
<td>46.7</td>
</tr>
<tr>
<td>8. Temperature of blow down water (°C)</td>
<td>38</td>
<td>35</td>
</tr>
</tbody>
</table>

Thus it is clear that $1.14 \times 10^6$ metric tons of water are pumped daily from the sea, of which $0.71 \times 10^6$ metric tons are returned from the desalination plants as blow down.
The blow down water affects the environment in two ways:

1) The temperature of the blow down water is about 10°C higher than the intake water. On average this difference between blow down and intake will be higher during winter than during summer.

2) The daily desalination of $0.43 \times 10^6$ metric tons of sea water would increase the salt budget of the adjoining sea by about $18 \times 10^3$ kg of salt. These environmental perturbations would be expected to be reflected in the physico-chemical and biological cycles in the nearshore waters.
MATERIALS AND METHODS

Sampling Programme

As one objective of this study was to compare the nearshore eutrophicated coastal waters with further offshore waters, several inshore and offshore stations were initially sampled. Analysis of the data revealed no substantial differences in measured variables within the seven inshore or within the six offshore (approximately 4 - 7 km) stations. In view of constraints of time and physical resources, and in order to broaden the scope of the study, it was therefore decided to restrict sampling to one inshore station and one offshore station (Figure 2).

Physical, chemical and biological oceanographic observations were made on a regular basis at these two stations of differing trophic status. The inshore station, referred to as the Sharm station (Figure 2) had a depth of approximately 40 m, and was sampled on 20 occasions during the period 28 March 1977 and 25 October 1978. The offshore station was located about 7 km seaward off the Sharm, and had a depth of approximately 200 m. It was sampled on 13 occasions from 2 November 1977 to 25 October 1978.

At the Sharm station the following variables were measured: temperature, salinity, dissolved oxygen, hydrogen ion concentration (pH), alkalinity and total carbon dioxide,
soluble reactive phosphorus (SRP), reactive silicate (SiO$_2$), nitrite (NO$_2$), ammonia (NH$_3$), chlorophylls a and b, and rate of photosynthetic carbon assimilation (C$_{14}$). Values of sigma-t (σt-density), oxygen percent saturation, and carbon assimilation ratios (mgC mgChla$^{-1}$ hr$^{-1}$) were calculated from these variables. Depths sampled included 0, 5, 10, 15, 20, 25, and 30 m. In addition, Secchi disc readings were obtained and phytoplankton species were enumerated from at least three depths and their diversity indices were calculated.

At the offshore station, the same variables were measured at 0, 25, 50, 75, 100, 150 and 200 m and the same calculations were made from these variables. All samples were taken either with a 1 litre Nansen bottle or 6 litre Van Dorn bottles. Actual depths of sampling were corrected for "wire angles" when necessary.
Physico-Chemical Methods

1. Temperature

Surface temperature was measured by immersing a mercury thermometer in the upper 30 cm layer of surface water, and allowing it to stay for at least 2-3 minutes. The temperature was read to the nearest 0.01 degree Celsius. In the upper 75 m, temperature was measured using a Schmidt thermometer fitted to a Nansen bottle. It was also allowed to stay for not less than 3 minutes at the required depth, and the temperature was measured to the nearest 0.01 degree Celsius. For sub-surface layers below 75 m, temperature was measured by the use of both protected and unprotected reversing thermometers fitted to the reversing bottle. The bottle was allowed to stay at least 3 minutes at the required depth before reversing. Readings obtained by the reversing thermometers were corrected according to procedures outlined in Sverdrup, Johnson and Fleming (1942). The depth of reversal was corrected by using the unprotected reversing thermometer when there was a wire angle. Otherwise, i.e. when there was no wire angle as in calm weather, it was sufficient to measure the length of this wire, and the error in this case would be negligible (Sverdrup et al. 1942)
2. Salinity

Since an inductive salinometer that could cover the high salinity values usually found in the Red Sea was not available, salinity was calculated from chlorinity values. Chlorinity was estimated by the titration method of Knudsen (Strickland and Parsons 1972). The silver nitrate solution was standardized periodically against standard sea water with a chlorinity of 19.376% prepared at the Institute of Oceanographic Science at Wormley, Surrey, U.K. From each sample, triplicate titrations were made and the average was calculated. Corresponding salinities from the chlorinities were read from Knudsen's tables (Oxner 1962).

3. In situ Density (σt)

In situ density (σt) was calculated from the salinity and temperature data at each depth according to the formula of Matthews (1932).

4. Sea Water Transparency

A 30 cm diameter weighted Secchi disc was lowered on a graduated ropeline. The average of the depth of disappearance, and on raising the disc, of its reappearance was recorded.
5. Dissolved Oxygen

The dissolved oxygen was determined by the classical Winkler procedure. Sea water samples were drawn gently into 300 ml BOD (Biological Oxygen Demand) bottles and all precautions were taken to avoid trapping any air bubbles. A volume of water at least equal to the volume of the BOD bottle was allowed to overflow from the top of the bottle and then the bottle was stoppered. Subsequent procedures and titrations followed methods outlined in Strickland and Parsons (1972).

6. Oxygen Saturation

Percentage oxygen saturation was calculated from oxygen content, temperature and salinity according to the formula of Weiss (1970).

7. pH

pH values were determined with a glass electrode using a Tacussel U9N pH meter, with a precision of ±0.1 units. Samples were read immediately after collection and temperature corrections were applied where necessary to obtain in situ pH values. pH readings were taken solely for the purpose of calculating C\textsuperscript{14} uptake rates.
8. Alkalinity and Total Carbon Dioxide

For alkalinity determinations, water samples were drawn into polyethylene bottles and tightly stoppered. Experimental procedures were as detailed by Strickland and Parsons (1972). Total carbon dioxide in the samples was calculated according to Strickland and Parsons (1972), based on the total alkalinity, salinity, initial temperature, pH and the temperature at which the pH was measured. The values of total carbon dioxide so determined were used only for the primary production calculations.

9. Soluble Reactive Phosphorus (SRP)

Sea water samples for the determination of soluble reactive phosphorus were stored frozen until analysis. Determination was carried out on samples brought to room temperature according to the method of Strickland and Parsons (1972). Extinctions of solutions were measured in 10 cm path cells using a Pye-Unicam SP 500 UV Spectrophotometer.

10. Reactive Silicate (SiO₂)

Samples for the determination of reactive silicate were stored frozen until analysis. Determination was carried
out on samples brought to room temperature according to the method of Strickland and Parsons (1972). Extinctions of solutions were measured in 10 cm path cells.

11. Nitrite (NO₂)

Determination was carried out according to the method of Strickland and Parsons (1972). Extinctions of solutions were measured in 10 cm path cells.

12. Ammonia (NH₃)

Determination was carried out according to the method of Strickland and Parsons (1972). Extinctions of solutions were measured in 10 cm path cells.

13. Because of lack of equipment when this study was carried out, nitrate (NO₃) was not measured.
Biological Methods

1. Qualitative and Quantitative Examination of Phytoplankton

On each sampling day, at each station net tows for phytoplankton were made using a 50 cm mouth diameter plankton net of 64 μm mesh. Surface horizontal tows were made at each station at a speed of about one meter per second for about 15 minutes. Additionally, at each station a vertical haul from 50 m to the surface was made. The plankton concentrates were drained into glass bottles and preserved in 4% neutral formalin. These net samples were used only for qualitative studies concerned with species identification.

For quantitative studies, sea water collected with modified Van Dorn bottles was used. One litre of the sample was preserved with 4% neutral formalin and sedimanted for at least 48 hours. The supernatant was gently siphoned off and a concentrate of about 50-100 ml was obtained. The concentrate was transferred to labelled glass bottles to which some more 4% neutral formalin was added to make up a known volume. Cells were counted at magnifications of 280X and 560X using Utermöhl's technique (Utermöhl 1958), under a Wild Heerbrugg M40 inverted microscope. From each sample 2 aliquots
were drawn and counted and average cell numbers calculated. On several occasions, especially during phytoplankton blooms, it was necessary to dilute the samples. Final cell numbers were calculated taking into consideration concentration and dilution factors. Cell numbers are expressed as cells litre⁻¹ of sea water. Single non-chain forms were counted as individuals; for colonial forms such as *Trichodesmium*, each filament was counted as an individual.

Taxonomic references included: Cleve-Euler (1951), Steidinger and Williams (1970), Wood (1963), and Dowidar (1976 and unpublished). Taxonomic nomenclature followed the above references. A complete list of taxonomic references is given in Appendix 8.

2. Species Diversity Index

A diversity index, expressed as information (D in "bits") per individual (Margalef 1957) was calculated from the formula:

\[ D = - \sum_{i=1}^{N} p_i \log_2 p_i \]

where:  
\( D \) is the diversity  
\( N \) is the total number of individuals  
\( p_i \) = \( n_i / N \), the proportion of the collection belonging to the \( i^{th} \) species.

3. Photosynthetic Pigments

Using a 6 litre modified Van Dorn bottle, water samples
were collected from pre-determined depths. The sample was mixed well and strained through a nylon mesh with a pore size of 300 µm to remove any larger zooplankters. Two litres of the screened sample were drawn into a polyethylene bottle and 0.2 ml of 1% magnesiuem carbonate solution was added. The samples were stored in darkness in a cooler on board the vessel. Soon after arrival at the laboratory on the same day of collection, photosynthetic pigments were determined following the procedure outlined by Strickland and Parsons (1972).

A two litre water sample was filtered through a Millipore filtration unit fitted with a 47 mm diameter (0.45 µm pore size) Millipore AA filter. In some cases when the filter was clogged due to excessive particulate material, it was necessary to complete the filtration using a second filter. In this case both filters were used for extraction. Filters were extracted in 8 mls of 90% acetone and allowed to stand in darkness in a refrigerator for about 24 hours before reading. Using a Pye-Unicam SP 500 UV Spectrophotometer, extinctions of the extracts were read against 90% acetone at 7500, 6650, 6450 and 6300 Å in 10 cm path cells.

Concentrations of chlorophyll a and b were calculated using Richards and Thompson equations (1952) (see Strickland and Parsons 1972):

\[
\text{chlorophyll a} = 15.6 \ E_{6650} - 2.0 \ E_{6450} - 0.8 \ E_{6300}
\]

\[
\text{chlorophyll b} = 25.4 \ E_{6450} - 4.4 \ E_{6650} - 10.3 \ E_{6300}
\]

Pigment concentrations are collected and reported as µg litre \(^{-1}\)
It was realised that the extinction coefficients in these equations would yield low estimates (Humphrey 1978), by as much as 23% for chlorophyll $a$. When comparing the Red Sea waters with other geographical areas or when comparing assimilation numbers ($\text{mg} \ C \ \text{mg} \ \text{chla}^{-1} \ \text{hr}^{-1}$) with those of other regions, chlorophyll $a$ values should have been corrected using the following equations (Humphrey 1978):

\[
\begin{align*}
\text{chlorophyll } a &= 0.766 \times \text{chl } a + 0.005 \times b + 0.005 \times C \\
\text{chlorophyll } b &= -0.049 \times \text{chl } a + 0.891 \times b + 0.059 \times C
\end{align*}
\]

Since the second and third terms of the chlorophyll $a$ equation are small compared to the first term, their effect on recalculation of chlorophyll $a$ is negligible. Consequently, the corrected chlorophyll $a$ value will be 0.766 times that obtained from the Richards and Thompson equation (Humphrey 1978). In this study this correction ($\times 0.766$) was made.

4. Carbon Assimilation

The carbon-14 tracer technique (Steemann Nielsen 1952) was employed to determine the photosynthetic carbon uptake rates. To a sample of sea water with a known quantity of total carbon dioxide, a known quantity of radio-active carbon ($\text{NaH}^{14}\text{C}_3$) was added and the sample was incubated in situ for 6 hours under ambient light levels. After incubation, the samples were filtered, the filters were washed, dried and their radio-activity determined. The uptake of carbon was calculated and expressed as $\text{mgC} \ m^{-3} \ hr^{-1}$. 

(or $\text{mg} \ m^{-3}$).

24
During the study only in situ incubations were carried out. At each station a plastic buoy was tied to a rope and the rope was held taut by anchoring a heavy weight at the bottom. Pre-screened (<300 µm) sea water samples described earlier, were used. About 125 ml of water were drawn into a 150 ml BOD bottle and the contents of one ampoule of NaHCO$_3$ (4 microcuries) were added and the bottle stoppered. After mixing the contents gently, the bottles were tied to a rope and suspended from a plastic buoy at the same depth from where the sea water was obtained. At each depth 2 light and 1 dark bottles were incubated for 6 hours, generally from 0800 hours to 1400 hours.

Following incubation, the bottles were hauled, arranged according to depth in a wooden box, and were protected from light. The samples were filtered at the sea station, Institute of Oceanography, King Abdulaziz University. Using a filtration apparatus and Sartorius membrane filters of 0.2 µm pore size, samples were filtered under gentle suction. The filters were washed with filtered sea water, sucked dry and were serially numbered. These filters were then stored in plastic cups and stored in a refrigerator. Determination of the activity of the filters was carried out by the International Agency for Carbon-14 Determination, Horshølm, Denmark, which also supplied the ampoules used in this study. Carbon uptake was calculated as follows:

$$\text{mgC m}^{-3} \text{hr}^{-1} = \frac{\text{CPM(a)} \times \text{mgC/l(c)} \times 1.05(d) \times 1.06(e) \times 10^3(f) \times K_1}{\text{CPM(b)}}$$

where: $a$ is the activity of the filter
b added activity from the ampoule
c total carbon content mgC\textsuperscript{-1} in the sea water
calculated by mgCO\textsubscript{2} x 12/44
d correction for isotopic discrimination (+5%)
e correction for respiration (+6%)
f conversion of mg \textsuperscript{\text{-1}} to mg m\textsuperscript{\text{-3}} = 10\textsuperscript{3}
f\textsubscript{1} correction for incubation time = 1/hrs of incubation.

It should be added that the activity of the filter from the light bottle is corrected for the dark uptake of carbon-14. No corrections for reassimilation of recently labelled (carbon-14) products were made. Corrections for isotopic discrimination (+5%) and respiration (+6%) are similar to those usually used by several investigators.

Statistical Methods

Differences between the means of variables or parameters (at the surface and 25 m depths) at the Sharm station and the offshore station were tested using Student's "t"test. Pearson's correlation coefficients were also calculated between the variables or parameters at the inshore and offshore stations to test for relationships.

Analysis of variance between means by month and means by depth (therefore with unequal sample sizes) was carried out for different variables and parameters. Computational methods for the statistical analysis are the same as detailed in Sokal and Rohlf (1973). All computation was carried out with
"Stalib" APL programmes in the Computer Centre at the University of Guelph, Ontario.
RESULTS

Physico-Chemical Data

The complete data set is presented in Appendix 1, and maximum and minimum values are summarized in Table 2.

1. Temperature

SHARM:

The temperature pattern followed a distinct seasonal cycle, (Figure 6). Lowest temperatures (26°-27°C) were observed during northern hemisphere winter months, i.e. December through March, following which temperatures increased. Highest summer temperatures were reached in August and September, and remained high during the fall. A minimum temperature of 25.10°C was observed at 20 m on 11/4/78 and a maximum of 32.20°C at the surface on 29/8/78 (Table 2). Due to the shallow water column at this station any changes at the surface tended to be transmitted throughout the water column.

Temperature gradients remained very weak and the waters were almost isothermal during December to March and during June
to September, suggesting little horizontal advection of water. During the summer months vertical temperature gradients at this station rarely exceeded 2°C; a maximum vertical gradient of 4.3°C was noted on 15/8/77.

OFFSHORE

A seasonal cycle of water temperatures was also evident at this station, (Figure 7). During the winter months, December through March, temperatures were low and a gradual warming was noted during the summer months. Temperatures remained high during the autumn. A maximum of 31.50°C was observed at the surface on 10/8/78 and a minimum of 22.10°C at 200 m on 25/10/78 (Table 2).

A comparison with the nearshore station (Figure 6) shows several similarities such as the isothermal nature of the upper layer during winter, and developing thermal stratification after April. The temperature gradient between the surface and 100 m layer was 1.4°C during August. During November and January, this gradient was only 0.8°C - 0.9°C. The lowest vertical temperature gradients between the surface and 200 m were recorded as 3.5°C from December to January. Thus, the water column at this station never becomes isothermal although effective winter mixing down to about 100 m occurs. Below 100 m, water temperatures were fairly constant at 23° - 24°C from February to November, and at 150 m, they were almost constant year round at about 23°C.
2. Salinity

SHARM:

The salinity distribution at the inshore station is shown in Figure 8. A minimum value of 38.40%o was noticed at the surface on 30/4/77 and a maximum of 39.98%o at 15 m on 2/11/77 (Table 2). The high salinity values during the summer months of June-August result from excessive evaporation. The relatively high surface salinity values in January and February were probably due to mixing of oceanic Red Sea water piling up on the Arabian Coast during the southeast monsoon. Variations in salinity values were also noticed in the sub-surface layers and generally followed events at the surface. However, during the summer months following excessive evaporation at the surface, salinity at 5 m may be lower than that of overlying waters (Figure 8).

The annual average salinity at the surface and 5 m are 39.20%o and 39.05%o respectively. At 10 m it was 39.23%o, at 15 m, 39.36%o and at 30 m, 39.26%o. The relatively high salinity at 10-15 m depths can be attributed to a sub-surface water current originating probably at the extreme east end of the Sharm and flowing westerly towards the sea. Near the bottom, an eastward current with salinity similar to that of the surface layer of the adjoining Red Sea region enters the Sharm (Dowidar, personal communication).
OFFSHORE:

The season distribution of salinity in the offshore waters is shown in Figure 9. A maximum of 40.54%o was noticed at 200 m on 31/1/78 and a minimum of 38.80%o at 25 m on 10/7/78 (Table 2). In the upper 50 m layer the salinities were always about 39.0%o except during November, February and July when values <39.0%o were encountered.

These low values are hard to explain and cannot be attributed to the Sharm water because the salinity of Sharm water was >39.10%o. Also, the run-off from land or the amount of effluents from Jiddah area are insignificant at the offshore station and thus dilution can be ruled out. The average salinity values for 50 m, 100 m and 200 m depths were 39.38%o, 39.88%o and 40.32%o, respectively. Variations in salinity below 100 m were not pronounced. During January, the water column from 0 to 150 m was almost isohaline, exhibiting a difference of only 0.28%o, again suggesting effective winter mixing to this depth.
3. Density Structure

SHARM:

The pattern of density distribution in the nearshore waters is shown in Figure 10. A minimum value of 24.214 was calculated for 29/8/78 at the surface and a maximum of 26.678 was calculated for 30 m on 25/1/78 (Table 2). Pronounced changes in the density were observed only in the top 10 m layer, which could be attributed to: (a) run-off from land, (b) discharge of effluents (November–March), and (c) surface warming during summer (April–September). Between 10-15 m, high density water (25.00-26.50) was observed most of the year; this represents the outflowing Sharm water.

As stated earlier (Dowidar, personal communication), this water originates near the eastern shallow end of the Sharm as a result of sinking surface water. Due to evaporation, the surface water has a higher salinity and hence higher density and results in periodic density inversions, e.g. October–November 1977.

OFFSHORE:

Density structure in the offshore waters is shown in Figure 11. Density ranged between 24.441 at the surface on 10/7/78
and 28.397 at 200 m on 31/1/78 (Table 2). Based on vertical density characteristics, three layers could be recognized:

(a) An uppermost layer with $\sigma_t$ values ranging from $<25.00$ to $26.50$ and affected by seasonal temperature and salinity changes. The effect of temperature variations on density was more pronounced than salinity. The lower boundary of this layer extended to about 50 m.

(b) An intermediate layer with $\sigma_t$ values ranging from $<26.50$ to $27.50$. Seasonal temperature and salinity variations were rather gradual and equally affected the density structure. This layer extended vertically to about 100-150 m.

(c) The lowermost layer, where the variations in neither temperature nor salinity were pronounced. It extended from about 100-150 m to the bottom. $\sigma_t$ values range from 27.00 to $<28.50$.

Formation of these three layers appeared to follow a seasonal pattern, thus during winter (December and January) the first two layers were present. In the top layer (100 m) winter cooling affected the density structure, and at greater depths salinity changes were important. A distinct third layer was, however, absent. During spring a top, intermediate and bottom layer, with boundaries at 50, 150 and 200 m respectively, were noticed. The top layer is formed as a result of seasonal surface warming, and the intermediate layer is formed of water with lower temperature than that which prevailed during winter (Figure 7).

During summer, transitional conditions from spring to summer occurred, and during June the lower boundaries of the
three layers were relatively established at 50, 100 and 200 m respectively. During autumn, two well-defined layers, an upper layer of 75 m thickness with a pronounced decreasing temperature gradient, and a second layer between 75 and 200 m, with nearly constant salinity and decreasing temperature, were noticed as in October. During November, due to surface cooling, the temperature gradient in the top 100 m was limited, and an increase between 100 and 200 m in salinity was the important factor.
4. Transparency

The transparency characteristics of the inshore Sharm and offshore waters are compared in Figure 12. Inshore, Secchi disc readings ranged from 10.0 m on 14/2/78 to 25.0 m on 20/6/78 (Table 2). In the offshore waters, the range was between 22.0 m on 10/7/78 and 32.0 m on 27/6/78 and 2/11/78 (Table 2). During November through February, the transparency of the inshore waters decreased slightly following which it increased steadily until June, except for a drop during April-May. During July through October, the waters became more turbid.

Offshore waters were less turbid than the Sharm waters, and in general, offshore Secchi readings were almost twice those inshore. The higher turbidity of Sharm waters could be attributed to the presence of quantities of terrigenous material brought about by land run-off and effluents, and also to biogenic material such as plankton. Although the offshore waters were more transparent, the seasonal patterns of transparency showed some similarities between inshore and offshore waters. As it is well known that Secchi disc readings are subject to errors such as time of observations, angle of sun's rays, cloud cover and human error, these readings will be considered as representing only the relative degree of water transparency.
5. Dissolved Oxygen

SHARM:

The seasonal distribution of dissolved oxygen in the inshore waters is shown in Figure 13. The oxygen content ranged from 2.10 ml O$_2$ l$^{-1}$ at 30 m on 28/5/78 to 4.72 ml O$_2$ l$^{-1}$ at 15 m on 15/8/77. The oxygen content was usually between 4.0-4.25 ml l$^{-1}$ and did not show any marked seasonal variations except for "domes" (here used in a spatial-temporal sense) of low oxygen values during May-June 1978. Complete absence of oxygen was never observed.

The Sharm waters are nearly saturated in their oxygen content (Figure 14). The oxygen saturation values ranged from 46.6% to 110.2% (Table 2). Domes of low saturation waters were observed during April-May 1978.

OFFSHORE:

Considerable seasonal variations in the oxygen content occurred of the offshore waters (Figure 15). Table 2 shows that the values ranged from 1.85 ml O$_2$ l$^{-1}$ at 200 m on 22/2/78 to 4.80 ml O$_2$ l$^{-1}$ at surface on 25/10/78. In the top layer (<50 m), the oxygen content was about 4.0-4.5 ml l$^{-1}$ and did not show any marked seasonal changes. Thus, the pattern is similar to that observed in Sharm waters. Also, formation of domes of
low oxygen content was noticed during May-June.

Below 50 m, there were marked changes in the oxygen content. With increasing depth, there was a marked decrease in the oxygen content. The isopleths showed formation of distinct domes of low oxygen (2.5-3.0 ml O$_2$ l$^{-1}$) during February-March, May-June and September. In the offshore waters, changes in oxygen saturation were also more marked (Figure 16). Values ranged from 38.5% at 200 m on 22/2/78 to 114% at the surface on 25/10/78. Domes of low saturation values were observed during February-March, May-June and September.

It may be generalized that the surface waters at both stations are usually saturated or almost saturated with oxygen but that absolute oxygen concentrations are low. This can be attributed to high temperatures, high salinity and little freshwater input. Organic matter contributed through the sewage and effluents will deplete oxygen through biochemical oxygen consumption, but no data are available to determine the biological oxygen demand.

While discussing the density structure, it was pointed out that density in the uppermost layer (<50 m) and intermediate layer (<100 m) are mostly affected by the temperature-salinity relationships. Figure 16 shows that below 100 m, the offshore waters are undersaturated in their oxygen content; this is probably partly due to lack of direct exchange with the atmosphere and partly due to low photosynthetic activity at these depths. Some of the low oxygen saturation domes could be the result of intrusion of oxygen-depleted water into the area of study, particularly in the May-June 1978 period.
6. Soluble Reactive Phosphorus

SHARM:

The seasonal distribution of soluble reactive phosphorus in the inshore waters is shown in Figure 17. On several sampling days, phosphate was undetectable ($<0.01 \mu$g-at) and reached a maximum of $0.76 \mu$g-at PO$_4$$_2$P$^{-1}$ on 14/3/78 at 15 m (Table 2). During winter, there was a general increase in phosphate, reaching a maximum during March in the surface waters. This increase could be attributed to lower biological activity following the peak in December (see section on Biological Data - 5. Primary Production). Following this, the phosphate concentrations decreased rapidly in the top 10 m to reach a minimum during October, which is probably due to increased biological activity during the summer months. At sub-surface levels there were domes of relatively high phosphate values during May-June, September-October and November, probably the result of sub-surface intrusions of nutrient rich Sharm water, or in situ nutrient regeneration.

OFFSHORE:

The seasonal change of soluble reactive phosphorus in the offshore waters is shown in Figure 18. The range here was
quite high, with a minimum of 0.01 µg-at\(\text{-}^{-1}\) at the surface on 25/10/78 and a maximum of 1.46 µg-at\(\text{-}^{-1}\) at 75 m on 11/4/78 (Table 2). Except during April, phosphorus values in the top 100 m were fairly constant (~0.2 µg-at\(\text{-}^{-1}\)) and showed little seasonal variation. Such a constant low value could be attributed to the assimilation of phosphorus being in a steady state with its supply.

During April, there was a rapid increase of this nutrient when it reached maximum values. Figure 18 shows the formation of a dome of high phosphorus during February at about 150–200 m, and the concentrations of phosphorus rapidly increasing into April, when high levels extended almost to the surface. Reasons for these high levels of phosphorus in April are not clear. They could be due to in situ remineralization of phosphorus following the crash of the peak in primary production which occurred in January–February (see section on Biological Data - 5. Primary Production). After April, there was a rapid decrease in this nutrient which could be attributed to renewed biological assimilation.
7. Silicate

**SHARM:**

The seasonal distribution of silicate in nearshore waters is shown in Figure 19. The values ranged between 1.09 µg-at-l at the surface on 25/1/78 and 7.40 µg-at-l at 30 m on 15/8/77 (Table 2). In the top 10 m, silicate concentrations were low and showed little variation. When compared to winter (November-December) values, the concentrations decreased during spring, which could be attributed to utilization by diatoms. During June-July (1978) months, domes of high silicates were noticed at sub-surface levels. During August 1977, unusually high concentrations of silicates were observed in the surface waters which was not the case during 1978.

For coastal waters which, in general, have high silicate concentrations, the values from the Sharm station are low; this must be mainly due to the low discharge of freshwater into the Sharm.

**OFFSHORE:**

The seasonal distribution of silicates in the offshore waters is shown in Figure 20. The values ranged from 0.98 µg-at-l at the surface on 23/9/78 to 4.69 µg-at-l at 200 m on
31/1/78 (Table 2). The distribution pattern was similar to that of phosphorus with very little seasonal variation with values <3.0 µg-at l⁻¹ in the top 100.

Such constant silicate values suggests the possible existence of a steady state system where consumption and replenishment rates are equal. During April and August, domes of higher silicate levels taking their origin from 100-200 m depths were noticed. A comparison with inshore values shows that the offshore waters are more impoverished in silicate. Lack of admixture of freshwater accounts for such low silicate levels.
8. Nitrite

SHARM:

The nitrite nitrogen distribution in the inshore waters is shown in Figure 21. On several occasions, there was total depletion of this nutrient at the surface; the maximum value recorded was 0.65 µg-at-l on 18/7/78 at the surface (Table 2). On a seasonal basis, values during winter, i.e. November to January months, were uniformly low in the water column (<0.2 µg-at-l and the values steadily increased during spring and summer to reach a maximum (> 0.6 µg-at-l). Later, a decrease in nitrite was observed during autumn and winter.

OFFSHORE:

The seasonal distribution of nitrite in the offshore waters is shown in Figure 22; values ranged between 0.01 µg-at NO₂ - N-at-l at the surface on 28/5/78 to 3.25 µg-at NO₂ - N-at-l at 200 m on 11/4/78 (Table 2). When compared with nearshore waters, this nutrient was in greater abundance offshore, and exhibited a strong seasonal pattern. During winter, values were about 0.3 µg-at-l, followed by a decrease during spring. There was no surface accumulation of nitrite during the summer.
and autumn, however, domes of high nitrite values were observed during April-May and September and October and reached from 50 m to the bottom.
9. Ammonia

SHARM:

The seasonal distribution of ammonia in the inshore waters is shown in Figure 23. Ammonia was undetectable at 5 and 10 m on 29/8/78; a maximum of 3.54 µg-at-l\(^{-1}\) was observed in the surface layer on 11/4/78 (Table 2). There was no marked seasonal change in ammonia distribution. During winter (November-January) and spring (February-March), concentrations were between 1.0-2.0 µg-at-l\(^{-1}\) and were almost uniformly distributed. In April, there was a sudden increase throughout the column (>3.0 µg-at-l\(^{-1}\)) followed by a rapid decrease during the summer months.

OFFSHORE:

The seasonal distribution of ammonia in the offshore waters is shown in Figure 24. There was complete depletion of this nutrient in the surface waters on 28/5/78 and the maximum of 3.90 µg-at-l\(^{-1}\) was observed at 200 m on 21/4/78 (Table 2). In the top 100 m, there was little seasonal variation in ammonia and the values were constant at about 1.0 µg-at-l\(^{-1}\). However, during March-April, the ammonia content doubled.
Below 100 m ammonia concentration was generally high (2.0-4.0 µg-at l⁻¹) during winter (November-February) and spring (March-April). During the summer months (May-September), values were uniformly low (<1.0 µg-at l⁻¹) throughout the water column. Domes of high values of ammonia were observed near the bottom during February-April and in October.


The relationships between salinity, silicate and phosphate have been used to indicate water mass origins or relative biological nutrient requirements.

Relationships between salinity and silicate (both stations combined) and between silicate and phosphate (Sharm and offshore stations) are presented in Figures 25, 26 and 27 respectively. These relationships will be examined further in the Physico-chemical environment section of the Discussion.
Biological Data

1. Seasonal Composition of the Major Groups of Phytoplankton and Diversity Indices

SHARM:

The seasonal composition of phytoplankton groups in the inshore waters at the Sharm station is shown in Figure 28. Diatoms, dinoflagellates and blue-green algae were represented, with diatoms constituting the bulk of the phytoplankton during most of the year except for May, June and October. During May and June, the blue-greens were dominant, and during October dinoflagellates were dominant. The appearance of blue-greens was limited to the summer months of May, June and July, whereas dinoflagellates and diatoms were present year round.

The diversity index (Figure 29) at the Sharm station ranged from 0.92 at 20 m during October to 4.56 at the surface in April. The general seasonal trend is for higher diversities in the early part of the year until April and again in August and September, with much lower values in October and variable values during the summer (May-July). Diversity indices for diatoms and dinoflagellates separately are tabled in Appendix 9.
OFFSHORE:

The seasonal composition of phytoplankton in the offshore waters is shown in Figure 30. There is a close similarity between inshore and offshore waters in the seasonal composition of phytoplankton. Diatoms were present all year except during October, and they dominated the phytoplankton community at the offshore station year round except for June and October. Dinoflagellates were also present year round, but only dominated the community in October as at the Sharm station. Blue-green algae were present as small proportions of the total phytoplankton crop in several months, but only reached significant proportions from May to August, and were dominant only in June. Again, this closely resembles the situation observed at the Sharm station.

The diversity index (Figure 31) at the offshore station ranged from 0.65 at 100 m in October, to a maximum of 4.62 at 100 m in July. The general seasonal trend is similar to that of the inshore station although there is much variation. Higher diversities were again generally observed early in the year and again in August and September, with much lower values in October and variable values from April to June. Diversity indices for diatoms and dinoflagellates separately are tabled in Appendix 10.
The low diversity indices at both stations in October clearly reflect the predominance of a few species of dinoflagellates. The low values during the summer months reflect the dominance of blue-green algae.
2. Quantitative Abundance of Phytoplankton

SHARM:

Cell numbers ranged from only $10 \, \text{cells l}^{-1}$ at 40 m on 20/8/78 to $69,755 \, \text{cells l}^{-1}$ at the surface on 25/1/78 (Table 3). The phytoplankton community showed a distinct bimodal distribution with a primary peak in January 1978 and a smaller secondary peak in late May (Figure 32). Although both diatoms and dinoflagellate contributed to the primary January peak, diatoms were far more abundant. The third apparent peak in August may be due simply to spuriously low cell counts on July 25 (c.f. Figure 34 - offshore station).

The abundance of major groups (number of cells l$^{-1}$ during the peak periods can be summarized from Table 3 as follows:

<table>
<thead>
<tr>
<th>Date</th>
<th>Primary Peak</th>
<th>Secondary Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>25 Jan 1978</td>
<td>28 May 1978</td>
</tr>
<tr>
<td>Total maximum</td>
<td>69,755</td>
<td>12,920</td>
</tr>
<tr>
<td>Average for water column</td>
<td>31,120</td>
<td>7,439</td>
</tr>
<tr>
<td>Diatoms maximum</td>
<td>68,435</td>
<td>8,030</td>
</tr>
<tr>
<td>Dinoflagellates maximum</td>
<td>1,320</td>
<td>1,690</td>
</tr>
<tr>
<td>Blue-greens maximum</td>
<td>Nil</td>
<td>4,500</td>
</tr>
</tbody>
</table>

During the primary peak 53 taxa of diatoms, 14 taxa of dinoflagellates and 1 chrysophyte comprised the cell counts
(based on Van Dorn collections), (Appendix 2), and a total of 65 diatoms, 44 dinoflagellates and 1 chrysophyte species were present (based on Van Dorn collections and plankton net hauls combined) (Appendix 4). During the secondary peak, 9 taxa of diatoms and 11 taxa of dinoflagellates together with blue-green algae comprised the cell counts (based on Van Dorn collections) (Appendix 2); a total of 33 diatom and 28 dinoflagellate species in addition to the blue-greens were present (based on Van Dorn collections and plankton net hauls combined), (Appendix 4).

In the vertical plane, dinoflagellates, diatoms and blue-greens exhibited marked variations with depth (Figure 33, Table 3). During periods when diatoms and dinoflagellates comprised the dominant flora, they were most abundant in the top 5 m, their numbers generally decreasing with depth. During the summer months, when blue-greens were most dominant, in the top 5 m they constituted more than 60% of the phytoplankton population.

OFFSHORE:

Total phytoplankton cell numbers at this station reached a maximum of 24,860 cells l⁻¹ in surface waters on 27/12/77 (Table 4). On 25/10/78 cell numbers were low throughout the water column, and phytoplankton were not noted in the deeper waters. Phytoplankton abundance in offshore waters followed a bimodal distribution with a primary peak during December and January and a secondary peak in July (Figure 34). The
seasonal cycle of phytoplankton abundance is thus very similar at the two stations, but the primary peak offshore occurred about three weeks earlier. The summer peak of abundance for blue-greens and dinoflagellates occurred in July and for the diatoms, in late August.

The abundance of the major groups (number of cells $\text{L}^{-1}$) during the peak periods can be summarized from Table 4 as follows:

<table>
<thead>
<tr>
<th>Date</th>
<th>Primary Peak</th>
<th>Secondary Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>27 Dec 1977</td>
<td>10 July 1978</td>
</tr>
<tr>
<td>Total Maximum</td>
<td>24,860</td>
<td>15,920</td>
</tr>
<tr>
<td>Average for water column</td>
<td>9,571</td>
<td>6,102</td>
</tr>
<tr>
<td>Diatoms maximum</td>
<td>24,250</td>
<td>7,180</td>
</tr>
<tr>
<td>Dinoflagellates maximum</td>
<td>610</td>
<td>3,320</td>
</tr>
<tr>
<td>Blue-greens maximum</td>
<td>Nil</td>
<td>9,650</td>
</tr>
</tbody>
</table>

During the primary peak 27 taxa of diatoms and 18 taxa of dinoflagellates comprised the cell counts (based on Van Dorn collections) (Appendix 3), and a total of 50 diatom and 31 dinoflagellate species were present (based on Van Dorn collections and plankton net hauls combined) (Appendix 5). During the secondary peak 28 taxa of diatoms and 30 of dinoflagellates, together with blue-green algae, comprised the cell counts (based on Van Dorn collections) (Appendix 3); a total of 32 diatom and 44 dinoflagellate species in addition to the blue-greens were present (based on Van Dorn collections and plankton net hauls combined) (Appendix 5).

In the vertical plane, the phytoplankton groups exhibited marked variations with depth (Figure 35), except during
October (Table 4). Diatoms constituted the bulk of the cell counts and were most abundant in the top 100 m (Table 4). During May to July, blue-greens were most abundant in the surface waters (60-80%) and during October, only dinoflagellates were noted (Table 4).
3. Seasonal Species Composition

A total of 283 taxa of phytoplankton (including 10 sub-species or varieties) have been recognized and identified from collections at the two stations. Seasonal species lists at the Sharm and offshore stations are presented in Appendices 4 and 5 respectively. A wide variety of taxa was present at both stations. The complete species list with authorities is presented in Appendix 6.

In the Bacillariophyta, 137 species (including 6 varieties) belonging to 48 genera were identified, together with a further 21 taxa (exclusive of the monospecific genera) of uncertain specific status (referred to as spp.). In the Dinophyta, 110 species (including 4 sub-species and varieties) were recognized, belonging to 27 genera; in addition a further 13 taxa (exclusive of the monospecific genera) of uncertain specific status (referred to as spp.) were noted. In the Chrysophyta a single species was observed and in the Cyanophyta the single genus *Trichodesmium* (not separated into species) was observed.

Based on their seasonal distribution, the phytoplankters can be grouped as:

A - those common to inshore and offshore waters during the major bloom,

B - those common to both inshore and offshore waters during the minor bloom,
A. During the major bloom, the following taxa were common to the inshore and offshore waters:

Diatoms

Bacteriastrum delicatulum
B. hyalinum
Chaetoceros affinis
C. atlanticus
C. coarctatum
C. compressus
C. didymum
C. Lauderii
C. peruvianum
Climacodium fraunfeldianum
Guinardia flaccida
Nitzschia closterium
N. longissima
N. seriata
Planktoniella sol
Rhizosolenia alata
R. bergonii
R. calcar-avis
R. delicatula
R. fragilissima
R. hebetata
R. imbricata
R. Shrubsolei
R. Stolterfothii
R. styliformis
Streptotheca thamesis

Dinoflagellates

Amphisolenia bidentata
Ceratium arietinum
C. carriense
C. contrarium
C. declinatum
C. furca
C. fusus
C. kofoidii
C. macroceros
C. massiliense
C. teres
C. trichoceros
C. tripos
Diplopsalis lenticula
Exuviaella spp.
Goniodoma polyedricum
G. sphaericum
Gonyaulux polygramma
Peridinium divergens
P. oceanicum
P. trochoideum
Prorocentrum micans
Pyrophacus horologium

B. The following taxa were common to the offshore and inshore waters during the minor bloom:

Diatoms

Chaetoceros curvisetum
Guinardia flaccida
Hemiaulus hauckii
Leptocylindrus danicus
L. minimus
Nitzschia closterium
N. delicatissima
Rhizosolenia alata
R. bergonii
R. calcar-avis
R. delicatula
R. Stolterfothii

Dinoflagellates

Ceratium breve
C. candelabrum
C. contrarium
C. declinatum
C. furca
C. fusus
C. kofoidi
C. massiliense
C. pentagonum
C. teres
C. trichoceros
Dinophysis caudata
Exuviaella spp.
Goniodoma polyedricum
Gonyaulux polygramma
Ornithocerus spp.
Peridinium brochii
P. spp.
P. divergens
P. granii
P. steinii
P. trochoideum
Peridinopsis asymmetrica
Prorocentrum micans

C. Of the above, the following species were common to both major and minor peaks.

Diatoms

Chaetoceros affinis
C. compressus
Guinardia flaccida
Nitzschia closterium
Rhizosolenia alata
R. bergonii
R. calcar-avis
R. delicatula
R. stolterfothii

Dinoflagellates

Ceratium contrarium
C. declinatum
C. furca
C. fusus
C. kofoidii
C. massiliense
C. teres
C. trichoceros
Exuviaella spp.
Goniodoma polyedricum
Gonyaulux polygramma
Peridinium divergens
P. trochoideum
Prorocentrum micans

D. The following were restricted to one of the blooms as shown:
Primary bloom Diatoms

Bacteriastrium delicatulum
B. hyalinum
Chaetoceros atlanticus
C. coarctatum
C. concaviformis
C. convolutus
C. didymum
C. lauderi
C. peruvianum
Climacodium fraunfeldianum
Nitzschia longissima
N. seriata
Planktoniella sol
Rhizosolenia fragilissima
R. hebetata
R. imbricata
R. shrubsolei
R. styliformis
Streptotheca thamesis

Primary bloom Dinoflagellates

Amphisolenia bidentata
Ceratium arietinum
C. carriense
C. macroceros
C. tripos
Diplopsalis lenticula
Goniodoma sphaericum
Gonyaulux polygramma
Peridinium oceanicum
Pyrophacus horologium

Minor bloom Diatoms

Chaetoceros compressus
C. curvisetum
Hemiaulus hauckii
Leptocylindrus danicus
L. minimus
Nitzschia delicatissima

Minor bloom Dinoflagellates

Ceratium breve
C. candelabrum
C. pentagonum
Dinophysis caudata
Ornithocercus spp.
Peridinium brochii
P. cerasus
P. divergens
P. granii
P. steinii

Peridinopsis asymmetrica
4. Phytoplankton Pigments

SHARM:

Chlorophyll \( a \) concentrations in the inshore waters ranged from 0.07 to 1.83 mg m\(^{-3}\) on 18/7/78 and 25/1/78 respectively (Table 5). Seasonal variations in chlorophyll \( a \) in the water column are shown in Figure 36. During the winter months, December and January, chlorophyll \( a \) reached a maximum in the top 10 m and decreased with depth. During February-May the values in the top 10 m were lower, but there was an increase at sub-surface (>10 m) levels. From the 28th of June values at the surface registered an increase. Subsequently, there was no marked variation in the chlorophyll \( a \) values.

Chlorophyll \( b \) values ranged between 0.03 and 1.42 mg m\(^{-3}\) (Table 5). Comparison of chlorophyll \( b \) (Figure 37) profiles with those for chlorophyll \( a \) show close similarity. Maximum chlorophyll \( b \) values were observed during December-January in the top 10 m. Following this, there was an increase or accumulation of this pigment at depths greater than 10 m until the 28th of May, and in surface waters until the 20th of June. There was an increase in its concentration in surface waters again in September. Thus, it may be concluded that these algal pigments showed a bimodal (or trimodal?) peak distribution with a major peak during December-January, and a minor peak during
May-June months.

OFFSHORE:

Chlorophyll a concentrations in the offshore waters ranged from 0 to 2.25 mg m$^{-3}$ and chlorophyll b from 0 to 1.86 mg m$^{-3}$ (Table 5). Chlorophyll a concentrations were generally low in the surface waters during October-November. During December there was a sudden and rapid increase at 75 m (Figure 38). The surface layers (0-25 m) next showed an increase in chlorophyll a, with a peak occurring on February 22nd. A second peak in surface waters was reached in June and July. Subsequently chlorophyll a levels in the surface waters declined concurrently with a substantial sub-surface increase at 75 m in September. Seasonal variations in chlorophyll b were similar to those of chlorophyll a (Figure 39). Values were low during October-November, and maximum concentrations were observed at 75 m during December. From January until April 11th, the values gradually increased in the top 25 m. On April 21st, surface values decreased, but the values at about 75 m increased. During May to September, values in the surface layer remained fairly high.

A comparison of chlorophyll a levels in the inshore and offshore waters shows certain similarities (Figures 36, 38 and 37, 39). At the offshore station, a very distinct sub-surface chlorophyll maximum layer developed in December. At the Sharm station, although there is a sub-surface maximum (e.g. April, May and July), this probably represents an
"accumulation" of pigments by sinking from surface waters, and this may also be occurring in September in the offshore waters.

There is general evidence at both stations of approximate seasonal bimodality, with the lowest chlorophyll values between the maxima occurring in October-November at both stations. At the Sharm station, the second seasonal minimum occurred in March, and at the offshore station, it occurred in April. Generally, the inshore waters had slightly higher levels of chlorophyll a than the offshore waters. This was especially true of the surface waters during December and January, which is consistent with the data on numerical abundance of phytoplankton at this time.
5. Primary Production

SHARM:

Seasonal variations in primary production profiles are shown in Figure 40. Primary production rates ranged from 0.31 mg C m\(^{-3}\) hr\(^{-1}\) at 20 m during August, to 6.34 mg C m\(^{-3}\) hr\(^{-1}\) at the surface on 21/4/78 (Table 5). The maximum integrated production rate of 199.84 mg C m\(^{-3}\) hr\(^{-1}\) was observed on 27/12/77 and the minimum was 29.16 mg C m\(^{-2}\) hr\(^{-1}\) on 29/8/78 (Table 5).

In general, production was high in the surface waters and decreased with depth, as evident from the profiles for November to October. The seat of maximum production was often at about 20 m except from late April to August when it was at the surface (Figure 40).

OFFSHORE:

Seasonal variations in primary production profiles at the offshore station are shown in Figure 41. On several occasions primary production was undetectable in deeper waters; it reached a maximum of 9.40 mg C m\(^{-3}\) hr\(^{-1}\) at the surface on 10/7/78. The maximum integrated production of 206.13 mg C m\(^{-2}\) hr\(^{-1}\) was measured on 10/8/78 and the minimum of 25.45
mg C m$^{-2}$ hr$^{-1}$ on 28/5/78. In the offshore waters, the highest rate of production was generally at the surface from March to September and in November, and at 25 m during October, January and February. Production seems to have started at 75 m during December, and gradually surfaced, where it attained a maximum similar to the chlorophyll $a$ pattern.

The annual cycle of integral production (mg C m$^{-2}$ hr$^{-1}$), shows several interesting features (Figure 42). In the inshore waters, production rapidly increased during winter to reach a maximum during December.

In the offshore waters, the corresponding seasonal maximum was not attained until February. Following this, production declined at both stations into May when minimum values were observed in offshore waters. Although the decline in production was similar from January to May, actual production was higher inshore than offshore. From May onwards, production offshore rapidly increased to reach high levels during July-August. Increase in inshore production was not as dramatic as in the offshore during June-July. Interestingly, minimum values were observed in the inshore during August, when production was at its peak offshore. Following this, production values registered an increase and were similar, both in the inshore and offshore waters, during October.

The annual cycle of production at the offshore station thus appears to be strongly bimodal with two peaks of almost equal integrated rates in February and July-August. The annual cycle at the Sharm station seems to precede events offshore by about two months, but no clear second peak of
production in autumn is evident. Rather, two smaller spring-summer peaks in April and June occur to give a possible trimodal annual cycle.
6. Carbon Assimilation Ratios (mg C mg Chl a⁻¹ hr⁻¹).

SHARM:

The pattern of seasonal variation in carbon assimilation ratios is shown in Figure 43. These ratios, which are a measure of the photosynthetic efficiency of the phytoplankton, ranged from 1.21 at 30 m during July to 14.57 at 5 m during February (Table 5). This range excludes the very high values (at the surface during July and similar high values at 10-20 m during October), as they appear to be suspect. Chlorophyll a values on those days were very low, and could have resulted in these high suspect values. The great majority of ratios lay between 1 and 10. In the inshore waters, photosynthesis was efficient during November and December at sub-surface levels (20-30 m), (Figure 43). Photosynthetic efficiency steadily increased throughout the column and ascended to the surface to attain a maximum during March. The efficiency continued to be reasonably high (~6) in the top 5 m, and reached a second maximum during July. There was increased photosynthetic efficiency in the whole column during October.
OFFSHORE:

The seasonal pattern of variations in carbon assimilation ratios at the offshore station is shown in Figure 44. The great majority of ratios about 75 m lay in the range of 0.5 - 7, but ranged from 0.11 at 75 m during January to 17.70 at the surface during October (Table 5).

The pattern suggests that efficient functioning of photosynthesis began at sub-surface levels (about 25 m) during January and reached the surface. However, it did not last long, as evident by the low assimilation ratios during February to June. From June, the photosynthetic efficiency increased rapidly and reached a maximum during August. In the vertical plane photosynthesis was efficient down to 75 m. This was followed by low efficiency during September. Again during October, the phytoplankton carried on photosynthesis effectively, as evident by the high assimilation ratios throughout the column.

Figure 44 also shows that from 50 m to 100 m, during the period November to July, photosynthetic efficiency was extremely low, whereas in the inshore waters photosynthetic efficiency continued to be high, even near the bottom, generally throughout the study period.
7. Inter-relationships of Physico-Chemical and Biological Data

In order to avoid lengthy description and repetition of these findings, the inter-relationships of the data presented above will be considered in the Discussion Section following.

Correlation matrices summarizing relationship between measured variables and derived parameters at the inshore (Sharm) and offshore stations, is presented in Tables 6 and 7.
DISCUSSION

There are very few bodies of water similar to the Red Sea i.e. which are landlocked, semi-enclosed and located in an arid zone where evaporation is far in excess of precipitation and run-off. Because of the uniqueness of the Red Sea and paucity of data from neighbouring seas, a comparison of the present data with that from other bodies of water becomes difficult. However, such comparisons will be made wherever feasible in order to place the present findings into some reasonable ecological perspective. The objectives of this discussion are therefore:

(i) to interpret as far as possible the physico-chemical and biological data obtained, their interactions and significance to primary production

(ii) to place these findings into perspective by comparison with previous biological oceanographic research.

The Physico-Chemical Environment

To the south of Jiddah in the Red Sea, and in the Indian Ocean, the reversal of the monsoon wind system is a dominant oceanographic force. During November-February under the influence of the northeast monsoon, it appears that oceanic
Red Sea water piles up on the Arabian Coast, gets cooled and mixes downward. The relatively high surface salinity values in January and February probably reflect this effect. During the Southwest monsoon period, May to September, surface waters warm up and some stratification is noticed. Although any evidence for upwelling of colder sub-surface waters is lacking, a distinct seasonal inclination of isotherms, isohalines and isobars is very evident at the offshore station (see Figures 7, 9, 11). This effect does not extend to the inshore Sharm station some 7 km away.

It may well be that Jiddah lies at the approximate limit of influence of the monsoon reversal, at least with respect to upwelling. The tendency for surface waters to upwell here during the summer will also be resisted by higher summer temperatures causing lower densities (Figure 11). In view of this apparent lack of outside influence (i.e. upwelling due to monsoon influence) attention will now focus on the local relationship between variables.

Pearson correlation coefficients between the various parameters are given in Table 6 for Sharm (inshore) waters and in Table 7 for offshore waters. Between the inshore and offshore waters, certain correlations were similar.

Significant positive correlations existed between advancing season (month) and temperature, depth and density, salinity and density, density and phosphate, oxygen and temperature, oxygen and oxygen saturation and temperature, phosphate and ammonia and silicate and depth.
Of these correlations, those between advancing season and temperature, increase in density with increase in salinity, increase of phosphate with an increase in density, increase in oxygen saturation level with oxygen concentration, increase of ammonia with an increase in phosphate and an increase of silicate with depth are obvious.

It is clear that with an increase in depth both density and nutrients increased, particularly in the offshore waters (Table 7). The increase of the nutrients at these depths could be either due to lesser utilization of nutrients below the euphotic zone or due to regeneration of nutrients or both. It is well known that a wide range of biogenic materials such as the siliceous diatoms, radiolarians and other sestonic material sinks in the water column where regeneration of inorganic phosphorus, silicon and nitrogen takes place. In landlocked basins, due to restrictions on the exchange of bottom water, accumulation of nutrients results. Such an accumulation of silicates and inorganic phosphates in basins was reported by Richards (1958) and Richards and Vaccaro (1956).

The correlations between temperature and oxygen saturation were positive and significant both in the inshore and offshore waters. This is clearly a reflection of increased oxygen utilisation in deeper, cooler waters due to processes of nutrient regeneration. The supersaturation values in surface waters can clearly be ascribed to oxygen production by photoautotrophic organisms. Such simple explanations are, however, not always adequate and departures from expected
correlations between temperature and dissolved gases, e.g. oxygen and carbon dioxide, are often recorded. For example, on the west coast of India, during April, May and June, high oxygen concentrations were recorded despite poor phytoplankton crops and high temperatures (Subrahmanyan 1959; Kasturirangan 1957).

**Significant negative correlations** existed between depth and temperature, temperature and density, depth and oxygen, oxygen and density, oxygen saturation and phosphate, and temperature and phosphate, both in the inshore and offshore waters. These correlations are generally expected and consistent with findings from research in other bodies of water.

Temperature and all nutrients were negatively correlated in the offshore waters, which shows that as the temperature decreased in deeper waters, there is an increase in nutrients. As stated earlier, increase in the subsurface nutrients results from lower utilization of nutrients and from regeneration.

There have been several accounts to show that the relative fertility of ocean waters can be understood by comparing the available nutrients. Table 8 summarizes the inorganic phosphate concentrations in some selected regions. Phosphate concentrations noted in the present study are comparable to records from the Gulf of Aqaba (Klinker et al. 1978), Gulf of Elat (Levanon-Spanier et al. 1979, Sournia 1977) and the N.E. Arabian Sea (Radhakrishna et al. 1978). Grasshoff (1969) and Hansen et al. (1968) recorded higher values in Red Sea waters than those recorded during this study. There was not always an abundant supply of this nutrient in these waters.
as indicated by low values such as 0 and 0.01 µg-at-l⁻¹. These low values could be attributed to the lack of input of phosphate through rainfall and land drainage.

Phosphate concentrations at the inshore station did not show a clear seasonal cycle. Although some features could be seasonally related to biological activity, there was no correlation to biomass (chlorophyll a) or to rate of production (Table 6). Overall, the seasonal distribution of phosphate was "episodic", with several high peaks of phosphate occurring at depths of 10-15 m. This is probably a consequence of periodic sub-surface pollution from the Sharm-Obhur area.

Offshore, the seasonal cycle is clearer, with a single peak in phosphate occurring in April. This was possibly a consequence of breakdown and remineralisation of phosphorus after the peak in primary production. Overall there was a significant negative correlation between phosphate and biomass (chlorophyll a) and production (Table 7).

Silicate values recorded during the present study are comparable with those reported earlier from the Red Sea area (Klinker et al. 1978, Hansen et al. 1968, Grasshoff 1969, Sournia 1977. See Table 9). When compared to the Bay of Bengal, Baltic waters and the Black Sea, which receive large quantities of freshwater, silicate concentrations in the Red Sea are quite low. These low concentrations can be attributed to lack of freshwater input. Besides freshwater inputs, replenishment of silicates takes place through regeneration from diatom frustules (Hart 1934, Cooper 1952, Harvey 1955) and
liberation of this nutrient from bottom muds (Hendey 1951).

In estuaries and coastal waters where there is considerable admixture of freshwater, low salinity together with high silicate values are used as indicators of incursion of freshwater (Nash 1947). In landlocked basins and fjords, because of slow dissolution of diatom shells, Grasshoff (1975) reasoned that silicates would behave in a conservative manner and therefore could be used in the identification of water masses. Grasshoff (1975), based on a silicate-salinity diagram, identified four water masses in the Red Sea. They are:

A. 35.1°/o S, 29 µg-at Si l⁻¹,
B. 36.8°/o S, 0 µg-at Si l⁻¹,
C. 40.6°/o S, 3 µg-at Si l⁻¹,
D. 38.16°/o S, 14.5 µg-at Si l⁻¹.

From the present data a silicate-salinity diagram was constructed (Figure 25), from which three main water masses can be identified as follows:

I is the surface water of the Sharm, relatively rich in silicates (3-7.4 µg-at Si l⁻¹) and salinities (39-39.7°/o)

II is the Red Sea water with intermediate values of silicates (0.5-5 µg-at Si l⁻¹) and salinities from 39.8-40.5°/o, and

III is Bab-el-Mandeb water with low silicates (1-3 µg-at Si l⁻¹) and lower salinities (38.4-39.7°/o).

Although the range of silicates in the present study is comparable to that observed by Grasshoff, the present salinity
values range from 38.4 to 40.5, whereas those of Grasshoff ranged from 31.5 to 40.6. For this reason, the water masses I, II and III do not readily correspond to water masses A, B, C, and D identified by Grasshoff. Water masses II and III could correspond to water masses C and D identified by Grasshoff. Water mass C originates from the Red Sea and D is the Red Sea water after it has cascaded down into the Gulf of Aden (Grasshoff 1975).

Nitrite values during the present study are comparable to those reported earlier from the Red Sea (Deuser et al. 1978, Hansen et al. 1968, Grasshoff 1969) (see Table 10). When compared to the N.E. Arabian Sea (Radhakrishna et al. 1978) or the Straits of Bab-el-Mandeb (Grasshoff 1969), the present values were low. Levanon-Spanier et al. (1979), and Sournia (1977), who also encountered low nitrite values in the same geographical area, are of the opinion that nitrogen (NO₂, NO₃ - N) is the major nutrient limiting primary producing in the Red Sea. This hypothesis of nitrogen limitation is widely held for other ocean areas.

It is necessary to point out that during this study, nitrates could not be determined and therefore we have to rely on the findings of Deuser et al. (1978) who furnished evidence for denitrification in adjacent geographical regions, i.e. the Persian Gulf and the Gulf of Oman. It is assumed that some denitrification also takes place in the study area, which leads to reduction of nitrate to nitrite. This in turn may result in a lower level of primary production, except in the blue-green algae which can fix atmospheric nitrogen.
In the offshore waters, two maxima of nitrite concentrations were observed; one of these was usually in the surface waters, i.e. euphotic layer, and the second maximum was in the deep layer ~200 m, i.e. below the euphotic zone. In this respect, these findings are similar to those of Gilson (1937) who reported two nitrite maxima. The offshore waters have more nitrite than nearshore waters. This could be either due to excretion of extracellular nitrite by phytoplankton as suggested by Vaccaro and Ryther (1960), or due to bacterial nitrification, or both. Grasshoff (1969) contends that the high nitrite values at the entrance to the Red Sea, where turbulent mixing takes place, are due to excretion by phytoplankton.

Maximum ammonia values observed during this study are comparable to those reported by Grasshoff (1969) from the Red Sea (Table 11). They are quite high when compared with values from the Gotland Deep and Oslo Fjord (Grasshoff 1975).

In the nitrogen cycle, the first step in the nitrification process is the formation of ammonia by bacterial decay of dead organic matter, excretion of ammonia by animals and photochemical oxidation of organic matter by solar ultraviolet radiation. Although some nitrogen is also contributed by river water and rain water, Morcos (1970) rules out such a possibility in the Red Sea. Some nitrogen is fixed by the blue-green alga Trichodesmium, but there are no estimates on rates for the Red Sea region. Ammonia is oxidized to nitrite and finally to nitrate. Thus Harvey (1955) demonstrated a succession in the production of ammonia, nitrite and nitrate
nitrogen peaks in the sea water. Comparison of ammonia values (Figure 23) with nitrites (Figure 21) shows that in the inshore Sharm waters there was no clear succession of ammonia and nitrite peaks. However, in the offshore waters (Figures 24 and 22), there was a succession of peak values of ammonia and nitrite. Peaks of high values of ammonia were observed at 100-200 m during February-April and high values of nitrites occurred during April-May.

The silicate to phosphate ratio in temperate waters is generally around 20:1, (Sverdrup et al. 1942). During this study, the ratio varied between <5 and >20 in the Sharm waters (Figure 26) and from <5 to >40 in the offshore waters (Figure 27). Comparison of these figures shows that in the inshore region, ratios were low, increased with depth and gradually increased during January and June. In the offshore waters, the ratios were higher decreased with depth and gradually increased from March until August. Such anomalies could be attributed to several factors, among them:

1. differential requirements for these two nutrients by phytoplankton groups in the water (Redfield 1934), and
2. differences in the rate of re-solution of either nutrient.

It is possible that in the inshore Sharm waters, re-solution of phosphate from phosphorite phosphates in the bottom sediments takes place as considered by Grasshoff 1969; this would explain the lower silicate:phosphorus ratios inshore.

A balance sheet for nutrient salts in the Red Sea is given by Morcos (1970), which shows that annually $153 \times 10^6$ tons of
phosphate, $1275 \times 10^3$ tons of nitrate and $1120 \times 10^3$ tons of silicates are lost through the outflow from the Red Sea. As discussed by Morcos, balancing the budget by contribution of nutrients from rivers as in the Mediterranean Sea, is not possible in the Red Sea. The suggestion of Hassan (1962), that irrigation water from land after being used may be diverted into the Red Sea, with a view to reduce the loss of nutrients, merits consideration.
Phytoplankton Ecology

One of the main objectives of this study was to investigate the factors that govern phytoplankton ecology and primary production in the study area, which is unique due to its semi-arid nature and monsoonal currents. As the magnitude of production is dependent on the abundance of phytoplankton biomass, it will be necessary to examine the factors that account for the distribution and seasonal succession of phytoplankton.

Earlier it was stated that certain groups of phytoplankton organisms were common to inshore and offshore waters, or to the major and minor blooms of phytoplankton. Restriction of a few species to either of the seasonal blooms was also mentioned. A biogeographical consideration of the phytoplankton species should give an insight into the origin and source of recruitment of phytoplankton in the area of study. It is proposed first to consider the biogeography of the phytoplankton of the study area and then to discuss the succession and quantitative abundance of phytoplankton. This will be followed by a discussion of physico-chemical factors that control the magnitude of primary production.
1. Biogeography of Phytoplankton

For the present purposes, the approach of Smayda (1958), Hasle (1976) and Guillard and Kilham (1977) was followed, which is based on physical features such as temperature and water movements. A phyto-geographical consideration of species associations such as that of Thorrington-Smith (1971) would be more revealing; however, this cannot yet be attempted for want of sufficient data on the distribution of each species.

In the present study, a total of 283 taxa of phytoplankton were recognised; this included 249 species or monospecific genera and a further 34 recognisable, but not fully identified, taxa. Included in the total were 110 recognised species, or monospecific genera, and a further 13 taxa of dinoflagellates. Halim (1969), in his review, lists only 88 dinoflagellate species from the Red Sea. The present study has added a total of 87 species of diatoms and dinoflagellates to the taxonomic list of phytoplankton in the Red Sea (Appendix 7).

The phytoplankton populations in this area can be compared with those of Thorrington-Smith (1971), who carried out a numerical investigation of phytohydrographic regions in the West Indian Ocean. Thorrington-Smith, based on a cluster analysis of the 237 species, recognised 11 different floral elements. The species encountered during the present study conform to these floral groups as follows:
1. Southwest monsoon floral element

Gossleriella tropica
Rhizosolenia styliformis
Rhizosolenia alata
Schroderella delicatula
Chaetoceros affinis
Gardinia flaccida

2. Equatorial sub-surface based floral element

Bacteriastrum hyalinum
Rhizosolenia hebetata
Chaetoceros affinis
Rhizosolenia alata
Planktoniella sol
Dactyliosolen mediterraneus
Chaetoceros peruvianum
Thalassionema nitzschioides
Nitzschia closterium
Chaetoceros danicus
Chaetoceros atlanticus
Nitzschia seriata

3. Predominantly pre-southwest monsoon floral element

Thalassiothrix fraunfeldii
Rhizosolenia calcar-avis
Chaetoceros messanensis
4. **Floral elements from fluctuating conditions**
   - Chaetoceros affinis
   - Dactyliosolen mediterraneus

5. **Equatorial undercurrent floral element, April-May**
   - Podolampas spinifera
   - Ceratium teres
   - Rhizosolenia hebetata
   - Thalassiothrix longissima
   - Hemiaulus hauckii
   - Oxytoxum scolopax

6. **Floral element with distribution centered on 5°S**
   - Prorocentrum gracile
   - Ceratium tripos
   - Chaetoceros decipiens

7. **Floral element 7**
   - No representatives from the study area

8. **Floral element 8**
   - Fragilaria oceanica
   - Rhizosolenia imbricata
   - Rhizosolenia bergonii
   - Ceratium furca
9. **Floral element from southern side of the equatorial undercurrent in April-May**
   - Ceratium vultur
   - Peridinium trochoideum

10. **Floral element from regions of fluctuating conditions**
    - Ceratium extensum
    - Rhizosolenia alata
    - Thalassiothrix mediterranea
    - Chaetoceros atlanticus
    - Climacodium fraunfeldianum
    - Ceratium fusus
    - Ceratium declinatum
    - Ceratium pentagonum
    - Ceratium tripos
    - Chaetoceros laciniosus
    - Chaetoceros dadayi
    - Rhizosolenia Stolterfothii
    - Ceratium Kofoidii
    - Ceratium trichoceros
    - Chaetoceros affinis
    - Leptocylindrus danicus
    - Ceratium carriense

11. **South-Equatorial current-based floral element**
    - Asterionella japonica
    - Ceratium extensum
Rhizosolenia alata
Thalassiothrix mediterranea
Chaetoceros tetrastichon
Chaetoceros atlanticus
Climacodium fraunfeldianum

A comparison of the distribution of phytoplankton during this study with that of Halim (1969) shows certain common features as follows:

1. Commonly abundant in the Red Sea
   Hemidiscus cuneiformis
   Striatella delicatula
   Rhizosolenia calcar-avis
   Rhizosolenia Shrubsolei
   Rhizosolenia alata
   Guinardia flaccida
   Thalassionema nitzschioides
   Bacillaria paradoxa

2. Diatoms found only to the south of 20°N
   Chaetoceros tetrastichon
   Streptotheca thamesis
   Striatella delicatula
   Thalassiothrix longissima

3. Mediterranean component
   Ceratium massiliense
   Peridinium trochoideum
4. **Indo-Pacific component**
   - *Ceratium egyptiacum*

5. **Strictly tropical but absent from Mediterranean**
   - *Ceratium breve*
   - *Ceratium reflexum*
   - *Ceratium vultur*

In addition to the two species listed as Mediterranean components, a comparison of the present study with that of Guillard and Kilham (1977) shows the following Mediterranean species in the study area:

- *Thalassiothrix fraunfeldii*
- *Nitzschia seriata*
- *Nitzschia delicatissima*
- *Rhizosolenia calcar-avis*
- *Chaetoceros decipiens*
- *Asterionella japonica*
- *Chaetoceros affinis*
- *Chaetoceros decipiens*
- *Ceratualina bergonii*
- *Dactyliosolen mediterraneus*
- *Rhizosolenia Stolterfothii*
- *Thalassionema nitzschioides*
- *Leptocylindrus danicus*
- *Thalassiosira subtilis*
- *Ceratium breve*
Ceratium contortum

To the Indo-Pacific group listed by Halim (1969), occurrence of the diatom Biddulphia pelagica should be added. A few species from the Adriatic Sea (see Guillard and Kilham 1977) were also found in the Red Sea, for example Bacteriastrum hyalinum, Chaetoceros curvisetum, and Thalassiosira decipiens.

During the present study, the following species considered as tropical (Smayda 1958, Sukhanov 1969) were also present:

- Planktoniella sol
- Gossleriella tropica

Similarly, species listed as cosmopolitan were also present:

- Chaetoceros compressus
- Leptocylindrus danicus
- Prorocentrum micans
- Thalassiothrix fraunfeldii
- Nitzshia seriata
- Nitzschia delicatissima

A few species recorded from the estuarine Nile plankton (Halim 1976b) were also recorded during this study. These include:

- Nitzschia longissima
- Chaetoceros affinis
- Thalassionema nitzschioides
- Asterionella japonica
- Peridinium trochoideum
Thus, in the study area a wide variety of phytoplankton groups, each originating from a different water mass, were present. For example, from the tropical Indian Ocean, phytoplankters from equatorial sub-surface waters, the equatorial under current boundary, the south equatorial current and sub-surface tropical waters were present. In addition to the flora restricted to the Red Sea, flora from the adjacent water bodies were also present as evident from the Mediterranean, Adriatic and Nile floral components. Periodic recruitment and exchange of phytoplankton in and out of the Red Sea could account for such a diversity of phytoplankton groups.

An examination of Appendix 5 shows that during the south-west monsoon season, i.e. June-August, the offshore waters have several phytoplankters listed above as Mediterranean and estuarine Nile components. It is possible that due to the southerly flow of the Red Sea waters and incursion of waters from the Mediterranean and Gulf of Suez, a recruitment of Mediterranean and Nile estuarine phytoplankton takes place at this time, which bloom under favourable hydrographic conditions.

During the northeast monsoon, December to June, with the peak activity during January-February, offshore oceanic waters from the Indian Ocean enter the Red Sea. Examination of Appendix 5 shows the presence of the equatorial sub-surface floral element, south-equatorial current based floral element and Indo-Pacific component. It is likely that these floral elements are brought into the Red Sea along with the offshore oceanic waters.
In view of the paucity of data on qualitative and quantitative seasonal abundance of phytoplankton from other areas in the Red Sea, it is not yet possible to establish any phytoplankton as indicators of different water masses. The significance of such studies is recognised and the need to carry out extensive surveys is pointed out here.

2. Phytoplankton Succession

In general in the Red Sea area, winter populations are dominated by diatoms, and summer populations have representatives of diatoms, dinoflagellates and cyanophytes (Table 12). During the northeast monsoon season (December-June) there was no succession of diatom and dinoflagellate peaks at either the inshore or offshore station; however blue-green algae became dominant or co-dominant at both stations in May and June. During the southwest monsoon season (July-November) there was a succession of dominance from diatoms to dinoflagellates and back to diatoms at both stations.

Such a seasonal pattern of succession in the major algal groups and their component species is often observed not only in temperate waters, but also in tropical and polar seas (Lebour 1917, Raymont 1963). The precise sequence of factors responsible for this ecological succession is still not clear, although the variables probably involved are apparent.

Off the Madras coast, where environmental conditions are rather stable, no succession of blooms of diatoms and
3. Factors influencing Phytoplankton Production

Because of several unique features of the Red Sea, i.e.: semi-enclosed body of water, location in an arid zone with little run-off from land, and seasonal reversal of the monsoon effect, it might be expected that factors governing phytoplankton production could be different from those in temperate seas. Although ambient nutrient levels in the study area were often low, photosynthetic production was high over the whole year. It is reasonable to assume that light was never a limiting factor especially since some of the highest rates of production coincided with the lowest seasonal levels of solar radiation. The bimodal pattern of production at the offshore station is very reminiscent of the "typical" pattern in temperate seas, with the exception of the earlier commencement of the first "spring" bloom. The unimodal (or possibly trimodal?) sequence of seasonal production at the inshore station is rather similar to that of Narragansett Bay (described by Smayda 1957). Pratt (1965) and Martin (1965) analysed the temporal relationships between phytoplankton and zooplankton in Narragansett Bay, and convincingly argued that the decline of the autumnal zooplankton population, and consequent release from grazing pressure, allowed the winter blooming of phytoplankton to occur. Unfortunately,
no zooplankton data is yet available for the present study area, but the trophic interactions of phyto-and zooplankton seem to be a logical step for future study. The spring blooming in temperate waters is usually ascribed to a reduction in depth of the upper mixed layer, and development of the seasonal thermocline (Sverdrup 1953). There is no such convincing relationship at the Sharm station.

At the offshore station, the February peak of production does correspond to the onset of seasonal stratification. However, the second peak of production here corresponds to the height of seasonal stratification (June-July). This does not correspond to the typical pattern in temperate waters where the autumnal bloom usually coincides with partial disruption of the density discontinuity layer.

This thesis represents the first work of its kind to be carried out in the study area. From the data collected here, no comprehensive explanation of the seasonal patterns of production observed can be advanced. It is worthwhile, however, to consider further some of the correlations obtained.

Reference to Tables 6 and 7 shows the correlation matrix for the inshore Sharm station and offshore waters respectively. In the inshore waters the correlations between depth and cell numbers and depth and C\textsuperscript{14} uptake were negative. Similarly in the offshore waters, the correlations between depth and all biological variables were negative, this is consistent with the general pattern observed by several researchers. With an increase in depth, the light energy available for phytoplankton decreases exponentially (Sverdrup et al. 1942)
and limits phytoplankton growth and production.

In the inshore waters, the correlation between temperature and species diversity index was negative and significant, whereas in the offshore waters the correlation between temperature and all biological variables were positive and significant. In the offshore waters, with an increase in temperature there is an increase in phytoplankton growth which is very difficult to explain. Comparison of inshore and offshore temperature structures (Figures 6 and 7) shows no marked differences in their pattern, yet the winter-spring peak of production offshore was delayed by about two months (Figure 42) and annual production was higher than inshore. It appears that in the offshore waters there must be some factor other than increased temperature which stimulates phytoplankton growth. Alternatively, some factor at the inshore station inhibits production during June to August.

Nutrients such as phosphate, silicate and nitrogen compounds are essential for the growth of the phytoplankton. Due to assimilation during periods of active growth, the nutrients will be depleted and a negative correlation results between nutrients and phytoplankton (Atkins 1923, Harvey et al. 1935, etc.) Such a correlation was not obvious in the inshore Sharm waters. Only in the offshore waters were negative correlations at a significant level noticed between phosphate and chlorophyll $a$, chlorophyll $b$, $^{14}C$ uptake and assimilation ratio, also between nitrite and species diversity index and between ammonia and $^{14}C$ uptake.
Again, the reasons for these differences in relationship between nutrients and biomass or production at the two stations is difficult to explain and requires further investigation. The salient differences between the two stations are clearly: the later timing of the winter-spring bloom offshore, and the lack of a late summer-early autumn bloom at the inshore station.

Comparison of inorganic phosphates (Figures 17, 18) with annual primary production (Figure 42) shows that domes of high phosphate values occurred first, followed by an increase in primary production. Thus, nutrient domes at the Sharm station were observed during October, February, May and July, and the primary production increases were during November, April, June and October respectively. In the offshore waters, also, such a time lag between the formation of nutrient domes and phytoplankton production can be seen. High phosphate levels were noticed during December-January and during April, while production was high during January-February and July-August.

A similar time lag was noticed between other nutrients, such as silicates, nitrites and ammonia, and phytoplankton production in this area. Unfortunately, data on the most important inorganic nutrient - nitrate, is lacking here.

There is evidence to show that, for tropical phytoplankton at least, the rate of nutrient regeneration is more critical than the instantaneous nutrient concentrations. Both the rate of consumption of phosphate (Volkovinskiiy, 1974) and its rate of regeneration (Maksimova, 1972) are faster in tropical
than in temperate waters.

Marine phytoplankton is widely regarded as nitrogen limited, with both NH$_3$ and NO$_3$ as significant sources. Recently, Harrison (1980) has provided a review of nutrient regeneration, contrasting the contributions of bacterial regeneration of NO$_3$ and zooplankton regeneration of NH$_3$. It seems clear that we shall not be able to fully understand seasonal cycles of primary production until attention focuses more heavily on nutrient kinetics. Thus, simultaneous information on: the seasonal dynamics of zooplankton grazing and excretion of NH$_3$, bacterial regeneration of NO$_3$, and advective-diffusive processes is required (Harrison, 1980).

Amongst the biological variables, correlations between assimilation number and species diversity index, chlorophyll $a$ and chlorophyll $b$ were negative and significant in the inshore Sharm waters. In the offshore waters the correlation between assimilation number and species diversity index was also negative and significant, similar to that of the inshore waters. Such a negative significant correlation between assimilation index and species diversity index supports the principle of Margalef (1978) that increasing species diversity index is associated with a decrease in production per unit biomass (= assimilation number). This is equivalent in fact to an increase in maturity of the plankton community. This negative correlation may also indicate the significance of detrital biomass to this ecosystem as proposed by Platt and Subha Rao (1970).
Other biological variables, such as cell numbers and species diversity index, chlorophyll $a$, chlorophyll $b$, and $^{14}C$ uptake, were positively correlated at a significant level and are self-consistent.

It should be remembered that the nanoplankton have not been enumerated during this study. Although their contribution to biomass and total chlorophyll $a$ values may be small, they may account for over 50% of annual production (Malone 1980). Thus even though cell numbers of blue-greens, diatoms and dinoflagellates may be low, primary production rates may still be high if nanoplankton are abundant.

4. Magnitude of Phytoplankton Biomass and Cell Densities

Phytoplankton biomass determined as cell numbers and chlorophyll $a$ showed great variations during the study period. The inshore waters of Sharm had higher cell numbers than the offshore waters. This is consistent with the general pattern of abundance of phytoplankton, as, for example, in the coastal waters and shallow ponds in the Cape Hatteras to Nantucket area (Smayda 1973). Table 13 shows that the cell numbers in the study area compare favourably with those reported from some adjacent waters such as the Suez Canal (Dowidar 1976), and some temperate waters like Aomori Bay (Kokubo 1932), Georges' Bank (Riley 1941), Block Island Sound (Riley 1952), and regions off Cape Cod and off Bermuda (Smayda 1973). However, in some of the waters adjacent to the Red Sea, such as the Gulf of Aden (Savich 1969),
Egyptian Mediterranean (Halim et al. 1976a), (Aleem and Dowidar 1967), and the Arabian Sea (Kuzmenko 1977), cell densities are decidedly higher.

Phytoplankton biomass in terms of chlorophyll a also showed a wide range with generally higher values in the inshore Sharm waters. Table 14 shows that the magnitude of chlorophyll a was comparable to that observed in the N.E. Arabian Sea (Radhakrishna et al. 1978). In the adjacent waters such as the Red Sea (McGill and Lawson 1966 and Gulf of Elat (Sournia 1977 and Levanon-Spanier et al. 1979) chlorophyll a values were lower than those reported in this study. A comparison with those values from the inshore waters on the west coast of India (Dehadri and Bhargava 1972; Bhargava and Dwivedi 1976) or with temperate waters (Henry et al. 1977), Peruvian waters (Koblentz-Mishke and Semenova 1977), Southern North Sea (Gieskes and Kraay 1977), St. Margaret's Bay (Platt and Subba Rao 1970) and Chesapeake Bay (Loftus et al. 1972) shows that the chlorophyll a values are lower in the study area (Table 14).

5. Magnitude of Primary Production

Primary production in the study area showed higher values in offshore waters than in the inshore Sharm waters. This is valid either on a volumetric basis (mg C m$^{-3}$ hr$^{-1}$) or on an areal basis (mg C m$^{-2}$ hr$^{-1}$). The values measured in the study area are higher than most of the values given in Table 15. Thus, the values in the Red Sea (Yentsch and Wood 1960),
Gulf of Elat (Sournia 1977; Levanon-Spanier et al. 1979), North Arabian Sea (Kuzmenko 1973), Goa Estuary (Bhattathiri et al. 1976), North Eastern Arabian Sea (Radhakriskna et al. 1979), Cochin backwaters (Qasim et al. 1969) are lower when compared to those reported in the present study. The present values are also higher than those from some temperate waters such as the Beaufort Channel (Williams and Murdoch 1966), and Chesapeake Bay (Flemor 1970), (Table 15).

Carbon assimilation ratios in the offshore waters are higher than inshore. Table 16 shows that a high range of values was observed in the study area. The values are higher than those for the Gulf of Elat (Levanon-Spanier et al. 1979), Red Sea (Yentsch and Wood 1960; Khemeleva 1970), inshore waters of the Arabian Sea (Radhakrishna 1969), Cochin backwaters (Qasim et al. 1969), Caribbean Sea (Malone 1971), Gulf of Thailand (Subba Rao 1965), Indian Ocean (Saijo and Takesue 1965) and Gulf of Panama (Smayda 1965). In its efficiency, phytoplankton in the study area is comparable to the Fladen Ground (Steele and Baird 1961) and to the Woods Hole area (Yentsch 1965) as evident by the high assimilation numbers. Overall, the high carbon assimilation ratios from the present study suggest a high efficiency of photosynthesis characteristic of "sun-adapted"phytoplankton.

In the surface waters of the Red Sea a north to south increase in the chlorophyll a was reported by Khemeleva (1970). In the north the concentration was 0.14 mg m$^{-3}$, 0.24 in the central region and 0.40 in the south. A similar north to south gradient in the photosynthetic rate was also observed.
by Khemeleva (1970). Thus it was $0.31 \text{ mgC m}^{-3} \text{ hr}^{-1}$ in the north, 0.71 in the central region and 3.42 in the southern waters. The corresponding assimilation numbers were 3.91, 4.14 and 7.01 mgC mg Chl a$^{-1} \text{ hr}^{-1}$ which suggest a southward increase in the photosynthetic efficiency in the Red Sea.

6. Duration, Range and Amplitude of Primary Production

In addition to the assimilation numbers already discussed, the functioning of any ecosystem in time can be judged by a comparison of the duration, range and amplitude of primary production following Cushing's (1975) method. Cushing (1975) described the production cycle as a bell-shaped curve, symmetrical at its peak, so that the magnitude can be described as the amplitude. The duration is the time interval between initial and terminal phases. It should be pointed out that comparison of amplitudes of phytoplankton cycles based on primary production measurements should be preferred to that based on biomass measurements, if one is interested in the functioning of the system. It is well known that several abiotic factors such as Langmuir convection cells (Loftus et al. 1975), convergence of water masses (Pomeroy et al. 1956), differential motion of surface and bottom waters (Tyler and Seliger 1978), vertical advection (Winters et al. 1975) and tidal front formation (Pingree et al. 1975), and biotic factors such as positive phototaxis and diurnal migration (Selinger et al. 1970, 1971) generate a patchyspatial and temporal distribution of phytoplankton.
Under such conditions, precise determination of the amplitude and duration of a growth cycle will require sampling at frequent intervals. To resolve any discrepancies in the amplitude determinations based on biomass, in the present study, primary production measurements were used. It should be also added that production measurements integrated under a unit surface area are used in preference to individual volumetric rates (mg C m\(^{-3}\) hr\(^{-1}\)) as the former seem to fall in a limited range.

The duration of production (Table 17) is 8 weeks in the inshore and offshore waters, but the amplitude in the inshore was 2.6 whereas it was 4.8 for the offshore waters. Observations from the Gulf of Elat (Levanon-Spanier et al. 1979) are comparable to the present study.

In the Gulf of Elat, the duration was 8 weeks and the amplitude was 5.7. With respect to the amplitude and the range of production, the present observations are similar to those from Lake Edku (Samman 1974) and Cochin backwaters (Qasim et al. 1969). The magnitude and amplitude of production in the study area compare favourably with some of the highly productive waters such as the Peruvian upwelling area (Beers et al. 1971), coastal tropical Pacific (Sorokin 1973) and west coast of India (Radhakrishna 1969).


In the study area the annual phytoplankton cycle follows a bimodal pattern with a major peak between December and
February, and a minor one between August and October. Although this is similar to the bimodal production cycle reported from temperate waters (see Cushing 1975), there appears to be a difference in the time of occurrence of the peaks. Even within the study area, there is a time lag between the inshore and offshore waters.

Table 18 shows that in the Red Sea, a bi- or tri-modal distribution pattern seems to be the rule, with regional differences in the occurrence of the peaks. While discussing the physiogeography and circulation pattern, it was pointed out that the northeast monsoon is active during December-February and the southwest monsoon during June-August. The two peaks of phytoplankton production offshore coincide with the activity of the monsoons. Several authors (Humphrey 1972; Subba Rao 1974; Halim 1969; Cushing 1971; Qasim et al. 1978) have elaborated on the dependence of the primary production cycle on the monsoonal activity in the Indian Ocean. Although the production cycle in the study area follows a bimodal pattern (clearly at least at the offshore station), and related possibly to the two monsoon events, nevertheless unlike other areas, i.e. the Bay of Bengal and the west coast of India, neither of the peaks in the Red Sea results from enormous land run-off.

The mean production for the Sharm station is calculated at 82.46 mg C m\(^{-2}\) hr\(^{-1}\), and for the offshore station 96.30 mg C m\(^{-2}\) hr\(^{-1}\). These production rates are about the same as for 'young' surface water and newly upwelled productive waters
(Steeman Nielsen 1963). Assuming 12 hours sunshine per day average, corresponding annual production rates are 361 gC m\(^{-2}\) yr\(^{-1}\) for inshore Sharm waters, and 422 gC m\(^{-2}\) yr\(^{-1}\) for offshore waters. These rates are rather high and favourably compare with the 44 - 423 (207 gC m\(^{-2}\) yr\(^{-1}\) average) calculated from Humphrey (1972) or the >180 gC m\(^{-2}\) yr\(^{-1}\) (second group) given by Cushing (1971). An average value of 392 gC m\(^{-2}\) yr\(^{-1}\) for this study area shows that production is comparable with that of upwelling zones (300 gC m\(^{-2}\) yr\(^{-1}\)) generalised by Ryther (1969). In this respect, it is interesting to have recorded these high values despite the absence of demonstrable upwelling related to monsoon reversal.

Since the observations on primary production in the Red Sea are very few, and may not be representative of the various regions, any calculations on the total annual areal production of the Red Sea will be subject to revision. However, from the present data the upper and lower limits of primary production can possibly be established. Caution is warranted for upper values in view of the probable pollution influence in the Jiddah area which will stimulate primary production.

Assuming a mean annual production of 392 gC m\(^{-2}\) and an area of 438,000 sq. km., the total annual production for the whole Red Sea will be:

\[ 392 \times 438,000 \times 10^6 = 171.7 \times 10^6 \text{ tons C yr}^{-1} \]

If the mean production is assumed as 196 gC m\(^{-2}\) (50% of the above calculated 392 gC m\(^{-2}\)) then the total annual production for the Red Sea will be 85.8 \times 10^6\text{ tons C yr}^{-1}, and this may
be considered as a lower limit of primary production.

From these upper ($171.7 \times 10^6$ tons C yr$^{-1}$) and lower ($85.8 \times 10^6$ tons C yr$^{-1}$) estimates it is interesting to speculate on the effect of photosynthetic production, and its possible relation to local fisheries. In calculating the tertiary production from the primary production, several approximations and assumptions have been made based on the procedures of Cushing (1971) as follows:

(i) The estimate of carbon production has already been raised by a factor of 1.45 to correct for losses (Nielsen 1964; Goldman 1968), in data supplied by the International Agency for C$^{14}$ Determination.

(ii) From primary to secondary production an ecological transfer coefficient of 7.23% is used (a lower estimate from the Arabian Sea from Cushing 1971). There is little information on efficiency of energy transfer between secondary and tertiary levels, but a nominal figure of 10% is used here. Therefore, tertiary production is given by:

$$171.7 \times 10^6 \times 0.0723 \times 0.1 = 124.14 \times 10^4 \text{ tons C yr}^{-1}$$

(iii) To convert this figure to wet weight of fish the conversion factor of carbon/wet weight (13.5%) is used (see Cushing 1971; Vinogradov 1953). Therefore the upper estimate of fish production is given by:

$$124.14 \times 10^4 \times \frac{100}{13.5} = 9.19 \times 10^6 \text{ tons wet wt yr}^{-1}$$

(iv) A lower estimate of fish production will be half this figure viz: $4.59 \times 10^6$ tons wet wt yr$^{-1}$. 

103
Cushing's (1971) estimate of potential fish production for the Arabian Sea with an area of 131,000 sq. km. is $2.50 \times 10^6$ tons wet wt yr$^{-1}$. This compares very favourably with the present estimates on an areal basis. However, the current fish landings from the area are about $0.53 \times 10^6$ tons annually (FAO 1978) which is low compared to the above estimates.

In calculating the tertiary production from primary production, and equating this to potential fisheries yield several approximations are made. The composition of the third trophic level is not completely known. It includes predatory copepods and other planktonic predators as well as clupeid fishes. However, as treated by Cushing (1971) these animals (with the exception of plankton eating fish and molluscs) are included in the secondary trophic level.

It must be remembered that the contribution of seaweeds and corals to overall production is not included in these calculations. Contributions from both these sources could be significant as indicated in recent reviews by Michanek (1975) and Muscatine (1980). Production by the extensive coral reefs of the Red Sea (Fishelson 1973a, 1973b) especially could be a significant contribution. Thus the fishery potential of the area would seem to be high and worthy of closer review.
SUMMARY AND CONCLUSIONS

During the present study observations were carried out on a regular basis at two stations; an inshore (Sharm) station that receives pollutants, and an offshore station that is relatively unpolluted.

Due to the influence of the southwest monsoon, during November-February surface water gets cooled and mixes downwards while during the northeast monsoon, surface water gets warmed up and this leads to some stratification.

Evaporation in excess of dilution results in high salinity of the waters in this region. Density inversions were also observed in the inshore waters. In the offshore, three density layers could be recognised (a) an uppermost layer with density values between 25.00 and 26.50 extending down to the 50 m level; (b) an intermediate sub-surface layer with values from 26.50 to 27.50 extending down to 100 m depth, and (c) a bottom layer with densities between 27.00 and 28.50 extending below 100 m. Formation of these three density layers followed a seasonal pattern.

Transparency of the offshore waters, judged by Secchi disc readings, was almost twice that of the inshore station. The higher turbidity of the Sharm waters is attributed to the biogenic material of terrigenous origin.
From data on the oxygen concentration and oxygen saturation values it is generalised that near surface waters are often saturated but rarely super-saturated. Prevailing high temperatures, high salinity, little freshwater input, biological oxygen demand and density stratification seem to account for any under saturation of oxygen.

In the inshore waters domes of high phosphate values were observed during May-June, and September-November, while in the offshore waters such domes were present during February to April. Domes of high silicate values were observed during June-July in inshore waters and during April and August offshore. Due to lack of inflows of silicate-rich freshwater, silicates were in general impoverished in this region.

Nitrite nitrogen was in greater abundance offshore than in the Sharm waters, where there was occasional total depletion of this nutrient. In the inshore waters, domes of high nitrite values were observed during September and November, while in the offshore waters they were observed during April-May and September. Ammonia concentration reached higher levels at the offshore station, but both stations showed some seasonal variation.

In general, with increase in depth there was an increase in nutrients which could be either due to lower utilisation of these nutrients below the euphotic zone, or due to rapid regeneration.

Nutrient levels in the study area are in agreement with those reported in the Gulf Region but are generally low when compared to other seas that receive large quantities
of freshwater. This results in various anomalies of silicate-phosphate ratios and certain interesting salinity-silicate relationships in the Red Sea.

Based on the salinity-silicate ratios three water masses: I surface water \((3-7.4 \, \mu g \text{ L}^{-1}; 39-39.50 \, S^\circ/\text{oo})\); II Red Sea water \((0.5-5 \, \mu g \text{ L}^{-1}; 40-40.5 \, S^\circ/\text{oo})\); III Bab el-Mandeb water \((1-3 \, \mu g \text{ L}^{-1}; 38.5-39.5 \, S^\circ/\text{oo})\) were recognised.

The phytoplankton cycle followed a bimodal peak distribution with a primary peak during January and a secondary peak during summer; in the inshore waters this was during May while in the offshore it was during July. There were several similarities between the nearshore and offshore waters in respect of phytoplankton abundance:

During the major peak 49 species were common to these two stations; 36 species were common to the minor bloom; 23 species commonly bloomed in these two regions during major and minor peaks. However, 29 species were restricted to the major peak and 17 species to the minor peak.

Both stations were dominated by diatoms during the northeast monsoon season, and no successional patterns were evident. A succession from diatom to blue-green to dinoflagellate dominance was recorded at both stations from April to October. Although blue-greens were most dominant during May and June, they were present offshore until September.

A biogeographical consideration of the phytoplankton observed during the study showed the presence of several floral elements: (1) southwest floral element (2) equatorial
sub-surface element (3) pre-southwest monsoon element
(4) equatorial undercurrent element (5) south-equatorial
floral element and floral elements from fluctuating conditions.
The phytoplankters based on their abundance can be recognised
as a Red Sea component, a Mediterranean component, an Indo-
Pacific component, a Nile estuarine component and a tropical
component, which suggests that periodic recruitment and
exchange of phytoplankton takes place in the study area.

The distribution pattern of chlorophyll a resembled that
of numerical abundance of phytoplankton. Inshore waters had
one subsurface chlorophyll maximum while the offshore waters
had two subsurface maxima. When compared to temperate waters
chlorophyll a values in the study area were low, but agreed
well with those previously reported from the Red Sea region.

The annual primary production cycle followed a bimodal
pattern with a time-lag of 2 months (earlier) between the
inshore and offshore waters. Production in the offshore
waters was higher than that in the Sharm waters. The magnitude
of production in the study area was higher than several
temperate and tropical waters.

A high range of carbon assimilation ratios was recorded
both in the inshore and offshore regions; values were
generally higher in the latter. In both regions, efficient
functioning of photosynthesis began at subsurface levels
(~25 m) and ascended to the surface. The carbon assimilation
ratios in the study area were comparable with those in the
adjacent seas or from the temperate waters.

The duration of a production cycle was about 8 weeks both
in the inshore and offshore waters; the amplitude of production was 2.6 and 4.8 in the inshore and offshore respectively. The duration and amplitude of production compare favourably with some of the highly productive temperate and tropical seas. The production cycle appears to be triggered by the activity of the monsoons in this region. The earlier blooming of phytoplankton in the inshore Sharm waters could be due to the availability of some growth triggering agents, such as humic substances.

Assuming an annual production of 392 gC m$^{-2}$ for the whole Red Sea area (438,000 sq. km), the total annual photosynthetic production was calculated as 171.7 x 10$^6$ tons C yr$^{-1}$. Using several transfer coefficients and conversion factors it is calculated that this production would be equivalent to between about 4.6 and 9.2 x 10$^6$ tons wet weight of fish which is considerably higher than the currently reported FAO fish landings.
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Table 1: Climatic data at Jiddah based on observations for the period 1966-1976

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Note: Meteorological Department (Climatic Section), Kingdom of Saudi Arabia.

* Neumann (1952)
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On several occasions similar values were obtained.
Table 3: Seasonal phytoplankton abundances (cells l\(^{-1}\)) and percentage composition of major groups at the Sharm station

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Average % Composition For November Samples: 21.1 78.6 0.3

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Average % Composition for April Samples: 24.2, 75.8

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Average % Composition for May Samples: 17.5, 41.2, 84.2

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Average % Composition for April Samples: 7.9% 90.4% 1.7%

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Table 5: Maximum and minimum values of biological variables and parameters at the Sharm and offshore stations.

**Sharm station**

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**Offshore station**

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* On several occasions, similar values were obtained.

* Suspect high values in July and October omitted.
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Table 6: Correlation matrix (Pearson's r) of chemical and biological variables and parameters at the Sharm station (n=64; p<0.05; *not significant)
Table 7: Correlation matrix (Pearson's r) of chemical and biological variables and parameters at the offshore station (n=65; p<0.05; *not significant).

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Table 8: Comparison of inorganic phosphate values (µg -at -1 ) from some selected regions

* episodic high values due to air-transported particulate phosphate from fertilizer
** citation
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<thead>
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<th>Region</th>
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<th>Maximum</th>
<th>Reference</th>
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</thead>
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<tr>
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<td>0.09</td>
<td>7.40</td>
<td>Present study</td>
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<tr>
<td>Sharm offshore station</td>
<td>0.98</td>
<td>4.69</td>
<td>Present study</td>
</tr>
<tr>
<td>Gulf of Aqaba (Elat)</td>
<td>0.03</td>
<td>6.46</td>
<td>Klinker et al. (1978)</td>
</tr>
<tr>
<td>Red Sea</td>
<td>0.01</td>
<td>1.30</td>
<td>Hansen et al. (1968)</td>
</tr>
<tr>
<td>Gull of Bengal</td>
<td>2.00</td>
<td>22.00</td>
<td>Jayaraman (1951)</td>
</tr>
<tr>
<td>Baltic</td>
<td>0.00</td>
<td>0.50</td>
<td>Grasshoff (1975)</td>
</tr>
<tr>
<td>Black Sea</td>
<td>2.90</td>
<td>29.00</td>
<td>Grasshoff (1975)</td>
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<tr>
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<td>2.55</td>
<td>Sournia (1977)</td>
</tr>
<tr>
<td>Bay of Bengal</td>
<td>0.03</td>
<td>6.46</td>
<td>Kitunker et al. (1978)</td>
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</table>

** Table 9: Comparison of silicate values (µg/L) from some selected regions. **
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<th>Maximum</th>
<th>Reference</th>
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<tr>
<td>Sharm inshore station</td>
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<td>0.58</td>
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<td>Offshore station</td>
<td>0.01</td>
<td>3.25</td>
<td>Present study</td>
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<tr>
<td>Arabian Sea</td>
<td>3.91</td>
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<td>Deuser et al (1978)</td>
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<tr>
<td>Red Sea</td>
<td>0.02</td>
<td>0.79</td>
<td>Hansen et al (1968)</td>
</tr>
<tr>
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<td>&lt;1.0</td>
<td>&gt;0.5</td>
<td>Grasshoff (1969)</td>
</tr>
<tr>
<td>Gotland Deep</td>
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<td>&gt;1.0</td>
<td>Grasshoff (1975)</td>
</tr>
<tr>
<td>N. E. Arabian Sea</td>
<td>0</td>
<td>6.01</td>
<td>Radhakrishna et al (1978)</td>
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** Table 10: Comparison of nitrite values (µg L⁻¹ N₂) from some selected regions. **
<table>
<thead>
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<th>Region</th>
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<th>Reference</th>
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</thead>
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<td>3.27</td>
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<td>0.01</td>
<td>3.90</td>
<td>Present study</td>
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<td>Red Sea</td>
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<td>~4.00</td>
<td>Grasshoff (1975)</td>
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<tr>
<td>Gotland Deep</td>
<td>&lt;1.00</td>
<td></td>
<td>Grasshoff (1975)</td>
</tr>
<tr>
<td>Oslo Fjord</td>
<td>0.00</td>
<td>1.00</td>
<td>Black Sea</td>
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<td>0.00</td>
<td>1.00</td>
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<tr>
<td>Present study</td>
<td>0.00</td>
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<tr>
<td>Present study</td>
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<td>3.27</td>
<td>Present study</td>
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Table II: Comparison of ammonite values (µg at 1-l) from some selected regions.
<table>
<thead>
<tr>
<th>Region</th>
<th>Bloom Season</th>
<th>Reference</th>
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<tr>
<td>Red Sea</td>
<td>Winter</td>
<td>Present Study</td>
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<tr>
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<td>Summer</td>
<td>Present Study</td>
</tr>
<tr>
<td>Gulf of Elat</td>
<td>Winter</td>
<td>Present Study</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>Present Study</td>
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<td>Gulf of Aqaba</td>
<td>Winter</td>
<td>Present Study</td>
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<tr>
<td></td>
<td>Summer</td>
<td>Present Study</td>
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Table 12: Composition of phytoplankton blooms in the Red Sea
Table 13: Comparison of abundance of phytoplankton cell numbers from selected regions (cell nos. $10^6$)

<table>
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<th>Region</th>
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<td>Georges Bank</td>
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<tr>
<td>Woods Hole</td>
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<td>3,000</td>
<td>9,362,000</td>
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<td>Amorat Bay</td>
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<td>87,900</td>
<td>427,000</td>
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<td>Rosetta straity-Suez</td>
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<td>700,000</td>
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<td>Bagnian Mediterranean</td>
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<td>2 x 10^6</td>
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<td>Singapore Sea</td>
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<td>Smayda (1973)</td>
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Table 14: Comparison of Chlorophyll a (pg ml$^{-1}$) from selected regions

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<td>0.80</td>
<td>Hofson et al (1968)</td>
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<td>2.00</td>
<td>McGill and Lawson (1966)</td>
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<td>4.90</td>
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<td>Off Columbia River</td>
<td>0.02</td>
<td>2.80</td>
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<td>42.00</td>
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<td>Dehadri and Bharata (1972)</td>
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<td>Bhardwaj and Bharata (1972)</td>
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<td>Cabrera-Spancer et al (1979)</td>
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<td>0.07</td>
<td>Souundra (1977)</td>
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<td>Present Study</td>
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<td>0.07</td>
<td>Souundra (1977)</td>
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</table>

References:
- Platt and Subba Rao (1970)
- Dehadri and Bharata (1972)
- Bhardwaj and Bharata (1972)
- Cabrera-Spancer et al (1979)
- Souundra (1977)
- Henry et al (1972)
- McGill and Lawson (1966)
- Sournia (1977)
- Levanon-Steiner et al (1972)
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<td>0.03</td>
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<td>0.70</td>
<td>0.03</td>
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Table 15: Comparison of primary production (C4 method) from selected regions.
Table 15 continued

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<thead>
<tr>
<th>Location</th>
<th>Daily Production</th>
<th>Hourly Production</th>
<th>Reference</th>
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<td>3.00</td>
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<td>3.00</td>
<td>0.34</td>
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<td>Brazil</td>
<td>83.70</td>
<td>28.00</td>
<td>0.30</td>
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Daily production is divided by 12 for hourly production calculations.
Table 16: Comparison of carbon assimilation ratios (mg C mg Chl a⁻¹ hr⁻¹) from selected regions.

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<th>Region</th>
<th>Minimum</th>
<th>Maximum</th>
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<td>Red Sea</td>
<td>3.91</td>
<td>7.01</td>
</tr>
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<td>Cochinn Sea</td>
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<td>2.70</td>
</tr>
<tr>
<td>Arabian Sea Inshore</td>
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</tr>
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<td>0.30</td>
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<tr>
<td>Fladen Ground</td>
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</tr>
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<td>Caribbean</td>
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<td>Red Sea</td>
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Reference:
- Present study
- Woods Hole
- Tropical Atlantic
- Gulf of Panama
- Fladen Ground
- Caribbean
- Gulf of Thailand
- Indian Ocean
- Arabian Sea Inshore
- Cochin
- Red Sea
- Red Sea
- Gulf of Bait
- Offshore Station
- Sharm Station

Regions:
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<td>Chesapeake Bay</td>
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Cahet et al (1972)
Hobson (1966)
Seligner et al (1975)
Table 17: Comparison of duration, range and amplitude of primary production during major phytoplankton blooms in selected regions.

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<th>Range</th>
<th>Amplitude Annual Pro.</th>
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<td>12 weeks</td>
<td>230-1300</td>
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<tr>
<td>(1971) Steeman, Nettlesen and Jensen</td>
<td>-</td>
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<td>Bay of Bengal</td>
<td>12 weeks</td>
<td>120-600</td>
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<td>Sahdana Bay</td>
<td>12 weeks</td>
<td>1426-3301</td>
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<td>West Coast of India</td>
<td>24 weeks</td>
<td>380-1110</td>
<td>-</td>
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<tr>
<td>Cochin</td>
<td>8 weeks</td>
<td>690-1520</td>
<td>-</td>
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<tr>
<td>Indian and Indonesian</td>
<td>&gt;12 weeks</td>
<td>422</td>
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<td>Current study</td>
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<tr>
<td>Levanon-Spanier et al (1979)</td>
<td>6 weeks</td>
<td>422</td>
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<tr>
<td>Aleem and Dowidar (1967)</td>
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<tr>
<td>Aleem and Samaan (1969)</td>
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<td>Take Martut Stn I</td>
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<td>357-10572</td>
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<td>Gulf of Bait</td>
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<td>85*</td>
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Cushing (1971)
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<td>Gulf of Panama</td>
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<tr>
<td>Peruvian upwelling area</td>
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* Based on 8 months' observations.

Smayda (1965)  
Sorokin (1973)  
Beers et al. (1971)

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<th>Value</th>
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<td>Coastal tropical Pacific</td>
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<tr>
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<td>Peruvian upwelling area</td>
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Table 17 continued
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<tr>
<th>Region</th>
<th>Reference</th>
<th>Sharm Station</th>
<th>Offshore Station</th>
<th>Rosetta Estuary (Nile) (Unpolluted)</th>
<th>Take Marjut I, II (Polluted)</th>
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<tr>
<td>I</td>
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<td>April October</td>
<td>April</td>
<td>Present Study</td>
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<td>II</td>
<td>Present Study</td>
<td>April</td>
<td>March</td>
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<td>III</td>
<td>Present Study</td>
<td>November</td>
<td>January</td>
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</table>

Table 18: Period of occurrence of phytoplankton blooms in the Red Sea area
Figure 1. The Red Sea, showing major geographic features.
Figure 2. Study area showing location of inshore (Sharm) and offshore stations.
Figure 3. Showing the major coastal features of the City of Jiddah.
Figure 4. Lithography and sediment types around Sharm-Obhor.
Figure 5. Monthly mean wind velocities (nautical miles per 24 hrs.) for the Red Sea area. Compass vectors indicate frequency of direction, and sum to 100%.

VELOCITY NAUTICAL MILES / 24 HRS

- 0 - 5
- 6 - 10
- 11 - 15
- 16 - 20
- 21 - 25
- 26 - 30
- 31 - 40
- 41 - 50
Figure 6. Seasonal temperature distribution at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10).
Figure 7. Seasonal temperature distribution at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11).
Figure 8. Seasonal salinity °/oo distribution at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10).
Figure 9. Seasonal salinity distribution at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11).
Figure 10. Seasonal density (ot) distribution at the Sharm station.
Figure 11. Seasonal density (µt) distribution at the offshore station.
Figure 12. Seasonal changes in Secchi disc visibility at the Sharm and offshore stations.
Figure 13. Seasonal distribution of dissolved oxygen at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10).
Figure 14. Seasonal distribution of percent ($\%$) oxygen saturation at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10).
Figure 15. Seasonal distribution of dissolved oxygen at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11).
Figure 16. Seasonal distribution of percent (°/o) oxygen saturation at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11.)
Figure 17. Seasonal distribution of soluble reactive phosphorus (PO$_4$-P) at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10).
Figure 18. Seasonal distribution of soluble reactive phosphorus (PO$_4$-P) at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11).
Figure 19. Seasonal distribution of reactive silicate (SiO$_2$) at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10).
Figure 20. Seasonal distribution of reactive silicate 
(SiO$_2$) at the offshore station. (TRANSPARENCY 
IN REAR POCKET - TO OVERLAY Figure 11).
Figure 21. Seasonal distribution of nitrite (NO$_2$) at the Sharm station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 10).
Figure 22. Seasonal distribution of nitrite (NO$_2$) at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11).
Figure 23. Seasonal distribution of ammonia (NH$_4$) at the Sharm station. (TRANSAPARENCY IN REAR POCKET - TO OVERLAY Figure 10).
Figure 24. Seasonal distribution of ammonia (NH$_4$) at the offshore station. (TRANSPARENCY IN REAR POCKET - TO OVERLAY Figure 11).
Figure 25. Salinity (°/oo) - reactive silicate (Si) relationships and water masses in the study area.
Figure 26. Seasonal distribution of reactive silicate: soluble reactive phosphorus ratios at the Sharm station.
SILICATE-PHOSPHATE RATIOS SHARM STATION
Figure 27. Seasonal distribution of reactive silicate: soluble reactive phosphorus ratios at the offshore station.
SILICATE-PHOSPHATE RATIOS OFFSHORE STATION
Figure 28. Seasonal composition of the phytoplankton by major groups at the Sharm station.
Sharm Station – Phytoplankton Composition
Figure 29. Seasonal variation in diversity indices of the phytoplankton community at the Sharm station, for surface (0) and 30 m depths, and total water column.
Figure 30. Seasonal composition of the phytoplankton by major groups at the offshore station.
Figure 31. Seasonal variation in diversity indices of the phytoplankton community at the offshore station, for surface (0), 100 m and 200 m depths, and total water column.
Offshore Station - Phytoplankton Diversity

Depth (m)
- 0
- 100
- 200
- Total

Diversity

NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT 1977 1978
Figure 32. Seasonal abundances of phytoplankton cells by major groups at the Sharm station.
SHARM STATION PHYTOPLANKTON ABUNDANCE

BLUE-GREENS
DINOFLAGELLATES
DIATOMS
TOTAL

PHOTPLANKTON ABUNDANCE IN THOUSANDS OF CELLS/LITRE

0 10 20 30 40 50 60 70

NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT 1977 1978
Figure 33. Examples of vertical distributions of the major phytoplankton groups at the Sharm stations.

N.B. Cells/l x 10² should read:

Cells x 10²/l
VERTICAL DISTRIBUTION OF PHYTOPLANKTON GROUPS SHARM STATION

DECEMBER 4, 1977

MAY 10, 1978

JULY 18, 1978

AUGUST 20, 1978

DIATOMS

DINOFLAGELLATES

BLUE-GREENS

CELLS/l x 10^2

DEPTH (m)

0 5 10 15 20 25 30

0 5 10 15 20 25 30

0 5 10 15 20 25 30

0 10 20 30

DIATOMS

DINOFLAGELLATES

DIATOMS

DINOFLAGELLATES
Figure 34. Seasonal abundances of phytoplankton cells by major groups at the offshore station.
OFFSHORE STATION PHYTOPLANKTON ABUNDANCE
Figure 35. Examples of vertical distributions of the major phytoplankton groups at the offshore station.

N.B. Cells/l x 10^2 cmmn ml; Cells x 10^6/l
VERTICAL DISTRIBUTION OF PHYTOPLANKTON GROUPS OFFSHORE STATION

DECEMBER 27, 1977

AUGUST 20, 1978

APRIL 11, 1978

JULY 10, 1978

CELLS/l x 10^2

DIATOMS

DINOFIAMELATES

DIATOMS

DINOFIAMELATES

BLUE-GREENS

BLUE-GREENS

CELLS/l x 10^2

DIATOMS

DINOFIAMELATES

DIATOMS

DINOFIAMELATES

BLUE-GREENS

BLUE-GREENS
Figure 36. Seasonal profiles of chlorophyll a concentration at the Sharm station.
Figure 37. Seasonal profiles of chlorophyll b concentration at the Sharm station.
Figure 38. Seasonal profiles of chlorophyll a concentration at the offshore station.
Figure 39. Seasonal profiles of chlorophyll b concentration at the offshore station.
Figure 40. Seasonal variations in vertical profiles of carbon fixation (primary production rate) at the Sharm Station.
Figure 41. Seasonal variations in vertical profiles of carbon fixation (primary production rate) at the offshore station.
Offshore Station
- C-14 Uptake

Depth (m)

Mg C m^-3 hr^-1

1977

1978

2 NOV 21 DEC 31 JAN 22 FEB 18 MAR 11 APR 21 APR 28 MAY 27 JUN 10 JUL 10 AUG 23 SEP 25 OCT
Figure 42. Integral primary production rates at the Sharm and offshore stations.
Integral Primary Production

Stations:
- Sharm
- Offshore

mg C m⁻² hr⁻¹

NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT

1977
1978
Figure 43. Carbon assimilation ratios (mgC mg Chl a\(^{-1}\) hr\(^{-1}\)) at the Sharm station.
CARBON ASSIMILATION RATIOS AT SHARM STATION
Figure 44. Carbon assimilation ratios (mgC mg Chl a⁻¹ hr⁻¹) at the offshore station.
CARBON ASSIMILATION RATIOS AT OFFSHORE STATION
PHYTOPLANKTON ECOLOGY AND PRODUCTION OF THE RED SEA
OFF JIDDAH, SAUDI ARABIA
VOLUME 2

by

ESSAM ABID SHAIKH B.A., M.Sc.
College of Oceanography
King Abdulaziz University, Jiddah, Saudi Arabia

A Thesis
Presented to
The Faculty of Science
of
The Open University
(In Two Volumes)

In partial fulfilment of requirements
for the degree of
Doctor of Philosophy
October, 1981

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### APPENDIX 1A: PHYSICAL, CHEMICAL AND BIOLOGICAL DATA - Sharm Station

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth (m)</th>
<th>T°C</th>
<th>S°/oo</th>
<th>O₂ (ml l⁻¹)</th>
<th>PO₄-P</th>
<th>SiO₂-Si</th>
<th>NO₂-N</th>
<th>NH₄-N</th>
<th>Chlorophyll (mg m⁻³)</th>
<th>C₁₄-uptake (mgC m⁻³ hr⁻¹)</th>
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## APPENDIX 1A continued.

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<th>Depth (m)</th>
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<th>Q₂ (ml l⁻¹)</th>
<th>Nutrients (µg-at l⁻¹)</th>
<th>Chlorophyll (mg m⁻³)</th>
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<td>SiO₂-Si</td>
<td>NO₂-N</td>
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## APPENDIX 1B: PHYSICAL, CHEMICAL AND BIOLOGICAL DATA - offshore station

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NOVEMBER 17, 1977
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**Abundance in cells/l**

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APRIL 21, 1978
Abundance in cells/ℓ
Depth in meters
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**MAY 10, 1978**

Abundance in cells/2

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JUNE 20, 1978
Abundance in cells/λ
Depth in meters

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## APPENDIX 2 continued.

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*JULY 25, 1978
Abundance in cells/l
Depth in meters*
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**Dinophyceae**

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**TOTAL PHYTOPLANKTON**

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Offshore station - Abundance in cells/l (Van Dorn bottle collections)

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**Dinophyceae**

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**JANUARY 29, 1978**

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**MARCH 18, 1878**

**Abundance in cells/\%**

**Depth in meters**

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Dinophyceae

- Ceratium bohmi: 20
- C. breve: 20
- C. candelabrum: 10 30 10
- C. declinatum: 40
- C. declinatum v. normale: 20
- C. furca: 30
- C. tripos: 30 50 10
- Dinophysis caudata: 20
- Diplopsalis lenticula: 30
- Goniodoma polyedricum: 30 20
APPENDIX 3 continued.

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**Dinophyceae**

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**JUNE 27, 1978**

Abundance in cells/\(\lambda\)  
Depth in meters

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**Dinophyceae**

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### Dinophyceae

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APPENDIX 4: PHYTOPLANKTON SPECIES RECORDED IN THE REGION OF JIDDAH - Sharm Station; Net hauls and bottle casts

NOVEMBER 3, 1977

**Bacillariophyceae**
- Biddulphia vesiculosa
- B. spp.
- Campylodiscus spp.
- Chaetoceros coarctatum
- C. convolutus
- Cocconeis spp.
- Gossleriella tropica
- Leptocylindrus danicus
- Licmophora abbreviata
- Nitzschia closterium
- N. delicatissima
- N. seriata
- Pennate diatoms

**Dinophyceae**
- Ceratium carriense
- C. contortum
- C. declinatum
- C. furca
- C. macroceros
- C. trichoceros
- Diplopsalis lenticula
- Exuviaella compressa
- E. spp.
- Goniodoma sphaericum
- Gonyaulax polygramma
- Gymnodinium spp.
- Prorocentrum micans

**Dinophyceae con't**
- Pyrocystis elegans
- P. fusiformis
- Unidentified

**Cyanophyta**
- Trichodesmium spp.
APPENDIX 4 continued.

NOVEMBER 17, 1977

Bacillariophyceae
Campylodiscus spp.
Chaetoceros affinis
C. coarctatum
C. decipiens
Gossleriella tropica
Leptocylindrus danicus
Licmophora flabellata
Nitzschia closterium
N. delicatissima
N. seriata
Pennate diatoms
Planktoniella sol

Dinophyceae
Ceratium carriense
C. contortum
C. declinatum
C. furca
C. teres
C. trichoceros
Exuviaella spp.
Goniodoma spp.
Gonyaulax spp.
Gymnodinium spp.
Naked dinoflagellates
Peridinium spp.
Prorocentrum micans
Pyrocystis elegans
P. fusiformis

Dinophyceae con't
Pyrocystis pseudonoctiluca

Cyanophyta
### APPENDIX 4 continued.

#### DECEMBER 27, 1977

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### Dinophyceae

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APPENDIX 4 continued.

**Dinophyceae con't**

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<tr>
<td>G. spaericum</td>
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<td>Gonyaulax monacantha</td>
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<tr>
<td>Naked dinoflagellates</td>
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<tr>
<td>Noctiluca miliaris</td>
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<tr>
<td>P. cerasus</td>
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<td>P. divergens</td>
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<td>P. steinii</td>
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<td>P. truncatum</td>
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<td>Protoceratum reticulatum</td>
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**Dinophyceae con't**

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<td>Pyrocystis elegans</td>
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<tr>
<td>Triposolenia bicornis</td>
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</table>
APPENDIX 4 continued.

JANUARY 25, 1978

Bacillariophyceae

Asterionella japonica
A. notata
Bacteriastrium delicatulum
B. hyalinum
Cerataulina bergonii
Chaetoceros affinis
C. atlanticus
C. brevis
C. coarctatum
C. compressus
C. concaviformis
C. convolutus
C. curvisetum
C. dadayi
C. danicus
C. decipiens
C. dichaeta
C. didymum
C. diversus
C. eibenii
C. laciniosus
C. Lauderii
C. pendulum
C. peruvianum
C. teres
C. tetrastichon
C. tortissimum
Climacodium fraunfeldianum
Coscinosira spp.

Bacillariophyceae con't

Coscinosira spp.
Dactyliosolen mediterraneus
Fragilaria oceanica
Guinardia blavyana
G. flaccida
Hemiaulus hauckii
Hemidiscus cuneiformis
Lauderia borealis
Navicula membranacea
Nitzschia closterium
N. longissima
N. seriata
Other pennates
Planktoniella sol
Rhizosolenia alata
R. alata v. spp. "A"
R. bergonii
R. calcar-avis
R. castracanei
R. delicatula
R. fragilissima
R. hebetata
R. imbricata
R. Shrubsolei
R. Stolterfothii
R. styliformis
R. spp.
Streptotheca thamesis
Striatella unipunctata

C. spp.
C. spp.
### APPENDIX 4 continued.

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<th>Bacillariophyceae con't</th>
<th>Dinophyceae con't</th>
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<td>G. sphaericum</td>
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<td>P. crassipes</td>
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<td>C. teres</td>
<td>Prorocentrum micans</td>
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<td>C. trichoceros</td>
<td>Pyrophacus horologium</td>
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<td>C. tripos</td>
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<td>Dictyocha fibule</td>
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</table>
APPENDIX 4 continued.

FEBRUARY 14, 1978

Bacillariophyceae

Asterionella notata
Benthic diatoms
Chaetoceros affinis
C. coarctatum
C. decipiens
C. tetrastichon
Dactyliosolen mediterraneas
Fragilaria oceanica
Guinardia flaccida
Nitzschia closterium
N. seriata
Planktoniella sol
Rhizosolenia alata
R. bergonii
R. Shrubsolei
R. Stolterfothii
Skeletonema costatum
Thalassiothrix spp. "A"

Dinophyceae

Ceratium arietinum
C. breve
C. carriense
C. candelabrum
C. contortum
C. declinatum
C. dens
C. furca

Dinophyceae con't

Ceratium fusus
C. Karstenii
C. longirostrum
C. macroceros
C. massiliense
C. pavillardii
C. teres
C. trichoceros
C. vultur
Diplopsalis lenticula
Goniodoma polyedricum
G. sphaericum
Naked dinoflagellates
Peridinium depressum
P. diabolus
P. globulus
P. pyriforme
Pyrocystis elegans
P. pseudonoctiluca
Pyrophacus horologium
APPENDIX 4 continued.

MARCH 14, 1978

**Bacillariophyceae**

Achnanthes brevipes  
Bacillaria paradoxa  
Chaetoceros affinis  
C. dadayi  
C. Wighami  
C. spp.  
Campylodiscus echensis  
Climacodium fraunfeldianum  
Dactyliosolen spp.  
Hemidiscus cuneiformis  
Leptocylindrus danicus  
Nitzschia closterium  
N. delicatissima  
Planktoniella sol  
Rhizosolenia acuminata  
R. alata  
R. Shrubsolei  
Schroderella delicatula  
Striatella delicatula  
S. unipunctata  
Thalassiosira decipiens  
T. rotula  
Thalassiothrix spp. "A"

**Dinophyceae**

Ceratium breve  
C. contortum  
C. declinatum  
C. dens

**Dinophyceae con't**

Ceratium extensum  
C. furca  
C. fusus  
C. incisum  
C. Kofoeldii  
C. massiliense  
C. pentagonum  
C. tenue  
C. teres  
C. trichoceros  
C. triplos  
Ceratocorys armata  
C. horrida  
Diplopsalis lenticula  
Goniodoma polyedricum  
Gonyaulax turbynei  
Ornithocercus spp.  
Peridinium conicum  
P. crassipes  
P. diabolus  
P. oceanicum  
P. steinii  
P. trochoideum  
Small dinoflagellates  
Triposolenia bicornis
APPENDIX 4 continued.

APRIL 11, 1978

**Bacillariophyceae**
- Amphiprora spp.
- Bacillaria paradoxa
- Bellerochea malleus
- Biddulphia aurita
- Chaetoceros decipiens
- Climacodium fraunfeldianum
- Cocconeis spp.
- Coscinodiscus excentricus
- Isthmia enervis
- Licmophora abbreviata
- L. flabellata
- Nitzschia closterium
- N. longissima v. reversa
- N. seriata
- Other benthic diatoms
- Pleurosigma rectum
- P. rigidum
- P. spp.
- Rhizosolenia alata
- R. bergonii
- R. calcar-avis
- Thalassionema nitzschioides
- Thalassiothrix mediterranea

**Dinophyceae**
- Ceratium bohmi
- C. breve
- C. candelabrum

**Dinophyceae con't**
- Ceratium declinatum
- C. egyptiacum
- C. furca
- C. fusus
- C. massiliense
- C. trichoceros
- C. tripos
- Ceratocorys armata
- Cladopyx brachiolata
- Dinophysis caudata
- Diplopsalis lenticula
- Exuviaella compressa
- E. oblonga
- Goniodoma polyedricum
- G. sphaericum
- Gonyaulax polygramma
- G. turbynei
- Ornithocercus magnificus
- Peridinium abei
- P. cerasus
- P. conicum
- P. crassipes
- P. depressum
- P. divergens
- P. granii
- P. oblongum
- P. steinii
- Peridiniopsis asymmetrica
APPENDIX 4 continued.

Dinophyceae con't

Peridiniopsis trochoideum
Phalacroma porodictyum
Podalampas bipes
P. palmipes
Prorocentrum gracile
P. micans
Triposolenia bicornis
APPENDIX 4 continued.

Bacillariophyceae
Benthic diatoms
Biddulphia obtusa
Chaetoceros decipiens
C. socialis
Coscinodiscus excentricus
Leptocylindrus danicus
Rhizosolenia alata
R. calcar-avis
Thalassiothrix spp.

Dinophyceae
Ceratium bohmi
C. breve
C. contrarium
C. declinatum
C. egyptiacum
C. furca
C. furca v. spp. "A"
C. fusus
C. massiliense
C. trichoceros
C. tripos
Exuviaella compressa
Peridinium depressum
P. divergens
P. grani
P. steinii
P. trochoideum
APPENDIX 4 continued.

MAY 10, 1978

Bacillariophyceae

- Amphiprora spp.
- Asterionella notata
- Benthic diatoms
- Leptocylindrus minimus
- Licmophora abbreviata
- Nitzschia closterium
- N. delicatissima
- N. longissima
- Rhizosolenia acuminata
- R. alata
- Striatella unipunctata
- Thalassiothrix longissima

Dinophyceae

- Ceratium breve
- C. contrarium
- C. furca
- C. fusus
- C. Kofoidii
- C. massiliense
- C. trichoceros
- C. tripos
- Ceratocorys armata
- Exuviaella compressa
- Ornithocercus spp.
- Peridinium brochii
- P. granii
- P. trochoideum

Dinophyceae con't

- Prorocentrum micans
- Pyrophacus horologium
- Small dinoflagellates

Cyanophyta

- Trichodesmium spp.
APPENDIX 4 continued.

MAY 28, 1978

Bacillariophyceae
Amphiprora alata
Asterionella notata
Cerataulina bergonii
Chaetoceros affinis v. Willei
C. compressus
C. curvisetum
C. danicus
C. peruvianum
C. pseudoperuvianum
C. socialis
Climacosphenia spp.
Cocconeis spp.
Ethmodiscus gazellae
Guinardia flaccida
Hemiaulus hauckii
Hemidiscus cuneiformis
Leptocylindrus danicus
L. minimus
Licmophora spp.
Nitzschia closterium
N. delicatissima
N. longissima
N. seriata
Pennate diatoms
Pleurosigma fasciola
P. spp.
Rhizosolenia acuminata
R. alata
R. bergonii
R. calcar-avis

Bacillariophyceae con't
Rhizosolenia delicatula
R. Shrubsolei
R. Stolterfothii
Thalassiothrix longissima
T. spp. "A"
Unidentified

Dinophyceae
Ceratium breve
C. candelabrum
C. contrarium
C. declinatum
C. extensum
C. furca
C. fusus
C. Kofo tidii
C. massiliense
C. pentagonum
C. tenue
C. teres
C. trichoceros
Dinophysis caudata
Exuviaella spp.
Goni odoma polyedricum
Gonyaulax polygramma
Ornithocercus spp.
Peridinium brochii
P. cerasus
P. divergens
P. globulus
APPENDIX 4 continued.

Dinophyceae con't
Peridinium granii
P. oceanicum
P. steinii
P. trochoideum
Peridiniopsis asymmetrica
Prorocentrum micans
Small dinoflagellates

Cyanophyta
Trichodesmium spp.
APPENDIX 4 continued.

Bacillariophyceae

Amphiprora spp.
Asterionella notata
Benthic diatoms
Biddulphia pelagica
Chaetoceros danicus
C. peruvianum
Climacosphenia moniligera
Diploneis crabro
Hemiaulus hauckii
Licmophora abbreviata
Nitzschia closterium
N. delicatissima
N. longissima
N. longissima v. reversa
N. paradoxa
N. seriata
Pleurosigma spp.
Rhizosolenia alata
R. bergonii
R. calcar-avis
R. delicatula
R. imbricata
R. Stolterfothii
Thalassiothrix longissima
T. spp. "A"

Dinophyceae

Ceratium breve
C. candelabrum
C. contrarium

Dinophyceae con't

C. declinatum
C. extensum
C. furca v. spp. "A"
C. fusus
C. Kofoidiii
C. massiliense
C. strictum
C. trichoceros
C. tripos
Cladopyxis brachiolata
Dinophysis caudata
D. tripos
Diplopsalis lenticula
Goniodoma polyedricum
Gonyaulax polygramma
Ornithocercus spp.
Peridinium cerasus
P. steinii
Peridiniopsis asymmetrica
Prorocentrum micans
Pyrophacus horologium
Small dinoflagellates

Cyanophyta

Trichodesmium spp.
APPENDIX 4 continued.

JULY 18, 1978

Bacillariophyceae
Chaetoceros compressus
C. curvisetum
C. dadayi
C. hispidus
C. peruvianum
C. pseudoperuvianum
C. Weissflogii
Hemiaulus membranaceus
Nitzschia closterium
N. delicatissima
N. longissima
Pennate, unidentified
Rhizosolenia alata
R. delicatula
R. hebetata
R. Stolterfothii
Thalassiothrix longissima
T. spp. "A"

Dinophyceae
Ceratium breve
C. candelabrum
C. declinatum
C. furca
C. trichoceros
C. tripos
Ceratocorys horrida
Dinophysis caudata

Dinophyceae con't
Goniodoma polyedricum
Gonyaulax polygramma
Naked Gymnodinium & Amphidinium
Ornithocercus spp.
Peridinium brochii
P. cerasus
P. crassipes
P. depressum
P. divergens
P. steinii
Prorocentrum micans
Pyrophacus horologium
Unidentified small dinoflagellates

Cyanophyta
Trichodesmium spp.
APPENDIX 4 continued.

JULY 25, 1978

Bacillariophyceae
Amphiprora alata
Bellerrochea malleus
Benthic diatoms
Biddulphia pelagica
B. spp.
Climacosphenia moniligera
Fragilaria spp.
Licmophora flabellata
L. spp.
Mastogloia spp.
Nitzschia closterium
N. longissima
N. seriata
Pleurosigma fasciola
P. naviculaceum
P. spencerii
Rhizosolenia alata
R. Shrubsolei
Surirella fastuosa
S. spp. "A"
S. spp.
Tropidoneis lepidoptera

Dinophyceae
Ceratium breve
C. furca
C. fusus
C. massiliense

Dinophyceae con't
Ceratium trichoceros
C. tripos
Ceratocorys armata
C. gouretti
C. horrida
Dinophysis caudata
Diplopsalis lenticula
Gonyaulax polygramma
G. turbynei
Naked dinoflagellates
Peridinium cerasus
P. conicum
P. depressum
P. pallidum
P. steinii
P. trochoideum
Peridiniopsis asymmetrica
Unidentified

Cyanophyta
Trichodesmium spp.
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<td>Chaetoceros affinis</td>
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<td>C. contrarium</td>
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<td>C. declinatum</td>
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<td>C. egyptiacum</td>
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<td>R. bergonii</td>
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<td>R. calcar-avis</td>
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<td>R. Stolterfotthii</td>
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<td>T. spp. &quot;A&quot;</td>
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</table>
### APPENDIX 4 continued.

**SEPTEMBER, 1978**

#### Bacillariophyceae
- Chaetoceros affinis
- C. decipiens
- Climacosphenia moniligera
- Guinardia flaccida
- Leptocylindrus danicus
- Licmophora spp.
- Nitzschia closterium
- N. seriata
- Rhizosolenia alata
- R. bergonii
- R. calcar-avis
- R. hebetata
- R. Shrub solei
- R. Stolterfothii

#### Dinophyceae (con't)
- Oxytoxum scolopax
- Peridinium brochii
- P. divergens
- P. pyriforme
- P. steinii
- Peridiniopsis asymmetrica
- Prorocentrum micans
- Pyrocystis elegans
- P. fusiformis
- P. pseudonocuitula
- Pyrophacus horologium
- P. spp. "A"
- Unidentified

#### Dinophyceae
- Ceratium breve
- C. egyptiacum
- C. furca
- C. fusus
- C. Kofoidii
- C. massiliense
- C. trichoceros
- Dinophysis caudata
- Diplopsalis lenticula
- Exuviaella spp.
- Goniodoma shaericum
- Gonyaulax monacantha
- G. polygramma
- G. turbinei
APPENDIX 4 continued.

OCTOBER, 1978

Bacillariophyceae
Diatom centric
Diatom pennate

Dinophyceae
Ceratium furca
C. furca v. spp. "A"
Exuviaella compressa
Peridinium pallidum
Prorocentrum micans
Unidentified dinoflagellates
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<th>Bacillariophyceae con't</th>
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<tr>
<td>Asterionella japonica</td>
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<td>R. Shrubsolei</td>
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<tr>
<td>C. brevis</td>
<td>R. Stolterfothii</td>
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<tr>
<td>C. coarctatum</td>
<td>Streptotheca thamesis</td>
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<td>C. compressus</td>
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<td>C. concaviformis</td>
<td>T. fraunfeldii</td>
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<td>C. curvisetum</td>
<td>T. spp. &quot;A&quot;</td>
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<td>C. decipiens</td>
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<td>C. didymum</td>
<td></td>
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<td>C. pendulum</td>
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<tr>
<td>C. peruvianum</td>
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</tr>
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<td>Coscinodiscus asteromphalus</td>
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APPENDIX 5 continued.

NOVEMBER 7, 1977

Bacillariophyceae

Chaetoceros concaviformis
Nitzschia closterium
N. longissima
N. seriata
Rhizosolenia alata

Dinophyceae

Amphisolenia bidentata
Ceratium breve
C. contortum
C. declinatum
C. dens
C. furca
C. macroceros
C. teres
Peridinium spp.
Pyrocystis elegans
P. fusiformis
Other dinoflagellates

Cyanophyta

Trichodesmium spp.
APPENDIX 5 continued.

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<td>D. spp.</td>
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DECEMBER 27, 1977

Histioneis spp.
APPENDIX 5 continued.

Dinophyceae con’t

Ornithocercus magnificus
O. steinii
Parahistioneis spp.
Peridinium abei
P. cerasus
P. divergens
P. granii
P. steinii
P. trochoideum
P. truncatum
Phalacroma doryphorum
Podalampas bipes
P. spinifera
Prorocentrum micans
Pyrocystis elegans
P. fusiformis
P. lunula
P. pseudonoctiluca
Pyrophacus horologium
Triposolenia bicornis
APPENDIX 5 continued.  

**JANUARY 29, 1978**

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<td>Nitzschia closterium</td>
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110
APPENDIX 5 continued.

Dinophyceae con't
Ceratium fusus
C. Kofoidii
C. macroceros
C. massiliense
C. teres
C. trichoceros
C. tripos
Diplopsalis lenticula
Exuviaella spp.
Goniodoma polyedricum
G. sphaericum
Gonyaulax polygramma
Peridinium divergens
P. oceanicum
P. pyriforme
P. sphaericum
P. spp.
P. steinii
P. trochoideum
P. truncatum
Prorocentrum micans
Pyrocystis lunula
P. pseudonoctiluca
Pyrophacus horologium
APPENDIX 5 continued.

FEBRUARY 22, 1978

Bacillariophyceae

Asterionella japonica
A. notata
Bacteriastrum hyalinum
Benthic diatoms
Chaetoceros affinis
C. coarctatum
C. compressus
C. concaviformis
C. curvisetum
C. decipiens
C. laciniosus
C. peruvianum
Guinardia flaccida
Hemidiscus cuneiformis
Planktoniella sol
Rhizosolenia alata
R. bergonii
R. hebetata
R. Shrubsolei
R. Stolterfothii
Skeletonema costatum
Thalassiothrix spp. "A"

Dinophyceae

Ceratium arietinum
C. bohmi
C. breve
C. furca

Dinophyceae con't

Ceratium fusus
C. spp.
C. trichoceros
C. tripos
Ceratocorys horrida
Cladopyxis brachiolata
Diplopsalis lenticula
Exuviaella compressa
Goniodoma sphaericum
Gonyaulax polygramma
Naked dinoflagellates
Peridinium cerasus
P. pellucidum
P. steinii
P. trochoideum
Phalacroma parvulum
Prorocentrum micans

112
APPENDIX 5 continued.

MARCH 3, 1978

Bacillariophyceae

Asterionella japonica
Bacillaria paradoxa
Chaetoceros affinis
C. dadayi
C. decipiens
C. peruvianum
C. Wighami
Climacodium fraunfeldianum
Guinardia flaccida
Hemidiscus cuneiformis
Leptocylindrus danicus
Nitzschia closterium
N. delicatissima
N. seriata
Planktoniella sol
Pleurosigma spp.
Rhizosolenia acuminata
R. alata
R. Shrubsolei
Striatella unipunctata
Thalassionema nitzschioides
Thalassiosira rotula

Dinophyceae con't

Ceratium dens
C. extensum
C. furca
C. fusus
C. incisum
C. Kofoidii
C. massiliense
C. pentagonum
C. schmidtii
C. tenue
C. teres
C. trichoceros
C. tripos
C. vultur
Ceratocorys armata
C. horrida
Cladopyxis brachiolata
Diplopsalis lenticula
Exuviaella spp.
Naked dinoflagellates
Ornithocercus spp.
Peridinium cerasus
P. conicum
P. crassipes
P. depressum
P. diabolus
P. granii
P. oblongum
Dinophyceae con't

Peridinium oceanicum
P. pallidum
P. steinii
P. trochoideum
Peridiniopsis asymmetrica
Podalampas spinifera
Prorocentrum spp.
Small dinoflagellates
Triposolenia bicorns
APPENDIX 5 continued.

APRIL 11, 1978

Bacillariophyceae
Amphiprora spp.
Asterionella japonica
Bacillaria paradoxa
Bacteriastrum delicatulum
B. hyalinum
Benthic diatoms
Chaetoceros affinis
C. compressus
C. decipiens
C. peruvianum
C. socialis
Climacodium fraunfeldianum
Coscinodiscus excentricus
Guinardia flaccida
Hemidiscus cuneiformis
Isthmia enervis
Leptocylindrus danicus
Nitzschia closterium
N. seriata
Planktoniella sol
Pleurosoma balticum
P. spp.
Rhizosolenia alata
R. bergonii
R. calcar-avis
R. hebetata
R. Shrubsolei
R. styliformis

Bacillariophyceae con't
Thalassionema nitzschioides
Thalassiothrix mediterranea

Dinophyceae
Ceratium bohmi
C. breve
C. candelabrum
C. contrarium
C. declinatum declinatum
C. declinatum v. normale
C. dens
C. egyptiacum
C. furca
C. fusus
C. horridum
C. massiliense
C. schmidtii
C. trichoceros
C. tripus
C. vultur
C. spp.
Ceratocorys armata
C. horrida
Cladopyxis brachiolata
Dinophysis caudata
Diplopsalis lenticula
Exuviaella spp.
Goniodoma polyedricum

115
APPENDIX 5 continued.

Dinophyceae con’t

Goniodoma sphaericum
Gonyaulax dicantha
G. monacantha
G. turbynei
Ornithocercus magnificus
O. quadratus
Peridinium brochii
P. cerasus
P. conicum
P. crassipes
P. depressum
P. diabolus
P. divergens
P. grani
P. oblongum
P. pellucidum
P. steinii
Peridiniopsis asymmetrica
Phalacroma argus
P. porodictyum
Podalampas spinifera
Prorocentrum spp.
Triposolenia bicornis

Cyanophyta

Trichodesmium spp.
Bacillariophyceae
- Asterionella japonica
- Bacteriasterum delicatulum
- B. hyalinum
- Campylodiscus echensis
- Chaetoceros compressus
- C. decipiens
- C. indicum
- C. messanensis
- C. socialis
- Climacodium fraunfeldianum
- Corethron hystrix
- Guinardia· flaccida
- Leptocylindrus danicus
- Nitzschia closterium
- N. longissima
- N. seriata
- Planktoniella sol
- Rhizosolenia alata
- R. bergonii
- R. calcar-avis
- R. hebetata
- R. imbricata
- Surirella spp. "A"
- Synedra crystallina
- Thalassionema spp.
- Thalassiosira decipiens
- T. spp.
- Unidentified diatoms

Dinophyceae
- Ceratium bohmi
- C. breve
- C. candelabrum
- C. contrarium
- C. declinatum
- C. egyptiacum
- C. furca
- C. furca v. hircus
- C. fusus
- C. inflatum
- C. longirostrum
- C. pentagonum
- C. schmidtii
- C. trichoceros
- C. tripos
- Ceratocorys armata
- C. horrida
- Cladopyxis brachiolata
- Diplopsalis lenticula
- Exuviaella compressa
- Gonyiodoma polyedricum
- Gonyaulax pacifica
- G. polygramma
- Naked dinoflagellates
- Ornithocercus magnificus
- Peridinium crassipes
- P. depressum
- P. divergens
- P. oblongum
- P. spp.
APPENDIX 5 continued.

Dinophyceae con't

Peridiniopsis asymmetrica
Phalacroma argus
P. parvulum
P. porodictyum
Podalampas palmipes
P. spinifera
Prorocentrum micans
Triposolenia bicornis

Cyanophyta

Trichodesmium spp.
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</table>
APPENDIX 5 continued.

Dinophyceae con't
Peridinium steinii
P. trochoideum
Peridiniopsis asymmetrica
Pyrophacus horologium
Triposolenia bicornis

Cyanophyta
Trichodesmium spp.
APPENDIX 5 continued.

JUNE 27, 1978

Bacillariophyceae
Amphiprora gigantea
Asterionella japonica
A. notata
Biddulphia pelagica
B. Schroderiana
Chaetoceros affinis v. Willei
C. compressus
C. curvisetum
C. peruvianum
C. pseudoperuvianum
C. socialis
Climacodium biconcavum
Coscinodiscus spp.
Coscinodiscus spp.
Hemiaulus hauckii
Hemidiscus cuneiformis
H. membranaceus
Leptocylindrus danicus
L. minimus
Licmophora abbreviata
Nitzschia closterium
N. delicatissima
Rhizosolenia alata
R. alata v. gracillima
R. bergonii
R. calcar-avis
R. clevei
R. hebetata

Bacillariophyceae con't
Rhizosolenia imbricata
R. Stolterfothii
Schroderella delicatula
Thalassionema nitzschioides
Thalassiothrix spp. "A"

Dinophyceae
Ceratium breve
C. candelabrum
C. contortum
C. declinatum
C. furca
C. fusus
C. Kofoidiid
C. longirostrum
C. tenue
C. teres
C. trichoceros
C. tripos
C. vultur
Ceratocorys armata
C. horrida
Cladopyxsis brachiolata
Diplopsalis lenticula
Goniodoma polyedricum
Gonyaulax diacantha
G. polygramma
G. turbynei
APPENDIX 5 continued.

JUNE 27, 1978

Dinophyceae con't

Ornithocercus magnificus
O. spp.
Peridinium brochii
P. cerasus
P. divergens
P. steinii
Peridiniopsis asymmetrica
Phalacroma doryphorium
Podalampas spinifera
Prorocentrum micans
Protoceratium spp. "A"
Spiraulax jolliffei
Triposolenia bicornis
Unidentified

Cyanophyta

Trichodesmium spp.
APPENDIX 5 continued.

JULY 10, 1978

Bacillariophyceae

- Amphiprora gigantea
- Biddulphia pelagica
- Chaetoceros affinis
- C. castracanei
- C. compressus
- C. curvisetum
- C. Wighami
- C. spp.
- Dactyliosolen mediterraneus
- Guinardia flaccida
- Hemiaulus hauckii
- H. membranaceus
- Leptocylindrus danicus
- L. minimus
- Nitzschia closterium
- N. delicatissima
- Pennate diatoms
- Rhizosolenia alata v. gracillima
- R. bergonii
- R. calcar-avis
- R. curviseta
- R. delicatula
- R. hebetata
- R. Shrubsolei
- R. Stolterfothii
- R. styliformis
- Schroderella delicatula
- Striatella unipunctata

Bacillariophyceae con't

- Thalassiosira decipiens
- Thalassiothrix longissima
- T. spp. "A"

Dinophyceae

- Amphidinium spp.
- Ceratium breve
- C. candelabrum
- C. contrarium
- C. declinatum
- C. dens
- C. egyptiacum
- C. furca
- C. furca v. spp. "A"
- C. fusus
- C. Kofoidii
- C. massiliense
- C. pentagonum
- C. teres
- C. trichoceros
- C. tripos
- Dinophysis caudata
- D. ovum
- D. sphaerica
- Diplopsalis lenticula
- Exuviaella spp.
- Goniodoma polyedricum
- Gonyaulax polygramma
APPENDIX 5 continued.

Dinophyceae con't

Gonyaulax turbynei
Gymnodinium spp.
Naked dinoflagellates
Ornithocercus spp.
Oxytoxum scolopax
Peridinium brochii
P. cerasus
P. conicum
P. crassipes
P. divergens
P. grani
P. leonis
P. pallidum
P. pellucidum
P. steinii
P. trochoideum
Peridiniopsis asymmetrica
Phalacroma porodictyum
Prorocentrum micans
Pyrophacus horologium
Small dinoflagellates
Spiraulax jolliffee
Triposolenia bicornis

Cyanophyta

Trichodesmium spp.
APPENDIX 5 continued.

AUGUST 20, 1978

Bacillariophyceae

Chaetoceros affinis
C. brevis
C. coarctatum
C. compressus
C. curvisetum
C. decipiens
C. dichaeta
C. Lauderii
C. peruvianum
C. teres
C. tortissimum
Corethron spp.
Corethron spp. "A"
Dactyliosolen mediterraneus
Gossleriella tropica
Guinardia flaccida
Leptocylindrus danicus
Nitzschia seriata
Planktoniella sol
Rhizosolenia acuminata
R. alata
R. bergonii
R. calcar-avis
R. fragilissima
R. hebetata
R. Shrubsolei
R. Stolterfothii
R. styliformis
R. temperei

Bacillariophyceae con't

Schroderella delicatula
Thalassiothrix delicatula
Thalassiothrix spp. "A"

Dinophyceae

Amphisolenia bidentata
Ceratium breve
C. carriense
C. contortum
C. declinatum
C. egyptiacum
C. extensum
C. furca
C. fusus
C. massiliense
C. teres
C. trichoceros
C. tripos
Cladopyxis brachiolata
Dinophysis caudata
D. spp.
Exuviella spp.
Gonyaulax polygramma
Peridinium conicum
P. depressum
P. pyriforme
P. steinii
P. trochoideum
APPENDIX 5 continued.

**Dinophyceae con't**

- Peridinium truncatum
- Pyrocystis elegans
- P. fusiformis
- Triposolenia bicornis

**Cyanophyta**

- Trichodesmium spp.
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Bacillariophyceae
Pennate diatoms

Dinophyceae
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C. contrarium
C. declinatum
C. furca
C. trichoceros
Exuviaella compressa
Podalampas spinifera
Prorocentrum micans
Pyrophacus horologium
Unidentified

Cyanophyta
**APPENDIX 6: TAXA LIST OF ALL GENERA AND SPECIES IDENTIFIED FROM THE RED SEA, 1977-1978.**

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APPENDIX 6 continued.

DINOPHYTA

Amphidinium
A. spp.

Amphisolenia
A. bidentata

Ceratium
C. arietinum
C. bohmi
C. breve
C. candelabrum
C. carriense
C. contortum
C. contrarium
C. declinatum
C. declinatum declinatum
C. declinatum v. normale
C. dens
C. egyptiacum
C. extensum
C. furca
C. furca v. hircus
C. furca v. spp. "A"
C. fusus
C. hexacanthum
C. horridum
C. incisum
C. inflatum
C. Karstenii
C. Kofoidii
C. longirostrum
C. lunula
C. macrroceros
C. massiliense
C. pavillardii
C. pentagonum
C. platycorne
C. reflexum
C. schmidtii
C. strictum
C. tenue
C. teres
C. trichoceros
C. tripos
C. vultur
C. spp. "A"

Ceratocorys
C. armata
C. gourettii
C. horrida

Claparedo & Lachmann
Stein
Schroder
Stein
 arrest
Stein
Cleve
Graham & Bronikovsky
(Ost. & Sch.)Schroder
(Ehrenberg)Stein
Schank
Cleve
Gourret
(Gourret)Cleve
(Gourret)Pavillard
Karsten
Jorgensen
Jorgensen
Ost. & Sch.
Halim
(Gourret)Cleve
(Ehrenberg)Clap. & Lachm.
(Schröder)
(Ehrenberg)Dujardin
Gourret
Gran.
(Karsten)Jorgensen
(Kofoid)Jorgensen
Pavillard
Jorgensen
Gourret
(Schimper)Jorgensen
(Ehrenberg)Vanh.
(Gourret)Jorgensen
Jorgensen
Gourret
Daday
Cleve
Jorgensen
(Kofoid)Jorgensen
Kofoid
(Ehrenberg)Kofoid
(O.F. Muller)Nitz.
Cleve
Stein
(Shütt)Kofoid
Paulsen
Stein

134
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APPENDIX 6 continued.

Parahistioneis
P. spp.

Peridinium
P. abei
P. breve
P. brochii
P. cerasus
P. conicum
P. crassipes
P. depressum
P. diabolus
P. divergens
P. globulus
P. granii
P. leoni
P. oblongum
P. oceanicum
P. pallidum
P. pellucidum
P. pyriforme
P. sphaericum
P. steinii
P. trochoideum
P. truncatum
P. spp. "A"
P. spp.

Peridiniopsis
P. asymmetrica
P. trochoideum

Phalacroma
P. argus
P. circumsutum
P. doryphorium
P. parvulum
P. porodictyum

Podalampas
P. bipes
P. palmipes
P. spinifera

Porella
P. spp.

Prorocentrum
P. gracile
P. micans
P. spp.

Kofoid v. Skogsberg
Ehrenberg
Paulsen
Paulsen
Kofoiid & Swezy
Paulsen
(Gran)Ost. & Schm.
Kofoiid
Bailey
Cleve
Ehrenberg
Stein
(Stein)Paulsen
Pavillard
Aurivilius
Vanhoffen
Ostenfeld
(Bergh.)Schütta
Paulsen
Murray & Whitting
Jorgensen
(Stein)Lemmermann
Graham
Lemmermann
Mangin
(Stein)Lemmermann
Stein
Stein
Karsten
Stein
(Stein)Jorgensen
Stein
Stein
Stein
Okamura
Schiller
Ehrenberg
Schütt
Ehrenberg
APPENDIX 6 continued.

Protoceratium
P. reticulatum
P. spp. "A"  
Pyrocystis
P. elegans
P. fusiformis
P. lunula
P. pseudonooctiluca  
Pyrophacus
P. horologium
P. spp. "A"  
Spiraulax
S. jolliffei
S. Kofoidii  
Triposolenia
T. bicornis  

CHRYSOPHYTA
Dictyocha
D. fibule  

CYANOPHYTA
Trichodesmium  

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APPENDIX 7: ADDITIONS TO THE PHYTOPLANKTON TAXONOMIC LIST FOR THE RED SEA FROM THE PRESENT STUDY IN 1977-1978

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138
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APPENDIX 7 continued.

Fragillaria F. spp. Lyngbye
Licmophora L. spp Agardh
Mastogloia M. spp Thwaites
Nitzschia N. longissima v. reversa Hassall
N. longissima v. reversa W. Smith
Pleurosigma W. Smith
P. balticum (Ehrenberg) W. Smith
P. fasciola (Ehrenberg) W. Smith
P. rigidae W. Smith
P. spencerii W. Smith
Surirella Turpin
S. fastuosa Ehrenberg
Thalassionema Grunow
T. spp
Thalassiothrix Cleve and Grunow
T. delicatula v. "A"

DINOPHYTA

Amphidinium Claparedo & Lachmann
A. spp
Ceratium Schank
C. bohmi Graham & Bronikovsky
C. furca v. spp. "A"
C. platycorne Daday
C. vultur Cleve
Dinophysis Ehrenberg
D. ovum Schutt
Exuviaella Cienkowski
E. spp
Goniodoma Stein
G. spp
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APPENDIX 8 : REFERENCES USED IN COMPILING THE PHYTOPLANKTON SPECIES LIST IN THE REGION OF JIDDAH 1977-78.


Cleve, P.T. 1903. Report on Plankton collected by Mr. Thorild Wulff during a voyage to and from Bombay.


143


APPENDIX 8 continued.


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Figure 10. (Repeated). Seasonal density (σt) distribution at the Sharm station.
Figure 11. (Repeated). Seasonal density (st) distribution at the offshore station.
Figure 6. TO OVERLAY Figure 10.
Figure 7. TO OVERLAY Figure 11.
Figure 9. TO OVERLAY Figure 11.
Figure 13. TO OVERLAY Figure 10.
Figure 14. TO OVERLAY Figure 10.
Figure 15. TO OVERLAY Figure 11.
Figure 16. TO OVERLAY Figure 11.
Figure 17. TO OVERLAY Figure 10.
Figure 18. TO OVERLAY Figure 11.
Figure 19. TO OVERLAY Figure 10.
Figure 20. TO OVERLAY Figure 11.
Figure 21. TO OVERLAY Figure 10.
Figure 22. TO OVERLAY Figure 11.
Figure 23. TO OVERLAY Figure 10.
Figure 24. TO OVERLAY Figure 11.

OFFSHORE STATION – 0°
NH₄-N (µg-at l⁻¹)