



Regional gravity variations in Europe from superconducting gravimeters

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Abstract

Recent satellite missions (CHAMP, GRACE) are now returning data on the time variation of the gravity field with harmonic coefficients computed every 4 weeks. The promise is to achieve a sub-microgal accuracy that will define continental mass variations involving large-scale hydrology. With this in mind, we examine the time varying gravity field over central Europe using a limited number of high quality ground-based superconducting gravimeter stations within the Global Geodynamics Project (GGP). Our purpose is to see whether there are coherent signals between the individual stations and to compare the regional component with that predicted from models of continental hydrology. The results are encouraging. We have found, using empirical orthogonal eigenfunctions of the gravity data that a clear annual signal is present that is consistent in phase (low amplitudes in summer) and amplitude (1–3 microgal) with that determined from a large-scale model of land water in connection with global climate modeling. More work is required to define how the gravity field is related to large-scale soil moisture and other mass variations, and we have yet to compare our results to the latest satellite-derived data.

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1. Introduction

Most of the data collected within the Global Geodynamics Project (GGP), a worldwide network of about 20 superconducting gravimeters (SGs), (Crossley et al., 1999), has been analyzed for local gravity

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variations at a single station. For the purpose of determining regional gravity variations, it is necessary to use a group of SGs, and this is only possible using existing GGP stations if we choose Europe, or possibly Japan, where such a grouping exists. In this study, we used nine gravity stations that were recording between July 1, 1997 and December 31, 2001, though not all simultaneously. Most of the stations are clustered in central Europe, but Metsahovi (ME, Finland) lies some distance to the north (Fig. 1). This paper is one of a series (Crossley and Hinderer, 2002; Crossley et al., 2003, 2004) whose goal is to determine regional gravity variations that might be explained by large-scale hydrology.

Our original purpose was to see if ground gravity could provide a test, or validation, for satellite-derived time-varying gravity, and was principally aimed at the GRACE mission (Wahr et al., 1998). Do the ground stations in Europe have the spatial coverage and accuracy to compete with the anticipated high quality of GRACE data? If so, are the data sets compatible, and do they correspond to what is known about variations of continental hydrology? We are not yet able to answer these questions because the GRACE satellite data is only now becoming available. In this paper we provide the most encouraging results to date that suggest a correlation between SG gravity and hydrology models, but we need the satellite data to strengthen the connection. We note that Neumeier et al. (2003) were the first to initiate a comparison study between monthly samples of CHAMP and SG data for a 1-year period (i.e. 2001).

In future it may be possible to deploy SG ground gravity arrays to help monitor geodetic motions in places such as Greenland for ice sheet mass estimate (Wahr et al., 2001), and for volcano monitoring, e.g.

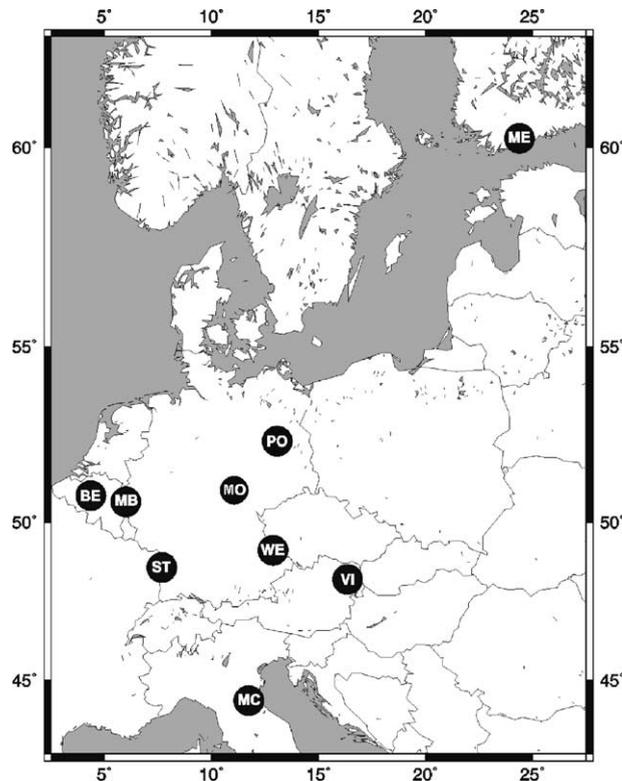


Fig. 1. Location of the GGP stations used in this study from July 1997–December 2001 (see Table 1).

as done in Indonesia by Gerstenecker and Suyanto (2000). If such arrays are to be useful, we have to be sure that SGs are not so biased by local effects as to miss the larger-scale signals. SGs are generally recognized to have an accuracy of about 0.1 microgal, with an instrument drift of 1–4 microgal/year, so technically they are capable of recording interesting geodynamic signals. They are, however, limited by the issue of sufficient network coverage and density, a requirement that is difficult to satisfy given the relatively high cost of SGs and limited research budgets. The current study is limited by the semi-permanent location of the existing SG stations and the availability of the data. Using the techniques described here, it is relatively easy to provide ground gravity in a limited region of Europe during the GRACE mission. Whether or not it is ground ‘truth’ remains to be seen.

2. Data processing

The stations and their locations are given in Table 1 and Fig. 1. We took data from the start of GGP (97/7/1) up to the end of 2001, all of it publically available. During this period, several station changes were made, so the coverage is not entirely homogeneous (Crossley et al., 2003). All stations have been regularly reporting data to GGP, except for Medicina (MC) whose data is available through the work of Zerbini et al. (2001). We first verified that the distance between station pairs gives a reasonable coverage of wavelengths between 200 and 1000 km, though the sampling is sparse. Station ME extends the range to 2000 km, though this distance range is only covered in the NE–SW direction. We used GGP uncorrected 1 min data, available through the International Centre for Earth Tides (ICET, <http://www.oma.be/KSB-ORB/ICET/index.html>).

The first step of the data processing is to remove well-modeled components from each station, beginning with a theoretical local tide (including ocean tide loading) using gravimetric factors (δ , κ) obtained from an independent analysis of data at each station. We fit all tides up to monthly periods and use nominal tidal factors (1.16, 0°) for waves of semi-annual and longer periods. We also subtract a nominal atmospheric effect, using an admittance of -0.3 microgal h Pa⁻¹, and both annual and Chandler polar motion using long-period nominal tidal factors again, using space geodetic data from the IERS website. These ‘nominal’ models are perfectly adequate for the 15-day averages of the gravity field we will eventually interpret.

Table 1
GGP stations used with estimated instrument drift

Station	Code	Type	Latitude (°N)	Longitude (°E)	Drift (microgal/year)
Brussels	BE	T003	50.7986	4.3581	0.1
Membach	MB	C021	50.6093	6.0066	4.90
Medicina	MC	C023	44.5219	11.6450	2.50
Metsahovi	ME	T020	60.2172	24.3958	3.75
Moxa	MO	CD034	50.6450	11.6160	3.21
Potsdam	PO	T018	52.3806	13.0682	1.64
Strasbourg	ST	C026	48.6217	7.6838	3.65
Vienna	VI	C025	48.2493	16.3579	2.25
Wetzell	WE1	SG103	49.1440	12.8780	-253.95
	WE2	CD029	49.1440	12.8780	0.18

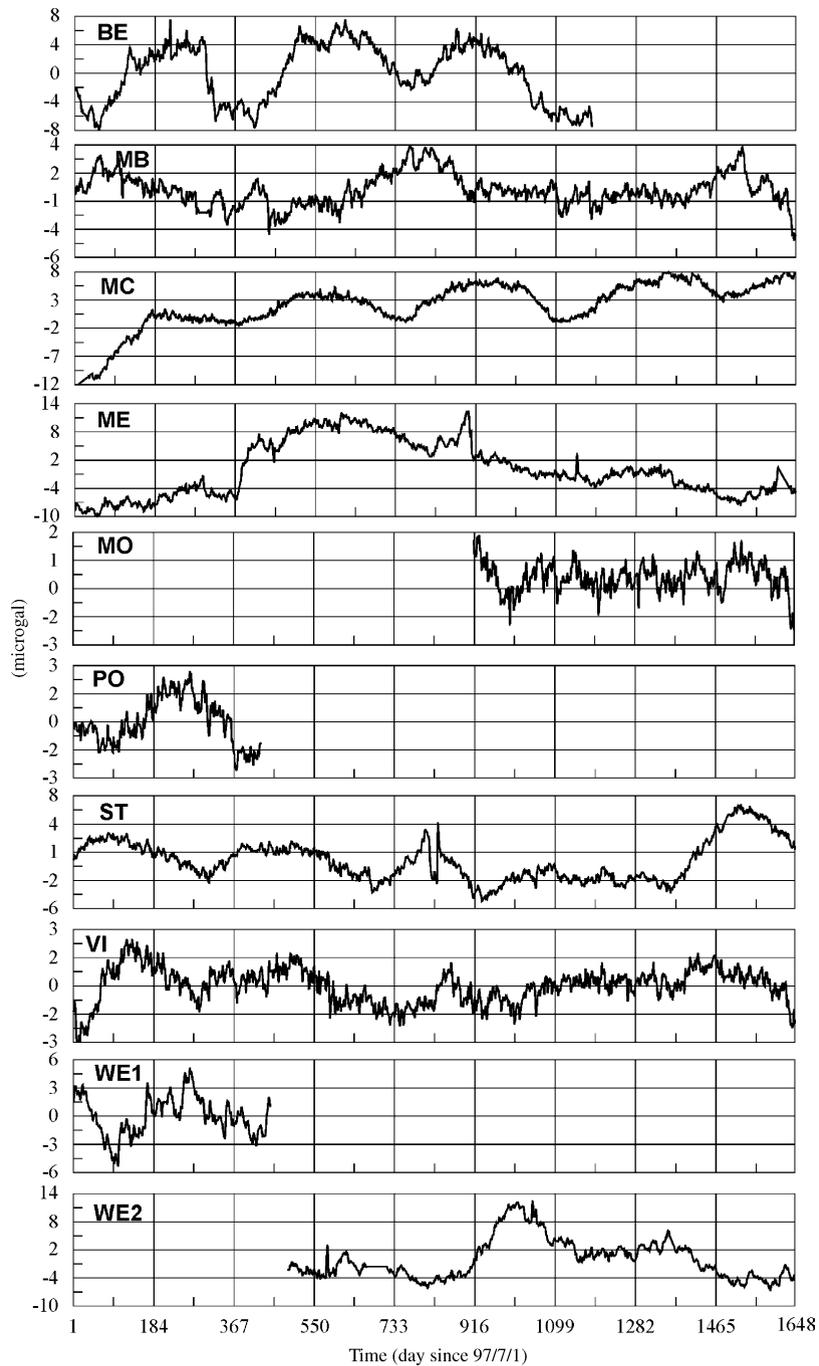


Fig. 2. Gravity residuals after removal of tides, local pressure, offsets, drift, and polar motion. Note the different scales of each data set; also station WE was occupied by two different instruments.

It is important to pay attention to the correction of instrumental origin and other offsets that occur in such data. At some stations, offsets are relatively rare and usually tied to known disturbances, e.g. helium refills, whereas other stations may have frequent offsets due to cultural effects, instrument glitches and power supply problems (due for instance to lightning strikes). For a general discussion, see e.g. [Hinderer et al. \(2002\)](#). Many offsets are easy to identify and to remove when their cause is well known. Others may be small and difficult to attribute to a known cause, or are due to unusual geophysical effects (such as shoveling snow from the roof of the station; [Virtanen, 2000](#)). The most difficult problem to correct is a gap in the data of several days or more, during which an offset could be ignored or wrongly assumed and corrected. Most of the sites are monitored with absolute gravimeters that help greatly in identifying instrument drift and potential offsets. The problem of disturbance and offset correction is the most time-consuming and delicate part of the processing.

Absolute gravimeters are also the most common method for amplitude calibration of SGs (see e.g. [Imanishi et al., 2002](#)). Also, where possible, it is much better to make an experimental determination of the phase calibration ([Richter and Wenzel, 1991](#); [Van Camp et al., 2000](#)) than to estimate the system time delay using specifications for the GWR anti-aliasing filter. Errors in either type of calibration (0.5% in amplitude and about 5 s in time) will have little impact on the results of our study.

The secular trend of the gravity field is obviously important in many long-term studies, but here we decide to ignore this effect and concentrate instead on seasonal fluctuations. SG drift needs to be verified by simultaneous measurement with an absolute gravimeter; and the drift rates of the latest compact instruments (prefix CO in [Table 1](#)) are between 1 and 4 microgal/year. We simultaneously remove offsets and a linear drift function for each station (taken as constant for the whole time period of each instrument), as these effects interact with each other. We show in [Fig. 2](#), the residual gravity after the above corrections, filtered to 1-day samples. Note the breaks in the series of stations BE, MO, PO and WE and that station WE was occupied by two different instruments, the older one with a large negative drift ([Crossley et al., 2003](#)).

3. Further atmospheric corrections

As mentioned above, we have removed a nominal local atmospheric loading and attraction using a single admittance between gravity and atmospheric pressure at each station. This is known to account for up to 90% of the total atmospheric effect, but can be improved by moving to a global atmospheric pressure field with various assumptions about its vertical structure (e.g. [Sun et al., 1995](#); [Boy et al., 2002](#)). For example, one can specify either (a) surface pressure or (b) surface pressure and temperature with a hydrostatic vertical structure based on the ideal gas law ([Merriam, 1992](#)). In this study, we use method (b), with NCEP (National Centers for Environmental Predictions) reanalysis data ([Kalnay et al., 1996](#)). [Boy and Chao \(2002, 2003\)](#) have shown that for the processing of GRACE data, a calculation using a fully 3-D model is a further improvement, but requires atmospheric pressure, temperature and humidity data as functions of altitude. This approach is numerically intensive, and requires more recent and more precise atmospheric datasets such as NCEP or ECMWF (European Centre for Medium-range Weather Forecasts). Because this approach can introduce differences in the seasonal zonal coefficients of about 10%, it will be required when seeking the most precise atmospheric corrections to satellite and ground gravity data.

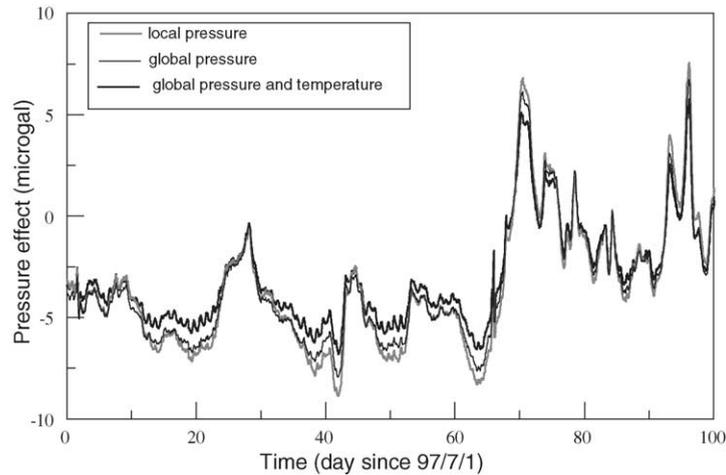


Fig. 3. Atmospheric loading effect and attraction for station ME using different assumptions for the atmospheric pressure (local pressure, global pressure, and global pressure with surface temperature). Data for only the first 100 days are shown.

Fig. 3 shows the differences between local air pressure loading and the differences introduced using methods (a) and (b) for station ME, which has the largest atmospheric loading of all the stations. The differences reach up to 1–2 microgal over short intervals of several weeks, but there are no long-term differences that would lead to a seasonal or annual signal. Gravity observations are also affected by vertical mass motions in the atmosphere that are caused by thermal effects and are not detectable in ground pressure data (Simon, 2002). In the case of the Medicina station, where data from 12 h radio balloon soundings was available, these annual effects were found to be less than a microgal (Zerbini et al., 2001).

After application of the respective corrections for loading and attraction effects, the final gravity residuals are shown in Fig. 4. We have filtered these to 15-day averages and plotted them to the same scale. Note that the amplitudes of stations ME and WE are significantly higher than those of the rest (also evident in Fig. 2), but other stations such as MO and VI have little variation over the data period. Although correlations obviously exist between the residuals at certain stations, the overall pattern is unclear because there is no account taken of station location, so this display is of limited use for regional interpretation.

4. EOF analysis of gravity

We need to spatially average the data to bring out possible large-scale regional variations, however, with only eight stations it is not possible to estimate reliable global spherical harmonics of the gravity field. Instead, we first interpolate the residual to a uniform rectangular x – y grid (longitude/latitude) using a minimum curvature algorithm. This provides the smoothest possible surface passing through all the data points and generates sufficient data for contour maps. We chose a grid of 161×129 points (increments of 0.1° in latitude and longitude) that stretches the map dimensions by some small factor in the x direction.

In previous work (Crossley and Hinderer, 2002; Crossley et al., 2003), we used a polynomial smoothing method to estimate a regional average of the data, but here we use the more objective empirical orthogonal

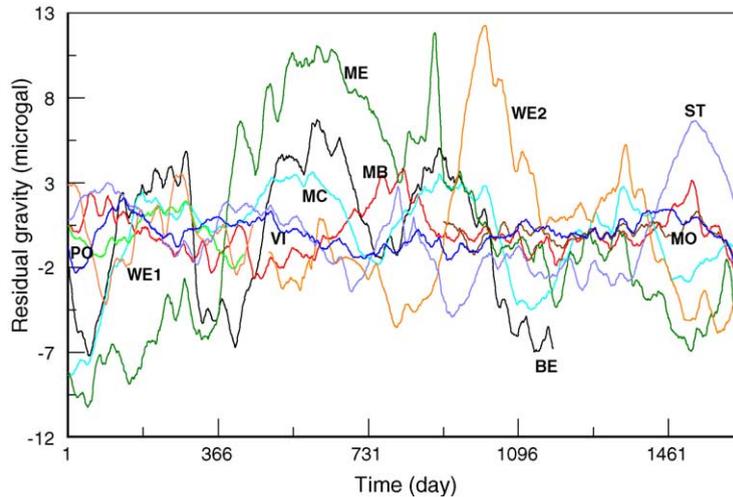


Fig. 4. Smoothed (15-day filter) gravity residuals from Fig. 2 after global pressure with surface temperature atmospheric correction, plotted to same scale.

function (EOF) method (Crossley et al., 2004). This technique has been widely used in finding the dominant spatial and temporal patterns in oceanographic and atmospheric data sets (e.g. Wilkes, 1995). The advantage of the method is that spatial and temporal variations are estimated simultaneously by performing a singular value decomposition (SVD) of the data, and that the dominant modes are easily recognized. When sorted from largest to smallest, these singular values (or eigenvalues) are associated with eigenvectors that represent the dominant spatial variability of the data, and principal components (vectors) that represent the time variability of the data. Computer code for the SVD technique is widely available; a convenient program that we used directly on our data is given by Pierce (2003).

As indicated above, we decimated the data in Fig. 4 to 15-day intervals, and fitted a minimum curvature surface at each interval. Then, each 2-D map (20,769 values) was packed into rows of a system matrix A , and each of the $nt = 110$ columns represents a different time interval. The SVD of $A = U\Lambda V^T$, where each column of U is an eigenvector that can be unpacked to give a 2-D (161×129) spatial map, and each column of V ($nt \times nt$) represents the time evolution of the corresponding eigenvector in U . The matrix Λ is diagonal with p principal values of which only the first few ($p \ll nt$) are generally significant. By ignoring the smaller eigenvalues, the dimensions of U , Λ and V are drastically reduced, thus leading to an efficient representation of the data.

The first few eigenvalues of the data appear in Fig. 5, showing a typically rapid decrease in value. For our problem, we need to consider eigenvalues only up to $p = 4$, the rest being small to negligible. An important criterion for selecting the cut-off is the variance reduction in the data; we found the first four eigenvalues give a cumulative variance reduction of 96%—meaning all but 4% of the entire data set can be represented by four eigenvector maps and four scalar time series. The results are shown in Fig. 6, where (a)–(d) are associated with the four largest eigenvalues. The first eigenvector, which is the dominant spatial pattern of the gravity field, shows that station BE is highly anomalous, being of opposite phase to its neighbor MB and the other northern group of stations. Station MC in the south is significantly less anomalous than BE, whereas the other stations are predominantly coherent.

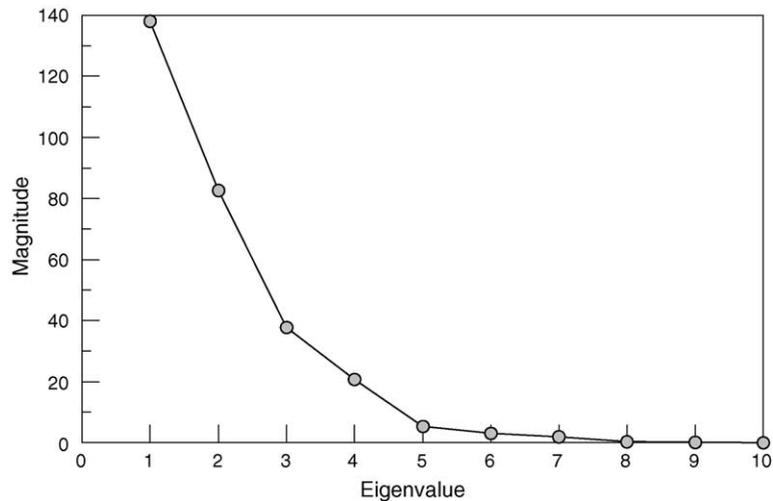


Fig. 5. Largest 10 eigenvalues of the EOF analysis of the gravity data, arbitrary units.

We may explain this pattern by noting that station BE is generally acknowledged to be the least reliable of this sub-network, being one of the earliest SG sites with an early type of the GWR full-size gravimeter that had no helium compressor. It was also subject to high cultural noise in the heart of the city of Brussels. The nearby station MB has a newer, compact, lower-noise type that is sited in a mine; therefore, the data is known to be much better. Station BE has now been closed and will no longer be in the network; we comment that in retrospect it may have been better to omit this station entirely from the analysis and rely on station MB for this part of the European gravity field. Station MC may be less coherent with the other stations due to its location on the southern side of the Alps. Mode 2 (Fig. 6b) shows that WE is anomalous within the central group of stations, and it is known that there are strong local groundwater effects at this station (Richter, personal communication). Modes 3 and 4 (Fig. 6c and d) are of much less influence (because their eigenvalues are smaller, Fig. 5) and they show more of the individual station anomalies.

Fig. 7 shows the first two principal components, i.e. the time variation of eigenvectors 1 and 2, again in arbitrary units. A clear annual signal dominates mode 1, with smaller 2-year and 6-month peaks (Fig. 8), and mode 2 also shows a 2-year peak. With only 4.5 years of data, the 2-year periodicity is questionable, but not the strong annual component. The peak at 6 months could be due to a residual tidal effect.

Part of the benefit of the SVD is that it allows an efficient representation of the whole gravity field. Fig. 9 shows a reconstruction of the gravity field for the first day of the data using 1, 2, and 4 modes (Fig. 9b–d, respectively), compared to the original ‘data’ (i.e. interpolated) in Fig. 9a. To obtain the reconstructed data, it is necessary to merely multiply the appropriate columns of U and V (because they are normalized by the eigenvalues), and this yields the field values in microgal. Fig. 9a and d are very similar, demonstrating the efficiency of the representation with only four modes (from a total of 110). Of course, we have a relatively simple data set derived from only eight stations, so this result is not too surprising.

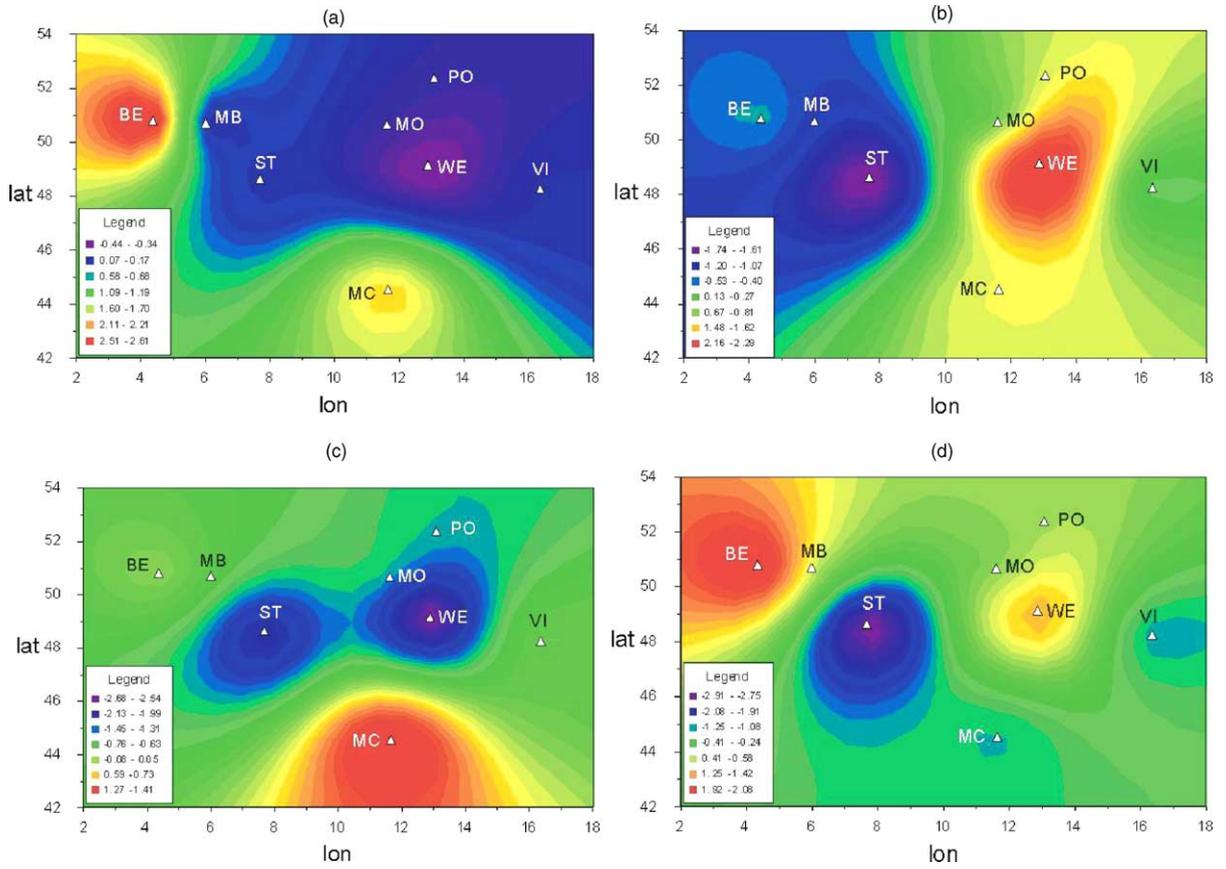


Fig. 6. The four largest EOF eigenvectors (out of a total of 110): (a) 47% variance reduction, (b) 28% variance reduction, (c) 13% variance reduction, and (d) 7% variance reduction. Units are arbitrary; see text for discussion.

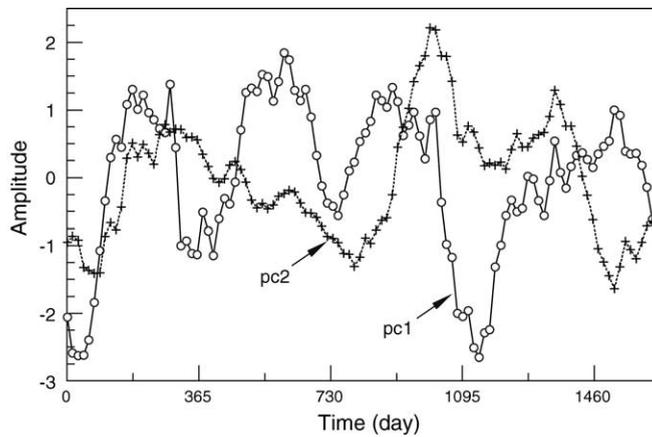


Fig. 7. EOF principal components associated with the two largest eigenvalues; pc1: first, pc2: second; arbitrary units.

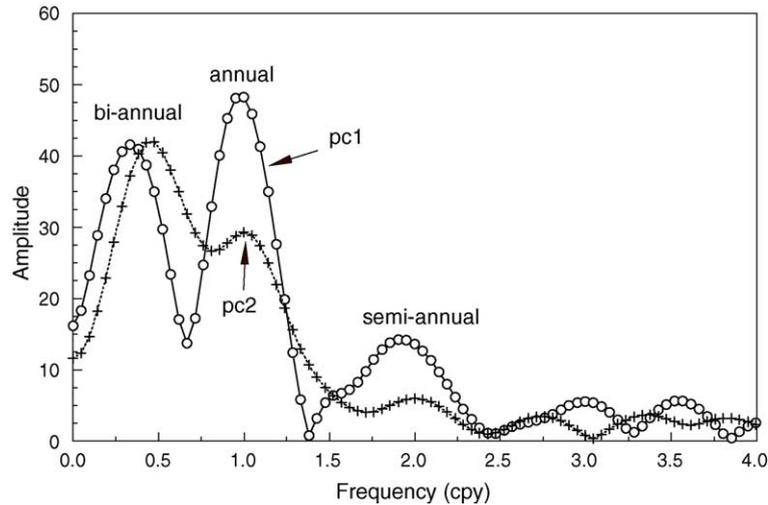


Fig. 8. Spectra of the two principal components shown in Fig. 7, arbitrary units. Note the strong annual term in pc1.

5. Hydrology

So far in the corrections, we have not allowed for effects due to local hydrology, arguing that effects confined to one station should in principle be smoothed out when averaged over distances of several 100 km. This is not a very good assumption unless we have sufficient stations to do a proper average, but in any case a regional gravity field (scales of 100 km) should reveal more of the coherent continental-size changes than individual stations. An additional problem comes from the fact that local and continental hydrological effects might be correlated because the external climate forcing is the same (e.g. rainfall; see Llubes et al. (2004), this issue).

The common practice of using local water table changes to derive a hydrology admittance (e.g. Crossley et al., 1998; Harnisch and Harnisch, 1999; Kroner, 2001; Takemoto et al., 2002; Virtanen, 2001), will remove both local effect and continental-size effect at the same time. This is particularly true if both have annual components, and this will defeat the purpose of our study. We choose, therefore, not to correct for the effects of local hydrology in this study. The downside of this assumption is that there may be different effects at each site (not necessarily continental hydrology) that just happen to have similar seasonal variations. Clearly a better strategy would be to use a much larger number of stations, but that is currently impossible. A satellite will naturally do the ideal spatial averaging over all hydrological effects (see Rodell and Famiglietti, 1999). We also note that it is, by no means, certain that hydrology is the only remaining long-term signal in the data. It is possible, for example, that the annual tidal response is not exactly described by nominal tidal factors, or that other effects, as noted in the next section, may be important.

The principal component of the first eigenmode (Fig. 7a) shows a clear annual signal with peak gravity values in the winter and low values in mid-summer (except for the last year, i.e. 2001). Obviously, this could be due to the annual climate cycle with a loss in soil moisture and thinning of the water table in summer. We, therefore, computed the climate-induced hydrology (soil moisture and snow) variations at the nine GGP stations using the model of Milly and Shmakin (2002a, 2002b), in which a realistic

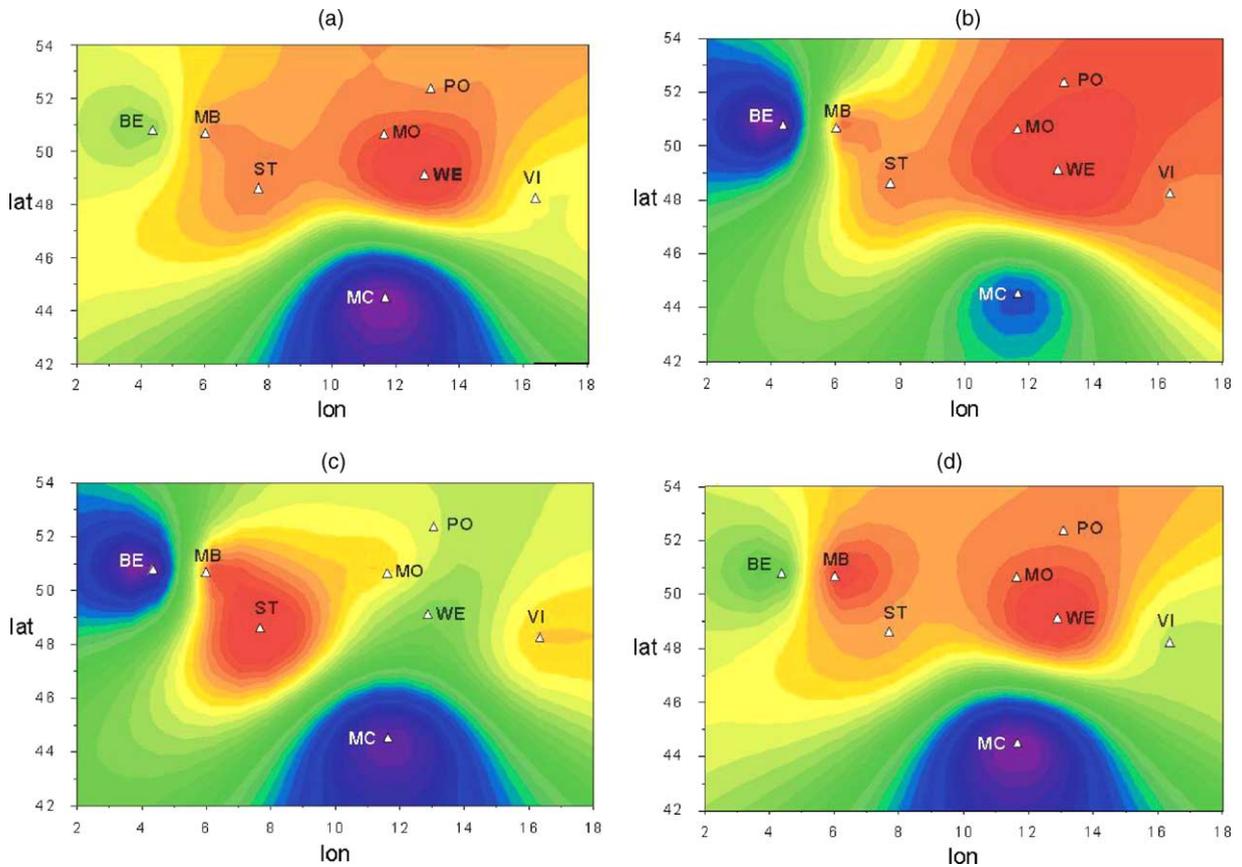


Fig. 9. Interpolated gravity (in microgal) for day 1 (97/7/1) of the analysis. Panel (a) shows the original data, the other plots show reconstructions using (b) one eigenvalue, (c) two eigenvalues, and (d) four eigenvalues, respectively.

land hydrology system is driven by observed climate parameters (temperature, rainfall, etc.). Because of some limitations of the model over permanent ice covered areas, we removed, from the monthly one degree by one degree soil moisture and snow input solutions, Greenland, Antarctica and glaciers (van Dam et al., 2001b). The effects of snow cover (Fig. 10a) and soil moisture (Fig. 10b) are computed separately, the former showing that station VI has an anomalously high response to snowfall, and station ME has an anomalously low response to soil moisture. These anomalies are present in the model of Milly and Shmakin, and we have not investigated their causes at this time. These anomalous effects will not significantly affect our results because we do not use ME in our conclusions, and the VI snowfall is still less than the soil moisture value. The sum of the two effects is shown in Fig. 11a and the mean of all stations in Fig. 11b. Note that the total is dominated by soil moisture for all stations except VI, and that all other stations are more or less comparable. The mean signal (in microgal) is remarkably similar to the first gravity mode (Fig. 7a), containing a strong annual signal with a peak each winter. We return to this comparison later.

The hydrology effect was also computed for a grid covering the whole of Western Europe, not just at the nine GGP gravity sites. It is, therefore, possible to do an EOF analysis of the whole data set,

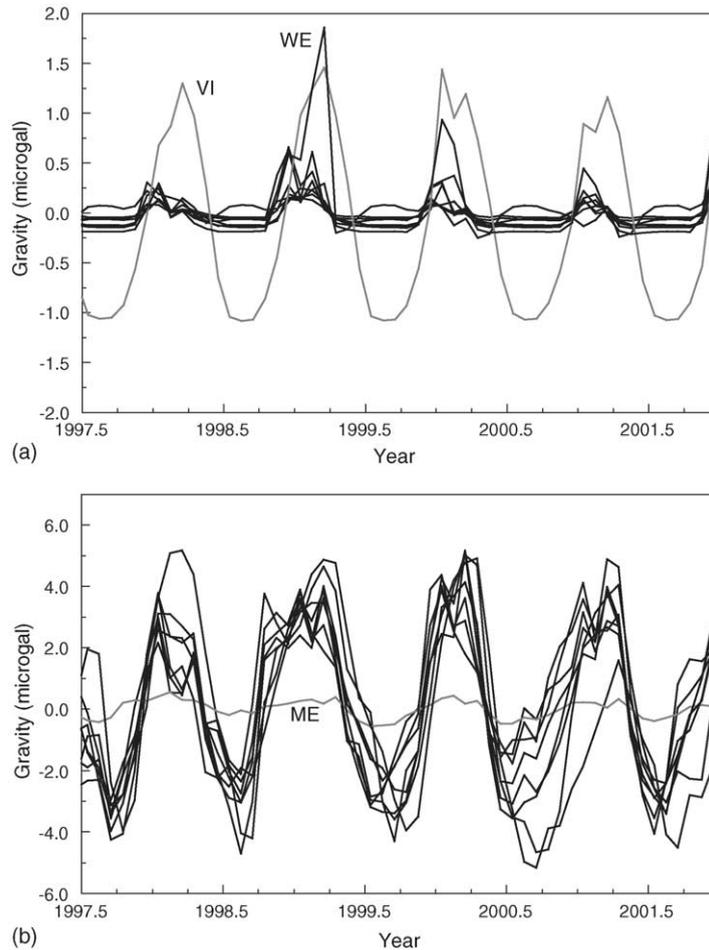


Fig. 10. Loading and attraction at nine GGP stations for the model of Milly and Shmakin (2002a, 2002b); effect of (a) snow, and (b) soil moisture.

concentrating on the first principal mode and its time variation (Fig. 12). The first eigenvector presented, in the upper panel, shows that the hydrology effect is relatively uniform over northern central Europe, with a small high in central Germany (MO), and a larger high in southern Europe (MC). Some of the coastal regions have a low hydrology signal. The first principal component, in the lower panel, is very similar to the mean hydrology effect in Fig. 11b, and this is partly due to the high spatial coherence (mode 1 explains 75% of the variance).

We also explored the effect of limiting the EOF hydrology analysis to the eight stations in central Europe, as for the gravity. We took the hydrology series, fitted a minimum curvature surface, and proceeded as for gravity. The first eigenvector is shown in Fig. 13, with an extremely high 91% of residual variance explained. The pattern is similar to the more detailed analysis in Fig. 12, with station MC showing the highest anomaly. Note that in the hydrology we do not see any conflict between stations BE and MB in central Belgium, because in the gravity we argued this was of instrumental origin.

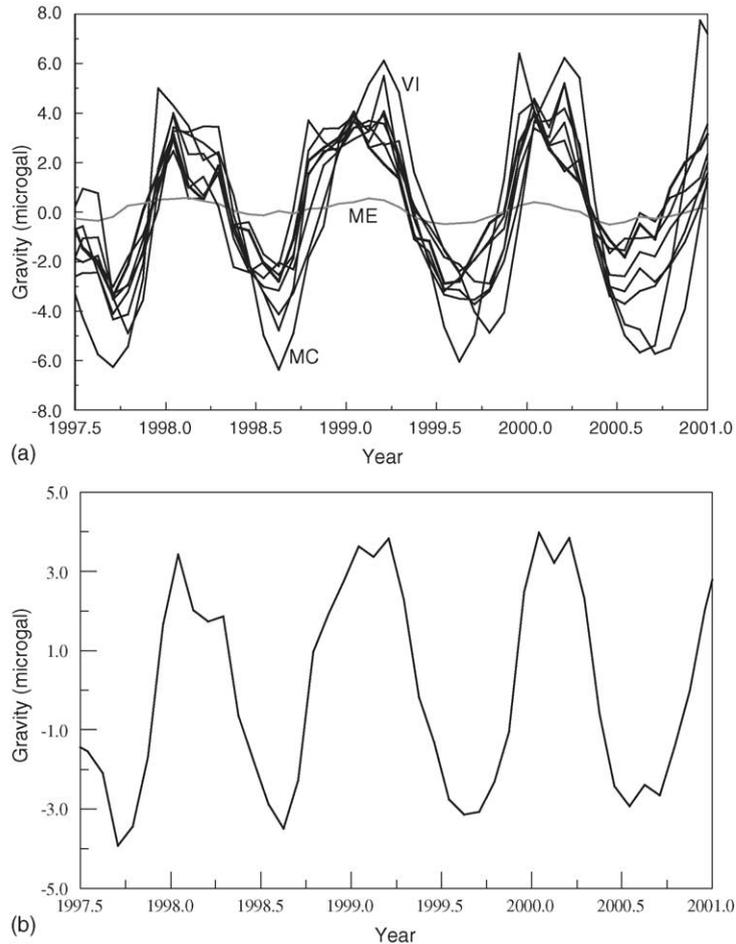


Fig. 11. (a) Combined loading and attraction from Fig. 10.b) Mean of all stations showing a clear annual signal; units in microgal.

Our hydrology signal is similar to that predicted earlier by Van Dam et al. (2001a) who found annual changes of 2–3 microgal for the European GGP stations. Van Dam et al. (2001a) also showed that at some of the other GGP stations (e.g. Bandung, Indonesia) the annual signals from continental hydrology could be as large as 10 microgal.

6. Discussion

We finally compare the first principal component of the hydrology model, associated with the eigenvector in Fig. 13, with the first principal component of the gravity from Fig. 7a; both are shown in Fig. 14. We caution that the amplitudes of these series are not at all related; they have been scaled only for convenience. Nevertheless, the agreement is persuasive, except for the final year where the gravity departs from its usual pattern, and the hydrology does not. We have no immediate

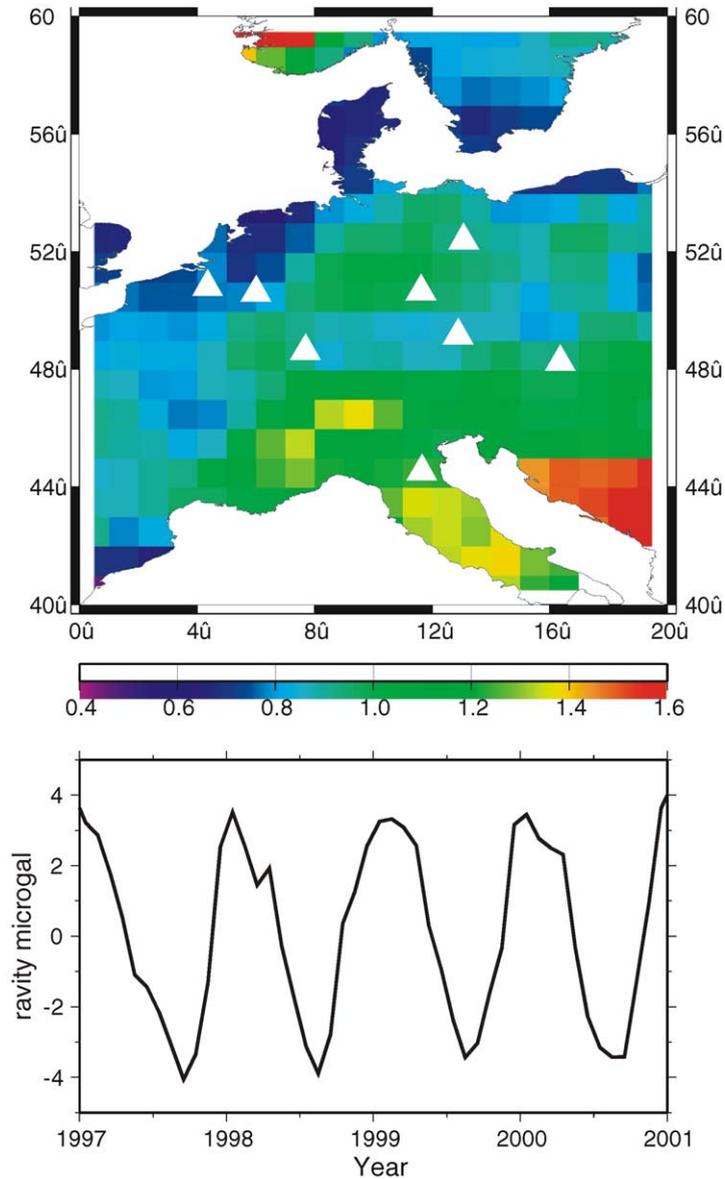


Fig. 12. EOF analysis of hydrology loading model for Western Europe. GGP Stations are shown as white triangles. Upper panel shows first eigenvector (75% variance reduction), lower panel shows first principal component with a clear annual signal.

suggestion for this part of the time series. Both series show some evidence of a double peak in the winter.

The agreement does not prove a causal relationship between hydrology and gravity, because there are other seasonal signals we have to consider. One possibility is the effect of a fully 3-D atmospheric model that is more realistic than the pseudo 3-D model we have used here (see the discussion in Section 3, above). As noted earlier, this can cause a measurable seasonal signal in gravity.

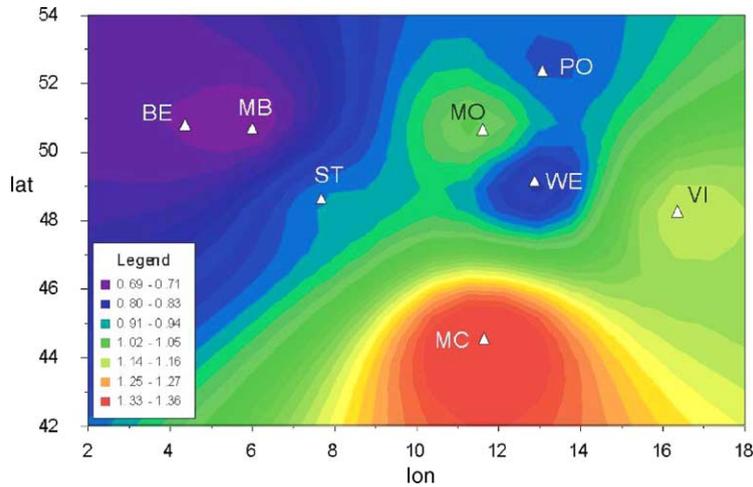


Fig. 13. First EOF eigenvector for the hydrology model using only the eight GGP stations in central Europe, 91% variance reduction; arbitrary units.

Another possibility may be due to changes in station elevations, due for example to atmospheric mass motions, that will contribute to an elevation effect in gravity but are not taken into account in the hydrology model. Such a signal, that can be observed directly by DORIS or GPS (Mangiarotti et al., 2001; Dong et al., 2002), has a vertical annual amplitude typically less than 1 cm which would lead to geometrically-induced gravity changes less than 3 microgal using the classical free air conversion factor. This effect cannot be neglected and needs to be removed from surface gravity data before comparison with satellite data because a satellite does not respond to elevation changes, but only to the total gravitational potential.

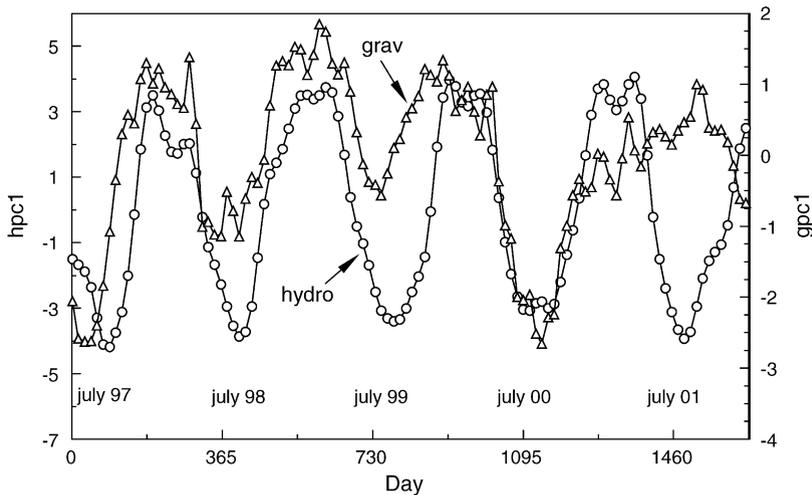


Fig. 14. Comparison of the first principal component of the EOF analyses of the gravity (gpc1) and hydrology (hpc1) using eight central GGP stations. Note that the scales are independent.

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