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In Memory of Peter Schwintzer †

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Foreword

We remember our highly appreciated colleague Dr. Peter Schwintzer, who left us too early and whom we miss. He was very interested in this work and supported it expressly. Together with Dr. Richard Biancale he recognized the importance of atmospheric tides for orbit computation and terrestrial gravity field modelling. The common activities to this publication began during the presence of Dr. Richard Biancale as guest scientist at the GFZ-Potsdam in the year 2002. He had the idea how to initialise this work and he integrated in every respect his rich experience and profound knowledge on tides and gravity field modelling as well as orbit processing and software development.

We thank Dr. Pascal Gegout at the University of Strasbourg for the computation of harmonic coefficients from atmospheric pressure data and several colleagues at the GFZ-Potsdam for their useful and competent contributions. The special interest of Dr. Frank Flechtner on the theme as GRACE Science Data System manager is to emphasize. He accompanied and supported the work by constructive hints, management of the tests and editorial activities. Dr. Rolf König, Jean Claude Raimondo and Ulrich Meyer performed the orbit tests and computed maps of geoid differences for different atmospheric tide models.

Albert Bode and Richard Biancale

Oberpfaffenhofen and Toulouse, December 14, 2005.

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1. Introduction

Actual and future satellite missions dedicated to improving terrestrial gravity field models are CHAMP, GRACE and GOCE. The growing sensitivity and accuracy of space geodetic measurements allow us on one hand to derive better gravity field models, but requires on the other hand to deal with improved standards for orbit computation. One important subject is the influence of the atmospheric mass of the Earth and its variations on the acceleration of a satellite. The corresponding disturbing potential can be derived from the atmospheric surface pressure.

The contribution due to the constant part of the atmospheric masses during a relatively short satellite arc of one or a few days can be taken into account by globally distributed atmospheric surface pressure data, which are collected by some institutions as for example the European Center for Medium Weather Forecast (ECMWF). Besides the constant part, the contribution of periodic mass variations of the atmosphere with highest frequencies of once and twice per day is essential. It can be taken into account by the daily and half-daily gravitational tides S1 and S2 of an atmospheric tide model, or more precisely, by a global tide model of atmospheric surface pressure, expressed by spherical harmonic functions.

Some atmospheric tide models are already available. They all include the half-daily tide S2 and some of them also contain the daily tide S1. One well known model is that of B. Haurwitz and Ann D. Cowley (1973), which contains prograde and retrograde waves of the S1 and S2 tides. Together with the tides (annual variations) also seasonal variations of S1 and S2 are published. Among the recent models the model of Richard Ray (2001) is known. It contains prograde and retrograde waves of the S2 tide. Furthermore there is an unpublished model of the Center of Space Research at the University of Austin (UTCSR), which is used in combination with the ocean tide model CSR-4.0 (1995). It consists only of two prograde main components of the S2 tide. An actual contribution of GRGS and GFZ is the model of R. Biancale and A. Bode (2003), consisting of prograde waves of the S1 and S2 tides. Besides the UTCSR-model, which is based on SLR data, the above models are solely based on atmospheric surface pressure data of globally distributed meteorological stations. The newer models are used at GRGS, GFZ and UTCSR for orbit processing and gravity model generation of the actual missions CHAMP and GRACE.

The model of Biancale and Bode (2003) is based on globally gridded ECMWF atmospheric surface pressure data, available with time steps of 6 hours starting from May 1985. Because of the restricted time resolution of 6 hours only one of two combined zonal S2 parameters could be solved. To get the zonal parameters completely, the phases of Haurwitz and Cowley were used for zonal components. Now the ECMWF atmospheric surface pressure data are also available with time steps of 3 hours, starting from January 1997. Their temporal resolution is sufficient to derive the zonal S2-parameters. Thus, two additional models using the higher-resolution data were computed. They contain again the prograde waves of the S1 and S2 tides.

To assess the quality of the Biancale and Bode model as well as of the two additional models some tests were carried out. These tests include orbit computations, calculation of geoid differences and geoid heights for different old and new atmospheric tide models. To test the influence of the yearly time variability of the S1 and S2 tides, also seasonal means of the amplitudes and phases were regarded. The tests show in principle no significant differences between all models. This allows to conclude, that actual atmospheric tide models are equivalent for data processing and gravity field modelling from the present gravity missions. The effect of atmospheric tides on the Earth's gravity field is small. But in view of the high accuracy to be expected from products of present and future space geodetic missions it should not be neglected.

2. Theoretical Background

The gravitational potential of a simple layer, which is induced by the atmospheric masses can be derived from the atmospheric surface pressure and its variations. For this reason we represent the atmospheric surface pressure by spherical harmonic functions :

$$\Delta P(\varphi,\lambda,t) = g \cdot q = g \cdot \sum_l \sum_m q_{lm}(\varphi,\lambda,t) =$$
$$= \sum_l \sum_m \left(\Delta C_{lm}(t)\cos m\lambda + \Delta S_{lm}(t)\sin m\lambda\right) p_{lm}(\sin\varphi) \tag{1}$$

The spherical harmonic function $q(\varphi,\lambda,t) = \Delta P(\varphi,\lambda,t)/g$ is the loading, which generates the potential U and the derived acceleration vector $\overline{A}$:

$$\overline{A} = \overline{grad}\,U\,, \quad U = 4\pi G a_e \sum_l \frac{1+k_l'}{2l+1}\left(\frac{a_e}{r}\right)^{l+1} \sum_m q_{lm}(\varphi,\lambda,t) \tag{2}$$

The corresponding ocean water height Δh is connected to the atmospheric surface pressure by the fundamental equation of hydrostatics :

$$\Delta P(\varphi,\lambda,t) = g \cdot \rho_w \cdot \Delta h(\varphi,\lambda,t) \tag{3}$$

To derive the periodic variations of the atmospheric surface pressure, ΔP or Δh can be decomposed into tides alternatively. We have chosen Δh for this decomposition. Modifying the harmonic representation by tide functions we get :

$$\Delta h(\varphi,\lambda,t) = \sum_n \sum_{\overset{-}{+}} \sum_l \sum_m C^{\pm}_{n,lm} \sin(\theta_n(t) \pm m\lambda + \epsilon^{\pm}_{n,lm})\; p_{lm}(\sin\varphi) \tag{4}$$
$$= \sum_l \sum_m \sum_n \sum_{\overset{-}{+}} C^{\pm}_{n,lm} \left[\sin(\theta_n(t)+\epsilon^{\pm}_{n,lm})\cos m\lambda \pm \cos(\theta_n(t)+\epsilon^{\pm}_{n,lm})\sin m\lambda\right] p_{lm}(\sin\varphi)$$

Residual functions at the right hand side of (1) and (4), which cannot be expressed by spherical harmonic functions of tides are subordinated to the following development and therefore neglected. By the expressions (4) the atmospheric tide model is represented by harmonic functions according to an usual spherical harmonic representation of ocean tides, but not applying a convention for the phases. The second formulation is derived by addition theorems of the trigonometric functions. Under an atmospheric tide model we understand a global tide model of the atmospheric surface pressure (expressed in terms of ΔP or Δh), derived from barometric measurements of globally (or widely) distributed stations. Its purpose is to represent the daily and half-daily tides S1, S2, which give a measure for the atmospheric mass variations of highest frequency and are caused by gravitation. Some actual atmospheric tide models are restricted to the S2 tide only. In the following all investigated tide models, presented by Tables or Figures, are related to fully normalised harmonics. External models, which originally are not related to fully normalised harmonics, have been transformed before (Appendix A1, A2 in chapter 9, 10).

Summary of Constants and Variables.

Constants:

G	gravitational constant : $6.672\ 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$
a_e	semi-major axis of the Earth's gravity field model : $6\ 378\ 137\ m$
k_l'	Love number of the loading
g	mean acceleration of gravity : $9.80\ m/s^2$
ρ_w	mean density of ocean water : $1025\ kg/m^3$
$C^{\pm}_{n,lm}, \epsilon^{\pm}_{n,lm}$	amplitudes in meter and phases (in degree) of the spherical harmonic tide model (n: tide index, l: degree, m: order, +: prograde component, -: retrograde component)

Variables and Functions:

(r,φ,λ)	polar coordinates of a point outside the surface of the Earth
t	mean sidereal time
$q(\varphi,\lambda,t)$	loading of the atmospheric surface pressure in $kg\ m^{-2}$
$\Delta P(\varphi,\lambda,t)$	atmospheric surface pressure in Pascal $(kg\ m^{-1} s^{-2})$
$\Delta h(\varphi,\lambda,t)$	water height in meter
$\Delta C_{lm}(t),\ \Delta S_{lm}(t)$	harmonic coefficients of the atmospheric surface pressure (temporal variations)
$\theta_n(t)$	astronomical argument according to the Doodson number of tide n

Insertion of the second formulation for $\Delta h(\varphi,\lambda,t)$ in (4) into the fundamental equation of hydrostatics (3) and comparison of the coefficients of the independent spherical harmonic functions $p_{lm}(\sin\varphi)\cos m\lambda,\ p_{lm}(\sin\varphi)\sin m\lambda$ with the coefficients of expression (1) at any time t yield the relations:

$$\begin{aligned} \Delta C_{lm}(t) &= g\cdot\rho_w \{ \sum_n \sum_{+}^{-} \quad C^{\pm}_{n,lm} \sin\left(\theta_n(t) + \epsilon^{\pm}_{n,lm} \right) \} \\ \Delta S_{lm}(t) &= g\cdot\rho_w \{ \sum_n \sum_{+}^{-} \pm C^{\pm}_{n,lm} \sin\left(\theta_n(t) + \epsilon^{\pm}_{n,lm} \right) \} \end{aligned} \tag{5}$$

Application of addition theorems of the trigonometric functions and rearrangement of the combined tide parameters $C^{+}_{n,lm}\sin(\epsilon^{+}_{n,lm})$, $C^{+}_{n,lm}\cos(\epsilon^{+}_{n,lm})$, $C^{-}_{n,lm}\sin(\epsilon^{-}_{n,lm})$, $C^{-}_{n,lm}\cos(\epsilon^{-}_{n.lm})$ in vectors, yield the representation by rotation matrices:

$$\begin{aligned} \begin{bmatrix} \Delta C_{lm}(t) \\ \Delta S_{lm}(t) \end{bmatrix} = \sum_n (&\begin{bmatrix} \cos\theta_n(t) & \sin\theta_n(t) \\ -\sin\theta_n(t) & \cos\theta_n(t) \end{bmatrix} \begin{bmatrix} C^{+}_{n,lm}\sin\epsilon^{+}_{n,lm} \\ C^{+}_{n,lm}\cos\epsilon^{+}_{n,lm} \end{bmatrix} + \\ &+ \begin{bmatrix} \cos(\pi/2-\theta_n(t)) & \sin(\pi/2-\theta_n(t)) \\ -\sin(\pi/2-\theta_n(t)) & \cos(\pi/2-\theta_n(t)) \end{bmatrix} \begin{bmatrix} C^{-}_{n,lm}\cos\epsilon^{-}_{n,lm} \\ C^{-}_{n,lm}\sin\epsilon^{-}_{n,lm} \end{bmatrix}) \end{aligned} \tag{6}$$

The matrix elements yield the partial derivates of the design matrix of the observation equations to determine the combined tide parameters from the time dependent spherical harmonic coefficients $\Delta C_{lm}(t),\ \Delta S_{lm}(t)$ (observations) by a least squares fit.

3. Computation Method

The method, applied for the computation of atmospheric tide models from atmospheric surface pressure data, is close to the mathematical representation, which is described by the expressions (1) and (5) or (6) respectively. Thus two main processing steps are performed.

First Processing Step.
The first step consists in the decomposition of the surface pressure data into harmonic functions according to (1), resulting in the spherical harmonic coefficients $\Delta C_{lm}(t), \Delta S_{lm}(t)$. This means at first a geometrical step of decomposition with respect to the position (φ, λ) . The coefficients are determined separately for continents and oceans from globally distributed atmospheric surface pressure data. Then they are added to take into account the entire influence of the atmosphere over the continents and oceans.

Second Processing Step.
The new tide models presented here are restricted to prograde waves. Therefore the second step according to (6) consists in the decomposition of the spherical harmonic coefficients into the amplitudes and phases $C^{+}_{n,lm}$, $\epsilon^{+}_{n,lm}$. This means a step of decomposition with respect to the time (t). Actually the amplitudes and phases are derived from the fitted combined parameters $C^{+}_{n,lm} \sin(\epsilon^{+}_{n,lm})$ **,** $C^{+}_{n,lm} \cos(\epsilon^{+}_{n,lm})$ **.** No convention is used for the phases. The resulting phases according to (6) are phase leads (in contrary to phase lags).

Numerical Stability.
The computation method following the two processing steps is an inverse method whose numerical stability can be awaited. Atmospheric surface pressure data of equal time steps were used. Consequently the correlation matrices of the least squares fit in the second step show only small correlations between the tide parameters. Therefore the numerical stability of the separation of tide parameters from the spherical harmonic coefficients is ensured.

A priori Informations.
Amplitudes and phases can be forced to initial values by a priori information introduced by pseudo observations. With the abbreviations a, ϵ for any amplitude and phase respectively, their initial values a_0, ϵ_0 and the corresponding tide parameters,

$$p = a \cdot \sin(\epsilon), \quad q = a \cdot \cos(\epsilon), \quad p_0 = a_0 \cdot \sin(\epsilon_0), \quad q_0 = a_0 \cdot \cos(\epsilon_0)$$

the pseudo observations in its original form can be expressed by

$a = a_0$ or $a - a_0 = 0$, where $a^2 = p^2 + q^2$, $a_0^2 = p_0^2 + q_0^2$, for the amplitudes,

$p/q = \tan(\epsilon_0)$ or $q_0 \cdot p - p_0 \cdot q = 0$, for the phases.

In its differential form the pseudo observations can be expressed by

$p_0 \cdot dp + q_0 \cdot dq = 0$ for the amplitudes, $q_0 \cdot dp - p_0 \cdot dq = 0$ for the phases.

In the least squares fit of the second computation step they can be introduced as additional observation equations and provided with an applicable weight. The residuals are not changed. The coefficient matrix is regularized, if for instance only one of two combined tide parameters is determinable.

Annual and Seasonal Means.
The amplitudes and phases in expression (4) – (6) are constants. A time dependence of the tides is not regarded. Therefore the resulting tides S1 and S2 consist of mean values with respect to the period, for which atmospheric pressure data are used. The usual atmospheric tide models are based on data, which are equally distributed over several years. Therefore (in contrast to other means) they are called **Annual** means. Besides the annual mean a tide model in a wider sense can contain seasonal means, for which the data base is restricted to a certain season of the years. Three seasons, related to the Northern hemisphere are distinguished. The **D-Season** contains the winter months November, December, January and February. The **E-Season** around the Equinoxes consists of the months March, April, September and October. The **J-Season** contains the summer months May, June, July and August.

4. Actual Available Models

Model A1.
Since the year 1973 the well known atmospheric tide model of B. Haurwitz and Ann D. Cowley is available. The base of the model consists of atmospheric surface pressure data, collected by meteorological stations of global distribution between Southern and Northern latitudes of up to 60 degrees. Annual and Seasonal Means for amplitudes and phases of prograde and retrograde waves of the daily and half-daily S1 and S2 tides are represented by spherical harmonic functions. The annual means of S1 and S2 are based on the data of 254 and 264 meteorological stations respectively. The seasonal means of S1 and S2 are based on the data of 201 and 211 stations respectively. Amplitudes and phases of prograde and retrograde waves are determined per order for the first 4 degrees. The prograde waves of S1 are presented for the orders 0 - 5 and the ones of S2 for the orders 0 - 4. The retrograde waves of S1 are presented for the orders 1 - 3 and the ones of S2 for the orders 1 – 2 [Haurwitz, B. and Cowley, Ann D., 1973] (Annual and seasonal means for S1, S2 see Table 2, 7, Figure 2, 6, 10, 14. Annual means of various models see Table 1, 5, 6, Figure 1, 5, 9, 13).

Model A2.
The model of Richard Ray originates from the year 2001. It contains the amplitudes and phases of prograde and retrograde waves of the S2 tide. The prograde waves are presented for the orders 0 - 4, the retrograde waves for the orders 1 - 4. The orders 0 and 1 contain the degrees 1 - 4, the orders 3 and 4 are developed up to degree 4. The model was derived by a fit of spherical harmonics to atmospheric surface pressure data of 427 globally distributed meteorological stations [Ray, R.D., 2001] (Amplitudes and phases see Table 5, Figure 1, 5, 9, 13).

Model A3.
The unpublished model of the UTCSR is restricted to the prograde main components of degree and order (2,2) and (4,2) of the atmospheric tide S2. It is used at UTCSR in connection with the ocean tide model CSR-4.0 of R. Eanes and S. Bettadpur (1995) for the data processing of the GRACE mission and gravity field modelling. It does not represent a separate model in the sense, that the coefficients are separated from those ones of the ocean tides (Amplitudes and phases see Table 5, Figure 1, 5, 9, 13).

Remark.
Concerning the prograde (2,2) and (4,2) main components of the S2 tide, the amplitudes and phases of the models A1 and A2 correspond each other (maximal difference of 0.019 cm for the (4,2) amplitude). The (4,4) component phases do not agree. The model A3, except of the (4,2) component amplitude, is more deviating, especially for the (4,2) component phase.

5. New Mean Annual and Seasonal Atmospheric Tide Models

Three new models including seasonal means were generated between 2003 and 2005. The data base consists of 6- and 3-hourly globally gridded atmospheric surface pressure data from ECMWF. The spatial resolution of the global grid amounts to 0.5 degree. The 6-hourly data were used for the long period from May 1985 to October 2002, the 3 hourly data for the essentially shorter period from January 2001 to December 2003. The computed atmospheric tide models represent verifications of the annual and seasonal means of B. Haurwitz and Ann D. Cowley for the atmospheric tides S1 and S2 on the base of actual data. They are restricted to prograde waves. In the first processing step the fully normalised spherical harmonic coefficients $\Delta C_{lm}(t)$, $\Delta S_{lm}(t)$ were computed from the gridded atmospheric surface pressure data up to degree and order l = m = 100. For the least squares fits in the second processing step all harmonic coefficients (observations) were equally weighted. As in the Haurwitz and Cowley model the prograde waves are developed for the first 4 degrees of the orders 0 - 5. To improve the residuals of the least squares fits, the annual and semi-annual tides Sa and Ssa, caused by solar radiation, were solved simultaneously. For the same purpose biases and trends of the harmonic coefficients were solved as well. To get the seasonal means of S1 and S2, moderate a priori informations on the annual means of Sa and Ssa were used for the simultaneous solution. A temporal resolution of 3 hours permits the determination of the zonal and non-zonal prograde parameters of the half-daily tide S2. A temporal resolution of 6 hours restricts the complete determination of the parameters of S2 to the non zonal ones. Instead of both of the zonal parameters $C^+_{2,l0}\sin(\epsilon^+_{2,l0})$ and $C^+_{2,l0}\cos(\epsilon^+_{2,l0})$ only one of them can be determined. Alternatively, if for example the phases $\epsilon^+_{2,l0}$ are known from a reliable model, the amplitudes $C^+_{2,l0}$ can be determined by insertion of the phases and vice versa. The following new models were computed.

Model N1.
The annual mean is the model of R. Biancale and A. Bode (2003), which is actually used by the GFZ-Potsdam and GRGS in Toulouse for the data processing and gravity field generation of the CHAMP and GRACE missions. The data base consists of the 6-hourly atmospheric surface pressure data for the long period from May 1985 to October 2002. Because of the temporal resolution of 6 hours, the zonal amplitudes were determined by insertion of the zonal phases of the annual means of B. Haurwitz and Ann D. Cowley, which seemed to be reliable enough. For this purpose the phases of Haurwitz and Cowley were provided with a priori information (Annual and seasonal means see Table 3, 8, Figure 3, 7, 11, 15).

Model N2.
The data base consists of a combination of the 6-hourly and 3-hourly atmospheric surface pressure data. The 6-hourly data were taken from the period May 1985 to December 2000, the 3-hourly data from the period January 2001 to December 2003. The harmonic coefficients of both periods were again equally weighted (second processing step). Because 3 hourly data are contained, the zonal tide paramaters could be determined completely. (Annual means see Table 1, 7).

Model N3.
The data base consists of the 3-hourly atmospheric surface pressure data for the period from January 2001 to December 2003. Because of the temporal resolution of 3 hours, the zonal tide parameters could be determined completely (Annual and seasonal means see Table 4, 9, Figure 4, 8, 12, 16).

Annual Means.
Under the assumption of time dependence of the S1 and S2 tides the annual means of the models N1--N3 must not necessarily agree, because the data bases belong to different periods. But they should not differ too much. Not all amplitudes and phases of the tides S1 and S2 of model N2, but most of them are between that of the models N1 and N3. Because of the shorter data period the annual and also seasonal means of model N3 are generally worse determined than those ones of N1 and N2. Well determined tide parameters of N1 and N2 become slightly worse for N3, badly determined parameters become much more worse (especially the phases). For the tide S1 there are some amplitudes of the models A1, N1, which correspond. But the phases of the two models deviate irregularly. The correspondence of amplitudes and phases of the S2 tide is better for the models A1 and N1 than for A2 and N1, A2 and N3 (Amplitudes and phases of the models A1 – A3, N1 - N3 for the tides S1, S2 see Table 1, 5, 6, Figure 1, 5, 9, 13. Dominant amplitudes and their phases see Table 10. Corresponding amplitudes and phases see Table 11, 12).

Seasonal Means.
The time dependence of the atmospheric tides S1 and S2 at least can be confirmed by their seasonal means. The mean amplitudes and phases for the E-Season are generally very close to their annual means. That is not the case for the D-Season and J-Season, which show distinct deviations. Because of shorter and less connected data periods the seasonal means are generally worse determined than the annual means (Table 2 - 4, 7 - 9, Figure 2 - 4, 6 – 8).

Model Differences.
By comparison of the models A1 – A3 and N1 - N3 considerable differences can be observed. The causes are various. At first view it is obvious, that some amplitudes and phases of the new models N1 - N3 could not be determined significantly. But it cannot be expected that all systematic and random variations of the atmospheric pressure can be modelled by harmonic functions and some elect tide parameters. A high level of noise remains in the residuals of a fitting step, resulting in high standard deviations, which decide on significance or non-significance. Non-significant amplitudes and phases in the Tables of Appendix A2 are put into brackets. From degree 3 upwards at most the sectorial amplitudes and phases of the S2 tide are significant (not for order 4 in N3). In view of the relatively high number of non-significant amplitudes and phases, distinct differences between all models must be expected. Generally the model differences are already caused by data of a different number of barometer stations, which originally represent the global distribution of the data. Subsequently the globally gridded barometric data can be generated for different spacious resolutions by various interpolation methods. For the ECMWF and NCEP barometric data the resolution amounts to 0.5 and 2.5 degree respectively. Additionally the epoch and the time steps of the barometric data can be different. Finally the method to derive the amplitudes and phases from the spherical harmonic coefficients must not agree. All these, especially the global distribution of the observation stations, epochs, time steps and resolution of the gridded barometric data, contribute to the model differences.

6. Test Results

Several tests have been performed to investigate the influence of the different old and new atmospheric tide models on precise orbit determination (POD) and geoid differences. To test how good the S1 and S2 tides are approximated, it would be necessary, to compare them with the tide components of some globally distributed stations, which was not performed here.

6.1. POD tests for different geodetic satellites and atmospheric tide models

Uniform processing standards with equal gravity field model and ocean tides were used for either of the following satellite test sets. The only difference in the tests was the atmospheric tide model. For atmospheric tide models without the daily S1 tide only the half-daily tide S2 (all existing prograde and retrograde waves) was taken into account. All orbits have been fitted to the measurements.
One set of geodetic satellites carrying Laser (LAS) retro-reflectors, PRARE range (PRA) and PRARE Doppler (PDO) equipment and Doris (DOR) was investigated using the gravity field model EIGEN--CG03C (120x120) and the ocean tide model FES2004 (50x50). Parameters of non-gravitational disturbing forces and empirical parameters have been solved. The (mean) RMS for the measurement residuals are shown in the following Table.

Table 6.1a : POD tests for different geodetic satellites and atmospheric tide models

Satellite	Residuals	H&C	CSR	Ray	B&B (6h)	B&B (3h)
GFZ-1 (5x3d)	LAS [cm]	15.122	15.125	15.122	15.122	15.123
Stella (5x3d)	LAS [cm]	3.045	3.050	3.046	3.040	3.042
Starlette (5x3d)	LAS [cm]	2.662	2.663	2.661	2.656	2.658
Ajisai (5x3d)	LAS [cm]	3.193	3.186	3.189	3.186	3.187
Lageos-1 (3x6d)	LAS [cm]	1.163	1.165	1.164	1.163	1.165
Lageso-2 (3x6d)	LAS [cm]	1.134	1.132	1.133	1.132	1.132
ERS-2 (6x6d)	LAS [cm]	5.359	5.360	5.360	5.359	5.359
ERS-2 (6x6d)	PRA [cm]	3.563	3.561	3.560	3.564	3.563
ERS-2 (6x6d)	PDO [mm/s]	0.347	0.347	0.347	0.347	0.347
Envisat (7x(4-8d))	LAS [cm]	4.392	4.411	4.403	4.460	4.427
Envisat (7x(4-8d))	DOR [mm/s]	0.496	0.496	0.496	0.496	0.496
Westpac (5x6d)	LAS [cm]	4.112	4.085	4.093	4.095	4.097

The CHAMP and GRACE satellites have been investigated for Laser (LAS), K-band range-rate (KRR), GPS code (GPC) and GPS phase (GPP) using the gravity field model EIGEN-CG01C (120x120) and the ocean tide model FES2002 (50x35). Accelerometer parameters and empirical parameters (thruster parameters) have been solved. The (global) RMS for the measurement residuals are shown in the following Table.

Table 6.1b : POD tests for CHAMP and GRACE and different atmospheric tide models

Satellite	Residuals	H&C	CSR	Ray	B&B (6h)	B&B (3h)
CHAMP (4x1.5d)	LAS [cm]	5.82	5.88	5.87	5.83	5.82
CHAMP (4x1.5d)	GPC [cm]	53.06	53.03	53.06	53.02	53.04
CHAMP (4x1.5d)	GPP [cm/s]	0.54	0.54	0.54	0.54	0.54
GRACE(4x0.5-1d)	LAS [cm]	5.18	5.15	5.20	5.21	5.20
GRACE(4x0.5-1d)	KRR [µm/s]	1.48	1.46	1.48	1.48	1.48
GRACE(4x0.5-1d)	GPC [cm/s]	51.97	51.97	51.98	51.97	51.98
GRACE(4x0.5-1d)	GPP [cm/s]	1.11	1.10	1.11	1.11	1.10

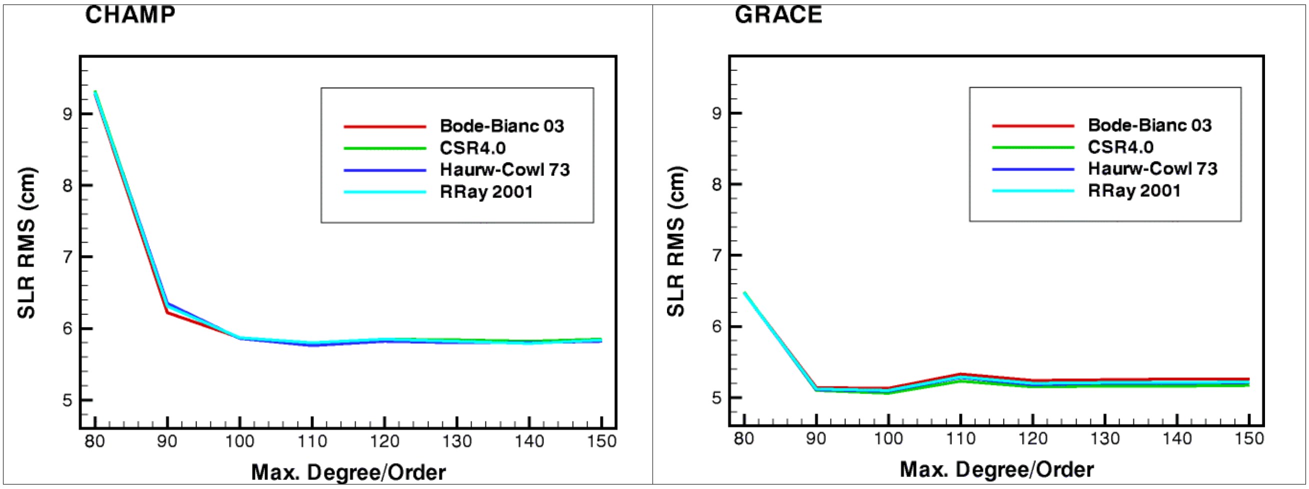

Figure 6.1a : SLR residuals for CHAMP (left) and GRACE (right) as a function of maximum degree and order of EIGEN-CG01C and different atmospheric tide models.

One GRACE arc over one day has been investigated using on one hand no atmospheric tide model and on the other hand the new model N1. Besides the orbit elements no other parameters have been solved. The orbit differences in three orthogonal directions as well as the standard deviations are shown in the following Table.

Table 6.1c : POD test for GRACE and model N1 versus no atmospheric tide model

	Minimum	Maximum	Mean value	Stand. dev.
Radial [cm]	-0.051	0.095	0.036	0.027
Cross-track [cm]	-0.893	0.829	0.021	0.317
Along-track [cm]	-0.436	0.368	0.000	0.190
RMS 3D [cm]	-	-	-	0.370

6.2. Geoid Differences and Geoid Heights

The atmospheric tide potential represented by spherical harmonic coefficients up to degree 8 and order 5 was calculated for August 2, 2003 with hourly temporal resolution for different atmospheric tide models. The domains of the derived geoid differences and geoid heights (minimum – maximum) are shown in the following Tables. M0 denotes the Zero-model. Thus, the lines 2 - 6 of Table 6.2a contain geoid differences and the last line contains geoid heights due to the gravitational potential of the models in the first line. The geoid differences for the models N1 and N3 are demonstrated for all 3 hours in Figure 6.2a .

Table 6.2a : Geoid differences and Geoid heights [mm] for different (mean) atmospheric tide models

Model	A1	A2	A3	N1	N3
A2	- 0.1 - + 0.1	-			
A3	- 0.1 - + 0.1	- 0.1 - + 0.1	-		
N1	- 0.7 - + 0.7	- 0.2 - + 0.2	- 0.4 - + 0.4	-	
N2	- 0.7 - + 0.7	-	-	- 0.12 - + 0.12	-
N3	- 0.7 - + 0.7	- 0.15 - + 0.15	- 0.3 - + 0.3	- 0.35 - + 0.35	-
M0	- 1.3 - + 1.3	- 1.2 - + 1.2	-	- 1.2 - + 1.2	- 1.35 - + 1.35

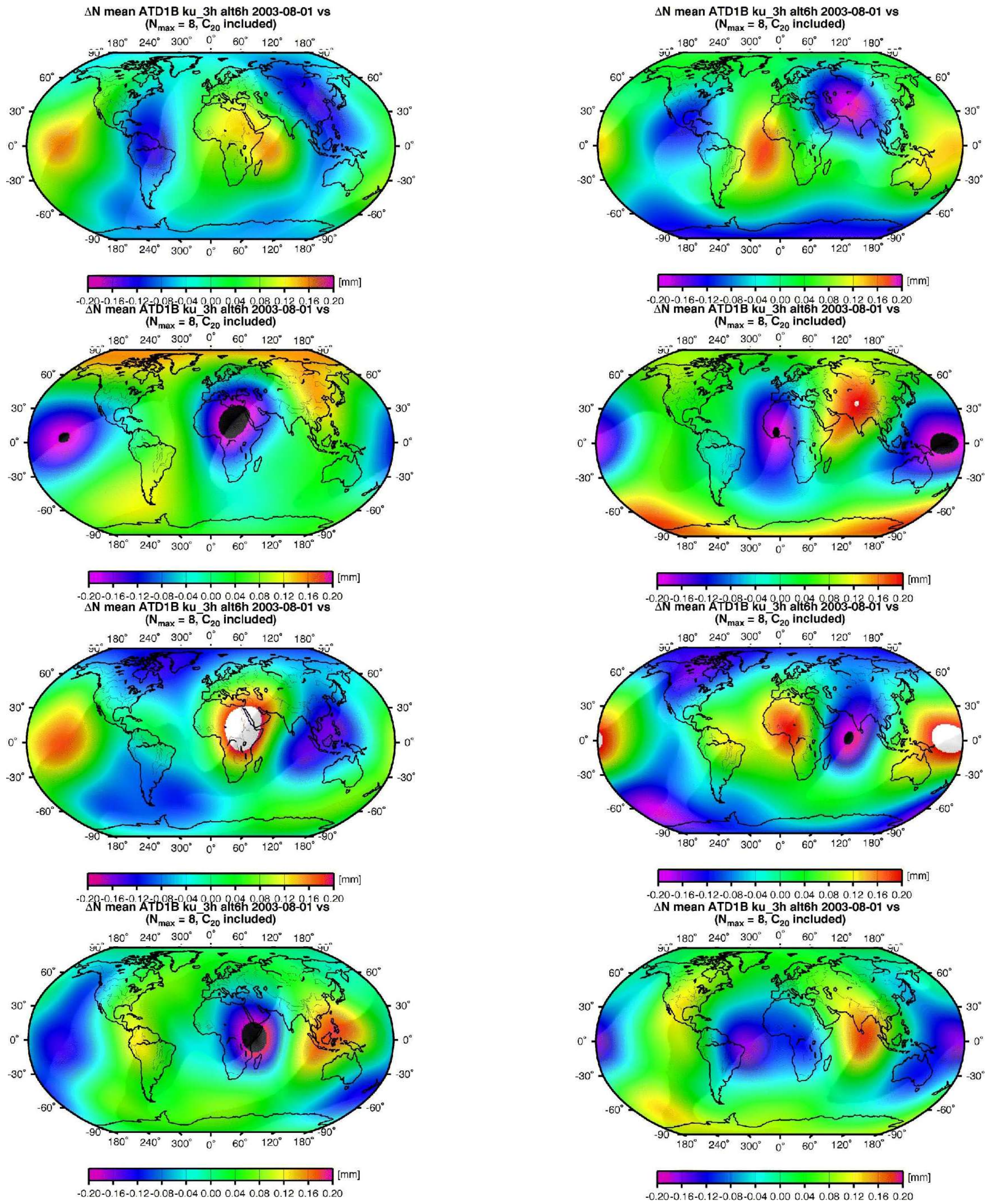

Figure 6.2a : Temporal evolution of the geoid differences derived from the mean atmospheric tide models based on 6h data (1985-2002, model N1) and 3h data (2001-2003, model N3) for August 2, 0h (top left), 3h (top right) up to 21h (bottom right).

Table 6.2b : Geoid differences [mm] for Mean Seasonal atmospheric tide models

Model	N1 D-Season	N1 E-Season	N1 J-Season
N1	- 0.15 - + 0.15	- 0.13 - + 0.13	- 0.17 - + 0.17

Equal domains result, if the model N1 is replaced by N2.

7. Conclusions

The conclusions are based on the orbit tests, geoid differences and geoid heights in the Tables of chapter 6. The orbit tests in Table 6.1a, 6.1b show for all atmospheric tide models no significant RMS-differences. The orbits have been fitted with all parameters, which are solved during the orbit processing for gravity field modelling. These parameters, for instance those ones representing the non-gravitational disturbing forces, accelerometer parameters and empirical ones absorb a high rate of the atmospheric tide effect when fitting the orbits. Taking these tests as a basis it can be concluded, that all tested atmospheric tide models are equivalent for orbit computation and gravity field modelling. To confirm or to disprove this statement it will be helpful to complete the tests choosing more adapted orbit parameters or even by some gravity recoveries. By restriction of the orbit parameters on the orbit elements can be shown in Table 6.1c, that the atmospheric tides have a distinct effect on orbits.
The effect of atmospheric tides on the gravity field measured by geoid heights can be expected in a domain about ± 1.3 mm. It is small, but it should not be neglected taking into account the high accuracy which can be expected from products of present and future gravity missions (last line in Table 6.2a). From the geoid differences between the new models N1 - N3 and the available models A1 - A3 a slight decrease from the older to the newer models A1 - A3 can be observed. But from a maximal effect of 0.7 mm on the geoid differences between the model N1 and the older one A1 and of 0.4 mm between N1 and the newer models A2, A3 significant differences on gravity modelling must not be expected, especially not when using the newer models (lines 2-6 in Table 6.2a). Obviously the mean seasonal variations of the atmospheric pressure with a maximal effect below 0.2 mm play only a subordinate role (Table 6.2b). The S2 tide proves to be dominant among the atmospheric tides S1, S2 how Table 6.2a and Table 10 (chapter 13) show, where models with and without the S1 tide are present.

8. References

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Ray, R.D., 2001, Comparisons of global analyses and station observations of the S2 barometric tide, Journal of Atmospheric and Solar-Terrestrial Physics, vol. 63, 1085-1097.

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9. Appendix A1: Figures

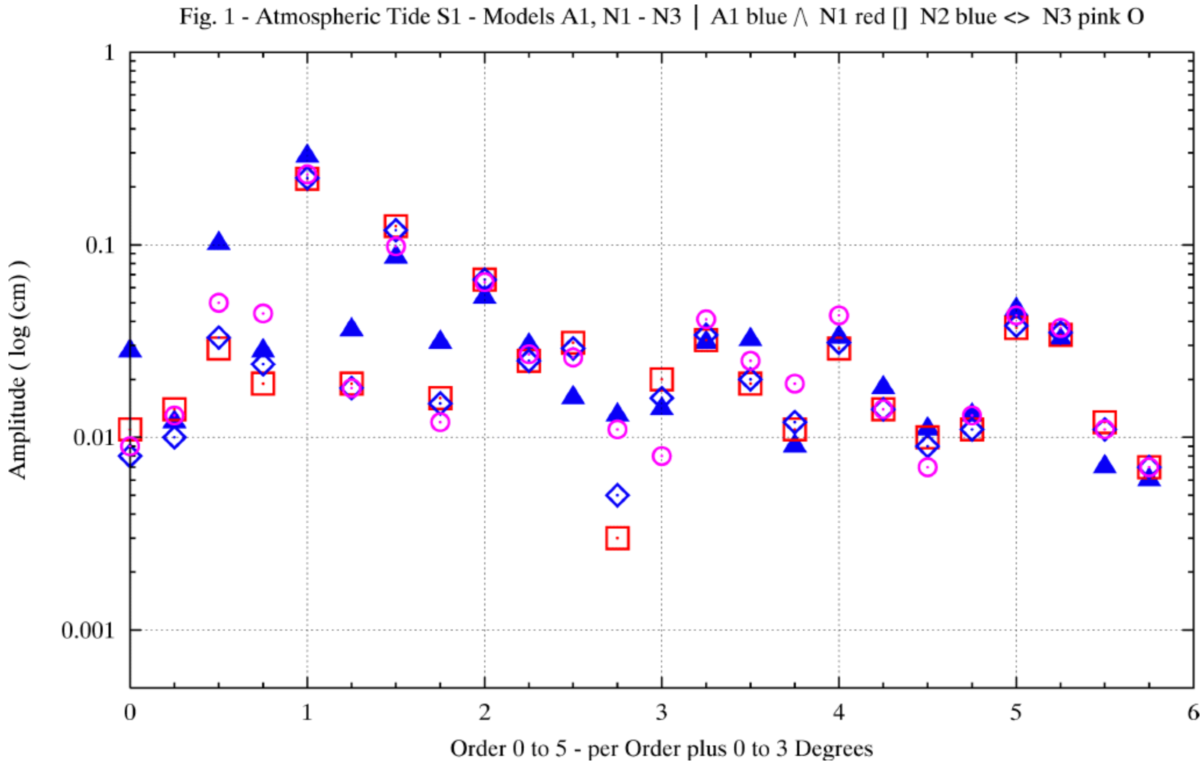

Figure 1: Atmospheric Tide S1: Mean (annual) Amplitudes of models A1, N1-N3

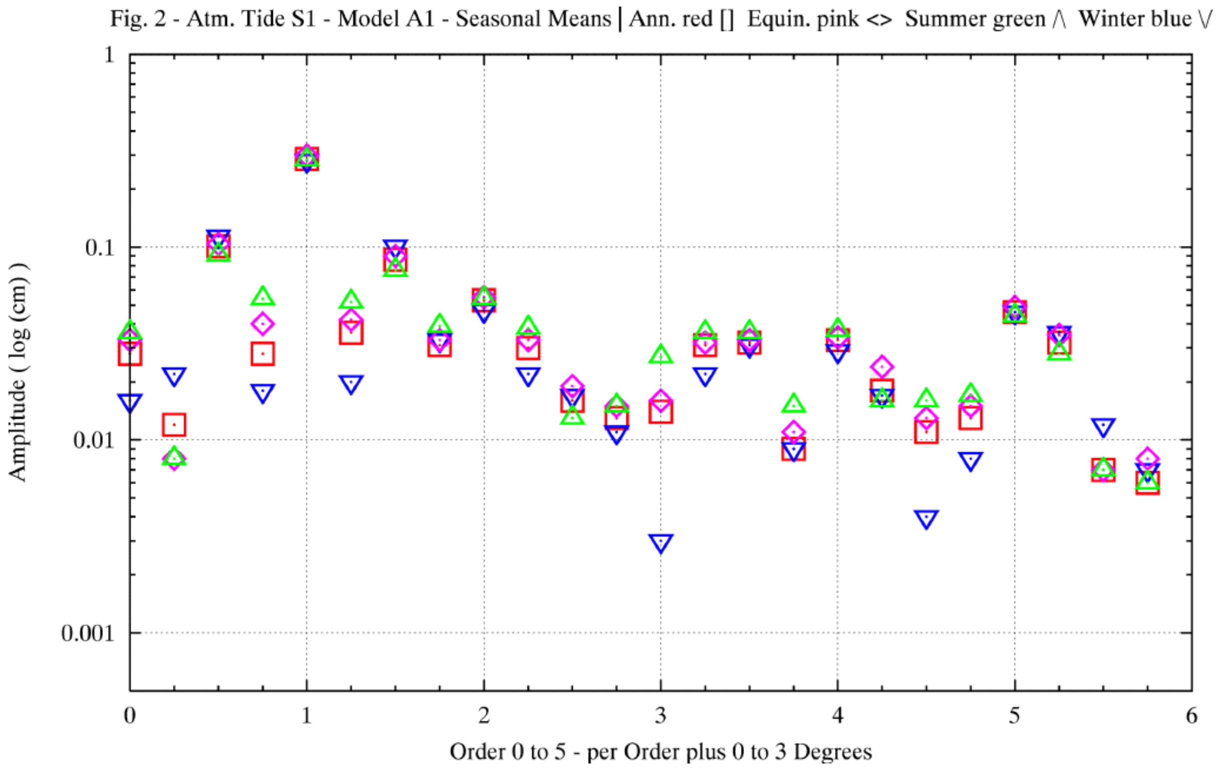

Figure 2: Atmospheric Tide S1: Annual and Seasonal mean Amplitudes of model A1

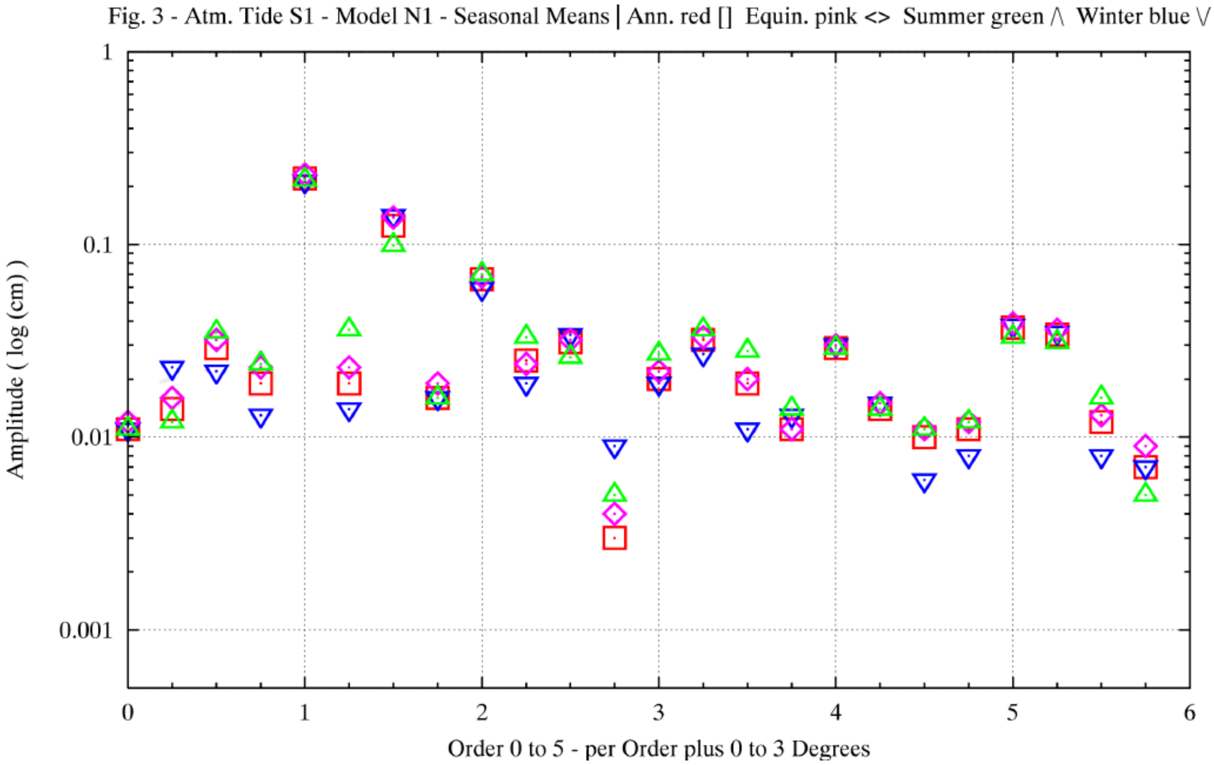

Figure 3: Atmospheric Tide S1: Annual and Seasonal mean Amplitudes of model N1

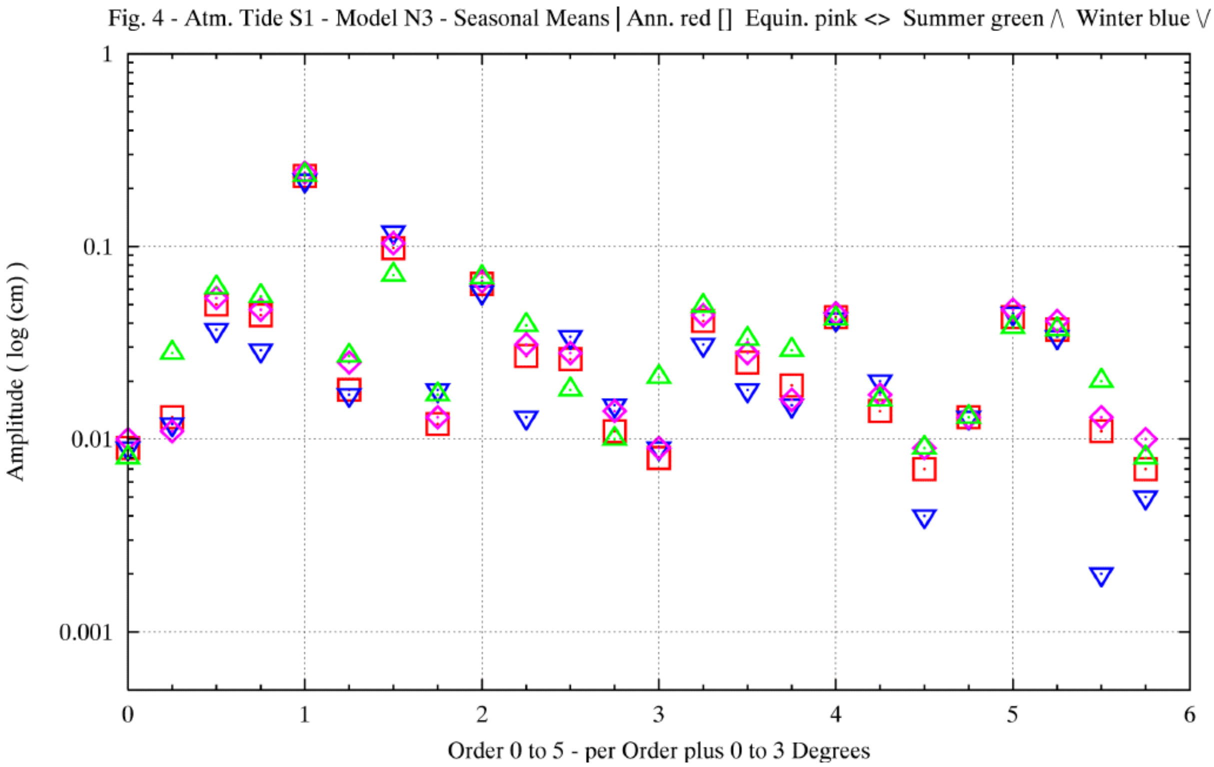

Figure 4: Atmospheric Tide S1: Annual and Seasonal mean Amplitudes of model N3

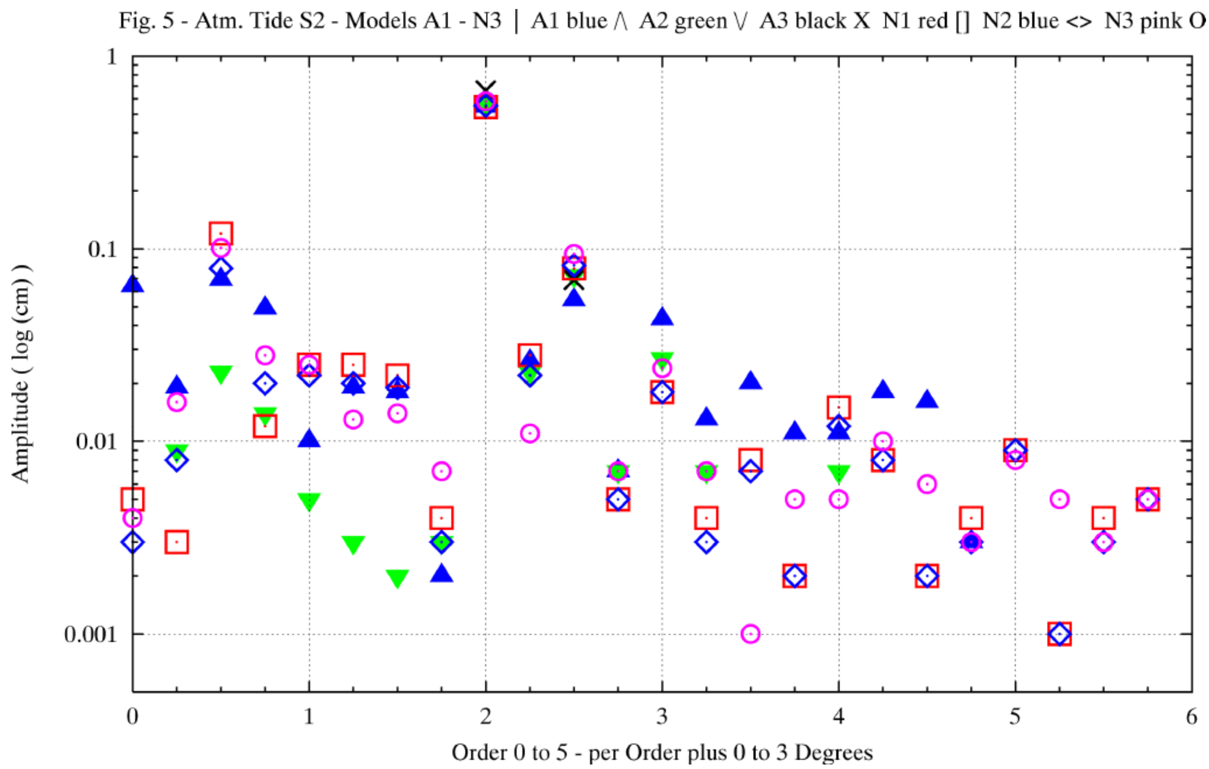

Figure 5: Atmospheric Tide S2: Mean (annual) Amplitudes of models A1-N3

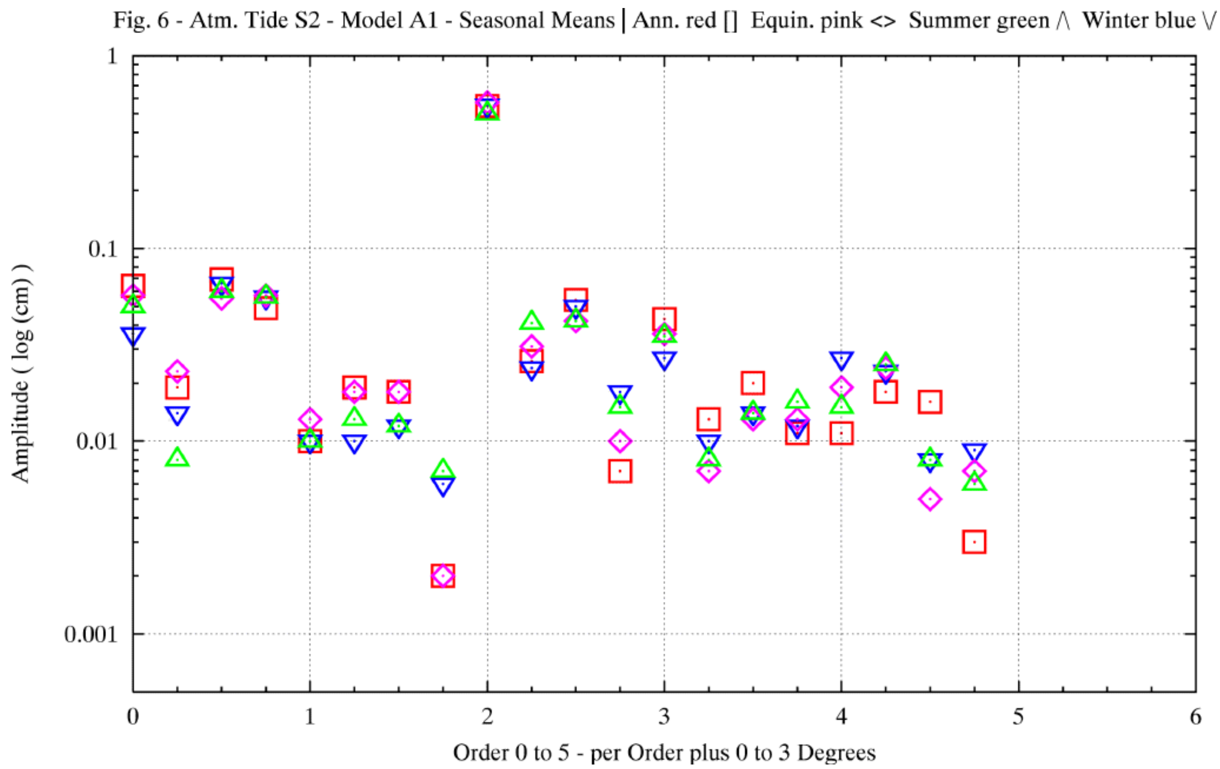

Figure 6: Atmospheric Tide S2: Annual and Seasonal mean Amplitudes of model A1

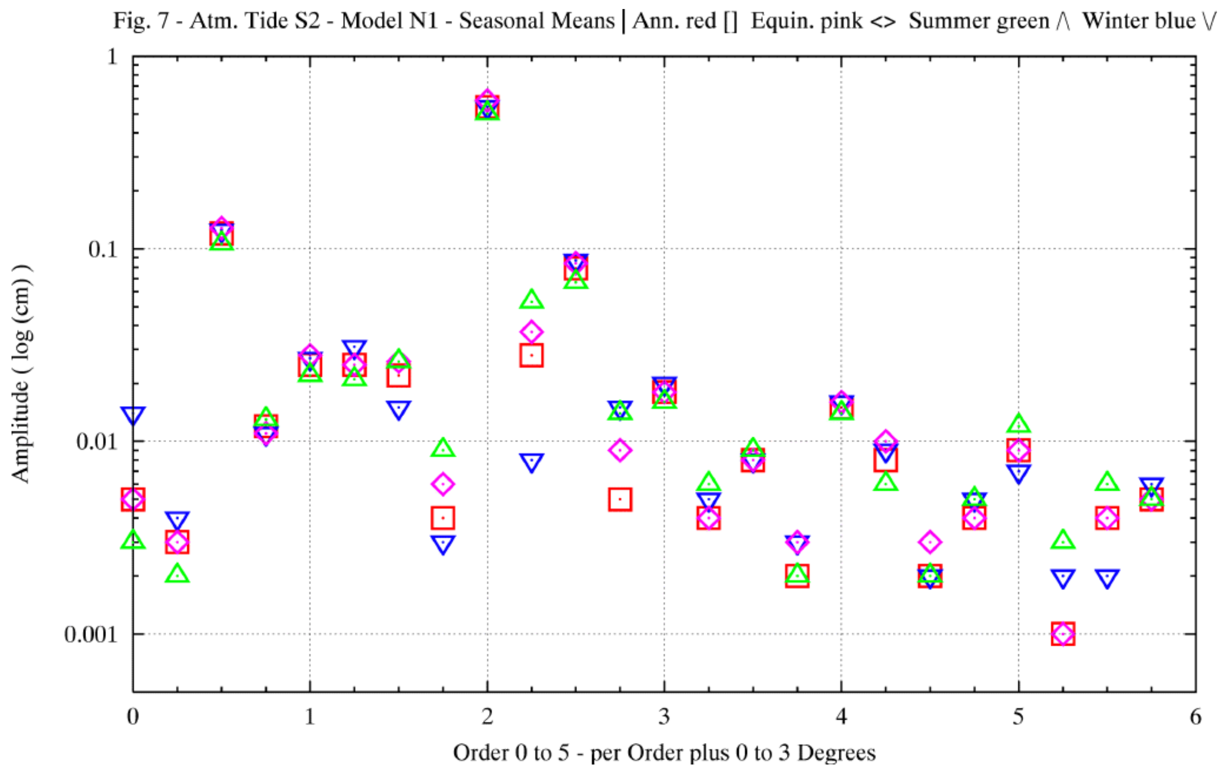

Figure 7: Atmospheric Tide S2: Annual and Seasonal mean Amplitudes of model N1

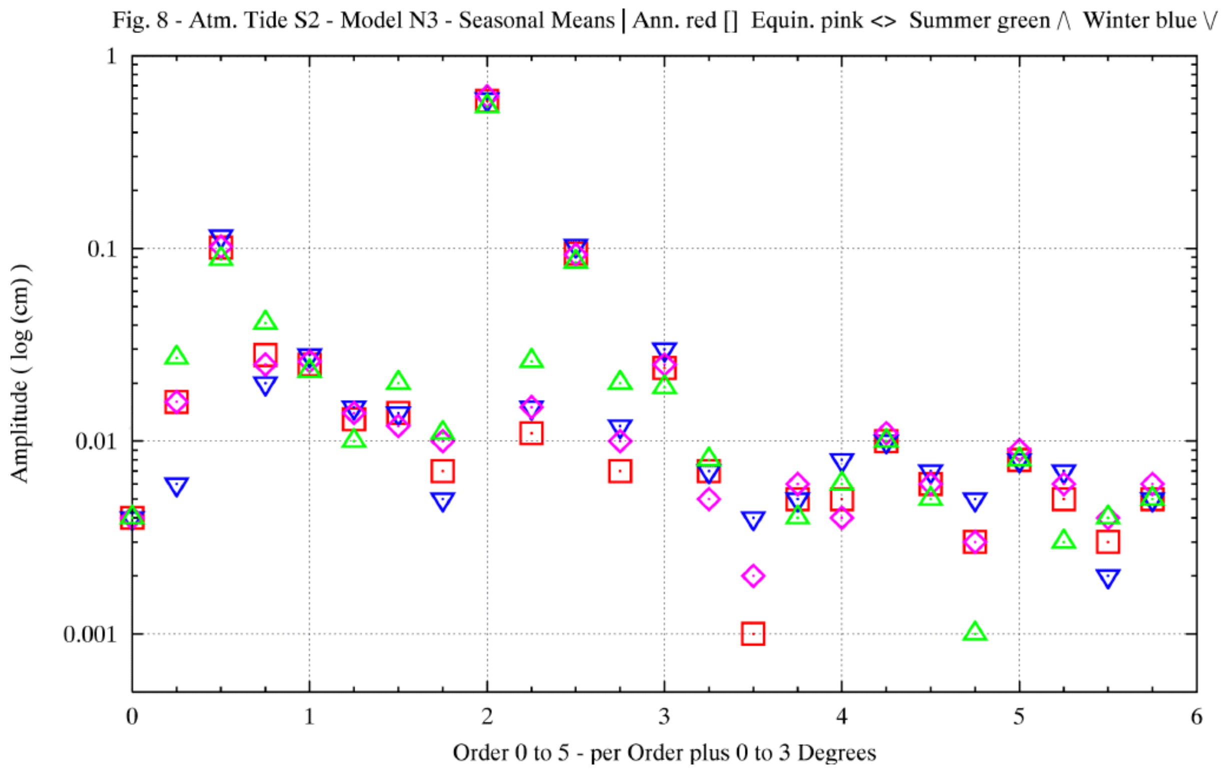

Figure 8: Atmospheric Tide S2: Annual and Seasonal mean Amplitudes of model N3

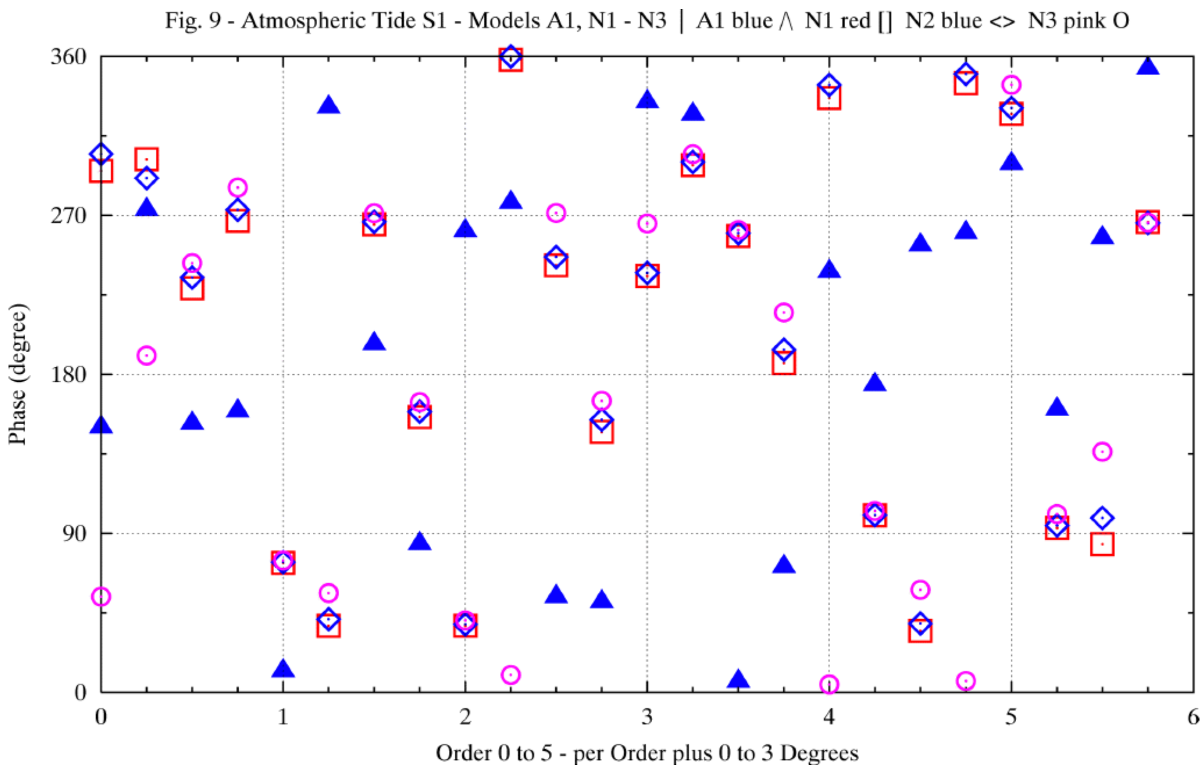

Figure 9: Atmospheric Tide S1: Mean (annual) Phases of models A1, N1-N3

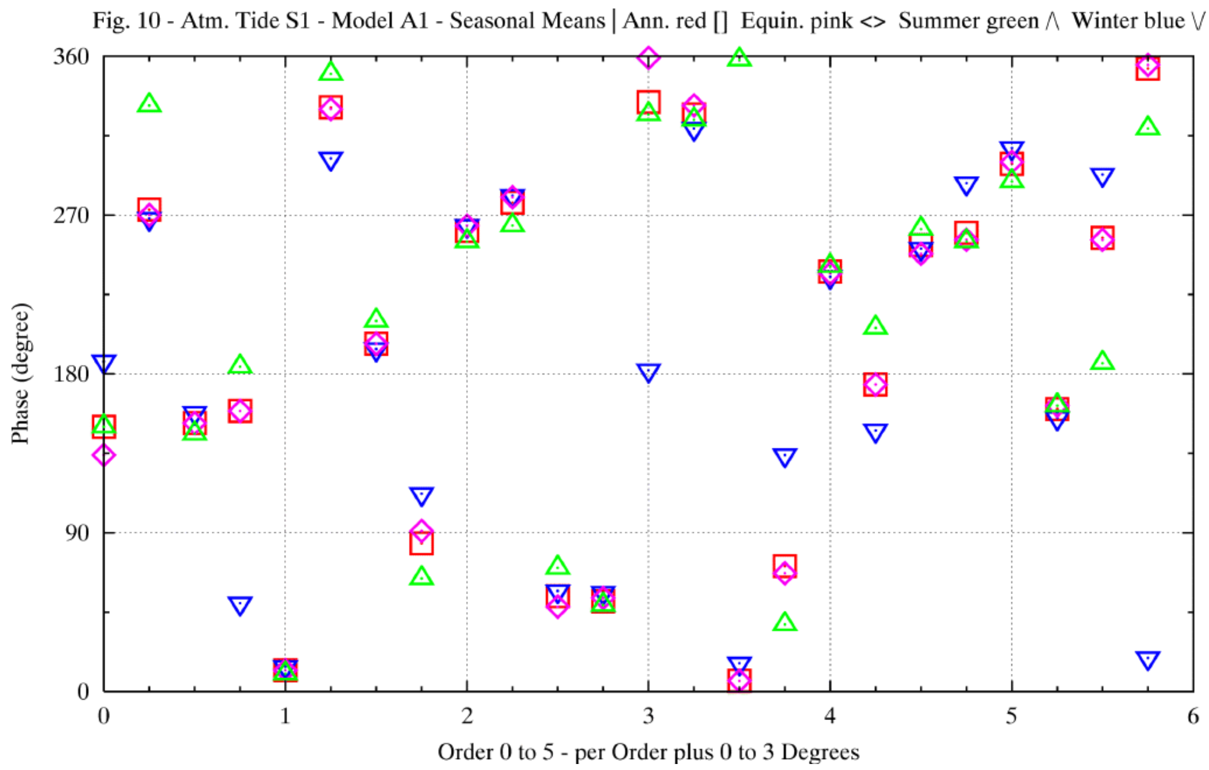

Figure 10: Atmospheric Tide S1: Annual and Seasonal mean Phases of model A1

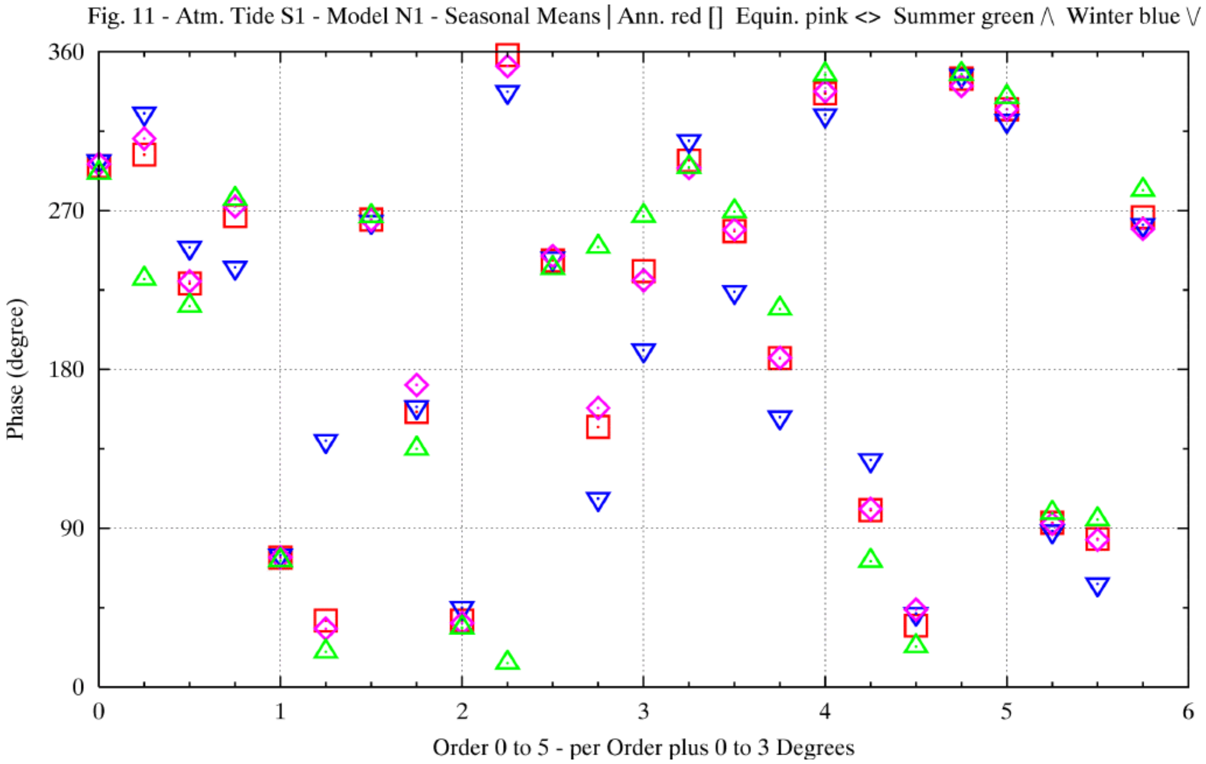

Figure 11: Atmospheric Tide S1: Annual and Seasonal mean Phases of model N1

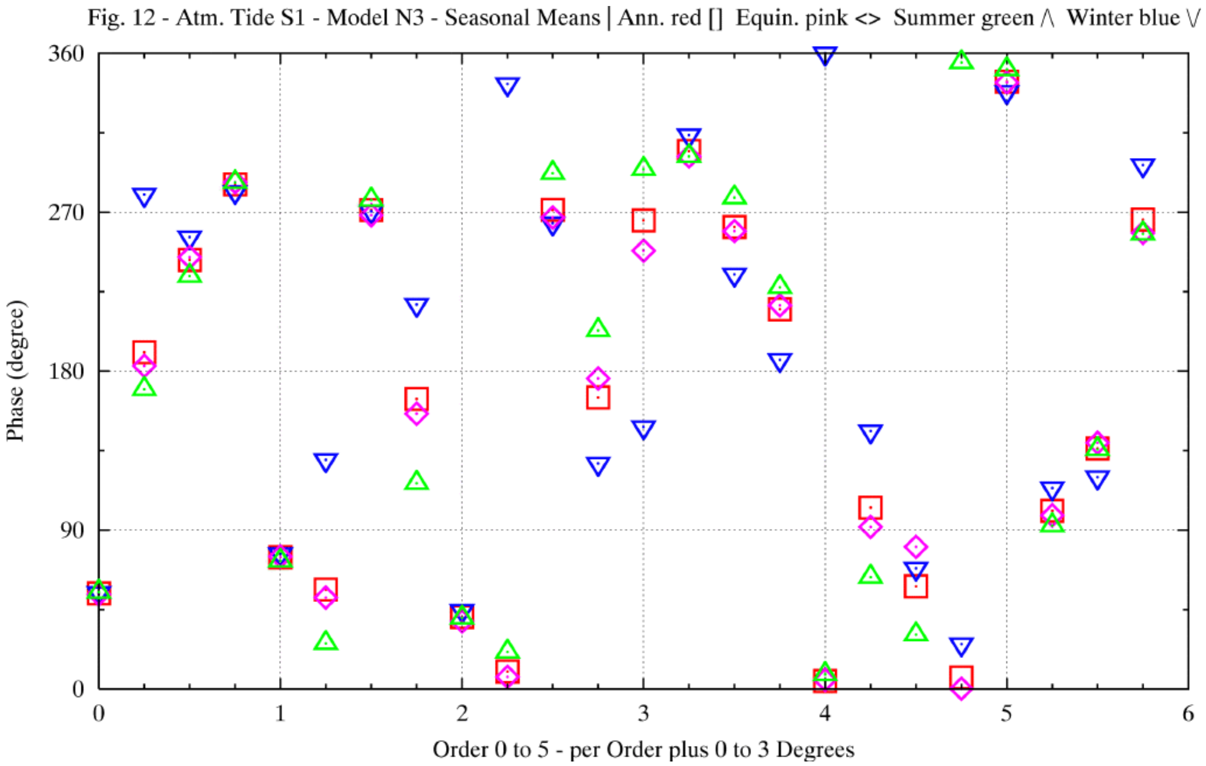

Figure 12: Atmospheric Tide S1: Annual and Seasonal mean Phases of model N3

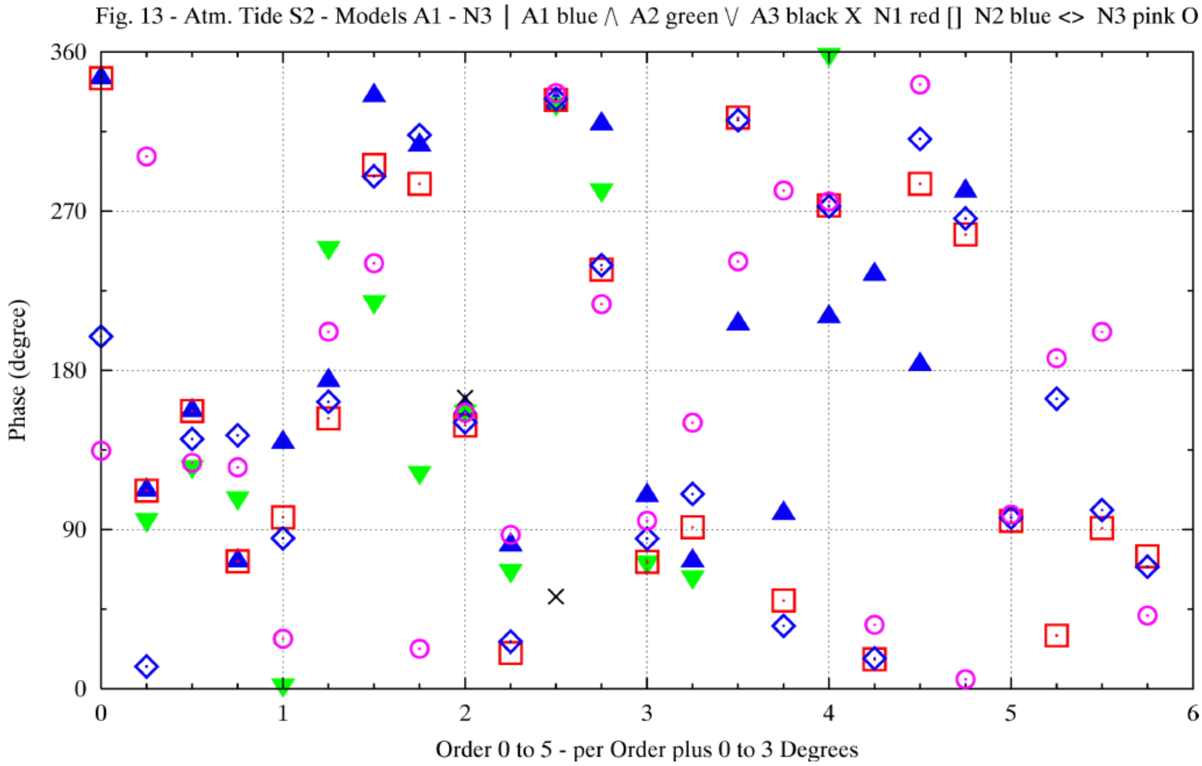

Figure 13: Atmospheric Tide S2: Mean (annual) Phases of models A1-N3

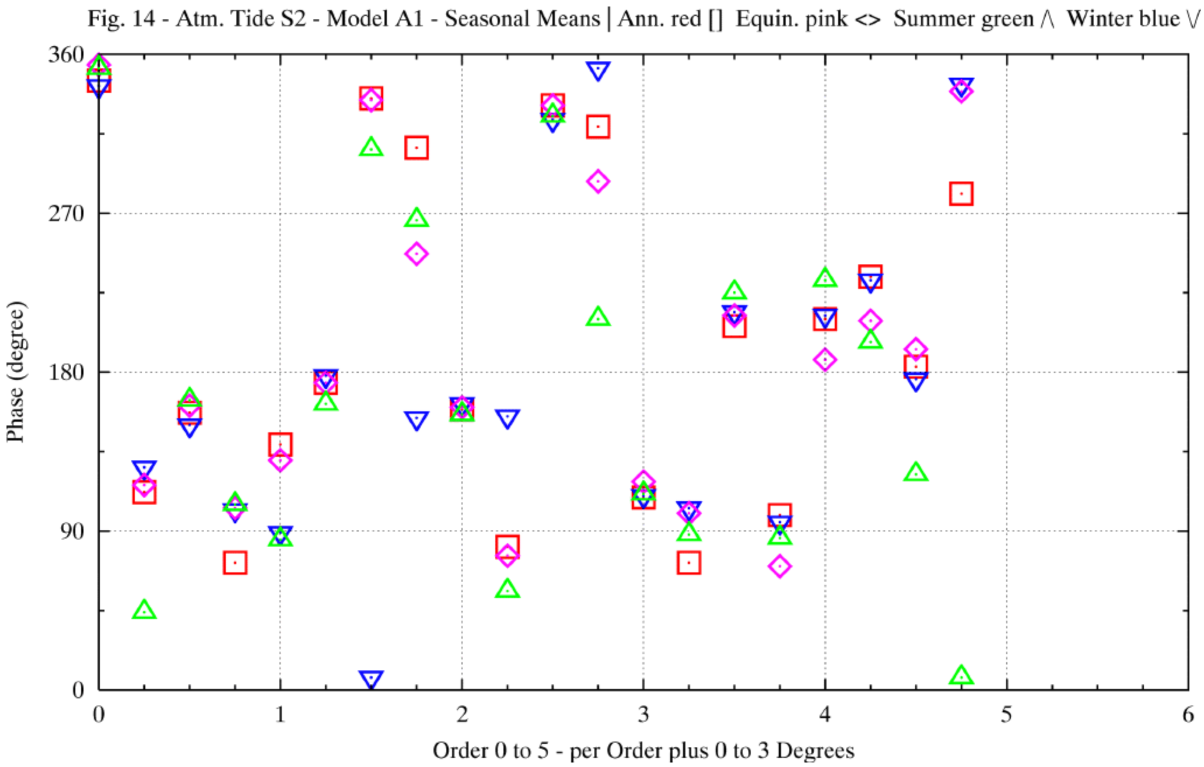

Figure 14: Atmospheric Tide S2: Annual and Seasonal mean Phases of model A1

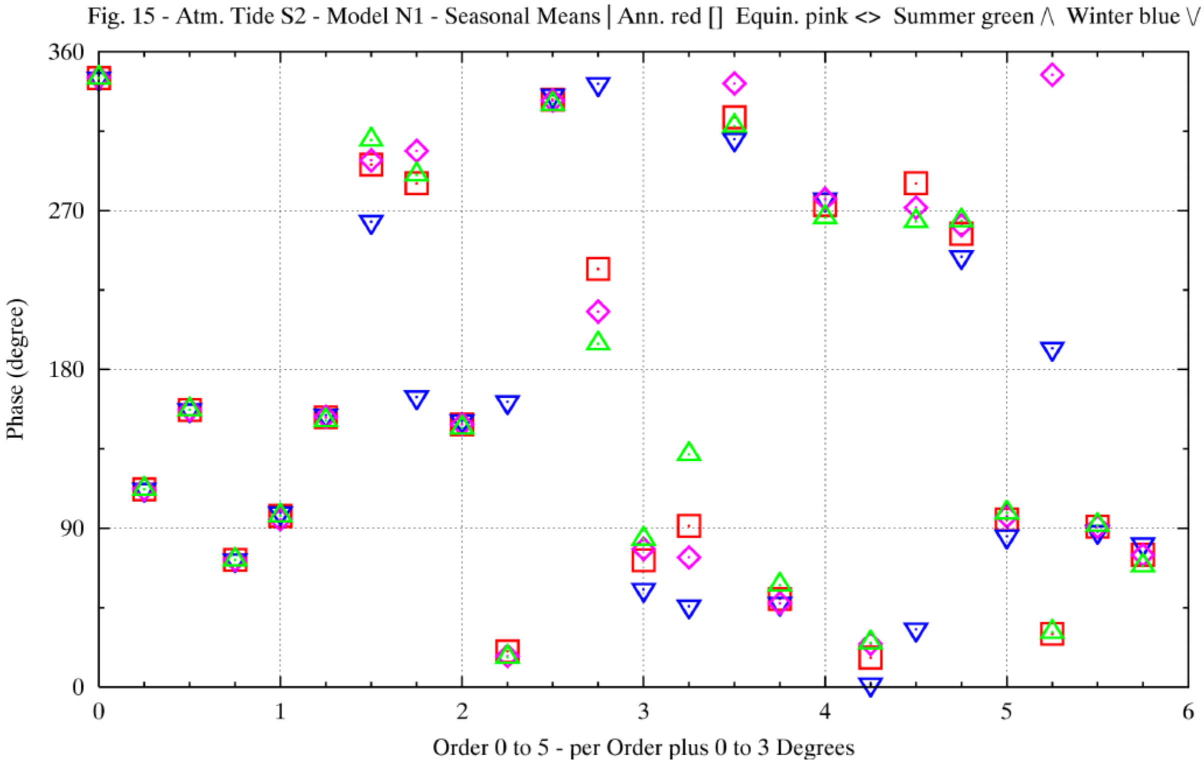

Figure 15: Atmospheric Tide S2: Annual and Seasonal mean Phases of model N1

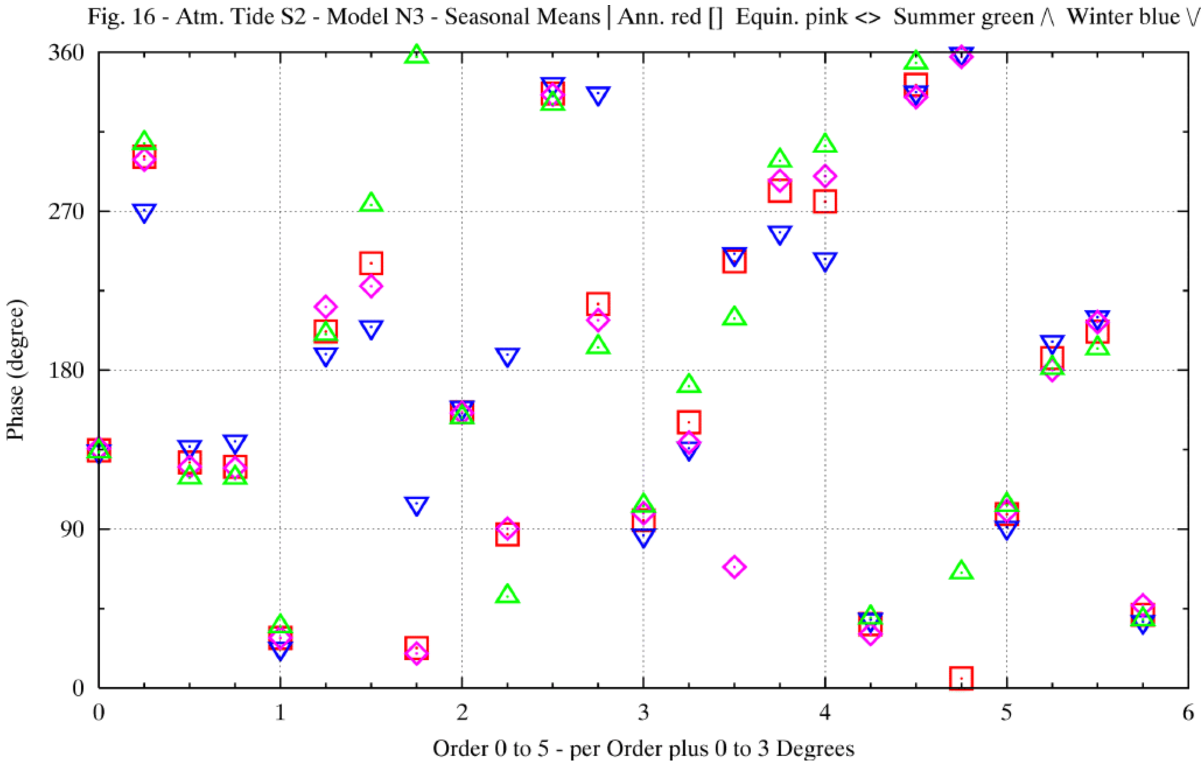

Figure 16: Atmospheric Tide S2: Annual and Seasonal mean Phases of model N3

10. Appendix A2: Tables

Table 1. Model A1, N1 – N3 - Amplitudes and Phases of S1 (Annual Means)

		Model A1		Model N1		Model N2		Model N3	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
0	0	0.028	150.0	0.011	295.1	0.008	304.7	0.009	54.2
1	0	0.012	273.0	(0.014)	(301.7)	(0.010)	(291.0)	(0.013)	(190.6)
2	0	0.101	152.0	0.029	228.6	0.033	234.7	0.050	242.9
3	0	0.028	159.0	(0.019)	(266.8)	0.024	273.1	0.044	285.7
1	1	0.287	12.0	0.220	73.2	0.222	73.6	0.232	74.6
2	1	0.036	331.0	0.019	37.6	0.018	41.4	(0.018)	(56.2)
3	1	0.086	197.0	0.125	264.8	0.119	266.3	0.098	271.2
4	1	0.031	84.0	0.016	155.8	0.015	158.9	(0.012)	(164.2)
2	2	0.053	261.0	0.066	37.7	0.066	38.5	0.064	40.7
3	2	0.030	277.0	0.025	358.1	0.025	359.9	0.027	9.8
4	2	0.016	54.0	0.031	241.7	0.029	246.4	0.026	271.3
5	2	0.013	51.0	(0.003)	(147.4)	(0.005)	(154.3)	(0.011)	(165.0)
3	3	0.014	334.0	0.020	235.6	0.016	237.4	(0.008)	(265.3)
4	3	0.031	327.0	0.032	298.3	0.034	300.2	0.041	304.6
5	3	0.032	6.0	0.019	258.3	0.020	259.9	0.025	261.6
6	3	0.009	71.0	(0.011)	(186.3)	0.012	193.9	(0.019)	(215.0)
4	4	0.033	238.0	0.029	336.3	0.031	343.7	0.043	4.5
5	4	0.018	174.0	0.014	100.1	0.014	100.3	(0.014)	(102.7)
6	4	0.011	253.0	(0.010)	(34.8)	(0.009)	(39.0)	(0.007)	(58.1)
7	4	0.013	260.0	(0.011)	(344.7)	(0.011)	(350.0)	(0.013)	(6.4)
5	5	0.046	299.0	0.037	327.4	0.038	330.7	0.043	343.8
6	5	0.032	160.0	0.034	93.0	0.035	94.5	0.037	100.9
7	5	0.007	257.0	0.012	83.9	0.011	98.7	(0.011)	(136.2)
8	5	0.006	353.0	(0.007)	(266.1)	(0.007)	(265.6)	(0.007)	(265.8)

Table 2. Model A1 - Amplitudes and Phases of S1

Seasonal Means of Prograde and Retrograde Waves

		Annual		D-Season		E-Season		J-Season	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
1	-1	0.019	148.0	0.022	164.0	0.024	149.0	0.014	107.0
2	1	0.050	102.0	0.047	86.0	0.053	107.0	0.053	112.0
3	1	0.028	167.0	0.017	182.0	0.026	169.0	0.043	158.0
4	1	0.028	280.0	0.033	283.0	0.031	286.0	0.021	264.0
2	-2	0.029	42.0	0.032	39.0	0.028	46.0	0.029	47.0
3	2	0.003	31.0	0.001	278.0	0.002	45.0	0.009	27.0
4	2	0.009	277.0	0.008	254.0	0.011	279.0	0.008	294.0
5	2	0.000	352.0	0.004	231.0	0.001	308.0	0.001	49.0
3	-3	0.054	86.0	0.056	87.0	0.056	83.0	0.051	87.0
4	3	0.034	316.0	0.036	314.0	0.036	320.0	0.030	318.0
5	3	0.017	253.0	0.017	230.0	0.020	257.0	0.018	260.0
6	3	0.019	147.0	0.021	149.0	0.019	147.0	0.017	138.0
0	0	0.028	150.0	0.016	187.0	0.033	134.0	0.036	150.0
1	0	0.012	273.0	0.022	268.0	0.008	270.0	0.008	332.0
2	0	0.101	152.0	0.114	158.0	0.104	152.0	0.091	146.0
3	0	0.028	159.0	0.018	50.0	0.040	159.0	0.054	184.0
1	1	0.287	12.0	0.282	14.0	0.298	12.0	0.284	10.0
2	1	0.036	331.0	0.020	302.0	0.042	330.0	0.052	350.0
3	1	0.086	197.0	0.101	194.0	0.090	197.0	0.076	210.0
4	1	0.031	84.0	0.033	112.0	0.033	91.0	0.039	64.0
2	2	0.053	261.0	0.047	264.0	0.055	264.0	0.054	255.0
3	2	0.030	277.0	0.022	281.0	0.033	280.0	0.038	264.0
4	2	0.016	54.0	0.017	57.0	0.019	48.0	0.013	70.0
5	2	0.013	51.0	0.011	56.0	0.015	53.0	0.015	49.0
3	3	0.014	334.0	0.003	182.0	0.016	359.0	0.027	327.0
4	3	0.031	327.0	0.022	319.0	0.032	332.0	0.036	324.0
5	3	0.032	6.0	0.031	16.0	0.033	6.0	0.036	358.0
6	3	0.009	71.0	0.009	134.0	0.011	67.0	0.015	38.0
4	4	0.033	238.0	0.029	235.0	0.034	237.0	0.037	241.0
5	4	0.018	174.0	0.017	148.0	0.024	174.0	0.016	206.0
6	4	0.011	253.0	0.004	251.0	0.013	248.0	0.016	262.0
7	4	0.013	260.0	0.008	288.0	0.015	256.0	0.017	255.0
5	5	0.046	299.0	0.046	308.0	0.049	300.0	0.044	289.0
6	5	0.032	160.0	0.036	155.0	0.035	162.0	0.028	162.0
7	5	0.007	257.0	0.012	293.0	0.007	256.0	0.007	186.0
8	5	0.006	353.0	0.007	19.0	0.008	355.0	0.006	319.0

Table 3. Model N1 - Amplitudes and Phases of S1

Seasonal Means (Prograde Waves)

		Annual		D-Season		E-Season		J-Season	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
0	0	0.011	295.1	0.011	298.1	0.012	296.3	0.011	291.1
1	0	(0.014)	(301.7)	(0.023)	(325.1)	(0.016)	(310.7)	(0.012)	(231.1)
2	0	0.029	228.6	(0.022)	(249.1)	(0.032)	(229.9)	(0.035)	(215.8)
3	0	(0.019)	(266.8)	(0.013)	(237.8)	(0.023)	(272.2)	(0.024)	(276.4)
1	1	0.220	73.2	0.213	74.7	0.231	73.4	0.216	71.6
2	1	0.019	37.6	(0.014)	(139.6)	(0.023)	(33.0)	0.036	19.9
3	1	0.125	264.8	0.141	263.7	0.138	264.6	0.099	266.7
4	1	0.016	155.8	(0.016)	(158.8)	(0.019)	(171.1)	(0.016)	(134.9)
2	2	0.066	37.7	0.059	45.0	0.068	36.2	0.070	33.5
3	2	0.025	358.1	(0.019)	(337.3)	0.024	351.8	0.033	13.5
4	2	0.031	241.7	0.034	243.0	0.032	244.2	0.026	237.2
5	2	(0.003)	(147.4)	(0.009)	(106.8)	(0.004)	(158.1)	(0.005)	(249.3)
3	3	0.020	235.6	0.019	190.9	0.022	230.4	0.027	266.8
4	3	0.032	298.3	0.027	309.5	0.033	294.1	0.036	294.4
5	3	0.019	258.3	(0.011)	(224.0)	(0.020)	(259.2)	0.028	269.4
6	3	(0.011)	(186.3)	(0.013)	(152.9)	(0.011)	(186.5)	(0.014)	(214.2)
4	4	0.029	336.3	0.030	324.2	0.030	337.5	0.029	346.9
5	4	0.014	100.1	0.015	128.7	(0.015)	(100.9)	(0.014)	(71.3)
6	4	(0.010)	(34.8)	(0.006)	(41.6)	(0.011)	(43.8)	(0.011)	(22.9)
7	4	(0.011)	(344.7)	(0.008)	(346.6)	(0.012)	(340.6)	(0.012)	(347.2)
5	5	0.037	327.4	0.038	320.9	0.039	327.4	0.033	334.2
6	5	0.034	93.0	0.035	88.3	0.036	92.5	0.031	98.5
7	5	0.012	83.9	(0.008)	(58.3)	(0.013)	(83.4)	(0.016)	(94.9)
8	5	(0.007)	(266.1)	(0.007)	(261.9)	(0.009)	(259.6)	(0.005)	(281.5)

Table 4. Model N3 - Amplitudes and Phases of S1

Seasonal Means (Prograde Waves)

		Annual		D-Season		E-Season		J-Season	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
0	0	0.009	54.2	0.009	54.4	0.010	53.6	0.008	54.8
1	0	(0.013)	(190.6)	(0.012)	(279.9)	(0.011)	(182.9)	(0.028)	(169.7)
2	0	0.050	242.9	(0.037)	(255.9)	(0.054)	(244.5)	(0.061)	(233.8)
3	0	0.044	285.7	(0.029)	(281.6)	(0.047)	(286.9)	(0.055)	(286.8)
1	1	0.232	74.6	0.221	76.5	0.242	75.0	0.234	72.5
2	1	(0.018)	(56.2)	(0.017)	(129.7)	(0.025)	(51.7)	(0.027)	(25.8)
3	1	0.098	271.2	0.119	270.5	0.104	268.2	0.071	276.9
4	1	(0.012)	(164.2)	(0.018)	(217.7)	(0.013)	(155.8)	(0.017)	(116.5)
2	2	0.064	40.7	0.058	44.4	0.066	38.2	0.069	40.1
3	2	0.027	9.8	(0.013)	(342.7)	(0.031)	(6.8)	0.039	20.9
4	2	0.026	271.3	(0.034)	(263.8)	(0.028)	(267.0)	(0.018)	(292.0)
5	2	(0.011)	(165.0)	(0.015)	(127.7)	(0.014)	(175.8)	(0.010)	(203.0)
3	3	(0.008)	(265.3)	(0.009)	(148.3)	(0.009)	(248.2)	0.021	294.3
4	3	0.041	304.6	0.031	313.6	0.044	301.6	0.049	301.6
5	3	0.025	261.6	(0.018)	(234.7)	(0.028)	(259.3)	(0.033)	(278.2)
6	3	(0.019)	(215.0)	(0.015)	(186.4)	(0.016)	(217.2)	(0.029)	(227.4)
4	4	0.043	4.5	0.042	360.0	0.045	5.2	0.042	8.2
5	4	(0.014)	(102.7)	(0.020)	(146.0)	(0.017)	(91.8)	(0.016)	(63.3)
6	4	(0.007)	(58.1)	(0.004)	(68.3)	(0.009)	(80.5)	(0.009)	(30.7)
7	4	(0.013)	(6.4)	(0.013)	(25.4)	(0.013)	(0.1)	(0.013)	(354.7)
5	5	0.043	343.8	0.045	338.2	0.047	343.4	0.038	350.7
6	5	0.037	100.9	0.034	113.8	0.041	98.3	0.037	92.4
7	5	(0.011)	(136.2)	(0.002)	(119.9)	(0.013)	(139.4)	(0.020)	(135.7)
8	5	(0.007)	(265.8)	(0.005)	(296.7)	(0.010)	(258.2)	(0.008)	(257.7)

Table 5. Model A1, A2, A3 - Amplitudes and Phases of S2

Prograde and Retrograde Waves

		Model A1 (Annual Mean)		Model A2		Model A3	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
1	-1	0.011	49.0	0.015	73.9	0.000	0.0
2	1	0.015	35.0	0.016	40.6	0.000	0.0
3	1	0.002	264.0	0.006	204.7	0.000	0.0
4	1	0.004	102.0	0.003	210.6	0.000	0.0
2	-2	0.009	206.0	0.010	157.2	0.000	0.0
3	2	0.015	144.0	0.010	153.7	0.000	0.0
4	2	0.005	25.0	0.010	322.4	0.000	0.0
5	2	0.006	318.0	0.007	290.1	0.000	0.0
6	2	0.000	0.0	0.006	196.6	0.000	0.0
7	2	0.000	0.0	0.006	137.1	0.000	0.0
8	2	0.000	0.0	0.002	54.4	0.000	0.0
9	2	0.000	0.0	0.006	309.8	0.000	0.0
10	2	0.000	0.0	0.001	33.5	0.000	0.0
3	-3	0.000	0.0	0.007	161.8	0.000	0.0
4	3	0.000	0.0	0.008	111.1	0.000	0.0
4	-4	0.000	0.0	0.003	222.2	0.000	0.0
0	0	0.064	345.0	0.000	0.0	0.000	0.0
1	0	0.019	112.0	0.009	95.8	0.000	0.0
2	0	0.069	157.0	0.023	125.9	0.000	0.0
3	0	0.049	72.0	0.014	108.2	0.000	0.0
4	0	0.000	0.0	0.006	358.3	0.000	0.0
1	1	0.010	139.0	0.005	2.4	0.000	0.0
2	1	0.019	174.0	0.003	249.6	0.000	0.0
3	1	0.018	335.0	0.002	219.1	0.000	0.0
4	1	0.002	307.0	0.003	122.5	0.000	0.0
2	2	0.549	159.0	0.563	157.2	0.663	164.4
3	2	0.026	81.0	0.023	67.1	0.000	0.0
4	2	0.054	331.0	0.073	331.0	0.069	52.1
5	2	0.007	319.0	0.007	282.2	0.000	0.0
6	2	0.000	0.0	0.004	12.2	0.000	0.0
7	2	0.000	0.0	0.003	329.1	0.000	0.0
8	2	0.000	0.0	0.007	214.1	0.000	0.0
9	2	0.000	0.0	0.001	29.2	0.000	0.0
10	2	0.000	0.0	0.011	36.5	0.000	0.0
3	3	0.043	109.0	0.027	71.8	0.000	0.0
4	3	0.013	72.0	0.007	63.5	0.000	0.0
5	3	0.020	206.0	0.000	0.0	0.000	0.0
6	3	0.011	99.0	0.000	0.0	0.000	0.0
4	4	0.011	210.0	0.007	358.8	0.000	0.0
5	4	0.018	234.0	0.000	0.0	0.000	0.0
6	4	0.016	183.0	0.000	0.0	0.000	0.0
7	4	0.003	281.0	0.000	0.0	0.000	0.0

Table 6. Model A1, N1 – N3 - Amplitudes and Phases of S2 (Annual Means)

		Model A1		Model N1		Model N2		Model N3	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
0	0	0.064	345.0	(0.005)	345.0	(0.003)	(199.1)	0.004	134.5
1	0	0.019	112.0	(0.003)	112.0	(0.008)	(12.6)	(0.016)	(300.9)
2	0	0.069	157.0	0.120	157.0	0.079	141.1	0.101	127.7
3	0	0.049	72.0	(0.012)	72.0	(0.020)	(143.3)	(0.028)	(125.2)
1	1	0.010	139.0	0.025	96.9	0.022	85.0	0.025	28.2
2	1	0.019	174.0	0.025	152.8	0.020	162.2	(0.013)	(201.8)
3	1	0.018	335.0	0.022	296.0	0.019	289.6	(0.014)	(240.5)
4	1	0.002	307.0	(0.004)	(285.4)	(0.003)	(313.0)	(0.007)	(22.6)
2	2	0.549	159.0	0.545	148.8	0.553	150.6	0.584	156.0
3	2	0.026	81.0	0.028	20.2	0.022	26.7	(0.011)	(87.0)
4	2	0.054	331.0	0.079	332.8	0.082	333.4	0.094	336.6
5	2	0.007	319.0	(0.005)	(236.9)	(0.005)	(239.4)	(0.007)	(217.4)
3	3	0.043	109.0	0.018	71.8	0.018	84.8	0.024	95.0
4	3	0.013	72.0	(0.004)	(91.3)	(0.003)	(110.1)	(0.007)	(150.4)
5	3	0.020	206.0	(0.008)	(322.8)	(0.007)	(321.3)	(0.001)	(241.6)
6	3	0.011	99.0	(0.002)	(49.9)	(0.002)	(35.6)	(0.005)	(281.6)
4	4	0.011	210.0	0.015	273.1	0.012	272.6	(0.005)	(275.5)
5	4	0.018	234.0	(0.008)	(16.6)	(0.008)	(17.1)	(0.010)	(36.1)
6	4	0.016	183.0	(0.002)	(285.4)	(0.002)	(310.7)	(0.006)	(341.5)
7	4	0.003	281.0	(0.004)	(256.8)	(0.003)	(265.8)	(0.003)	(5.4)
5	5	0.000	0.0	0.009	94.9	0.009	96.6	0.008	98.4
6	5	0.000	0.0	(0.001)	(30.1)	(0.001)	(163.9)	(0.005)	(186.8)
7	5	0.000	0.0	(0.004)	(90.8)	(0.003)	(101.0)	(0.003)	(201.7)
8	5	0.000	0.0	(0.005)	(74.9)	(0.005)	(69.0)	(0.005)	(41.4)

Table 7. Model A1 - Amplitudes and Phases of S2

Seasonal Means of Prograde and Retrograde Waves

		Annual		D-Season		E-Season		J-Season	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
1	-1	0.011	49.0	0.021	63.0	0.022	102.0	0.019	94.0
2	1	0.015	35.0	0.022	40.0	0.018	31.0	0.013	37.0
3	1	0.002	264.0	0.003	315.0	0.004	318.0	0.005	311.0
4	1	0.004	102.0	0.007	145.0	0.003	188.0	0.003	253.0
2	-2	0.009	206.0	0.011	188.0	0.004	198.0	0.010	226.0
3	2	0.015	144.0	0.009	126.0	0.011	169.0	0.011	155.0
4	2	0.005	25.0	0.001	37.0	0.005	63.0	0.005	65.0
5	2	0.006	318.0	0.007	262.0	0.007	293.0	0.006	283.0
0	0	0.064	345.0	0.036	342.0	0.057	354.0	0.050	352.0
1	0	0.019	112.0	0.014	126.0	0.023	116.0	0.008	44.0
2	0	0.069	157.0	0.066	150.0	0.055	161.0	0.060	164.0
3	0	0.049	72.0	0.056	102.0	0.057	103.0	0.056	105.0
1	1	0.010	139.0	0.010	89.0	0.013	130.0	0.010	85.0
2	1	0.019	174.0	0.010	178.0	0.018	174.0	0.013	162.0
3	1	0.018	335.0	0.012	7.0	0.018	334.0	0.012	306.0
4	1	0.002	307.0	0.006	154.0	0.002	247.0	0.007	266.0
2	2	0.549	159.0	0.553	162.0	0.571	160.0	0.499	156.0
3	2	0.026	81.0	0.024	155.0	0.031	76.0	0.041	56.0
4	2	0.054	331.0	0.050	323.0	0.042	331.0	0.042	325.0
5	2	0.007	319.0	0.018	352.0	0.010	288.0	0.015	210.0
3	3	0.043	109.0	0.027	110.0	0.036	118.0	0.035	111.0
4	3	0.013	72.0	0.010	103.0	0.007	100.0	0.008	88.0
5	3	0.020	206.0	0.014	214.0	0.013	212.0	0.014	225.0
6	3	0.011	99.0	0.012	95.0	0.013	70.0	0.016	86.0
4	4	0.011	210.0	0.027	212.0	0.019	187.0	0.015	232.0
5	4	0.018	234.0	0.023	232.0	0.024	209.0	0.025	197.0
6	4	0.016	183.0	0.008	176.0	0.005	193.0	0.008	122.0
7	4	0.003	281.0	0.009	343.0	0.007	339.0	0.006	7.0

Table 8. Model N1 - Amplitudes and Phases of S2

Seasonal Means (Prograde Waves)

		Annual		D-Season		E-Season		J-Season	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
0	0	(0.005)	345.0	(0.014)	345.0	0.005	345.2	(0.003)	345.0
1	0	(0.003)	112.0	(0.004)	112.0	(0.003)	112.0	(0.002)	112.0
2	0	0.120	157.0	0.125	157.0	0.128	157.0	0.106	157.0
3	0	(0.012)	72.0	(0.011)	72.0	(0.011)	72.0	(0.013)	72.0
1	1	0.025	96.9	0.027	98.7	0.028	95.0	0.022	97.0
2	1	0.025	152.8	0.031	154.0	(0.025)	(153.1)	(0.021)	(151.0)
3	1	0.022	296.0	(0.015)	(263.7)	(0.026)	(298.4)	0.026	309.9
4	1	(0.004)	(285.4)	(0.003)	(164.3)	(0.006)	(303.8)	(0.009)	(290.2)
2	2	0.545	148.8	0.546	150.8	0.588	148.9	0.503	146.8
3	2	0.028	20.2	(0.008)	(161.6)	0.037	17.5	0.053	16.8
4	2	0.079	332.8	0.087	335.4	0.084	332.3	0.067	330.2
5	2	(0.005)	(236.9)	(0.015)	(341.8)	(0.009)	(212.7)	(0.014)	(194.4)
3	3	0.018	71.8	0.020	55.2	0.018	78.2	0.016	83.8
4	3	(0.004)	(91.3)	(0.005)	(45.8)	(0.004)	(73.4)	(0.006)	(131.8)
5	3	(0.008)	(322.8)	(0.008)	(310.4)	(0.008)	(342.0)	(0.009)	(317.7)
6	3	(0.002)	(49.9)	(0.003)	(47.3)	(0.003)	(47.4)	(0.002)	(57.7)
4	4	0.015	273.1	0.016	276.4	0.016	276.5	0.014	266.0
5	4	(0.008)	(16.6)	(0.009)	(1.6)	(0.010)	(24.4)	(0.006)	(25.0)
6	4	(0.002)	(285.4)	(0.002)	(32.7)	(0.003)	(271.7)	(0.002)	(263.8)
7	4	(0.004)	(256.8)	(0.005)	(243.8)	(0.004)	(261.6)	(0.005)	(264.2)
5	5	0.009	94.9	0.007	85.4	0.009	96.7	0.012	98.7
6	5	(0.001)	(30.1)	(0.002)	(191.9)	(0.001)	(346.9)	(0.003)	(31.0)
7	5	(0.004)	(90.8)	(0.002)	(88.1)	(0.004)	(90.8)	(0.006)	(91.6)
8	5	(0.005)	(74.9)	(0.006)	(81.0)	(0.005)	(74.8)	(0.005)	(68.6)

Table 9. Model N3 - Amplitudes and Phases of S2

Seasonal Means (Prograde Waves)

		Annual		D-Season		E-Season		J-Season	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
0	0	0.004	134.5	0.004	134.1	0.004	135.7	0.004	133.6
1	0	(0.016)	(300.9)	(0.006)	(270.5)	(0.016)	(299.2)	(0.027)	(308.4)
2	0	0.101	127.7	0.116	136.7	0.102	125.3	0.088	118.9
3	0	(0.028)	(125.2)	(0.020)	(139.7)	(0.025)	(124.6)	(0.041)	(118.8)
1	1	0.025	28.2	(0.028)	(22.5)	(0.026)	(28.4)	(0.023)	(34.7)
2	1	(0.013)	(201.8)	(0.015)	(189.1)	(0.014)	(215.8)	(0.010)	(200.3)
3	1	(0.014)	(240.5)	(0.014)	(204.4)	(0.012)	(227.5)	(0.020)	(273.5)
4	1	(0.007)	(22.6)	(0.005)	(104.5)	(0.010)	(19.5)	(0.011)	(357.4)
2	2	0.584	156.0	0.595	158.9	0.615	155.7	0.545	153.1
3	2	(0.011)	(87.0)	(0.015)	(188.8)	(0.015)	(90.2)	(0.026)	(51.7)
4	2	0.094	336.6	0.104	342.2)	0.093	335.9	0.085	330.7
5	2	(0.007)	(217.4)	(0.012)	(336.8)	(0.010)	(208.2)	(0.020)	(192.9)
3	3	0.024	95.0	0.030	86.5	0.025	98.9	0.019	103.1
4	3	(0.007)	(150.4)	(0.007)	(135.8)	(0.005)	(139.0)	(0.008)	(170.8)
5	3	(0.001)	(241.6)	(0.004)	(245.8)	(0.002)	(68.5)	(0.000)	(209.1)
6	3	(0.005)	(281.6)	(0.005)	(258.0)	(0.006)	(287.2)	(0.004)	(298.4)
4	4	(0.005)	(275.5)	(0.008)	(242.9)	(0.004)	(289.9)	(0.006)	(306.9)
5	4	(0.010)	(36.1)	(0.010)	(38.7)	(0.011)	(30.5)	(0.010)	(39.7)
6	4	(0.006)	(341.5)	(0.007)	(337.4)	(0.006)	(334.6)	(0.005)	(354.0)
7	4	(0.003)	(5.4)	(0.005)	(359.2)	(0.003)	(357.4)	(0.001)	(65.2)
5	5	0.008	98.4	(0.008)	(91.0)	(0.009)	(100.2)	(0.008)	(103.4)
6	5	(0.005)	(186.8)	(0.007)	(196.1)	(0.006)	(180.0)	(0.003)	(181.0)
7	5	(0.003)	(201.7)	(0.002)	(210.0)	(0.004)	(207.2)	(0.004)	(192.2)
8	5	(0.005)	(41.4)	(0.005)	(37.6)	(0.006)	(46.8)	(0.005)	(38.7)

Table 10. Model A1 – A3, N1 – N3 – Dominant Components of S1, S2

10.1 Prograde Components of S1 with Dominant Amplitudes (Annual Means)

		Model A1		Model N1		Model N2		Model N3	
L	M	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)	C (cm)	E (°)
2	0	0.101	152.0	0.029	228.6	0.033	234.7	0.050	242.9
1	1	0.287	12.0	0.220	73.2	0.222	73.6	0.232	74.6
3	1	0.086	197.0	0.125	264.8	0.119	266.3	0.098	271.2
2	2	0.053	261.0	0.066	37.7	0.066	38.5	0.064	40.7

10.2 Dominant Prograde Amplitudes (cm) of S2 (Annual Means)

L	M	A1	A2	A3	N1	N2	N3
2	0	0.069	0.023	0.000	0.120	0.079	0.101
2	2	0.549	0.563	0.663	0.545	0.553	0.584
4	2	0.054	0.073	0.069	0.079	0.082	0.094
3	3	0.043	0.027	0.000	0.018	0.018	0.024

10.3 Prograde Phases (°) of S2 with Dominant Amplitudes (Annual Means)

L	M	A1	A2	A3	N1	N2	N3
2	0	157.0	125.9	0.0	157.0	141.1	127.7
2	2	159.0	157.2	164.4	148.8	150.6	156.0
4	2	331.0	331.0	52.1	332.8	333.4	336.6
3	3	109.0	71.8	0.0	71.8	84.8	95.0

Table 11. Model A1, N1 - N3 – Atmospheric Tide S1

Corresponding Amplitudes (A) and Phases (E) of S1 (Annual Means).
See Table 1, Fig. 1, 9 .

Accepted Maximal Differences.
Amplitudes: up to 30% (20% - 30% only for small Amplitudes),
Phases: 14° for differences between N1, N2, N3
22° for differences of model A1 versus N1

11.1 Corresponding Amplitudes and Phases of the Models N1, N2, N3

M \ L	M + 0		M + 1		M + 2		M + 3	
0	A	-	A	-	-	E	-	-
1	A	E	A	-	A	E	A	E
2	A	E	A	E	A	-	-	-
3	-	-	A	E	A	E	-	-
4	-	-	A	E	A	-	A	-
5	A	-	A	E	A	-	A	E

11.2 Corresponding Amplitudes and Phases of the Models A1, N1

M \ L	M + 0		M + 1		M + 2		M + 3	
0	-	-	A	-	-	-	-	-
1	-	-	-	-	-	-	-	-
2	A	-	A	-	-	-	-	-
3	A	-	A	-	-	-	A	-
4	A	-	A	-	A	-	A	-
5	A	-	A	-	-	-	A	-

For the phases no agreement of A1 and N1 could be found and no systematic differences, which is coming from a convention applied for A1. The minimal phase difference amounts to 29° for (M,L) = (4,3). All other phase differences are distributed between 60° and 333°. At time the cause is unknown. But for the tide S2 corresponding phases can be found (Table 14).

Table 12. Model A1, N1 - N3 – Atmospheric Tide S2

Corresponding Amplitudes (A) and Phases (E) of S2 (Annual Means).
See Table 6, 7, Fig. 5, 13 .

Accepted Maximal Differences.
Amplitudes: up to 30% (20% - 30% only for small Amplitudes),
Phases: 14° for differences between N1, N2, N3
22° for differences of A1, A2 versus N1, N3

12.1 Corresponding Amplitudes and Phases of the Models N1, N2, N3

M \ L	M + 0		M + 1		M + 2		M + 3	
0	A	-	-	-	-	-	-	-
1	A	-	-	-	-	-	A	-
2	A	E	-	-	A	E	A	-
3	A	-	A	-	-	-	A	-
4	-	E	A	-	-	-	A	-
5	A	E	-	-	A	-	A	-

12.2 Corresponding Amplitudes and Phases of the Models A1, N1

M \ L	M + 0		M + 1		M + 2		M + 3	
0	-	E	-	E	-	E	-	E
1	-	-	A	E	A	-	A	E
2	A	E	A	-	-	E	A	-
3	-	-	-	E	-	-	-	-
4	A	-	-	-	-	-	A	-
5	Model A1 without order M = 5							

For order M = 0 the phases of model N1 are fixed to that of A1 by a priori information.

12.3 Corresponding Amplitudes and Phases of the Models A2, N1

M \ L	M + 0		M + 1		M + 2		M + 3	
0	-	-	-	E	-	-	A	-
1	-	-	-	-	-	-	A	-
2	A	E	A	-	A	E	A	-
3	-	E	-	-	-	-	-	-
4	-	-	end of model A2					

12.4 Corresponding Amplitudes and Phases of the Models A2, N3

M \ L	M + 0		M + 1		M + 2		M + 3	
0	-	-	-	-	-	E	-	-
1	-	-	-	-	-	-	-	-
2	A	E	-	E	A	E	A	-
3	A	-	A	-	-	-	-	-
4	A	-	end of model A2					