Modelling of the field of gravity variations induced by the seasonal air mass warming during 1998- 2000

by Dietrich Simon*

Abstract
The paper informs about results of model calculations concerning the gravity variation component $g_c(t)$ induced by the seasonal warming of air masses. The modelling used the data of radio sounding launchings from eight Western European stations. The monograph of SIMON [2002] (Mitteil. des BKG, Band 23, in press) will contain an extended description of the model used for this purpose, the software AMACON and a test sample for its application. In the first step of modelling the air mass attraction functions A(t) have been calculated. Then, we correlated the A(t) functions with the corresponding time series of measured ground air pressure, p (t), to eliminate the components which are proportional to the local air pressure variations. The relative best elimination of this component was attained when using a value r_{AP} = 0,40 µGal/hPa for the coefficient of regression. This is valid for all the eight meteorological stations. The regression coefficients obtained from the correlation of gravimetric curves of measurement and local air pressure variations at ground level are known to be 25- 30% smaller as a consequence of the reducing influence of the loading effect.

The modelling work aimed at the determination of the component $A_c(t)$ of air mass attraction occurring with constant air pressure at ground level in the expression

$$A_c(t) = A(t) - r_{AP} * p(t).$$

So far, $A_c(t)$ has not been taken into account in routine evaluations of gravimetric series of measurement (SUN, DUCARME & DEHANT [1994], BOY, HINDERER & GEGOUT [1998]). For the change-over from the attraction component $A_c(t)$ to the gravity component $g_c(t)$ the relation

$$g_c(t) = - A_c(t)$$

is used.

The calculations showed that the main constituent of $A_c(t)$ is an annual wave, which reaches double amplitude of 1.6 µGal at 7 of the 8 stations mentioned. But at Ny Alesund (Spitsbergen) the double amplitude is about 2.0 µGal. The differences between the maximum and minimum values of $A_c(t)$ are 2,5 µGal at Medicina /Italy and 4,0 µGal at Ny Alesund/ Spitsbergen island. The mean amplitude of the annual wave $A_c(t)$ is latitude dependent and the maxima and minima occur in January and July, respectively. AMACON calculates the attraction of a cylindrical body of air masses at its ground (earth surface). The 10 mb pressure level is the upper boundary surface of the cylinder, which has the constant radius of 113 km. Assuming a varying air volume of time-constant mass (air pressure at ground level being constant!), the seasonal warming will primarily result in a volume expansion in the vertical direction. The centre of gravity of this volume will shift in the same direction. In the area of the Stuttgart weather station, for example, the altitude of this centre of gravity of the air body was found to be 247 m higher in July 1983, as compared to December of the same year.

The annual waves induced by air mass warming can explain only part of the seasonal components measured by high-precision gravimeters. But the elimination of these components from the series of gravimeter measurements may improve the chance of identifying and modelling more precisely other annual components, for instance the effects of seasonal sea level variations (CHAMBERS, D. P., CHEN, J. L., NEREM, R.S., TAPLEY, B. D.: [2000]).

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1. Introduction

The task of the modelling work consisted in determining of the component gc(t) of gravity variations occurring as an effect of seasonal warming or cooling of the atmospherical air layers under the condition of a constant air pressure at ground level. The calculations are basing on the aerological data of eight Western European radio sounding stations: Stuttgart, München, Essen, Dresden, Meiningen, Lindenberg in Germany, Medicina in Northern Italy and Ny Alesund at the Spitsbergen island, Norway. The measuring period was 01.01.1998 – 31.12.2000. The 8 stations are located in an area which is influenced almost by the Atlantic climate. This area has a North- South extension of about 34 ° and an East West extension of about 7° only. This array of stations was intended to allow the determination of a possible dependence of the component gc(t) on the latitude.

Table 1 gives a sample of a complete aerological data record in the form required for the calculation of a single value of $g_c(t)$. The modelling was carried out by means of the software package AMACON (SIMON [2002]).

Pressure [hPa] Fixed levels	Geopotential height [gpm]	Station height [m]
980	315,3	315
925	774	
850	1439	
800	1912	
700	2933	
600	4099	
500	5440	
400	7000	
300	8910	
250	10060	
200	11420	
150	13190	
70	17900	
50	19960	
30	23080	
20	25540	
10	29840	

Table 1: Stuttgart station, 28.01.1998, 12 h GMT: Sample of an aerological data record

2. Proof of the existence of an air mass attraction component, which does not depend on the variations of the local air pressure

So far the routine correction work of gravimetric series of measurements concerning atmospherical influences has not taken into account the existence of vertical air mass displacements also in the case that the air pressure at the earth does not vary (DUCARME & DEHANT [1994], BOY, HINDERER & GEGOUT [1998]). Therefore, it was necessary to prove the existence of such an effect at the beginning of the modelling . For this purpose the aerologic data of the radio sounding station Hannover / Germany of 1972 – 1994 were used. The data were published by the DWD in a manner comparable with Table 1, but as monthly mean values.
To exclude the influence of air pressure variations on A(t) the modelling was carried out with the aerological data sets only where ground pressure values were 1010 hPa (31 sets) or 1008 hPa (27 sets). Table 2 shows the geopotential heights of the pressure level 30 mb and marks in this way the month the data set comes from. The geopotential heights of the 30 mb surface are in July / August about 1100 gpm higher than in December/ January.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972												
1973					24062				24061			

1974			23345	23680				24304				
1975							24368		24099		23571	
1976							24374					
1977					24131							
1978								24301				
19793					24075							
1980	23215			23804	24050						23461	
1981						24257			24048			
1982												
1983												
1984												
1985							24321					
1986							24307					
1987			23471									
1988									24058			
1989										23703		
1990												23329
1991				23716					24075	23851		
1992							24332					
1993						24154				23674		
1994										23673		

Table 2a: Hannover: Geopotential heights of the 30 mb surface (ground pressure: 1010 hPa)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972			23769			24276						
1973												
1974					24003							23265
1975	23444			23807								
1976									24055			
1977												
1978					23994		24403					
19803						24339						
1980								24351				
1981							24414					
1982											23450	
1983												
1984						24205						
1985								24282				
1986			23516									23258
1987		23356			23952		24375				23403	
1988					24017							
1989												
1990				23753								
1991												
1992												
1993							24305					
1994					23946			24274				

Table 2b: Hannover: Geopotential heights of the 30 mb surface (ground pressure: 1008 hPa)

Concerning the 1010 hPa set group there is no data set in February, and in the case of the 1008 hPa set group there is no data set in October. After the calculation of the corresponding air mass attraction values A(t) these gaps were closed by interpolation, and mean values were determined for months with more than one set of data.

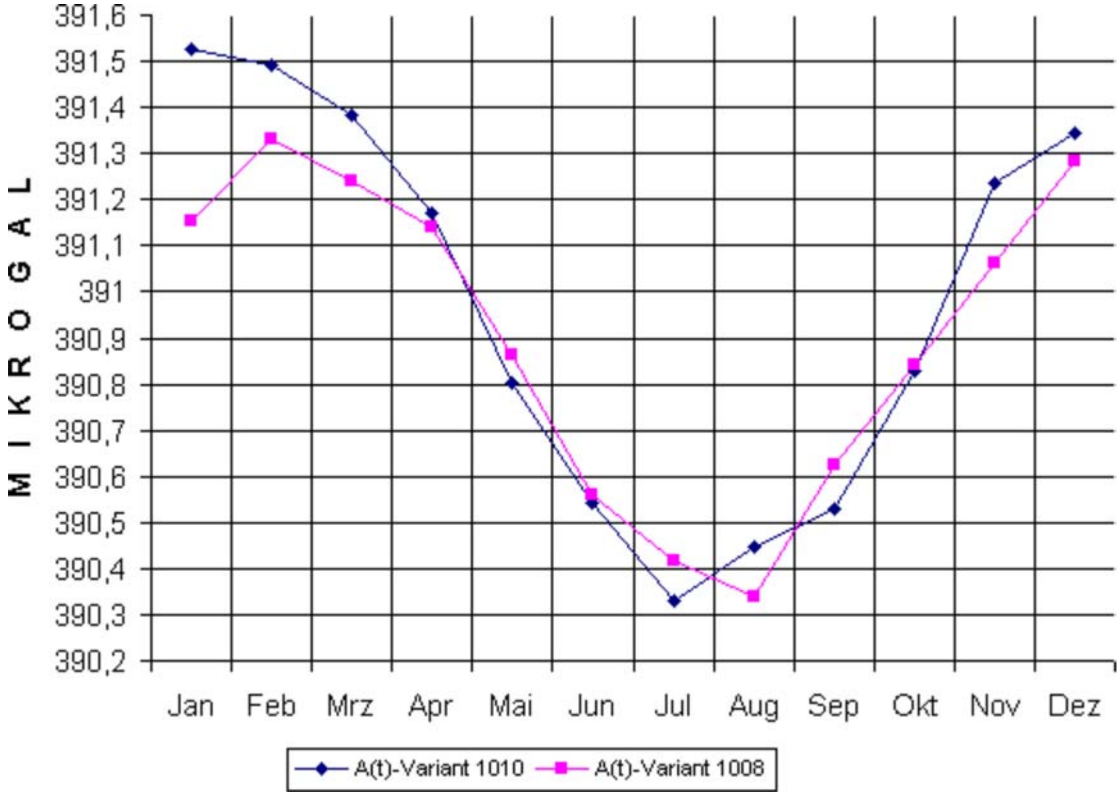

Fig.1: Hannover: Seasonal variation of the air mass attraction A(t) in the case of a constant ground air pressure (1010 hPa or 1008 hPa, respectively) during the year

Fig.1 shows the seasonal variation of the air mass attraction A(t) for this special case, in which there are not any variations of local air pressure at the earth's surface. The double amplitude of the seasonal wave reaches a measurable amount of about 1,2 μGal. The air mass attraction $A_c(t)$ reached maximum values in January/February and minimum ones in July /August. The corresponding component of gravity variation has the opposite sign:

$$g_c(t) = - A_c(t). \qquad (1)$$

3. Empirical determination of the coefficient r_{AP} for the regression between air mass attraction A(t) and the local air pressure variations p(t) at the ground

Differing from the situation represented by Fig.1 the component $A_c(t)$ of air mass attraction is generally small in relation to the second component $A_p(t)$ defined by (2):

$$A_c(t) = A(t) - A_p(t) = A(t) - r_{AP} * p(t). \qquad (2)$$

A(t) = air mass attraction, $A_p(t)$, $A_c(t)$ = components of A(t)
p (t) = air pressure at the ground, $r_{AP} = r_{AP}$ [μGal/ hPa] regression coefficient
To separate the component $A_c(t)$ from the total effect A(t) of air mass replacements we need a well- fitting numerical value of the regression coefficient r_{AP} . It is possible to determine such a value empirically by a stepwise change of r_{AP} and subtraction of the corresponding $A_p(t)$ from A(t) using the condition that the residual curve $A_c(t)$determined by this iteration method must be completely free from any components depending on the local air pressure variations p(t). An example of application of this method is shown in Fig.2:

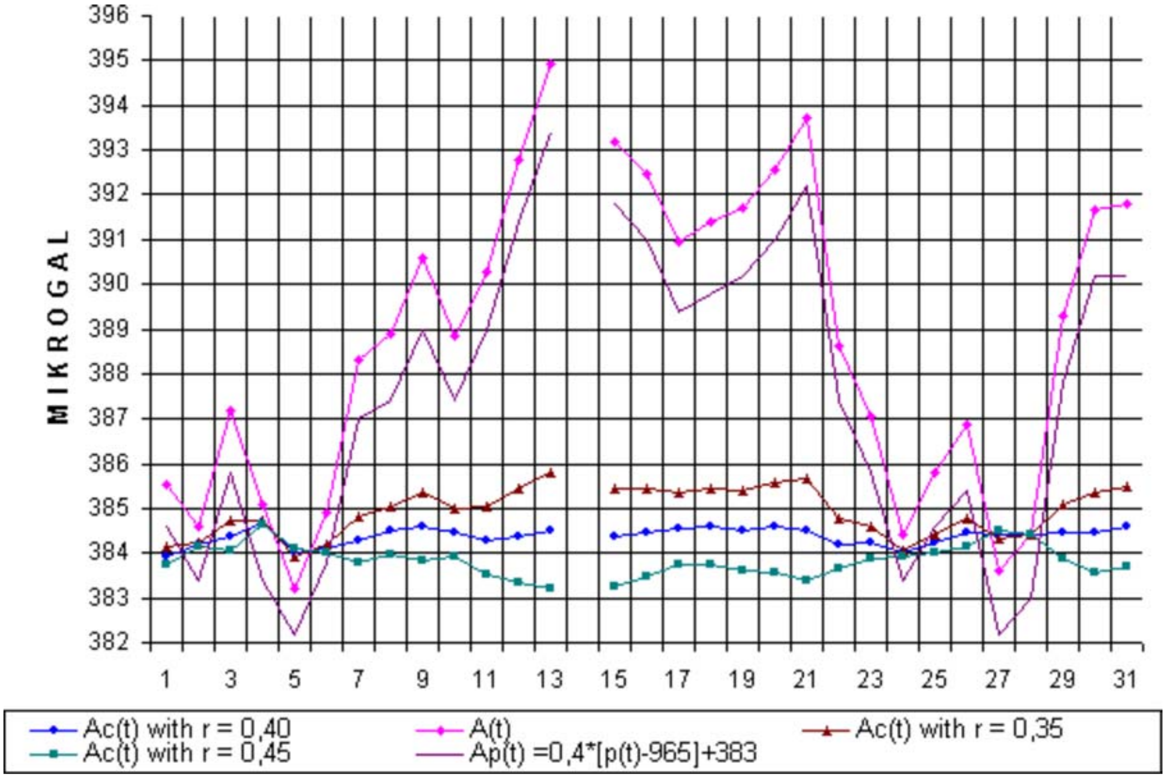

Fig.2: Stuttgart, 01. -31.01.2001: Air mass attraction A (t) and its components $A_p(t)$ and $A_c(t)$, determined with different numerical values of the coefficient r_{AP}

According to Fig. 2, there is a relative minimum of correlation between the model curves $A_c(t)$ and $A_p(t)$ in the case that the coefficient r_{AP} = 0,40 µGal/ hPa was used for the calculation of $A_p(t)$. Analogical tests with the data of other radio sounding stations, for instance Medicina, Hannover or Ny Alesund, respectively, led to the same result.

The numerical value of r_{AP} = 0,40 µGal/ hPa determined by this iteration method is in accordance with the results of modelling carried out by BOY, HINDERER & GEGOUT (1998, p.165, Fig. 2). The authors have calculated the atmospherical components of the gravity variations at the earth's surface for a spherical cap model body. In the case that the radius R of this model body is equal to 113 km or 1°, the numerical value of r_{AP} is equal to 0,40 µGal/ hPa .

4. Calculation of the components $A_c(t)$ of air mass attraction for 8 Western European stations during the period 1998 – 2000

Using the software AMACON (SIMON [2002]) the components $A_c(t)$ of the air mass attraction were calculated at 8 surface measuring points (radio sounding stations) located in Western Europe. The measuring period was 01.01.1998 – 31.12.2000. The raw data of the modelling are aerological data sets (like table 1) of the radio sounding launchings carried out daily at 12 h GMT . The same pressure coefficient 0,40 µGal/ hPa was used for the separation of the attraction components $A_c(t)$ at all the 8 stations. A first look at the diagrams in Fig. 3 – 6 shows several common characteristics and also some deviations between the 8 model curves:

4.1 Dependence of $A_c(t)$ on phase and latitude

- The attraction components $A_c(t)$ reach their maximum values regularly in the winter months January and

February, respectively, at all the 8 stations

- The time position of the summer minimum of attraction is shifting with decreasing latitude of the station from July (Ny Alesund) to August (Medicina)
- The double amplitude of the seasonal wave $A_c(t)$ or its width of variation, respectively, reaches its maximum values at the North (Ny Alesund) and at the North- East (Lindenberg, Dresden) of the area of investigation.

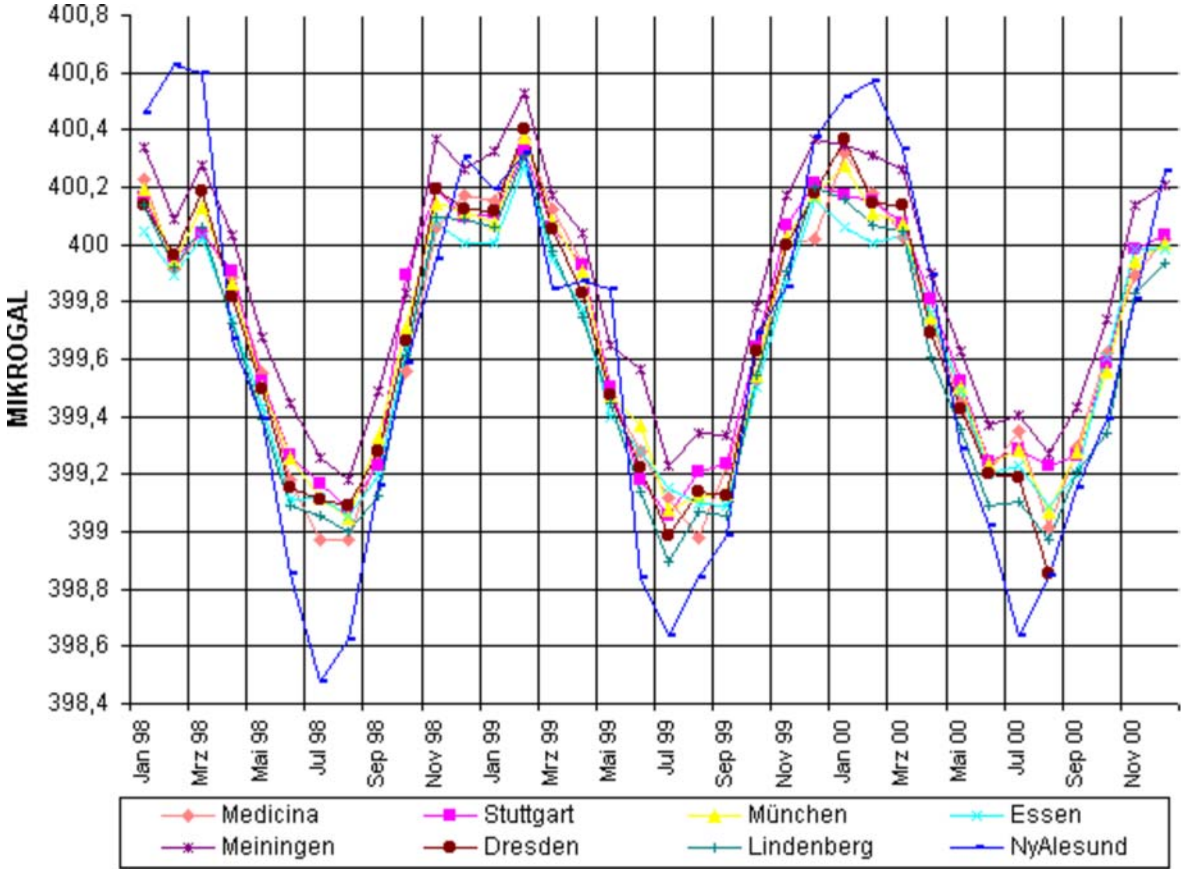

Fig. 3: Seasonal variations of $A_c(t)$ at 8 European weather stations. Consideration of the air masses from the earth's surface up to the height of the 10 mb pressure level

4.2 Deviations from the regular course induced by anomalies of the climate

- Samples for such anomalies: 1. Relative minimum in 1998, February; 2.Relative maximum in 1999, February; 3. Relative minimum in 2000, July. The effect number 3 may have been induced by a series of weeks spoilt by rain (July 2000) after a hot spring (May - June 2000). The July 2000 effect did not occur at Ny Alesund.

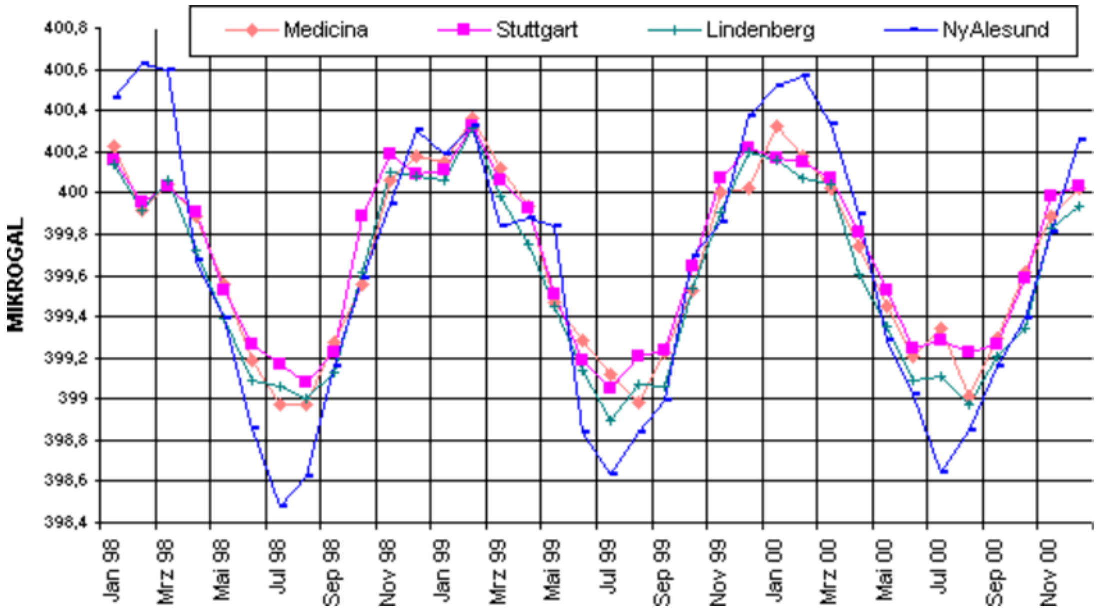

Fig.4: Model curves for the component A_c (t) of air mass attraction calculated for 4 Western European stations located at latitudes between 44°N and 78°N

4.3 Hints on influences of the Atlantic and continental climate

- "Atlantic climate influence zone": Stuttgart, Essen, Meiningen (winter month 1999, 2000)
- "Atlantic climate influence zone": Strong intermediate anticyclone during 2000, July.
- "Continental influence zone": München, Dresden (winter months 1999, 2000)

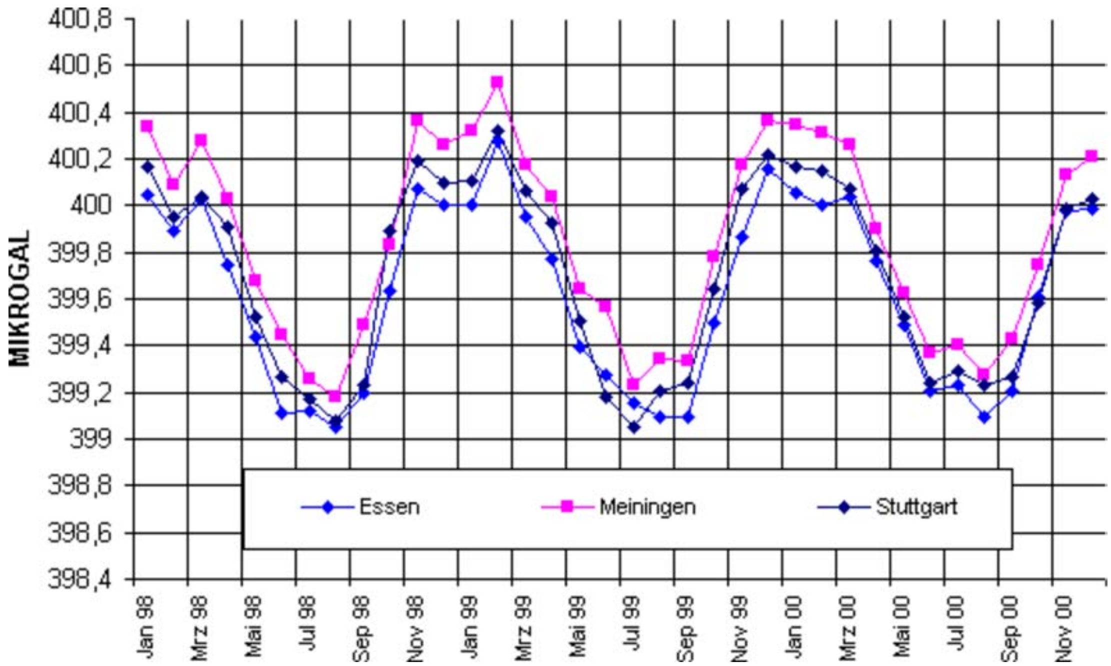

Fig.5: Model curves A_c(t) of air mass attraction calculated for 3 stations located

inside the Atlantic climate influence zone

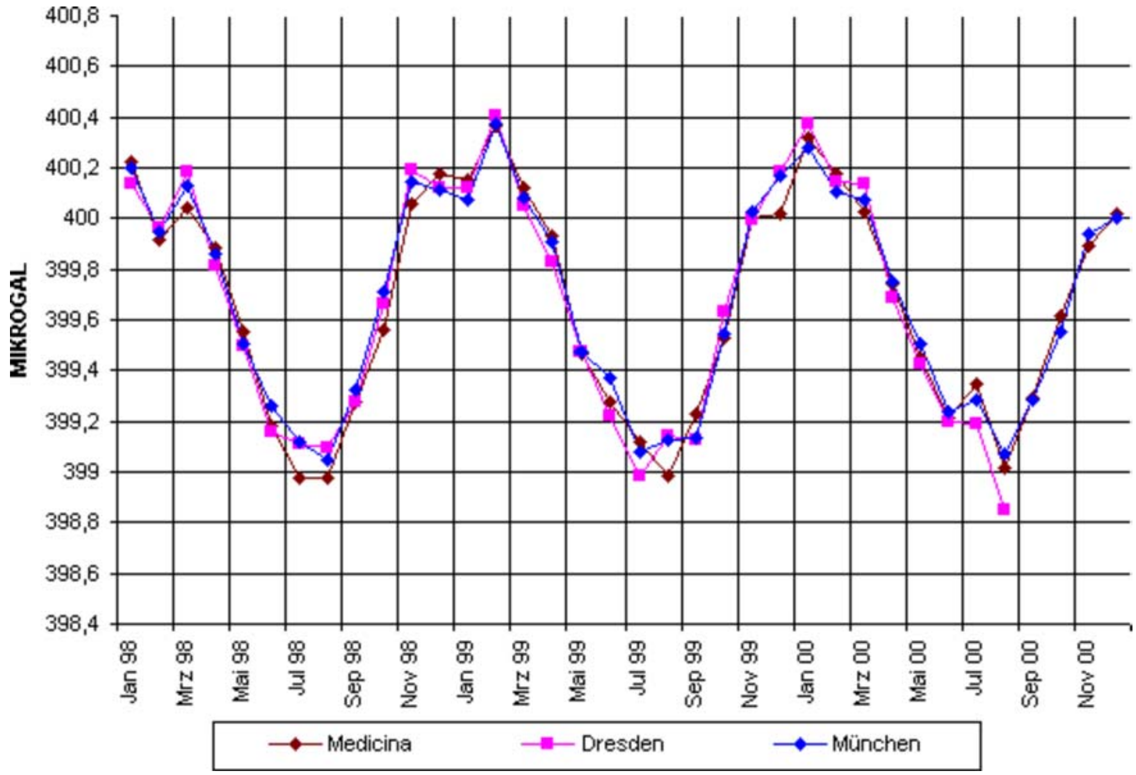

Fig.6: Model curves $A_c(t)$ of air mass attraction calculated for 3 stations located near the continental climate influence zone

5. Modelling of the gravity variations induced by the seasonal air mass warming at Bad Homburg during 1981- 1984

A first application of the new software AMACON was the calculation of the model function $g_c(t)$ for the gravimeter station Bad Homburg where a superconducting gravimeter installed by RICHTER [1987] had recorded continuously during 1 August 1981– 1 May 1984. Radio sounding measurements are not carried out at Bad Homburg. The next radio sounding stations were located at Stuttgart and Essen, respectively, during that period. Table 3 shows the coordinates of both the meteorological stations and their distances to Bad Homburg:

Station	Longitude	Latitude	Distance to Bad Homburg
Bad Homburg	8,611°	50,229°	
Essen	6,967°	51,400°	175 km
Stuttgart	9,200°	48,850°	163 km

Table 3: Distances of the next radio- sounding stations to Bad Homburg

To check the regional variability of the model curves the air mass attraction components $A_c(t)$ were calculated for both radio- sounding stations, Stuttgart and Essen. The result is shown in Fig. 7:

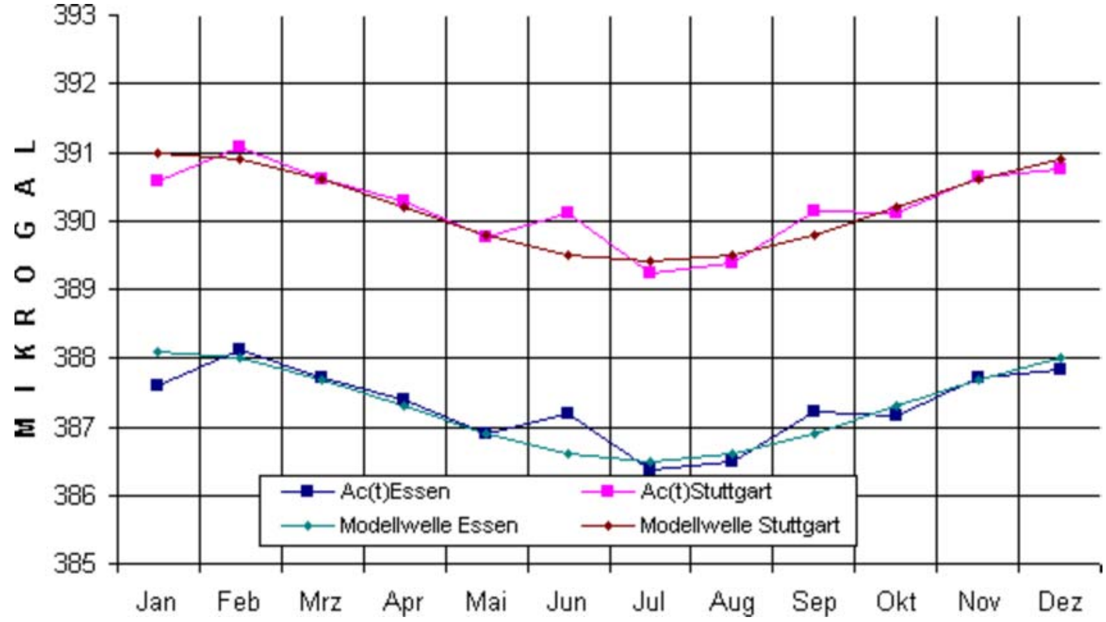

Fig. 7: Radio- sounding stations Stuttgart and Essen 1983: Attraction components $A_c(t)$ induced by the seasonal warming

The Bad Homburg gravimeter station is located about halfway between Essen and Stuttgart. As a consequence of the small differences between both $A_c(t)$- curves represented in Fig. 7 the modelling of the gravity variations of Bad Homburg was made by means of the radio sounding data of Stuttgart only. Fig. 8 shows the gravity component $g_c(t)$ at Bad Homburg together with a model cosinus function. The latter has an amplitude of 0,8 μGal and reaches its maximum value on 31 July. The evident deviations of $g_c(t)$ from the cosinus function during January/February 1982 and 1983, respectively, appeared during a time as the climate in Europe was influenced by the so-called Atlantic pendant of the "El Ninjo" phenomenon (LATIV & GRÖTZNER [2000]).

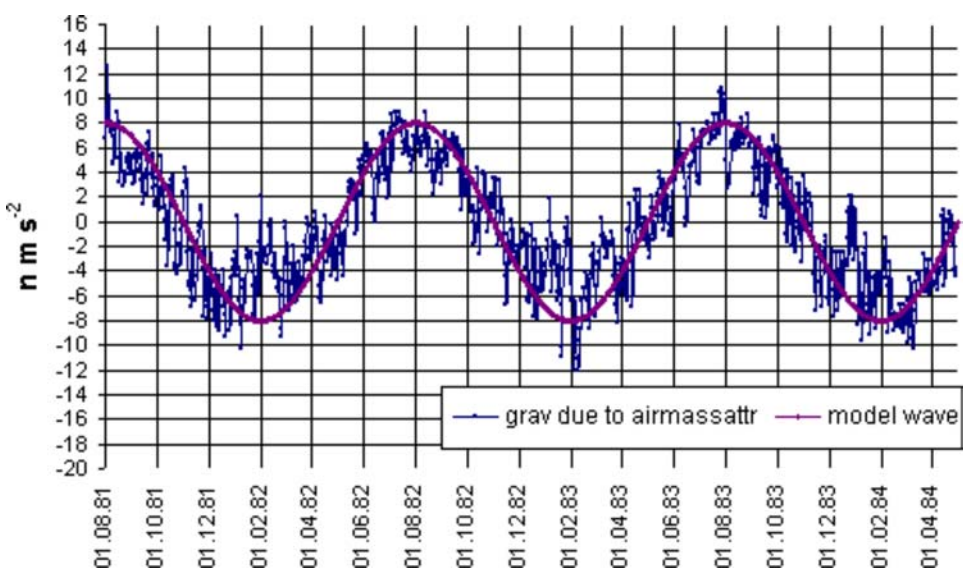

Fig.8: Model curves of the gravity variations $g_c(t)$ at Bad Homburg 1981-1984

The change-over from the attraction component $A_c(t)$ to the gravity component $g_c(t)$ was carried out using formula (1).

The model curve $g_c(t)$ varied during 1981-84 by 2,5 µGal. The maximum value was reached at August 1981, and the minimum ones at February 1983. In Fig. 9 the $g_c(t)$ curve was compared with a cosinus function having a double amplitude of 1,6 µGal. The relative maximum of this model function of gravity as on 31 July corresponds with a minimum of air mass attraction caused by the seasonal warming. Concerning the deviations from the model cosinus function the strongest anomalies were observed during the winter month, for instance in January- February 1982 or January- February 1984. Additionally, the gravity component induced by the polar motion was included in Fig. 9. The diagram gives an impression of the amplitude relation of both effects at Bad Homburg during 1981-84. The seasonal component of $g_c(t)$ reached about 1/6 of the maximum gravity variation induced by polar motion:

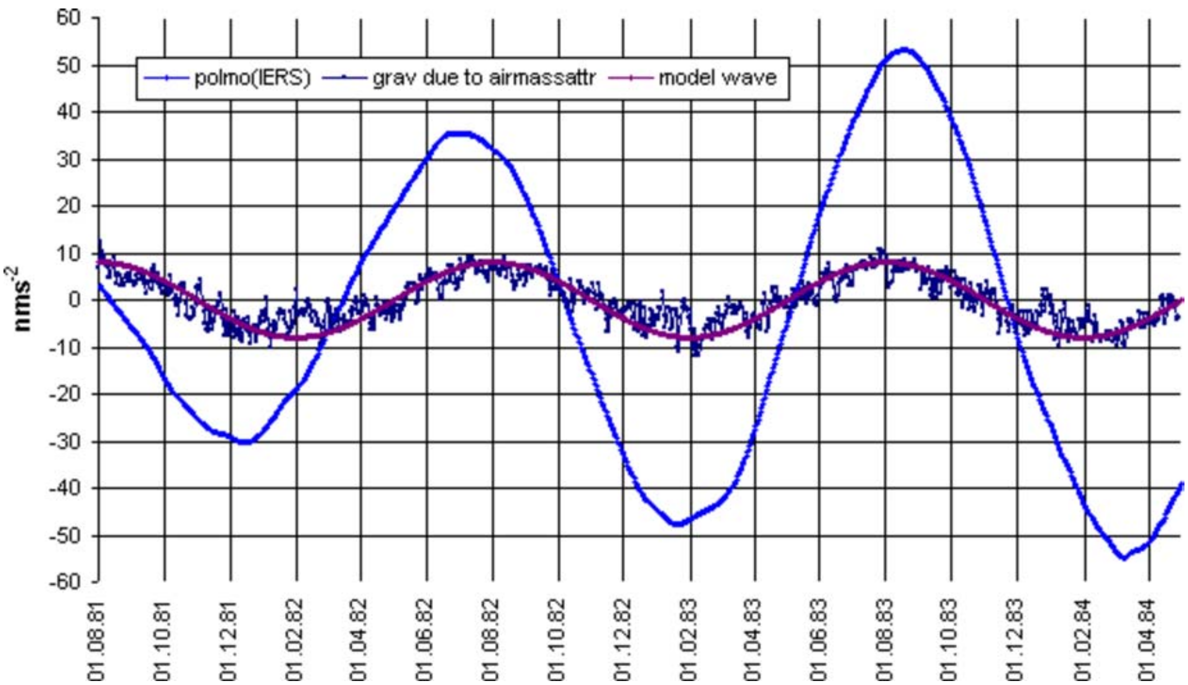

Fig. 9: Bad Homburg station: Gravity components induced by the seasonal warming of the atmospherical air masses and by the polar motions, respectively

The deviations of $g_c(t)$ from the model cosinus function referring to Jan./ Feb.1982, Jan./ Feb.1983 and Jan./ Feb.1998 (Fig. 3– 6) coincided with known El Ninjo (ENSO) events in the Southern Pacific. The effect of Jan./ Feb.1999 having the opposite sign could maybe correspond with the La Ninja event 1999. The directions of the deviations from the regular (Cosinus-) course of the $g_c(t)$ curve are compatible with such an interpretation (relative warming of air masses during Jan./ Feb.1998). In accordance with the results of investigations obtained by BARNETT, HURREL and LATIV (LATIV & GRÖTZNER [2000]) there is a pendant of the Southern Pacific ENSO phenomenon in the Atlantic. The Atlantic El Ninjo/ La Ninja effects are considered to be of considerable importance for the weather events in Europe.

The next step of investigation was to answer the question whether, e.g. the residual curve rk2 of the gravimetric measurements at Bad Homburg 1981-84 contains indeed an annual wave with the harmonic constants of the calculated model curve $g_c(t)$. To determine the residual curve rk2 of the gravimetric TT40 series of measurements we had to subtract three additional components from the gravimetric measuring data. These components are induced by tidal influences, by atmospherical and by instrumental effects, respectively. For this purpose the following formulas were used in accordance with M. HARNISCH, G. HARNISCH, G. RICHTER und W. SCHWAHN [1998]:

rk2 = rk1 –2nd degree polynomial (3)

rk1 = TT40 + 3,4*airpr - tides (Ri) (4)

TT40 [nms^{-2}] = measuring data of the TT40 gravimeter
2nd degr. polynomial = approximation of the instrumental drift of TT40
r_{TT40} = -3,4 nms^{-2}/hPa = air pressure coefficient (including the loading effect)
airpr = airpr [hPa] local air pressure variations p(t)
tides (Ri) = tidal model according to an analysis by RICHTER [1987, S.85].

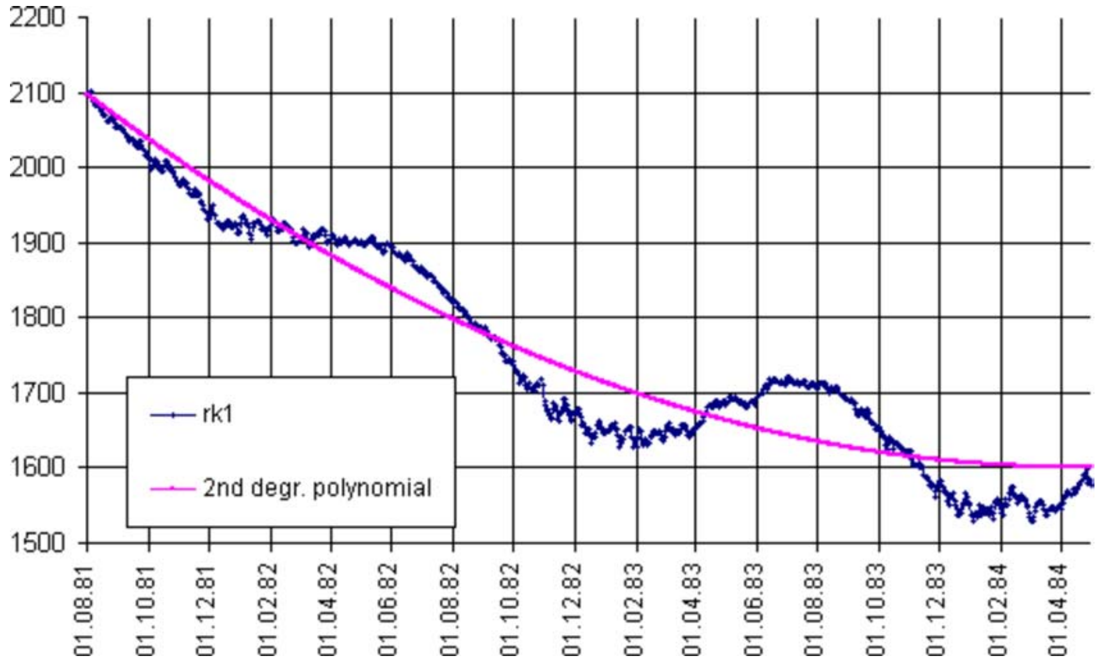

Fig. 10: Residual curve rk1 and the 2nd degr. polynomial (approximation of instrumental drift)

The regression coefficient r_{TT40} = -3,4 nms^{-2}/ hPa was determined by M. HARNISCH et al. [1998] using the ETERNA tidal analysis software. The negative sign of r_{TT40} is a consequence of formula (1).

Concerning the amount of the air pressure coefficient calculated for Bad Homburg 1981-84 it seems to be too large in comparison with those ones determined for other stations, to which values of about r_{TT40} = –3,0 nms^{-2}/hPa apply. Furthermore, M. & G. HARNISCH [2001] derived from the gravimetric data series 1999 –2001 of Bad Homburg a value of –2,95 nms^{-2}/ hPa. That means, it is probable that the residual curves rk1 and rk2 in Fig.s 10- 12 are not completely free of air pressure constituents.

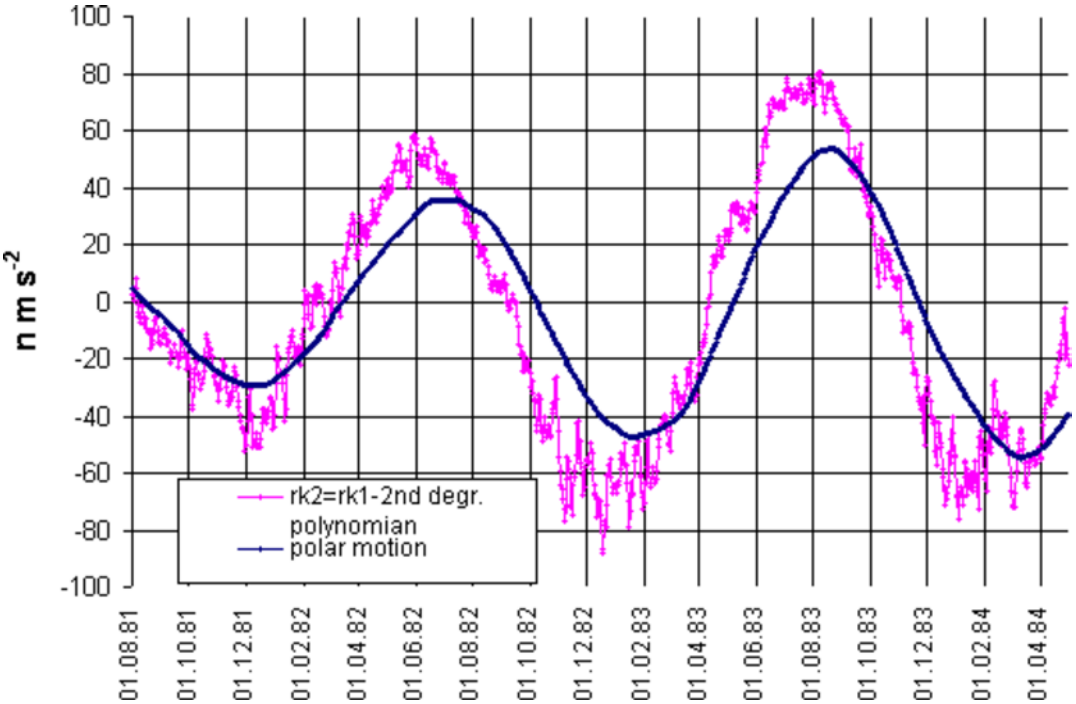

Fig.11: Residual curve rk2 of the TT40 measurements at Bad Homburg 1981 -84 in comparison with the local gravimetric component induced by polar motion

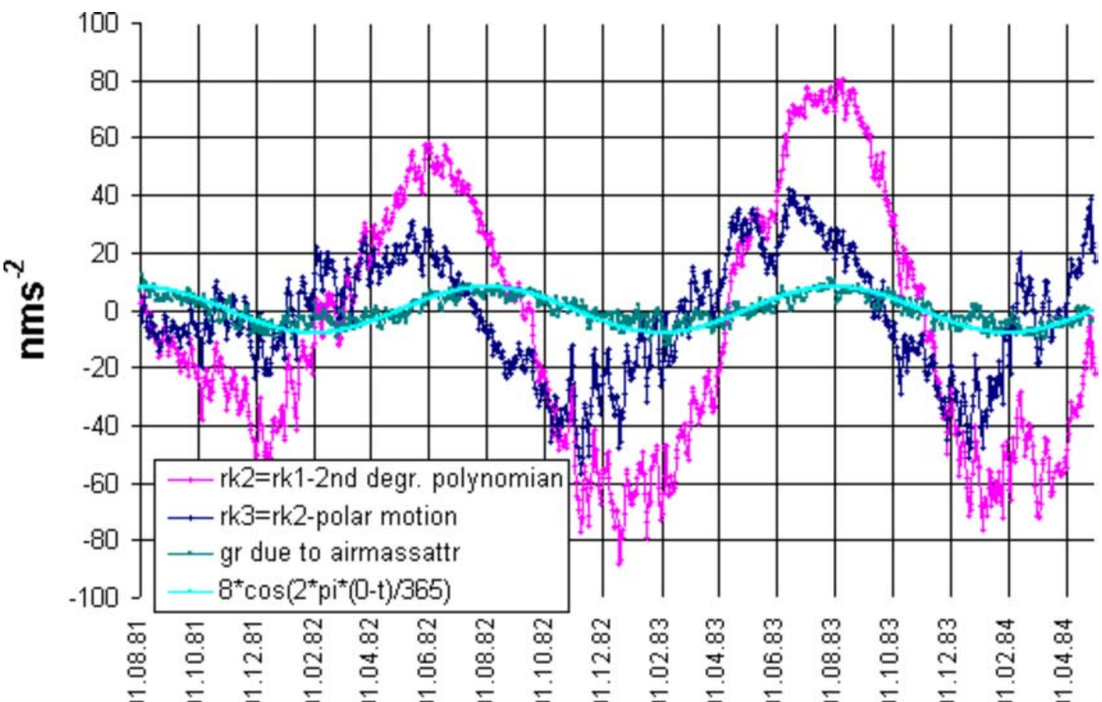

Fig.12: Bad Homburg, 1981-84: Residual curves rk2 and rk3 in comparison with the gravity components $g_c(t)$ induced by the seasonal warming of atmospherical air masses

In accordance with Fig. 12 an annual component with the double amplitude of 7– 8 μGal obviously predominates in the gravimetric residual curve rk3 of Bad Homburg 1981-84. This seasonal wave has its minimum values in November – January and its maximum values in June – July. The main constituent of the gravity variation $g_c(t)$ calculated from radio sounding data is an annual wave with about the same phase, too. But the double amplitude of the $g_c(t)$ wave reaches only 20 % of that one included in the gravimetric residuum rk3. However the residual curve rk3 of Bad Homburg 1981 – 1984 has not been corrected as yet concerning hydrological components.

7. Modelling of the gravity component $g_c(t)$ caused by air mass warming for Medicina 1998 – 2000 and comparison of the latter with the gravimetric residual curve

The gravity components induced by air mass attraction and by polar motion, respectively, were determined for Medicina 1998 – 2000 (Fig.13) and compared with an cosine function in an analogical manner as in the case of Bad Homburg 1981-84:

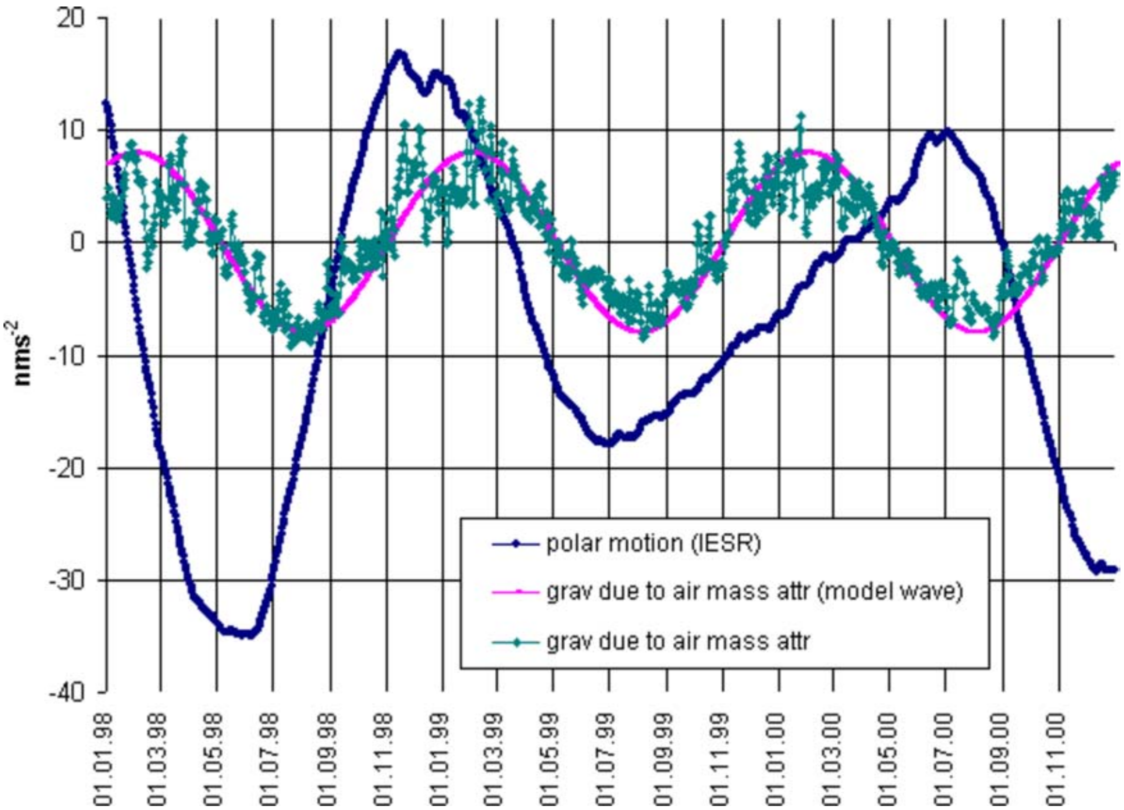

Fig.13: Medicina station: Gravity components induced by seasonal air mass warming and by polar motion, respectively

The component $g_c(t)$ was calculated for Fig.13 with a sampling rate of 24 hours. The same was performed for the polar motion effect. As a consequence, the fine structure of the regional anomalies as shown in Fig. 3- 6, was made perceptible. The polar motion component, which presented relatively small amplitudes during the period Sept. 98 – Sept. 99, allows a look on its fine structure for a short time, too. Here, the anomaly occurring during the La Ninja event at Jan/ Feb. 1999 is interesting. The $g_c(t)$ model curve of Fig.13 was used in Fig.14 for the correction of both the time series of measurements received by means of the superconducting gravimeter SG023 and by 3 absolute gravimeters of the FG5 type:

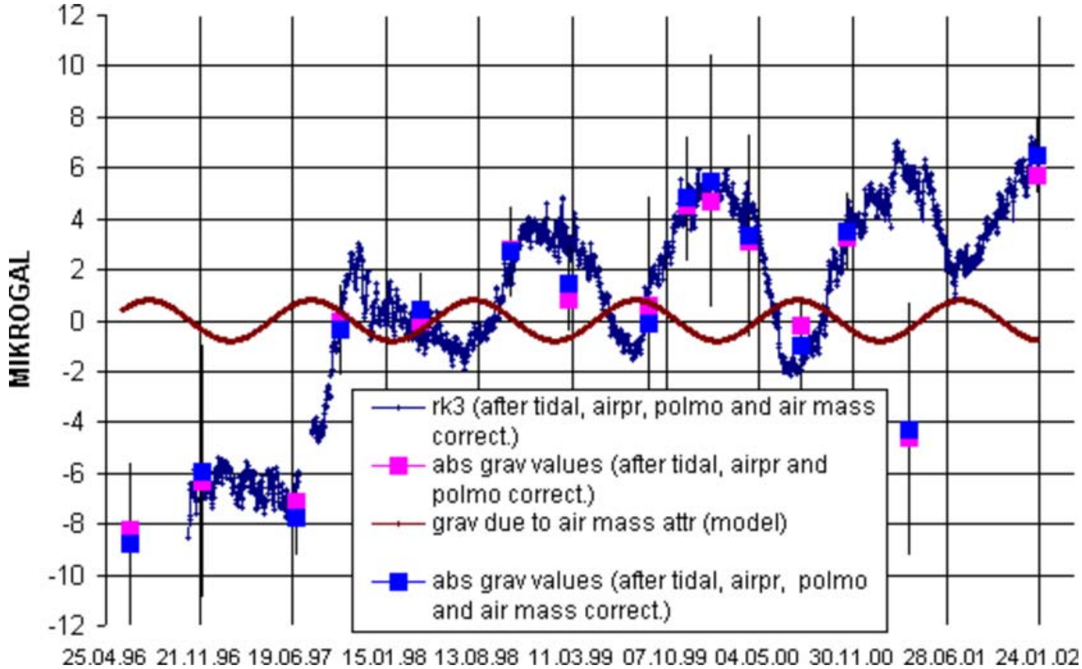

Fig.14: Medicina station: Residuals of the SG023 and FG5 measurement series 1996- 2000

8. Modelling of the gravity component $g_c(t)$ for Ny Alesund (Spitsbergen) 1998 – 2001

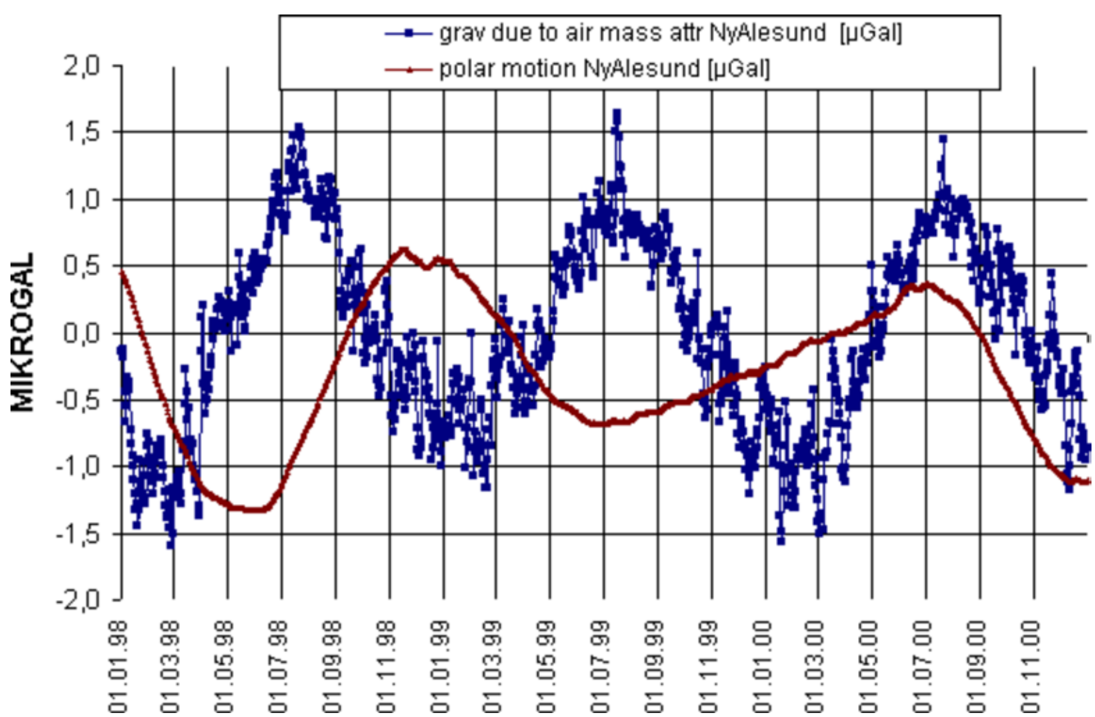

Fig.15: Ny Alesund station: Comparison of the gravity components induced by polar motion and by the seasonal warming of atmospherical air masses

In accordance to Fig.15 the effect of polar motion has the same order of magnitude at the Ny Alesund station as the $g_c(t)$ component of gravity variations caused by seasonal air mass warming. This phenomenon is induced by the high geographical latitude of the station.

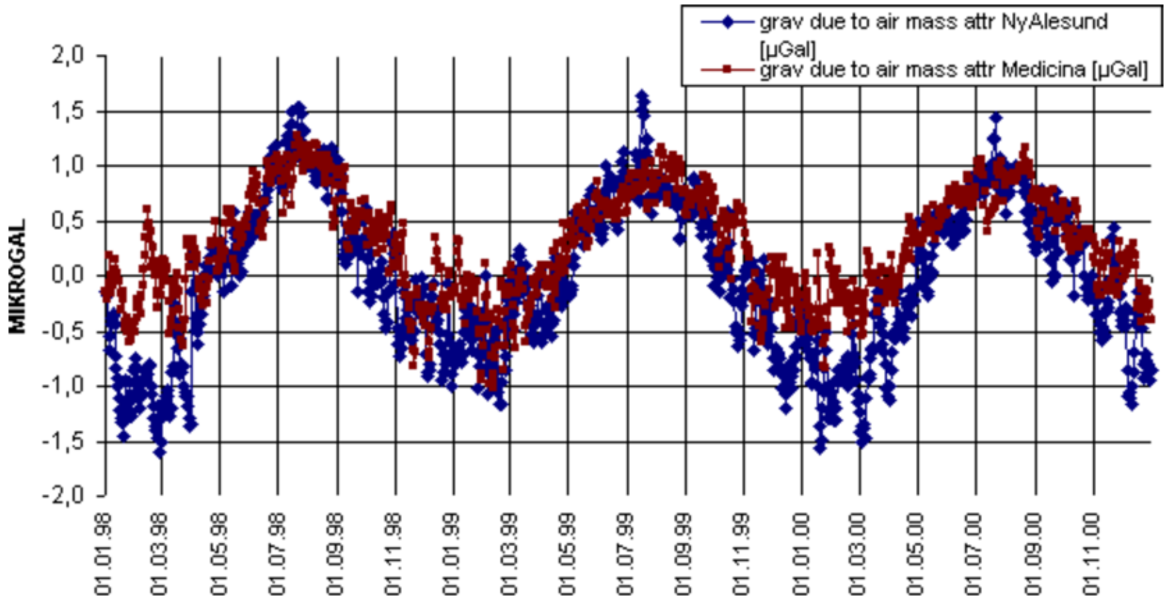

Fig.16: Ny Alesund and Medicina stations: Comparison of the gravity variations induced by the seasonal air mass warming

According to Fig.16 the maximal variation of the $g_c(t)$ component (sampling rate: 24 h) of Ny Alesund station is about 1,5 µGal larger than that of the Medicina station (Fig.16). But the polar motion effect of Ny Alesund reaches only 35 % of the corresponding effect observed at Medicina/ Italy (Fig.17):

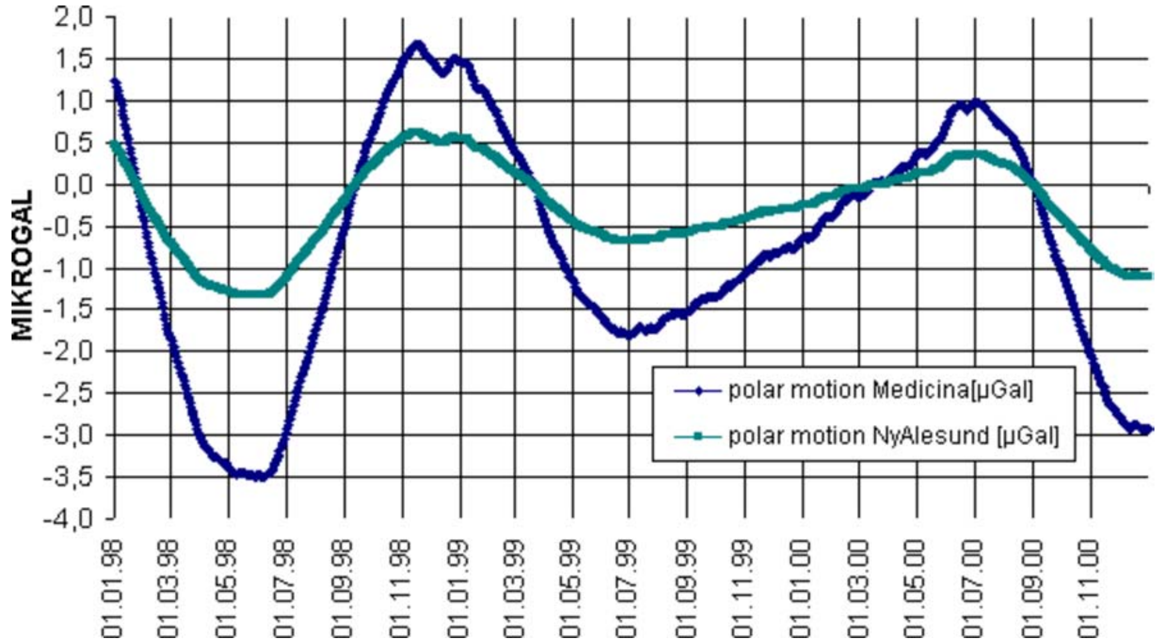

Fig.17: Comparison of the polar motion effects at Ny Alesund and Medicina

9. Conclusions and Outlook

- The seasonal warming/ cooling of the atmospherical air masses and special climatic anomalies, for instance the anomalies of Jan/Feb 19882, Jan/Feb 1983 and Jan/Feb 1998 comparable with El Ninjo effects or other anomalies, as for instance that of Jan/Feb 1999, produced in Western Europe gravity variations of at least 2,5 – 4,0 μGal (Fig.18). The effect could even be greater eventually at stations located in the influence zones of the continental climate, for instance at Warsaw, Budapest or Moscow.
- The modelling of the seasonal warming effect considered the effects of atmospheric air layers up to the height of the 10 mb pressure level. However, test calculations by SIMON [2002] have shown that the magnitude of the $g_c(t)$ variation increases with growing thickness of the model air layer packet. The radio soundings can seldom reach a ceiling which surpasses the height of the 10 mb surface by more than 2-3 km. The number of the model air layers considered could further increase if meteorological data of the CHAMP/ GRACE projects were available for this purpose. It was estimated that the $g_c(t)$ variation would increase by 20 % if the calculation was made on the basis of CHAMP/ GRACE data instead of radio sounding data.
- To obtain a first impression of the $g_c(t)$ field of gravity variations by means of radio sounding data we planned to perform a completion of the results presented here by the modelling of the effects at 2-3 inner-continental radio- sounding stations The results of these additional calculations should be included in the monograph of SIMON [2002], too.

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10. Literature

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