Tidal gravity measurements in Southeast Asia revisited.

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Abstract. In the region of Southeast Asia, there is an overall disagreement between tidal gravity observations and the tidal predictions. The predictions are based on a theoretical tidal model that calculates oceanic loading and attraction effects based on existing global ocean tides models. The loading and mass attraction effects for the M_2 tidal wave are calculated here using two recent ocean tide models. We demonstrate that the higher spatial resolution and precision of the new models still do not resolve the discrepancies between observations and predictions in this region.

Introduction

Almost 20 years ago, Melchior et al. (1996) reported observing large tidal residuals for the principal semi-diurnal, M2, tides in the Southeast Asia. The authors compared the observed tidal factors from 17 temporary tidal gravity stations with modeled body and ocean loading tides. In that study, the team carefully checked the calibration of the gravimeters, and rejected tidal stations for which the calibration could not be verified. Using the Schwiderski oceanic co-tidal map, Melchior et al. (1996) found that the tidal loading and direct attraction were modeled with a precision of only 2.5 microgals. This result was intriguing as one could do at least five times better anywhere else on the globe.

Two explanations were put forward for the disagreement between the observations and predictions. First, a defect in the oceanic co-tidal maps could be the result of a complicated tidal regime in the adjacent seas: South China Sea, Java Sea, Arafura Sea and Coral Sea. For example, no less than ten amphidromic points are known to exist in the nearby China and Yellow seas. A second explanation for the discrepancy was the influence of a large geoid "low" that could induce a regional anomaly in the Earth tide deformation.

To investigate the effects of the complicated tidal regime and the geoid anomaly, Melchior et al. (1996) used the newly available co-tidal maps from Grenoble, FES952, hoping to improve the agreement between the observation and the modeled ocean loading and attraction. However, the discrepancy still existed. At that time, the authors were unable to find a firm and definitive answer to the cause of the discrepancies between the observed and modeled Earth tides in this region.

In this paper, we reinvestigate the discrepancy between tidal observations and predictions in Southeast Asia. New oceanic co-tidal models with greater spatial resolution and precision, as compared to FES952, are available today. We restricted our analysis to the M_2 tides only.

Recent Ocean Tidal Models

Recently, two new global ocean tides models are available to the scientific community. The first, a new FES model FES2012 that represents an improvement over FES2004 (Lyard et al, 2006), and is widely used in satellite altimetry. FES2012 provides estimates of 33 tidal waves (instead of 15 for FES2004) with an unprecedented resolution of 1/16 x 1/16 degree. The second model is the last born from the EOT family EOT11a (Savcenko and Bosch, 2008). It contains 14 tidal waves and a resolution of 1/8 x 1/8 degree.

The increased spatial resolution and the expected higher precision of these models gave us hope that the new models would resolve the discrepancy between the observed and modeled Earth tides described in the paper of Melchior et al. (1996) once for all.

Oceanic Loading and Attraction Effects.

The observed tidal parameters were taken from the paper of Melchior et al. (1996). An elastic ocean-less Earth model response was subtracted from these parameters. The differences should represent the oceanic attraction and loading effects at the stations. Using the notation from Melchior's (1983) in which a graphical representation can be found: the vector **A**(A,α) is the observed tidal response and the vector **R** (R,0) is the elastic oceanless Earth model response (calculated). Then we can calculate:

1. **B**(B, β) = **A**-**R**; **L**(L,λ) the oceanic attraction and loading vector (calculated with an ocean tides model);
2. **X**(X,χ) = **B – L** = **A – R – L** the final residual vector.

In Table 1, the vector **B** is given for all the stations along with the oceanic and loading vector computed for the Schwiderski model, the standard ocean tide model for many decades, and the two new models FES2012 and ETO11a. We immediately notice that two new models give similar results that are only slightly different from Scwhiderski. However, the new models do not reduce significantly the final residual vector X (Table 2) as compared to Schwiderski. In fact, the new models are not better at all on average.

In Table 3, we calculate the difference between the final residuals obtained with the three ocean tide models. The residuals of the two new models differ by only 0.1+/-0.1 microgal on average, and give almost identical results. The differences with the results based on the Schwiderski model are larger: 0.75+/-0.45 microgal. Despite the smaller residuals of the new models as compared with Schwiderski, the new models did not improve the agreement between the observed and predicted M_2 tidal loading and attraction effects in Southeast Asia.

Conclusion.

The calculation of the loading and attraction effects of the M2 tide in the Southeast Asia using new ocean tides models does not improve the discrepancy between observations and predictions there. Despite the higher spatial resolution and precision of the new models, there is no reduction in the final residuals. Moreover, the two models give the same results. It is clear that the solutions of the global models are converging for the region of Southeast Asia. However, it appears that defects in the ocean tidal models are no longer a candidate for explaining the discrepancy between observed and predicted gravity tides in the Southeast Asia. A systematic calibration error, although highly improbable, could be verified by installing a few new tidal stations equipped with well-calibrated superconducting gravimeters. If these future observations confirm the anomaly, then the role that the geoid anomaly is playing in the discrepancy might be elucidated. In conclusion, despite our efforts to improve the loading calculation in the Southeast Asia, the mystery behind the discrepancy remains unsolved.

We would like to dedicate this short paper to the late Prof. Paul Melchior who maintained a long and sincere friendship with Prof. Houze Hsu.

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T**able 1.** Coordinates of each tidal gravity station in the Southeast Asia. The M_2 observed residuals vector B is compared to the oceanic attraction and loading computed with the Schwiderski, FES2013 and EOT11a ocean tide models, respectively. The amplitudes are given in microgal and the phases in degree.

					Observed		SCHWIDERSKI		FES2012		EOT11a	
NUM	**STATION**	**LONG**	**LAT**	**D**	**B**	**β**	**L**	**λ**	**L**	**λ**	**L**	**λ**
2460	**COLOMBO**	**79,87**	**6,90**	**3**	**4,01**	**162**	**1,44**	**158**	**1,54**	**132**	**1,55**	**131**
2502	**CHIANG MAI**	**98,98**	**18,79**	**300**	**1,24**	**-141**	**1,43**	**250**	**0,87**	**266**	**0,84**	**267**
2501	**BANGKOK LATPRAO**	**100,60**	**13,79**	**25**	**1,19**	**-158**	**1,57**	**247**	**1,06**	**263**	**1,00**	**260**
2551	**PENANG**	**100,30**	**5,36**	**1**	**2,51**	**-162**	**1,51**	**232**	**0,61**	**223**	**0,43**	**220**
2550	**KUALA LUMPUR**	**101,65**	**3,12**	**30**	**0,66**	**82**	**0,51**	**302**	**1,83**	**21**	**1,86**	**22**
2701	**SAIGON**	**106,70**	**10,78**	**60**	**1,44**	**-111**	**0,67**	**200**	**0,09**	**154**	**0,14**	**93**
4100	**BANDUNG JAVA**	**107,63**	**-6,90**	**70**	**4,84**	**-37**	**2,51**	**311**	**2,69**	**327**	**2,70**	**328**
4210	**DARWIN/MANTON DAM**	**131,13**	**-12,85**	**60**	**1,32**	**22**	**0,24**	**21**	**1,40**	**33**	**1,01**	**49**
4010	**BAGUIO**	**120,58**	**16,41**	**25**	**3,33**	**-31**	**2,56**	**344**	**2,53**	**345**	**2,55**	**346**
4011	**MANILA OBSERV.**	**121,07**	**14,64**	**20**	**1,35**	**-21**	**2,47**	**347**	**2,49**	**343**	**2,50**	**344**
2555	**K.KINABALU SABAH**	**116,07**	**5,95**	**2**	**1,28**	**-128**	**0,78**	**312**	**1,06**	**312**	**1,03**	**317**
4105	**BANJAR BAR KALIM.**	**114,78**	**-3,33**	**20**	**1,79**	**-7**	**1,31**	**323**	**1,16**	**335**	**1,16**	**339**
4111	**MANADO SULAW.**	**124,83**	**1,45**	**4**	**5,39**	**-7**	**3,08**	**0**	**4,33**	**3**	**4,37**	**4**
4120	**JAYAPURA IRIAN JAYA**	**140,67**	**-2,50**	**5**	**3,83**	**-41**	**2,02**	**338**	**3,09**	**331**	**2,97**	**333**
4110	**UJUNG PANDANG SULAW.**	**119,63**	**-5,67**	**12**	**3,48**	**-58**	**1,59**	**231**	**1,86**	**208**	**1,89**	**205**
4115	**KUPANG TIMOR**	**123,57**	**-10,20**	**1**	**5,14**	**-119**	**5,67**	**230**	**6,09**	**219**	**6,15**	**218**
4160	**PORT MORESBY**	**147,15**	**-9,41**	**5**	**4,92**	**-6**	**1,49**	**-93**	**1,99**	**272**	**1,94**	**272**

D= distance to the sea in km

Table 2. Final residues for the M_2 tidal waves for the difference ocean tide models. The amplitudes are given in microgal and the phases in degree.

		Schwiderski map		FES2012 map		EOT11a map	
NUM	**STATION**	X	χ	X	χ	X	χ
2460	**COLOMBO**	2,58	164	2,79	178	2,80	179
2502	**CHIANG MAI**	0,75	130	0,91	174	0,92	176
2501	**BANGKOK LATPRAO**	1,10	116	1,15	148	1,07	150
2551	**PENANG**	1,51	164	1,97	-170	2,12	-166
2550	**KUALA LUMPUR**	1,10	99	1,62	180	1,63	-178
2701	**SAIGON**	1,12	-84	1,45	-107	1,57	-109
4100	**BANDUNG JAVA**	2,44	-25	2,16	-42	2,17	-44
4210	**DARWIN/MANTON DAM**	1,08	22	0,27	-80	0,62	-25
4010	**BAGUIO**	1,09	-69	1,13	-69	1,15	-71
4011	**MANILA OBSERV.**	1,15	176	1,15	168	1,17	171
2555	**K.KINABALU SABAH**	1,38	-162	1,52	-171	1,56	-169
4105	**BANJAR BAR KALIM.**	0,94	38	0,77	21	0,73	16
4111	**MANADO SULAW.**	2,37	-16	1,37	-41	1,40	-45
4120	**JAYAPURA IRIAN JAYA**	2,04	-60	1,04	-80	1,20	-79
4110	**UJUNG PANDANG SULAW.**	3,33	-31	4,06	-31	4,17	-31
4115	**KUPANG TIMOR**	1,19	-8	2,32	-16	2,46	-17
4160	**PORT MORESBY**	5,07	11	5,04	17	5,04	16
Average		1.78		1.81		1.87	
Std Dev		1.11		1.21		1.20	

Table 3. Differences between the calculated loading and attraction effect s for the M_2 tidal waves for the difference ocean tide models. The amplitudes are given in microgal and the phases in degree.

		X(FES2012) –X(SCHWI)		X(FES2012) –X(ETO11a)	
NUM	**STATION**	**Amplitude/microgal**	**Phase/Degree**	**Amplitude/microgal**	**Phase/Degree**
2460	**COLOMBO**	**0,68**	**-117**	**0,03**	**71**
2502	**CHIANG MAI**	**0,64**	**-131**	**0,03**	**64**
2501	**BANGKOK LATPRAO**	**0,63**	**-143**	**0,09**	**126**
2551	**PENANG**	**0,91**	**-122**	**0,19**	**52**
2550	**KUALA LUMPUR**	**1,8**	**-143**	**0,07**	**79**
2701	**SAIGON**	**0,61**	**-154**	**0,13**	**54**
4100	**BANDUNG JAVA**	**0,73**	**-145**	**0,08**	**57**
4210	**DARWIN/MANTON DAM**	**1,17**	**-145**	**0,52**	**-180**
4010	**BAGUIO**	**0,04**	**-58**	**0,05**	**48**
4011	**MANILA OBSERV.**	**0,15**	**82**	**0,05**	**58**
2555	**K.KINABALU SABAH**	**0,28**	**133**	**0,08**	**67**
4105	**BANJAR BAR KALIM.**	**0,31**	**-92**	**0,07**	**68**
4111	**MANADO SULAW.**	**1,27**	**-169**	**0,08**	**70**
4120	**JAYAPURA IRIAN JAYA**	**1,12**	**138**	**0,17**	**107**
4110	**UJUNG PANDANG SULAW.**	**0,72**	**-30**	**0,11**	**134**
4115	**KUPANG TIMOR**	**1,15**	**-24**	**0,14**	**158**
4160	**PORT MORESBY**	**0,52**	**107**	**0,05**	**109**
	Mean	**0.75**		**0.11**	
	Std Dev	**0.45**		**0.11**	