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A diatom dataset and diatom-salinity inference model for southeast Australian estuaries and coastal lakes

Krystyna M. Saunders

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Abstract To quantify the relationship between diatom species assemblages and the water chemistry of southeast Australian estuaries and coastal lakes, a new dataset of 81 modern diatom samples and water chemistry data was created. Three hundred and ninety-nine species from 53 genera were identified in 36 samples from 32 coastal water bodies in eastern Tasmania and 45 samples from 13 coastal water bodies in southern Victoria. Multivariate statistical analyses revealed that the sampling sites were primarily distributed along salinity and nutrient gradients, and that salinity, nitrate + nitrite, phosphate and turbidity explained independent portions of variance in the diatom data. Species salinity optima and tolerances were determined and a diatom-salinity inference model (WAinv $r^2 = 0.72$, r^2jack $= 0.58$, RMSEP $= 0.09$ log ppt) was developed. This new information on diatom species' salinity preferences provides a useful tool for quantitatively reconstructing salinity changes over time from diatom microfossils preserved in the sediments of a range of estuaries and coastal lakes in southeast Australia. This is valuable for studies investigating long-term human impacts and climate change in the region.

Keywords Diatoms · Multivariate analyses · Transfer function · Australia · Water quality · Coast

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K. M. Saunders (✉)
Institute of Geography and Oeschger Centre for Climate Change Research, University of Bern, Bern 3012, Switzerland
e-mail: krystyna.saunders@giub.unibe.ch

K. M. Saunders
Institute of Antarctic and Marine Studies, University of TAS, Hobart, Tasmania 7001, Australia

Introduction

Diatoms are excellent indicators of environmental change in aquatic ecosystems as many taxa have distinct ecological requirements, limited tolerances to different water quality parameters and are highly sensitive to changes in their environment (Reid et al. 1995). Quantitative methods for relating diatom assemblages and water chemistry include modern calibration datasets and diatom inference models (i.e. transfer functions). These can be applied to sub-fossil diatom assemblages in sediment cores to reconstruct past water chemistry and to investigate past environmental and climate changes (Birks 1998). Much published work has been focused on inland lakes (e.g. Fritz et al. 1991; Bennion et al. 1996; Bigler and Hall 2003) but there are relatively few equivalent datasets for coastal lake and estuarine environments. However, some inference models have been developed and applied (e.g. Juggins 1992; Gehrels et al.

2006; Ryves et al. 2004; Ellegaard et al. 2006; Horton et al. 2006; Weckström et al. 2004; Hassan et al. 2009). In Australia, diatom inference models for coastal lake and estuarine environments have so far been developed for relatively small geographic regions (e.g. Hodgson et al. 1996; Saunders et al. 2007, 2008; Taffs et al. 2008). Yet in some studies it is desirable to have diatom-based inference models that span a wider range of modern analogues, over a wider geographic area to better encompass the range of variability encountered in sub-fossil deposits. This is particularly important in regions that have experienced diverse and extensive environmental changes and/or human impacts, such as parts of coastal Australia. The development of larger, combined datasets has previously been undertaken in Africa (e.g. Gasse et al. 1995), Europe (e.g. Juggins 2004; Bennion 2010) and North America (e.g. Wilson et al. 1996).

Many Australian ecosystems have been highly modified since European settlement and with the majority of the population (85%, SoE 2006) living in coastal regions, water quality is a key issue for environmental managers. Diatoms are recognised as one of the potentially most useful groups for water quality assessments in Australia (ANZECC 2000), but limited information regarding their ecological preferences has, to date, restricted their use. This paucity of data along Australia's extensive coastline needs to be addressed if diatoms are to be more widely applied to long term monitoring and management of the coastal zone.

This paper presents a new dataset quantifying the relationship between diatom species assemblages and the water chemistry of southeast Australian estuaries and coastal lakes. It extends a previously published dataset from Victoria (Saunders et al. 2008) with 36 sites from eastern Tasmania. The addition of the Tasmanian sites is useful because many of them have experienced only minor or transitory human impacts compared with their Victorian counterparts, and therefore provide additional potential analogues for diatom assemblages associated with pre-impact conditions in sediment cores. The specific aims of this study were to (a) provide species-level data on the composition and distribution of surface sediment diatom species assemblages in coastal water bodies in southeast Australia; (b) investigate and identify the environmental gradients influencing diatom species distributions and individual species ecological preferences; (c) develop inference models (i.e. transfer functions) based on the relationship between diatom species assemblages and environmental variables; and (d) discuss potential applications of the inference model to ecological and paleoecological investigations, with the aim of providing information to facilitate better environmental management.

Materials and methods

Study area

Rising sea levels last submerged the land bridge between Tasmania and Victoria approximately 13,000 years ago and the present coastline started forming near the end of the post-glacial marine transgression approximately 7–8,000 years ago. The coastline of the study area consists of quartzose beaches and dunes with a small number of calcareous beaches and dunes west of Wilson's Promontory. Geomorphological characteristics of the coastal estuarine habitats range from semi-enclosed bays that are characterize by marine waters with little fresh water inflow through to coastal water bodies that are brackish and rarely, if ever, connected to the ocean. The nature of these connections to the ocean determines the exchange of water and the salinity of these water bodies.

Climatologically southeast Australia has a variable, temperate climate (BOM 2009). Victoria's climate is typified by warm summers and mild winters and the climate is dominated by the El Niño Southern Oscillation (ENSO), with El Niño events often leading to drought and La Niña events sometimes resulting in flooding (BOM 2009). Tasmania's climate has four distinct seasons, with rainfall greatest in winter. The eastern half of the island is in the rain-shadow of the west and is more influenced by the ENSO. Victorian coastal systems experience seasonally variable rainfall, are infrequently flushed, not often stratified and tend to be more nitrogen-limited. Tasmanian coastal systems tend to receive more regular rainfall, are more commonly vertically stratified, frequently flushed and more likely to be phosphorus-limited (Davis and Koop 2006). The coastlines of both regions contain many coastal water bodies of high conservation value that range from small, closed lakes to large, open estuarine systems.

These systems support the majority of the human population in both regions as well as key industries. They are consequently of significant environmental, societal and economic importance.

Sample collection

Thirty-six sites from 32 coastal water bodies in Tasmania were sampled and combined with the Victorian dataset (Saunders et al. 2008), which consisted of 45 sites from 13 coastal water bodies, creating a merged dataset of 81 sites. Sites spanned >1,500 km of coastline (37.50°S–42.92°S and 144.4°E–149.7°E, Fig. 1, Table 1). Water chemistry was measured both in August 2004 and February 2005 in order to capture some of the seasonal variation in limnology. Salinity, temperature, pH, turbidity and dissolved oxygen were measured in situ with a Horiba U-10 Water Quality Checker at 1 m water depth. Duplicate 10 mL water samples were collected for soluble reactive phosphate (referred to as phosphate hereafter), nitrate + nitrite and silicate analyses. Sample tubes were rinsed several times in lake/estuarine water at each site prior to collection. Samples were then frozen and analyzed using a Lachat Instrument (Injection Flow Analyzer) at the Commonwealth Scientific and Industrial Research Organization Marine and Atmospheric Laboratories, Hobart, within two months of collection. The auto-analyzer uses the principles of colorimetric analysis in a continuous flow system with all manipulations of the samples automated. Each analytical channel was calibrated using standards of known concentration (Eriksen 1997). The water chemistry measurements for each site were combined to determine a mean value for each variable for the statistical analyses.

Surface sediment samples (top 1 cm), which provide a spatially and temporally integrated sample of the diatom communities at each site (Lim et al. 2007), were collected from approximately 1 m water depth using a hand-operated gravity corer (Glew 1991). Surface sediment samples were collected at the end of the water sampling period (February 2005) to ensure that the diatom species identified more closely corresponded with the water chemistry measured. The number of samples taken from each water body was variable (ranging from 1 to 14 sites), depending on size and complexity, to try and account for spatial variability in diatom habitats and water chemistry.

Diatom preparation and analysis

Diatom samples were prepared following standard methods (Battarbee 1986). At least 400 frustules per sample were counted using oil immersion at 1000× magnification on a Zeiss 20 light microscope. The relative abundance of all species (including unidentified forms) was recorded as a percentage of the total number of frustules counted (Battarbee et al. 2001). Taxonomy was principally based on Australian taxonomic literature (i.e. Hodgson et al. 1997; John 1983; Sonneman et al. 2000) and datasets (i.e. Hodgson et al. 1996; Saunders et al. 2007; Taffs 2005), with additional reference to European coastal diatom taxonomic references (e.g. Witkowski et al. 2000). As diatom taxonomy requires further development in this region (see Vyverman et al. 1995) all taxa were photographed and are archived with the author.

Statistical analyses

Multivariate statistical analyses were used to identify major environmental gradients, explore diatom-environment relationships and identify environmental variables that explained independent portions of the variance in the diatom data.

Prior to statistical analyses, each environmental variable was checked for skewness, and nutrients and turbidity were $\log(x + 1)$ transformed. Principal Components Analysis (PCA) was performed on the environmental data to determine the major environmental gradients. Detrended Correspondence Analysis (DCA) with detrending by segments and downweighting of rare species was performed on the species data to establish whether species distribution was unimodal or linear. As gradient lengths were greater than 2 standard deviation units, unimodal ordination techniques were used (ter Braak 1995). Species data were $\log(x + 1)$ transformed in an attempt to stabilize the variance in the dataset (Birks et al. 2001).

A series of Canonical Correspondence Analyses (CCA) were performed with scaling focused on inter-species distances, biplot scaling and downweighting of rare species. Variance Inflation Factors (VIFs) were identified and any environmental variables with VIFs > 20 were removed. A series of CCAs of each environmental variable alone was performed, followed by CCAs of individual environmental variables with the remainder as covariables (i.e. forward

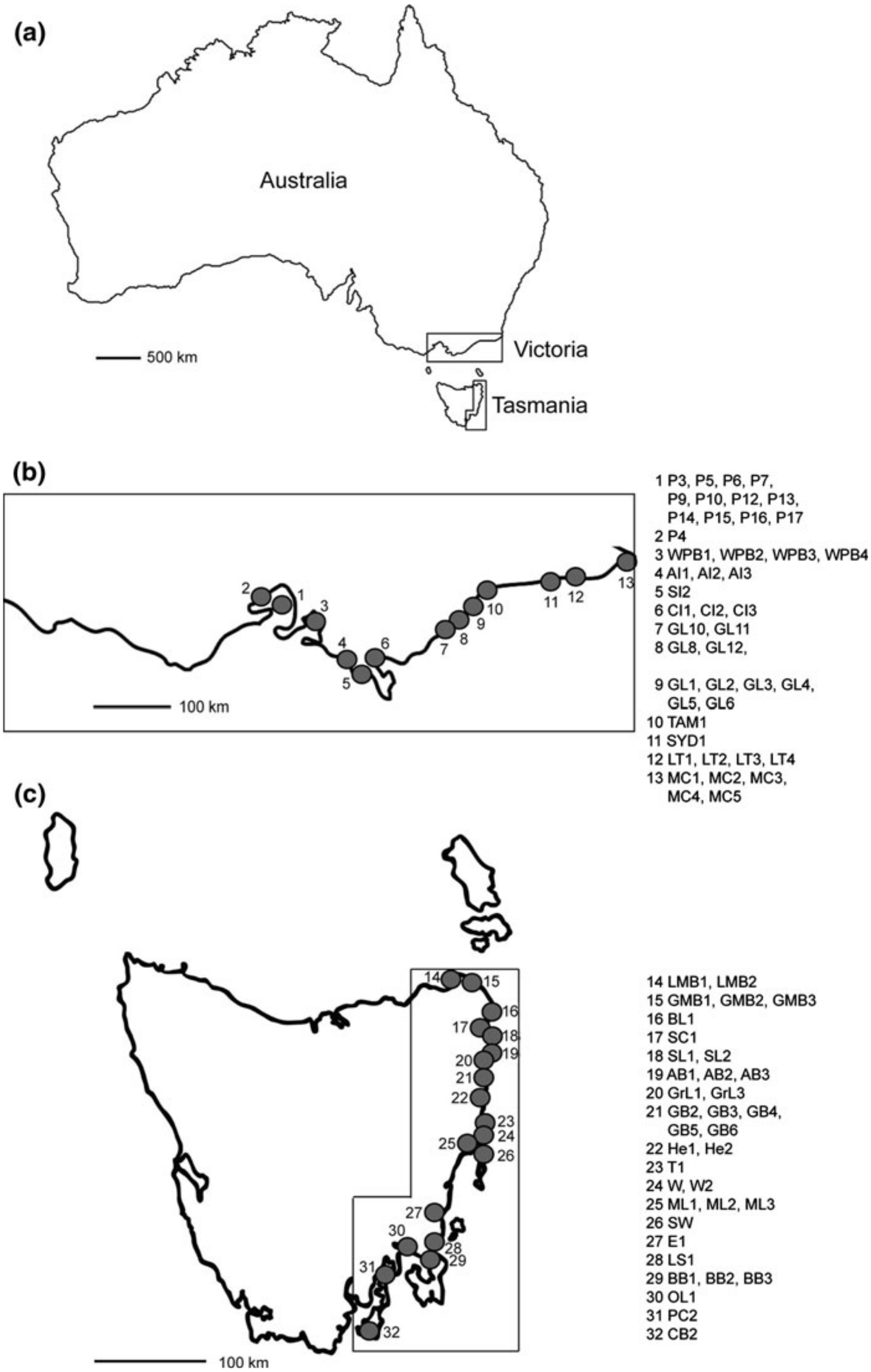

Fig. 1 **a** Location of study area; **b** location of sampling sites in Victoria and **c** Tasmania with specific sites numbered. See Supplementary Material for specific locations and details of sampling sites

selection) to determine which made independent, significant contributions to explaining the variation in the species data (i.e. $p < 0.05$, based on 999 Monte Carlo permutation tests without Bonferroni or other adjustments). Variance partitioning was used to determine the amount of variation explained by each variable and the interaction between them. Detrended Canonical Correspondence Analysis (DCCA), where the ratio of the constrained axis (axis 1) to the first unconstrained axis (axis 2) should be >0.5 (Kingston

Table 1 Summary of estuaries and coastal lakes in the dataset

No.	Name	Site code(s)	State	Location	Estuary type	Area (km^2)	Tidal range (m)	Opening √, √/x, x	Status
1	Port Phillip Bay	P3, P5, P6, P7, P9, P10, P12, P13, P14, P15, P16, P17	Vic	144 84′E 37 86′S	WDE	193	1.2	√	Modified
2	Cherry Lake	P4	Vic		CL	0.5	0	x	Extensively modified*
3	Western Port Bay	WPB1, WPB2, WPB3, WPB4	Vic	145 20′E 38 25′S	WDE	469	2.3	√	Modified
4	Andersons Inlet	AI1, AI2, AI3	Vic	145 20′E 38 35′S	WDE	12.7	2	√	Modified
5	Shallow Inlet	SI2	Vic	146 10′E 38 50′S	WDE	5	n/a	√	Largely unmodified
6	Corner Inlet	CI1, CI2, CI3	Vic	146 20′E 38 45′S	WDE	377	n/a	√	Largely unmodified
7	Lake Wellington	GL10, GL11	Vic	147 20′E 38 08′S	WDE	138	0.9	√/x	Extensively modified
8	Lake Victoria	GL8, GL12	Vic	147 32′E 38 02′S	WDE	110	0.9	√	Extensively modified
9	Lake King	GL1, GL2, GL3, GL4, GL5, GL6	Vic	147 45′E 37 55′S	WDE	92	0.9	√	Extensively modified
10	Tamboon Inlet	TAM1	Vic	149 08′E 37 45′S	WDE	10	n/a	√	Largely unmodified
11	Sydenham Inlet	SYD1	Vic	148 59′E 37 46′S	WDE	10	n/a	√	Largely unmodified
12	Lake Tyers	LT1, LT2, LT3, LT4	Vic	148 09′E 37 86′S	WDE	13.1	0.9	√	Largely unmodified
13	Mallacoota Inlet	MC1, MC2, MC3, MC4, MC5	Vic	149 48′E 37 32′S	WDE	5	n/a	√/x	Near pristine
14	Little Mussleroe Bay	LMB2, LMB2	Tas	148 04′E 40 76′S	CL	0.5	1.2	√/x	Modified
15	Great Musselroe Bay	GMB1, GMB2, GMB3	Tas	148 17′E 40 83′S	WDE	3.4	1.3	√/x	Modified
16	Big Lagoon	BL1	Tas	148 16′E 41 11′S	CL	0.5	0	x	Near pristine
17	Swimcart Lagoon	SC1	Tas	148 19′E 41 14′S	CL	0.03	0	x	Near pristine*
18	Sloop Lagoon	SL1, SL2	Tas	148 16′E 41 12′S	CL	0.3	0	x	Near pristine
19	Ansons Bay	AB1, AB2, AB3	Tas	148 16′E 41 03′S	WDE	5	1.3	√	Modified
20	Grants Lagoon	GrL1, GrL3	Tas	148 17′E 41 15′S	WDE	0.5	0	x	Modified
21	Georges Bay	GB2, GB3, GB4, GB5, GB6	Tas	148 33′E 41 27′S	WDE	21.1	0.7	√	Modified
22	Henderson Lagoon	He1, He2	Tas	148 16′E 41 29′S	WDE	1	0.3	√/x	Modified
23	Templestowe Lagoon	T1	Tas	148 17′E 41 44′S	WDE	0.55	0.1	√/x	Modified*
24	Wrinklers Lagoon	W, W2	Tas	148 15′E 41 26′S	CL	0.07	0	x	Near pristine*
25	Moulting Lagoon	ML1, ML2, ML3	Tas	148 11′E 42 01′S	WDE	40	0.5	√	Near pristine
26	Saltwater Lagoon	SW	Tas	148 16′E 42 03′S	CL	0.2	0	x	Near pristine*
27	Earlham Lagoon	E1	Tas	147 57′E 42 39′S	WDE	0.23	0.4	√	Modified
28	Little Swanport	LS1	Tas	147 58′E 42 20′S	WDE	5	0.6	√	Modified
29	Blackman Bay	BB1, BB2, BB3	Tas	147 51′E 42 42′S	WDE	27	0.8	√	Modified

Table 1 continued

No.	Name	Site code(s)	State	Location	Estuary type	Area (km^2)	Tidal range (m)	Opening √, √/x, x	Status
30	Orielton Lagoon	OL1	Tas	147 61′E 42 85′S	WDE	0.5	1.2	√	Extensively modified
31	Pipeclay Lagoon	PC2	Tas	147 31′E 42 58′S	WDE	5	0.7	√	Modified*
32	Cloudy Bay Lagoon	CB2	Tas	147 14′E 43 26′S	WDE	6	0.4	√	Near pristine

No. corresponds to Fig. 1, *WDE* wave dominated estuary, *CL* coastal lagoon (as defined by Ryan et al. 2003), status is determined by NLWRA (2000), except where highlights with *. These sites were not included in NLWRA (2000) and their status is designated by the author, based on NLWRA (2000) guidelines. √ = permanently open, √/x = intermittently open, x = closed to the sea

et al. 1992), was used to determine which environmental variable was most suitable for transfer function development (Birks 1998). All ordinations were performed using the software program R (R Development Core Team 2006) and CANOCO 4.5 for Windows (ter Braak and Smilauer 2002).

Species ecological preferences (i.e. optima and tolerances) were determined using simple Weighted Averaging (WA) on untransformed species data. Transfer functions were developed using simple WA with inverse and classical deshrinking and with/without tolerance downweighting, and Weighted Averaging Partial Least Squares (WAPLS) to determine which technique led to the best performing transfer function. Performance was assessed using leave-one-out cross validation (i.e. jackknifing, Birks 1998). When assessing which model to use, a WAPLS model with a higher number of components was only accepted if there was $\geq$5% improvement in RMSEP over alternatives with less components (Birks 1998). Sites were selected for deletion based on visual inspection of the residual difference between predicted and observed salinity, with outliers removed until model performance did not improve. Species ecological preferences and transfer functions were determined using the software program C2 version 1.4 (Juggins 2003).

Results

Environmental data and diatom assemblages

The water chemistry data for Tasmanian and Victorian estuaries and coastal lakes that were sampled are summarized and outlined in Tables 2 and 3. Salinity ranged from near fresh to hypersaline, while nutrient concentrations ranged from oligotrophic to eutrophic. In general, the Victorian sites had poorer water quality, as represented by higher nutrient and lower dissolved oxygen concentrations than the Tasmanian sites. Information for each site is provided in the Supplementary material.

PCA of the environmental data showed that the first two axes explained 42% of the variation in the environmental data. Variation along the first axis was explained by nitrate + nitrite, while variation along the second axis was explained by pH (Fig. 2).

In total, 399 diatom species were identified from 53 genera. Of these, 186 species (47%) were common

Table 2 Summary of water quality data for Tasmanian and Victorian sites

	Mean	Median	Min	Max	Mean	Median	Min	Max
	Dissolved oxygen (mg L^{-1})				Nitrate + nitrite (μg N L^{-1})			
Tasmania	9.28	9.58	4.06	13.0	8.00	7.17	3.02	52.5
Victoria	4.99	4.50	0.61	18.9	63.4	2.04	0.00	696
All sites	6.89	6.71	0.61	18.9	38.4	2.43	0.00	696
	pH				Phosphate (μg P L^{-1})			
Tasmania	7.90	7.79	7.10	8.87	8.24	4.76	1.13	67.5
Victoria	7.94	7.96	7.46	8.46	47.7	13.5	0.00	348
All sites	7.92	7.94	7.10	8.87	30.2	6.27	0.00	348
	Salinity (ppt)				Silicate (μg Si L^{-1})			
Tasmania	25.0	29.1	1.75	35.3	345	280	46.0	1132
Victoria	27.7	31.1	0.75	40.0	410	305	55.3	1291
All sites	26.5	29.6	0.75	40.0	380	290	46.0	1291
	Temperature (°C)				Turbidity (NTU)			
Tasmania	15.1	15.3	10.4	18.7	18.8	6.5	0.0	151
Victoria	16.2	16.4	9.6	19.2	17.1	6.0	0.0	140
All sites	15.7	15.9	9.6	19.2	17.8	6.0	0.0	151

N nitrate-nitrite, *P* phosphate, *Si* silicate

between Tasmania and Victoria. Most of the diatom taxa were benthic. Thirty-five percent were rare (occurring only once), while 46% occurred at low (<1%) relative abundance. Thirty-nine species were abundant (i.e. ≥10% maximum relative abundance in one or more samples, Table 4), while 29 were widespread (i.e. occurring in ≥20 sites). *Opephora guenter-grassii* (Witkowski and Lange-Bertalot) Sabbe and Vyverman, and *Planothidium hauckianium* agg. (Kützing) Round and Bukhtiyarova were the most abundant and widespread: *Opephora guenter-grassii* occurred in 67 (83%) sites with 47.6% maximum relative abundance; *Planothidium hauckianium* agg. occurred in 78 (96%) sites with 57.5% maximum relative abundance. For the statistical analyses, only those species occurring with a maximum relative abundance ≥2% and in ≥2 samples were included, resulting in a total of 141 taxa. All taxa are listed in the Supplementary material (including their mean and maximum relative abundances).

Multivariate analyses: diatom-environment relationships

An initial CCA indicated the environmental data explain 16.3% of the variation in the diatom data (Table 5). As all VIFs were <10, all environmental variables were retained. Salinity was correlated to axis 1, while the remaining variables were correlated to both axis 1 and axis 2 (Fig. 3). Nitrate + nitrite, phosphate, salinity and turbidity explained independent portions of the variance in the diatom data (as determined by forward selection) and CCA of these variables indicated they explained 10% of the variation in the diatom data (Fig. 3, Table 5). Variance partitioning indicated that 7.3% of the variation in the diatom data was due to these environmental variables alone and the total interaction between them was 1.3% (Fig. 4). Salinity explained the most variation (2.6%), followed by phosphate (2.0%), nitrate + nitrite (1.7%) and turbidity (1.0%). The greatest interaction occurred between nitrate + nitrite and the other variables (0.6%).

To determine which, if any, of the environmental variables were suitable for transfer function development, DCCA was performed with axis 1 constrained to each environmental variable in turn, with axis 2 left unconstrained. DCCA indicated that salinity was suitable (i.e. $\lambda_1/\lambda_2 = 0.6$).

Species optima and tolerances and model development

Simple WA was used to determine species optima and tolerances for salinity. Information for all species

Table 3 Water chemistry results for sites in the dataset

Code	Latitude (°S)	Longitude (°E)	Silicate (μg Si L^{-1})	Phosphate (μg P L^{-1})	Nitrate + nitrite (μg N L^{-1})	Salinity (ppt)	pH	Temp. (°C)	Turbidity (NTU)	Dissolved oxygen (mg L^{-1})
AB1	−41.0625	148.289	306.51	3.79	8	31.9	8.08	16.2	2	10.1
AB2	−41.0536	148.27	365.88	67.46	2.28	30.3	7.77	16.1	151	5.6
AB3	−41.0366	148.285	298.04	4.8	1.27	30	8.13	15.7	1	10.45
AI1	−38.6734	145.797	1290.96	81.72	389.25	11.4	7.89	17.6	73	4.52
AI2	−38.6614	145.783	864.33	42.78	164.78	23.1	7.84	16.3	16	0.79
AI3	−38.6617	145.77	422.3	19.17	33.12	30	7.88	16.8	23	5.42
BB1	−42.8466	147.844	48.37	2.59	2.43	33.6	8.11	15.5	0	9.19
BB2	−42.8905	147.809	58.28	1.13	2.19	33.3	8.06	15.6	1	9.4
BB3	−42.8905	147.809	93.29	12.82	52.5	33.7	8.23	17.8	1	11.37
BL1	−41.1847	148.267	639.01	2.96	3.33	11.6	7.1	11	8	10.25
CB2	−42.959	147.524	92.98	2.03	4.08	32.7	7.91	13	8	5.4
CI1	−38.7008	146.455	104.55	1.66	2.12	34.3	8.03	17.2	3.5	0.61
CI2	−38.691	146.336	211.59	13.71	0.62	33.8	8.13	17.4	32.5	1.3
CI3	−38.8136	146.267	55.26	1.75	0.57	34.6	8.46	19	1.5	1.58
E1	−42.6545	147.939	83.6	2.59	2.19	33.6	7.98	14.4	7	7.9
GB2	−41.2952	148.273	204.95	3.69	6.58	31.4	7.81	12.5	8	7.69
GB3	−41.3112	148.27	161.69	2.65	2.75	32.1	7.91	13.9	0	9.65
GB4	−41.3316	148.248	258.6	7.03	4.9	33	7.73	14	7	9.9
GB5	−41.3254	148.298	175.09	6.01	5.17	31.8	7.85	13.7	7	9.3
GB6	−41.3035	148.315	151.59	10.13	15.13	32.6	7.46	13.9	5	8.82
GL1	−37.8788	148.004	270.28	29.92	0.08	24.7	8.13	16	1.5	3.44
GL2	−37.8837	147.978	437.71	2.25	0.4	24.6	8.09	15.4	2.5	3.18
GL3	−37.8826	147.975	444.49	2.15	0.04	23.9	8.06	15.7	6	3.33
GL4	−37.8839	147.89	282.24	2.66	0.01	21.7	8.09	15.4	0.5	3.32
GL5	−37.8986	147.855	289.8	6.29	0.02	21.3	8.16	15.5	1.5	3.32
GL6	−37.9276	147.711	550.73	13.98	1.31	20.9	8.07	14.7	0.5	1.53
GL8	−37.8939	147.684	337.54	13.5	0.29	21.4	8.16	16.3	1	3.3
GL10	−37.8876	147.677	1184.42	26.1	13.33	12	8.04	16	5	3.02
GL11	−37.8823	147.718	1080.08	10.16	14.52	9.6	8	15.8	9	3.27
GL12	−37.8823	147.718	474.44	25.52	0.1	20.9	8.14	16.7	4	6.2
GrL1	−41.2539	148.287	320.34	1.55	0	29.1	7.88	14.7	5	10
GrL3	−41.2535	148.298	445.39	2.17	0	27.8	7.67	14.9	29	8.72
GMB1	−40.8324	148.176	731.91	8.52	33.46	14.5	7.94	16.7	11	10.7
GMB2	−40.8361	148.176	236.71	5.65	16.49	20.3	8.22	18.4	5	12.95
GMB3	−40.8399	148.174	390.08	5.23	16.07	18.4	8.11	18	6	11.62
He1	−41.4789	148.252	194	6.3	9.49	29.6	7.89	14.4	26	9.2
He2	−41.5051	148.269	1132.13	15.43	6.04	23.6	7.85	13.7	10	10.25
LMB1	−40.7657	148.035	286.42	2.2	3.96	29.1	8.26	18.3	1	6.05
LMB2	−40.7659	148.034	292.38	5	3.17	27.2	8.12	18.7	0	8.72
LS1	−41.9949	147.989	118.51	4.12	2.87	32.6	7.94	14.2	3	5.95
LT1	−37.8532	148.084	185.02	11.18	1.86	35.6	7.75	16.4	5.5	2.45
LT2	−37.8529	148.063	149.67	4.63	1.5	36.1	7.65	16.5	18	4.77
LT3	−37.8357	148.074	322.63	2.06	2.4	35.8	7.69	16.3	1.5	4.03

Table 3 continued

Code	Latitude (°S)	Longitude (°E)	Silicate (μg Si L^{-1})	Phosphate (μg P L^{-1})	Nitrate + nitrite (μg N L^{-1})	Salinity (ppt)	pH	Temp. (°C)	Turbidity (NTU)	Dissolved oxygen (mg L^{-1})
LT4	−37.8123	148.057	465.66	11.97	0.36	27.7	7.64	17.5	6	4.5
MC1	−37.5099	149.692	842	2.69	0.16	25.6	7.81	16.5	8	5.53
MC2	−37.4993	149.702	569.63	5.22	2.58	25.3	7.84	16.9	7	6.91
MC3	−37.5327	149.74	242.19	3.31	0.85	24.7	7.93	15.7	3	6
MC4	−37.5367	149.742	137.17	4.14	2.04	25.8	7.98	15.7	6	6.71
MC5	−37.511	149.702	469.13	1.35	0.02	26.2	7.91	16.8	1.5	5.33
ML1	−41.2678	148.192	274.42	11.63	1.23	29	8.22	15.7	2	11.46
ML2	−42.0285	148.221	685.36	11.55	1.16	11.2	7.98	15.9	36	10.15
ML3	−41.9924	148.245	545.84	28.79	0.19	6.5	7.76	15.6	109	7.61
OL1	−42.959	147.524	98.29	7.12	1.06	35.3	8.19	18.2	150	4.06
P3	−37.86	144.866	183.38	68.33	28.25	33	7.63	9.6	6	2.99
P4	−37.8639	144.838	973.33	100.57	434.17	0.8	8.39	16.3	139.665	2.22
P5	−37.8746	144.817	84.72	264.43	1.55	34.1	8	16.9	12.5	1.64
P6	−37.9543	144.721	304.65	199.27	696.14	33.7	7.97	17.1	47	1.41
P7	−37.9718	144.699	264.62	195.11	586.14	34.2	8.01	17.3	36.5	1.42
P9	−38.0292	144.563	154.45	347.61	25.04	34.7	8.05	19	10	1.6
P10	−38.0865	144.424	148.63	140.13	0.95	36.5	8.22	19.2	7.25	1.85
P12	−38.1599	144.455	261.99	64.33	4.76	35.6	8.11	17	2	7.71
P13	−38.1164	144.671	62.48	48.85	1.93	34.9	7.96	15	0	6.03
P14	−38.1616	144.714	225.53	161.75	4.31	40	8.05	11.8	131	11.93
P15	−38.369	144.858	258.69	55.97	1.94	33.7	7.92	17	1	7.77
P16	−38.0992	144.782	331.19	59.1	97.35	33.5	7.67	13.8	2	18.9
P17	−38.0864	145.463	418.99	55.6	189.33	31.1	7.94	17	5	9.58
PC2	−42.959	147.524	45.97	3.62	1.17	33.2	8.02	17.3	3	8.49
SC1	−41.2299	148.282	452.35	15.16	2.03	1.8	7.27	10.4	19	11.15
SI2	−38.8423	146.151	86.14	16.91	4.71	33.9	7.92	15.6	24.5	5.57
SL1	−41.2091	148.272	110.78	4.03	12.82	19.4	7.79	11.2	0	10.2
SL2	−41.2043	148.26	304.7	3.75	11.29	4.9	7.29	12.5	14	10.21
SW	−41.4401	148.27	940.9	13.07	0.14	20.2	8.87	15.3	5	12.65
SYD1	−37.7625	148.971	355.3	3.79	6.35	16.4	7.63	15.6	14	9.77
TAM1	−37.7434	149.136	891.7	5.87	1.08	19	7.46	15.1	10	8.46
T1	−41.7238	148.272	1068.1	4.71	1.72	28.6	7.75	15.3	23	9.5
W1	−41.4401	148.27	152.67	3.21	19.94	13.8	7.59	13.7	8	10.4
W2	−41.4401	148.27	670.69	4.31	1.17	14	7.62	18.1	4	8.96
WPB1	−38.4094	145.419	274.37	1.55	7.19	33.3	7.9	17.5	7.5	5.31
WPB2	−38.3082	145.52	835.57	11.83	71.01	32	7.76	18	44.5	4.52
WPB3	−38.217	145.376	461.25	4.74	57.04	32.1	7.79	18.9	22.5	6.44
WPB4	−38.3755	145.221	84.24	0	0	34	7.68	12.4	9	14.98

is provided in the Supplementary material and is summarized in Fig. 5. There were clear differences in the relative abundance of the most common diatoms along the salinity gradient (Fig. 6). For example, *Diatomella* cf. *balfouriana* Greville was most abundant at low (<5 ppt) salinity sites, *Rhopalodia acuminata* Krammer and *Cyclotella choctawhatcheeana* Prasad were most abundant at brackish (5–30 ppt)

Table 4 Number of occurrences (N), effective number of occurrences (Hill's N^2) (Hill 1973), maximum relative abundance, and weighted averaging salinity optima (WA opt) and tolerances (WA tol) of the most dominant (i.e. maximum relative abundance ≥ 10%) diatom taxa

Taxa	Code	N	N2	Max	WA Opt (ppt)	WA Tol (ppt)
Achnanthes angustata	OPE3	53	37.36	17.12	27.95	7.30
Achnanthes angustata var. 1	OPE6	57	40.49	21.14	28.71	6.10
Achnanthes brevipes var. *intermedia*	EPI1	8	3.41	10.87	23.69	5.23
Achnanthes sp. 1	PLAhau3	18	9.57	35.71	25.68	11.41
Actinocyclus subtilis	CEN10	4	2.73	40.33	31.03	3.48
Amphora acutiuscula	AMPcof	70	51.68	12.17	27.55	7.24
Amphora exigua	AMPcof2	44	29.48	10.87	29.41	5.97
Amphora sp. *1*	AMP3	21	13.95	15.21	28.23	7.83
Catenula adherens	AMP1	68	52.93	39.56	28.21	6.67
Cocconeis peltoides	ACH3	53	40.93	15.88	27.15	7.08
Cocconeis placentula	COCpla	51	33.68	51.00	26.95	7.83
Cocconeis scutellum	COCscu	57	39.27	30.47	27.07	8.27
Cocconeis scutellum var. 1	COCdis	54	34.86	56.22	29.93	6.57
Cocconeis sp. *1*	UNK107	21	15.24	16.50	31.82	3.13
Coscinodiscus centralis	CEN1	43	21.97	54.25	29.88	6.59
Cyclotella choctawhatcheeana	CYCstr2	33	19.31	29.01	27.10	7.49
Cyclotella striata	CYCstr	25	15.88	12.80	25.97	6.96
Diatomella cf. *balfouriana*	UNK37b	3	2.45	51.38	10.94	12.00
Diploneis cf. *domblitlensis*	FAL2	20	10.84	14.88	30.58	5.76
Fragilaria ellipta	CEN5	32	19.70	14.50	28.51	6.70
Grammatophora angulosa var. *angulosa*	GRA3	6	2.78	16.75	31.71	5.25
Grammatophora marina	GRAoce	39	24.19	41.87	27.94	6.36
Gyrosigma balticum	GYRbal	40	24.84	12.56	30.47	5.54
Mastogloia pusilla	MAS2a	14	6.54	24.88	31.87	3.04
Melosira nummuloides	MEL1	13	7.81	16.46	30.10	8.07
Navicula cf. *lusoria*	ACH14	15	11.36	21.16	33.42	2.10
Navicula perminuta	NAVper	59	43.75	14.29	28.20	6.62
Navicula recens	NAV1	62	45.75	14.07	28.36	6.97
Navicula salinarum var. *salinarum*	NAV3	49	34.03	11.47	29.18	6.57
Nitzschia cf. *valdestriata*	NITval	54	35.81	14.85	29.36	5.94
Opephora guenter-grassii	OPEgue	67	47.91	47.65	28.08	6.49
Opephora pacifica	OPEbur2	3	2.28	20.29	31.91	3.97
Opephora pacifica var. 1	OPEbur	58	42.36	64.22	27.68	6.65
Paralia sp. 1	PARsul	33	24.77	12.37	28.66	5.89
Planothidium delicatulum	PLAdel	64	50.34	28.75	27.16	6.75
Planothidium delicatulum var. 1	PLAdel3	26	19.72	12.90	29.20	5.65
Planothidium hauckianium	PLAhau	78	60.71	57.53	28.58	6.40
Rhopalodia acuminata	RHA3	42	25.96	34.15	26.40	6.45
Trachyspenia australis var. *australis*	VIK8a	10	6.15	12.20	31.82	3.73

sites, while *Cocconeis scutellum* Ehrenberg var. 1 and *Navicula* cf. *lusoria* Giffen were more abundant at high (≥33 ppt) salinity sites.

Simple WA with inverse deshrinking resulted in the best performing salinity transfer function. Six sites were identified as outliers and removed. The final model consisted of 75 sites ($r^2 = 0.72$, r^2jack = 0.58, RMSEP = 0.09 log ppt, Table 6, Fig. 7). WAPLS did not significantly improve transfer function performance.

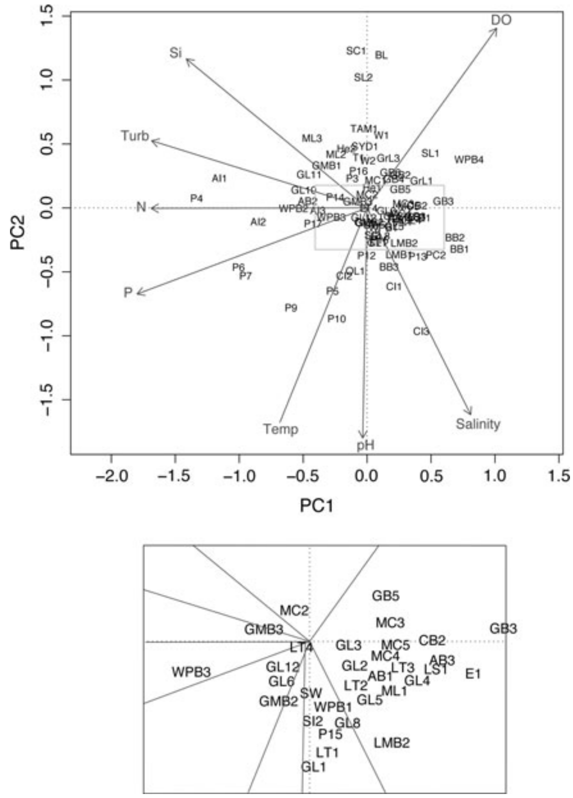

Fig. 2 Principal Components Analysis of the environmental data. *Boxed region* in the *upper panel* expanded below. *DO* dissolved oxygen, *N* nitrate/nitrite, *P* phosphate, *Si* silicate, *Temp* temperature, *Turb* turbidity. See Table 3 for site codes and water chemistry information

Table 5 Canonical correspondence analyses of (a) all the environmental variables and (b) forward selected variables only (i.e. nitrate-nitrite, phosphate, salinity and turbidity)

Axis	1	2	3	4
(a) All variables				
Eigenvalues	0.106	0.062	0.054	0.044
∑ canonical eigenvalues	0.390			
∑ all eigenvalues	2.392			
(b) Forward selected variables				
Eigenvalues	0.103	0.054	0.043	0.038
∑ canonical eigenvalues	0.238			
∑ all eigenvalues	2.392			

∑ = sum

Discussion

The overall aims of this study were to quantify the relationship between diatom species assemblages and the water chemistry of southeast Australian estuaries and coastal lakes, develop regional inference models, and discuss potential applications of the inference models to ecological and paleoecological studies investigating natural variability and human impacts in coastal ecosystems.

Environmental data and diatom assemblages

Water chemistry differences between Tasmania and Victoria were primarily related to differences in nutrient and dissolved oxygen concentrations (Table 2). This is likely associated with different land use types, freshwater inputs, influence from the sea and other local and regional factors that influence estuarine nutrient cycling. Mean nitrate + nitrite and phosphate concentrations were nine and six times greater, respectively, in Victorian coastal water bodies compared to Tasmanian sites and no Tasmanian sites had nitrate + nitrite concentrations ≥55 μg N L^{-1} or phosphate concentrations ≥ 70 μg P L^{-1} (Table 2). However, the low median nitrate + nitrite concentration and, to a lesser extent phosphate concentration, in Victorian sites indicated that high nutrient sites were in the minority (Table 2). This was also found by Philibert et al. (2006) in their study of southeast Australian streams, where the majority of sites had low nutrient values. Mean and median dissolved oxygen in Victorian sites was almost half that of Tasmanian sites (Table 2), despite the maximum dissolved oxygen recorded in Victorian sites being greater than in Tasmanian sites. This indicates that, in general, Tasmanian sites have lower nutrient concentrations and higher dissolved oxygen than Victorian sites, which reflects generally better water quality and lower levels of nutrient enrichment in Tasmanian compared to Victorian sites.

The number of taxa identified (399 in total) highlights the wide diversity of diatom taxa in the southeast Australian coastal region. The most common and widespread taxa (Table 4) are considered cosmopolitan species, characteristic of brackish, coastal and marine water bodies (Witkowski et al. 2000) and have been identified in previous Australian coastal diatom studies (e.g. Fluin et al. 2007; Haynes et al. 2007; Saunders et al. 2007; Taffs et al. 2008).

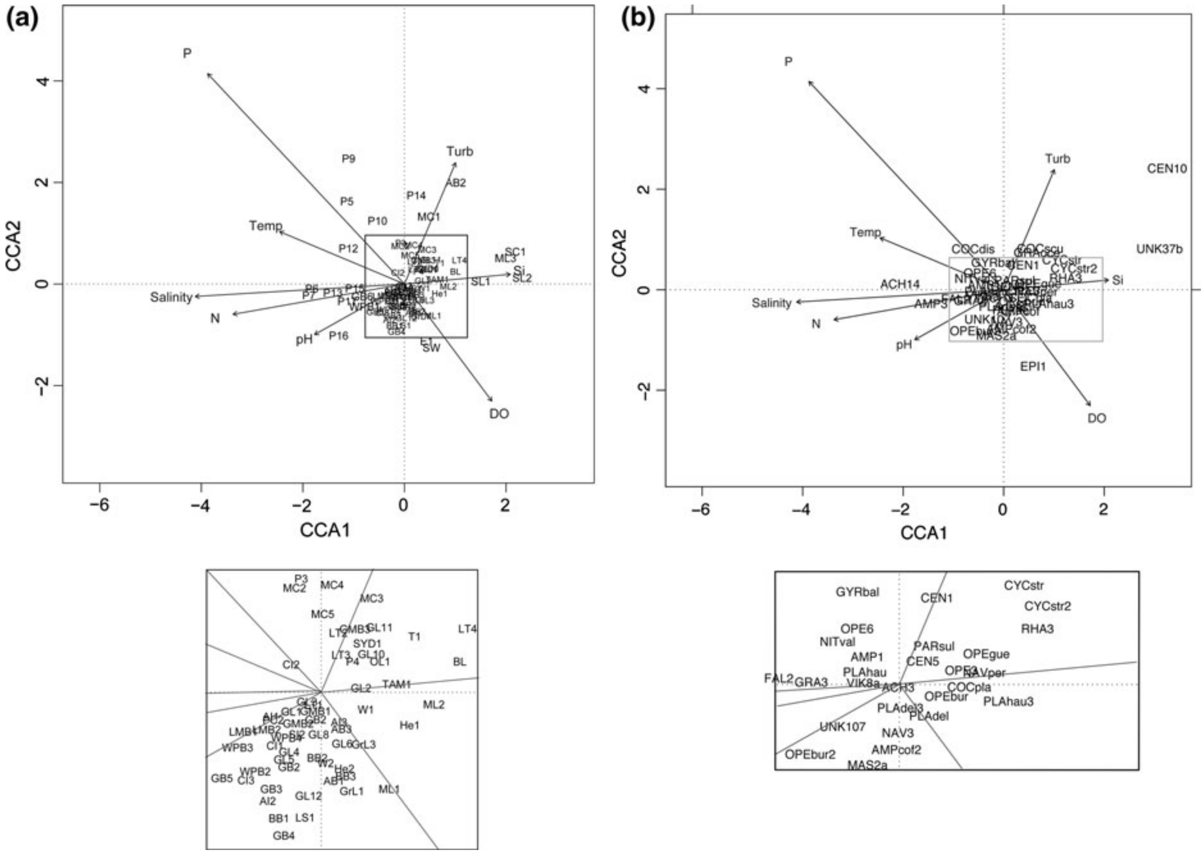

Fig. 3 Canonical Correspondence Analysis of the dataset with all environmental variables. **a** Sites displayed; **b** species displayed. Boxed region in the upper panels expanded below. *DO* dissolved oxygen, *N* nitrate/nitrite, *P* phosphate, *Si* silicate, *Temp* temperature, *Turb* turbidity. See Table 4 and Supplementary Material for species names

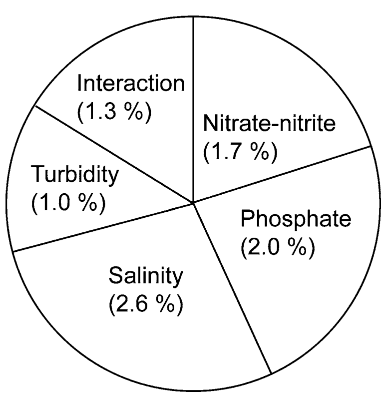

Fig. 4 Summary of Variance Partitioning results

Major environmental gradients and diatom species ecological preferences

This study demonstrated that diatom assemblages in southeast Australian coastal lakes, lagoons and estuaries are primarily influenced by salinity. Salinity has previously been found to be the overriding environmental variable influencing Australian diatom communities and diatom-salinity (or -conductivity) relationships have been described (e.g. Hodgson et al. 1997; Blinn and Bailey 2001; Gell et al. 2002; Philibert et al. 2006; Saunders et al. 2007; Tibby et al. 2007; Taukulis and John 2009). With the exception of Hodgson et al. (1997) and Saunders et al. (2007), none of these studies were conducted in coastal ecosystems.

Other factors not measured, such as grain size, water depth and light availability, can influence the composition of diatom communities (Stoemer and Smol 1999). For example, water depth has previously been found to have an important influence on benthic diatom communities (e.g. Weckström and Juggins 2005). The influence of depth was minimized in this study as all samples were collected from 1 m water depth. Similarly, light availability and grain size have

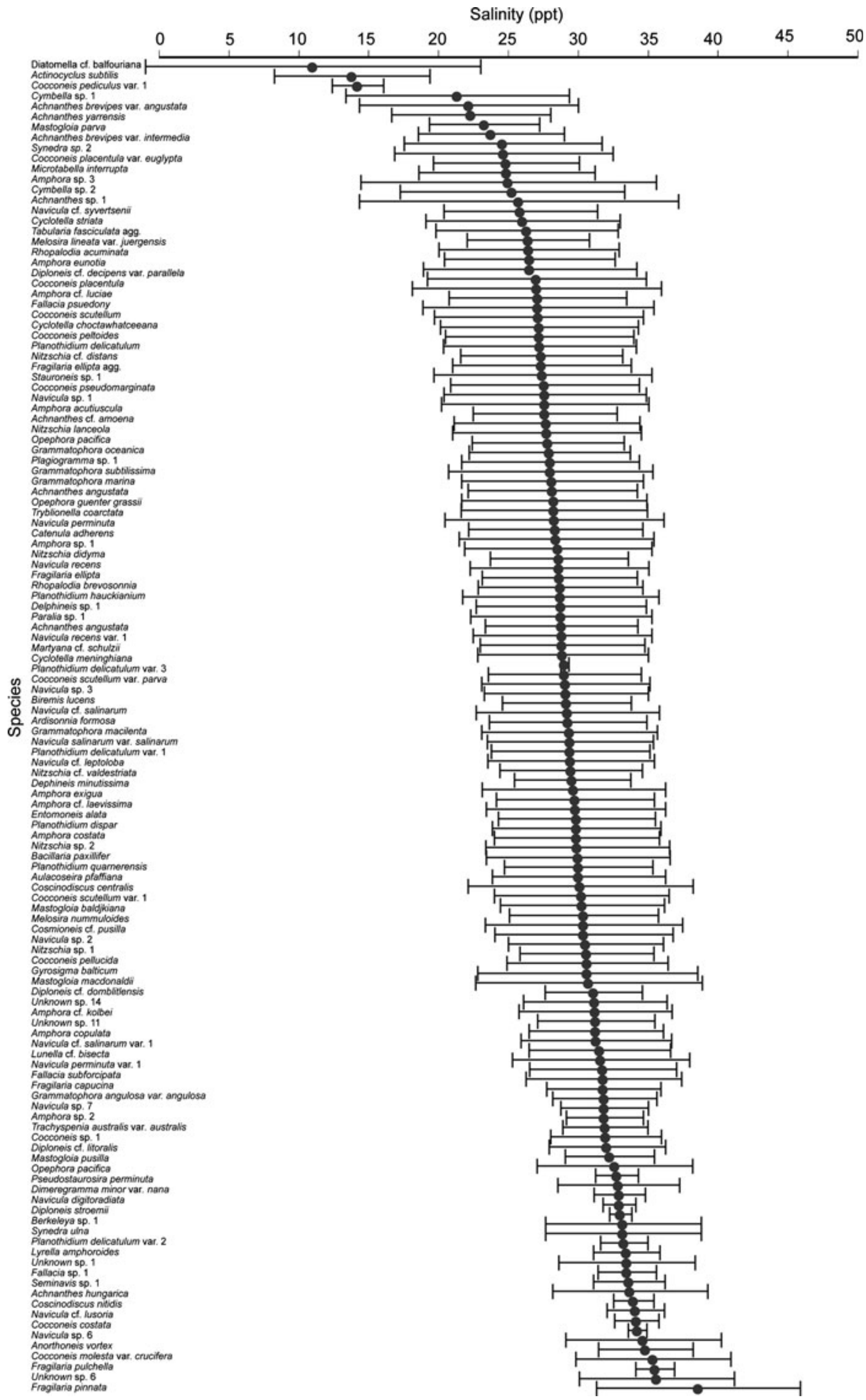

Fig. 5 Species salinity optima and tolerances, derived by simple weighted averaging

previously been found to have an important influence on coastal diatom communities (e.g. Hassan et al. 2007). However, studies including these factors have still found salinity is the overriding factor in explaining changes in diatom species assemblages (e.g. Hassan et al. 2009).

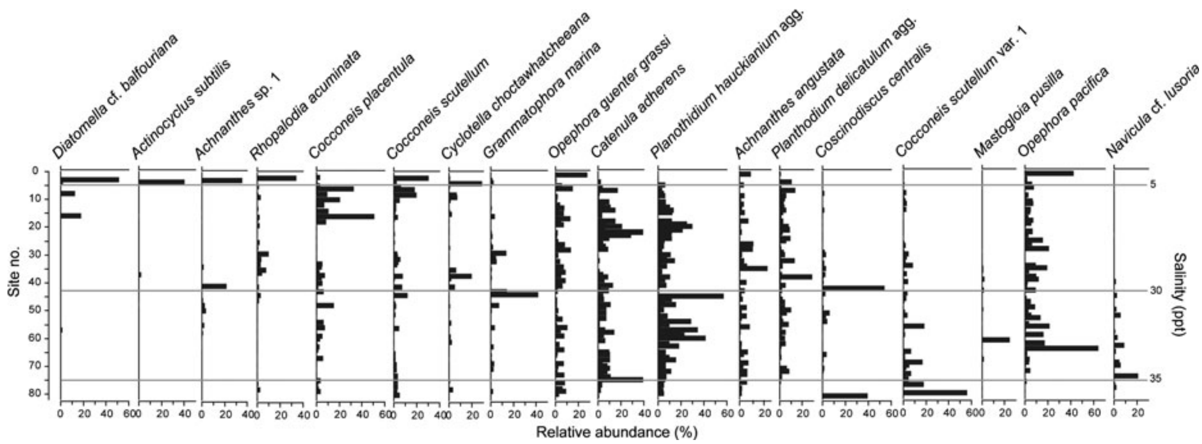

Fig. 6 Occurrence of most dominant (≥20% maximum relative abundance) taxa in the dataset. Sites ordered by salinity. Species ordered by their salinity optimum

Table 6 Transfer function results and comparisons with similar studies

Model	r^2	r^2p	RMSE	RMSEP	References
WAinv	0.73	0.54	0.07 log ppt	0.10 log ppt	This study
WAcla	0.84	0.60	0.17 log ppt	0.26 log ppt	Saunders et al. (2007)
WAcla	0.44	0.29	9.44 ppt	10.6 ppt	Saunders et al. (2008)
WAPLS-2	0.87	0.75	3.12 ppt	4.42 ppt	Hassan et al. (2009)
WAPLS-2	0.977	0.887	0.11 log g L^{-1}	0.246 log g L^{-1} salinity	Ryves et al. (2004)
WAPLS-2	0.84	–	–	0.15 log g L^{-1} salinity	Clarke et al. (2003)

r^2p r^2 of prediction, *RMSE* root mean squared error, *RMSEP* root mean squared error of prediction, *ppt* parts per thousand

The covariance of environmental gradients in coastal areas and estuaries (particularly with nutrients, e.g. Underwood et al. 1998) may make it difficult to determine the environmental factor to which species are primarily responding to (Ryves et al. 2004). Although it is possible to separate and test the independent effects of different parameters, there is often a large proportion of the variance unexplained (e.g. Ryves et al. 2004; this study). This is likely due to a combination of factors including potential mismatches between time-integrated sedimentary assemblages compared to 'spot' measurements of environmental variables. Additionally, even if spot measurements of environmental variables are repeated they may still fail to adequately capture the variation in physical chemical conditions that affect diatom growth. Therefore, whilst measurements in this study were made both in summer and winter, it is unlikely that the full ranges of the environmental parameters measured was captured at all the sites, which together with unmeasured parameters, contributes to the unexplained portion of diatom species-environment relationships seen in this dataset.

Prior to this study little was known about diatom species ecological preferences in southeast Australian coastal lakes and estuaries. The determination of species optima and tolerances and gradual transitions in species abundances and occurrences along the salinity gradient (Figs. 6, 7) allows the identification taxa that are more abundant at particular salinities. Whilst most of these more abundant taxa have been previously described as 'brackish-marine' taxa, this study permits a finer scale discrimination of their salinity preferences. For example, *Cocconeis placentula* has previously been identified as a brackish, shallow water species (Hodgson et al. 1996; Fluin et al. 2007), and this study is consistent with these observations (i.e. it was most abundant in brackish conditions, 5–30 ppt, Fig. 7). *Grammatophora marina* (Lyngbye) Kützing, *Planothidium hauckianium* agg.,

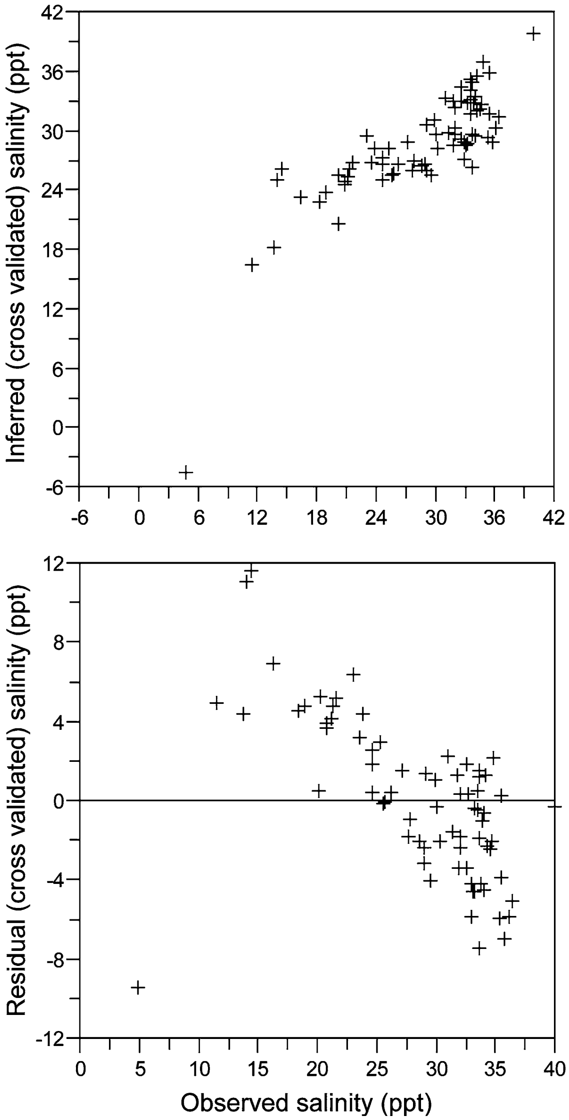

Fig. 7 Plots of observed versus inferred salinity and observed versus residual salinity based on simple WA regression and calibration

Mastogloia pusilla Grunow and *Opephora pacifica* Petit were most abundant at marine (30–35 ppt) sites (Fig. 7). This agrees with previous descriptions of *Grammatophora marina* and *Opephora pacifica* which have been classified as marine taxa (Vos and de Wolf 1993; Fluin et al. 2007). *Planothidium hauckianium* agg. was very common in the dataset and occurred at most sites. This is a consistent with previous descriptions, which have identified this as a cosmopolitan taxon commonly found in brackish sites, especially on sandy substrates (Witkowski et al. 2000).

Evaluation of the diatom-salinity transfer function

The best performing diatom-salinity transfer function was developed using simple WA with inverse deshrinking. The large number of different waterbody types included in this dataset, ranging from small coastal lakes to large open estuarine systems, provided a wide range of species assemblages distributed along long environmental gradients and a good range of modern analogue assemblages with which to interpret subfossil data. Six sites were identified as outliers and removed (P4, SC1, ML2, ML3, GL10, GL11). All were from low salinity (≤12 ppt) sites with very high phosphate concentrations (>450 μg PL^{-1}). While the predictive ability of the diatom-salinity transfer function has a 0.09 log ppt (i.e. 4.3 ppt) error, its performance is better than a previously published transfer function based only on Victorian sites (Saunders et al. 2008). In contrast the Tasmanian transfer function presented by Saunders et al. (2007) has slightly better performance (Table 6) than the current study.

Potential applications of the dataset: ecological and paleoecological investigations of natural variability and human impacts

Environmental impacts on coastal lakes and estuaries in southern Australia are a major management concern. Large-scale environmental problems have arisen due to upstream river regulation, water extraction for irrigation, salinization, enhanced sedimentation rates, modifications of openings to the sea, urbanization of coastal catchments, acidification and eutrophication (SoE 2006; Fluin et al. 2007; Taukulis and John 2009). Management efforts are increasingly focused on alleviating environmental problems (SoE 2006). However, historical documentation and water quality monitoring data are usually inadequate for providing the long term perspective needed (SoE 2006). In the absence of long term water quality monitoring, paleoecological methods play a crucial role in establishing 'baseline' conditions and rates of change as they can identify the timing and progressive impact of different human activities and provide a long enough temporal perspective to disentangle natural from anthropogenic-related changes (Willis and Birks 2006). They also provide an opportunity to assess whether ecosystems have crossed critical thresholds (e.g. Smol and Douglas 2007) and take into account natural variability, which is essential for being able to evaluate the capacity of coastal ecosystems to adapt and respond to future changes, particularly predicted climate change and further pressure from human activities (Duke et al. 2003; Davis and Koop 2006). The dataset and transfer function developed in this study may be applied to sediment cores collected from coastal lakes and estuaries in southeast Australia to reconstruct past salinity changes and address issues arising from direct (e.g. hydrological modifications to estuary entrances) and indirect (e.g. changes in catchment land use and/or upstream irrigation schemes) human activities, together with the impacts of recent climate change (e.g. reduced rainfall). This provides a tool for understanding whether current conditions are outside the range of natural variability, attribute causes of change (e.g. Saunders et al. 2008) and assist in determining appropriate management strategies.

Conclusion

This study has presented a new diatom dataset quantifing the relationship between diatom species assemblages and the water chemistry of southeast Australian estuaries and coastal lakes. Salinity explained the most variation in the diatom assemblages and a diatom inference model for reconstructing salinity was developed. This is a potentially valuable tool for monitoring both modern changes in salinity using time-smoothed diatom species assemblages (rather than spot measurements) and reconstructing past salinity changes from sub-fossil species assemblages to identify long term natural variability and human impacts in southeast Australian coastal water bodies.

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