
Sea Level Variability in the Bras d'Or Lakes

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ABSTRACT *An analysis of sea level variability during summer indicates that semi-diurnal and diurnal tidal components are rapidly attenuated as they propagate into the Bras d'Or Lakes. On the other hand, low frequency sea level fluctuations originating in Sydney Bight, immediately outside the Lakes, are only moderately affected. The fluctuations in Sydney Bight are predominantly the result of the isostatic adjustment of sea level to atmospheric pressure changes. The resulting sea level gradient drives flow into or out of the Lakes. A simple numerical model consisting of a balance of acceleration, pressure gradient and friction accounts for most of the observations.*

RÉSUMÉ *Au cours de la saison de l'été, une analyse de la variabilité du niveau de la mer indique que les éléments de la marée semi-diurne et diurne sont rapidement atténués à mesure qu'ils se propagent dans les lacs du Bras d'Or. D'autre part, les fluctuations du niveau de la mer de basse fréquence provenant de Sydney Bight, immédiatement à l'extérieur des lacs, sont les seules affectées de façon modérée. Les fluctuations dans Sydney Bight sont surtout le résultat de réajustement isostatique du niveau de la mer aux changements de pression atmosphérique. Le gradient résultant du niveau de la mer entraîne un flux vers les lacs ou hors de ceux-ci. Un modèle numérique simple comprenant les éléments d'accélération d'équilibre, de gradient de pression et de friction tient compte de la plupart des observations.*

1 Introduction

The Bras d'Or Lakes are connected to the Atlantic Ocean by a 30-km long, narrow, shallow passage, the Great Bras d'Or Channel (Fig. 1). The channel has an average width of about 1.3 km, a minimum width of 0.32 km, an average depth of about 19.5 m and a maximum depth of 95 m. The most severe restriction is at the mouth of the channel which has a width of 320 m, a maximum depth of 16.2 m and a cross-sectional area of 2400 m². The 8-km long Little Bras d'Or Channel, the only other permanently open connection to the ocean, is an even more restrictive feature that is less than 100 m wide and 5 m deep on average. It does not appear to play a major role in

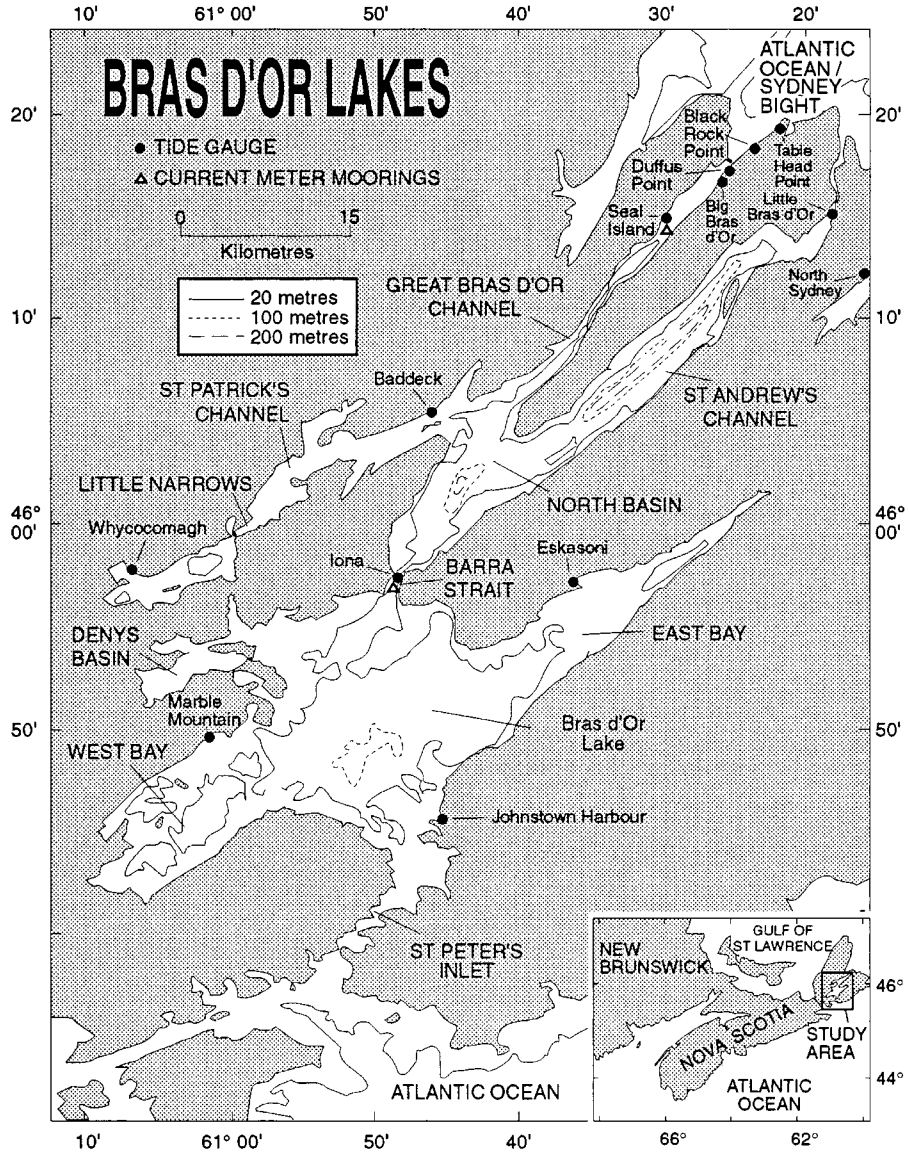


Fig. 1 Geography of the Bras d'Or Lakes with locations of sea level gauges (solid dot) and current meter moorings (open triangle).

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the temperature and salinity distributions in the Lakes (Gurbutt and Petrie, 1995). A lock on St. Peter's Inlet on the southern side of Bras d'Or Lake is open occasionally to allow vessels to enter or leave the Lakes. The Lakes consist of several interconnected basins and channels with a maximum depth of 280 m in St. Andrew's Channel.

Krauel (1975a) conducted a broad scale survey of the Lakes from 1972 to 1974. His program consisted of hydrographic measurements, dissolved oxygen, current meter moorings, current profiling and sea level stations. Gurbutt and Petrie (1995) have discussed the temperature, salinity and dissolved oxygen distributions of the Lakes for the spring, summer and fall, though there were few data from the latter season. They also formulated a multiple-layer, multiple-region box model of the low frequency circulation in the Lakes based on mass, heat and salt conservation. The circulation was estuarine-like with horizontal transports ranging from 5 to nearly 3000 m³/s and vertical transports from 1 to about 2600 m³/s depending on location. Verification of the model was based on the distribution of dissolved oxygen and some current meter records.

In addition to hydrographic and current meter data, Krauel moored a number of sea level gauges (Ott float-type water level recorders, resolution 1 cm) in the Lakes, 8 in 1973 and 6 in 1974 (Fig. 1). Records ranged from 7 to 67 days long, with an average length of 35 days. Half of the records have gaps of varying lengths. Krauel (1975a) presented the results as tables of hourly observations. Krauel (1975b) gave a brief discussion of the tides, noting that harmonic constituents (not tabulated) "varied greatly in both amplitude and phase depending on which 15-day segment of the records was used". He attributed this to the fact that the range of the tides was so small within the Lakes and that the variations of sea level caused by meteorological disturbances can be the same order of magnitude or larger than the tides; consequently, water levels within the Lakes could not be predicted with any degree of accuracy. Desplanque (1980) noted that the inverted barometer effect contributed substantially to the sea level variability in the Lakes. The problem of sea level prediction in the Bras d'Or Lakes has intrigued the public as well. The Yachtsman's Guide to the Bras d'Or Lakes (1987) contains the interesting statement: "tidal predictions ... are a matter of consternation. In a number of instances the lunar component in our semi-diurnal tidal area defies the 12-hour period by as much as 5 days at Barra Strait".

The next section of the paper presents the tidal constants in the Lakes based on an analysis of the data collected by Krauel (1975a); in addition, constants for locations just outside of the mouth are included in order to examine the decrease of tidal amplitudes and the variation of phases from Sydney Bight to the western end of the Lakes. Section 3 examines the non-tidal sea level variations in the Lakes. The final section presents a summary and discusses possible mechanisms to account for the observed response.

2 Tidal Analysis

The five principal tidal constituents for the Bras d'Or Lakes are compiled in Table 1 and shown in Fig. 2 (where two sets of constants are available, the ones from the

TABLE 1. The harmonic constants for the five principal tidal constituents in and outside of the Bras d'Or Lakes. An asterisk indicates that the data were collected during the Bras d'Or Lakes field program. Other constants are from the Marine Environmental Data Service (Ottawa) compilation.

Location	Record Length (d)	Constituent (m, degrees referenced to Greenwich)				
		M2	S2	N2	K1	O1
North Sydney	362	0.368	0.109	0.076	0.077	0.082
		353	37	330	325	287
Table Head Pt.	37	0.342	0.081	0.067	0.064	0.086
		353	41	322	320	283
Black Rock Pt.	20	0.374	0.124	0.111	0.075	0.106
		359	60	307	316	282
Duffus Pt.	16	0.161	0.027	0.034	0.026	0.056
		344	42	329	339	305
Big Bras d'Or	15	0.164	0.048	0.033	0.033	0.033
		342	44	318	329	282
Big Bras d'Or (1974)	46.9	0.165	0.033	0.035	0.038	0.032
		339	33	328	320	282
Seal Island (1973)*	41.8	0.073	0.011	0.016	0.012	0.014
		343	30	320	360	305
Baddeck (1973)*	34	0.037	0.010	0.009	0.015	0.015
		68	121	40	68	9
Baddeck (1974)*	14.9	0.030	0.004	—	0.012	0.012
		63	150	—	65	359
Iona (1973)*	31	0.038	0.008	0.006	0.014	0.012
		77	155	58	81	354
Iona (1974)*	28.7	0.040	0.008	0.008	0.017	0.019
		84	144	74	57	18
Marble Mountain (1973)*	24.1	0.044	0.007	—	0.022	0.021
		132	158	—	67	37
Marble Mountain (1974)*	34.5	0.046	0.006	0.007	0.018	0.019
		124	183	121	58	28
Johnstown Hbr (1973)*	22	0.045	0.007	—	0.016	0.017
		127	205	—	84	31
Eskasoni (1973)*	45	0.045	0.008	0.009	0.017	0.018
		121	185	91	73	25
Eskasoni (1974)*	24.5	0.041	0.008	—	0.018	0.018
		131	201	—	74	30

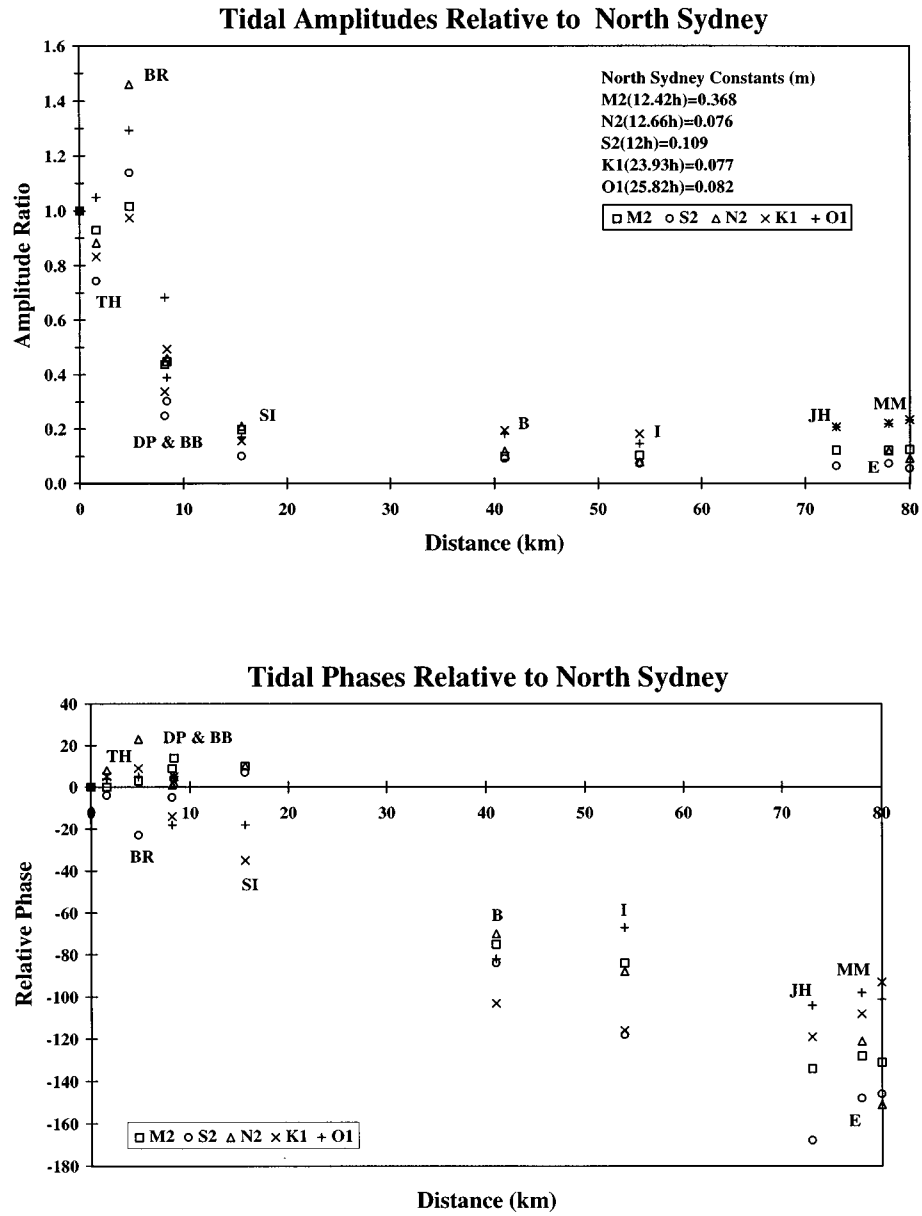


Fig. 2 Tidal amplitudes and phases relative to North Sydney for Table Head Point (TH), Black Rock Point (BR), Duffus Point (DP), Big Bras d'Or (BB), Seal Island (SI), Baddeck (B), Iona (I), Johnstown Harbour (JH), Eskasoni (E) and Marble Mountain (MM). Distance is measured from the mouth of the Lakes.

longest record are plotted). The plots in Fig. 2 use the harmonic constants from North Sydney, the reference port for the area, to construct relative tidal amplitudes and phase differences. North Sydney constants were taken as representative of the tide immediately outside of the entrance to the Lakes.

The tidal amplitudes change dramatically as they progress through the Lakes. At Table Head Point, the amplitudes generally decrease relative to North Sydney; however, at Black Rock Point the amplitudes, derived from a 20-d record, are larger than those at North Sydney except for K1. About 1 to 1.5 km inside the most constricted cross-section of the Great Bras d'Or Channel at Duffus Point and Big Bras d'Or, the tidal amplitudes decrease substantially. The M2 amplitude falls from 0.37 m to about 0.16 m, a reduction of more than 50%. Farther up the channel at Seal Island, the M2 amplitude again decreases by about one half to 0.073 m, with similar reductions for the other tidal components. In the first major basin at Baddeck and Iona, the M2 amplitude is about 0.03 to 0.04 m. In the Bras d'Or Lake, the second major basin, the M2 amplitude ranges from 0.04 to 0.046 m, on average 8 mm greater than in the first basin. The S2 component, with the shortest period, shows the greatest attenuation at 8 of the 9 sites where constants are available for all five constituents. The O1 component, with the longest period, has the least attenuation.

Phases also show significant variability. Near the entrance of Great Bras d'Or Channel, the phases have a tendency to lead the phase at North Sydney. This is opposite to what would be expected for the semi-diurnal tides based on the direction of propagation (Godin, 1980); little difference would be anticipated for the diurnal tides (Godin, 1980). As the tidal components proceed up the Great Bras d'Or Channel into the two major basins, phase lags for all constituents increase until in Bras d'Or Lake they correspond to about one third of a period. The M2 phases in Bras d'Or Lake have a range of 11° (121° to 132°). At 7 of 9 locations, S2 has the greatest or next greatest lag; whereas, M2 and N2 usually had the smallest lags except in the second basin where the diurnal components had the smallest lags.

Sea levels were also measured at Whycomagh and Little Bras d'Or. The harmonic analysis of the Whycomagh record indicated that the tidal variability was too small to produce a reasonable set of tidal constants. At Little Bras d'Or, the M2 amplitude was 0.11 m; the amplitudes of the other constants ranged from 0.024 to 0.035 m. This site could be affected by the external tide through the Little Bras d'Or Channel.

For the 4 sites where data were collected both in 1973 and 1974, the average differences between amplitudes and phases at the same site for all constituents were 2.8 mm and 12.5° . Given the small amplitudes of all the constituents and the 0.01 m resolution of the sea level gauges, this agreement is quite good. There is no apparent problem predicting tides; predicting sea level is another matter.

Large tidal currents were found only in the Great Bras d'Or Channel and Barra Strait, i.e., at 2 of the 13 current meter mooring sites in the Lakes (Fig. 1). The strongest component by far was M2 with an amplitude (phase) of the major axis ranging from 0.32 to 0.8 m/s (188 – 223°) in Barra Strait (Fig. 3). For the Great Bras d'Or

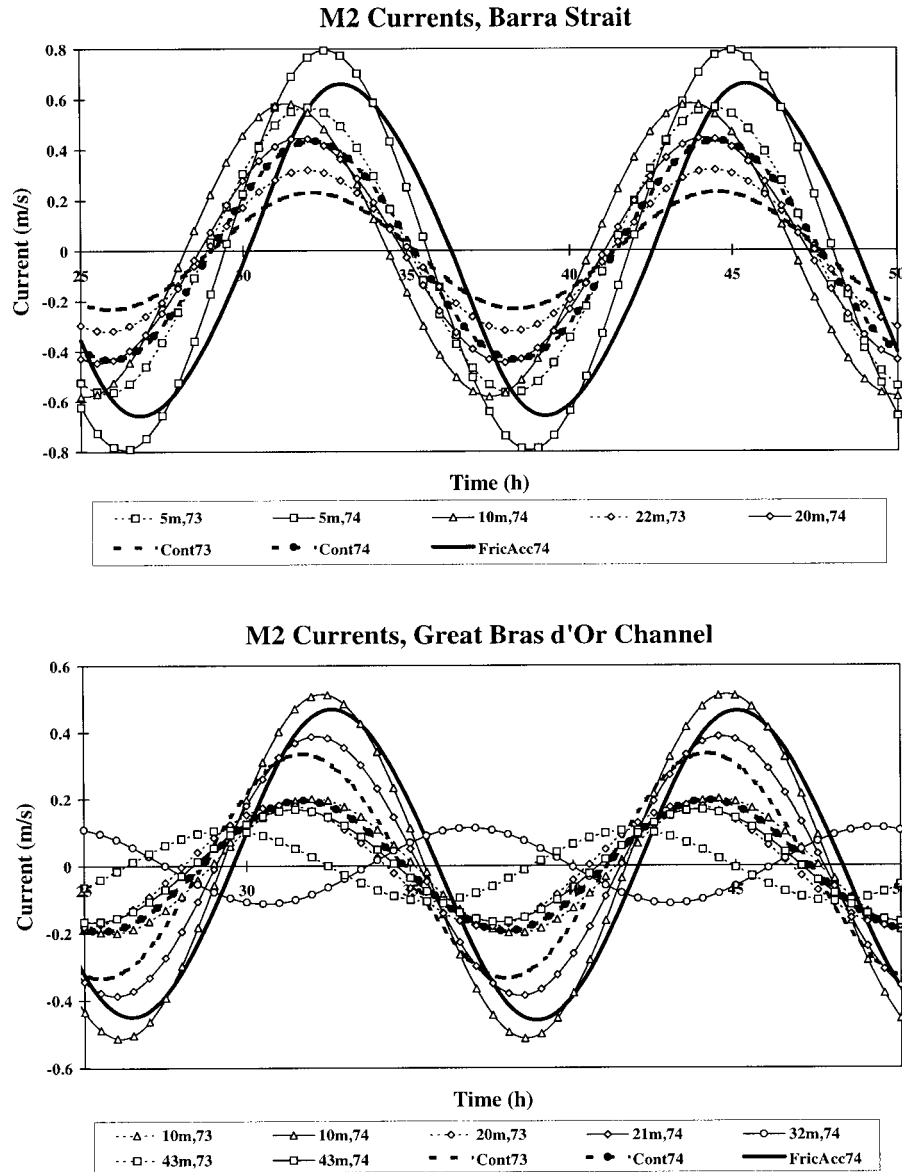


Fig. 3 M2 tidal currents at various depths from Barra Strait and Great Bras d'Or Channel in 1973 and 1974. The results from harmonic analysis of current meter data, continuity calculations (Cont) and a local momentum balance (FricAcc) are shown.

Channel, the major axis current (phase) was 0.11–0.51 m/s (132–347°). (Note that the large spread of phases for Great Bras d’Or Channel is accounted for by two of the records, from 43 m in 1973 and from 32 m the following year. The phases of the remaining 5 records range from 183 to 217°, a considerably narrower band.) The major current axes in both locations were oriented along the channels, on average along 27° in Barra Strait (geographic orientation is about 23°), and on average along 33° in Great Bras d’Or Channel (geographic orientation is about 41°). Minor axis components were generally less than 0.02 m/s. The other main tidal constituents had typical major axis amplitudes of 0.08 m/s. The following discussion is restricted to the major axis of the M2 constituent.

The amplitudes in Barra Strait have a broad range but the phases are reasonably compact. In the Great Bras d’Or Channel, both amplitudes and phases show more variation, casting doubt on the data. Peak flows in both locations reached 1.5 m/s likely leading to large tilts in the moorings and thus degradation of the measurements. The mooring positions in both areas changed from 1973 to 1974. The Barra Strait mooring was located about mid-channel in 1973; in 1974, it was placed near the northeastern mouth of the Strait. The 1973 Great Bras d’Or mooring was located about 600 m southwest of Seal Island near mid-channel; the mooring log for 1974 gives a position that is on land. The position assumed for the 1974 mooring was the nearest point with the same bottom depth recorded in the log.

Depth-averaged tidal currents, determined from the continuity equation (Eq. 1, using tidal constants and basin areas to determine volume transport, i.e., the areas of West Bay, East Bay and Bras d’Or Lake for the flow through Barra Strait, the area of the entire Lakes for the flow through the Great Bras d’Or Channel) and from a balance of acceleration, pressure gradient and quadratic bottom friction (using Eq. 2, with $c_d = 0.0025$ and a finite difference, time stepping technique), are compared to the observed M2 tidal flows in Fig. 3. The continuity calculation used the channel cross-section at the current meter location. The pressure gradients for Barra Strait and the Great Bras d’Or Channel were calculated from the difference from the M2 sea level components at Iona and Eskasoni, and Big Bras d’Or and Iona. The constants from the longest records were used and the gradients estimated on the basis of the length of Barra Strait (3.2 km) for the former and the distance from Big Bras d’Or to the North Basin (26.4 km) for the latter. That is, the tides at Iona and Eskasoni were assumed to represent the tides in the entire North Basin and Bras d’Or Lake. The agreement of the tidal constants at Baddeck with those from Iona (North Basin), and Marble Mountain and Johnstown Harbour with those from Eskasoni (Bras d’Or Lake) indicates that this is a reasonable assumption. Water depths at the current meter locations were used in the momentum balance calculations.

$$S_A \partial \zeta / \partial t = -uA \quad (1)$$

$$\partial u / \partial t = -g \partial \zeta / \partial x - c_d u |u| / h \quad (2)$$

In Eq. 1 and 2, S_A is the surface area, ζ is the sea level, t is time, u the along-channel current, A the cross-sectional area, c_d the bottom drag coefficient and h the depth.

The continuity calculation underestimates the average current strength in Barra

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Strait by about 0.2 m/s in both years but has excellent phase agreement. On the other hand, the local momentum balance (only 1974 is shown since the result is nearly the same for both years) overestimates the average flow by about 0.2 m/s in 1973 but only by 0.05 m/s in 1974. However, the calculated phase lags the observed phases by about 1 hour. A number of factors could contribute to the disparities between currents based on a local momentum balance and the observed flows, e.g., neglect of currents other than M2 in the friction term, the choice of a length for the pressure gradient term and, as indicated earlier, questionable data quality. Another factor could be the choice of c_d . Campbell et al. (1998) have found that values of c_d from about 0.004 (cross-sectional, averaged flow) to 0.008 (depth averaged flow at mid-channel) fit the momentum balance (Eq. 2) for observations made in Menai Strait better than the standard value of 0.0025. Using a value of 0.008 in Eq. 2 reduces the amplitude of the modelled flow in Barra Strait by about 0.17 m/s and advances the phase by about 1.5 h compared to the standard case; i.e., the current is very similar to the continuity calculation for 1974. Thus, a higher value of c_d could fit the current observations in Barra Strait better. Finally, the non-linear term, $u\partial u/\partial x$, is estimated to be about the same magnitude as acceleration and friction by assuming that the current is zero outside of the Strait. The sign of this term will change as the flow increases as it enters the Strait on one side, and decrease as it exits on the other. A precise evaluation of the term at the mooring site is not possible with existing data. On the other hand, the observed amplitudes of the non-linear tidal constituents are not large, with M4 amplitudes ranging from 0.014 to 0.029 m/s. This indicates that the non-linear terms may not be as large as estimated.

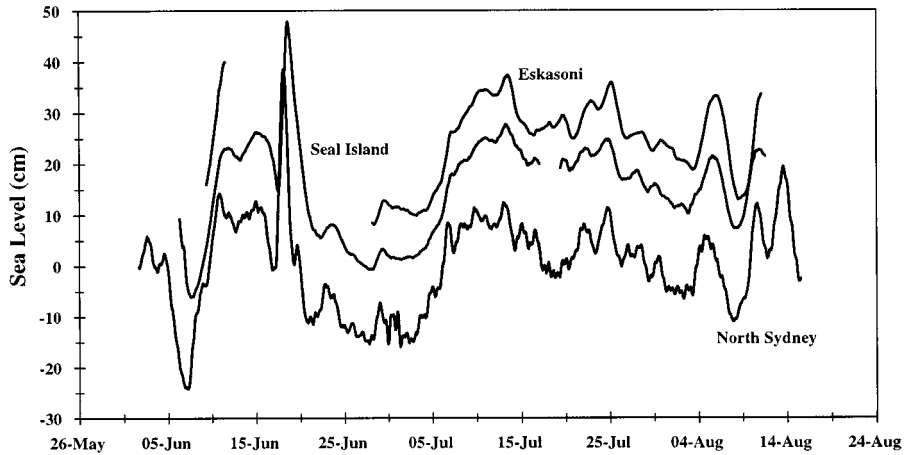
The observed tidal constants in the Great Bras d'Or Channel have their problems – particularly the ones derived from the 43-m record in 1973 and the 32-m record in 1974. Disregarding these records, the continuity calculation agrees with the average amplitude to within 0.03 m/s in both years; moreover, the phases fall within the observed phases. The local momentum balance (results nearly identical for both years) overestimates the average flow by 0.3 m/s and 0.1 m/s in 1973 and 1974. The calculated phase lags the observed phases by a little less than an hour. Taking $c_d = 0.008$ has less effect in the Channel than it did in Barra Strait.

In summary, there is a rapid decrease of amplitudes and, after an initial phase lead, an increase in phase lags as the tides move into the Lakes. There is some tendency for the amplitudes of the higher frequency components to show greater attenuation. Tidal amplitudes and phases are quite consistent from year to year at the same site. Tidal currents are strong in narrow passages between basins but currents calculated from continuity and local momentum balances only roughly agree with the observed flows.

3 Low Frequency Variability

The sea level records from the Bras d'Or Lakes show considerable low frequency variability. The time series of sea level for North Sydney and the locations with the longest records within the Lakes are shown in Fig. 4. In both years, non-tidal sea level changes are large, about 0.5 m in 1973 and 0.3 m in 1974. There is also an

Sea Level 1973



Sea Level 1974

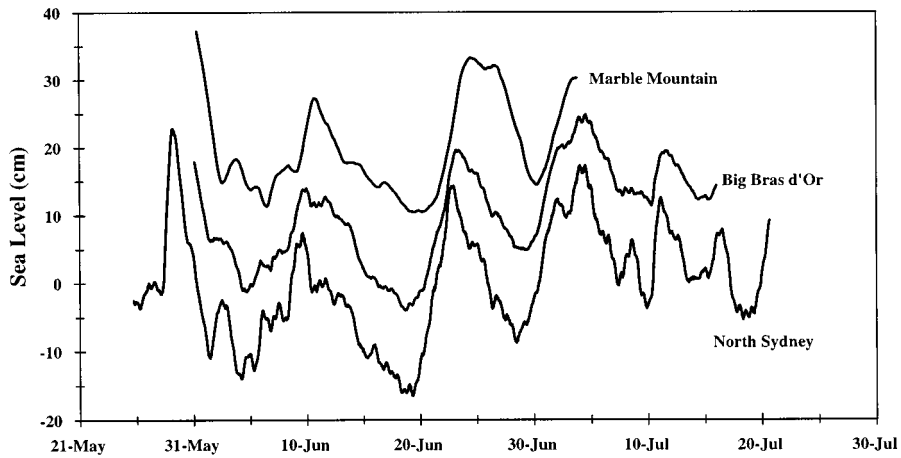


Fig. 4 Sea level from North Sydney and locations inside the Bras d'Or Lakes for 1973 and 1974. The means have been removed from all records and offsets applied for clarity. A 25-h running mean filter has also been applied to filter out most of the tidal variability.

indication that the low frequency amplitudes do not change much from North Sydney, outside the Lakes, to Marble Mountain and Eskasoni, both located in the innermost basin. However, the sea level variations appear to occur first at North Sydney and then get progressively later farther into the Lakes, though the phase lags relative to the timescale of the variability do not appear to be as large as for the tides.

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TABLE 2. Maximum correlation and corresponding linear regression slope and lag of sea level relative to North Sydney.

Location	Correlation	Slope	Lag (hours)
Seal Island 1973	0.95	0.94	12
Baddeck 1973	0.91	0.92	15
Eskasoni 1973	0.95	1.01	16
Big Bras d'Or 1974	0.97	0.85	8
Iona 1974	0.92	0.83	16
Marble Mountain 1974	0.94	0.86	36

To examine this observation quantitatively, the lagged correlations and the linear regression of records from within the Lakes were calculated relative to the North Sydney time series (Table 2). The computations show that correlations exceed 0.9 for both years for records from Great Bras d'Or Channel, and for the first and second large basins. There is a small reduction of amplitude at all sites except Eskasoni in 1973 relative to North Sydney. The reduction is greater in 1974 than in 1973, and is essentially independent of location. The time lags increase into the Lakes from Sydney Bight though the increase is small in 1973 compared to 1974. A periodogram of the 1973 North Sydney sea level data indicates that the variance is concentrated between periods of 2–4 weeks with a minor secondary peak at 6 days. Taking 3 weeks as the mean period of the variability and a time lag of 15 h, gives a phase lag of about 11° for the inner basins. In 1974, the variance is concentrated at shorter periods of 1–2 weeks with a very low frequency peak centred at 52 days. Taking 1.5 weeks as a representative period and the time lags for Iona and Marble Mountain (Table 2), yields phase lags of 23 and 51° .

A representative current through the narrow entrance of the Lakes associated with these sea level changes can be derived from Table 2 and Fig. 4. Taking the entire surface area ($1.1 \times 10^9 \text{ m}^2$) inward of the smallest cross-section (2400 m^2), a lag of 15 h (Table 2), and an amplitude of 0.1 m (Fig. 4, the standard deviation of the North Sydney records was about 0.09 m and 0.08 m in 1973 and 1974), gives a current at the entrance of 0.86 m/s, a reasonable value.

The major cause of the non-tidal sea level variability is evident in Fig. 5, where the negative barometric pressure anomaly from Sable Island is plotted along with North Sydney sea level for 1973 and 1974. Sea level at North Sydney is responding to changes of atmospheric pressure in the classic inverted barometer sense; that is, high (low) atmospheric pressure over Sydney Bight causes sea level to fall (rise), subsequently forcing water out of (into) the Lakes through the Great Bras d'Or Channel. This response was noted by Desplanque (1980). The inverted barometer effect does not account for all of the sea level variability however (Fig. 5). Additional analysis examined the relationship between sea level and adjusted sea level at North Sydney with two orthogonal components of windstress. The best relationship was with adjusted sea level during 1974 when the two components of windstress could account for only 19% of the variance. This indicates that remote forcing is the most likely cause of sea level variability not accounted for by the inverted barometer effect.

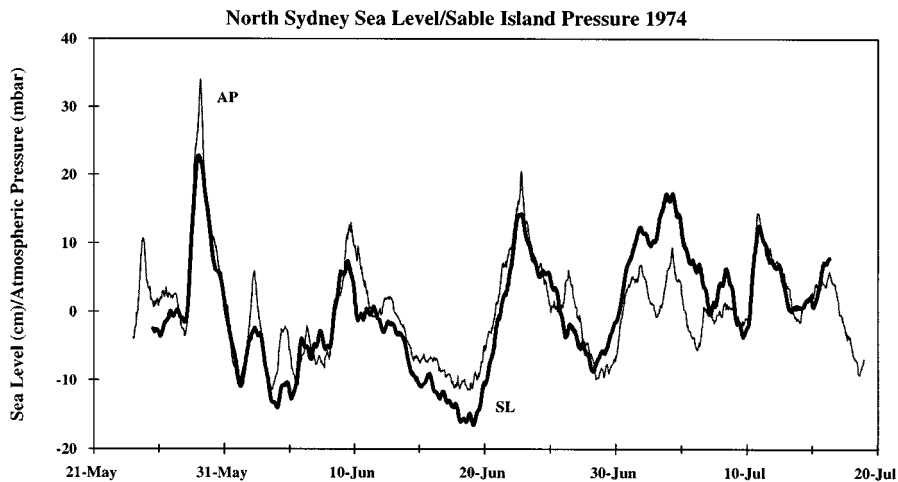
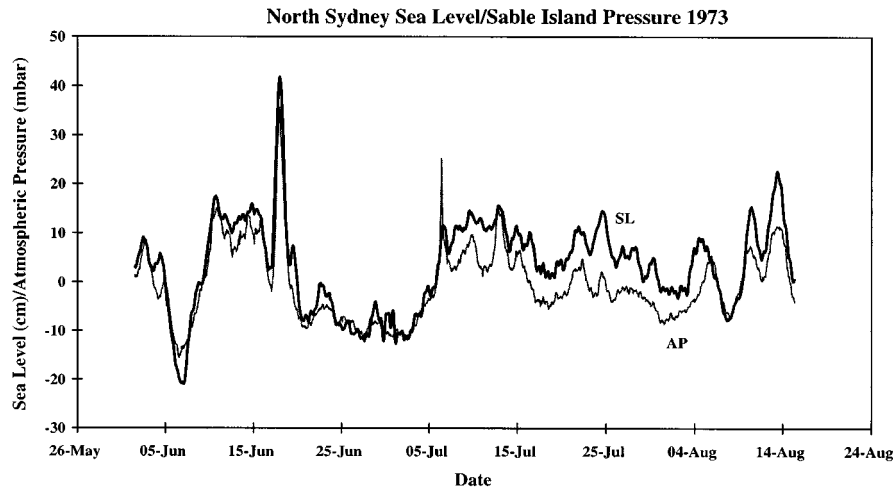


Fig. 5 North Sydney sea level (SL, heavy line) and Sable Island sea level pressure (AP, thin line, 1 mbar = 0.1 kPa) for 1973 and 1974. In both cases the means have been removed. For sea level, the observed – mean is plotted, for atmospheric pressure, the mean – observed data are plotted.

Within the Lakes themselves, a typical windstress for the summer period when the sea level data were collected is 0.03 Pa, based on the tabulated winds for Bras d'Or Lake (Krauel, 1975a). A balance of windstress and surface pressure gradient along the longest fetch (60 km) of the Lake gives a setup of about 0.01 m, considerably less than the observed sea level changes.

In summary, atmospheric pressure variations cause isostatic sea level fluctuations

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in Sydney Bight and consequently at the entrance to the Bras d'Or Lakes. The resulting sea level gradient drives a flow into or out of the Lakes depending on the direction of the forcing. Sea level in the Lakes subsequently rises (or falls) with an amplitude response and phase difference that are, frequency dependent. Gains are larger and phase lags smaller for the low frequency variability than for the higher frequency tidal components.

4 Discussion and Summary

Proudman (1953, pp. 322–323) has considered the variation of the amplitudes and phase for an infinite, narrow, uniform channel governed by a force balance of acceleration, pressure gradient and linearized friction and driven by sea level fluctuations at the mouth (similar to Eq. 2). His solutions for the channel have elevation decreasing with a decay constant λ given by

$$\lambda^2 = (\omega^2/2gh)(-1 + \sqrt{1 + F^2/\omega^2}). \quad (3)$$

The wavenumber κ , and consequently the phase variations, is given by

$$\kappa = \omega F/2gh\lambda \quad (4)$$

where ω is the frequency and F the friction parameter which in our case is $F \sim c_d|u|/h$. For low frequency fluctuations, i.e. $\omega \ll F$,

$$\lambda = \kappa = \sqrt{\omega F/2gh} \quad (5)$$

and the decay scale is dependent on the square root of the frequency. For high frequency fluctuations, $\omega \gg F$,

$$\lambda = F/2\sqrt{gh} \quad (6)$$

$$\kappa = \omega/\sqrt{gh} \quad (7)$$

and the decay scale approaches a constant value.

This agrees qualitatively with our observations that there is more attenuation and greater phase shift at higher frequencies. Quantitatively though, the agreement is poor. Applying the solutions to the Great Bras d'Or Channel we have, $c_d = 0.0025$, $|u| = 0.5$ m/s, $h = 20$ m, and $F = 6.25 \times 10^{-5} \text{ s}^{-1}$. For M2 this would give an e-folding decay scale of about 450 km, much too large compared to the observations.

Figure 6 shows the along-channel variations of the average and maximum depths, and the cross-sectional areas for Great Bras d'Or Channel. It is evident that the channel is far from uniform with cross-sectional areas that vary by a factor of 30. This indicates that the non-linear friction term may dominate in areas of small cross-section and control the variation of tidal height. Therefore, a numerical technique employing an explicit finite difference scheme was used to solve the momentum

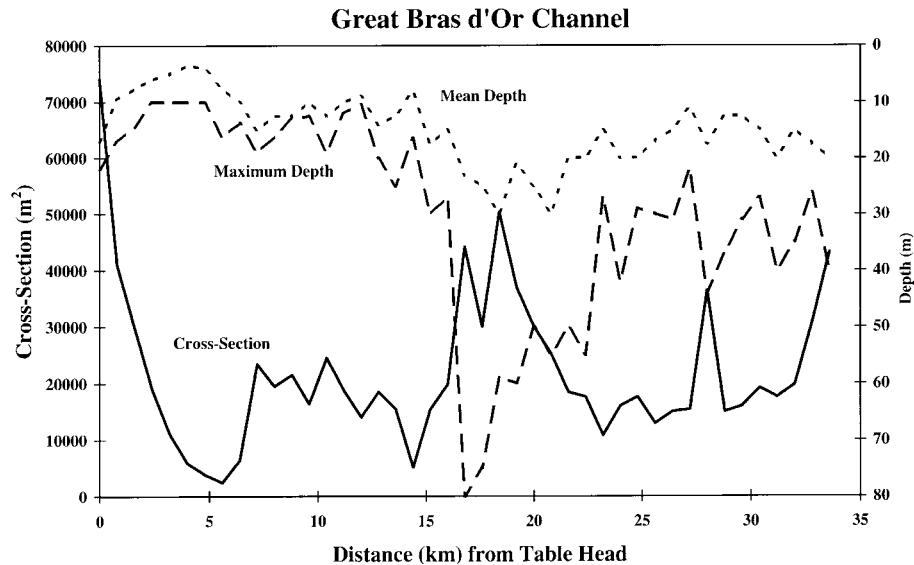


Fig. 6 Along-channel variations of average and maximum depth, and the cross-sectional area for the Great Bras d'Or Channel.

equation (Eq. 2) and the continuity equation (Eq. 8), where W is the channel width. The finite difference form that was used accounted for the varying width of the channel,

$$\partial\zeta/\partial t = -(1/W)\partial uA/\partial x. \quad (8)$$

The aim of the model was to determine if it could reproduce the overall behaviour of the major tidal constituent M2 and the low frequency variability without dealing in detail with the complicated geography of the region. Thus, Great Bras d'Or Channel was represented by a staggered finite difference grid with 1.6 km separation between grid points representing sea level or current. Barra Strait was treated similarly. The complicated geometries of the North Basin (which includes St. Andrew's and St. Patrick's Channels for the model simulation) and Bras d'Or Lake (with East and West Bays) were simplified to rectangular basins of dimensions (length*width*depth) of 16 km* 20 km* 37.2 m and 21.6 km* 34 km* 26 m. The average depths and surface areas were from Gurbutt and Petrie (1995). The model was forced by sea level at Black Rock Point near the mouth of the Lakes. The model was run over many cycles until the principal oscillations reached an equilibrium. The amplitudes and phases were extracted by harmonic analysis, a necessary step because seiches were evident in the model time series of sea level. The following test cases were considered: forcing by M2 alone (amplitude 0.37 m), by low frequency fluctuations with periods of 3 and 7 days (0.2 m amplitudes), by a combination of M2 and a 7-day oscillation.

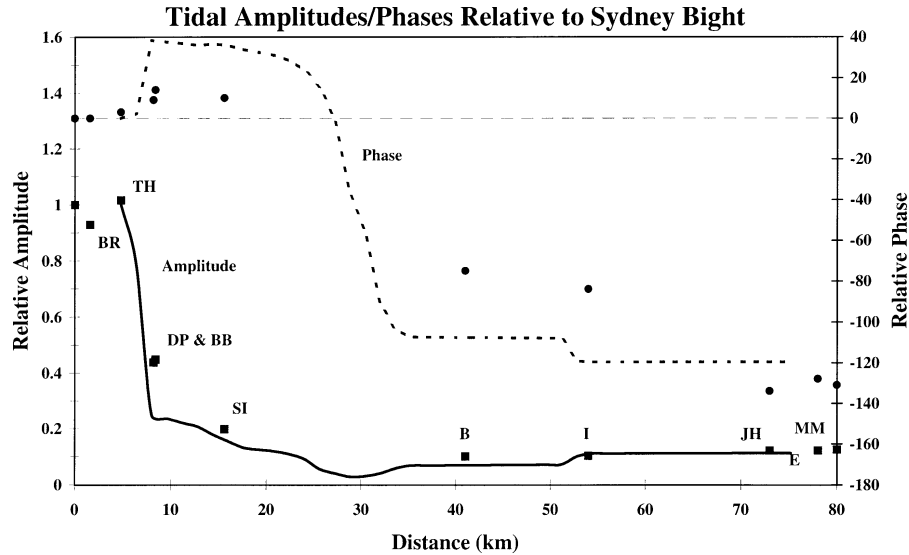


Fig. 7 Comparison of the modelled (lines) and observed (points) M2 amplitudes and phases, for the Bras d'Or Lakes. Place name abbreviations are the same as in Fig. 2.

a Tides

The model amplitude for M2 decreases somewhat faster than the observed harmonics in the Great Bras d'Or Channel but the agreement is encouraging (Fig. 7). The rapid decrease emphasizes the role of friction in the narrow and shallow first third of the channel. Agreement in the first basin at Baddeck and Iona is very good. The model also gives slightly higher (by 16 mm) tidal amplitudes in the inner basin compared to the first basin as do the observations (by 8 mm).

Phase agreement is qualitatively good. Both the modelled and observed phases initially lead in the channel, though they are overestimated by the former. The model shows a rapid change of phase near the entrance to the North Basin but again overestimates the lag at Iona and Baddeck. Agreement is better for the 3 sites in Bras d'Or Lake.

The M2 model transports (not shown) in the Great Bras d'Or Channel and Barra Strait are in phase and essentially equal along their lengths. This agrees with the formulation of Vennell (1998) who predicts nearly non-divergent, in phase transports for channels with the parameter $\varepsilon = L_o \omega_o \zeta_o / H_o u_o \ll 0$, where L_o , H_o , u_o , ζ_o , and ω_o are a typical channel length, depth, velocity, surface displacement and frequency of the motion. The parameter ε is about 0.1 for Great Bras d'Or Channel and 0.002 for Barra Strait.

Examination of the friction and advective ($u\partial u/\partial x$) terms from the model results shows that at the restricted entrance of the Lakes, where the geographic variations are realistically accounted for, the friction term is about 3.5 times greater than the

advective one; on the other hand, in Barra Strait, where the geography is poorly modelled because of the simplification of the north and south basins, the two terms are nearly equal in value.

Overall, the model captures the variation of M2 amplitude and phase in the Lakes. Additional runs could be done, for example, to examine the effects of varying c_d and by including more realistic topography, and hence better account for the advective terms. However, the major thrust of this paper is to present the observations and identify the important physical processes rather than to carry out detailed modelling.

b *Low frequency*

The runs for the 3- and 7-day period forcing reflect the qualitative behaviour demonstrated by the Proudman (1953) solutions, i.e., gain increases and phase lags decrease at longer periods. For 3-day forcing, the amplitude and phase lag come to nearly constant values within a few grid spacings of the mouth. The amplitude gain is about 0.7 and the phase lag is 54° . At 7-day forcing, the behaviour is similar with a gain of 0.95 and a phase lag of 16° . The combined M2 and 7-day forcing has little effect on the M2 amplitude (about a 3% reduction) and phase (generally less than a 1° change). There is a much greater effect on the 7-day component, whose amplitude gain is reduced from 0.95 to 0.73 and whose phase lag is increased from 16° to about 45° . This result is what would be expected from the non-linear nature of the friction.

In general then, the model results are in agreement with the observation because:

- there was good overall agreement with the observed M2 amplitudes and phases;
- the amplitude reduction and phase lags were greater for the tides (i.e., the high frequency components) than for the low frequency fluctuations; furthermore, in the semi-diurnal and diurnal tidal bands the higher frequency components tended to have the smaller gains and largest phase lags;
- in 1973 the low frequency variability was dominated by longer periods, and consequently had higher gains and smaller phase lags, more than in the 1974 records. The range of observed gains, 0.83–1.01, and phase lags, 10 – 50° , for both years are qualitatively in agreement with the model's results.

Encouraged by these comparisons, a final test of the model was conducted by forcing the entrance of the Lakes with the hourly sea level observations recorded at North Sydney. These observations of course include all tidal components, the response to changing atmospheric pressure and windstress as well as any other sea level variations in Sydney Bight. The North Sydney record was subsampled at 80-s intervals to meet the model stability criterion. The results indicate that the rapid decrease of the M2 tidal amplitude is relatively unchanged from the case where the model was forced at a single frequency (Fig. 8). The model forced by M2 alone gave gains/phase lags in the North Basin and Bras d'Or Lake of 0.071/ 108° and 0.112/ 119° ; whereas when forced by observed North Sydney sea level the values were 0.066/ 107° and 0.106/ 120° in 1973, and 0.066/ 106° and 0.108/ 119° in 1974. The low frequency variability is also evident in these records.

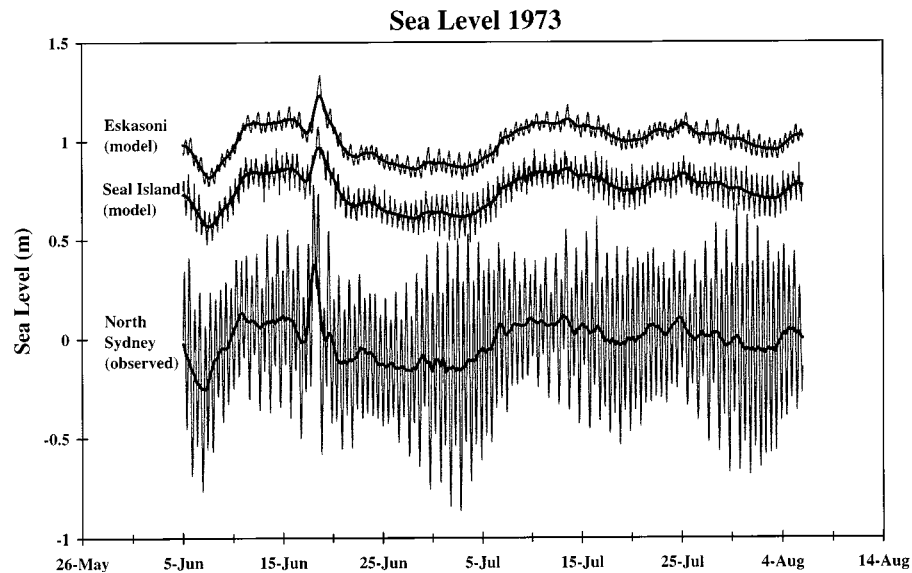


Fig. 8 The 1973 observed sea level variations at North Sydney, and the modelled sea level variations at Seal Island and Eskasoni.

The 1973 and 1974 filtered time series of observed sea level at North Sydney, and modelled and observed sea level in the Lakes are shown in Fig. 9. The qualitative agreement of the model and observed low frequency fluctuations is excellent. However, the model predicts more attenuation in 1973 than is observed, with gains of about 0.84 at Seal Island, Baddeck (not shown) and Eskasoni compared to the observed values of 0.92 to 1.01 (Table 2). Time lags of about 14 h at Seal Island and 16 h at Baddeck and Eskasoni gave maximum correlations of 0.96 in good agreement with the observations. For the 1974 data, the model gains were about 0.83 at Big Bras d'Or, Iona (not shown) and Marble Mountain agreeing well with the observed gains of 0.83 to 0.86. However, the phase lags at maximum correlations of 0.97 were about 16 h at Big Bras d'Or, 18 h at Iona and 19 h at Marble Mountain, not the wider variation of 16 to 36 h that the data give. The correlation of 0.83 from the observations for Marble Mountain at 19-h lag was substantially smaller than the 0.94 value at 36 h.

In conclusion, the sea level variations in the Bras d'Or Lakes are dominated by large components at low frequencies. The available data indicate that these arise primarily from the adjustment to atmospheric pressure variations outside the Lakes in Sydney Bight. These external fluctuations are only slightly attenuated as they penetrate the lake system. On the other hand, the semi-diurnal and diurnal tides are significantly reduced in amplitude and modified in phase as they enter the Lakes. It is perhaps not surprising then that a casual observer would suffer consternation when

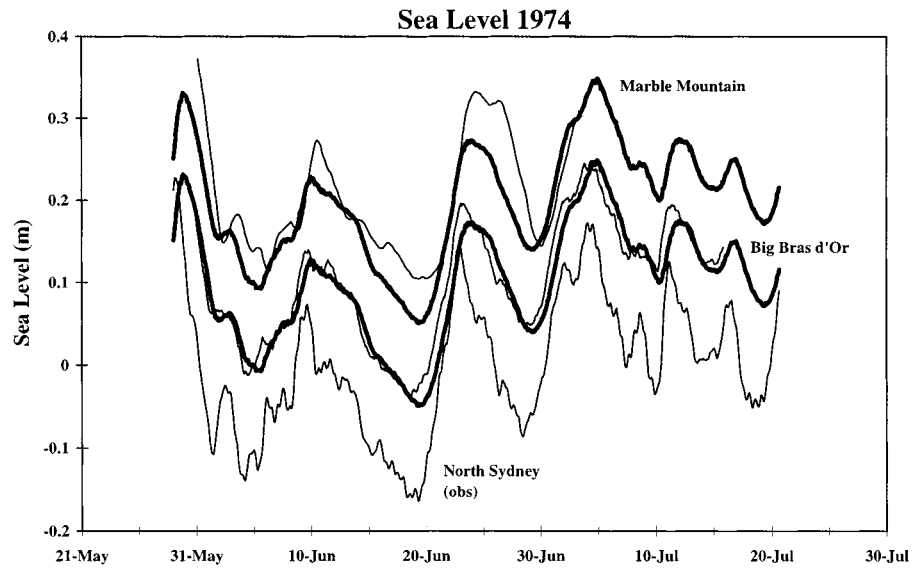
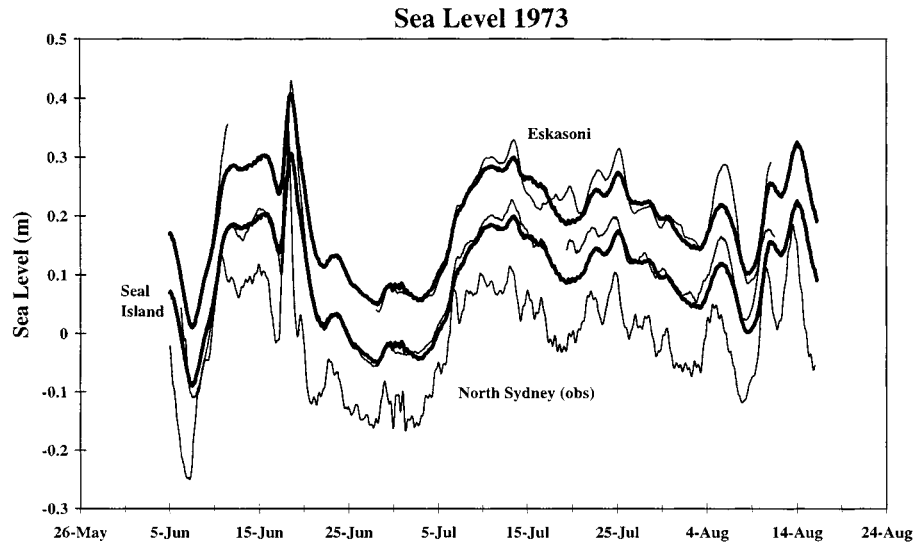


Fig. 9 Filtered (25 h RMF) sea level at North Sydney (observed), Seal Island and Eskasoni (1973, modelled heavy line, observed light line), and Big Bras d'Or and Marble Mountain (1974).

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sea level did not rise or fall as indicated by the tide tables. A simple numerical model has had considerable success in accounting for the variation of the tidal and lower frequency components of sea level in the Bras d'Or Lakes.

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