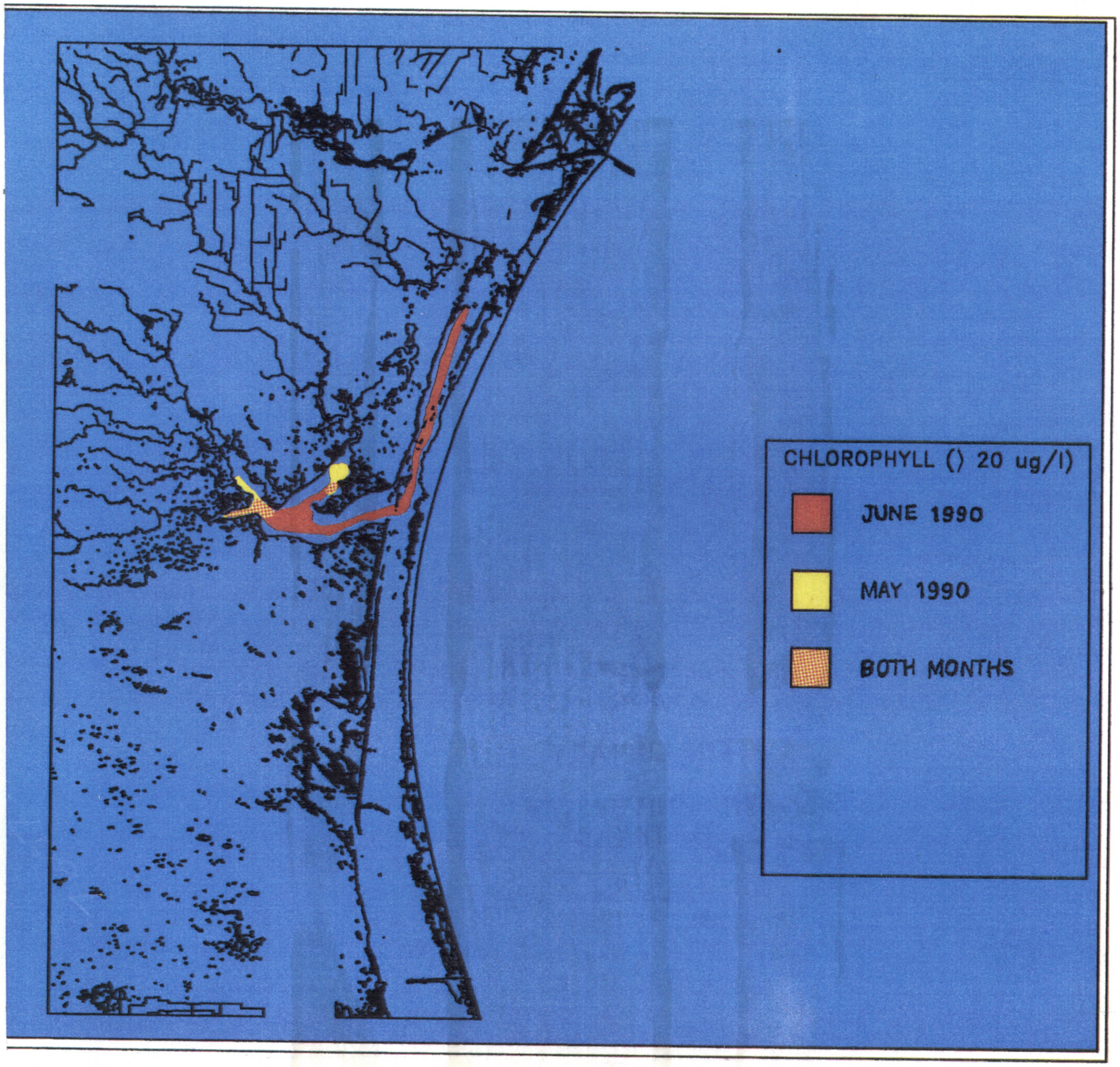

Report
Brown Tide Symposium and Workshop
15-16 July 1991

T. E. Whitledge, Marine Science Institute
W. M. Pulich, Jr., Texas Parks and Wildlife Department

Marine Science Institute
The University of Texas
P.O. Box 1267
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September 1991

Cover Figure: The distribution of chlorophyll a concentrations greater than 20 μg/liter during the bloom initiation of the brown tide in 1990. Yellow and stipled areas represent the abundant distributions of brown tide in the upper reaches of Baffin Bay (Laguna Salada, Cayo del Grullo and Alazan Bay) during May. Red areas illustrate the spread of the brown tide through upper Laguna Madre during the month of June.

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Sponsored by

The University of Texas at Austin
Marine Science Institute

Texas Parks and Wildlife Department

EPA Gulf of Mexico Program

Conveners: T. E. Whitledge, UTMSI
W. M. Pulich, Jr., TPWD

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The University of Texas Marine Science Institute
Technical Report No. TR/91-002

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BROWN TIDE SYMPOSIUM AND WORKSHOP

INTRODUCTION

The "brown tide" bloom of an aberrant Chrysophyte sp. phytoplankter occurred for more than 18 months and extended into both upper (cover map) and lower Laguna Madre, Texas.

Great concern for the Laguna Madre ecosystem was shown during the brown tide event by local, state and regional groups, but little previous knowledge was available about this unusual phytoplankton bloom. Since field data had been collected by an ongoing UTMSI field program in the Laguna, it was felt that a workshop format meeting should be convened with national and international experts to discuss the data and results on brown tide and other unusual phytoplankton blooms. A relatively quick response was needed as planning for the workshop started in May 1991 for a meeting date in July, with support supplied by the Gulf of Mexico Program of U.S. Environmental Protection Agency (Grant No. X006242-01-0), The Resource Protection Division of the Texas Parks and Wildlife Department and The University of Texas Marine Science Institute.

This report includes the agenda, abstracts of presentations and summary of findings by the workshop participants. The participants also strongly agreed that long term research support was necessary to further understand the brown tide bloom and its effects. To that end, a resolution was drafted and unanimously approved by all the workshop participants.

We would like to thank the sponsors, particularly Dr. Larry McKinney of TPWD and all participants, especially our U.S. and foreign invited guests, for their dedicated efforts and enthusiastic participation.

T.E. Whitledge - UTMSI
W. M. Pulich, Jr. - TPWD

GOALS

The convened brown tide workshop had the following goals:

1. To present descriptions of our present scientific knowledge of the brown tides in Peconic Bay and Great South Bay on Long Island, Narragansett Bay in Rhode Island, and Laguna Madre in Texas;

2. To collate our current knowledge of brown tides and provide guidelines for research on its causal conditions, autecology, effects on seagrasses, effects on grazer populations, overall ecosystem effects and requirements for monitoring, environmental protection and management;

3. To prepare a written summary document that included abstracts of presentations and a list of research recommendations developed from the workshop discussions.

RESOLUTION

We, the participants at the "brown tide" workshop convened at UTMSI, are concerned that the ongoing 1990 - 1991 Laguna Madre brown tide epidemic may become a chronic problem in this ecosystem, producing unknown impacts on marine resources and satellite industries. Moreover, this remarkable bloom appears to be a manifestation of an epidemic of similar outbreaks now appearing to occur with increased frequency in the coastal waters of the United States and globally. Present knowledge of such blooms is extremely limited, preventing effective forecasting, understanding of, and regulation of such bloom episodes. We, therefore, recommend that both state and federally funded programs be initiated to sponsor research into the growing problems, including economic and public health issues, associated with "brown tides" and other noxious and harmful bloom episodes. Such funding, which presently is lacking, is needed for research on harmful algal blooms in representative habitats and regions over suitable time period of at least 10 years' duration for proper, scientifically-based protection of coastal marine resources, tourism and public health impacted by such bloom events.

FINAL AGENDA

Brown Tide Symposium and Workshop

Sponsored by

UT Marine Science Institute

Texas Parks and Wildlife Department

EPA Gulf of Mexico Program

15-16 July 1991

Visitors Center Auditorium

Marine Science Institute

The University of Texas

Port Aransas, Texas 78373

Monday 15 July

0800	Registration
0830	Introduction and Welcome Bob Jones Larry McKinney Frederick Kopfler
0845	Workshop Overview of Goals and Format (Whitledge)
0900	Peconic Bay and Great South Bay - Cosper
0930	Narragansett Bay - Smayda

1000	Coffee	
1030	Seagrasses - Dennison	
1100	Grazers - Caron	
1130	European Blooms - Graneli	
1200	Lunch (Mexican)	
1320	Nutrients and Hydrography - Whitledge	
1340	Primary Production - Stockwell	
1400	Seagrass Distributions - Onuf	
1420	Seagrass Production - Dunton	
1440	Benthos - Montagna	
1500	Coffee	
1520	Zooplankton - Buskey	
1540	Larval fish - S. Holt and J. Holt	
1600	Adult fish - McEachron	
1620	Isotope Markers - Parker	
1640	Panel Discussion of Regional Similarities and Differences of Brown Tide Blooms (Buskey, Cosper, Smayda)	
1730	Adjourn	
1800	Social Hour	
1900	Dinner (Shrimp Boil)	
Tuesday 16 July	Future Research Recommendations	
0830	Discussion Topic	Causal Conditions (Smayda)
0900	Discussion Topic	Brown Tide Organism Growth Rate, Primary Production and Ecology (Cosper, Stockwell and Suttle)

0930	Discussion	Seagrass Effects (Dennison and Dunton)
1000	Coffee	
1030	Discussion Topic	Effects on Consumer Populations - Zooplankton, Fish and Shellfish (Buskey and Caron)
1100	Discussion Topic	Overall Effects of Brown Tide on Ecosystem (Graneli and Montagna)
1130	Discussion Topic	Environmental Monitoring, Protection and Management (Pulich and McEachron)
1200	Summary of Research Recommendations (Whitledge)	
1230	Adjourn to Lunch	

ABSTRACTS

The following abstracts are arranged in the order of presentation at the symposium.

THE BROWN TIDE IN NEW YORK COASTAL WATERS

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Several coastal embayments along the northeast coast of the USA have within the last six years experienced novel microalgal blooms for which there is no previous record. These monospecific blooms were popularly called the brown tide due to the resulting water color. In the early summer of 1985 the first appearance of the brown tide occurred over a wide geographic Narragansett Bay, Rhode Island, Long Island embayments in New York, and Barnegat Bay in New Jersey. The extent of the blooms was restricted to these coastal bay systems; blooms did not appear to follow a pattern of spreading from one bay system to the next. This suggests that the environmental factors contributing to these brown tide blooms were not just localized to specific conditions in a bay system but probably were more regional, e.g. involving meteorologically induced changes. The blooms on Long Island markedly reduced the extend of eelgrass (*Zostera marina*) beds because of increased light attenuation, and decimated populations of commercially valuable bay scallops (*Argopecten irradians irradians*) since the scallops were unable to graze adequately and starved to death. Similarly in Narragansett Bay the mussels were unable to feed and populations were severely reduced.

In 1986 the blooms recurred throughout the summer months in the same Long Island embayments as previously. In Long Island and in Barnegat Bay, N.J. during the summers of 1987, 1988, 1989 the brown tide blooms returned only in diminishing levels. During the summer of 1990 very brief outbreaks of the blooms were recorded in certain Long Island bay areas by the monitoring program of Suffolk County, but during June of this year, 1991, it has returned at substantial levels over extensive bay areas threatening the scallops and eelgrass again. Since 1985 brown tide blooms have not returned to Narragansett Bay.

The brown tide species was dominant in terms of cell number and contributed greater than 80% of total cellular phytoplankton volume throughout most of the bloom period during the summer months. During the blooms phytoplankton biomass, as indicated by chlorophyll a levels, was not particularly elevated for Long Island bays, in comparison to other years, since concentrations reached levels less than 30 $\mu g\ l^{-1}$, but chlorophyll a was concentrated in the smaller (less than 5 μm) fraction. Primary productivity levels were high but also were not different from pre-bloom years. The less than 10 μm fraction of the phytoplankton contributed greater than 90% of the total photosynthetic activity throughout the bloom period; estimates of picoplankton carbon turnover were rapid, on the order of hours. Changes in inorganic nutrient levels, as nitrate, nitrite, phosphate and ammonium, were not different from pre-bloom years. Variations in inorganic macro-nutrients were not correlated with variations in the productivity of the brown tide and there is no evidence to support increased macro- nutrient loading as a cause of the blooms. These findings are consistent with similar studies in Narragansett Bay, Rhode Island.

Since the brown tide alga, *Aureococcus anophagefferens*, is a new species not previously known to cause blooms, environmental conditions contributory to the blooming could in part relate to new anthropogenic influences in these bays. Physiological studies have identified certain micronutrients as conducive to the growth of this species, such as specific chelators (which have replaced phosphates in detergents), selenium and iron, and organic phosphates and nitrogen sources. Drought conditions, which elevated salinities to levels of 30 ‰, conducive to the growth of *A. anophagefferens*, along with pulses of rain which delivered specific nutrients to the bay waters, and the restricted flushing of bay waters set the scenario for the formation of the bloom. Selective grazing pressures against the brown tide species during the early bloom phase could have further allowed for the development of large populations. Most recently the evidence for a virus associated with this algal species, perhaps controlling bloom dynamics through infective activities, has been considered another possibility to be investigated. Since this species is still present in Long Island bays, and continuing to bloom, if only sporadically, the problem now seems to be more chronic and the ecology of this nuisance microalga must be defined in order to understand the causes of these blooms and perhaps remedy the situation.

The brown tide bloom scenario has some similarity to the "green tide" blooms of the 1950's in Great South Bay which also affected the bivalve oyster populations. During the early fifties a lowering of salinity selected for two estuarine species, *Nannochloris sp.* and *Stichococcus sp.*, with a salinity of 17 ‰ optimal for growth. The recurrence of the "green tides" for several summers afterwards appeared to depend on the restricted circulation of the inshore bays and the overwintering of large enough seed populations to initiate the next summer's growth. Effluents from duck farms, which flowed into Great South Bay through creeks, were found to be supplying nitrogenous nutrients and promoting the growth of these two species of microalgae and these effluents were subsequently restricted. The closing and opening of Moriches Inlet and the subsequent altering of circulation patterns which would have modified the salinity and nutrient regimes in the bay were also considered contributory.

OCCURRENCE AND DISTRIBUTION OF THE 1985 BROWN TIDE IN NARRAGANSETT BAY

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The brown tide became evident in early May 1985 at a permanent station sampled weekly in lower Narragansett Bay. Beginning in July, coverage of this bloom was extended baywide to weekly analyses at 7 stations. Observations made at three depths at each station: temperature, salinity, NO_3, NH_4, PO_4, SiO_2, chlorophyll, ATP-carbon, phytoplankton species composition and abundance, and nitrate reductase activity. Water column light transmission was also measured, and a sample pooled from the 3 sampling depths used to determine carbon-14-based primary productivity at 5 light levels. Zooplankton net tows were made to determine zooplankton and benthic larvae species composition and abundance, dry weight, carbon and nitrogen; ctenophores were also collected to determine their abundance in 4 different size classes.

Some principal findings are:

- The brown tide bloom abundance occurred throughout Narragansett Bay. Up to 1.2 billion cells per liter were found. This bloom was part of a mesoscale event extending over 250 km of coastline, including Long Island and New Jersey. This suggests a climatological role.

- Although *Aureococcus anophagefferens* was numerically dominant, significant blooms and succession of red tide dinoflagellates and phytoflagellates co-occurred during the brown tide. That is, this bloom was not a monospecific event.

- Maximum abundance occurred in nutrient-poorer waters; hence, the brown tide bloom does not suggest a response to eutrophication.

- The causative species grew at division rates of about 1 doubling per day.

- Maximum biomass levels were within the normal range, despite the tremendous numerical abundance of the picoplanktonic *Aureococcus*.

- The normal summer diatom flora and the flagellate *Olisthodiscus luteus* were insignificant.

- The 1985 brown tide began to collapse in September prior to Hurricane Gloria. *In situ* events, therefore, rather than washout, appeared to be responsible for its decline and disappearance; microzooplankton abundance was then high.

- Following the demise of the brown tide, an extensive, prolonged bloom of euglenids occurred throughout Narragansett Bay. This bloom was also extremely anomalous relative to the historical phytoplankton data set. By November 1985, the euglenid bloom terminated.

- The 1985 brown tide event was the longest, sustained bloom (5 months) recorded in Narragansett Bay since observations began in 1949.

- The winter-spring diatom bloom began in December. Its species composition, abundance and dynamics were quite normal relative to previous years in contrast to the anomalous summer brown tide and euglenid blooms.

- Ctenophores, which normally disappear in October, persisted throughout the winter in high numbers. Zooplankton populations were more or less normal.

- A significant die-off of the edible mussel *Mytilus edulis* occurred during the brown tide, accompanied by serious impairment of fecundity prior to mortality. Zooplankton grazing was also reduced, as was their fecundity, in experiments. The summer cladoceran community failed to develop and the bay anchovy, *Anchoa mitchelli*, failed to spawn. Thus, the brown tide was a noxious (if not toxic) bloom.

- Failure of the scallop population in local coastal salt ponds, where the brown tide bloomed, also occurred. In contrast, the quahog *Mercenaria mercenaria* appeared quite hardy based on its "condition index".

- A short-lived brown tide development re-occurred in May 1986, but failed to develop and collapsed soon after; the microzooplankton community was then abundant, unlike in May 1985.

- We have concluded that the 1985 Narragansett Bay brown tide was primarily regulated by grazing failure and/or grazer modification.

BROWN TIDE EFFECTS ON SEAGRASSES

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The Long Island brown tide algal blooms of 1985-1987 created a severe reduction in light availability for the seagrass *Zostera marina* (eelgrass). The reduction in light penetration in the water column was not due to an increase in phytoplankton biomass, measured as chlorophyll a, rather it appeared to be due to an increased density of small particles in the water (*Aureococcus anophagefferens*). Reduced light availabilities led to large scale reductions of bay bottom covered by eelgrass, assessed with before and after aerial and ground surveys. The minimum light requirement for eelgrass, established experimentally, is about 20% of incident light. The brown tide reduced light below this level and eelgrass responses were observed within months.

The effect of the Laguna Madre brown tide in shading the resident seagrasses, principally *Halodule wrightii* (widgeon grass), should be similarly studied with comparisons of seagrass distributions before and after the algal bloom. The deeper reaches of seagrass depth penetration are most susceptible to light reductions and surveys concentrating on this portion of the bed are most important. Previous studies of widgeon grass indicate a minimum light requirement of about 17%. The abundance of carbon storage products (starch and sugars) is important in determining the overall survival of seagrasses to a shading event. Eelgrass has little capacity for below ground storage of carbon compounds based on plant architecture, yet widgeon grass has abundant rhizomes which could harbor sufficient reserves for this species to withstand prolonged shading. Careful monitoring following immediate bloom conditions will be required to fully assess the effect on seagrasses.

RELEASE FROM GRAZING PRESSURE AS A FACTOR CONTRIBUTING TO OUTBREAKS OF THE BROWN TIDE

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One of the major questions facing researchers investigating blooms of non-toxic algae is...how are these blooms initiated? Clearly, stimulation of the growth of the causative alga(e) is required, but it is also probable that processes that remove algal biomass (e.g. predation, sedimentation, parasitism) are small relative to algal growth during the period that algal biomass increases rapidly. In the brown tides that have occurred in coastal waters of New York, Rhode Island and New Jersey in recent years (Cosper *et al.*, 1989)*, the causative alga has been a 2-3 μm Chrysophyte (*Aureococcus anophagefferens*). Because of the small size of this species, it is probable that sedimentation and losses due to larger (crustacean) zooplankton feeding have not been an important mechanism for the removal of algal biomass. Furthermore, although it has been speculated that viral infection could be a factor, as yet there is no conclusive evidence that viruses contribute to the demise of these blooms. Consequently, grazing by small (<200 μm) zooplankton, primarily protozoa, has been proposed as a potential mechanism of removal of *A. anophagefferens* from the water column. The size of the alga implicates these organisms as their primary consumers. Field and laboratory experiments conducted to investigate the potential for protozoan populations to consume *A. anophagefferens* have indicated that these protozoa may be important consumers of this alga. Several cultured species of bacterivorous protozoa have been shown to be capable of ingestion and growth on *A. anophagefferens* in laboratory studies. Field studies have demonstrated that the ingestion rates of particles similar in size to the brown tide alga were comparable to rates observed in environments not affected by the alga, and selectivity against *A. anophagefferens* by consumers, if it occurred at all, was not great. Because these studies have not indicated acute toxicity by the alga or selectivity against *A. anophagefferens* by grazers it is probable that the alga is consumed in nature, and it is hypothesized that some mechanism leading to the release of the alga from protozoan grazing may have been a factor contributing to bloom initiation. In general, herbivorous protozoa grow rapidly and should have been able to keep pace with algal growth when algal density was at normal levels. It was clearly demonstrated, however, that once the bloom became established, protozoan grazing was capable of removing only a small portion of the algal biomass each day (<5%), requiring a considerable period to significantly reduce algal densities. If this hypothesis is true, then one key to explaining blooms of the brown tide may be understanding the factor(s) which removed or inhibited herbivorous protozoa at the time of the bloom initiation. Possible mechanisms include chemical or physical factors that might affect protozoan growth or feeding activity (temperature, salinity, etc.), the removal of planktonic protozoa by larger (crustacean) zooplankton at a critical time during the beginning of the bloom, or poor nutritional quality of the brown tide alga to the protozoa that consume it. The role that microbial grazing plays in blooms of the brown tide alga and other non-toxic algae should not be underestimated, and investigations of unusual algal blooms should incorporate studies of this aspect of the ecology of the algae causing these phenomena.

*Cosper, E.M., Bricelj, V.M. and Carpenter, E.J. (ed.). 1989. Novel phytoplankton blooms: causes and impacts of recurrent brown tides and other unusual blooms. Springer-Verlag, Berlin, Vol. 35, P. 799.

SOME INTERESTING ALGAL BLOOMS IN EUROPEAN COASTAL WATERS

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Organisms and Areas Involved

A) Blooms

North Sea: *Phaeocystis pouchetti, Noctiluca scintillans,* recurring blooms.
Black Sea: Blooms of e.g. *Noctiluca* (?) increasing in intensity.
Adriatic Sea: 1989: widespread up to 20 cm gelatinous layer composed mainly of "marine snow", connection to algal blooms or certain species uncertain, however, probably originating in spring bloom. This phenomenon has also been observed earlier, but with less intensity.
Kattegat and Skagerrak: Ceratium blooms occur annually, but they have been much larger than "normal" since 1980. A single and totally unexpected bloom of *Chrysochromulina polylepis* (Prymnesiophyceae) in May-June 1988.
Baltic Sea: Large scale (seen on satellite pictures) blooms of *Nodularia spumigena* a regular phenomenon since at least the last century, but probably increasing. *Aphanizomenon flos-aquae, Mesodinium rubrum* blooms of more local character in polluted areas.
South Norwegian west coast: *Prymnesium parvum* bloom in 1989.
North Norwegian coast: *Chrysochromulina leadbeatherii* bloom in 1991.

Blooms of several dinoflagellates, toxic as well as non-toxic, have occurred repeatedly in European waters. Among these species, *Gymnodinium aureolum* and *Prorocentrum minimum* are especially worth mentioning.

For the Adriatic Sea, North Sea and Baltic Sea algal blooms were reported already during the last century. However, the size and duration of the blooms seem to have increased, as well as the biomass of algae.

B) Some features of the blooming organisms

Ceratium: Biomasses higher than during the spring bloom. No detectable inorganic nutrients in the water when they are growing. Are they using the organic nutrient fractions; vertical migrations? Stimulated by humic acids? No effective grazing upon ceratia from the dominating copepod during this period, *Oithona similis*.
Chrysochromulina polylepis: This small organism, up to several 10s of million organisms/liter, never built up to a large biomass. Just before *C. polylepis* started to increase, there was a bloom of *Skeletonema costatum*. Is there a connection? Could Vitamin B12 be produced by *S. costatum* and used by *C. polylepis*, which is stimulated by this vitamin? We found that there is an increase in biomass accumulation for *C. polylepis* growing under cobalt addition, while for a diatom (*Ditlylum brightweellii*) and a

dinoflagellate (*Prorocentrum minimum*) no effect was seen, either on the growth rate or for the biomass accumulation. In the Kattegat-Skagerrak, nitrogen limitation predominates. However, before the bloom there was an increase in nitrogen from riverine input (high precipitation during winter), and as a consequence there was probably a short period of phosphorus limitation. *C. polylepis* produces a toxin which the algae release maybe as a repellent to grazers. The toxin production increases when the algae is growing under phosphorus limitation. *C. polylepis* has also been shown to be phagotrophic.
Phaeocystis pouchetii: This species is also found blooming in Arctic and Antarctic waters, where inorganic nutrient concentrations are high to extremely high. It is, therefore, temptating to connect the large blooms of *P. pouchetii* in the North Sea with eutrophication, which is severe due to large quantities of nutrients from the Rhine.

Effects on Higher Trophic Levels

C. polylepis caused extensive fish-kills, especially of caged Atlantic salmon, but also of various wild fish species. Benthic mortalities were also seen, and most curiously, macroalgae, e.g. red algae, were affected. The plankton community was extremely impoverished during the bloom, and laboratory studies have revealed strong toxic effects on potential grazers, e.g. copepods and ciliates.

Possible Environmental Triggers

A) Climatic and hydrographic conditions in connection with blooms

Phaeocystis pouchetii: Lancelot *et al.* (1987 Ambio 6:38-46) reported more frequent occurrence in the last 20 years, probably due to nutrient enrichment from river discharge. Blooms of **Nodularia** and other colonial blue-greens in the Baltic Sea appear especially during dry and hot summers in stratified waters; this may be simply due to a collection of algae at the surface as a consequence of gas vacuoles. Low N:P ratios and high P availability are thought to promote the growth of this nitrogen fixing species.
C. polylepis: Rainy winter, warm and hot spring, abnormal nutrient situation (N instead of P surplus), and abnormal diatom blooms might condition the water? (e.g. first, a normal spring diatom bloom, then later a bloom of *Skeletonema costatum*).
Prymnesium parvum: ?? Summer 1989 - west coast of Norway.
Chrysochromulina leadbeatherii: ?? May - June 1991 - north coast of Norway.

B) Salinity requirements of organisms

Nodularia spumigena is an obligate brackish-water species which does not occur in fresh water or in water with salinities greater than about 20 ‰. *Phaeocystis pouchetii* on the other hand is found in full-strength oceanic water, and does not bloom in low-saline water. *Chrysochromulina polylepis* was found in laboratory studies to have a salinity optimum of approximately 25‰, which is in accordance with its blooming in the Kattegat and the Skagerrak. Also *Ceratium* species seem to prefer a salinity somewhat below the one in full strength sea water.

Management (in Sweden)

After the first large Ceratium-bloom in Kattegat in 1980, a multidisciplinary project was conducted, aimed at the investigation the possible roles of eutrophication and below-halocline anoxia in the blooms. About 2 million US dollars (not including salaries for all participating scientists and ship costs) per year for six years were invested by the Swedish National Environment Protection Board. Results from this project have been published in a special number of AMBIO (Vol. XIX, Number 3, May 1990). Nitrogen was found to be the key element for algal growth. All sewage treatment plants discharging directly into coastal waters of the Swedish west coast are now required to introduce at least 50% nitrogen removal (through denitrification). However, a much larger contribution of nitrogen comes from diffuse sources, agriculture and transportation. This nitrogen is transported both through the atmosphere and in surface runoff. To intercept nitrogen in surface waters, wetlands are restored or created, but only on an experimental scale. Changes in agricultural practices have been introduced, but the problem is obviously of an international character. International scientific cooperation as well as political agreements on pollution control, are being intensified, especially for the Baltic Sea and the North Sea.

Prevention

The most severe direct effects of the blooms are on cage-cultured fish, a billion-dollar industry in Norway. Indirect effects, e.g. losses in tourism due to unpleasant water and beaches covered with dead organisms, and anoxia leading to benthic mortalities, are probably even larger. There is nothing that can be done to prevent blooms. However, during the *Chrysochromulina polylepis* bloom in 1988, fish-cages were towed away into fjords and river mouths, where the blooms did not penetrate, possibly due to unfavorable salinity conditions. In this way great economic values were saved. However, the detection of the bloom in a rather early stage was a pure coincidence, and there was no regular monitoring of phytoplankton.

Monitoring

There is little regular long-term phytoplankton monitoring in Sweden, or indeed in Europe as a whole (the most famous, but methodologically somewhat deficient, is the English continuous plankton recording). In Sweden there are 3-4 coastal stations where samples for nutrients, primary production and phytoplankton counting are taken 20-30 times per year. These programs are, however, of recent origin. After the *C. polylepis* bloom in 1988, national and regional authorities, with the help from universities, have set up a monitoring program during spring and summer, covering areas where *C. polylepis* and similar organisms might bloom again. This program is rather informal, with frequent telephone meetings among the participants to discuss results in close connection to sampling. No new *C. polylepis* bloom has appeared since 1988, although the organism is frequently found in phytoplankton samples.

THE NUTRIENT AND HYDROGRAPHIC CONDITIONS PREVAILING IN LAGUNA MADRE, TEXAS, BEFORE AND DURING A BROWN TIDE BLOOM

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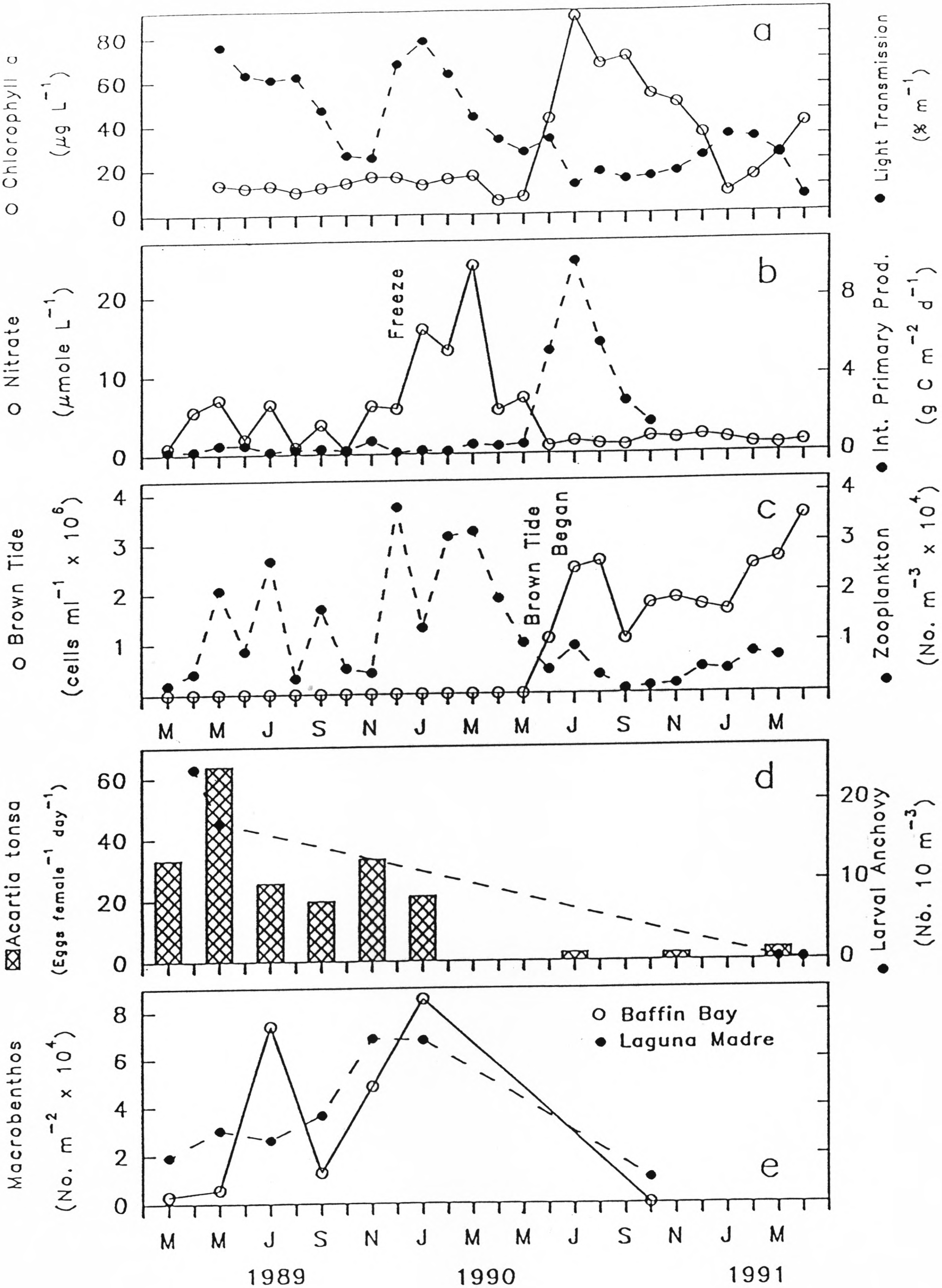
Monthly samples for hydrographic, nutrient and pigment measurements were analyzed for about 18 months previous to the onset of a brown tide bloom of an unidentified aberrant chrysophyte. The bloom conditions persisted for more than 12 months throughout the hypersaline Laguna Madre. The hydrography distributions showed north to south gradients of salinity in Laguna Madre with maximum values in the upper reaches of Baffin Bay. The dissolved inorganic nitrogen concentrations also displayed maximum concentrations in Baffin Bay with ammonium accounting for 60-95% of the total.

The salinity variations over a seven year period indicate that the seasonal differences in upper Laguna Madre were about 20‰, but in the upper reaches of Baffin Bay where the brown tide was most dense, the annual salinity variations were as large as 65‰. The salinity ranged between 40 and 60‰ during the bloom and the dissolved inorganic nitrogen (DIN) was nearly 20 μmole/l at the time of bloom initiation (Fig. 1). More than 80% of the DIN was in the form of ammonium at this time.


a
b
c
d
e
○ Chlorophyll a
(μg L⁻¹)
● Light Transmission
(% m⁻¹)
○ Nitrate
(μmole L⁻¹)
● Int. Primary Prod.
(g C m⁻² d⁻¹)
Freeze
○ Brown Tide
(cells ml⁻¹ x 10⁶)
● Zooplankton
(No. m⁻³ x 10⁴)
Brown Tide
Began
Acartia tonsa
(Eggs female⁻¹ day⁻¹)
● Larval Anchovy
(No. 10 m⁻³)
Macrobenthos
(No. m⁻² x 10⁴)
○ Baffin Bay
● Laguna Madre
M M J S N J M M J S N J M
1989
1990
1991

STUDIES ON CONDITIONS CONDUCIVE TO THE DEVELOPMENT AND MAINTENANCE OF A PERSISTENT BROWN TIDE IN THE LAGUNA MADRE, TEXAS

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The 1990 occurrence of a Texas brown tide appeared quite rapidly within the waters of Baffin Bay and the Upper Laguna Madre of South Texas and has persisted within these hypersaline waters for twelve months. Pigment data and ultrastructural studies from this almost monospecific bloom suggest that this small (4-5 μm diameter) organism is characteristically similar to the Type III, aberrant group of Chrysophytes. Maximum abundances and spatial distributions occurred within the second month (July, 1990) of the bloom. During maximal distribution, the brown tide reached cell densities of 10^9 cells/liter and mean chlorophyll concentrations approached 70 μg Chl a/liter.

Direct comparisons to *Aureococcus anophagefferens* and *Pelagococcus subviridis* have been made using poly-clonal antibody assays. These tests indicate that this organism although closely allied is apparently a new species, not previously described. Like *Aurecoccus,* the Texas brown tide organism also can produce substantial amounts of DMS (dimethlsulfide). Preliminary radioisotope techniques suggest that although carbon uptake rates are high, the cell division rates are typically less than one division per day. This does not appear to be an exceptionally high value. Additionally, during maximal bloom conditions, the normally high microzooplankton grazing pressures, previously observed for Laguna Madre, were greatly reduced.

SEAGRASS DISTRIBUTION IN UPPER LAGUNA MADRE IN 1988 AND PREDICTED RESPONSES TO BROWN TIDE

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Corpus Christi, Texas

In 1988, the National Wetlands Research Center conducted a survey of seagrass distribution in Laguna Madre to document historical trends, following up on surveys of the mid-1960's and mid-1970's. This survey provides a baseline for determining whether light reduction caused by the brown tide event of 1990-91 has affected seagrass distribution. Sampling was at intervals of 300 to 400 m along transects mostly across the Laguna. Four 80 cm^2 cores were collected approximately 3 m apart at each station. This allowed an appraisal of continuity of cover from presence and absence information aggregated for many cores. Along every second or third transect, two samples randomly selected at each station were retained for biomass determination. Aerial photography at a scale of 1:65,000 flown November 1987 was used in interpolating between transects.

Depths at which light became limiting for the support of continuous seagrass meadow were determined from 1988 distribution to be around 1.5 m near the mouth of Baffin Bay and in excess of 1.8 m farther north. As inferred from extensive monitoring of the light regime of the lower Laguna in relation to the outer edge of seagrass meadows, around 15% of surface light is necessary at the bottom to support continuous seagrass cover. Estimating from these initial conditions and Beer's law light attenuation relations, a 25% reduction in light transmission caused by brown tide should reduce the maximum depth at which continuous meadow can be sustained from 1.5 to 1.3 m near Baffin Bay and from 1.8 to 1.56 m farther north. A 50% reduction in light transmission should result in a shift from 1.5 to 1.1 m near Baffin Bay and from 1.8 to 1.32 m farther north. At the one station monitored the year before and the year of the brown tide by K. Dunton, The University of Texas, light reduction exceeded 50%.

In 1988, the only area of continuous bare deep bottom was near the mouth of Baffin Bay. According to the predictions above, a 25% reduction of light reaching the bottom would result in a narrow bare zone extending more than half the way to Corpus Christi Bay. A 50% reduction would expand the bare zone to more than half the width of the Laguna between Pita Island and Point of Rocks. Alternatively, light limitation may be operative but mortality may not have occurred yet, because the plants are expending stored reserves. In this case, biomass should be reduced in deep areas in 1991 compared to 1988. A survey is planned for fall 1991 to determine seagrass distribution after 15 months of brown tide and to test the predictions of brown tide effects made here on the assumption that light is limiting.

THE EFFECT OF EXTENDED PERIODS OF LOW LIGHT ON GROWTH AND PHOTOSYNTHESIS IN THE SEAGRASS *HALODULE WRIGHTII*

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A chrysophyte bloom in the Laguna Madre estuary in south Texas began in June 1990 and has since had noticeable effects on both the biological and physical environment. The Laguna Madre is a long narrow estuary that stretches from Corpus Christi to the Rio Grande, and is dominated by seagrasses along its entire 125 mile length. The high densities (10^9 L^{-1}) and chlorophyll content (up to 100 μg chl *a* L^{-1}) associated with this algal bloom significantly increased light absorption in the water column and reduced the light available to benthic plants. Measurements of growth and photosynthesis in *Halodule wrightii*, the predominant seagrass, and underwater PAR collected before, at the onset, and during the algal bloom, provided a unique opportunity to assess the effects of extended periods of low light on a ubiquitous subtropical seagrass.

The brown tide has had a significant effect on underwater light levels in Laguna Madre, reducing irradiance 60 to 70% compared to pre-bloom levels. Based on continuous hourly measurements of irradiance made since May 1989 and photosynthetic data, the seagrass *Halodule wrightii* was only able to achieve maximum photosynthesis for one hour per day, compared to 6 to 10 hours under normal conditions. The initiation of the bloom in June 1990 occurred during the period of maximum growth in *H. wrightii*, and leaf elongation decreased about 30% compared to previous years and unimpacted sites. The present re-occurrence of the bloom (following a slight winter die-back) coincides with the onset of new spring growth and consequently may reduce their overall growth and production significantly. However, despite the significant reduction in water transparency, which resulted in only 1 to 2 hours of PAR at photosaturation on a daily basis (compared to 6-8 hours prior to the bloom), no significant changes were observed in P-I parameters or in tissue chlorophyll *a* levels in the first nine months. The continuation of the bloom through summer 1991, during the period of rapid growth in *H. wrightii*, may provide the best test of the resilience of *H. wrightii* to extended periods of low light.

EFFECTS OF THE LAGUNA MADRE, TEXAS, BROWN TIDE ON BENTHOS

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The main effect of brown tide on benthos in other areas of the U.S. was the decline of bivalve mollusk densities due to clogging of feeding appendages by the small chrysophyte. This led to a severe economic loss in shellfish fisheries of the northeast. In Texas, there is a climatic gradient from northeast to southwest of decreasing rainfall and concomitantly decreasing freshwater inflow to estuaries. Due to a lack of sufficient inflow, only the northeastern estuaries of Texas support a commercial oyster industry. Therefore, the economic effects of brown tide in south Texas would not be direct effects on benthos, but indirect effects could alter food webs and have dramatic consequences.

A variety of benthic studies have been performed to examine productivity of (both autotrophic and heterotrophic) microbial producers, and abundance and community structure of macrobenthic organisms. These studies were performed in Baffin Bay and the upper Laguna Madre. Benthic nutrient regeneration, oxygen consumption, and bacterial biomass and productivity were studied bimonthly for one year before the brown tide event. Biomass, productivity and responses to light by microphytobenthos were studied before and after the brown tide. Macrofauna were sampled bimonthly until January 1990 and quarterly thereafter.

Baffin Bay is deeper and more turbid than the Laguna Madre, so one may suppose that benthic primary production by microphytobenthos is low. Prior to the brown tide, the shade-adapted microphytobenthos produced up to 3 g $C{\cdot}m^{-2}{\cdot}d^{-1}$ in Baffin Bay sediments. The amount fluctuates daily, decreasing with wind-induced resuspension of sediments, which blocks light reaching bottom. After the brown tide, no benthic photosynthesis occurred because of a lack of light reaching the bottom. This represents a great loss of autotrophic production, and consequently high quality food, to the benthic food web.

Sediment bacterial production is correlated with bacterial cell abundance. Sediment oxygen consumption and inorganic nitrogen regeneration are correlated with bacterial production. Baffin Bay sediments are sources of regenerated nitrogen, and Laguna Madre sediments are sinks for nitrogen. The uptake of nitrogen by Laguna Madre sediments is probably due to absorption by seagrass roots.

There are indications that a disturbance of some sort was already occurring in the sediments of Baffin Bay and Laguna Madre prior to the brown tide. In early 1989, the macrofauna community was very abundant and diverse. However, from August 1989 to January 1990, abundance was increasing while diversity was decreasing. The community in Baffin Bay was dominated by a single species, the polychaete worm *Streblospio benedicti*. This pattern is typical of a disturbed benthic community. During the onset of the brown tide, abundances and diversity decreased to near zero. As found in the northeast, bivalve mollusks disappeared within weeks after the brown tide onset. Baffin Bay is now completely dominated by *Streblospio*, while Laguna Madre is dominated by polychaetes and gastropods. *Streblopsio* is a suspension feeder and a deposit feeder. There has been a complete alteration of the benthic food web. the loss of the bivalves, particularly *Mulinia* *lateralis*, is of great concern, since it is reported to be the dominant food source of black drum.

The hypersaline Baffin Bay-Laguna Madre ecosystem is a very fragile environment. This is indicated by the lack of stability in the ecosystem. When the equilibrium was put out of balance by the loss of diversity, the benthic system rapidly deteriorated and crashed. This crash could be either a pre-condition, causal mechanism, or a contributing factor for the onset of the brown tide. The ecosystem was apparently already disturbed and did not have the stability to withstand further disturbance. An alternative hypothesis is that what ever caused the disturbance that led to the benthic response before the brown tide, also caused the brown tide. If this is true, then benthos could play the role of "canary" to future blooms.

EFFECTS OF A PERSISTENT BROWN TIDE ON ZOOPLANKTON POPULATIONS IN THE LAGUNA MADRE OF SOUTH TEXAS

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Regions of the South Texas coast centered around the Laguna Madre experienced dense populations of a nanoplanktonic chrysophyte from June 1990 through July 1991. High concentrations of this 4-5 μm diameter chrysophyte (up to 6 x 10^6 cells ml^{-1}) have reduced light transmission in the Laguna Madre, threatening seagrass beds and disrupting sports fishing activities. Monthly sampling of the mesozooplankton and microzooplankton populations of the Laguna Madre has been carried out from March 1989 through July 1991 at four stations in the upper Laguna Madre and Baffin Bay. Peak concentrations of brown tide cells occurred in August 1990 and March 1991. Baffin Bay and much of the upper Laguna Madre were hypersaline through most of this period, with salinities in excess of 40 ppt, through April 1991. Mesozooplankton populations, dominated by the neritic copepod *Acartia tonsa* were generally quite abundant before the onset of the brown tide, although populations showed considerable spatial and temporal variability. Following the beginning of the brown tide, mesozooplankton population declined sharply and remained low until the brown tide began to diminish in the late spring of 1991. The mesozooplankton was also characterized by low species diversity during the brown tide, with >95% of the mesozooplankton in Baffin Bay being composed of a single species, *Acartia tonsa*. Prior to the brown tide, prosome length of adult female *A. tonsa* varied between 0.6 and 0.75 mm, with seasonal variation due to temperature changes. During the year of the brown tide, prosome lengths remained below 0.6 mm, suggesting poor nutrition and growth. Egg release, (an index of nutritional status) by adult female *A. tonsa* decreased significantly during the brown tide. Gut pigment concentrations were also significantly decreased during the brown tide, indicating that the brown tide chrysophyte was not being consumed by *A. tonsa*. Microzooplankton populations, mainly ciliates and heterotrophic dinoflagellates, were also reduced significantly following the onset of the brown tide. Microzooplankton community grazing rates, measured using the seawater dilution technique, showed that microzooplankton were grazing most of the daily phytoplankton production before the brown tide. During the brown tide, microzooplankton grazing rates were extremely low, with less than 5% of the daily production grazed.

THE RESPONSE OF ICHTHYOPLANKTON TO THE BROWN TIDE

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Ichthyoplankton sampling in the Yarborough Pass area of the upper Laguna Madre from March 1989 through January 1990 provided background densities of eggs and larvae of sciaenids and anchovies prior to the brown tide outbreak. Larval black drum (*Pogonias cromis*) densities average 40-50 larvae per 100 m^{-3} in March 1989 and in January 1990. Larval spotted seatrout (*Cynoscion nebulosus*) densities averaged 8-10 larvae per 100 m^{-3} in March 1989. Larval anchovy spp. averaged 200-400 larvae per 100 m^{-3}. Salinities at that time were about 45 ppt.

The brown tide developed there in the early summer of 1990. The next larval fish sampling effort in that area was in March 1991. At that time the brown tide was in relatively high concentration and the salinity was 55 ppt. By mid-April 1991, the salinity was down to below 40 ppt, well within the spawning range of all the species mentioned here. There were sciaenid eggs in March and April 1991 collections from the upper Laguna Madre although in lower than expected numbers. Sciaenid eggs taken in March were of the correct size to be black drum and the April collections also had smaller eggs which were probably spotted seatrout. In some samples but not in all, there were anchovy eggs as well. There were very few sciaenid larvae in any of the Laguna Madre samples, only 1-3 larvae per 100 mm^{-3}, compared to 20-30 per m^{-3} in the 1989 collections. There were reasonably good numbers of juvenile and adult anchovies but virtually no larvae. The juvenile anchovies were large enough (and hence old enough) to have immigrated into the Yarborough Pass area from areas not affected by the brown tide. Juvenile and adult fishes do not appear to be affected by brown tide.

In concurrent samples taken in Aransas Bay near Mud Island there were both large numbers of sciaenid and anchovy eggs, and good numbers of all sciaenids we would expect in the spring except spotted seatrout. Even without spotted seatrout larvae in either Aransas Bay or the Upper Laguna Madre, it is clear that there are virtually no fish larvae in the brown tide water in the Laguna Madre and there are plenty of larvae in the water without brown tide in Aransas Bay.

Preliminary data from laboratory experiments show that feeding rate of red drum larvae may be substantially reduced in the presence of the brown tide. Red drum larvae consumed 13.5 rotifer $larvae^{-1}$ h^{-1} in control tanks and only 5.1 rotifers $larvae^{-1}$ h^{-1} in tanks which contained brown tide at 1.24 10^6 cells ml^{-1}. Rotifer concentrations were held constant at 3 ml^{-1} in both control and experimental tanks. Zooplankton data from the Laguna Madre (Buskey, this volume) indicates that the density of microzooplankters (the primary food of larval fish) has diminished substantially since the brown tide bloom began. Our hypothesis is that the lack of food means the larvae are starving and in addition, the larvae may be inhibited from feeding on what food is there.

IMPACTS OF BROWN TIDE ON UPPER LAGUNA MADRE FINFISH AND SHELLFISH POPULATIONS

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Brown tide is the latest in a series of natural events to affect Texas coastal waters. Unlike the freezes of 1983 and 1989 and the red tide in 1986, all of which impacted the entire Texas coast, brown tide has mainly affected upper Laguna Madre. There were documented outbreaks of brown tide from Rockport to Port Isabel but they were generally short term. Only in upper Laguna Madre has brown tide persisted continually since May 1990.

Since 1936 most major natural events have been documented somewhere in the literature. Prior to 1936, records of happenings along the Texas coast were not well kept. Ernest Simmons in his study of upper Laguna Madre stated *"Discolored water, often present in upper Laguna Madre, is usually spoken of as red water or bad water. Actually, the water may be reddish, yellowish or even brown. It is not muddy and is not exceptionally turbid as light transmission is normally about 92%. This discolored water is commonly associated with high salinity but not necessarily so. One form of discoloration present in the Point of Rocks area, appears to originate in Baffin Bay".* Simmons goes on to describe several causes for water discoloration but it appears brown tide may have occurred with more regularity in the past than it has in recent years.

For events affecting the natural environment, it is advantageous to have a program in place that can assess impacts of the event with minimal extra effort. It costs money, time and man-power to implement special studies - usually after the fact.

The Coastal Fisheries Branch of the Texas Parks and Wildlife Department (TPWD) has a coastwide monitoring program, including upper Laguna Madre, that has been in place since 1974 to evaluate events such as the brown tide. Two primary objectives of the program are to: 1) Develop long term trend information on finfish and shellfish population abundance and stability; and 2) Monitor select environmental factors which may influence finfish and shellfish availability. These data have enabled us to evaluate impacts of freezes, commercial and sport fishing regulations, algae blooms, red tide, freshwater inflow into the bays and other man-made and natural events on marine fish and shellfish.

To ensure random sampling, upper Laguna Madre has been sectioned into 1 minute latitude by 1 minute longitude grids. Each grid has been further subdivided into 144 "gridlets". With this grid system, each section of shoreline and open bay water has a chance to be sampled, depending on gear used. All sample sites are selected randomly before going to the field.

Three sampling gears are used routinely in upper Laguna Madre. Bag seines are 60 ft. long, 6 ft. deep with 0.75 inch mesh in the wings and 0.50 inch mesh in the bag; 16 different sites are sampled each month. Trawls are 20 ft. wide and have 1.50 inch stretch mesh throughout the trawl; 10 different stations are sampled each month. Gill nets are 4 ft. deep with 150 ft. panels of 3-, 4-, 5- and 6 inch stretched mesh tied end to end with the smallest mesh on shore; 45 overnight gill net sets are made during a 10 week period in both fall and spring. all organisms caught in the gears are processed. At each sample site salinity, dissolved oxygen, temperature and turbidity are determined.

Salinity only declined 4 ppt from January 1990 to May and June when the brown tide started. The 1989 salinities followed a pattern similar to 1990 so there appears to be some other factor triggering brown tide. The June 1991 salinity is the lowest in three years and the brown tide still persists.

Bag seines give us a measure of relative abundance (fish numbers per hectare). Depending on the species, we can either assess the population "as a whole" or assess recruitment. The 1991 bag anchovy population estimate (March-June) is the highest recorded since sampling began. Spotted seatrout recruitment in fall 1990 was slightly below the 13 year average. Black drum recruitment, from June and July combined, was the highest recorded in both 1990 and 1991. The striped mullet 1991 May-June recruitment was the 2nd highest recorded since 1978. The pinfish population estimate (April-July) was much greater than the 13 year average in both 1990 and 1991. For brown shrimp, the 1991 recruitment is slightly above average. Blue crab recruitment was the third highest on record in 1991.

Spring gill nets provide a measure of relative abundance (#/ha) of sub-adults and adults, depending on species. The spring 1991 black drum catch rate is the highest recorded. It is over 2 times greater than the previous spring high which occurred in 1990. Spotted seatrout and red drum catch rates are about average compared to the 1982-1991 period. For hardhead catfish and striped mullet there was a decline in 1991 catch rates compared to 1990.

Based on TPWD data through July 1991, it does not appear brown tide has negatively impacted sub-adult and adult fish and shellfish populations in upper Laguna Madre up to now. Quite the contrary, many prey and predator species have actually increased compared to the period prior to the brown tide event. However, we need to be cautious because it is really too early to predict what the long-term effects will be on the populations if the brown tide persists. Fortunately, the TPWD has a program in place that will allow assessment of these impacts once the brown tide has run its course.

ISOTOPIC INVESTIGATIONS ON THE BROWN TIDE AND PRESENT ECOSYSTEM RELATIONSHIPS IN LAGUNA MADRE

by

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Our Baffin Bay core studies were done on two 20-foot cores. These represent about 2000 years in time. The $\delta^{13}C$ values of the total organic carbon of the sediment varied in a systematic way between -17 and -12. This strongly suggests that in the past 2000 years the Laguna Madre - Baffin Bay system has been dominated first by seagrass then by phytoplankton. The cycle is repeated several times in the 2000 year interval. It is probable that local weather conditions and hurricanes created an environment which was favorable to one or the other of these plant types. The brown tide we see today may represent the phytoplankton dominance which is seen in the cores.

In the two years prior to the brown tide outbreak, the UTMSI isotope chemistry group had been studying short term and long term patterns in the Laguna Madre carbon cycle. The short term studies were directed at food web relationships reflected by stable carbon isotope variations. The long term studies were based on the isotopic records left in the total organic matter of Baffin Bay sediments (cores). For the Laguna Madre, the two major carbon reservoirs, phytoplankton and seagrasses, show isotopic ratios of:

$\delta^{13}C$ seagrass = ~ -10 per mil

$\delta^{13}C$ phytoplankton = ~ -20 per mil

Our studies of $\delta^{13}C$ in redfish and spotted seatrout indicate that seagrass carbon was dominant in fish in the Laguna Madre prior to the brown tide: most fish had $\delta^{13}C$ values of -12 to -14. On the other hand, North Texas fish were -20 to -25, suggesting a plankton and riverine source of carbon. Post brown tide studies of biota have not been done, but are planned. We do know that the brown tide organism has a $\delta^{13}C$ of -20.3.

WORKSHOP RESULTS

The following summary results were developed from verbal and written comments taken by the conveners and the discussion leaders. The wide-ranging ideas and comments brought up during the discussions make it appropriate to summarize them in this tabular, contrasting format. It is apparent that, while common denominators do exist, an underlying mechanism must reconcile many diverse and seemingly, unrelated, factors. Comparison of characteristics of three geographically distinct brown tide blooms was expected to reveal common patterns or fundamental biological processes at work. Based on the environmental and ecological relationships identified in these discussions, research recommendations were formulated for programs to integrate the different types of data and to fill in gaps in the database pertaining to noxious phytoplankton blooms.

Table 1. SUMMARY OF SIMILARITIES AND DIFFERENCES AMONG NEW YORK, RHODE ISLAND, AND TEXAS BROWN TIDE BLOOMS

A. SIMILARITIES

The phytoplankton organisms are small.
The organisms are taxonomically very similar in the three areas.
The organisms excrete organic material.
The intense blooms started in May which could be a function of photoperiod.
There is possible germination or encystment in the bottom sediments which goes pelagic.
The benthic feeding elements disappear from the ecosystem.
Laguna Madre and Peconic Bay are similar in low flushing rates, in contrast to Narragansett Bay.
The ecosystems all experienced drought with sudden rainfalls prior to blooms.
Most of the living carbon is contained in the phytoplankton.
Cellular pigments allow the organism to adapt to a wide range of light environments.
Benthic and pelagic phases appear needed to explain appearance and reappearance.
The blooms must be caused by several factors.
Dredging may be a common element.
The source of the large quantities of nutrients needed to support the bloom is unknown.

B. DIFFERENCES

Laguna Madre has low flushing, while Narragansett Bay has high flushing.
Nutrient enrichment was apparent before the bloom in Laguna Madre.
Laguna Madre is an analog of a coral reef ecosystem.
The Intracoastal Waterway may be analogous to a chemostat.
The freeze of December 1989 may have killed substantial benthic biota on intertidal flats.
Laguna Madre has a reduced diversity in water column and benthos.
Laguna Madre had an order of magnitude more water column chlorophyll.
Laguna Madre had an order of magnitude higher bacterial biomass.
The Laguna Madre organism had carbon/nitrogen ratios of 20-30:1.
Laguna Madre had carbon/chlorophyll ratios of 200-300:1.

Table 2. BROWN TIDE GEOGRAPHIC COMPARISON

<table>
<tr><th rowspan="2"></th><th rowspan="2">Narragansett Bay</th><th colspan="2">Long Island</th><th rowspan="2">Laguna Madre</th></tr>
<tr><th>Peconic Bay</th><th>Great South Bay</th></tr>
<tr><td><u>Characterization</u></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cell density</td><td>10^6/ml</td><td colspan="2">10^6/ml</td><td>10^6/ml</td></tr>
<tr><td>Light reduction</td><td>~ 50%</td><td colspan="2">~ 50%</td><td>~ 50%</td></tr>
<tr><td>Biomass</td><td>22 μg Chl/l</td><td colspan="2">18 μg Chl/l</td><td>44 μg Chl/l</td></tr>
<tr><td>Timing of onset</td><td>May</td><td colspan="2">May, Aug.</td><td>May</td></tr>
<tr><td><u>Causes</u></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Weather</td><td>drought</td><td colspan="2">drought</td><td>drought</td></tr>
<tr><td>Salinity</td><td>?</td><td colspan="2">elevated</td><td>elevated</td></tr>
<tr><td>Watershed use</td><td>↑ urbanization</td><td colspan="2">↑ urbanization</td><td>↑ agriculture</td></tr>
<tr><td>Nutrient input</td><td>pulsed rainfall</td><td colspan="2">pulsed rainfall</td><td>freeze, NH_4</td></tr>
<tr><td>Dredging</td><td>yes</td><td>no</td><td>yes</td><td>yes</td></tr>
<tr><td>Virus</td><td>present</td><td colspan="2">?</td><td>absent</td></tr>
<tr><td>H_2O exchange</td><td>?</td><td colspan="2">reduced</td><td>?</td></tr>
<tr><td><u>Impacts</u></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Shellfish</td><td>↓ mussels</td><td>↓ scallops</td><td>↓ clams</td><td>↓ clams</td></tr>
<tr><td>Seagrass</td><td>No Zostera</td><td colspan="2">↓ Zostera</td><td>?</td></tr>
<tr><td>Benthos</td><td>?</td><td colspan="2">?</td><td>(↓ #s/m^2; ↓ density)</td></tr>
<tr><td>Fish larvae + eggs</td><td>↓</td><td>?</td><td>↑ except bivalve</td><td>↓</td></tr>
<tr><td>Adult fish</td><td>?</td><td colspan="2">?</td><td>↑</td></tr>
</table>

OUTLINE OF INFORMATION NEEDED TO UNDERSTAND BROWN TIDE BLOOMS

A. CAUSAL CONDITIONS

1. Requirements for Bloom

   a. Inoculum source
   b. Growth
   c. Competitive Exclusion Mechanisms
      - growth
      - allelopathy
      - indirect
      - foodweb dynamics

   d. Bloom Decline Mechanisms

2. Causes of Bloom

   a. Climatology
      - short term vs. long term
      - freeze
      - drought/precipitation
      - circulation/winds
      - hindcast using cores to determine variability of climatic factors

   b. Disturbance of Habitat
      - nutrient stimulants
        - nitrogen/phosphorus
        - dissolved organics
      - exotic stimulants from farms or petroleum
        - trace metals
        - Herbicides/pesticides
      - elevated ammonium
      - elevated salinity
      - freeze/fish kill
      - non-point runoff
      - dredging

   c. Abnormal Existing Food Chain Conditions
      - low diversity food chain populations (*Chrysophyte, Acartia, Streblospio*)
      - interference with grazing processes
        - algal toxicity/toxic fatty acids
        - palatability
        - threshold grazing response
        - top down removal of primary consumers
      - absence of algal pathogens
        - mutations
      - ecosystem carrying capacity
      - meteorology/hydrography removal of key species

B. AUTECOLOGY

1. Identification of Bloom Organism

    a. Fluorescent probe
    b. Chemical biomarker
    c. HPLC pigment biomarker

2. Field Studies During Non-bloom Conditions

3. Laboratory Culture Studies

    a. Life history
        - cyst formation
    b. Physiology and growth rates
        - temperature
        - salinity
        - light
        - nutritional aspects
        - trace metal factors
            - humics
    c. Chemical composition of cell material
        - carbohydrates
        - fatty acids
        - sterols
        - elemental ratios

C. EFFECTS OF BROWN TIDE ON SEAGRASSES

1. Survey Laguna Madre for Seagrass Distribution

    a. Biomass
    b. Chlorophyll
    c. Root penetration

2. Continuous *In Situ* Irradiance Measurements

    a. Deep beds near depth limit
    b. Shallow beds near edge
    c. Shallow beds in center

3. Physiological Responses

    a. Stored Carbohydrate Reserves
    b. Dissolved organic carbon Release
        ethanol
        other

    c. Allocation of chlorophyll in plant
    d. Utilization of Sediment Nutrients

4. Epiphyte-Irradiance Interactions

D. EFFECTS OF BROWN TIDE ON PHYTOPLANKTON CONSUMER POPULATIONS

1. Laboratory Grazing Studies on Microzooplankton

   a. Dilution experiments
   b. Gut pigment analysis

2. Laboratory Grazing Studies on Larval Fish

3. Mesocosm Experiments

   a. Threshold of grazing inhibition
   b. Grazing rates of zooplankton
   c. Grazing studies on shellfish, especially *Mulinia*

4. Field Surveys for concentrations of Shellfish and Larval Fish as related to brown tide abundance.

E. ECOSYSTEM EFFECTS OF BROWN TIDE

1. Fisheries/Economic Declines

   a. Scallops, mussels and clams
   b. Larval finfish
   c. Tourism (avoidance)
   d. Aquaculture problems

2. Habitat Degradation

   a. Loss of seagrasses
   b. Loss of biodiversity
   c. Loss of ecosystem stability
   d. Loss of utilization without seagrass loss

3. Environmental/Ecological

   a. Change in ecosystem nitrogen budget
   b. Change in ecosystem carbon budget
   c. Change in trophic structure
   d. Replacement of desirable species
   e. Change in quality

4. Alterations in Natural Cycles vs. Anthropogenic Inputs

   a. Natural Cycles
      - geological
      - global
      - climatic
   b. Anthropogenic Inputs
      - acute
      - chronic

F. ENVIRONMENTAL MONITORING, PROTECTION AND MANAGEMENT

1. Long Term Monitoring is Vital

    a. Water Column Monitoring for noxious phytoplankton
        Use fluorescence probe technique
        Goal is pre-bloom detection
    b. Remote Sensing Applications for broad scale monitoring of blooms
    c. Trend Monitoring needed on coastwide basis
        Water quality in each estuary
        Indicator organisms in each estuary
    d. Develop Citizen Participation Mechanism
        Example: colored Water Telephone Number
    e. Continue Studies on Basic Biology with goal of predicting grown tide outbreaks

2. Interagency Coordination and Cooperative Programs

    a. Texas Water Commission
        Water quality monitoring
    b. Texas Parks and Wildlife Surveys
        Coastal Habitat Mapping
    c. Texas Water Development Board
        Inflow and bay circulation modeling
    d. U.S. Fish and Wildlife Service
        Seagrass Surveys and habitat trends

3. Develop Long Term Funding Mechanisms for Coastal Assessment

    a. EMAP Program
    b. Gulf of Mexico Program
    c. State Programs

RECOMMENDATIONS FOR PRIORITY RESEARCH:

The following projects were recommended for priority research to improve our knowledge base of brown tide blooms. They should be addressed in the near future because they could provide new and critical information about 1) the presence or absence of the brown tide organism, 2) the ability of grazing zooplankton populations to utilize the brown tide organism, and 3) the physiology of this phytoplankton in various salinity environments. Such information on causal conditions and autecology of the organism was identified as the major deficiencies in understanding the mechanism(s) that triggers the bloom. The first three recommendations were specifically directed to answer questions associated with the ongoing Laguna Madre event. These research objectives were considered accomplishable in a limited amount of time (i.e. over the next 9-12 months) while the Texas brown tide might still persist. The last three recommendations refer to the synthesis and integration of results after the short-term research is completed.

1. Continue monitoring brown tide bloom dynamics through growth rate, carbon content, and chlorophyll content analyses and establish clear relationships of phytoplankton with environmental and hydrographic factors.
2. Develop a fluorescent probe immunochemical technique to aid in identification and monitoring of brown tide cells at low ambient concentrations.
3. Establish grazing thresholds for zooplankton and fish larvae presence of brown tide cells.
4. Publish results of Laguna Madre brown tide research in a single volume which would focus on brown tide bloom mechanisms and effects.
5. Use comparative approach to analyze data between Narragansett vs. Long Island vs. Texas.
6. Join with other U.S. and International groups for federal support of further research on noxious phytoplankton blooms.

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