National Oceanography Centre, Southampton

Research & Consultancy Report No. 31

5 years of plankton monitoring in Southampton Water and the Solent including FerryBox, Dock Monitor and discrete sample data

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Revised September 2007

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DOCUMENT DATA SHEET

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PUBLICATION DATE 2007

TITLE

5 years of plankton monitoring in Southampton Water and the Solent including FerryBox, Dock Monitor and discrete sample data.

REFERENCE

Southampton, UK: National Oceanography Centre, Southampton, 66pp.
(National Oceanography Centre Southampton Research and Consultancy Report, No. 31)
(Unpublished manuscript)
Major revision of SOC Research & Consultancy Report No. 82, 2004, 62pp.

ABSTRACT

The Environment Agency (EA) has to make a eutrophication status assessment of the Solent and its harbours every four years. This requires a review of the frequency and magnitude of phytoplankton blooms. To assist with this process SOC has prepared this report to provide a "meta-data base" describing the relevant data sets collected by SOC between 1999 and 2003. It provides details of :- (1) methods used to collect the data (2) errors associated with the methods (3) calibration and quality control procedures used (4) changes in procedures (5) references to technical reports and theses containing detailed descriptions of the methods used. Changes in concentrations of chlorophyll in relation to concentrations of nutrients at SOC study sites in Southampton Water are plotted in graphs. The occurrence of bloom events and processes of bloom limitation are described. In particular observations of the variation of chlorophyll concentrations made using the FerryBox route between Town Quay Southampton and Cowes Isle of Wight are described and the development of the systems and associated problems are detailed. The information is presented as (i) graphs of the whole data set at all locations against time for each year (ii) 3D maps of the variation in concentrations with location and time (iii) time series for single locations along the FerryBox track.

KEYWORDS

eutrophication, FerryBox, monitoring, nutrients, plankton blooms, Solent, Southampton Water, time series

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Acknowledgements

The support of Red Funnel Ferries Ltd is gratefully acknowledged for allowing SOC access to their ferry the Red Falcon to make the measurements reported here. This work would not have been possible without the help of their shore based staff and the crews on the ferry - particularly the engine room staff during frequent visits to the ferry. W.S.Oceans Systems Ltd (Mark Rawlinson and David Menzies) helped significantly with the design and installation and initial operation of the Dock Monitor and the Ferry Box on the Red Falcon. Discrete sample data were supplied by Arantza Iriarte, Elham Ali (PhD), Sinhue Torres-Valdez (PhD), Mark Collins (MSc) and Eric Muxagata (PhD) from their thesis work and post doctoral studies.

EXECUTIVE SUMMARY

Concentrations of nitrate (~ 6 mg N L^{-1}) and phosphate (~ 0.3-0.6 mg P L^{-1}) entering Southampton Water are moderate relative to other UK rivers (Hydes et al 2001, Nedwell et al., 2002) This report makes available to the Environment Agency all data collected by the Southampton Oceanography Centre (SOC) in Southampton Water and the Solent relevant to the nutrient status of the system between 1999 and 2003, to assist the Agency in its 2004 review of the frequency and magnitude of phytoplankton blooms in the Solent system.

A key effort by SOC has been the development of continuous monitoring systems designed to capture all bloom events through the spring and summer, and so develop a better understanding of what controls the frequency of blooms in the system. All the data available from the two systems: a the Dock Monitor fixed at the entrance to Empress Dock and the mobile system on the Red Funnel Ferry "Red Falcon", are presented. They show the improvements that were necessary to obtain the most reliable data set from the ferry system that was achieved in 2001.

In 2001 the main bloom measured as Chlorophyll-Fluorescence occurred off Cowes and in the Mid-Solent during May and concentrations in May exceeded 10 mg Chl m^{-3}. In June Chlorophyll-Fluorescence was higher in Southampton Water equivalent to a maximum of about 15 mg Chl m^{-3} (see Figs 4.6 a & b pages 36 &37, 4.7 & 4.8 page 38) for short periods. The Figure 4.8 shows how variable the intensity of a bloom can be over the period of a day.

In 2002 the Ferry system detected significantly less phytoplankton activity than in 2001. This was also observed in boat based surveys in Southampton Water (and coincidentally also in the outer Thames Estuary, Hartman et al., 2003).

Data have also been collected through several different student (PhD) projects over the same period. In this work samples were collected by boat at a range of different time intervals and at different locations in the estuary from Eling in the upper Test estuary to Horse Elbow in the eastern Solent. This data provides information both on concentrations of nutrients (ammonia, nitrate, phosphate and silicate) and phytoplankton biomass measured as chlorophyll-a.

Off Calshot and in the Solent, concentrations of phosphate in winter are close to concentrations in Atlantic Ocean surface water (~ 0.5-1.0 μM P). Following the Spring bloom in 2001, 2002 and 2003 the phosphate concentration in the Solent reached minimum values of <0.02 μM.

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APPENDIX

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CD3 Hartman, S.E. Hydes, D.J., Mills, D.K.,Wanieck, J. & Sivyer, D.B., 2003. FerryBox and databuoy measurements of plankton blooms. pp568-573. In Building the European Capacity in Operational Oceanography , (H. Dahlin, N.C. Flemming, K. Nittis & S.E. Petersson, eds) EuroGOOS Publication 19. Elsevier Oceanography Series, 69. Elsevier Amsterdam

CD4 Hydes, D.J. Hartman, S.E Kelly-Gerreyn, B.A. Dodgson, J. Campbell, J.M. Crisp, N.A. Edwards, M. Dupee, B. Lavin, A. M. Gonz·lez-Pola C. M. 2003 Use of a Ferrybox system to look at shelf sea and ocean margin process pp 297-303 In Building the European Capacity in Operational Oceanography , (H. Dahlin, N.C. Flemming, K. Nittis & S.E. Petersson, eds) EuroGOOS Publication 19. Elsevier Oceanography Series, 69. Elsevier Amsterdam

CD5 Holley, S.E., J. Waniek & D.J.Hydes, 2003b Ferrybox measurements of phytoplankton dynamics in a hypernutrified estuary (Southampton Water, UK) ICES CM 2003/L:02 (ICESpaper03 on the CD)

CD6 Holley, S.E & D.J Hydes, 1999a, Report on a new data station collecting biological, physical and meteorological data in Southampton Water (February to July 1999), SOC Internal document 49, 79pp

CD7 Holley, S.E & D.J Hydes, 1999b, Report on the new FerryBox monitor collecting biological and physical data in Southampton Water (March to November 1999), SOC Internal document 50, 74pp

CD8 Holley, S.E & D.J.Hydes, 2001a, Data from the Ferrybox and Dockhead monitors collecting biological, physical and meteorological data in Southampton Water (April-September 2000), SOC Internal Report No. 77, 2001, 49 pp

CD9 Holley, S.E, Hydes, D.J, Alderson, S and Hartman, M, 2001b. Calibration and installation of the FerryBox 2001, SOC Internal Report No. 78, 2001, 60 pp

CD10 Holley, S.E & D.J.Hydes 2003a The "Red Falcon" FerryBox 2002, with a review of data collected since 1999 FerryBox 2002. SOC Internal document 87, 24pp

CD11 Hydes, D J, S E Holley, J Xiong, A C Le Gall, B A Kelly-Gerreyn, S Lei, D A Purdie, R N Bonner, J H T O'Mahony and A R Weeks, 2001. Southampton Oceanography Centre Research & Consultancy Report No. 52. The Southern Nutrient Study Phase Two: SONUS-2 Final Report to the Department of the Environment Transport and the Regions on SONUS - Field Study 2 (January 1998 - March 2000) 124pp.

CD12 Wright P. N. &D. J. Hydes, 1998. Report on the methods used over the duration of the SONUS project 1995-1997. Report for UK Department of the Environment contract PECD 1/9/36 Southern Nutrient Study (SONUS) Fieldwork 43pp

CD13 "daily maps.gif" Presents data in format shown in Figure 2.4 of the report. A separated map for each days crossings has been drawn were

data was available. All the available days from the ferry for 2001 are used in this animation

CD14 Spring bloom 2001.gif Presents data in format shown in Figure 2.3 Data is shown for individual ferry crossings from Day 129 to day 145 (235 frames)

CD15 Summer bloom 2001.gif Data is shown for individual ferry crossings from Day 159 to day 174 (187 frames)

CHAPTER 1

OBJECTIVES AND BACKGROUND

1.1 Objectives

To provide:

- A "meta-data base" describing the purposes for which the data sets were and are being collected and including a listing of :- (1) methods used to collect the data (2) errors associated with the methods (3) calibration and quality control procedures used (4) changes in procedures (5) references to technical reports and theses containing detailed descriptions of the methods used.
- Summary of data collected, listing the type of data and when and where it was collected and details of the format in which the numerical data are held.
- Description of chlorophyll concentrations based on observations by the FerryBox route between Town Quay Southampton and Cowes Isle of Wight. This will be presented as (i) graphs of the whole data set at all locations against time for each year (ii) 3D maps of the variation in concentrations with location and time (iii) time series for single locations along the FerryBox track.
- Time series description of changes in chlorophyll levels in relation to hydrographic information and concentrations of nutrients at SOC study sites in Southampton Water.
- Description of the occurrence and nature of bloom events and processes of bloom limitation, taking into account the magnitude, location and duration of any bloom events.

1.2 Background

The Environment Agency (EA) has to make eutrophication status assessments of the Solent and its harbours every four years. This requires a review of the frequency and magnitude of phytoplankton blooms. This has been done by examining principally the data available from the EA's own data sets. The primary relevant sources of data are measurements of chlorophyll made each month through the summer at a number of routine sampling points. For the previous assessment in 2000 Southampton Oceanography Centre (SOC) made available annual reports from the Southampton "FerryBox" study and this information was used by the EA to verify their conclusions based on their data.

The EA recognises that SOC holds data specifically relevant to the assessment of eutrophication and the variation in the intensity of algal growth in Southampton Water, the Solent and off shore waters in recent years. This data has been collected in a

number of different research projects since 1998, including the FerryBox project and Dock Monitor (organised by David Hydes and Susan Hartman) and in a number of PhD research and other projects (supervised and lead by Duncan Purdie). As the data currently exists in various locations and formats there is value in synthesising it into a format that makes it readily available for the assessment, and its potential to enhance the validity the assessment, of the eutrophication status of Southampton Water and the Solent.

Southampton Water is not considered eutrophic (with sustained phytoplankton blooms, anoxic waters, fish kills or toxic algal blooms). However Southampton Water is a hypernutrified system (Xiong, 2000) that requires monitoring. Phytoplankton blooms (indicated by chlorophyll measurements of over 10 mg m^{-3}) occur throughout the spring and summer months. They tend to be short lived and intense and the timing and duration of these blooms varies from year to year. One of the aims of the Red Falcon FerryBox project is to investigate variations in timing of phytoplankton blooms in Southampton Water and controls on these blooms using ancillary meteorological and tidal data. It is important to examine the quality of the data obtained and make comparisons with discrete datasets to resolve these features.

CHAPTER 2

DATA COLLECTION

2.1 Background

Natural variability in estuaries is poorly described due to a lack of appropriate long and short-term observations (Smayda, 1998). Reliable annual estimates of production for example would require at least twice weekly measurements of chlorophyll (Dahl & Johannessen, 1998) but because of the cost involved few monitoring programmes sample at that frequency. Variations in concentrations of chlorophyll have proved to be a useful index of responses to physical variations and anthropogenic influences on an environment (Cloern, 1996). Concentrations of chlorophyll are directly related to the biomass of photosynthetic organisms present in the water. Measurements of chlorophyll provide an index of biomass without the need for the high manpower over head involved in counting and identifying plankton in water samples examined by microscope. Chlorophyll measurements however can only be made on individually collected waters samples each of which needs processing in a laboratory. Currently temporal resolution of changes in plankton biomass at time scales shorter than a few days can only be made by measuring fluorescence. An estimate of biomass can be obtained by measuring the in-vivo fluorescence induced in chlorophyll containing plankton cells by exposing them to blue light. This can be done in-situ using continuous and autonomous measuring devices. The temporal coverage of the data can be increased to the stage where all bloom events in a study area can be detected. With the caveat that the data being collected does not provide a quantitative measure of biomass but a measure that needs to supplemented by data collected to calibrate the system.

In biological marine science the measurement of in situ chlorophyll-fluorescence has become a routine tool to measure the relative spatial variability in phytoplankton biomass and can be converted to a measurement of chlorophyll-a through calibration of the data. Unattended measurements provide a detailed and continuous view of changes in chlorophyll-fluorescence, (Abbott et al., 1990, Rantajarvi, 2003). *However data need to be viewed with caution for regulatory purposes as the measurement of fluorescence provides a qualitative rather than quantitative measure of plankton biomass.* The principal reasons for this are (these factors will be discussed in Chapter 3.):-

- Biofouling of unattended sensors
- Variations in the fluorescence to chlorophyll ratio (e.g.: with species, season and nutrient status)
- Interference from humic substances

2.2 Sources Of Data In Southampton Water And The Solent

In Southampton Water and the Solent data are available from a number of different sources. The data collated in this report are from both unattended measurements of chlorophyll-fluorescence (FerryBox and Dock Monitor) and discrete samples collected, from a research boat as part of various PhD projects. The data sources are tabulated in a Gantt chart (Table A.4 in the Appendix). Table A.4 shows when the samples were collected and what measurements were made. Each of the main data sources (e.g. FerryBox) are introduced below and resolutions of the sensors used are tabulated in Table 2.1. The data have all been collated and converted to a single format for comparison. The data files available are listed in Table A.3 of the Appendix.

In Southampton Water and the Solent the FerryBox has supplied temporal and spatial coverage of the estuary whilst the Dock Monitor provided increased temporal resolution at a fixed site and this has been complemented by sampling carried out by a number of student projects during which water and plankton samples were collected in Southampton Water and the Solent for chemical and microscopic analysis.

The route of the FerryBox is shown in Figure 2.1 & 2.2. Figure 2.3 & 2.4 show examples of presentations of data collected on the route – on single crossing (Figure 2.3) and over one day (Figure 2.4). In Figure 2.2 the position of the Dock Monitor is shown along with the location of the principal sampling stations used in student projects (these are Eling, SG6 (Swinging Ground), NW Netley and Calshot. Data from the continuously recorded FerryBox data has been extracted to show changes with time at locations along the route (Cowes 50.760°N, mid Solent 50.783 °N, Calshot 50.807 °N, BP jetty 50.847 °N, NW Netley 50.872 and the latitude of the Dock Monitor 50.888 °N).

The FerryBox and Dock Monitor systems were set up as part of the SONUS (Southern Nutrient Study) and were jointly funded by DEFRA, NERC and EA). Details can be found in the SONUS II Report (Hydes et al., 2001) in the Appendix CD.

2.2.1 FerryBox

A FerryBox is a collection of sensors carried on a ferry (or other ship of opportunity running a consistently repeated route). The SONUS II system was developed to collect data with high enough temporal resolution that the timing of phytoplankton blooms in Southampton Water could be related to specific events such as the changing tidal energy in the system (Iriarte and Purdie 1994). The Red Falcon ferry operated by the Red Funnel Group makes up to 16 crossings a day between Southampton and Cowes on the Isle of Wight. This FerryBox first operated in 1999 and a full description of the work and data collected since then can be found in Holley & Hydes (1999b, 2001a, 2003a);

Holley *et al*. (2001b), (all available on Appendix CD) with initial interpretation of the data in Holley & Hydes (2002).

The variables measured by tapping into the engine cooling water flow are temperature, conductivity (for calculation of salinity), turbidity and fluorescence (for estimates of chlorophyll a). On the bridge the data are merged with GPS position data and 10-minute summaries of the data were transmitted ashore using a vodaphone Paknet system. Raw data files, 1 second and 1 minute average, are logged on PC on the ferry's bridge. The logged files are downloaded to a zip disk once a week. The sensors used have been the WS Ocean UMI (CTD, measuring conductivity, temperature, turbidity and pressure) and a Chelsea Instrument Aquatraka (which replaced the Seapoint fluorimeter in 2001). The days during which the FerryBox was in operation are summarised in the Gant chart (Table A.4 of the Appendix). The variables measured by the FerryBox are listed in Table 2.1.

The FerryBox principal was first tested in 1999 and the methods modified over the following years. For example the sensors were repositioned in 2000 to minimize particles settling out; the sensors were cleaned with increased frequency in 2000 and 2001 compared with 1999 to limit biofouling of the sensors. The flow through fluorimeter was also exchanged for one that was easier to clean in 2001 and 2002. Unfortunately some GPS problems were encountered in 2002 so the most complete and reliable FerryBox data coverage was in 2001 (when the sensors were cleaned on a weekly basis). Alterations to equipment, its position and maintenance are documented in the Appendix section A.1.

2.2.2 Dock Monitor

In 1999 and 2000 continuous *in situ* measurements were made at the Dock Monitor site at the entrance to Empress Dock (Figure 2.2). A WS Oceans Ltd "Coastal Monitor" provided the same variables as the FerryBox with additional meteorological (wind speed, direction, barometric pressure and air temperature) and tidal parameters (see Hydes et al., 2001 for details). The unattended fluorimeter is subject to the same problems associated with the FerryBox fluorimeter and as such provides a qualitative rather than quantitative view of chlorophyll variations. Also the sensors were located 1m above chart datum so will not be directly comparable with surface sampling by the FerryBox or discrete sampling at the surface. The instrumentation was cleaned and calibrated weekly during 1999 so provides a reliable picture of chlorophyll variation. Full details of the work carried out at the site and the data available can be found in Holley & Hydes (1999a and 2001a) and in Ali (2003). The days during which the Dock Monitor was in operation are summarised in the Gantt chart (Table A.4 in the Appendix).

2.2.3 Boat surveys

Discrete samples for chlorophyll, nutrients, salinity and temperature were collected between 1998 and 2003 at various sampling sites in Southampton Water and the Solent (as detailed in the Gantt chart (Table A.4 in the Appendix). These were collected as part of the PhD projects of various students (Ali, 2003; Torres 2004; Muxagata, 2005) and an EU funded project (HABES awarded to DAP) and were analysed following standard techniques (Table 2.2).

Discrete data collected from the boat sampling is sparse compared with the FerryBox coverage but the spatial scale is wider in some years extending further up the Test estuary or out into the western Solent. The FerryBox and Dock Monitor data includes both night and day measurements whereas the discrete readings tend to be taken in the day.

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TABLES CHAPTER 2

Table 2.1: A list of the variables measured by the FerryBox, manufacturers' quoted resolution and names used in all data files

Variable measured	Name in files	Sensor type	Resolution and units
Latitude & longitude	Lat & Lon	GPS	Decimal degrees
Date and time	day (1st Jan = day 1)	PC on Bridge	
UMI sensor			
Conductivity	cond	Induction	0.001 mS cm^{-1}
Temperature	rawtemp	Thermistor	0.005°C
Calibrated temp	temp	derived	°C
Salinity	salin	derived	0.001
Turbidity	turb	Seapoint OBS	FTU
Pressure	press	Strain gauge	0.015% (m)
Fluorimeter			
Fluorescence	fluor	Blue led	mg m^{-3}
Chlorophyll	chl	derived	mg m^{-3}

Table 2.2: A list of the variables measured from discrete boat survey samples

Variable measured	Method
Temperature	YSI sonde
Salinity	YSI sonde
Chlorophyll-a	Acetone extracted (Welschmeyer 1994)
Nutrients (Ammonium, Nitrate, Phosphate& Silicate	Autoanalyser (Wright & Hydes 1998)

FIGURES CHAPTER 2

Figure 2.1: Map of the route on the Red Funnel ferries between Town Quay Southampton and Cowes Isle of Wight

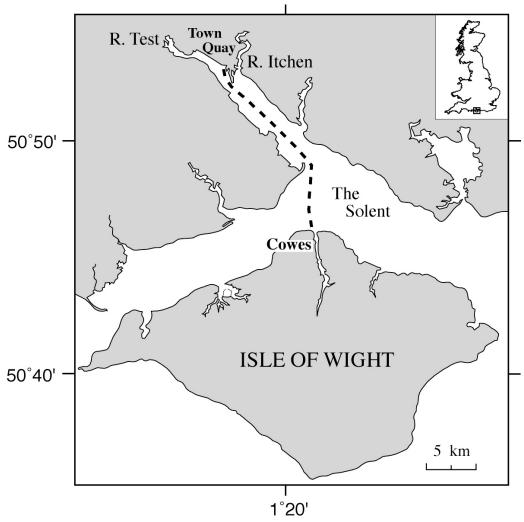


Figure 2.2: Map of ferry route, in Southampton Water showing the location of Dock Monitor sensors and discrete water sampling stations in Southampton Water

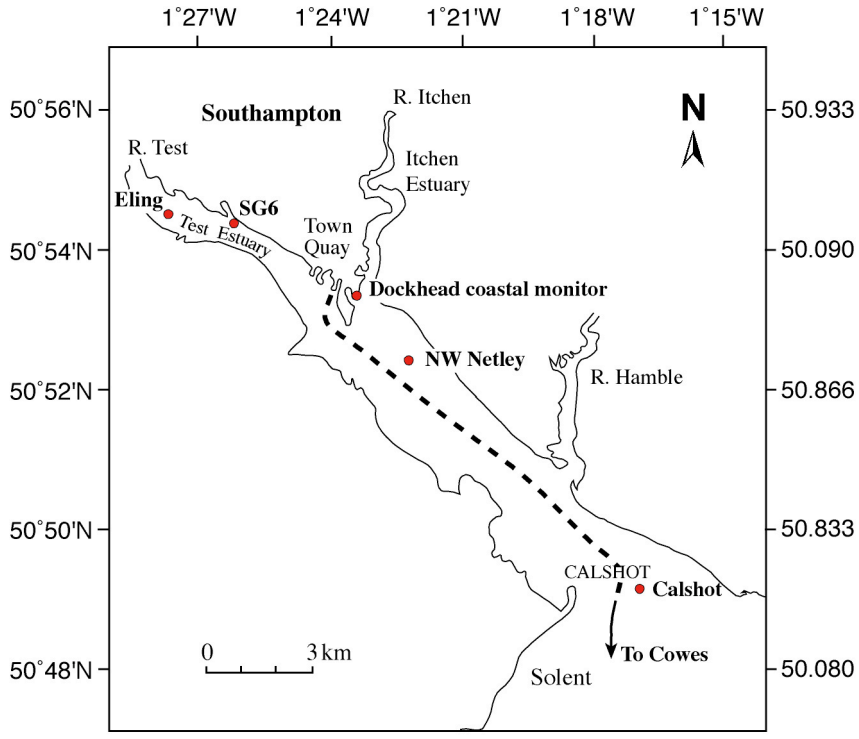


Figure 2.3: An example of data collected on single ferry crossing between Southampton and Cowes (day 137 17th May, 2001). The variation in chlorophyll a (mg m^{-3}) is shown as a colour scale, the y-axis is °N and the x-axis °E.

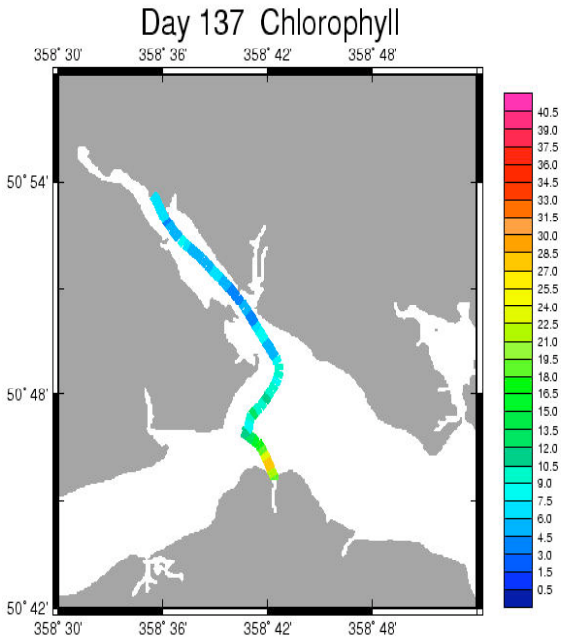
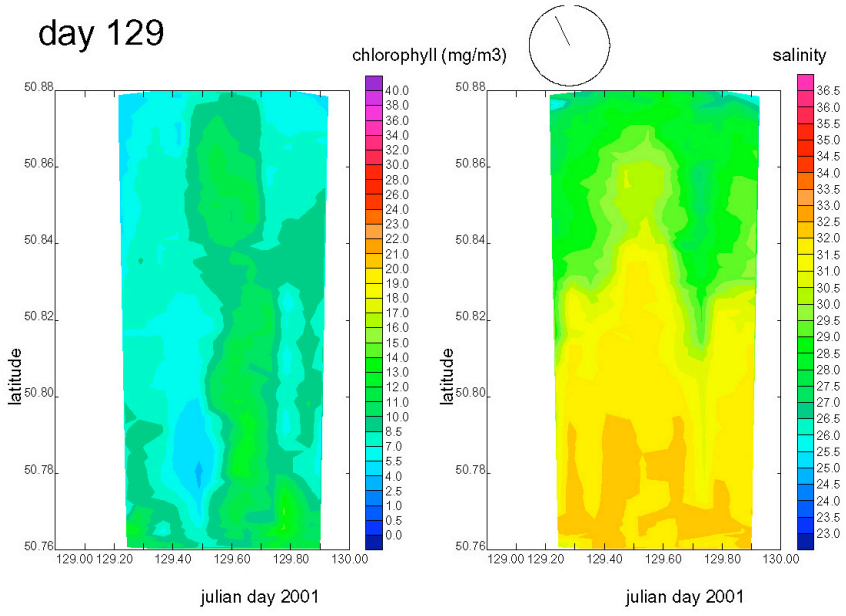


Figure 2.4: Example of salinity and chlorophyll contour plots from a single day in 2001. Diagrams 2.3 & 2.4 are single frames of the animations of the FerryBox data from 2001. The full animation is included in the Appendix CD.



CHAPTER 3

CALIBRATION AND DATA VALIDATION

3.1 Introduction

The Southampton Water FerryBox was first tested in 1999. From 1999 to 2002 conversion of fluorescence to chlorophyll-a has been performed in a number of different ways, each representing an improvement on the last method as problems of fluorimeters calibration were addressed. In this chapter the methods for calibrating the salinity and chlorophyll data are briefly described. (Both the Dock Monitor and FerryBox system carried a turbidity sensor but to date the turbidity results have not been calibrated.) The problems inherent in obtaining quantitative data from measurements of fluorescence are discussed. The data for chlorophyll based on measurements of fluorescence on the ferry are compared with results for measurements of chlorophyll extracted from water samples collected on boat surveys.

3.2 Calibrations

3.2.1 Calibration of Dock Monitor data

Calibration of Dock Monitor salinity and fluorescence data in 1999 and 2000 was carried out by hauling the sensors out of the water on a weekly basis, into a large container of surface water that was then sub-sampled. This was performed 15 times in 1999 and 10 times in 2000 to obtain the calibration equations. A single calibration was applied to the data from both years to obtain the data shown in this report.

3.2.3 Calibration of FerryBox Salinity Data

The FerryBox salinity sensor was calibrated by the manufacturer and then a correction factor was established by comparison with salinities measured in bottled samples which were taken on the cleaning and calibration visits. This correction is necessary because the WS Oceans Ltd UMI measures conductivity using an Aanderaa inductive head. The field around this head is distorted by the wall of the sensor housing. In 2001 comparison with weekly samples suggested a good correlation (r2=0.97) and a consistent offset in the calibrated salinity that was corrected for through post processing of the data. The correction applied was “true salinity = 0.9122*measured salinity +2.4002”.

3.3 Discussion of the use of fluorescence measurements to estimate concentrations of chlorophyll-a

By convention fluorescence measurements are presented in units corresponding to concentrations of chlorophyll-a and in associated discussions the two measurements fluorescence and chlorophyll tend to be used interchangeably (Marra, 1997). The problem with this is that the fluorescence to chlorophyll ratio is known to vary with:- (i)

the light environment (Variations in the Red Falcon FerryBox fluorescence to chlorophyll ratio and day/night variations are discussed later in this chapter.) (ii) the different absorbance and scattering properties of different species (iii) changes in yield between in vivo fluorescence from phytoplankton per unit chlorophyll (McKee et al., 1999). Therefore the calibration of fluorescence into chlorophyll is not necessarily straightforward. Additionally, in low salinity coastal regions, humic substances can cause interference with fluorescence readings and affect the calibration (Rantajarvi, 2002). In this work, conversion of the Red Falcon FerryBox fluorescence data, to chlorophyll-a, also varies with time as the fluorimeters used have been changed and repaired over the 4 year period that the FerryBox has been in operation. The fluorimeter was changed from a Seapoint to an Aquatracka in 2001 - the position of the sensors was changed to minimize settling of particles - the Aquatracka was repaired at the end of 2001. Any of these changes would conceivably alter the fluorescence calibrations, as would removal and cleaning of the sensors during maintenance visits (listed in Appendix A.1).

3.3.1 FerryBox calibrations

For the data plotted in this report, for each year a single calibration was applied. Applying a single calibration is not necessarily realistic due to the mixed species populations that exist in the estuary. However the alternative would require various factors to be known (e.g.: the species present, nutrient status of the cells, light environment that the cells are subjected to and various other factors). Therefore, despite the calibration improvements that have been made it is important to note that the FerryBox results can really only be used qualitatively. These calibrations are tabulated for comparison in Table 3.1. In 1999 for example the calibration used was that supplied by the manufacturers and the sensor was only cleaned on one occasion therefore the calibration could not be reliably checked. In 2000 the fluorimeter was calibrated through introduction of a series of known chlorophyll concentrations on a single date (as described more fully in Holley, 2001a). The fluorescence to chlorophyll relationship suggested a good correlation (r^2=0.9) and the calibration was checked through comparison with the chlorophyll samples taken on the cleaning visits. In 2000 the sensors were cleaned on 7 occasions compared with just once in 1999.

The Seapoint fluorimeters used in 1999 and 2000 proved difficult to keep clean as it was a flow-through fluorimeter and the measurement windows were hidden from view. Therefore in 2001 the fluorimeter was replaced with a Chelsea Instrument Aquatraka, which was easier to clean. The sensor was calibrated in the laboratory using 4 different phytoplankton single species cultures and chlorophyll in acetone. Manufacturer's calibrations are based on the fluorescence of chlorophyll in acetone rather than in

phytoplankton cultures so this could be a potential error with the calibration used in 1999 and 2000. In 2001 sampling was increased to weekly (13 times) and the results were used to check the calibration. The 2001 calibration was applied to the data and comparisons made with the 9 samples collected in situ that year suggest that the manufacturers calibration was valid (dates tabulated in the Appendix A4)..

An estimate of the errors in salinity and chlorophyll data has been made from comparison of the calibrated salinity and fluorescence data with data collected at service visits through the year. The discrete chlorophyll samples were analysed ashore following the same methods and standardisation procedures as the discrete samples collected from the boat surveys. In 2001 the relationship was Ferry Chl = 0.56 * Sample Chl + 0.78 (r^2 = 0.65 n = 13) and in 2002 Ferry Chl = 0.34 * Sample Chl - 0.31 (r^2 = 0.72 n =9).

3.3.2 Variations due to time of day

The ratio of fluorescence yield to concentration of chlorophyll may vary due to the time of day. This will affect both FerryBox and Dock Monitor data. The strength of the fluorescence signal is subject to variations caused by changing solar radiance which may result in photoinhibition and/or photoadaptative response in the plankton population (Marra, 1997). For example photoinhibition (also known as quenching) is a rapid, protective mechanism and fluorescence will be directly related to levels of sunlight (Marra, 1997) so the ratio of fluorescence to chlorophyll will tend to be lower around mid-day. In addition the biological response to ambient light is modified by factors such as temperature, nutrient availability and growth rate, mean light intensity and day length, and cell size distribution (Stamska & Dickey, 1992). Fluorescence decreases may be due to changes in the concentration of quinone type quenchers, which redistributes energy between the 2 photosystems, changing the fluorescence yield, chloroplast shape and position. Fluorescence increases may result from reduced self-shading of chloroplasts, light adaptation of phytoplankton cells.

To investigate light and dark variations calibrated fluorescence from the FerryBox has been separated into day and night samples: day is midday ± 2 hours and night is midnight ± 2 hours. A comparison of these values, which will be on the same state of the tide, at the same location and time is shown in Figure 3.1 for the 2001 FerryBox dataset. This figure however suggests quenching is not a serious factor to be considered in quality control of this particular dataset.

3.3.3 The ratio of fluorescence to chlorophyll

To date a single calibration has been applied for the whole of each year of the Red Falcon FerryBox chlorophyll-fluorescence data. For the Red Falcon FerryBox the

calibrated fluorescence (after applying the single yearly calibration) was compared against measurements of chlorophyll from extracted discrete samples (measured ashore). The ratio was calculated for each occasion that boat sampled discrete data coincide with FerryBox data. Variation in the ratio through the year for 2000, 2001 and 2002 is shown in Figure 3.2. Generally the ratios are most variable in 2000, with a peak in July (note 2000 ratios are on a different y-axis, when a bloom of *Mesodinium rubrum* and higher chlorophyll values were reported). In each year there is a decrease in the ratio over the year, which would result in the observed low readings of chlorophyll fluorescence from FerryBox data (compared with discrete data) later in the year.

3.3.4 Laboratory Calibration of Fluorimeters

The manufacturers calibration is usually made using commercially available chlorophyll dissolved in acetone. Figure 3.3 shows variations in the relation of fluorescence to chlorophyll with acetone-extracted chlorophyll and 4 different phytoplankton species grown in the laboratory. For the 2001 laboratory calibration (in Figure 3.3) the fluorescence from commercially acquired chlorophyll dissolved directly into acetone is much higher than for any of the individual cultures tested. The relationship of fluorescence to chlorophyll also differs with species. In this case *Phaeodactylum* sp. and *Tetrasalmis* sp have higher fluorescence for a given extracted chlorophyll than *Isochrysis* sp and *Pavlova* sp. The estuarine environment has mixed species composition and there is also species succession to consider. When it is also considered that for example the light environment and nutrient status also varies with time, and each of these factors affects the fluorescence to chlorophyll ratio, this plot clearly indicates the lack of accuracy that is inherent in applying a single conversion factor to fluorescence data in order to generate an estimate of concentration of chlorophyll.

3.4 Comparison of boat survey data and FerryBox data

FerryBox data were extracted at the same latitude as the Calshot and NW Netley sampling sites for direct comparison with the discrete boat samples. Discrete samples from a boat survey tend to be taken at or close to the sampling marker buoys whereas FerryBox data are taken on route and from different depths (surface and 2m data have been used for discrete sample comparisons compared with a water intake of about 3m from the ferry). Discrete water samples taken onboard the ferry during the year tended to be at the Dock Monitor location. It is a challenge to match up the data sets to see if calibrated FerryBox fluorescence is equivalent to the discrete extracted chlorophyll measurements made from the boat surveys. As the fluorimetric measurements are qualitative rather than quantitative the results would be expected to display similar trends in the data but should not be expected to display exactly matching magnitudes.

The 2001 chlorophyll data (calibrated fluorescence from the FerryBox and discrete extracted chlorophyll from the boat surveys) from similar times and locations are compared in Figures 3.4 and 3.5. There will be some discrepancy between the time of day and also the distance from the ferry track to the sample site (which tends to be at or close to a channel marker buoy rather than in the main channel). However this gives a broad indication of the comparability between the two data sets. On the whole the data for 2001 indicate the same trends and are complimentary.

Another problem with matching up the data sets is that because the sampling could not be closely coordinated due to logistical constraints, some data were taken when the FerryBox was out of action and visa versa. For example, at the Calshot site, FerryBox data were missing between days 212 and 216 but the peak in chlorophyll was detected on day 213 by discrete sampling. Likewise days 171 to 174 are missing from the FerryBox data set but a peak in chlorophyll was seen by discrete sampling. The FerryBox detects peak chlorophyll values around day 133 and also various peaks in chlorophyll between 145 and 153, days when discrete sampling was not carried out. At the NW Netley site, FerryBox data are missing between days 182-189, 191-195 and 212-216. Peaks in chlorophyll were detected by discrete sampling during each of these periods: on day 186, 193 and 214. The FerryBox data indicate a peak in chlorophyll on day 166 (15 mg m^{-3}) when there was a break in discrete sampling between days 162-169. Comparing the FerryBox and discrete measurements over time indicates some discrepancies between the data sets indicating lower chlorophyll concentrations on the Ferry where chlorophyll is calculated from the fluorescence data. For example: at the Calshot latitude (Figure 3.2) the FerryBox suggests low chlorophyll (~2.1 mg m^{-3}) whilst the discrete measurements indicate a chlorophyll peak (~15.5 mg m^{-3}); likewise day 162 (FerryBox 4.9 mg m^{-3} compared with 11 mg m^{-3} from the discrete measurements). At the NW Netley site the discrete data suggest a chlorophyll peak on day 162 (11 mg m^{-3}) whereas the FerryBox records 2.6 mg m^{-3}.

Given the large errors inherent in converting measurements of fluorescence to estimates of concentrations of chlorophyll (discussed above) the agreement in trends in the data and absolute values appears to be reasonable. Figure 3.6 is derived from data shown in Figures 3.4. and 3.5. FerryBox estimates of chlorophyll concentration are matched to water samples collected on boat surveys taken on the same day at the Calshot and NW Netley locations. A line of best fit through the combined Netley and Calshot data, through the origin and with the two high values removed) suggests an overall factor of 2 between the two data sets. However the scatter in the data does indicate the uncertainty present in the calibration of the fluorimeter data.

TABLE CHAPTER 3

Table 3.1 : Calibrations applied to obtain chlorophyll data

Variable	Year	Calibration equation
Chlorophyll	1999	Supplied calibration chl=20*fluor/65535 After day 126 *fluor by 3
	2000	*In situ* calibration chl= (0.0031 * fluor) - 63.16
	2001	Laboratory calibration chl = exp ((fluor - 20205)/5162
	2002	2001 equation applied note lab equation 2002: chl = exp ((fluor - 75322)/1366.8

FIGURES CHAPTER 3

Figure 3.1 A comparison of day and night FerryBox chlorophyll measurements at the Netley location.

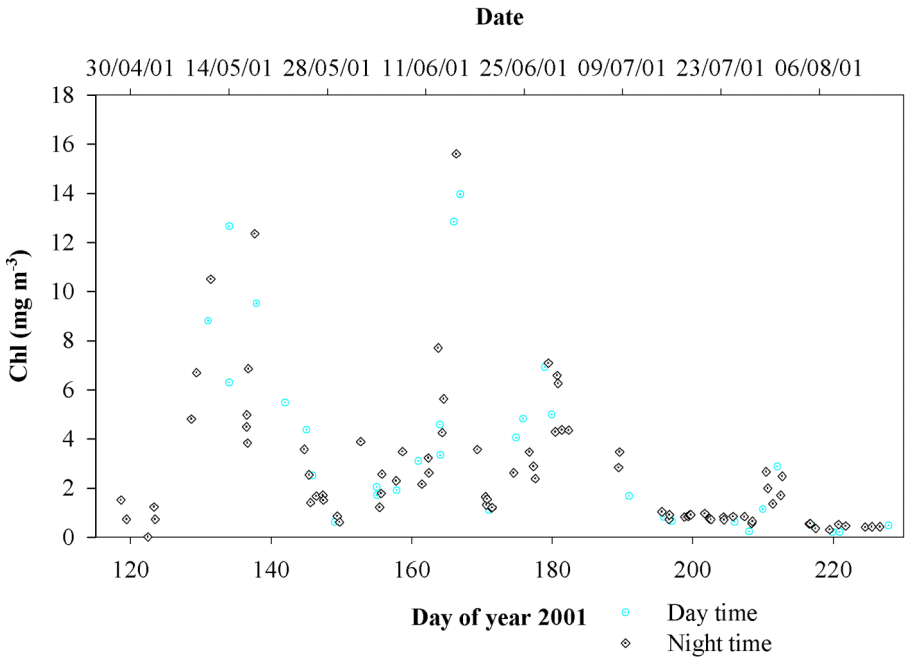


Figure 3.2 Variation in the fluorescence to chlorophyll ratio. The ratio of FerryBox fluorescence to discrete chlorophyll measured in water samples collected on the same day and at a similar location. Data available from all years is plotted.

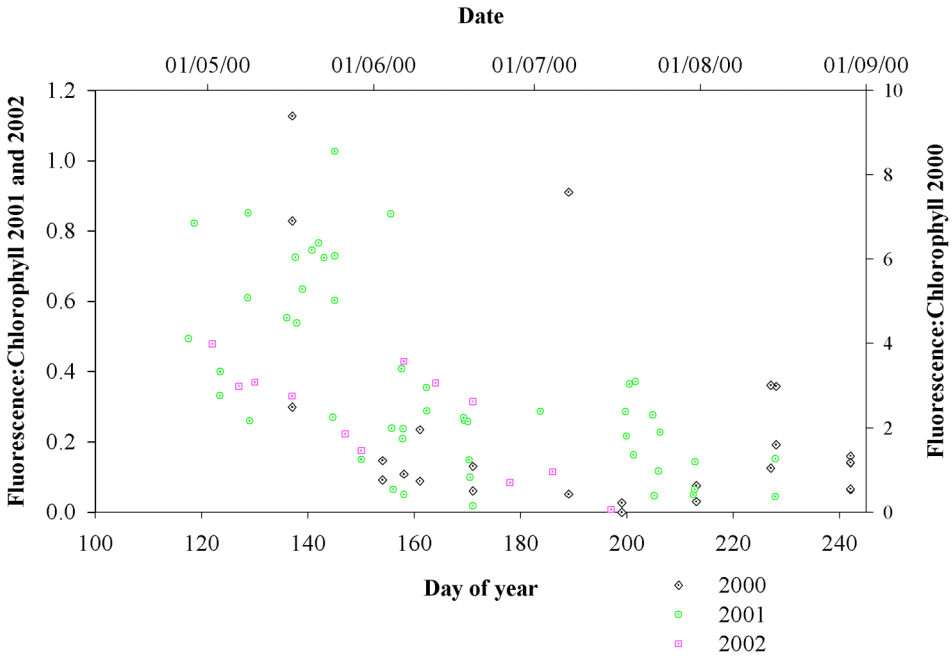


Figure 3.3 Variation in fluorescence: chlorophyll relationship with species and acetone extracted chlorophyll from the 2001 laboratory calibration of the Aquatracka.

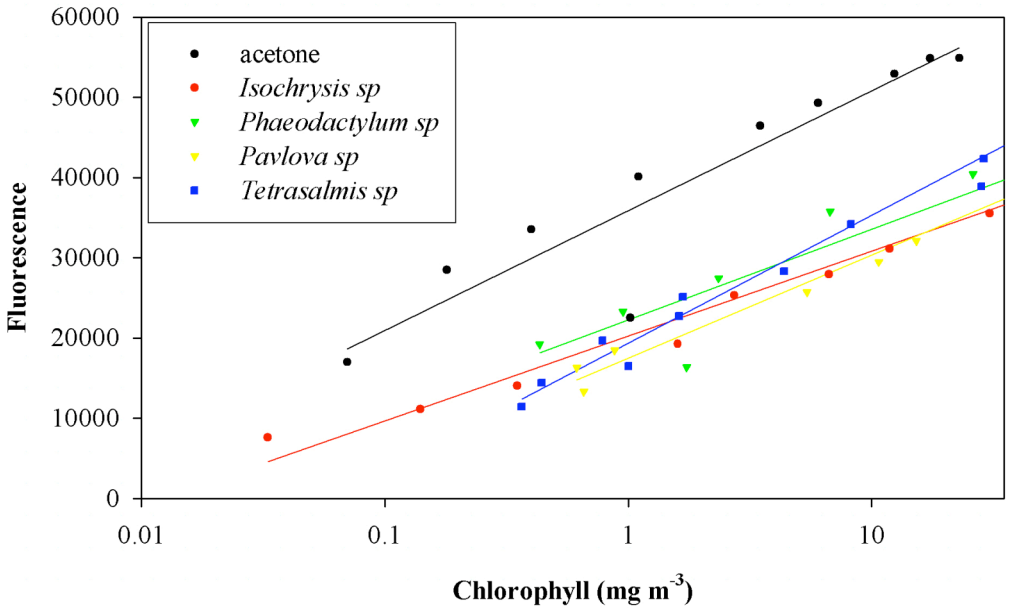


Figure 3.4 A comparison of FerryBox data and boat sampled chlorophyll data in 2001 at Calshot showing the variation in chlorophyll with time.

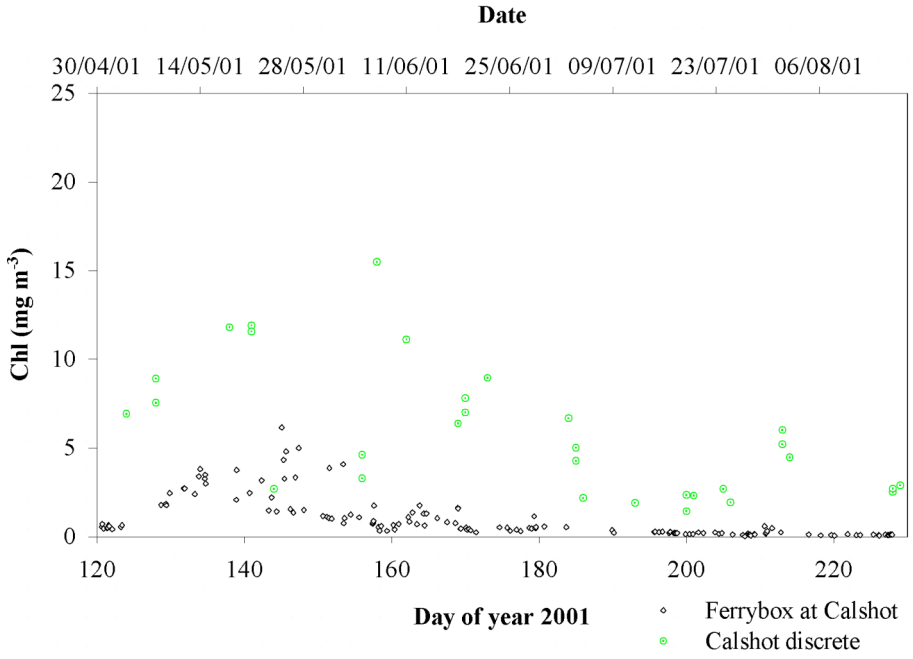


Figure 3.5 A comparison of FerryBox data and boat sampled chlorophyll data in 2001 at NW Netley showing variation in chlorophyll with time.

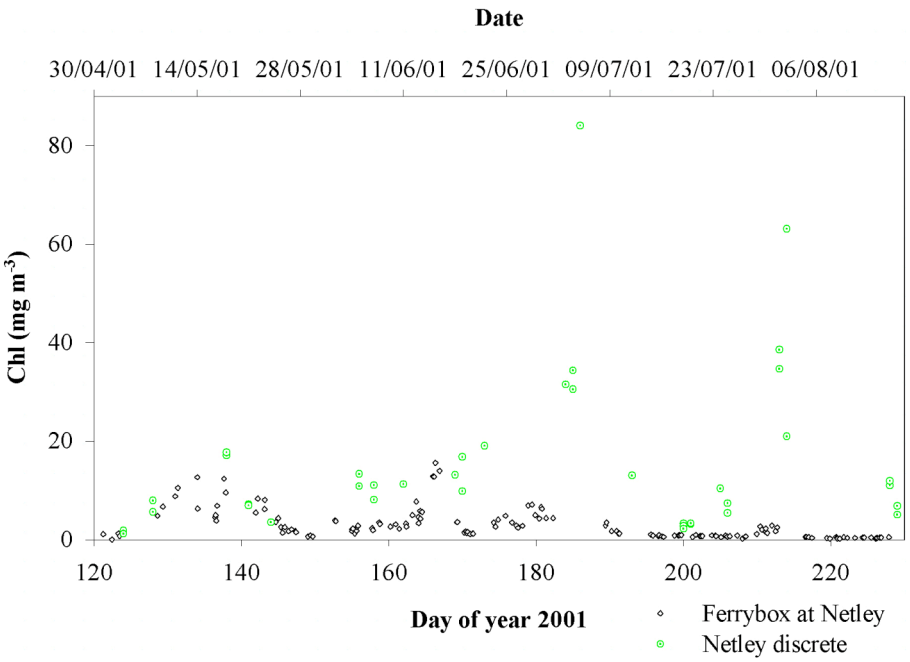
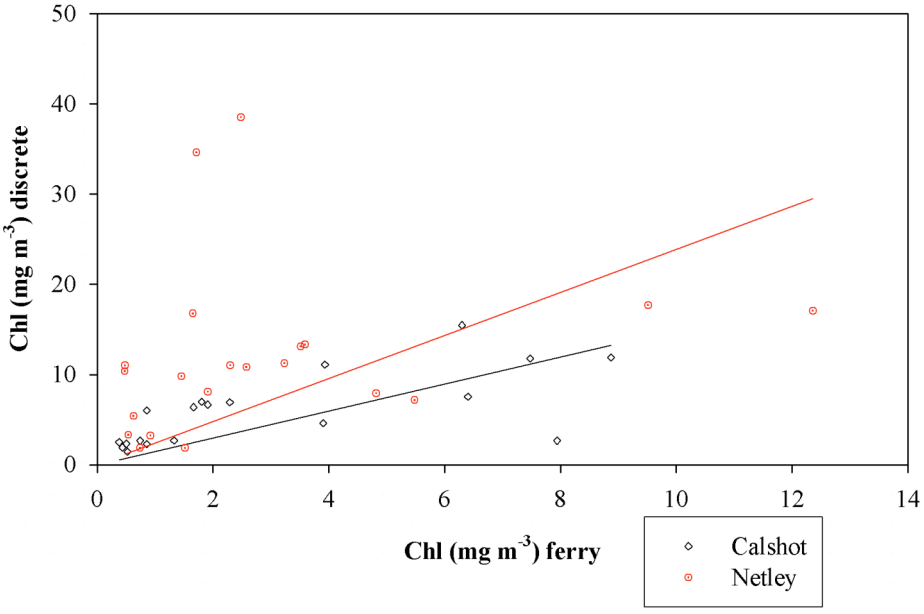


Figure 3.6 Direct comparison of Calshot and NW Netley discrete and FerryBox chlorophyll samples taken on the same day (and similar location) 2001.



CHAPTER 4

AN OVERVIEW OF THE DATA COLLECTED

4.1 Introduction

In this Chapter we present the data collected by SOC between 1999 and 2003 as a series of diagrams and provide a brief description of the plots and their content. In Chapter 5 we discuss our current understanding of the concatenation of processes controlling the growth of phytoplankton in Southampton water and the Solent. The figures presented in this Chapter are drawn from data collected from:-

- The Dock Monitor system, which recorded data at the entrance to Empress Dock in 1999 and 2000 (Figures 4.1 – 4.2).
- The "FerryBox" system on the Red Funnel ferry *Red Falcon* operating between Town Quay, Southampton and Cowes, Isle of Wight between 1999 and 2002 (Figures 4.3 – 4.8).
- Water samples collected on boat surveys in Southampton Water and the Solent between 1999 and 2003 (Figures 4.9 – 4.13).

4.2 Dock Monitor

The chlorophyll-fluorescence data from **1999** (Figures 4.1 a & b) show a peak exceeding 20 mg m^{-3} around day 140 followed by a secondary peak at day 160. The contracted spread of the data after day 160 suggests the detector was fouled at this stage. The plot of the mean daily concentrations (Figures 4.1 b) suggests there were peaks in biomass around days 210 and 240.

In **2000** there were problems with the system at the start of the year and recording of chlorophyll-fluorescence data did not start until day 148. Figures 4.2 a & b suggest peaks in biomass occurred around days 155, 210 and 240. In comparison to the data for chlorophyll extracted from water samples collected at NW Netley and at Calshot, the biomass detected at the Dock Monitor is similar to both sites around day 160. The Dock Monitor appears to have underestimated biomass relative to the Netley site between days 180 and 240.

4.3 Red Falcon FerryBox

In **1999** (Figure 4.3 a & 4.4 a) the data from the ferry system was severely degraded by fouling up to day 190. After this time the signal matched the pattern seen at the Dock Monitor with peaks in biomass recorded around days 210 and 240. In Figures 4.5a & b data have been extracted at fixed positions along the route so that time series plots can be drawn representing changes in salinity and chlorophyll-fluorescence - off Cowes, Mid Solent, Calshot, BP/ESSO, NW Netley and at the latitude of the Dock Monitor.

In **2000** (Figure 4.3 b & 4.4 b) the ferry system was severely affected by fouling throughout the spring and summer and no patterns can be discerned in the data.

In **2001** (Figure 4.3 c & 4.4 c) the redesigned ferry system probably collected reliable data for chlorophyll-fluorescence from day 118 to about day 190. Over this period the mean daily average concentration estimated by the ferry follows a similar pattern to the values determined in water samples collected at Calshot. After day 190 the variation seen in the fluorimeters output is low. This was probably due to penetration of moisture into the fluorimeter. The more reliable nature of the ferry data in **2001** enables the potential of the data set to be used to observe variations in bloom characteristics along the estuary. In Figures 4.6a & b data along the route have been extracted at the fixed positions of Cowes, Mid Solent, Calshot, BP/ESSO, NW Netley and the Dock monitor latitude as for 1999.The salinity data shows a progressive decrease in salinity up the estuary and greater spread in salinity in the greatest region of freshwater influence in the confines of Southampton Water. At all locations salinity increased as freshwater inputs i.e. river flow decreased through the summer and decreased again towards autumn.

The plots show that the spring bloom was most intense towards day 140 and in the Solent towards Cowes. Secondary blooms were then seen in Southampton Water around days 165 and 185. This change in bloom position and magnitude can be clearly seen in the map of change in chlorophyll-fluorescence with time and location in 2001 (Figure 4.7). Figure 4.7 is a useful guide to trends in the data although the contouring has smoothed the data and some of the detail, such as relatively small patches of high values, may be lost. Figure 4.8 shows the change in chlorophyll-fluorescence for individual days mapped in detail – for day 137 when the bloom was near its peak off Cowes and for day 167 when the bloom was near its peak in the upper estuary. The scale and contour intervals have been altered from Figure 4.7 to highlight the distribution of the bloom.

In **2002** Figures 4.3d & 4.4d show a series of small peaks in chlorophyll-fluorescence lower than in previous years. Levels of chlorophyll measured in water samples were also lower in 2002.

4.4 Boat Surveys

Data for chlorophyll and nutrients determined in surface water samples collected on boat surveys in Southampton Water and the Solent between 1999 and 2003 are plotted in Figures 4.9 –4.13.

Water samples were collected furthest out into the Solent in spring **2002** when the EU funded HABES project enabled sampling both at Calshot and Horse Elbow buoy (Figure 4.9). This data shows similar values for chlorophyll, nitrate, phosphate, silicate

and ammonium at both sites in the Solent. As mentioned above chlorophyll values were generally low in 2002. The data shows a chlorophyll peak relatively late in the year in June just exceeding 10 mg m^{-3} on one occasion at Calshot. At this stage concentrations of phosphate fall to low values i.e. < μmol L^{-1} in the outer estuary. The earlier decrease in concentration of silicate is not associated with a change in chlorophyll biomass and may be due to changes in characteristics of the dominant off shore water mass.

Sufficient data from water samples is available to compare changes in concentrations of nutrients and chlorophyll between 2000, 2001, 2002 and 2003 at both the Calshot (Figure 4.10) and NW Netley sites (Figure 4.11). In both sets of diagrams lines demarking the 10 mg m^{-3} concentration of chlorophyll-a are drawn. At Calshot in 2000 this level of chlorophyll was not exceeded although sampling frequency was limited to once every 2 weeks between May and September. In 2001 and 2003 concentration of chlorophyll increased in May and remained relatively high until July. During this period concentrations of nitrate and silicate are reduced to relatively low concentrations (1-2 μM N and <0.5 μM Si).. In the winter, phosphate concentrations are close to Atlantic surface water concentrations (~0.5 - 1.0 μM P) but decrease in May/June to the detection limit of the method (0.02 μM P).

At NW Netley (Figure 4.11) in 2000 the data suggests a significant phytoplankton bloom was present in Southampton Water through July and August reaching a peak of 38 mg m^{-3} chlorophyll in July. In 2001 the concentration of chlorophyll exceeded 10 mg m^{-3} on several dates between May and September although the variability between sampling dates was high. Peak recorded chlorophyll concentration was 35 mg m^{-3} in August 2001. In 2002 a concentration of chlorophyll in excess of 10 mg m^{-3} was not observed until late June when the peak was 17 mg m^{-3}. In 2003 the 10 mg m^{-3} level was first exceeded in May and , a peak of 20 mg m^{-3} was observed in July. The variability between sampling visits was high in 2001 and 2003 with several peaks in chlorophyll between May and August.

In 2001 and 2002 sufficient water samples were collected in the Upper Test Estuary at the Eling site for a time series to be plotted (Figure 4.12). These plots show correspondingly high biomass in 2001 relative to 2002. A peak of 90 mg m^{-3} was measured in July 2001 whereas the maximum measured in June 2002 was 17 mg m^{-3}. In 2001 the variation in concentrations of chlorophyll over the summer period was greater at Eling than NW Netley. The concentration of chlorophyll was less than 3 mg m^{-3} on the three sampling visits following the one on which the maximum concentration was observed at Eling.

Data for concentrations of ammonium are available for the Calshot, NW Netley and Eling sites in 2001 and 2002. These data are plotted in comparison to concentrations of chlorophyll in Figure 4.13. Ammonium concentrations were similar in both years.

In 2001 water samples were collected from 5 different depths in the water column on some dates at the Eling, NW Netley and Calshot stations. The data for chlorophyll is presented in Table 4.1. This shows that in general conditions were well mixed, with the exception that following an initial spring bloom on the 21 May the deepest sample at NW Netley and Calshot contained a higher concentration of chlorophyll probably indicating settling out of the earlier diatom bloom. Under summer bloom conditions (4 July, 1 & 8 August) surface chlorophyll concentrations are higher at Eling and NW Netley.

TABLE CHAPTER 4

Table 4.1 Vertical distribution of chlorophyll concentration (mg m^{-3}) at each station in 2001 (from Torres-Valdez, 2004)

	Sample Depth				
Date	1 m	2 m	4 m	7m	9 m
Eling	Concentration of chlorophyll mg m^{-3}				
20/04/01	1.3	1.5	1.3	1.2	1.3
08/05/01	<=no data	<=no data	<=no data	<=no data	<=no data
21/05/01	<=no data	<=no data	<=no data	<=no data	<=no data
05/06/01	5.6	5.3	5.4	4.9	5.6
19/06/01	6.9	7.4	8.5	17.2	10.6
04/07/01	64.0	47.4	34.7	26.4	23.2
20/07/01	2.2	2.3	2.1	2.0	1.6
01/08/01	36.8	35.9	25.6	4.2	2.8
16/08/01	9.1	2.9	2.0	1.3	1.3
30/08/01	20.6	10.4	8.0	7.0	6.9
17/09/01	1.6	2.0	1.5	1.5	1.6
01/10/01	2.3	1.9	1.6	1.5	1.5
15/10/01	1.7	0.8	0.9	1.2	1.2
31/10/01	1.0	1.1	0.6	0.7	0.3
NW Netley					
20/04/01	1.0	1.0	1.1	1.3	1.7
08/05/01	7.9	5.6	8.3	8.0	5.5
21/05/01	6.9	7.2	14.6	7.1	41.6
05/06/01	10.8	13.3	15.8	17.0	11.5
19/06/01	16.8	9.8	17.9	11.3	9.8
04/07/01	34.3	30.5	29.4	26.5	24.0
20/07/01	3.3	3.1	3.6	2.4	2.2
01/08/01	38.5	34.6	26.2	7.3	6.0
16/08/01	11.9	11.0	4.3	4.6	3.4
30/08/01	28.5	24.9	15.6	10.5	9.1
17/09/01	1.9	1.7	2.0	2.0	1.8
01/10/01	1.9	1.8	1.8	2.0	2.1
15/10/01	1.4	1.3	1.2	1.2	1.2
31/10/01	0.9	1.0	0.9	0.8	0.4
Calshot					
20/04/01	<=no data	<=no data	<=no data	<=no data	<=no data
08/05/01	7.5	8.9	8.7	7.4	8.9
21/05/01	11.6	11.9	13.5	18.7	20.7
05/06/01	3.3	4.6	4.9	6.8	6.7
19/06/01	7.0	7.9	7.4	7.2	7.9
04/07/01	4.3	5.0	4.5	3.6	3.5
20/07/01	2.3	2.3	2.1	2.1	2.1
01/08/01	5.2	6.0	5.3	4.9	4.7
16/08/01	2.7	2.5	2.7	2.4	2.3
30/08/01	3.1	3.4	3.1	3.1	3.1
17/09/01	1.8	2.1	1.8	1.9	2.0
01/10/01	1.9	1.7	2.2	2.1	1.7
15/10/01	1.4	1.4	1.4	1.5	1.6
31/10/01	1.1	1.0	1.0	1.0	1.0

FIGURES CHAPTER 4

Figure 4.1a Plot of all data for chlorophyll, turbidity and water temperature data from Dock Monitor **1999**

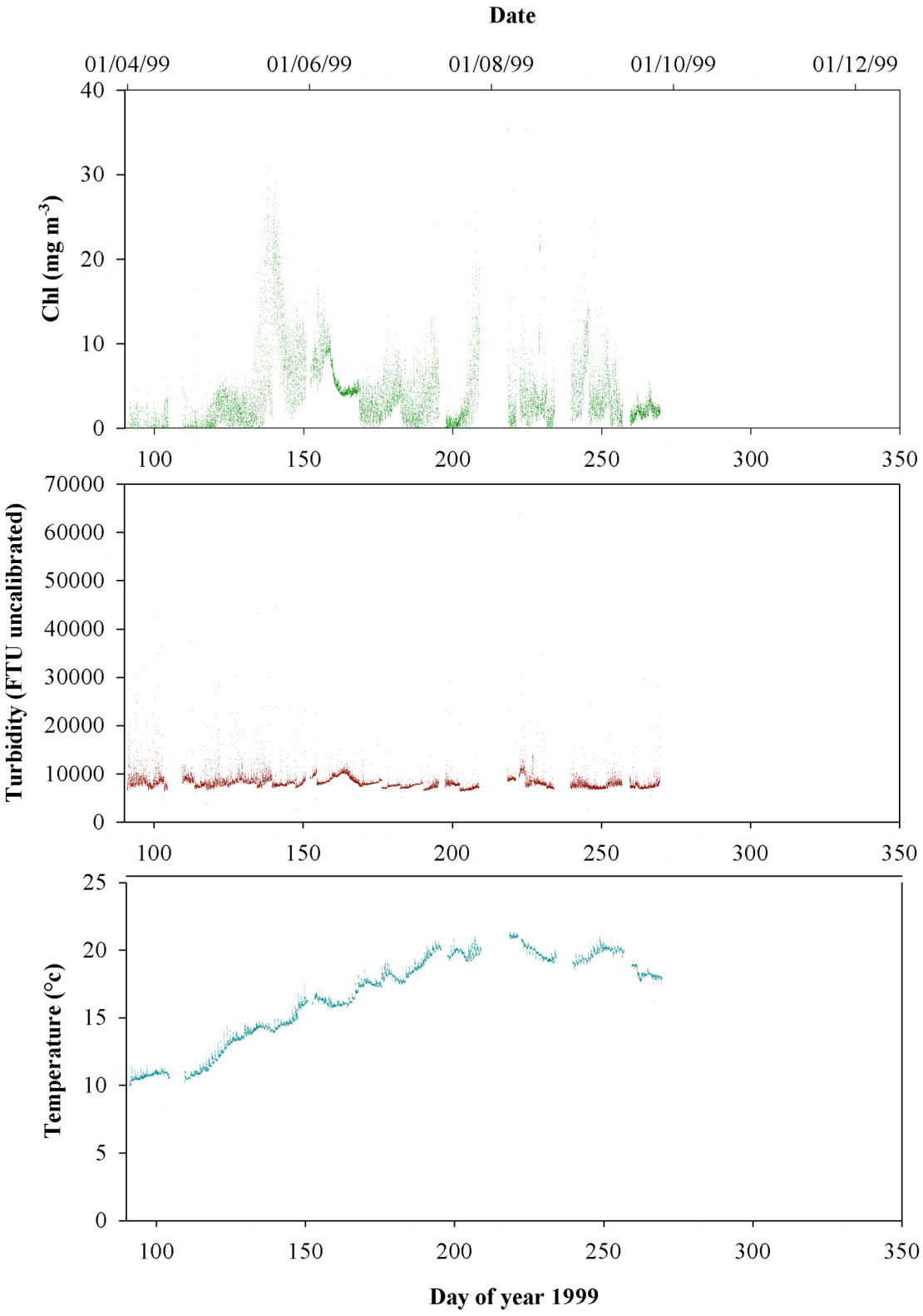


Figure 4.1b Plot of the daily mean concentration of chlorophyll and error bar (= ± 1 standard deviation) at the Dock Monitor station in **1999** the predicted tidal range is also shown.

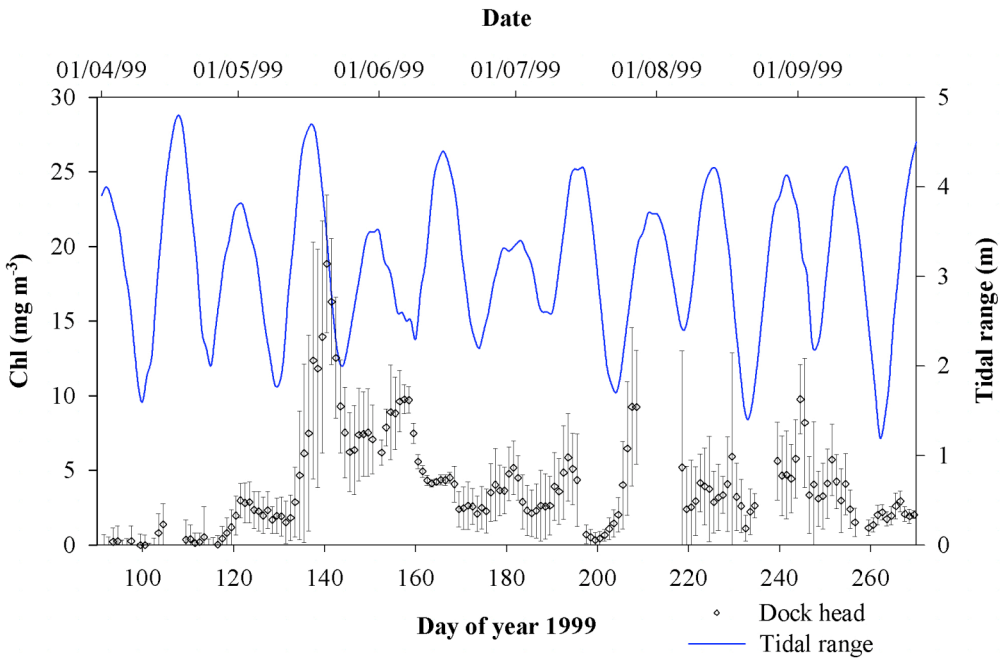


Figure 4.2a Plot of all data for chlorophyll, turbidity and water temperature data from Dock Monitor **2000.**

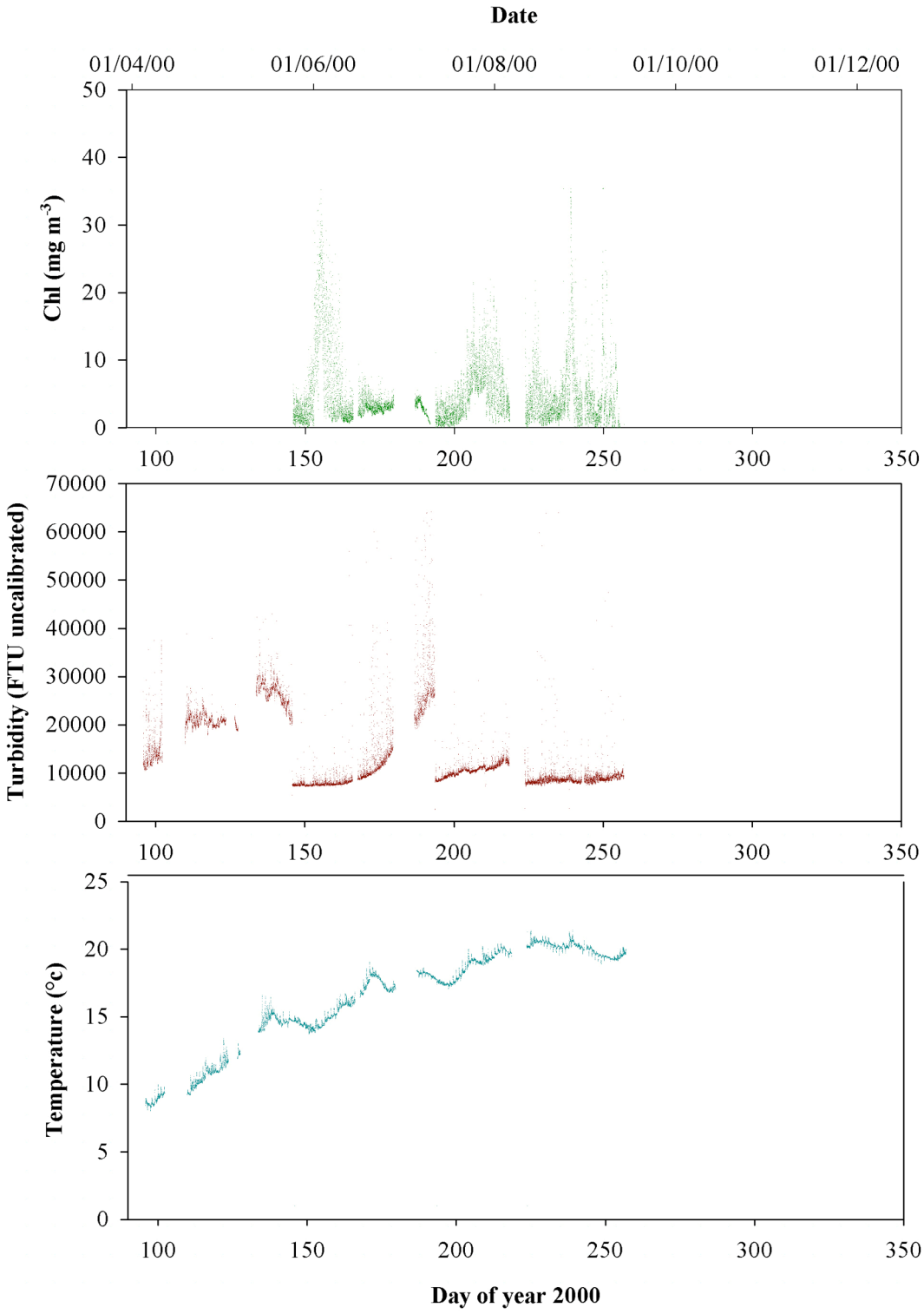


Figure 4.2b Plot of the daily mean concentration of chlorophyll and error bar (= ± 1 standard deviation) at the Dock Monitor station in **2000** the tidal range is also shown. The values of chlorophyll measured in water samples collected at the NW Netley site are also shown

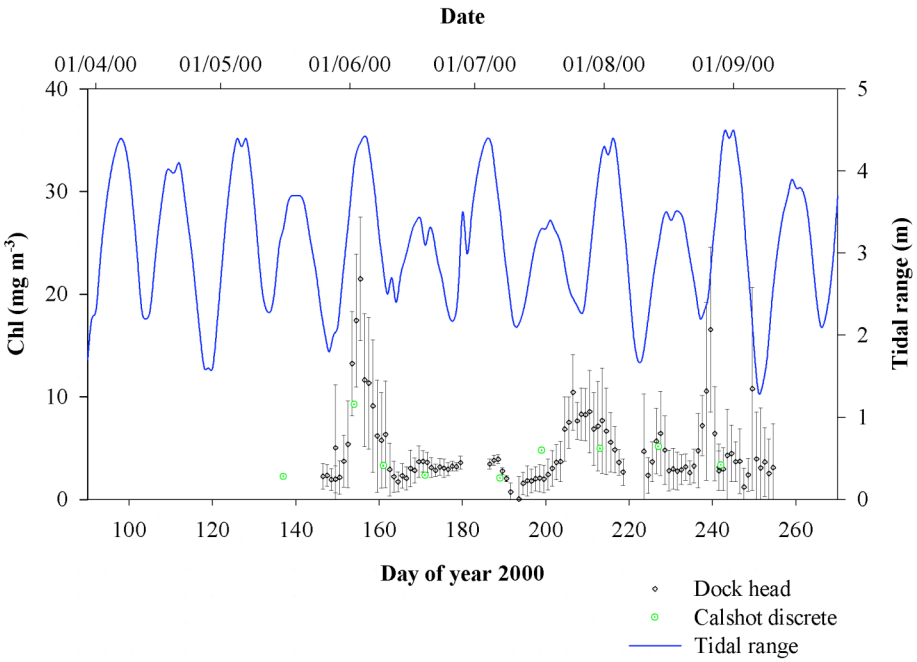


Figure 4.2c As Figure 4.2b but showing values of chlorophyll measured in water samples collected at the Calshot site in **2000**.

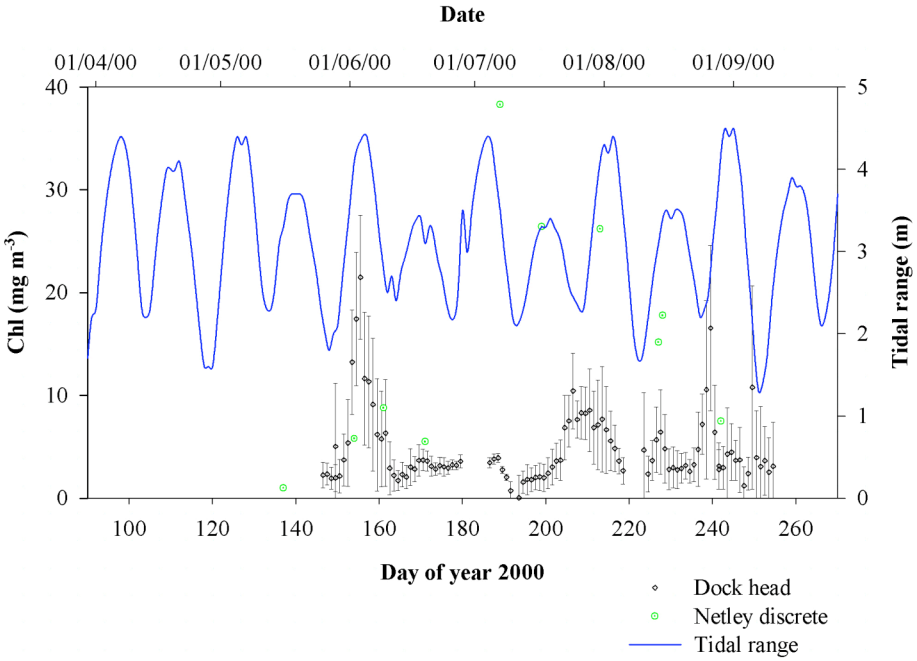


Figure 4.3a Plot of all data for chlorophyll, turbidity and water temperature data from Red Funnel FerryBox system collected in **1999.**

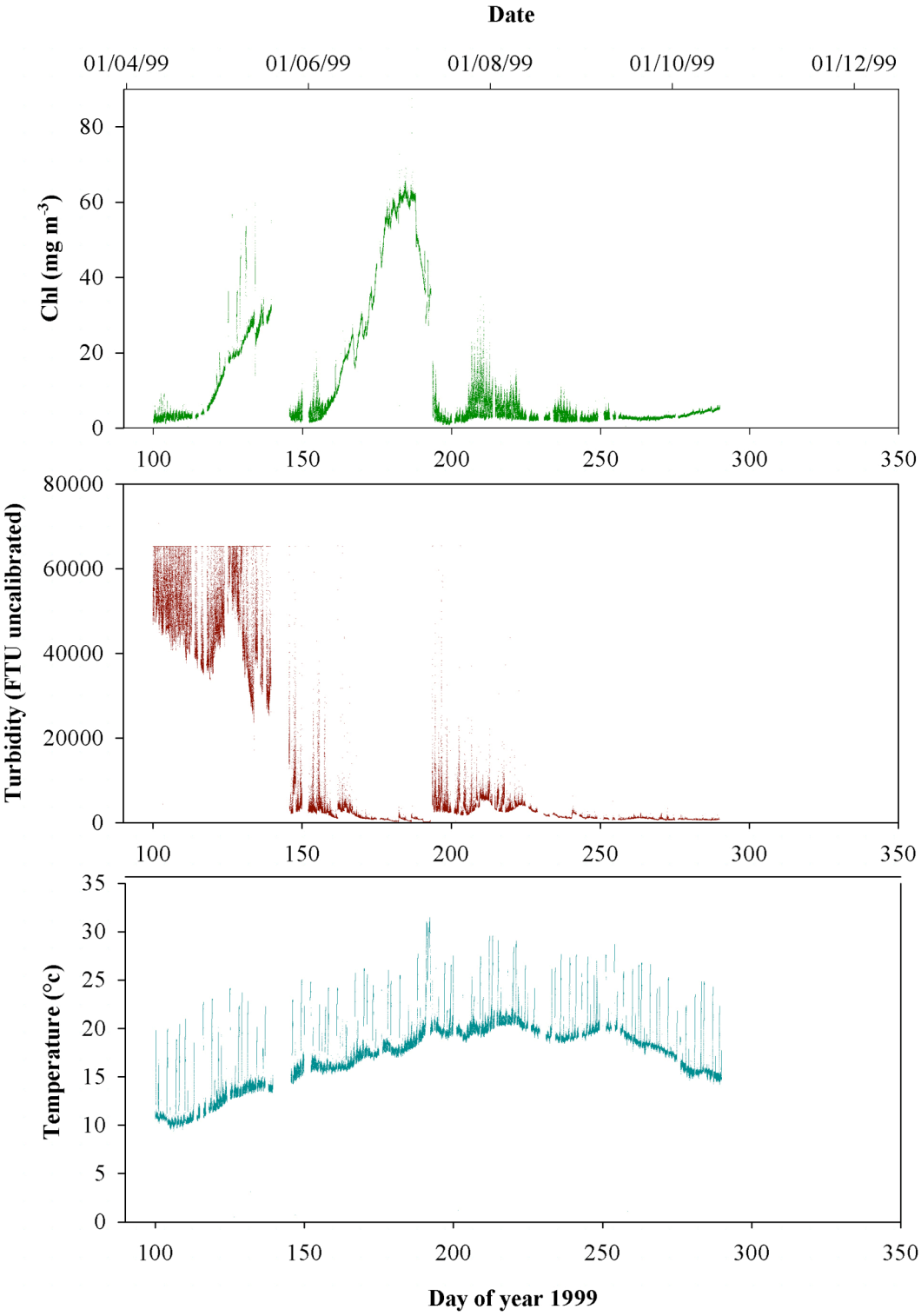


Figure 4.3b Plot of all data for chlorophyll, turbidity and water temperature data from Red Funnel FerryBox system collected in **2000.**

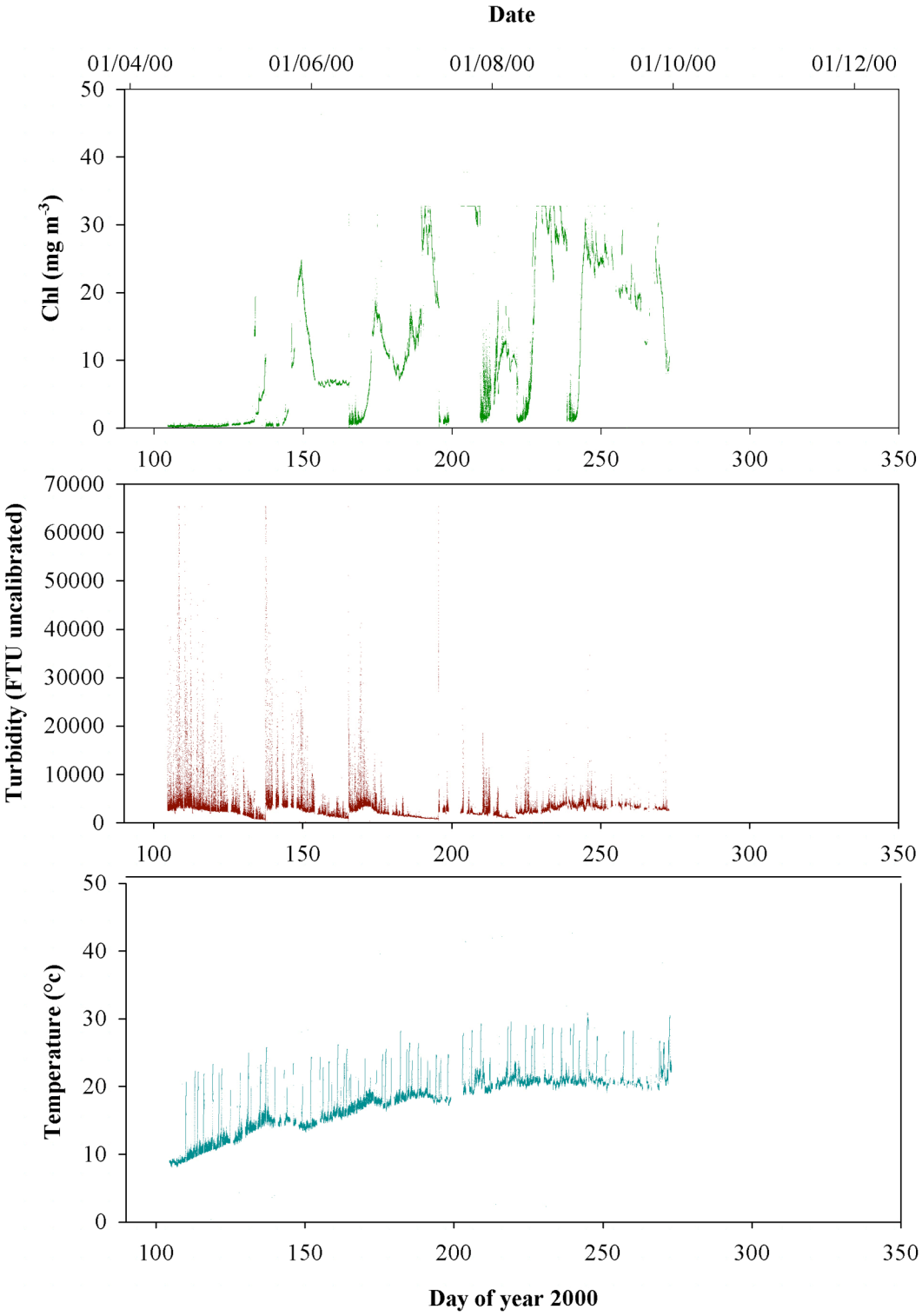


Figure 4.3c Plot of all data for chlorophyll, turbidity and water temperature data from Red Funnel FerryBox system collected in **2001.**

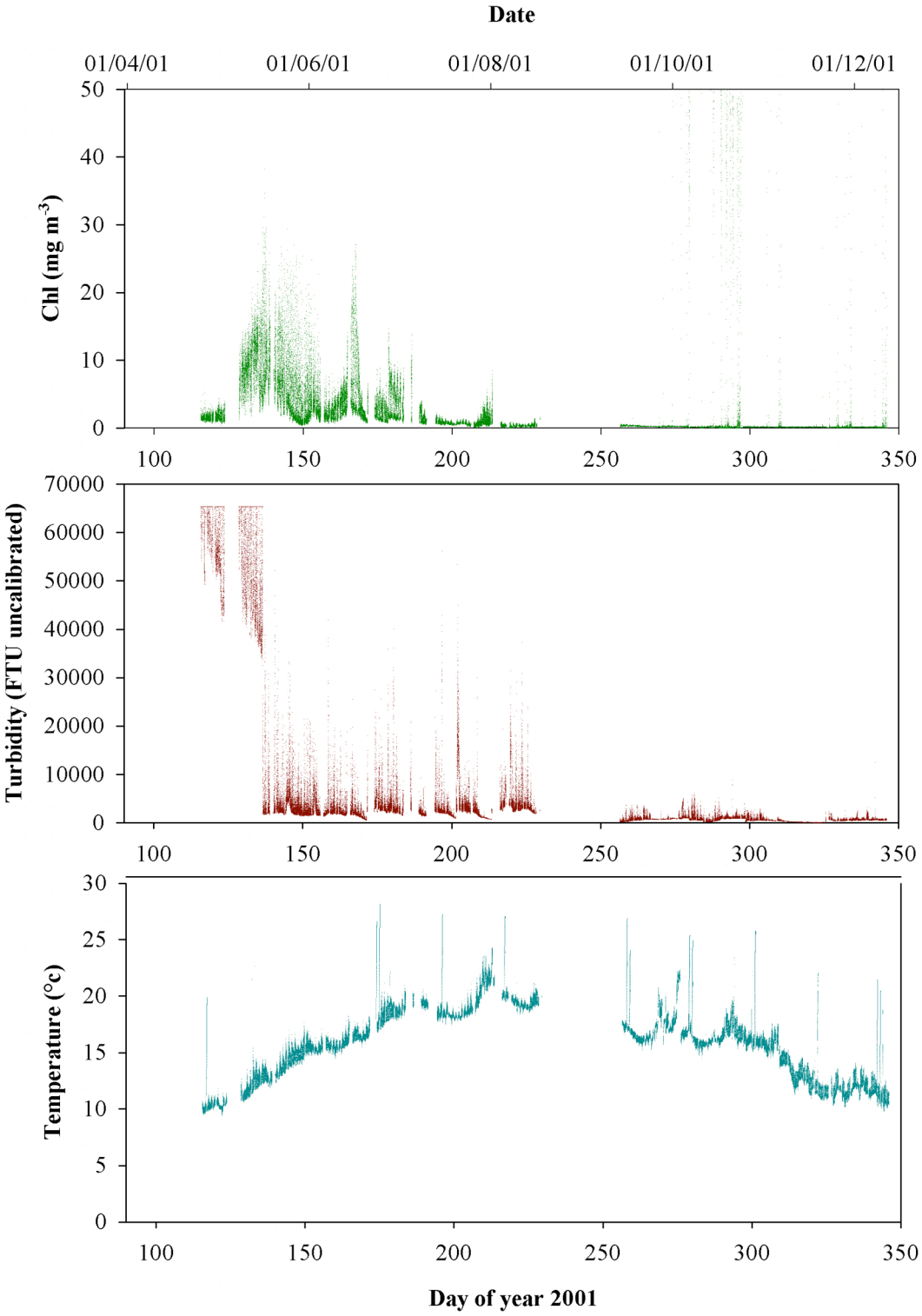


Figure 4.3d Plot of all data for chlorophyll, turbidity and water temperature data from Red Funnel FerryBox system collected in **2002.**

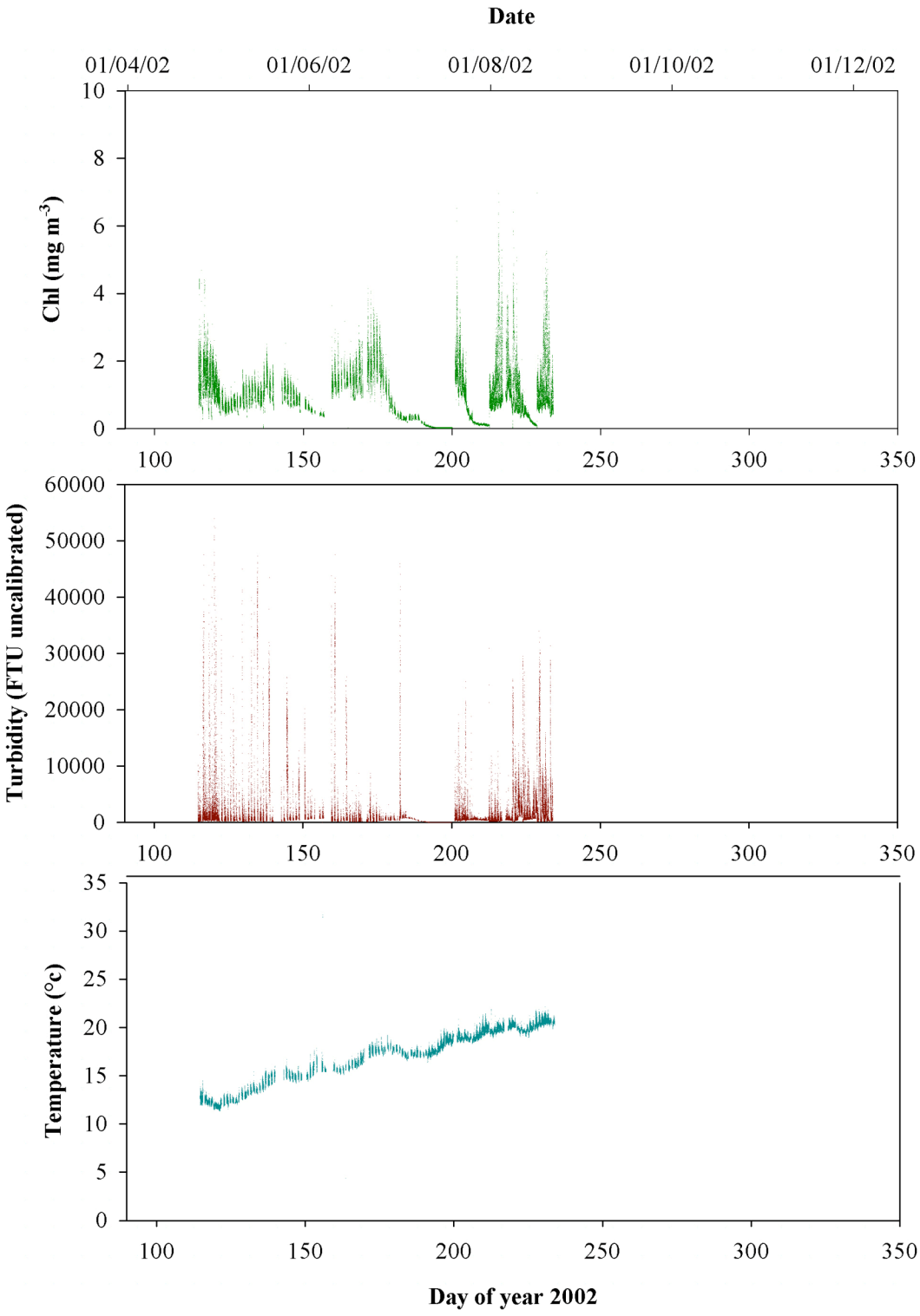


Figure 4.4a Plot of the daily mean concentration of chlorophyll and error bar (= ± 1 standard deviation) measured by the Red Funnel FerryBox system in **1999** the tidal range is also shown.

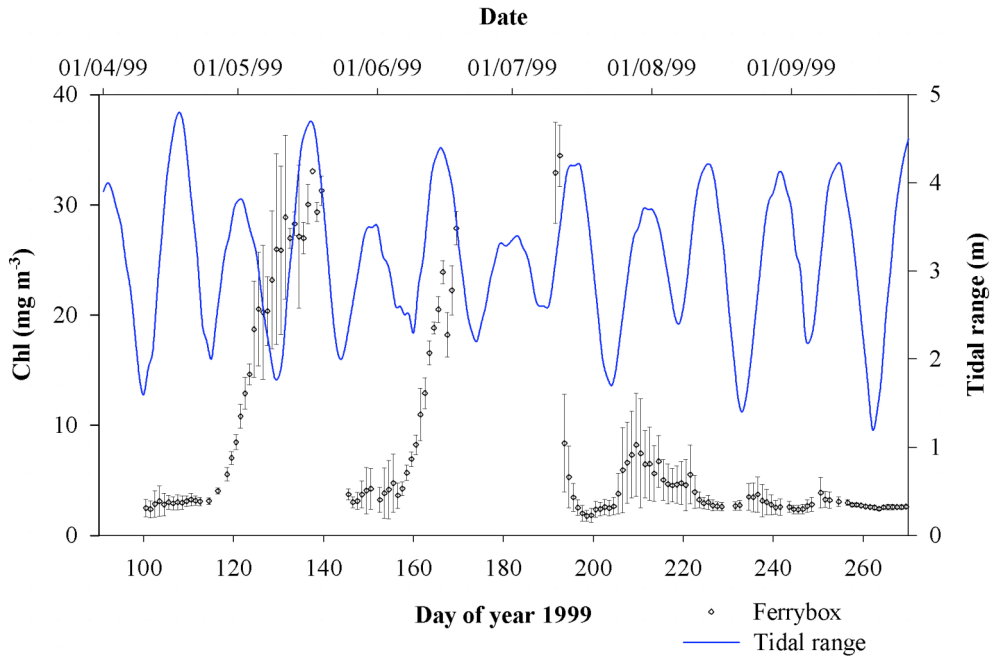


Figure 4.4b Plot of the daily mean concentration of chlorophyll and error bar (= ± 1 standard deviation) measured by the Red Funnel FerryBox system in **2000.** Tidal range and Calshot chlorophylls are also shown.

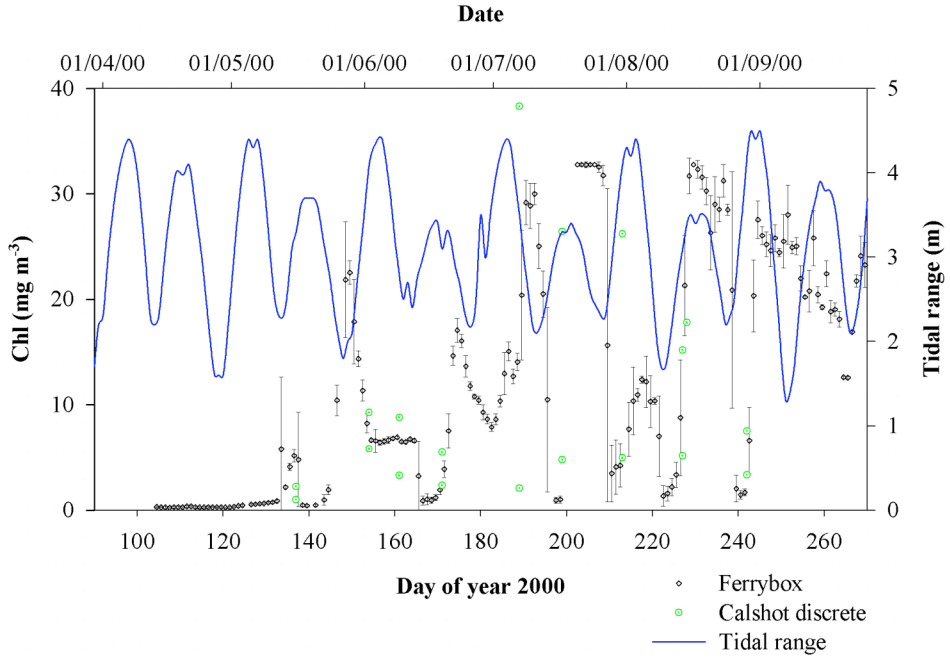


Figure 4.4c Plot of the daily mean concentration of chlorophyll and error bar (= ± 1 standard deviation) measured by the Red Funnel FerryBox system in **2001.** Tidal range and Calshot chlorophylls are also shown.

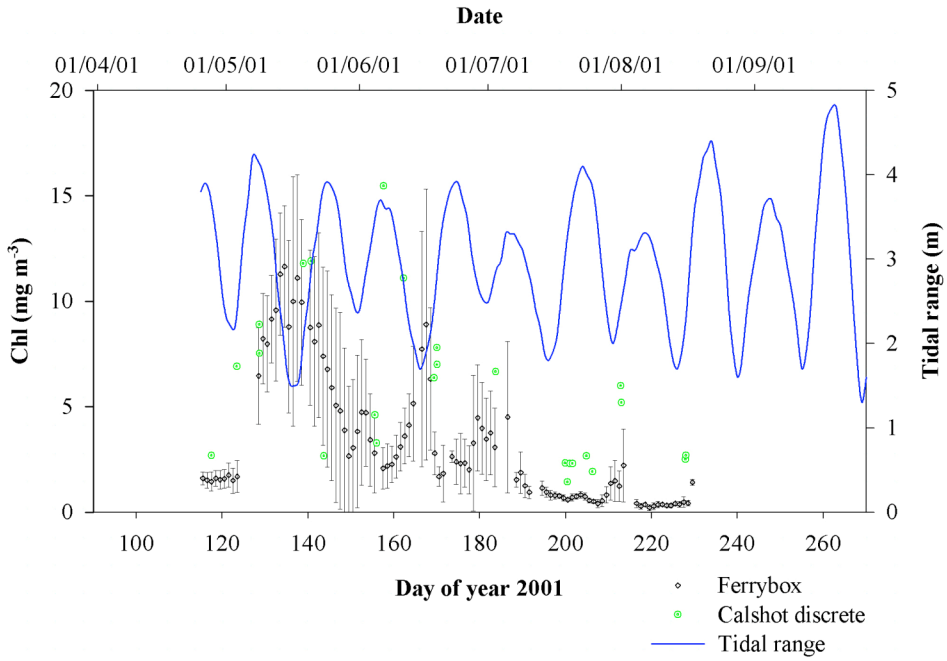


Figure 4.4d Plot of the daily mean concentration of chlorophyll and error bar (= ± 1 standard deviation) measured by the Red Funnel FerryBox system in **2002.** Tidal range and Calshot chlorophylls are also shown.

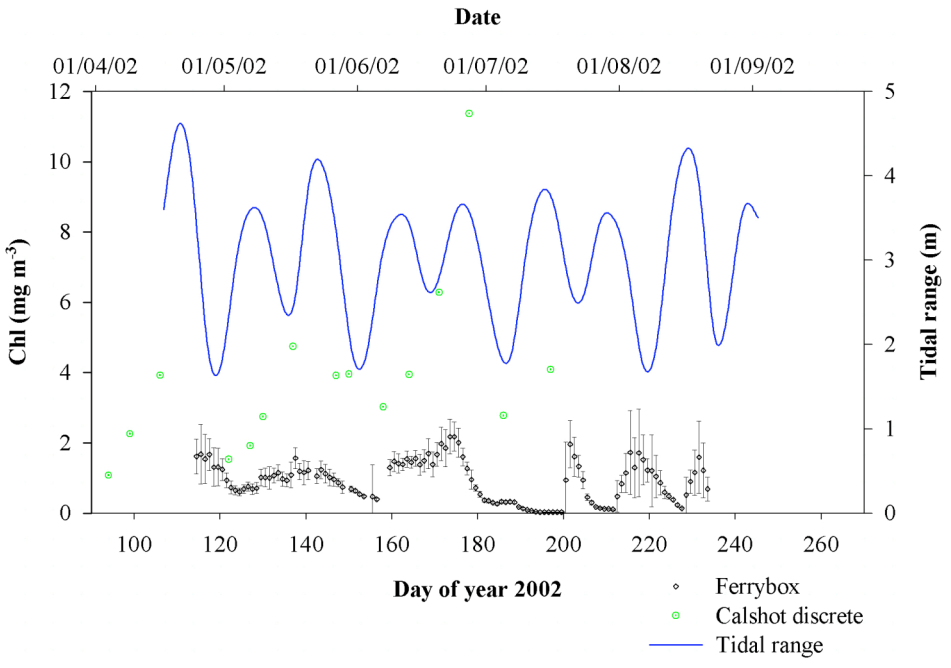


Figure 4.5a Plot of chlorophyll and salinity data measured by the Red Funnel FerryBox system in **1999** extracted from the full data sets at the position of Cowes, Mid Solent and Calshot

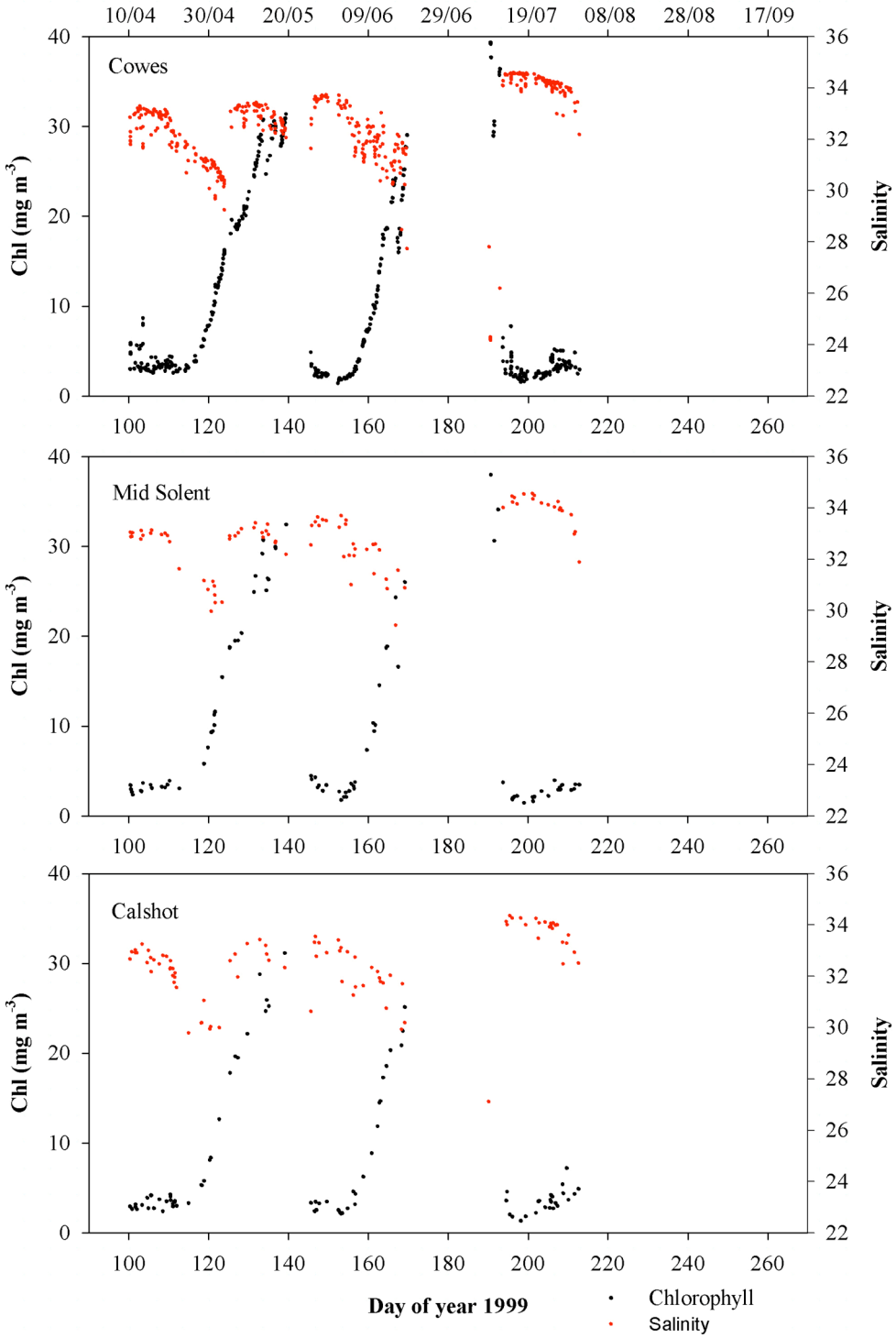


Figure 4.5b Plot of chlorophyll and salinity data measured by the Red Funnel FerryBox system in **1999** extracted from the full data sets at the latitudes of BP/ESSO, NW Netley and the Dock Monitor.

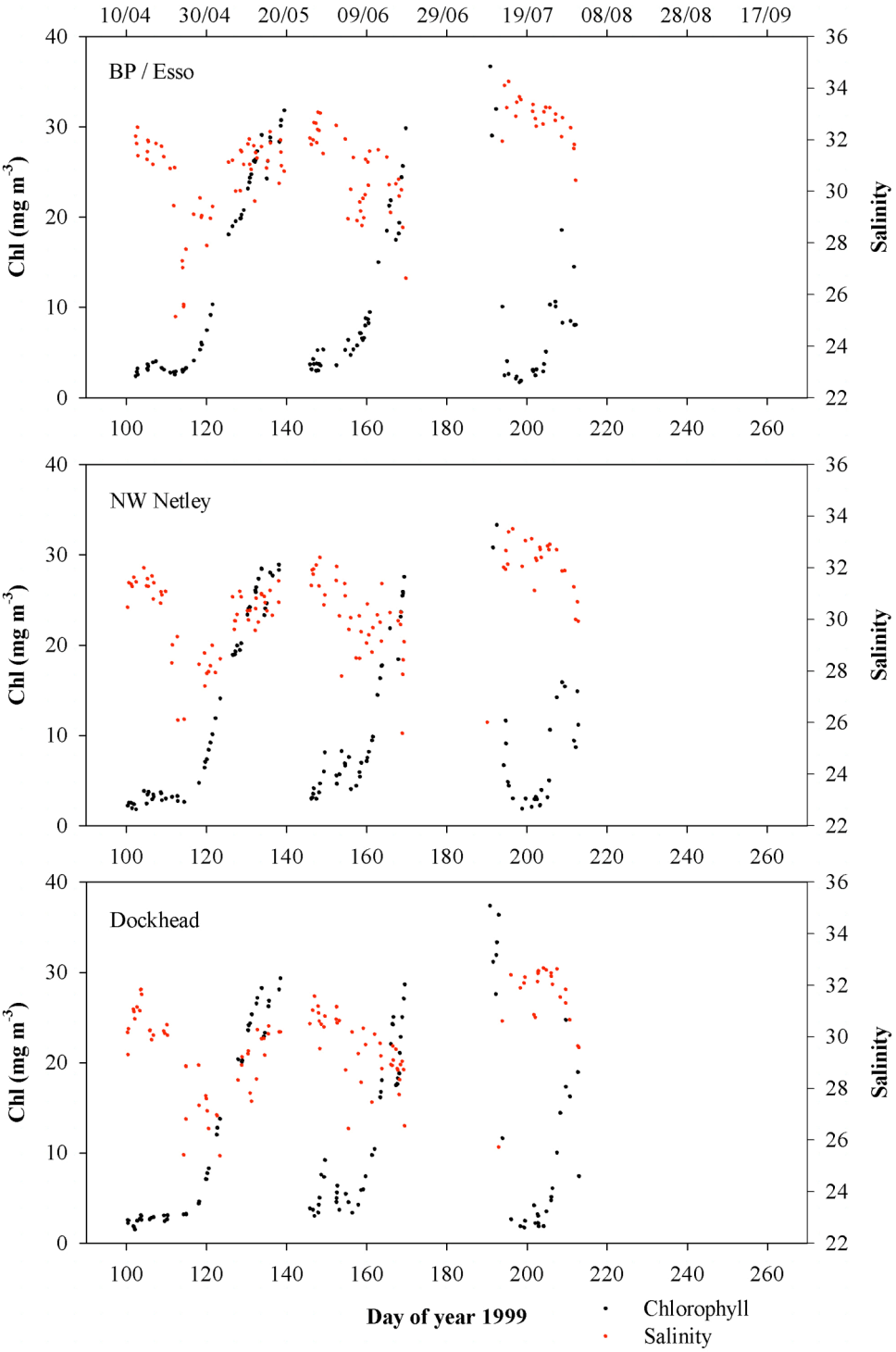


Figure 4.6a Plot of chlorophyll and salinity data measured by the Red Funnel FerryBox system in **2001** extracted from the full data sets at the position of Cowes, Mid Solent and Calshot.

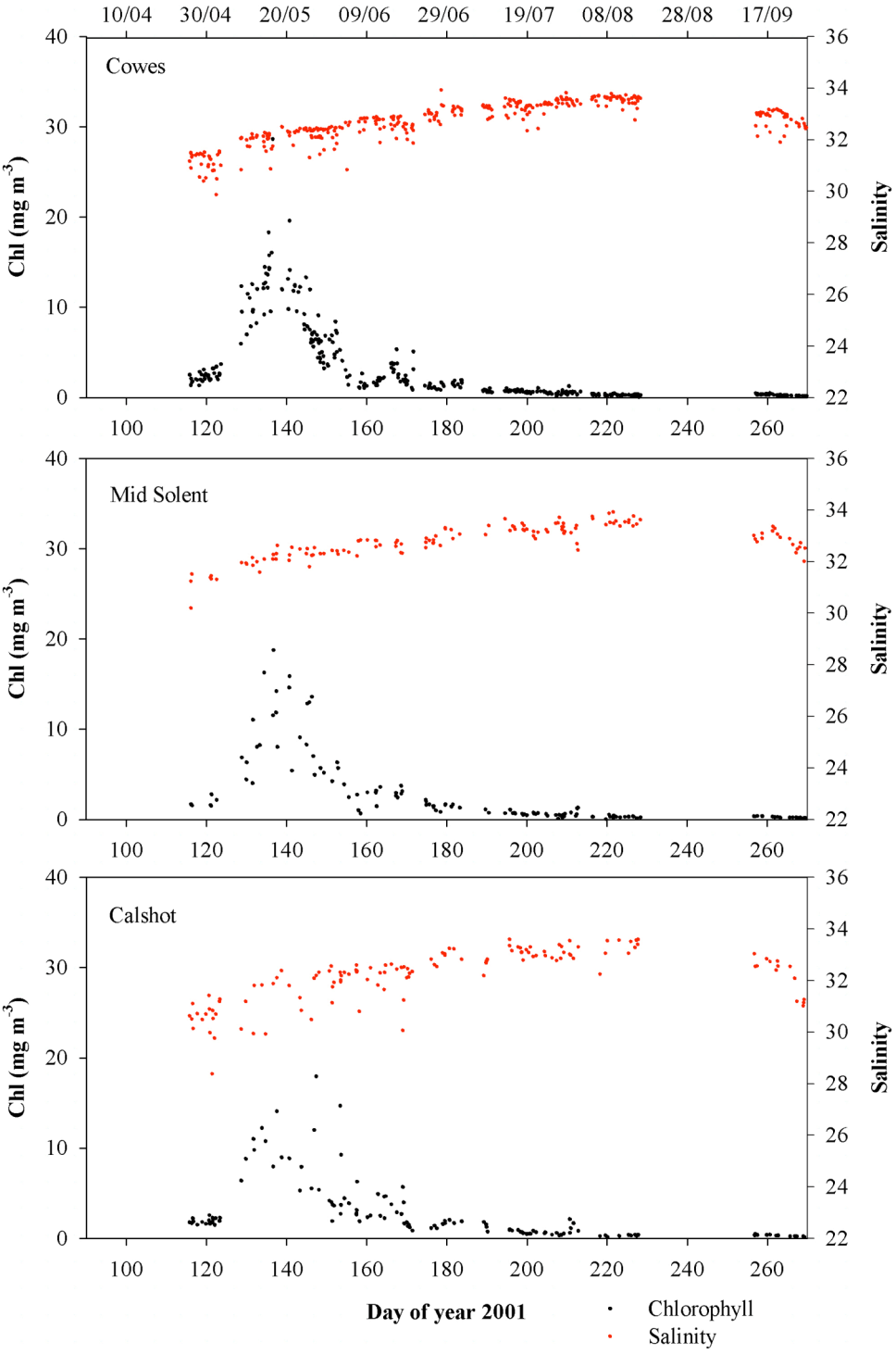


Figure 4.6b Plot of chlorophyll and salinity data measured by the Red Funnel FerryBox system in **2001** extracted from the full data sets at the latitudes of BP/ESSO, NW Netley and the Dock Monitor.

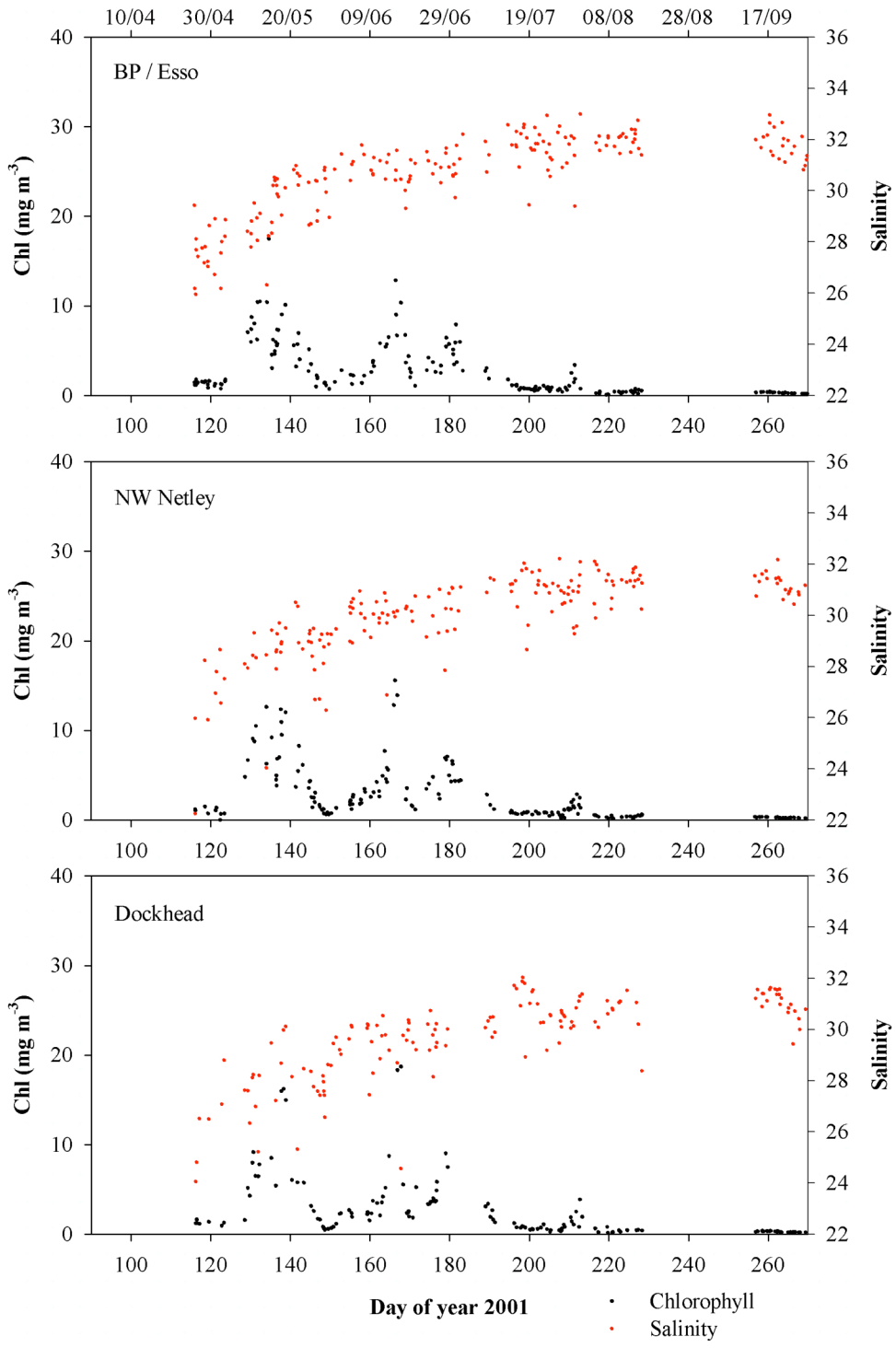


Figure 4.7. Data from the Red Funnel Ferry System plotted as contour map of the variation in measured fluorescence calibrated in units of chlorophyll-a (mg m^{-3}) showing the variation through time x-axis and position in the estuary y-axis (April to July 2001).

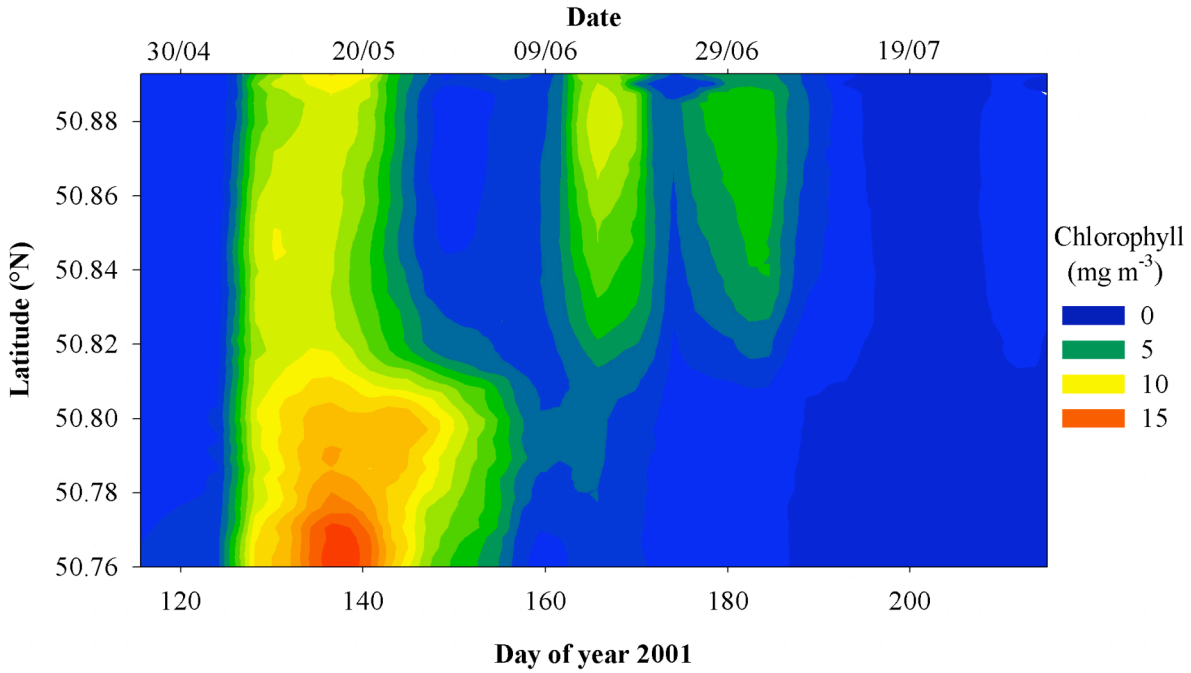


Figure 4.8. Data from the Red Funnel Ferry System plotted as contour map of the variation in measured fluorescence calibrated in units of chlorophyll-a (mg m^{-3}) showing the variation through time x-axis and position in the estuary y-axis on individual days in 2001

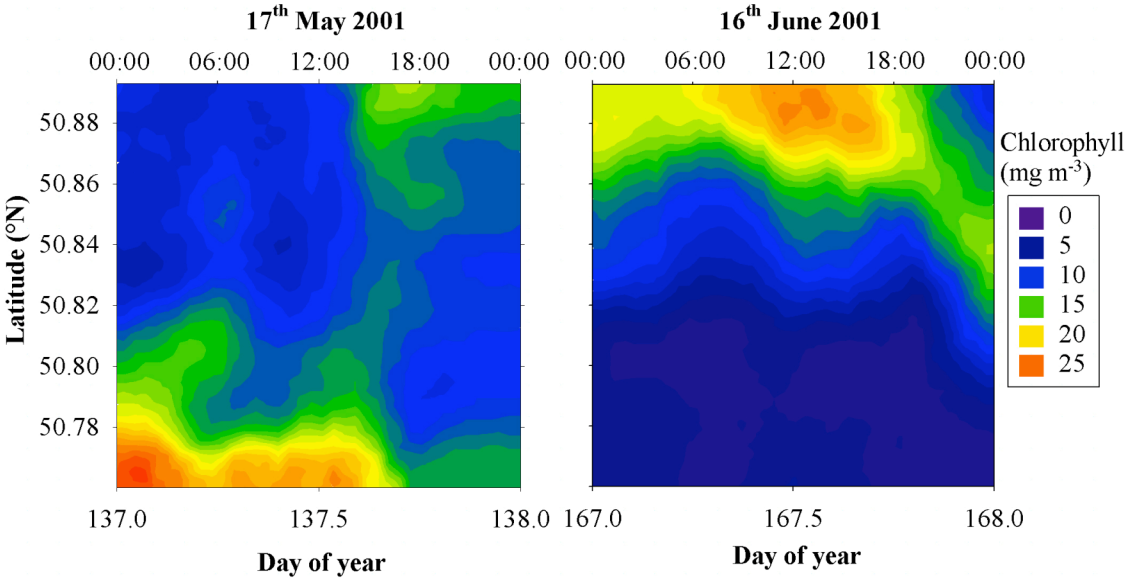


Figure 4.9 Weekly boat survey data from the Solent collected in Spring and Summer 2002. Surface water samples collected off Calshot and Horse Elbow buoys in eastern Solent. Plots of the variation in chlorophyll-a, nitrate, phosphate, silicate and ammonium.

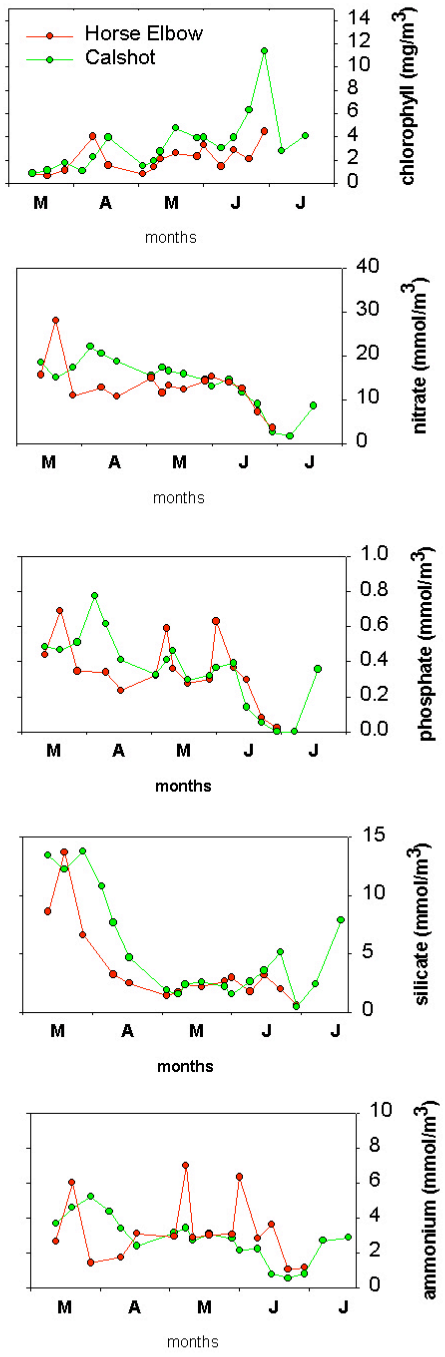


Figure 4.10 Data from measurements of surface water samples collected of Calshot in 2000, 2001, 2002 and 2003. The variation in changes in concentrations of chlorophyll-a are compared to change in concentrations of nitrate, phosphate and silicate. (missing phosphate and silicate data for 2003 from later part of year).

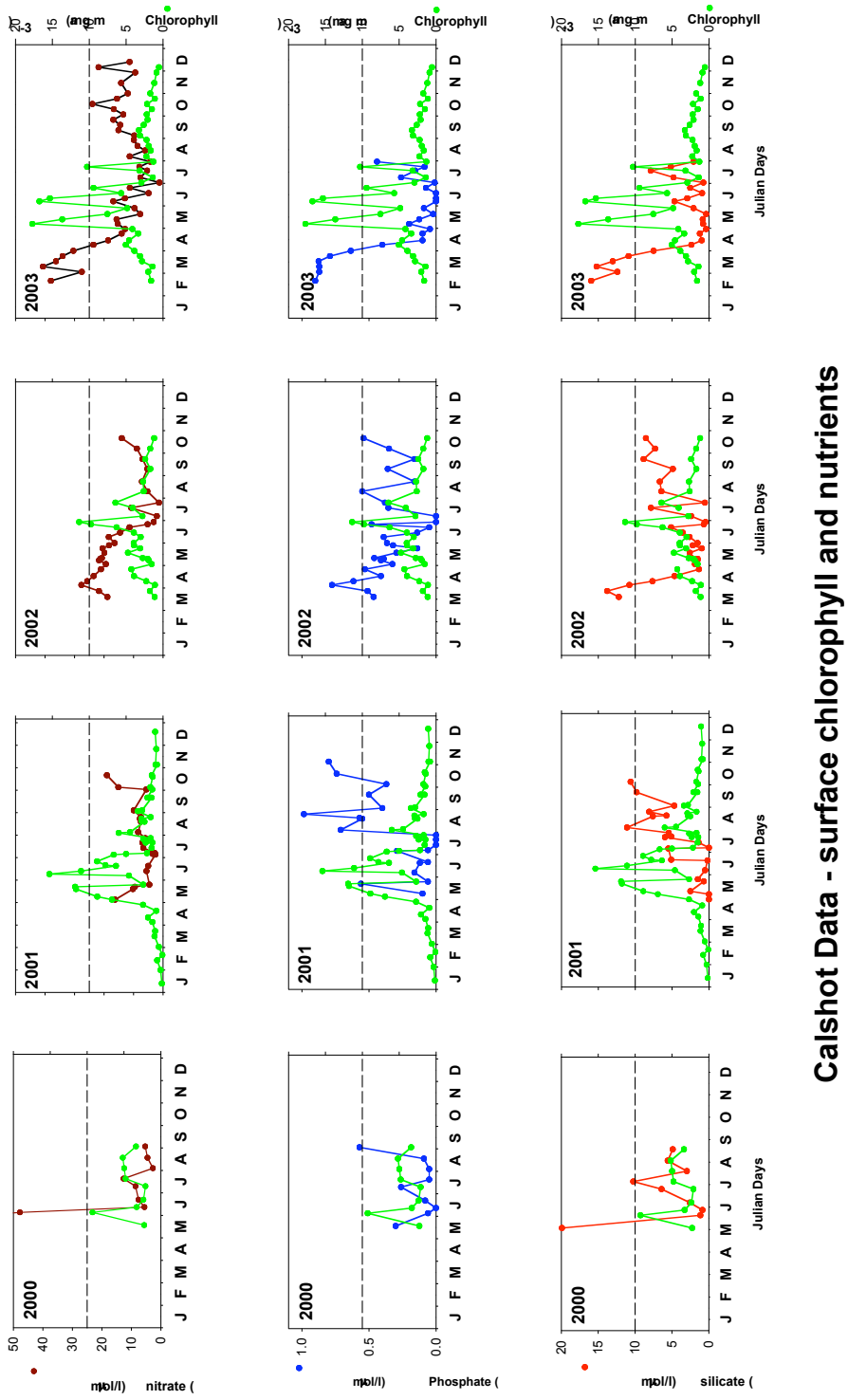


Figure 4.11 Data from measurements of surface water samples collected of NW Netley in 2000, 2001, 2002 and 2003. The variation in changes in concentrations of chlorophyll-a are compared to change in concentrations of nitrate, phosphate and silicate. (missing phosphate and silicate data for 2003 from later part of year).

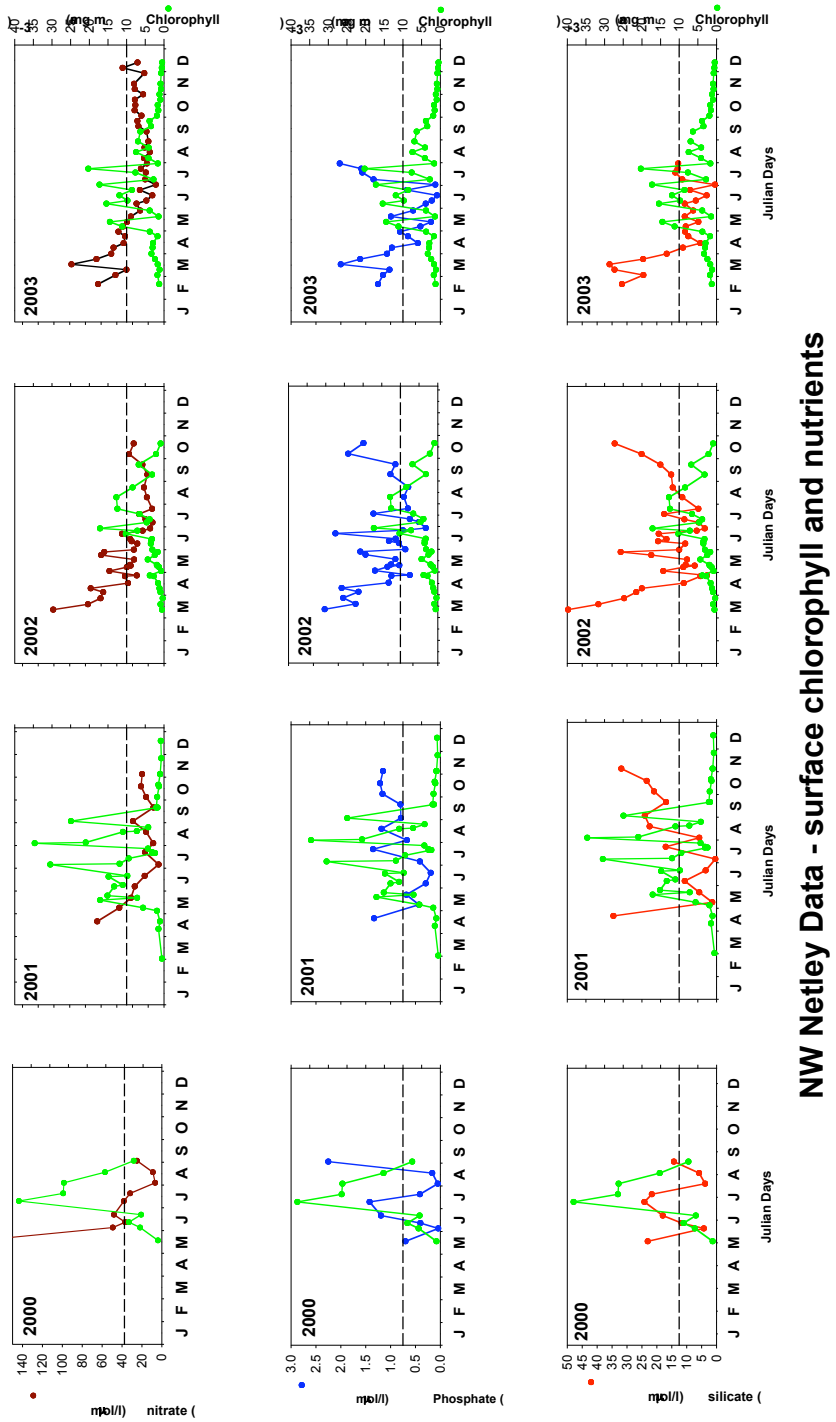


Figure 4.12 Data from measurements of surface water samples collected at the Eling buoy in the upper Test estuary in 2001 and 2002. The variation in changes in concentrations of chlorophyll-a are compared to changes in concentrations of nitrate, phosphate and silicate.

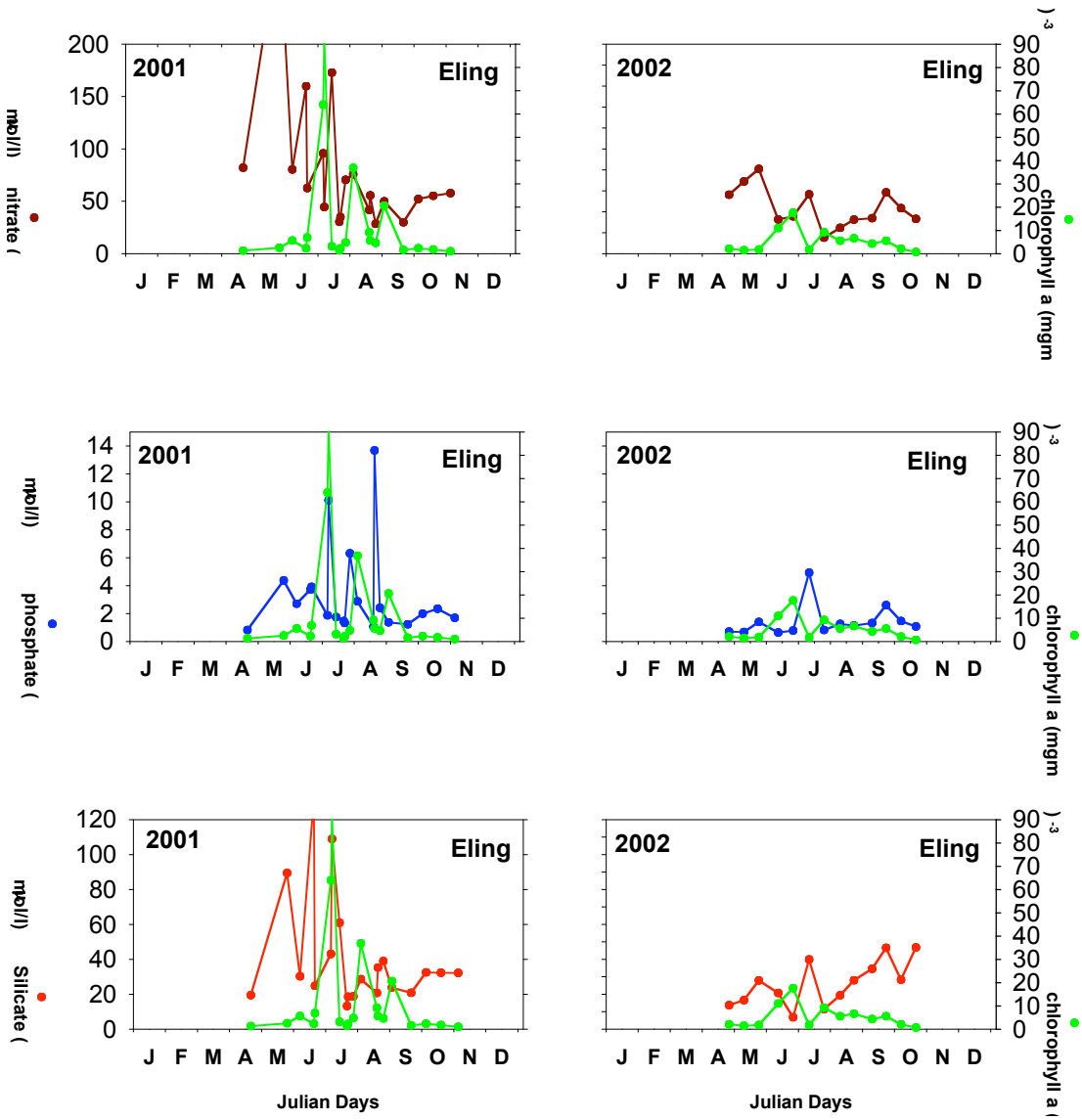
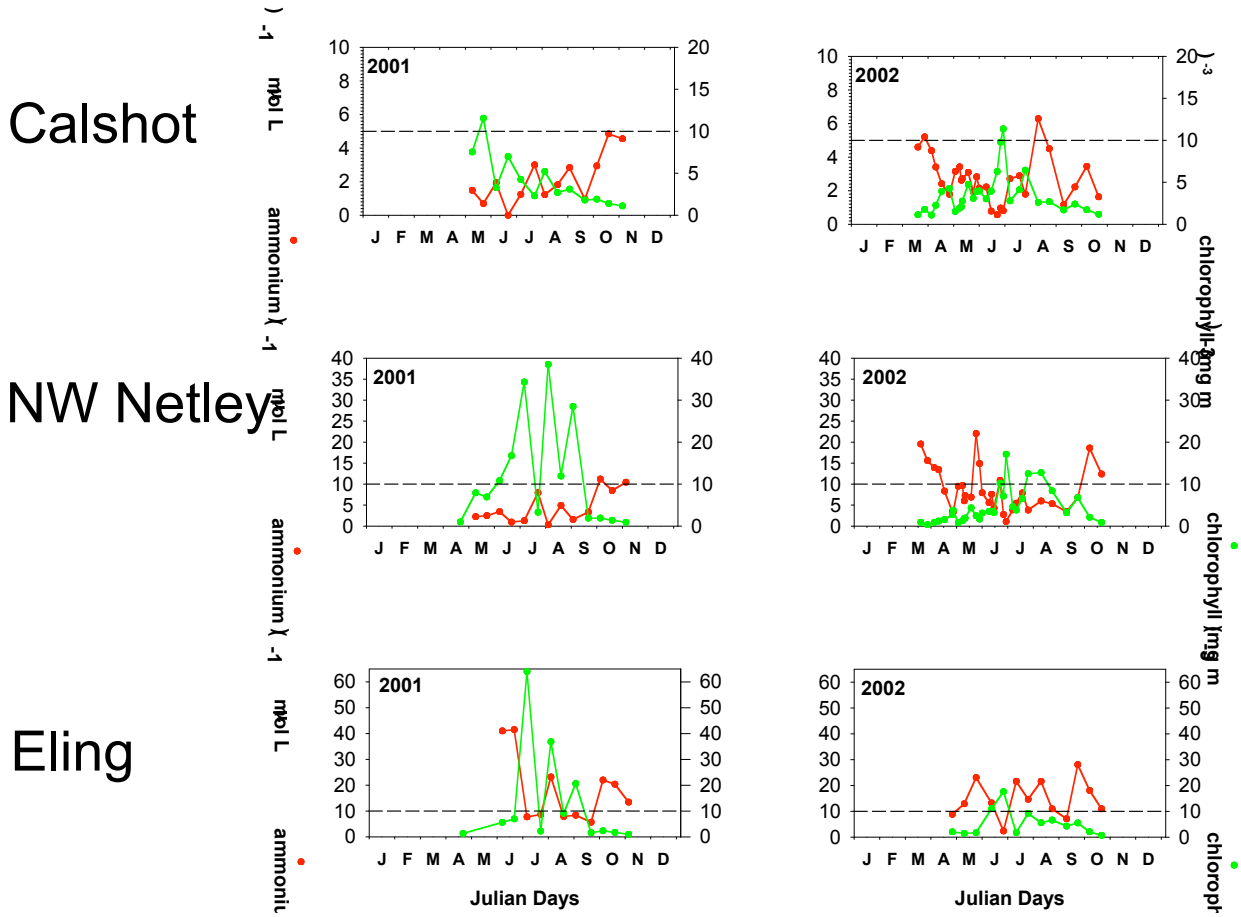


Figure 4.13 Plots comparing concentrations of chlorophyll-a and ammonium in surface water samples collected at Calshot, NW Netley and Eling in 2001 and 2002.



CHAPTER 5

OCCURRENCE AND NATURE OF BLOOM EVENTS RELATIVE TO OTHER FACTORS

5.1 Introduction

An increase in phytoplankton biomass, marked by an increase in chlorophyll concentration above 10 mg m^{-3}, is often referred to as a bloom. A combination of meteorological, physical and biological factors control bloom development in coastal waters principally through their affect on nutrients mixing and light availability. As these factors are greatly influenced by the weather (Cole & Cloern, 1984) high inter-annual variation is seen in the timing of the initiation of blooms, their duration and magnitude (Smayda, 1998) in coastal temperate regions.

Blooms tend not to be discrete events but a series of fluctuations with variations in biomass and species composition (Cloern, 1996). Increases in biomass result from increased net production or physical aggregation; decreases in biomass result from reduced production, sedimentation, dispersion and grazing (Ragueseau et al., 1996).

The main spring bloom throughout the Solent and Southampton Water tends to occur in May and is followed by a series of blooms restricted by nutrient availability to the mid and upper estuarine waters throughout the summer months. Here we give a brief analysis of data presented in earlier chapters with reference to phytoplankton species that have been shown to dominate bloom events in Southampton Water and the Solent (see Table 5.1).

5.2 The Spring bloom

In the winter months, nutrient levels increase throughout the estuary however phytoplankton biomass remains low, due to limiting surface light availability and tidal and wind mixing. In the spring, incident light increases and water column turbidity decreases allowing a rapid increase in phytoplankton biomass. This short period of growth known as the Spring bloom tends to be dominated by diatoms, which have a low threshold for light and are not affected by physical mixing.

In macrotidal estuaries like Southampton Water, tidal processes dominate water column mixing with alternate periods of increased and decreased relative turbulence over spring and neap tides. Diatom blooms in Spring have been shown to develop in Southampton Water over both spring tides, as seen clearly in May 1999 (Figure 5.1a), or neap tides (May 2001, Figure 5.1b). This is in contrast to other tidal regions where for example in

San Francisco Bay blooms tend to develop during periods of weak tidal energy and dissipate after the spring tide (Cloern, 1996). In the Bay of Brest the spring diatom bloom occurs on the neap tide where high turbidity, decreased vertical mixing and inputs of freshwater nutrients are important (Ragueseau, 1996).

From an analysis of the Spring bloom data from Calshot over several years Iriarte and Purdie (2004) have shown the onset of the spring bloom in the estuary to be strongly influenced by water column irradiance, which is a function of both surface irradiance and water column turbidity. This first peak in phytoplankton biomass occurs once the water column attenuation coefficient decreases below a critical value of 0.5 m^{-1} and the whole 10 m water column is within the euphotic zone. In the Solent (e.g. at Calshot) the main chlorophyll peak is in Spring with lower chlorophyll levels in summer due to nutrient depletion (Figure 4.10). Typically in Southampton Water the spring bloom is initiated offshore and tends to develop in the high salinity waters towards the Isle of Wight. A Spring bloom usually occurs in May in the mid estuary (NW Netley, Fig 4.11) but is often delayed until June/July in the upper estuary (Eling, Fig 4.12).

The temporal and spatial resolution available from FerryBox chlorophyll fluorescence data means it can be used to estimate the period and intensity of phytoplankton bloom development allowing inter-annual comparisons. Some important features emerge from year to year data comparisons over the 4 years that the Red Falcon FerryBox was in operation. This data together with frequent measurements made on discrete water samples collected from several stations in the estuary (Eling, NW Netley and Calshot) can provide a good overview of the phytoplankton bloom events through out Southampton Water and the Solent.

In Spring, chlorophyll levels at Calshot rarely exceed 15 mg m^{-3} and bloom duration is less than 1 week. In 1999 a large diatom spring bloom dominated by the chain forming *Guinardia delicatula* (formally *Rhizosolenia delicatula*) developed over the spring tidal period in May (peak chlorophyll > 20 mg m^{-3}; Figure 5.1a).

In May 2001 (Figure 4.10 & 5.1b) chlorophyll values were sustained for a period longer than a week probably related to increased nutrient fluxes following the very wet winter and sustained high river flow rates through the Spring. Peaks in chlorophyll in 2001 were dominated by diatoms and *Phaeocystis* and widespread blooms of *Phaeocystis* were noted in the Solent and mid Channel during this period (see Fig 5.2a organic slicks from *Phaeocystis* blooms). Peak chlorophyll values were also high at NW Netley (Fig 4.11) and Eling (Fig 4.12) in 2001 in comparison to other recent years. Figure 5.2b shows the patchy nature of the *Phaeocystis* sp mapped by the FerryBox chlorophyll data in outer parts of Southampton Water and the Solent. This bloom persisted on the spring

tide and followed the main spring diatom dominated bloom (which occurred on the neap tide) as seen in Figure 4.4c.

In 2002 there was no clear early spring bloom compared with 2001 (Figure 5.3) and the chlorophyll peak was not reached at Calshot and NE Netley until 27 June (Table 5.1). This has been shown to be due to unusually high turbidity throughout the water column in May due to high rain fall and increased wind speeds during this period (Iriarte and Purdie, 2004)

In 2003 an increased sampling frequency was adopted (weekly samples collected throughout most of the year at Calshot and NW Netley) and several peaks in chlorophyll were measured between May and July. These were mostly doinated by diatoms with some *Phaeocystis* in May.

5.3 Summer blooms

The spring bloom is followed by a sequence of summer blooms in the main estuary. The estuary is known to be hypernutrified with high nutrient levels maintained by inputs from the Rivers Itchen and Test (Nedwell et al., 2002) however in the summer months nutrient levels tend to decrease in the higher salinity waters offshore and may limit bloom development (Hydes et al 2001, Xiong, 2000). Summer blooms with higher chlorophyll values that may be sustained over longer periods are seen in the mid and upper estuary (e.g. at NW Netley and Eling) in most years caused by the increased nutrient concentrations at lower salinity values in the estuary (SONUS data Hydes et al., 2001). Neap tides are associated with higher water column stability and summer phytoplankton populations dominated by dinoflagellates and in some years the photosynthetic ciliate *Mesodinium rubrum* increases during neap tides (e.g. day 167 2001 as seen in Figure 4.4c). Dinoflagellates have slower growth rates than diatoms but due to their motility can avoid surface waters on the ebb tide to reduce wash out from the estuary (Lauria etc., 1999)

In July 1999 chlorophyll-fluorescence from the Ferry box was high only in the afternoon and distribution appears patchy (Figure 5.4). This may be due to motile organisms such as *Mesodinium rubrum* which can vary its position in the water column during the day in response to changing light conditions and to minimise dispersion (Crawford & Purdie, 1992; Lauria et al, 1999).

Figure 5.5a and b shows the results of a boat survey carried out in July 2000 by Southampton Institute (Paterson, pers com.). Samples taken from within a bloom of the photosynthetic ciliate *Mesodinium rubrum* (patches of growth were visible by the colour of the water) showed high chlorophyll levels in excess of 200 mg m^{-3}. Figure 5.5c shows FerryBox fluorescence on the day of the survey and suggests that the sensors

were fouled and out of range (also seen in Figure 4.4b). However 2 days later, after cleaning, the patchy nature and high fluorescence values of the bloom can be seen in Figure 5.5d. In 2001 high chlorophyll levels, in the order of 90 mg m^{-3}were detected at Eling in July due to *Mesodinium* and some small diatoms (Table 5.1).

TABLE CHAPTER 5

Table 5.1 Peak chlorophyll values at Calshot, NW Netley, and Eling plus dominant species identified.

Diatoms: *G. del = Guinardia delicatula; Thal = Thalassiosira sp ; Lepto = Leptocylindricus sp; Bid = Biddulphia sp.; Ast glac= Asterionella glacialis:* **Flagellates**: *Phaeo = Phaeocystis globosa*; **Dinoflagellates:** *Proro= Prorocentrum micans:* **Ciliates:** *Meso = Mesodinium rubrum;*

--- indicates cell counts not made

Year	Calshot			NW Netley			Eling		
	Peak chl conc >10mg m^{-3}	Date	Dominant species	Peak chl conc >10 mg m^{-3}	Date	Dominant species	Peak chl conc >10 mg m^{-3}	Date	Dominant species
2000	9.3	2 June	*G. del*	38.2 26.4 26.2 15.1	7 July 17 July 31 July 14 Aug	*G. del.+ Phaeo* *Thal+Meso+Scrip* *Thal+Meso* *Thal+Proro*		Not sampled	--
2001	11.9 15.4 11.1	21 May 7 June 11 June	*G. del + Phaeo* --- ---	17.0 15.1 14.8 30.5 34.6 24.9	18 May 24 May 18 June 4 July 1 Aug 30 Aug	--- --- --- --- --- ---	64.0 90.6 36.8 20.6	4 July 5 July 1 Aug 30 Aug	*Ast glac+ Meso* --- *Bid + Meso* ---
2002	11.4	27 June	*G. de +Lepto.*	10.2 17.1 12.7	20 June 27 June 7 July	--- --- ---	11.0 17.6	10 June 24 June	--- ---
2003	17.7 13.7 16.7 15.3 10.3	6 May 12 May 5 June 9 June 21 July	*G. de* --- *Thal + G. del* --- ---	14.5 15.4 17.2 20.3	12 May 5 June 30 June 21 July	*G. del* --- --- ---		Not Sampled	--

FIGURES CHAPTER 5

Figure 5.1a Full data record for chlorophyll-fluorescence measured at the Dock Head monitor from the spring bloom in 1999 compared to the predicted daily tidal range.

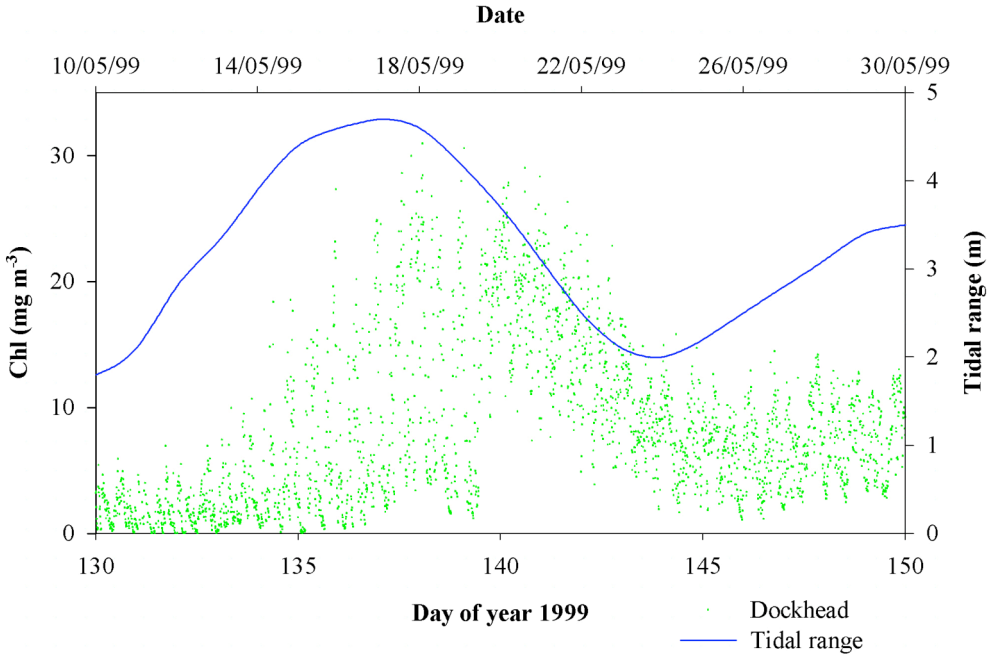


Figure 5.1b Full (1 minute averaged) data record for chlorophyll-fluorescence measured by the Red Funnel Ferry Box system from the spring bloom in 2001 compared to the predicted daily tidal range.

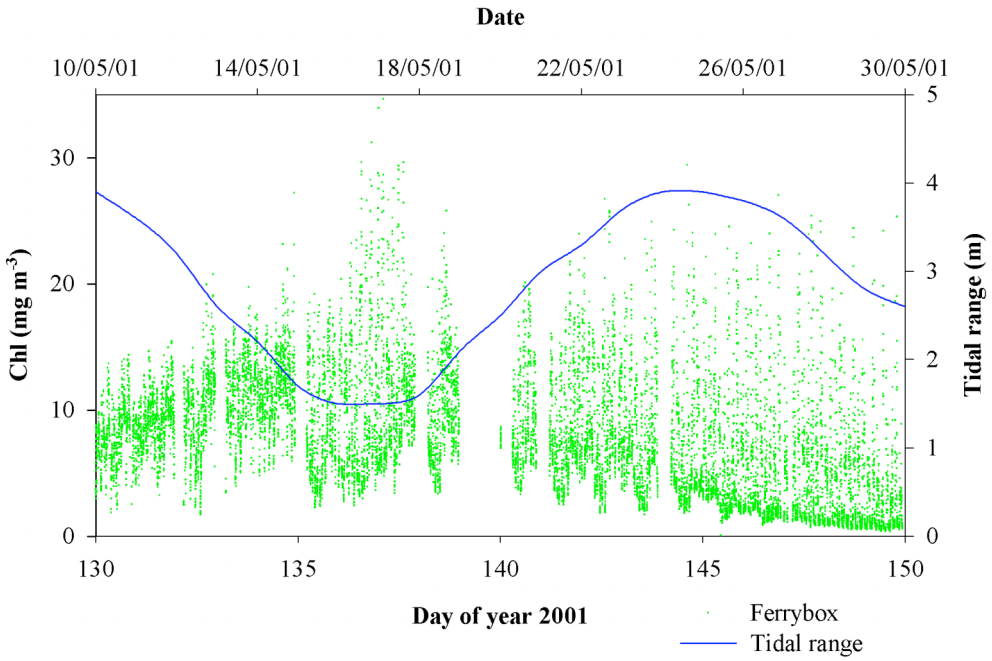


Figure 5.2a: Patchy nature of the *Phaeocystis sp*. Bloom on 24th May 2001

Figure 5.2b Contour plot of variation in chlorophyll-fluorescence drawn from Ferry Box data collected on 25 May 2001. The positions for the data points are shown by the white line.

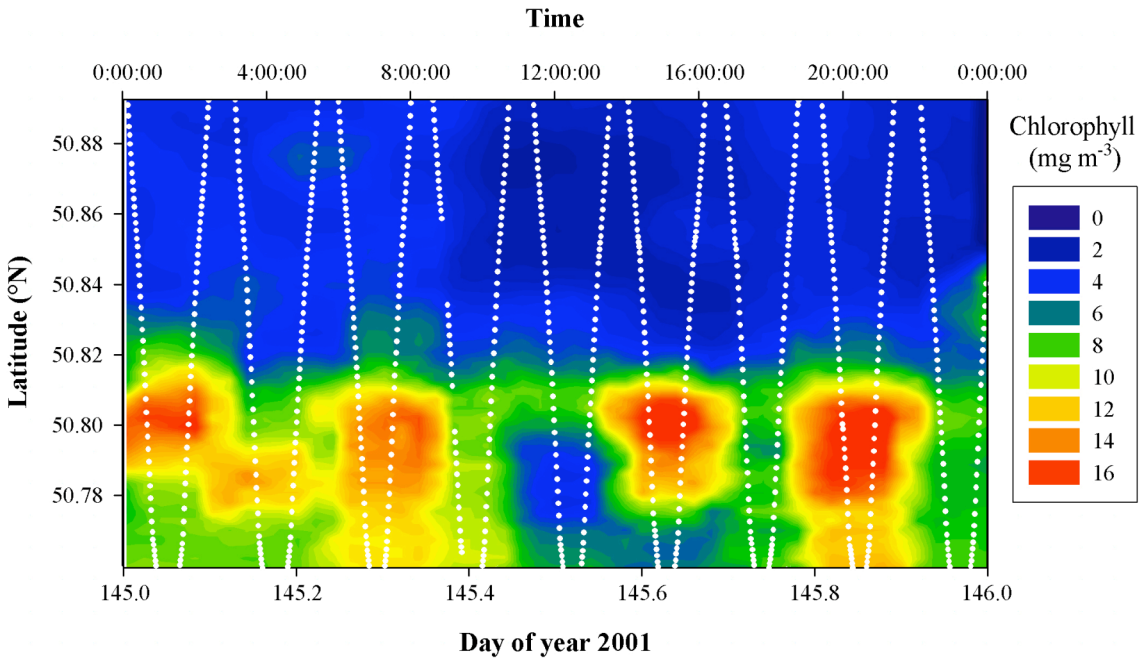


Figure 5.3 Plot comparing the daily mean chlorophyll-fluorescence measured by the FerryBox system between April and August 2001 compared to the same period in 2002.

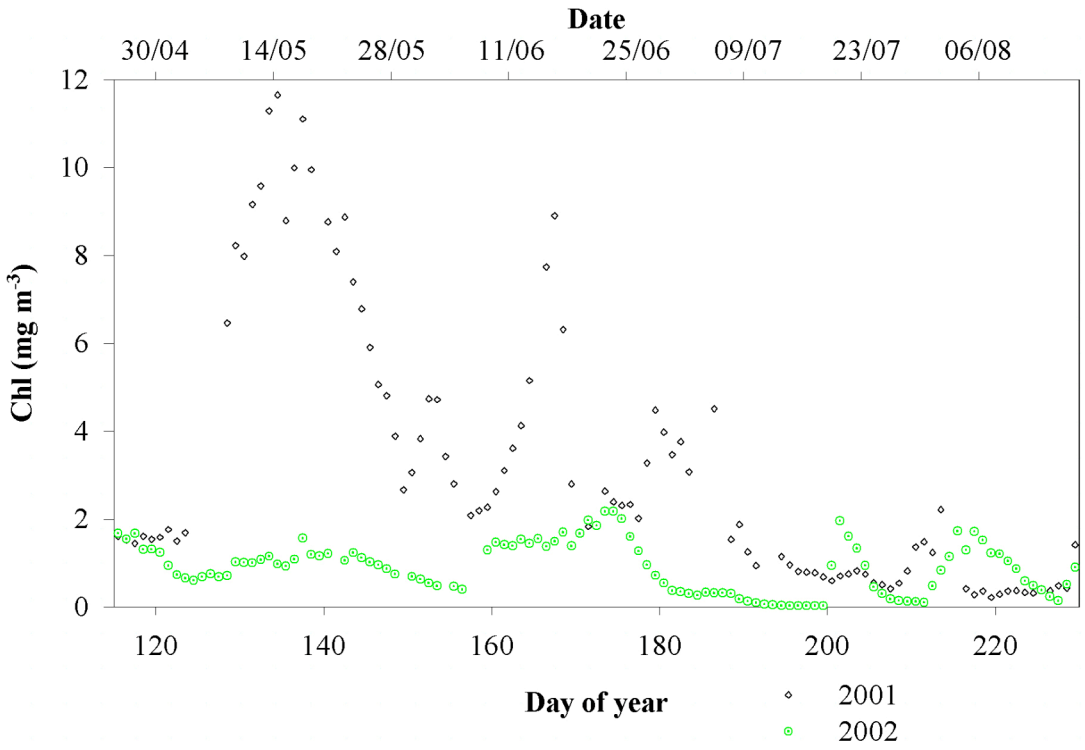


Figure 5.4 FerryBox fluorescence distribution over a single day 26th July (day 207) 1999

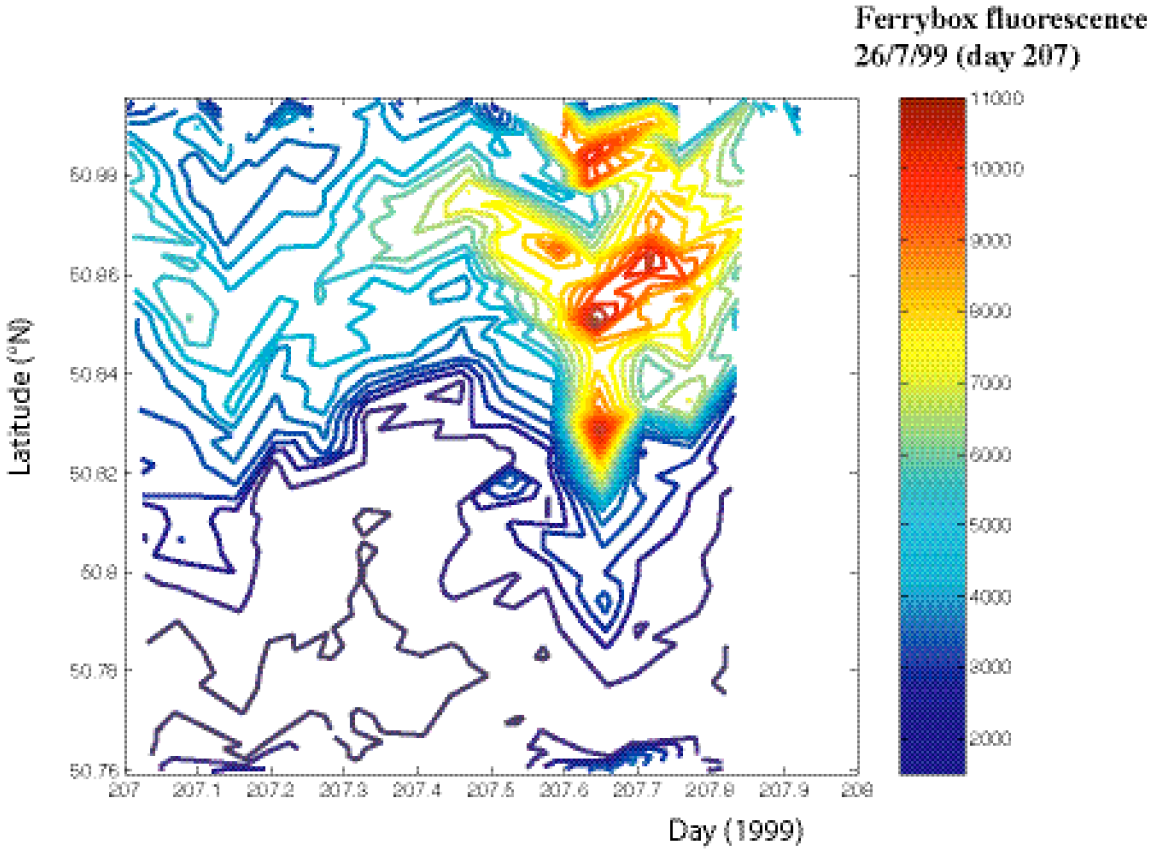
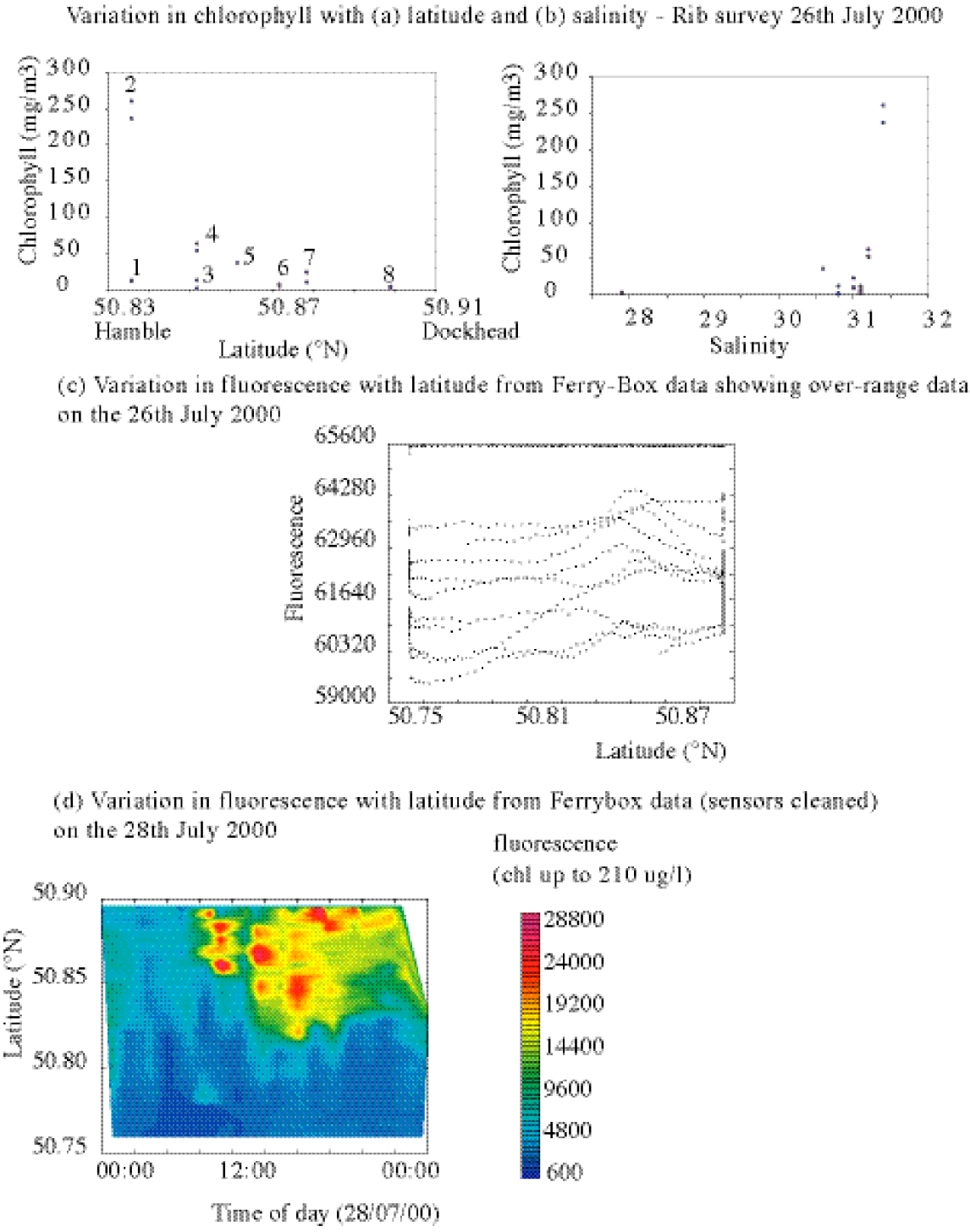


Figure 5.5 Results from a boat survey of Southampton Water in July 2000 (Paterson, pers com.) during a visible *Mesodinium rubrum* bloom.



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APPENDIX

A.1 CHANGES IN PROCEDURES

1999:

From day 100 to 213 90% data return. The fluorometer range had been set too low and was altered on day 126, after this time all fluorescence readings have to be multiplied by 3 to apply the equation supplied with the fluorometer. The sensors were removed from day 140 to 144 (so the peak and crash of the spring bloom was missed). There is no GPS data from day 231, as the GPS sensor had become water logged. The system was only cleaned once, on day 193. From day 290 excessive fouling is seen (increase in fluorescence) and data are unusable.

2000:

92% data return. No GPS initially until day 134, however data should not be used before day 145 (date of the first cleaning), as values are very low. The Seapoint fluorometer is a narrow flow through tube and proved difficult to clean frequently and reliably as the measurement windows were not visible. The fluorometer was repositioned vertically on day 195 to reduce possible settling on the window. From day 104 to 273 there were feeder valve problems (noted at the end when the equipment was removed for servicing). Periods of no water flow (when the ferry is out of action every third night) were noted to be a potential problem. A *Mesodinium rubrum* bloom resulted in very high fluorescence readings (chlorophyll samples in excess of 200mg m^{-3} compared with highest values of 30mg m^{-3} in 1999 and 2001). The fluorescence to chlorophyll calibration used presently is probably not correct as the high chlorophyll values have not been included (due to the different fluor:chl ratio). During a rib survey of Southampton Water on the 26th July extracted chlorophyll readings ranged from 7mg m^{-3} close to Hamble in visably green surface water to chlorophyll of 260mg m^{-3} at the same latitude but further offshore in surface waters with a deep red colouration. The range on the FerryBox fluorometer was briefly reset between day 214 and 221.

2001:

Change to using the CI Aquatracka, as it is easier to clean and maintain. All sensors were repositioned horizontally and a fresh water flow was introduced to clean the system intermittently. The fluorometer and conductivity cell were calibrated ashore before the system was set up onboard and *in situ* samples were taken during the frequent cleaning visits. The sensors were also checked on a calibration crossing when more frequent samples could be taken and comparisons were made with boat data on day 123 and 130. The system stopped logging on day 229 and there was a leak at the CTD to day 256.

2002:

83% data return. There was a delay at the start while the fluorometer was being fixed. The fluorescence data are intermittent up until day 194 (a possible fault at the lead). From day 194 to day 200 the fluorescence measurements did not vary, possibly due to a block in the system. From day 200 the values were no longer intermittent. At this time the sensor leads were disconnected and reconnected onboard. The main problem in 2002 was with the GPS system on the bridge, as it was not working until day 206. The real time transmission of data has not been used since day 171 due to unexpected high costs, not encountered on previous years. This has disadvantages, as any problems cannot be immediately detected.

APPENDIX

A.2 DATA QUALITY

The sensors are all sensitive to biofouling (the build up of plankton growth, jellies and calcium deposits). The cleaning frequency is shown in Table 1, these dates are associated with shifts in the data whenever biofouling was excessive. The sensors had to be cleaned more thoroughly in 2002 using hot water and detergent, due to excessive biofouling (including calcium deposits and small fish).

Appendix Table 1: Cleaning frequency for engine room sensors

Year	Date (year day number) cleaned
1999	137, 193
2000	137, 165, 195, 209, 214 (change in range), 221 (reset range), 238
2001	122, 129, 143, 145, 150, 158, 164, 171, 178, 185, 192, 201, 206
2002	136, 157, 166, 171, 200, 210, 220, 228, 235

The engine cooling water has sufficient pressure to pass through the cylindrical casings but positioning of the sensors has been altered to improve flow as detailed in Table 2.

Appendix Table 2: Positioning of sensors in the engine room

Sensor casing	Position	Date
UMI	Vertical	1999, 2000
Seapoint fluorometer	Horizontal	1999
Seapoint fluorometer	Vertical	2000
Aquatracka fluorometer	Horizontal	2001, 2002
UMI	Horizontal	2001, 2002

In 2001 extra tubing was included to provide a fresh water flow (which was initiated every few days by the engineers onboard to aid in cleaning the sensors). This was not used in 2002. The short periods of time that the sensors were flushed for were insufficient to clean the sensors so flushing was not reintroduced in 2002.

APPENDIX

A.3 SUMMARY OF DATA COLLECTED

FerryBox data availability

The 1-minute data files obtained from the bridge are appended together for each year and calibrations have then been applied to the data using PSTAR (Unix based) routines. All of the data files are in PSTAR format (eg: data99.pst) and have also been listed in ASCII format eg: data99.asc (although the ASCII files do not contain the longitude data due to a restriction of only 10 variables per listing; units and variable names are held in the header).

The PSTAR and ASCII data files are available in the following UNIX directory:

/working/gdd/ecomod/Temp_Epoch/suh

The ASCII listings of the data also found on POLARIS: **GDD\shared1\GDD\data\ferrybox\suhFILES\EAreport\rawdata**

Appendix Table 3: EXCEL files for calibrated FerryBox, Dock Monitor and discrete sample data

Year	File name	Size MB		Year	File name	Size MB	Day range
Ferry 1999	data99a.asc	4.4	100-124	Ferry 2001	data01a.asc	5.1	115-173
	data99b.asc	3.7	125-150		data01b.asc	4.6	174-229
	data99c.asc	4.7	151-175		data01c.asc	3.8	256-291
	data99d.asc	4.7	176-200		data01d.asc	5.4	292-345
	data99e.asc	5	201-225	Ferry 2002	data02a.asc	3	114-140
	data99f.asc	3.6	226-250		data02b.asc	1.9	141-170
	data99g.asc	4.2	251-275		data02c.asc	3.4	171-200
	data99h.asc	2.6	276-290		data02d.asc	3.3	201-217
Ferry 2000	data00a.asc	4.4	104-129		data02e.asc	3.3	218-235
	data00b.asc	4	130-154				
	data00c.asc	4.8	155-179	Discrete:			
	data00d.asc	3.9	180-204	2000	dapdata00.xl	94k	137-242

	data00e.asc	4.6	205-229	2001	dapdata01.xl	94k	12-348
	data00f.asc	4.2	230-254	2002	dapdata02.xl	188k	71-197
	data00g.asc	1.8	255-273	2002	dapnutdata02.xl	94k	12-348
				2002	dapnutdata02b.xl	94k	71-197
Dock 1999	dhdata99.asc	3.7	91-269	2003	dapdata03.xl	94k	50-209
Dock 2000	dhdata00.asc	3.3	95-256	2003	dapnutdata03.xl	94k	50-209

In the files the FerryBox and Dock Monitor variables appear in the following order: DATA CYC, jday (dayofyr), lat (degrees N), cond (no units), rawtemp (°C), press (m), fluor (no units), turb (FTU), chl (mg m^{-3}), temp (°C), salin (no units)

APPENDIX

A.4 GANTT CHART SHOWING WHEN AND WHERE SAMPLES WERE COLLECTED BETWEEN 1998 AND 2003

(a) January to April

	JAN	FEB	MAR	APRIL
1998				
Discrete samples : NW Netley	16	26	30	27, 28
Calshot	16	26	30	27, 28
1999				
Ferry data				starts 10th
fluorometer range reset (*all by 3)				
Sensors removed				
No GPS (sensor water logged)				
Excessive fouling (cooling water?)				
Discrete samples : Dock monitor				daily means
NW Netley	19	16	19	
Calshot	19	16	19	
2000				
Ferry data				13th
No GPS				
Fluor low prior to 1st clean, do not use				
Vertical fluorometer (reduce settling)				
power failure onboard, reset time				
fluorometer range reset				
Mesodinium rubrum (chl >200mgm-3)				
Discrete samples : SG6				
NW Netley				
Calshot				
Dock mooring				
2001				
Ferry data Aquatraka				25th
System stopped logging				
Horizontal sensor, fresh water flow				
Discrete samples : Eling				20
NW Netley	12,30	12,19	2,16,23	4,10,19,20,27
Calshot	12,30	12,19	2,16,23	4,10,19,20,27
2002				
Ferry data				24th
No GPS				
Block in fluorometer (reconnect leads)				
no real time transmision of data				
Discrete samples: Eling				25
NW Netley			12,19,27	4,9,16,22,25,26,30
Calshot			12,19,27	4,9,16,22,25,26,30
Horse Elbow			12,19,27	4,9,16,22,26,30
2003				
Ferry data Minipack, no GPS				day 103
Discrete samples : NW Netley		19	3,10,17,24,31	8,14,23,29
Calshot		21	3,10,17,24,31	8,14,23,31

(b) May to July

	MAY	JUNE	JULY
1998			
Discrete samples : NW Netley	12,23	5,12,17	23
Calshot	12,23	5,12,17	23
1999			
Ferry data		90% data return	
fluorometer range reset (*all by 3)	on 6th		
Sensors removed	20th - 24th		
No GPS (sensor water logged)			
Excessive fouling (cooling water?)			
Discrete samples : Dock monitor	daily means	daily means	daily means
NW Netley		10	22
Calshot			
2000			
Ferry data		92% data return	
No GPS	13th		
Fluor low prior to 1st clean, do not use	to 24th		
Vertical fluorometer (reduce settling)			13th
power failure onboard, reset time			from 21th to 1st Aug
fluorometer range reset			
Mesodinium rubrum (chl >200mgm-3)			
Discrete samples : SG6	14	2,9,17	7,17,29
NW Netley	16	2,9,19	7,17,26,31
Calshot	18	2,9,21	7,17,33
Dock mooring			
2001			
Ferry data Aquatraka			
System stopped logging			
Horizontal sensor, fresh water flow			
Discrete samples : Eling	8,21,24	5,18,19	4,5,12,19,20,25
NW Netley	4,8,18,21,24	5,7,11,18,19,22	3,4,5,12,19,20,24,25
Calshot	4,8,18,21,24	5,7,11,18,19,22	3,4,5,12,19,20,24,25
2002			
Ferry data		83%	
No GPS			25th
Block in fluorometer (reconnect leads)			13th to 19th
no real time transmision of data		20th	
Discrete samples: Eling	9,23	10,24	8,23
NW Netley	2,7,9,10,17,23,27,30	7,10,13,20,23,24	5,8,16,23
Calshot	2,7,9,10,17,23,27,30	7,10,13,20,23,24	5,8,16,23
Horse Elbow	2,7,,10,17,3,27,30	7,13,20,23,	5,16
2003			
Ferry data Minipack, no GPS	to 121		
Discrete samples : NW Netley	6,12,19,27	5,9,16,23,30	7,16,21,28
Calshot	6,12,19,29	5,9,16,23,32	7,16,21,30

(c) August to November

	AUG	SEPT	OCT	NOV
1998				
Discrete samples : NW Netley	12	24	20	
Calshot	12	24	20	
1999				
Ferry data			to 17th	
fluorometer range reset (*all by 3)				
Sensors removed				
No GPS (sensor water logged)	start 19th			
Excessive fouling (cooling water?)			17th	
Discrete samples : Dock monitor	daily means	daily means		
NW Netley				
Calshot				
2000				
Ferry data		to 29th		
No GPS				
Fluor low prior to 1st clean, do not use				
Vertical fluorometer (reduce settling)				
power failure onboard, reset time				
fluorometer range reset	1st to 8th			
Mesodinium rubrum (chl >200mgm-3)				
Discrete samples : SG6	14,15,27			
NW Netley	14,15,29			
Calshot	14,15,31			
Dock mooring				
2001				
Ferry data Aquatraka				
System stopped logging	17th Aug to 13th sept			
Horizontal sensor, fresh water flow				
Discrete samples : Eling	1,17,18,22,30	17	1,15,31	15
NW Netley	1,2,6,17,20,22,30,31	17,28	1,15,17,31	21
Calshot	1,2,6,17,20,22,30,31	17,28	1,15,17,31	21
2002				
Ferry data	22nd			
No GPS				
Block in fluorometer (reconnect leads)				
no real time transmision of data				
Discrete samples: Eling	7,20	5,19	4,17	4
NW Netley	7,20	5,19	4,17	4
Calshot	7,20	5,19	4,17	4
Horse Elbow				
2003				
Ferry data Minipack, no GPS				
Discrete samples : NW Netley				
Calshot				

(d) Depth for discrete boat samples and references for all data collected

1998			
Discrete samples : NW Netley	2	1m	SONUS Lei (2001) +other stations
Calshot	2	1m	SONUS Lei (2001) +other stations
1999			
Available Ferry data			Holley & Hydes (1999)
fluorometer range reset (*all by 3)			
Sensors removed			
No GPS (sensor water logged)			
Excessive fouling (cooling water?)			
Discrete samples : Dock monitor		Surface	Ali (2003) + Holley & Hydes (1999)
NW Netley			
Calshot			
2000			
Available Ferry data			Holley & Hydes (2000)
No GPS			
Fluor low prior to 1st clean, do not use			
Vertical fluorometer (reduce settling)			
power failure onboard, reset time			
fluorometer range reset			
Mesodinium rubrum (chl >200mgm-3)			
Discrete samples : SG6		1m	Ali (2003)
NW Netley		1m	Ali (2003)
Calshot		1m	Ali (2003)
Dock mooring			
2001			
Available Ferry data Aquatraka	to 12th Dec		Holley et al (2001)
System stopped logging			
Horizontal sensor, fresh water flow			
Discrete samples : Eling		several depth	Torres, Muxagata (in prep), Collins
NW Netley	14	several depth	surface data from other stations
Calshot	14	several depth	
2002			
Available Ferry data			Holley & Hydes (2002)
No GPS			
Block in fluorometer (reconnect leads)			
no real time transmision of data			
Discrete samples: Eling		several depth	Iriarte (HABES) + Torres (in prep)
NW Netley		several depth	Iriarte (HABES) + Torres (in prep)
Calshot		several depth	Iriarte (HABES) + Torres (in prep)
Horse Elbow		several depth	Iriarte (HABES)
2003			
Available Ferry data Minipack, no GPS			
Discrete samples : NW Netley		Integrated 2m sample	
Calshot		Integrated 2m sample	