Tellus (1979), *31*, 75–81

Evidence for interfacial effects between oceanic and atmospheric lunar tides

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(Manuscript received August 29, 1977; in final form May 19, 1978)

ABSTRACT

The lunar semidiurnal atmospheric tide $L_2(p)$ is determined to a high level of significance at station Gan in the middle of the Indian Ocean.

The behaviour of the analysed data from Gan and other oceanic stations, when compared with both the world-wide pattern of the oceanic M_2 and atmospheric $L_2(p)$ tides, can be explained in terms of a marked oceanic tidal effect on $L_2(p)$.

1. Introduction

The world-wide distribution of the lunar semidiurnal atmospheric tide $L_2(p)$, though sufficiently determined (Haurwitz and Cowley, 1969), requires further essential refinements for the explanation of unsolved questions related to the topic itself, because of its importance for the knowledge of the structure of the atmosphere and in connection with other topics such as the geomagnetic external and internal induced fields, the internal structure of the Earth, and oceanic tides.

The oceanic effect on $L_2(p)$ has only recently been investigated by Hollingsworth (1971), whose results indicate that the oceanic tide has a significant and probably dominant effect on the lunar air tide.

$L_2(p)$ data have been submitted to severe criticism, which is here exhaustively reported for only the stations of the Indian Ocean, since it would require extensive description for all the other stations.

2. Worldwide data for $L_2(p)$ and M_2: correlation

The first attempt to compute a correlation between both the amplitude and the phase angle of the oceanic lunar semidiurnal tide M_2 (Admiralty Tide Tables) and the atmospheric amplitude and phase angle (Haurwitz and Cowley, 1969) of $L_2(p)$ for all available seaside stations was largely unsuccessful, since the correlation co- efficients were found to be very small indeed (about 0.04).

This is mostly due to general, large world-wide variations of M_2 (Hendertshott and Munk, 1970), which often show amphidromic regions and strong local gradients of phase angle on the one hand, and because of the significant influence of the mean atmospheric pressure on $L_2(p)$ investigated by Palumbo (1975), on the other.

In searching for an oceanic-atmospheric interface tidal effect, one may reasonably hypothesize that such an effect depends on the width of the oceanic area surrounding the station and having virtually the same phase angle, on the phase lag between the atmospheric and oceanic oscillation, and on the amplitude of the M_2 oceanic tide.

Fig. 1, taken from Pekeris and Accad (1969) and Table 1 of Haurwitz and Cowley (1969), show that such wide ocean areas, for which $L_2(p)$ determinations are available, are located as approximately indicated in Table 1. They will be designated here by the order number of this Table.

3. Data for Gan

The need to determine a better value of $L_2(p)$ in the centre of the Indian Ocean suggested the analysis of data for the island station Gan (S lat.

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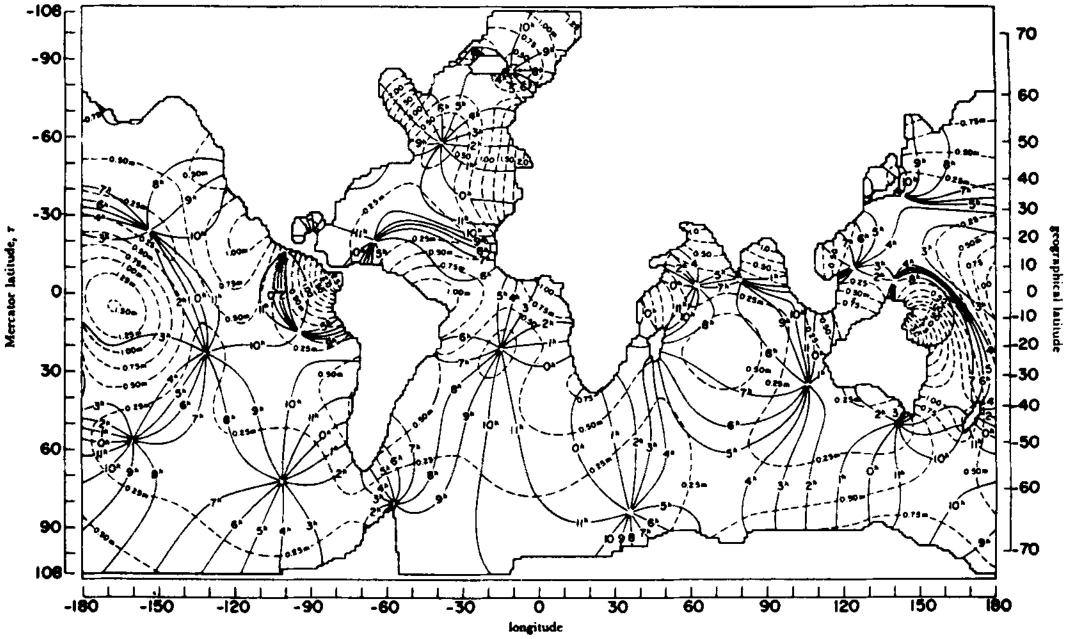

Fig. 1. Computation of the M_2 ocean tide by Pekeris and Accad (1969). Isophase lines are denoted by solid contours, that of iso-amplitude by dashed contours. Amplitudes are given in metres, phases in mean lunar hours.

Table 1. *Geographical positions of oceanic areas investigated and data on lunar semidiurnal atmospheric and oceanic tide*

Oceanic areas	Colat. belt (deg.)	E. long. belt (deg.)	Mean M_2 amplitude (cm)	M_2 isophase lines contouring the area (h)	Phase lag $\lambda_2 - M_2$ phase (h)
1. Cen. Indian	90–120	40–80	25	7–8	7
2. W. Atlantic	45–65	260–310	25	10–11	1.5
3. W. Pacific	70–130	170–210	100	3	2.5
4. W. Pacific	95–135	150–170	100	7–8	7
5. N.E. Pacific	35–55	160–230	50	7–8	7
6. N.E. Pacific	55–100	230–250	75	10–11	1.5

Table 2. *Lunar and solar semidiurnal pressure tide at Gan, amplitude in μb; phase angle in degrees*

Mean pressure p_m (mb)	Season	No. of days	l_2 (μb)	p.e.	λ_2	s_2	p.e.	σ_2
1010.26	year	2765	62.2	3.4	85°.2	1360	2.6	156°.3
1010.13	j	982	77.3	4.8	89°.0	1210	3.8	153°.5
1010.49	d	955	47.0	4.6	66°.7	1460	3.7	156°.6
1010.27	e	970	75.9	5.7	92°.7	1460	5.0	159°.2

00°41'26", E long. 73°08'59", $h = 2$ m asl). Three-hourly pressure data for the period 1963–70, provided by the Meteorological Office of Bracknell, were here analysed according to the Chapman and Miller (1940) method.

In order to eliminate unusually disturbed data from the determination of $L_2(p)$, the days on which the difference between two subsequent values was higher than 4 mb were omitted. Only 8 days out of 2765 were found to have a daily pressure range higher than 5 mb. This indicates the high quality of the present data series.

The solar and lunar semidiurnal amplitudes s_2 and l_2, the vector probable error p.e., and the phase angles σ_2, λ_2 are reported in Table 2, where L_2 is given in the form: $L_2 = l_2 \sin(2\tau + \lambda_2)$.

We shall not deal with the solar terms except as a criterion for checking the validity of the data used to determine $L_2(p)$. This was determined very significantly for each Lloyd season (d months: November, December, January, February; e months: March, April, September, October; j months: May, June, July, August) and for the year. It shows a large seasonal variation with a relatively small value of the amplitude l_2 and the phase angle λ_2 in the "d" months. This is consistent with both the planetary analyses of Haurwitz and Cowley (1969) and Malin (1973).

Since the atmospheric pressure "p_m" at Gan shows only a very small seasonal variation (Table 2), such a variation in $L_2(p)$ cannot be related to "p_m", nor obviously to M_2.

4. Data for Indian Ocean stations

Fig. 1 shows that λ_2 is almost opposite to the phase angle of M_2 in the middle of the Indian Ocean whereas it is almost in phase along the East African coast and on West Indonesia. The data for these three areas are reported in Table 3.

The anomalous values of the amplitude and the phase angle at Gan, Mauritius and Tananarive, located in the same oceanic area as Gan, are not spurious because of the high significance level of the determinations and for the following reasons.

Table 3. *Lunar semidiurnal pressure tide in the Indian Ocean, amplitude in μb, phase angle in degrees*

	Stations	Colat.	E. long	l_2 (μb)	p.e.	λ_2
Central Indian Ocean (*group* (*a*))	Gan	90.7	73.1	62.2	3.4	85.2
	Tananarive	108.9	47.5	53.4	1.8	82.1
	Mauritius Is.	110.1	57.5	51.0	1.1	98.0
	Mean values	103.2	59.4	55.5		88.4
East Africa (*group* (*b*))	Kololo Hill	89.7	32.6	91.2	5.3	77.9
	Kabete	91.3	36.8	87.4	4.3	72.5
	Kwai	94.8	38.3	61.8	4.7	74.6
	Tabora	95.0	32.9	59.4	3.4	89.5
	Chuckwani Palace	96.2	39.2	91.5	16.5	65.9
	Dar es Salaam	96.8	39.3	64.3	3.1	83.4
	Broken Hill	104.4	28.4	84.4	5.5	66.7
	Mean values	95.5	35.4	77.1		75.8
West Indonesia (*group* (*c*))	Singapore	88.7	103.8	89.0	8.9*	76.0
	Batavia	96.2	106.8	83.0	2.1	68.0
	Mean values	92.5	105.3	86.0		72.0
	Vector difference: ($b - a$)			26.0		46.0
	($c - a$)			36.0		46.0
	Oceanic contribution			15.5		46.0

* Estimated by Malin (1973).

If these anomalous values arose from the data we should also have anomalous determinations for the solar terms. The mean ratio of s_2/l_2 and the phase difference $\sigma_2 - \lambda_2$ have been evaluated for these stations and compared with the mean values computed from twelve other stations at roughly the same latitude:

	s_2/l_2	$\sigma_2 - \lambda_2$
Gan, Mauritius, Tananarive	19.5	69°
Mean value of twelve other stations	17.4	80°

which show differences much higher than the mean probable error. Since the solar terms are within the range expected for their latitude, the discrepancies depend on the low value of l_2 and the high value of λ_2 at the three oceanic stations.

For a more positive evaluation, the annual values of $L_2(p)$ are considered. It is reasonable to assume that the mean value of these three stations, group "a" of Table 3, represents $L_2(p)$ for this area. The results are compared with the groups of stations surrounding this oceanic area, i.e. the continental East African stations (group "b") and the Indonesian western stations (group "c") located at about the same latitude as our oceanic area. The mean value of these stations is assumed to represent $L_2(p)$ along the East African coast and West Indonesia. The results are reported in Table 3.

It is readily seen that data for the stations of group "a" $L_2(p)$, though significantly determined, show both the phase angles λ_2 much higher than the average world-wide value (Haurwitz and Cowley, 1969) whereas the amplitudes are too small for this latitude, the opposite is true for l_2 at group "b" and "c" stations. It seems pertinent to discuss here the large values of the linear barometric tide over East Africa since the amplitude for Kazeh Hill, Kololo Hill, Kabete, Broken Hill and Chuckwani Palace found by Chapman and Tchu (1948) are higher than those found for Tabora, Neuwied, Dar es Salaam and Kwai by Haurwitz and Cowley (1967).

A detailed investigation was unsuccessfully carried out by Haurwitz and Cowley (1967) for Tabora which had previously been studied by Chapman and Tchu (1948) under the name of Kazeh Hill. It can be seen that apart from the large difference between these two determinations, there are still unexplained significant differences in $L_2(p)$ obtained by Haurwitz and Cowley (1967) out of the homogeneous analysis of separate sets of data for Tabora. They obtained for the following periods:

1899–1911	$l_2 = 42.0 \pm 3.2$
1931–1945	$l_2 = 59.4 \pm 3.4$

Firstly, we observe that for the second determination, obtained out of a longer series of data, the v.p.e. increases from 3.2 to 3.4. For both determinations the disturbed days (i.e. when the daily pressure range was larger than 5 mb) were eliminated. For the second set of data the percentage of omitted disturbed days was about 20%. The amount of disturbed days (range $\geqslant$ 5 mb) found at Gan (at about the same latitude) was 0.3%, so that the number of disturbed days at Tabora appears to be very high. This allows the suggestion that the discrepancies found in the determinations for this station might be due to the quality of the data.

In any case we have reported in Table 3 the most significant determination obtained by Haurwitz and Cowley at Tabora and discarded the earlier one found by Chapman and Tchu at Kazeh Hill, supporting our thesis, even if there is no proof that the latter is not correct.

In Table 3 we have omitted the determination for Neuwied (Ukewere Island on the Victoria Lake) since it was obtained by Haurwitz and Cowley from three daily observations, and there is no definite evidence that this determination would have been the same if, as is usual, it was obtained from 12 or 24 daily values. In fact the same authors obtained, from the same set of data (1899–1911), the following values for Tabora:

at 8, 14 and 20 h	$l_2 = 35.5; \lambda_2 = 82.0$
bihourly	$l_2 = 42.0 \pm 3.2; \lambda_2 = 91.1$

showing a statistically significant difference.

On the other hand it is reasonable to admit that such a determination might be influenced by the lake's tide.

It is not possible at the moment to examine in detail all other determinations of group "b". Since we shall consider here the average of seven determinations, each one showing a high significance level, we cannot doubt the statistical significance of the mean value.

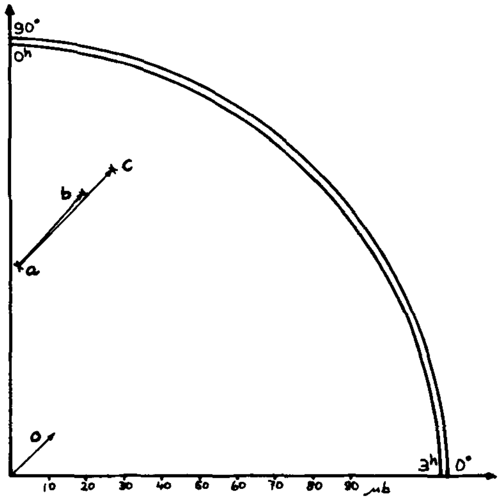

Fig. 2. $L_2(p)$ at Indian Ocean (a), E. Africa (b) and W. Indonesia (c); oceanic contribution to $L_2(p)$ in Indian Ocean (o).

5. Oceanic effect on $L_2(p)$

5.1. *Central Indian Ocean, area no. 1*

Let us investigate whether the mean amplitude and phase angle differences, reported in Table 3, are consistent with the suggestion of a local oceanic contribution to the atmospheric $L_2(p)$. We notice that the world-wide M_2 patterns show oscillations in phase (0 h) with the atmospheric oscillation (0.5 h) near the East African coast and West Indonesia while it is almost opposite (7–8 h) in the oceanic area no. 1. On the harmonic dial in Fig. 2 the three mean annual vectors L_2 relative to the Oceanic ("a"), African ("b") and Indonesian ("c") stations have been plotted together with the vector differences (b – a) and (c – a) (Table 3).

From such representation one deduces that the mean vector differences have respectively amplitudes of 26 and 36 μb and a phase angle of 46° nearly equal for both (b – a) and (c – a). This means that the amplitude is larger than the probable uncertainty of the data and that the maximum of such vectors takes place at 1.5 h, i.e. is almost opposite to the 7–8-h isophase lines contouring the Indian oceanic area and in phase with the oceanic oscillation along the East African coast and West Indonesia. Since the oceanic contribution to $L_2(p)$ is thus in opposite phase in the two areas, it must have an amplitude roughly half the mean of the two vector differences. Adding this contribution to the L_2 vector at the stations of group "a" we would obtain $l_2 = 69$ μb, $\lambda_2 = 79°$; subtracting it from stations of group "b" and "c" we would obtain respectively $l_2 = 64$ μb, $\lambda_2 = 83°$; $l_2 = 72$ μb, $\lambda_2 = 77°$. Similar results have been obtained from seasonal data.

The above values, showing differences within their p.e., are then in perfect agreement with those expected according to actual world-wide models for the mean latitude of the stations. In this way the anomalous small value of L_2 in the Indian Ocean and the large one on the East African coast, and on West Indonesia, found by Haurwitz and Cowley and Chapman and Westfold (1956), are explained.

5.2. *West Atlantic Ocean, area no. 2*

In Table 4 the mean $L_2(p)$ at Bermuda and Greensboro located within area no. 2, where λ_2 is almost in phase with the oceanic oscillation, is compared with Oklahoma City and Dodge City at about the same latitude but inside the continental U.S.A. where there is presumably no oceanic effect.

The comparison provides an oceanic effect, in this case represented by the vector difference, of $L_2 = 15.8 \sin (2\tau + 72°)$ μb, to be subtracted to $L_2(p)$ at Bermuda and Greensboro.

5.3. *West Pacific Ocean, area no. 3 and no. 4*

In Table 5 $L_2(p)$ at Apia, located within area no. 3, where the oceanic and atmospheric oscillations have a phase lag of 2.5 h, is compared with mean $L_2(p)$ at Port Moresby, Rockhampton, Norfolk

Table 4. *Lunar semidiurnal pressure tide in the West Atlantic Ocean, amplitude in μb, phase angle in degrees*

Stations	Colat.	E. long	l_2 (μb)	p.e.	λ_2
Oklahoma City	54.6	262.4	24.3	8.4	70.4
Dodge City	52.2	260.2	21.8	5.0	73.3
Mean values	53.4	261.3	23.0		71.9
Greensboro	53.9	280.0	36.1	5.1	78.3
Bermuda	57.6	295.3	41.5	5.9	66.8
Mean values	55.8	287.7	38.8		72.6
Vector difference			15.8		72.0
Oceanic contribution			15.8		72.0

Table 5. *Lunar semidiurnal pressure tide in the West Pacific Ocean, amplitude in μb, phase angle in degrees*

Stations	Colat.	E. long	l_2 (μb)	p.e.	λ_2
Apia (Samoa)	103.6	188.2	73.0	4.0*	59.0
Port Moresby	99.4	147.2	40.2	3.8	75.8
Rockhampton	113.4	150.5	41.7	3.8	83.0
Norfolk Is.	119.0	167.9	52.2	2.9	71.5
Lord Howe Is.	121.5	159.0	34.2	5.1	71.2
Mean values	113.3	156.2	42.1		75.4
Corrected for latitude effect			50.4		
Vector difference			29.0		29.0
Oceanic contribution			14.5		29.0

* Estimated by Malin (1973).

Table 6. *Lunar semidiurnal pressure tide in the North East Pacific, amplitude in μb, phase angle in degrees*

Stations	Colat.	E. long	l_2 (μb)	p.e.	λ_2
San Francisco	52.2	237.6	14.7	2.3	57.2
Lick Obsy	52.1	237.7	10.9	1.6	67.7
Mean values	52.2	237.7	12.8		62.5
Burbank	55.8	241.6	25.8	2.3	64.0
Mt. Wilson	55.8	241.8	15.9	2.4	75.5
San Diego	57.3	242.8	23.2	3.0	68.8
Mean values	56.3	242.1	21.6		69.4
Dodge City	52.2	260.0	21.8	5.0	73.3
Oklahoma City	54.6	262.4	24.3	8.4	70.4
Mean values	53.4	261.2	23.1		71.9
Oceanic contribution			11.0		83.0

Island and Lord Howe Island within the neighbouring area no. 4 where λ_2 is almost opposite to the phase angle of M_2.

The oceanic effect on $L_2(p)$, computed according to the same criterion as for area no. 1 and taking into account the latitude correction, is $L_2 = 14.5 \sin(2\tau + 29°)$ μb, to be subtracted at Apia and added to the others.

5.4. *North East Pacific Ocean, area no. 5 and no. 6*

Further evidence for an oceanic contribution is provided by the data of San Francisco and Lick Obsy, Table 6, adjacent to the wide oceanic area no. 5, where λ_2 is almost opposite to the phase angle M_2, for which the mean $L_2 = 12.8 \sin(2\tau + 62°5')$ μb, with an amplitude much lower than at Mt. Wilson, San Diego and Burbank, adjacent to the ocean area no. 6, where λ_2 is almost in phase with the phase angle M_2 and for which stations the mean $L_2 = 21.6 \sin(2\tau + 69°)$ μb. The oceanic contribution to $L_2(p)$ for this area is evaluated to $4.4 \sin(2\tau + 263°)$ μb.

The lower value of this oceanic contribution, when compared to that of other areas, may be attributed to the interference of the effect between the neighbouring areas no. 5 and no. 6. Moreover $L_2(p)$ at San Francisco and Lick Obsy, when compared to $L_2(p)$ at Oklahoma City and Dodge City, at about the same latitude but inside the continental U.S.A., shows an oceanic contribution at the former stations of $11 \sin(2\tau + 83°)$ μb. This value will be assumed to represent the oceanic contribution on $L_2(p)$ in the N.E. Pacific.

6. Conclusion

The oceanic effect on $L_2(p)$ provided by each oceanic area of Table 1 has been evaluated as follows:

area no. 1	$L_2 = 15.5 \sin(2\tau + 46°)$ μb
no. 2	$15.8 \sin(2\tau + 72°)$
no. 3, 4	$14.5 \sin(2\tau + 29°)$
no. 5, 6	$11.0 \sin(2\tau + 83°)$

The fair agreement between the above amplitudes and their large values exceeding the incertitude of the determinations, the small range of variation of the phase angles, the agreement of the local determinations corrected for oceanic contribution and those expected according to the theory, support the suggestion of a local oceanic effect on the atmospheric lunar tide.

The definite evaluation of such effect and a new world-wide representation of $L_2(p)$, computed according to new individual values of $L_2(p)$ corrected for oceanic effect, would contribute to eliminate some of the unexplained features such as, particularly, the large scattering of the phase angles, the asymmetry of $L_2(p)$ relative to the Equator, and the great number of spherical harmonic coefficients of $L_2(p)$ in actual models (Malin, 1973).

On the other hand, the present results, which have explained the anomalous local values of $L_2(p)$ in terms of an oceanic tidal effect, support the actual model of M_2 obtained from observations which are almost concentrated along the coasts but are unavailable for the centre of the oceans and the seas.

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СВИДЕТЕЛЬСТВО ОБ ЭФФЕКТЕ ВЗАИМОДЕЙСТВИЯ МЕЖДУ ОКЕАНИЧЕСКИМИ И АТМОСФЕРНЫМИ ЛУННЫМИ ПРИЛИВАМИ

Для станции Ган в середине Индийского океана с высоким уровнем значимости определен лунный атмосферный полусуточный прилив $L_2(p)$. Поведение данных, проанализированных для Гана и других океанических станций, при сравнении глобальных картин распределений океанических—M_2—и лунных—$L_2(p)$—приливов может быть объяснено заметным приливным влиянием океана на $L_2(p)$.