GRACE 327-750
(GR-GFZ-AOD-0001)

Gravity Recovery and Climate Experiment

AOD1B Product Description Document
for Product Releases 01 to 04

(Rev. 3.1, April 13, 2007)

Frank Flechtner
GeoForschungszentrum Potsdam
Department 1: Geodesy and Remote Sensing

Prepared by:

Frank Flechtner, GFZ
GRACE Deputy Science Operations Manager

Contact Information:
GeoForschungsZentrum Potsdam
Department 1: Geodesy and Remote Sensing
C/o DLR Oberpffaenhofen
D-82234 Wessling
Germany
Email: flechtne@gfz-potsdam.de

Reviewed by:

Srinivas Bettadpur, UTCSR, GRACE Science Operations Manager

Maik Thomas, TU Dresden, GRACE Science Team Member

Tatyana Pekker, UTCSR

Approved by:

Byron D. Tapley, UTCSR
GRACE Principal Investigator

Christoph Reigber, GFZ
GRACE Co-Principal Investigator

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Document Change

Issue	Date	Pages	Description of Change
Draft	22.09.2003	all	First version
1.0	22.10.2003	all	Included GRACE project comments on draft version
2.0	20.09.2005	6	Added changes w.r.t release 03 (substitution of the barotropic ocean model PPHA by the baroclinic model OMCT)
		7	Updated description of the necessary ECMWF forcing fields
		16	Added description of OMCT model to chapter 2.2.3
		21	Added processing strategy of OMCT to chapter 3.1
		28	Updated chapter 3.3 on mean fields
		32	Defined new chapter 4 (Available Releases)
		33	Updated chapter 5 (Validation of AOD product)
		37	Chapter 6.2: Added remark that OCN1B read s/w is available at the archives
		39	Added OMCT references to Chapter 7
		40	Updated Chapter 8 (Abbreviations)
			Deleted appendix
2.1	04.11.2005	22	Corrected explanation to equation 3-3
		23	Corrected explanation to equation 3-5
		25	Corrected first sentence after figure 3-3
		26	Corrected explanation to equation 3-20
		27	Corrected last sentence of 3.2.2.1
2.2	26.04.2006	32	Updated RL03 availability period
		33	Changed title of Chapter 5 and included recommendation for TN04
		34	Changed title of Chapter 6
		36	Added comment on OCN1B availability
		38	Included new Chapter 7 "Average of AOD1B products: GAA, GAB and GAC"
3.0	23.02.2007		Included RL04 relevant issues in Chapters 4-7, added clarification and recommendation on use of different products
3.1	13.04.2007		Added clarifications in Chapter 6 and 7 for AOD1B "oba" data type and GAD products

1 Introduction

GRACE data processing requires the removal of short term mass variations in the atmosphere and in the oceans because these mass changes cause time variant gravity field forces acting on the orbiting satellites. These time varying forces have to be taken into account during data processing, if they are not eliminated by repeated observations within short periods. Due to the mission profile of GRACE (and also the CHAMP and GOCE missions) this generally is not the case. Therefore, the effect has to be removed prior to or during the gravity field determination process. For computing these time variations in the gravity field mainly external data sources have to be used.

The following sources for gravity field variations are known:

- High frequency variation sources: Tides (improved tide models are necessary for all missions); Atmosphere; Oceans; Continental water (snow, ice, hydrology).
- Seasonal variation sources: Atmosphere; Oceans; Continental water; Ice mass

For GRACE data processing only the short term variations are of importance, because with the monthly GRACE gravity field solutions it is planned to provide data for determination of the seasonal variations.

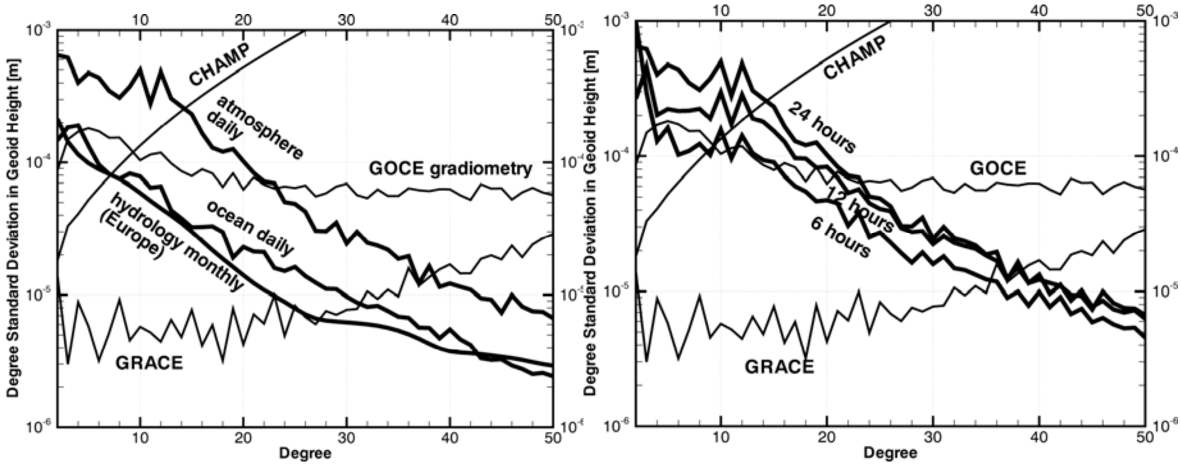

Figure 1-1: Gravity variation signals from different sources in different time scales compared to mission sensitivities (from left to right): a) Comparison of daily atmosphere, daily oceanic and monthly hydrological signals. b) Comparison of 6, 12 and 24 hourly ECMWF signals.

Figure 1-1 shows the effect of some of these mass variations in the gravity field in terms of degree standard deviations in comparison to the expected performance of the three gravity field missions. It clearly becomes visible, that the high frequency mass variations in the atmosphere have impact to all three gravity missions and therefore have to be reduced very carefully. It also becomes visible, that high frequency mass variations in the oceans are much smaller than in the atmosphere, but still have impact on CHAMP and GRACE observations. Because the GOCE gradiometer measures second derivatives of the gravity potential, the sensitivity of the gradiometer to long wavelength mass variations is much smaller. But, as GOCE also carries a GPS receiver, a similar error spectrum as for CHAMP can be expected for the long wavelengths. This means, when combining high-low SST and gradiometer observations of GOCE also oceanic mass variations have impact on the GOCE solution. A similar signal is visible from the monthly hydrology signal over Europe (precipitation minus evaporation). GRACE will detect this long wavelength signal by computing monthly gravity models and comparing them in their sequence of time. It becomes clear, that these monthly variations in the continental water have impact on GOCE, because there are no observations over a full year. Similar signals are caused by seasonal variations in the atmosphere and the oceans. Consequently the monthly GRACE gravity field solutions have to be used for removing this so-called seasonal bias from the GOCE observations.

The document describes in chapter 2 the used meteorological input data and the ocean models used in release 01 and 02 (barotropic model provided by Victor Zlotnicky (JPL) and implemented at GFZ Potsdam) and release 03 and release 04, respectively (baroclinic model operated at Technical University of Dresden). Because the AOD1B (atmosphere and ocean de-aliasing level-1b) product has to be provided to the GRACE Science Data System within 11 days for level-2 gravity field processing the input meteorological data have to be acquired on a routine basis within a short time interval. Therefore GFZ has signed a contract with the German Weather Service (DWD) to regularly acquire the necessary ECMWF fields. ECMWF surface pressure data have been compared with sample NCEP reanalysis and DWD global model surface pressure fields to investigate the influence of data sets of different weather services on the calculated geoid variation.

In chapter 3 the processing strategy to derive atmospheric and oceanic geoid height changes is described. For the atmosphere two mathematical approaches have been investigated. A simplified formula immediately transforms the surface pressure to spherical harmonic gravity coefficients by spherical harmonic analysis of a single layer on the Earth surface (up to degree and order 100). A more complicated, but physically correct approach, performs the vertical integration of the atmospheric density and computes then the gravity coefficients by spherical harmonic analysis. The mean atmosphere and ocean fields needed to derive residual mass variations are described as well as the combination of the atmospheric and oceanic contributions. Because presently no global hydrological models with sufficient accuracy and resolution are available, corresponding short-term variations due to continental water redistribution are not considered here.

Chapter 4 describes some statistical output derived during the generation of the AOD1B product. In chapter 5 the formats of the AOD1B and OCN1B (output from the barotropic or baroclinic model runs) products are explained. The document is supplemented by a list of references and abbreviations.

Acknowledgements

Special thanks to Tatiana Pekker (UTCSR) for her constructive contributions on vertical integration of the atmosphere and to my former colleague Thomas Gruber (now TU Munich) who developed the coarse processing strategy and main components of the de-aliasing software package.

Additionally I want to thank Ahmed Ali (JPL) for his support installing the JPL barotropic ocean model on GFZ Sun hardware. Last but not least many thanks to Victor Zlotnicki (JPL) for his advice to combine the barotropic ocean model output with atmospheric pressure variations and the intensive discussions during the past 2 years.

Special thanks to Maik Thomas and Henryk Dobslaw (TU Dresden) who provided the baroclinic ocean model output grids and helped to install the software and operational interfaces to the AOD software package.

2 Input Data and Models

For the calculation of the GRACE Level-1B de-aliasing AOD1B product different atmospheric fields and a ocean model are required. In the following chapters the input data and the ocean model are described.

2.1 Atmospheric Data

For the de-aliasing analysis atmospheric data from 3 different Numerical Weather Services are available: Deutscher Wetter Dienst (DWD), National Center for Environmental Predictions (NCEP) and European Center for Medium-range Weather Forecast (ECMWF). The required fields for this analysis shall be available with a spatial resolution of 0.5° and a temporal resolution of 6 hours. While the ECMWF fields fulfill this requirements, the DWD and NCEP fields are only available at GFZ for dedicated time periods (days to weeks) and have a lower spatial resolution (0.75° resp. 2.5°).

GFZ regularly extracts operational analysis data at the ECMWF Integrated Forecast System (IFS) at synoptic times 0:00, 6:00, 12:00 and 18:00. Details on the used models can be found at http://www.ecmwf.int/research/ifsdocs/index.html. The spatial resolution is defined on a gaussian n160 grid which corresponds to 0.5°. The temperature and the specific humidity is given for 60 layers (surface up to 0.1 hpa). The necessary fields to perform the vertical integration of the atmosphere are

- Surface Pressure (PSFC)
- Multi-level Temperature (TEMP)
- Multi-level Specific Humidity (SHUM)
- Geopotential Heights at Surface (PHISFC)

and to run the barotropic ocean model PPHA

- Surface Pressure (PSFC)
- Wind Speed at 10m height in U and V direction (U10M, V10M)
- Sea Surface Temperature (SST)
- Dew Point Temperature at 2m level (TDEW2M)
- Temperature at 2m level (TEMP2M)

and are available at GFZ´s Information System and Data Center (ISDC) for the time span starting on July 1, 2000 until today.

To run the baroclinic ocean model the following ECMWF IFS data are acquired by TU Dresden (see also chapter 2.2.2):

- Wind Speed at 10m height in U and V direction (U10, V10)
- Temperature at 2m level (TEMP2M)
- Surface Pressure (PSFC)
- Freshwater fluxes deduced from precipitation minus evaporation (taken from operational forecasts) (PmE)
- Sea Surface Temperature (SST) (*)
- Specific Humidity (SHUM) (*)
- Temperature at 10m level (TEMP10M) (*)
- Charnock parameters (CHAR) (*)

(*): Necessary for the transformation to wind stress components τ_x, τ_y

2.1.1 Comparison of DWD, NCEP and ECMWF Surface Pressure Fields

To show the differences in geoid height variations some tests have been performed using surface pressure data from DWD, NCEP and ECMWF which are described below.

The following 3 figures represent the surface pressure for February 23, 2001 as derived from DWD, ECMWF and NCEP.

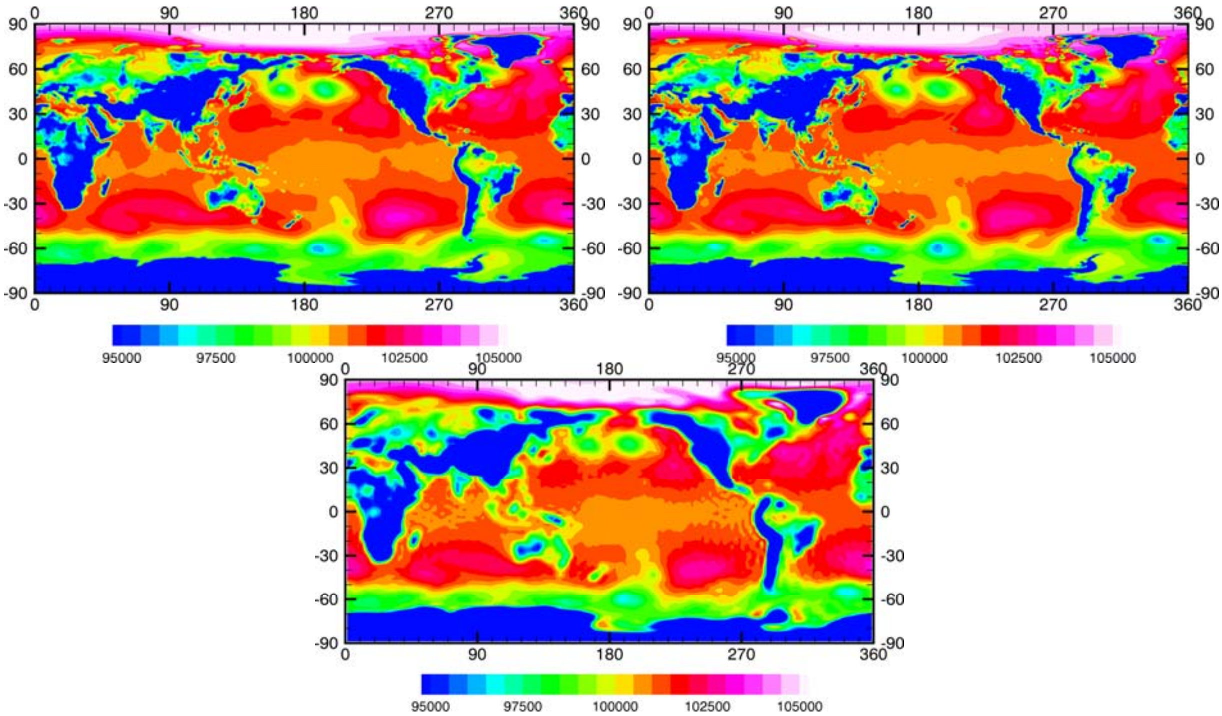

Figure 2-1: Surface pressure from 23. Feb. 2001, 00h: DWD (upper left) global model (resolution 45’), ECMWF (upper right) operational analysis (resolution 30’) and NCEP (lower middle) re-analysis (resolution 2.5 degree)

From these surface pressure fields for various time steps gravity field spherical harmonic coefficients are computed (without subtraction of the mean field). In order to identify the signal changes within 6, 12, 18 and 24 hours coefficient differences are plotted in terms of geoid height degree standard deviations. Further on these coefficients are translated into geoid height changes and differences of geoid height changes for the three atmospheric models for the four time steps.

2.1.2 Spherical harmonic coefficient differences for different time intervals

The lower signal of the NCEP re-analysis partly is caused by the lower resolution of the model with respect to both other models. But the main reason still is the smaller signal in the NCEP model.

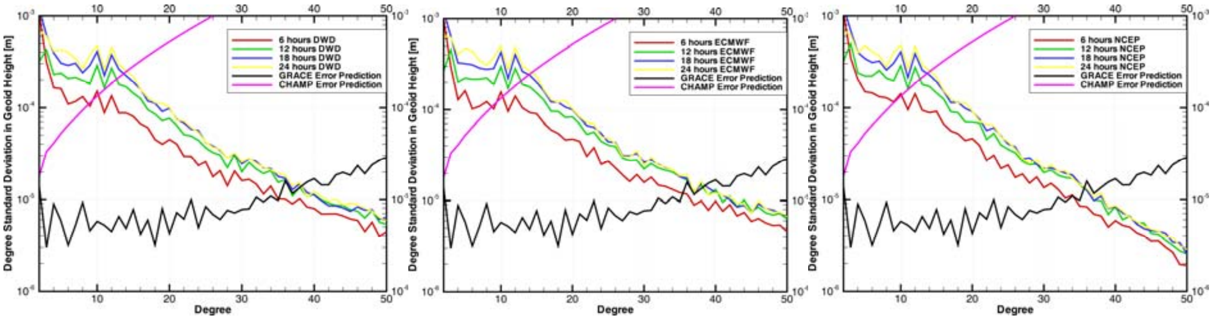

Figure 2-2 Gravity variations in terms of geoid height degree standard deviations with mission error predictions

2.1.3 Geoid height variation based on ECMWF surface pressure for different time intervals

The following figure shows the geoid height variation based on ECMWF operational analysis surface pressure data of February 23, 2001 for 6, 12, 18 and 24 hours respectively. The variation has been calculated by subtraction of a 2001 surface pressure mean field from the actual 6-hourly fields.

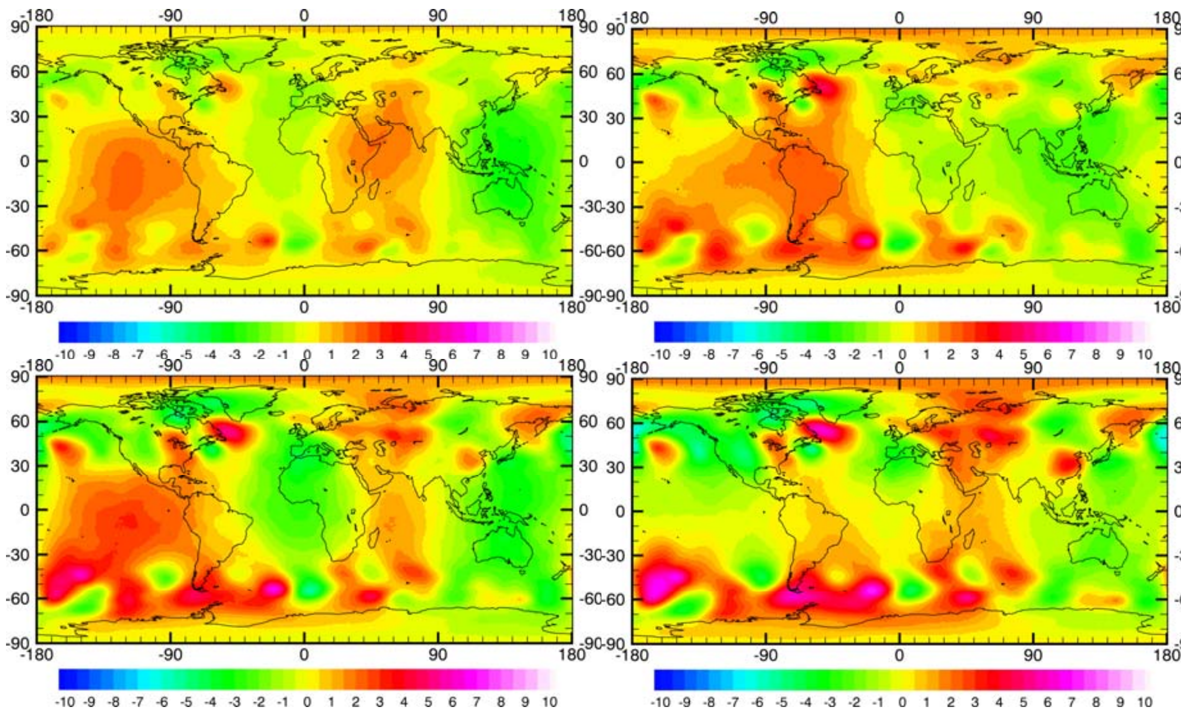

Figure 2-3: Geoid height variations for ECMWF operational analysis on February 23, 2001 (upper left: 6 hours, upper right 12 hours, lower left 18 hours, lower right 24 hours time difference, all in [mm])

2.1.4 Differences of geoid height variations for different time intervals and different atmospheric analysis centers

The following figures show the differences between geoid height variations for February 23, 2001 for 6, 12, 18 and 24 hours derived from ECMWF and DWD and ECMWF and DWD surface pressure data, respectively.

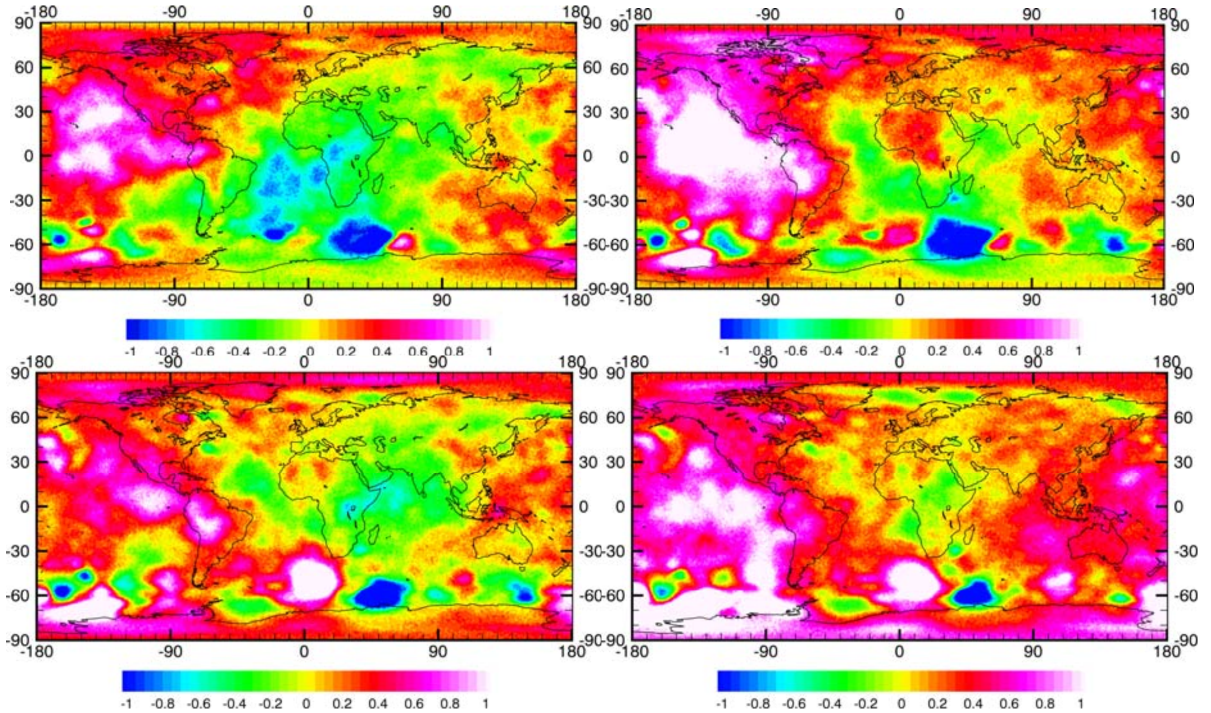

Figure 2-4: Differences of geoid height variations between DWD global model and ECMWF operational analysis on 23.Feb. 2001 (upper left: 6 hours, upper right 12 hours, lower left 18 hours, lower right 24 hours time difference, all in [mm])

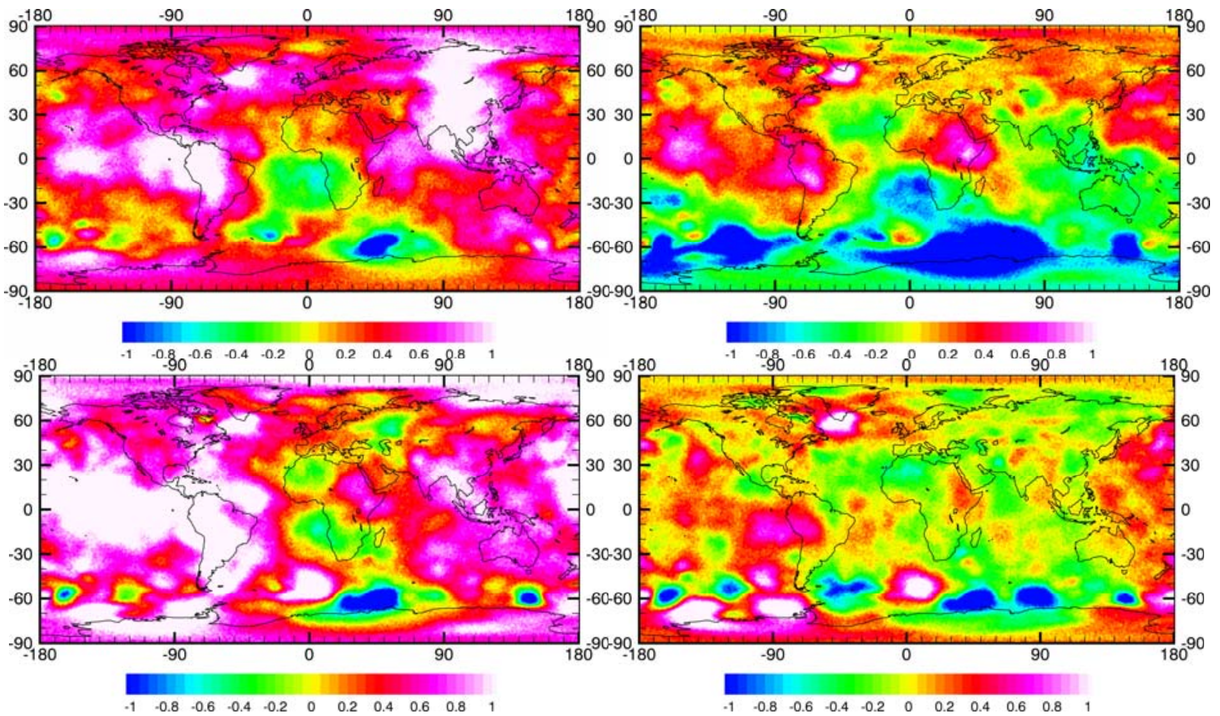

Figure 2-5: Differences of geoid height variations between NCEP re-analysis and ECMWF operational analysis on 23.Feb. 2001 (upper left: 6 hours, upper right 12 hours, lower left 18 hours, lower right 24 hours time difference, all in [mm])

2.2 Ocean Model

For the operational calculation of the atmosphere/ocean de-aliasing product a barotropic or baroclinic ocean model is required. A barotropic ocean model was provided to GFZ by JPL in July 2002, since beginning of 2005 also the output of a baroclinic ocean model is provided to GFZ by TU Dresden.

2.2.1 Barotropic Ocean Model PPHA

Some details which describe the model in more general terms are given in the following (courtesy by V. Zlotnicki, October 22, 2003). Further details can be found in (Ali and Zlotnicki, 2003) and (Ponte and Ali, 2002) which exactly used this ocean model implementation. Chapter 6 gives a list of related literature.

Chapter 3.1 describes the barotropic ocean model implementation and processing strategy at GFZ.

ALGORITHM TITLE: Barotropic Ocean Model for GRACE Dealising.

ALGORITHM NUMBER: (not assigned)

ALGORITHM VERSION: PPHA 1.1

HERITAGE: NONE.

PREPARED BY: Victor Zlotnicki <vz@pacific.jpl.nasa.gov>, 1-818-354-5519

LAST UPDATED: 2003-10-01

FUNCTION: This algorithm computes the component of oceanic mass redistribution due to wind and pressure, with periods between 1 day and approx. 60 days. The purpose is to remove the gravity effect of this mass signal from those measured by GRACE before combining data for several weeks to make a gravity field estimate. This minimizes aliasing of fast signals from the ocean (too fast to be properly sampled by GRACE) into the n-weekly gravity estimates. Note: ocean mass redistribution over similarly short timescales, but due to tidal forcing, are computed in another algorithm. It is intended that the output of this model over the oceans be combined with atmospheric mass distribution on land before converting to spherical harmonic mass distributions, and from there into gravity field coefficients.

THEORETICAL BASIS and NUMERICAL IMPLEMENTATION:

The ocean responds to atmospheric forcings (wind, pressure, evaporation minus precipitation, radiation fluxes). The ocean's response can be divided in two classes: barotropic and baroclinic. The barotropic component has non-zero vertical-average (velocity, pressure, etc); the baroclinic component is the rest (e.g., Gill, 1982).

Generally speaking, barotropic motions are fast (fraction of a day to a few weeks), and baroclinic motions slow (weeks to centuries). The tides are the best example of barotropic motion, even though they include a little baroclinic energy in special places. El Niño is a predominantly baroclinic phenomenon.
A barotropic numerical ocean model ('barotropic model' in what follows) is one in which the whole water column has a single density; it is only forced by wind and pressure. A baroclinic model includes vertical density changes (as the real ocean has) and their effects, and requires the additional forcings (E-P, radiation, etc) to handle thermodynamic effects. The barotropic component in the real ocean (and in baroclinic models) can be the result of energy conversion from baroclinic modes and thus will not necessarily be the same as one obtained from a barotropic model. A barotropic model is simpler, has fewer dubious parameterizations, and runs faster on a computer than a baroclinic model.

Tierney et al (2000) showed that the difference between barotropic and baroclinic models in terms of sea surface height change was negligible in a global average (< 0.1 mm of seawater) for periods shorter than 100 days, and at those short periods only noticeable in some steep topography regions.

Barotropic model. For this algorithm we have chosen to run the barotropic model originally coded by R. Pacanowski, modified and described by Ponte (1991, 1997, 1999), then modified by Hirose et al (2000), and more recently by A. Ali at JPL. The code is dubbed 'PPHA' after its various authors.

The model is a finite-differences implementation of a simplification of the Navier-Stokes equations for shallow water (thin shell) and constant vertical density. The equations it satisfies (modified from Ponte et al, 1991) with wind and pressure forcing are:

$$d_t u - 2\Omega v.\sin(\varphi) - \frac{uv.\tan(\varphi)}{a} = -\frac{g}{a.\cos(\varphi)}\partial_\lambda\left(\zeta + \frac{p_a}{\rho g}\right) - b\frac{u}{H} + \frac{\tau_\lambda}{\rho H} \quad (1a)$$

$$d_t v + 2\Omega u.\sin(\varphi) + \frac{u^2.\tan(\varphi)}{a} = -\frac{g}{a.\cos(\varphi)}\partial_\varphi\left(\zeta + \frac{p_a}{\rho g}\right) - b\frac{v}{H} + \frac{\tau_\varphi}{\rho H} \quad (1b)$$

$$\partial_t \varsigma + \frac{1}{a.\cos(\varphi)}\{\partial_\lambda[(H+\zeta)u] + \partial_\varphi[(H+\zeta)v.\cos(\varphi)]\} = 0 \quad (1c)$$

with d_t given by

$$d_t = \partial_t + \frac{u}{r.\cos(\varphi)}\partial_\lambda + \frac{v}{a}\partial_\varphi = 0 \quad (2)$$

where λ, φ are longitude and latitude; $\partial_t, \partial_\lambda, \partial_\varphi$ are partial derivatives with respect to time, longitude or latitude; u, v are the eastward and northward components of velocity; ζ is the sea level departure from rest; H is the depth of the sea floor to sea level at rest; p_a is atmospheric surface pressure; τ_λ, τ_ϕ are the eastward and northward components of wind stress; ρ is the density of seawater, assumed a constant 1040 kg m^{-3}; g is the Earth's gravity acceleration, assumed a constant 9.806 m s^{-2}; Ω and a are the Earth's angular velocity and average radius, both assumed constant. A generalized no-slip boundary conditions is applied on the side and bottom bathymetry boundaries (Hirose et al, 2001). The numerical implementation involves choices of differencing scheme (Arakawa c-grid), integration scheme (leapfrog), and many other important numerical details (Ponte et al., 1991; Ponte, 1997).

The specific parameters used in the integration are:

- Resolution: 1.125° x 1.125° in longitude and latitude
- Time step: 1 minute
- Coverage: global, 75°S to 65°N
- subsurface no-slip condition of Hirose et al (2001)
- fine topography: a 1.125deg average of ETOPO5. Depths greater than 6000, are set to 6000m to allow for the 1 min time step. Depths shallower than 50m are set to the land flag.
- optimized Rayleigh friction parameter: -bu/H, b=2 cm/s, from the fit to TOPEX data.
- forced by wind stress and sea level pressure from either ECMWF or NCEP models (see below, 'inputs').

Wind stress. The model requires **wind stress** at the surface as input. ECMWF and NCEP do no make this parameter available in operational models. Rather, they have wind at various pressure levels (1000 mbar is the lowest), and through a PBL (planetary boundary layer) model, they convert these to 10 m wind (wind

10 m above the surface). This 10 m wind needs to be converted to a wind **stress** before it can be used to force the model.

$$\tau = C_d(|\mathbf{U}|)\mathbf{U}|\mathbf{U}| \qquad (3)$$

where τ is the surface wind stress vector, **U** is the horizontal wind vector 10 m above the ocean surface (from ECMWF or NCEP), | | denotes magnitude, and C_d is a drag 'coefficient' with a weak dependence on the magnitude of **U** itself, as well as the stability of the boundary layer above the ocean. The conversion of wind to stress uses the stability-dependent formulation of Liu et al. (1979), discussed in Ali and Zlotnicki (2003)

Spinup. The model needs to be run with real wind and pressure forcing for at least 4 model months before operational output is desired, so as to minimize the effect of spinup transients. The code we use can be restarted from the model state of the last run so the spinup does not need to be rerun. Since we have been running it for 9+ model years at JPL, this is not a problem.

Sea Level, Ocean Bottom Pressure. The output of the finite-difference code is barotropic sea level in cm, and includes the effects of both wind and pressure forcing, so no assumption about 'inverted barometer' needs to be made. The above parameters and their effect on matching the model's output sea level to TOPEX/POSEIDON data are described in Hirose et al (2001) and in Ali et al (2000).

The sum of the model's output, multiplied by ρg to convert it to pressure in mbar, plus the atmospheric pressure at each grid point, is the pressure at the ocean's bottom, a quantity measured by bottom pressure recorders (although these are few and scattered, we have used them to spot-check the model's output).

$$p_B = p_A + \rho g\zeta + \rho gH = p_A + (1.004 \text{ mbar/cm\_seawater})(\zeta+H) \qquad (4)$$

where p_A is atmospheric pressure at sea level, p_B is ocean bottom pressure, ζ is the model's sealeavel (time-varying), H is the depth (time-invariant). All variables except ρg are functions of latitude and longitude. 1.004 mbar/cm_seawater assumes (a) that seawater density ρ= 1.040 g/cm^3; (b) that g=9.806 m/s^2. This 'ocean bottom pressure' quantity is the exact equivalent of atmospheric surface pressure over land (the overall 'weight' of the ocean and atmosphere above). If we used surface atmospheric pressure to dealias GRACE over land, then equation (4) would be used over the oceans.

Loading. This algorithm computes sea level relative to the ocean floor (ζ+H). It performs no spherical harmonic decomposition, and does not correct for elastic loading. It is expected that the output of this model be combined with the atmospheric output before Love loading coefficients are applied.

Time-mean. As pointed out by T. Gruber, it is necessary to remove a time-mean value from the atmospheric and oceanic fields to avoid several problems. Per email of S. Bettadpur (15 Oct 2001) we have agreed to remove a simple 1 year time-mean from both ocean and atmosphere, and maintain it fixed at least for the first year of GRACE. Note that sealevel ζ is defined as departure from *rest,* not from the time mean. It does have a time-mean circulation in it.

Output Filter. As opposed to atmospheric pressure from ECMWF or NCEP, which is reasonably accurate over both short and long periods, this model and its output, ζ, are known to be inaccurate at periods longer than 120 days or so, because of the barotropic approximation. However, the output does have energy at these longer periods because the wind and pressure forcing themselves change over long periods. Therefore it is necessary to filter out these incorrect, long period components from the output to avoid misinterpreting the resulting GRACE data.

This simple procedure has been agreed to for GRACE dealiasing: no time or frequency filter will be applied to the output of the ocean model. After the monthly-averaged gravity fields are computed and before being interpreted over the oceans (this is outside the GRACE ground system), they shall be converted to surface mass density anomalies expressed as cm of water height, and the monthly averaged ocean model output in terms of water height (which was removed from the GRACE data by the level 2 processing), shall be added back.

INPUT DATA:

Time varying:

- The end state output by the previous model run, which is used as initial state of the current run.
- tpemrun.inp, a parameter file output in the previous model run, and described in a separate readme file.

- Gridded U,V Wind (N and E) components, at 10m height
- Gridded Pressure at Sea Level.

Both the U,V wind and the P pressure are expected on a 1.125 degree grid, in GDF (Gitter Daten Format), at 00, 06, 12, 18 hours. As explained in previous sections, these fields are from the European Center for Medium Range Weather Forecast and have been acquired at GFZ as part of the GRACE ground system as described in previous sections.

Time invariant:

- whether the input is ECWMF or NCEP
- friction coefficient
- bathymetry file, interpolated to model grid
- a flag to indicate whether Kondo or LKB wind to stress conversion should be used.

PROCESSING STEPS:

The steps related to obtaining the ECMWF files, changing their format, resampling them to the 1.125 grid, etc. have been described in an earlier section.

As delivered to GFZ, the JPL executable completes two distinct steps internally:

Step 1: convert wind vector to wind stress using LKB algorithm, and outputs them in a format used in the next step

Step 2: restarts barotropic model from last saved state (24 hours earlier), and runs for 24 hours or longer, saving 1/hour grids. On termination, the last model state and last forcing fields are saved.

Processing time on a Cray J90 (nebula at JPL in 2001). is approx. 4 hrs per 6 month model run. A SUN ULTRA10 correctly ran at the rate of 1 model day in under 30 minutes (note that both are obsolete computers in 2003; the timing runs were performed in 2001)

OUTPUT:

The output includes the following files:

tpemrun_end.res: final model state and input to the next run

tpemrun.sl: total sea level height, from rest, in cm, at the grid node positions..

tpemrun_sl.Header: ASCII header file describes the .sl file

Only the four files are useful to the GRACE processing.

The other files, which are output are:

tpemrun.ibd:	sea level minus inverted barometer
tpemrun.tpa:	global average atmosphere pressure
tpemrun.u:	east water velocity
tpemrun.v:	north water velocity

NOTE: The tpemrun.sl output file is renamed by GFZ's scripts as pressol.yyyymmdd.DAT, where yyyy is the year mm the month and dd the day (see figure 3-1)

Model output is packed into 1-day files, 24 grids per file. Each file is under 4 MB/day, including header information.

INTERFACE:

- GFZ shall deliver periodically the pressol.yyyymmdd files, and their associated tpemrun.tpa, .u and .v files for JPL/Oceans to perfom continuous testing and possibly model improvements, including the computation of Earth rotation components from the output.
- GFZ shall report to JPL/Oceans (V. Zlotnicki) any problems encountered in execution. JPL/Oceans shall be responsible for prompt correction, recompilation, and delivery of a corrected executable to GFZ.
- JPL/Oceans shall inspect the output pressol files on a routine basis and in a timely manner, and inform GFZ promptly of any problems encountered. JPL/Oceans shall fix such problems to the extent they are not caused by the external inputs.

ERROR ANALYSIS:
TBD

KNOWN PROBLEMS/LIENS/RESTRICTIONS:

1) Although the model has a Mediterranean sea, Hudson Bay, North Sea, and shallow waters, the model's performance in these enclosed or shallow areas, is not as good as in the deep, open ocean, as measured by variance reduction in the TOPEX/POSEIDON data. This is of special concern for the Mediterranean. This may hurt LAND estimates of gravity as the nearby ocean aliasing is improperly accounted for.

2) Model does not reproduce baroclinic behavior, which begins to compensate barotropic mass anomalies for periods > ~100 days. This must simply be kept in mind.

Proposed handling: use full model output to 'correct' sat-sat tracking data, then after monthly gravity field is computed, remove the barotropic monthly-mean surface mass distribution from the gravity field solution (of course, both in the same terms: either gravity or surface mass distributions).

3) Model does not currently include gravitational self-attraction.

4) Model does not include mass additions due to river inflow, nor mass fluxes at the surface due to precipitation minus evaporation, nor mass exchange at high latitude due to freezing or thawing.

COMMENTS:
None.

CREDITS:
All the design, coding and testing of this algorithm package was performed by Dr. Ahmed H. Ali, of Raytheon ITSS, in collaboration with Dr. V. Zlotnicki, JPL/Oceans.

REFERENCES:
See chapter 7 (References on Barotropic Model)

2.2.2 Baroclinic Ocean Model OMCT

Introduction

The Ocean Model for Circulation and Tides (OMCT) is a further development of the Hamburg Ocean Primitive Equation (HOPE) model. Prognostic variables are the three-dimensional horizontal velocity fields, the sea-surface elevation, and the thermohaline variables. The originally climatological HOPE model has been adjusted to the weather timescale and coupled with an ephemeral tidal model. Implemented is a prognostic thermodynamic sea-ice model that predicts ice-thickness, compactness, and drift. In contrast to HOPE, OMCT is discretised on a Arakawa-C-grid and allows the calculation of ephemeral tides and the thermohaline, wind-, and pressure driven circulation as well as secondary effects arising from loading and self-attraction of the water column and nonlinear interactions between circulation and tidal induced ocean dynamics. Since tidal induced oceanic mass redistributions and corresponding gravity effects are removed from GRACE measurements by means of another algorithm, in the OMCT version applied here tidal dynamics are not taken into account.

Details concerning the applied model equations, numerical implementations, and parameterizations can be found in Wolff et al. [1996], Drijfhout et al. [1996], and Thomas [2002]. In the following, only the model components of OMCT which were not included in HOPE and relevant for short-period mass redistributions will be described.

Model equations and numerical implementations

The numerical model OMCT is based on nonlinear balance equations for momentum, the continuity equation for an incompressible fluid, and conservation equations for heat and salt. The hydrostatic and Boussinesq approximations are applied. Three-dimensional horizontal velocities, water elevation, potential temperature as well as salinity fields are calculated prognostically; vertical velocities are determined diagnostically from the incompressibility condition. Implemented is a sea-ice model with viscous-plastic rheology [Hibler, 1979] allowing a prognostic calculation of sea-ice thickness, compactness, and velocities. The temporal resolution of the originally climatological model [Drijfhout et al., 1996; Wolff et al., 1996] is now 30 minutes. Thirteen layers exist in the vertical, the horizontal resolution is a constant 1.875° in longitude and latitude on a Arakawa-C-grid [Arakawa and Lamb, 1977] covering the global ocean including the Arctic (77°S to 90°N). The bathymetry is a 1.875° average of ETOPO5. Depths shallower than the uppermost layer thickness, i.e., 20m, are set to 20m; the applied semi-implicit algorithm does not require the definition of an upper depth limit.

Spinup. Initially, OMCT was spun up for 265 years with cyclic boundary conditions, that is, climatological wind stresses [Hellermann and Rosenstein, 1983] as well as annual mean surface temperatures and salinities [Levitus, 1982]. The resulting mean circulation and internal variability is discussed in Drijfhout et al. [1996]. Starting from this climatological quasi steady-state circulation, a real-time simulation was performed for the period 1958-2000 driven by 6-hourly wind stresses, 2m-temperatures, freshwater fluxes, and sea level pressure from ECMWF´s 40 years reanalysis project ERA-40. The resulting model state is used as initial model state for the operational OMCT simulations driven with ECMWF´s analysis and forecast fields.

Wind stress. To reproduce the wind-driven component of the general circulation the model requires wind stress at the ocean´s surface as forcing data. Since wind stress components are not provided by ECMWF´s operational analyses, wind velocities 10m above the surface need to be converted to wind stresses via

$$\tau = \rho C_D |U| U,$$

where τ is the wind stress vector at the ocean´s surface, ρ the density of air, U the horizontal wind vector 10m above the ocean´s surface, and C_D a transfer coefficient for momentum (drag coefficient) depending on U itself as well as on the stability of the boundary layer above the ocean. The algorithm is, in principle, an inversion of the transformation from wind stresses to wind velocities done within operational ECMWF analyses and was provided by A.C.M. Beljaars from ECMWF [Beljaars, 1997].

Steric correction, freshwater fluxes, mass conservation. Baroclinic ocean general circulation models (OGCM) using the Boussinesq approximation conserve rather volume than mass and, thus, artificial mass changes are introduced. Since the artificial mass variations would cause corresponding artificial changes of ocean bottom pressure, following Greatbatch [1994] steric anomalies are accounted for by adding/subtracting a spatially uniform layer, $\delta\zeta_\rho$, to the sea-surface [see, e.g., Ponte and Stammer, 2000; Gross et al., 2003]

$$\delta\zeta_\rho = -\frac{1}{O}\int_V \frac{\delta\rho}{\rho_0} dV ,$$

where $\delta\rho$ is the instantaneous density anomaly, ρ_0 a reference density, and O, V the ocean´s surface and volume, respectively. However, the ocean´s mass undergoes subseasonal to secular variations due to time-variable freshwater fluxes in the global hydrological cycle. The latter is taken into account by applying an additional source term determined from precipitation minus evaporation at the ocean´s surface. Thus, the ocean in fact conserves salt. Although the model allows the inclusion of mass additions due to river inflow, too, continental freshwater fluxes are neglected due to the lack of corresponding forcing fields in ECMWF´s operational analyses.

Since realistic and numerical induced longterm variations of precipitation and evaporation cannot be separated and the neglect of continental freshwater fluxes would introduce an artificial loss of oceanic water masses, additional constraints are required to prevent unrealistic oceanic water mass trends. Thus, it is necessary to define an appropriate period in which the oceanic integral of net freshwater fluxes vanishes. To take into account at least seasonal mass variations [cf., Chambers et al., 2004] this period should cover more than one year. However, since in the operational case a calculation of integral freshwater fluxes is possible for only very short periods, in general, instantaneous mass conservation is prescribed. Alternatively, a mean trend can be extrapolated into the future what – surely – will not ensure mass conservation exactly. The OMCT principally allows to demand instantaneous mass conservation as well as to define periods with vanishing net freshwater flux integrals.

Loading and self-attraction. The secondary potential, Φ_{LSA}, that arises from loading and self-attraction (LSA) of the water column is parameterized by a modified formulation of Accad and Pekeris [1978]. In the barotropic case, Accad and Pekeris [1978] concluded that LSA is proportional to the local (tidal) elevation. In the baroclinic case, local water elevations and vertical density distributions tend to compensate each other. Thus, LSA is taken into account by a term proportional to the density, ρ, of the local weater column:

$$\Phi_{LSA} = g\varepsilon\int \frac{\rho}{\rho_0} dz ,$$

where $g=9.806 ms^{-2}$ is the mean gravitational acceleration, ε a proportionality factor, and the integral is taken over the actual height of the water column. Sensitivity studies led to $\varepsilon=0.085$, which is consistent with Accad and Pekeris [1978], who used a similar grid resolution.

Oceanic bottom pressure. The output of the three-dimensional finite-difference code is ocean bottom pressure in Pa, and accounts for the effects of the thermohaline, wind- and pressure driven baroclinic circulation as well as the impact of loading and self-attraction of the water column. Since pressure forcing is included, no assumption with respect to the response of the ocean´s surface to atmospheric pressure is required. With the hydrostatic equation the ocean bottom pressure, p_B, as a function of latitude and longitude can be written as [cf., Wünsch et al., 2001]

$$p_B = p_A + g\int_{-H}^{\zeta}\rho\, dz \approx p_A + g\rho_0\zeta + g\int_{-H}^{0}\rho\, dz\,,$$

where p_A is the atmospheric pressure at sea level, g=9.806m^2/s the mean gravitational acceleration, H the time-invariant water depth, ζ the sea surface elevation, ρ the time-space dependent sea water density, and ρ_0=1030kg/m^3 a mean reference density. The impact of individual components of the baroclinic oceanic circulation on oceanic bottom pressure and, thus, on the Earth´s time-variable gravity field is analysed in Thomas and Dobslaw [2005].

Time-mean. From atmospheric fields and OMCT output a mean for the period 2001-2002 has been removed. As for the barotropic case, the baroclinic sea level, ζ, the density, ρ, and consequently the bottom pressure, p_B, are defined as departures from rest; thus, these fields contain a time-mean baroclinic circulation.

Input data

Time invariant:
- bathymetry file;
- proportionality factor for LSA parameterization (default: ε=0.085);
- definition of a period with vanishing integrals of net freshwater fluxes;
- definition of time resolution of model output (default is 6h).

Time varying:
- gridded wind velocities in 10m height;
- gridded atmospheric temperature fields 2m above sea level;
- gridded freshwater fluxes deduced from precipitation minus evaporation (since freshwater fluxes are not provided operationally by ECMWF´s analyses, these fields are taken from ECMWF´s operational short range forecasts);
- gridded pressure at sea level.

Processing steps:

Simulation time on a NEC SX-6 using 1 node is approximately 2 CPUh per year. Almost the same processing time is necessary for preparation of atmospheric forcing data (grid interpolation, wind conversion etc.).

Output:

The output useful for GRACE processing includes the following files:
- oceanic bottom pressure (contribution of the water column alone);
- atmospheric pressure at sea level (interpolated to OMCT grid);
- sea level height;
- final model state and restart information for the next run.

Known problems:
1) Although the model has a Mediterranean sea connected with the subtropical Atlantic, the horizontal resolution is not sufficient to reproduce dynamics properly in this enclosed area.
2) Although the model´s performance allows to take into account mass additions due to continental river inflow, actually these mass additions are not taken into account due to the lack of corresponding fields from ECMWF´s operational analyses.

Overview of basic model parameters

basic equations	nonlinear balance equation for momentum (Navier-Stokes), continuity equation, conservation equations for heat and salt
coverage	global, 77°S – 90°N
topography	1.875° average of ETOPO5; minimal water depth: 20m
spatial resolution	1.875° x 1.875°; 13 levels
temporal resolution	30 minutes
forcing	wind stress/velocity, heat flux/2m-temp., atmospheric pressure from ECMWF analyses, freshwater fluxes (precipitation minus evaporation) from ECMWF forecasts
mass conservation	steric and freshwater flux correction
function	simulation of short-term oceanic mass redistributions due to thermohaline, wind- and pressure driven circulation under consideration of sea ice, loading and self-attraction, and nonlinear effects

3 Processing Strategy for the Atmosphere and the Ocean

In this chapter the processing strategy for the ocean and the atmosphere is described. Additionally, the corresponding mean fields which are necessary for the calculation of residual pressure values are defined. Finally, the combination of the ocean and the atmosphere is explained.

3.1 Processing Strategy Ocean

3.1.1 Processing Strategy PPHA

The following figure describes the processing strategy to run the barotropic ocean model PPHA (see chapter 2.2.1) to generate barotropic sea level

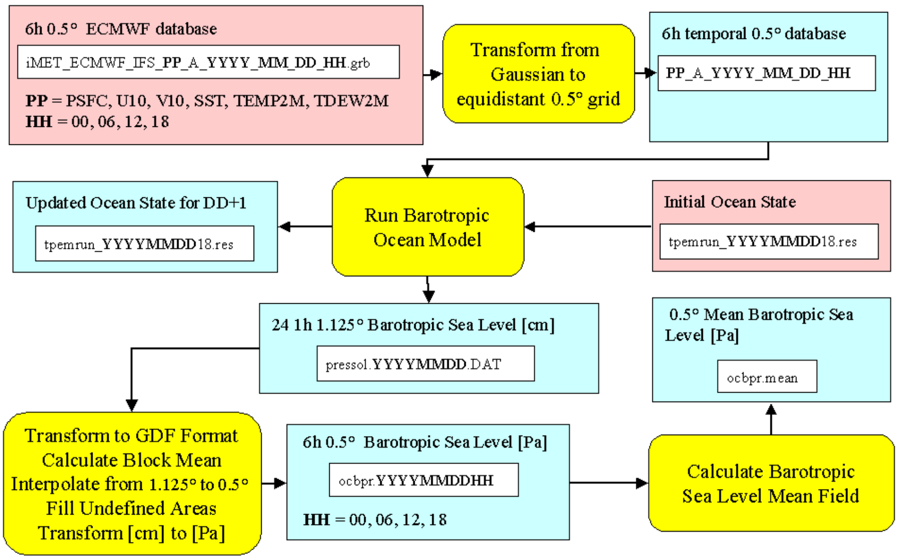

Figure 3-1: Processing Strategy Ocean using PPHA (red: input, yellow: processing step, light blue: output)

- Input data are the following 6 hourly ECMWF atmospheric fields (see chapter 2.1)
  - IMET_ECMWF_IFS_PSFC_A_YYYY_MM_DD_HH.grb: surface pressure
  - IMET_ECMWF_IFS_U10_A_YYYY_MM_DD_HH.grb: U wind speed
  - IMET_ECMWF_IFS_V10_A_YYYY_MM_DD_HH.grb: V wind speed
  - IMET_ECMWF_IFS_SST_A_YYYY_MM_DD_HH.grb: sea surface temperature
  - IMET_ECMWF_IFS_TEMP2M_A_YYYY_MM_DD_HH.grb: temperature at 2 m level
  - IMET_ECMWF_IFS_TDEW2M_A_YYYY_MM_DD_HH.grb: dew point temperature at 2 m level

  and an initial ocean model state "tpemrun_YYYYMMDD18.res" which has been provided by JPL for July 1, 2000
- The ECMWF data are transformed from a 0.5° gaussian grid to a 0.5° equidistant grid. This temporal ECMWF data base and the initial ocean model state force the ocean model. As a result 24 1 hourly 1.125° barotropic sea level states are produced by the ocean model represented in one binary file "pressol.YYYYMMDD.DAT". Additionally the ocean model state to initiate the next day´s run is calculated.
- For the later combination with the atmosphere the epochs at 0, 6, 12 and 18 hours are extracted, transformed to an internal GDF (grid data format) format and interpolated to 0.5° block mean values. Also the output unit [cm] is transformed to [Pa] using the constant gravity value and salt water density

of the ocean model. Undefined ocean areas (generally above +65° and below -75° latitude) are filled with 0. As a result every day 4 files "ocbpr.YYYYMMDDHH" with barotropic sea level [Pa] are available.

- This "ocbpr files" have been used to calculate an ocean model mean field (see chapter 3.3) which is necessary to derive residual barotropic sea level (see chapter 3.4) for individual days.

The processing time for a 1 model day on a SUN Ultra 450 using one (out of 4) 400 MHz CPU is 18 minutes.

3.1.2 Processing Stragegy OMCT

The following figure describes the processing strategy to run the baroclinic ocean model OMCT (see chapter 2.2.2) to generate ocean bottom pressure.

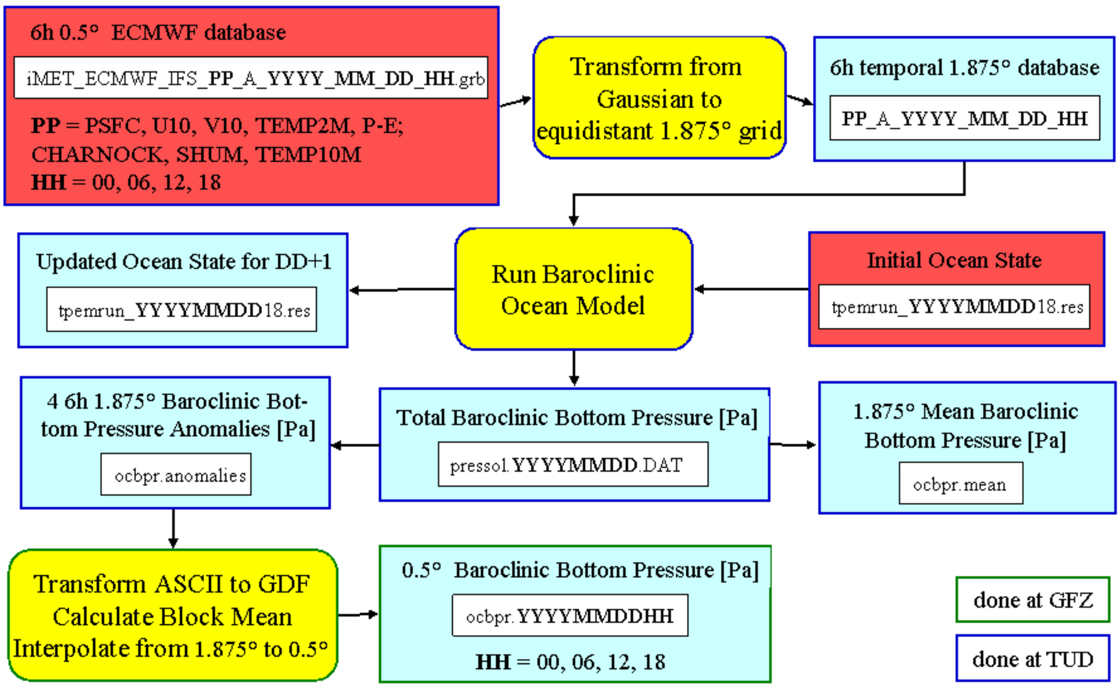

Figure 3-2: Processing Strategy Ocean using OMCT (red: input, yellow: processing step, light blue: output)

- Input data are the following 6 hourly ECMWF atmospheric fields (see chapter 2.1)
  - IMET_ECMWF_IFS_PSFC_A_YYYY_MM_DD_HH.grb: surface pressure
  - IMET_ECMWF_IFS_U10_A_YYYY_MM_DD_HH.grb: U wind speed
  - IMET_ECMWF_IFS_V10_A_YYYY_MM_DD_HH.grb: V wind speed
  - IMET_ECMWF_IFS_SST_A_YYYY_MM_DD_HH.grb: sea surface temperature
  - IMET_ECMWF_IFS_TEMP2M_A_YYYY_MM_DD_HH.grb: temperature at 2 m level
  - IMET_ECMWF_IFS_TEMP10M_A_YYYY_MM_DD_HH.grb: temperature at 10 m level
  - IMET_ECMWF_IFS_SHUM_A_YYYY_MM_DD_HH.grb: specific humidity
  - IMET_ECMWF_IFS_PmE_for_A_YYYY_MM_DD_HH.grb: freshwater fluxes deduced from precipitation minus evaporation according to ECMWF short term forecasts and an initial model state of the baroclinic oceanic circulation.
  - IMET_ECMWF_IFS_CHAR_A_YYYY_MM_DD_HH.grb: Charnock parameters

- The ECMWF data are transformed from a 0.5° gaussian to a 1.875° equidistant grid. This temporal ECMWF data base linearly interpolated to the OMCT time step of 30 minutes and the initial ocean model state force the OMCT. As a result the ocean bottom pressure fields of the epochs at 0, 6, 12, 18 hours are produced by OMCT. Additionally, restart information to initiate the next OMCT run is stored.
- For the later combination with the atmosphere the output grids are interpolated to 0.5° block mean values. Since the simulated baroclinic ocean bottom pressure contains the influence of time-space variability of salt water density and OMCT also covers the Arctic Ocean, in contrast to PPHA here. no additional assumptions have to be applied.
- The baroclinic ocean bottom pressure fields for the period 2001-2002 have been used to calculate a mean ocean bottom pressure field which is used to derive residual bottom pressure fields for individual days.

3.2 Processing Strategy Atmosphere

To take into account the atmospheric mass variations for the calculation of the de-aliasing product two different methods have been coded: The surface pressure (SP) and the vertical integration (VI) approach. Both are described in the following chapters.

3.2.1 Surface Pressure

3.2.1.1 Fundamental Formulas

Surface pressure data can be easily transformed into gravity harmonics by spherical harmonic analysis with integration and by applying specific factors for re-scaling the spherical harmonic coefficients. The gravitational potential V at a point outside the Earth due to heterogeneous mass distribution inside the Earth is expressed by a spherical harmonic expansion using normalized coefficients C_{nm} and S_{nm} of degree n and order m (Heiskanen and Moritz, 1967, 2-34, 2-35 with 2-40).

$$V = \frac{kM}{r} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n P_{nm}(\cos\theta)\left(C_{nm} \cos m\lambda + S_{nm} \sin m\lambda\right) \tag{3-1}$$

$$\begin{aligned} C_{nm} &= \frac{1}{(2n+1)Ma^n} \iiint_{Earth} r^n P_{nm}(\cos\theta) \cos m\lambda dM \\ S_{nm} &= \frac{1}{(2n+1)Ma^n} \iiint_{Earth} r^n P_{nm}(\cos\theta) \sin m\lambda dM \end{aligned} \tag{3-2}$$

with the mass, volume or surface elements:

$$dM = \rho dV = \rho r^2 dr \sin\theta d\theta d\lambda = r^2 q \sin\theta d\theta d\lambda = r^2 q dS \tag{3-3}$$

k	Gravity constant
a	Radius of sphere
M	Earth mass
P_{nm}	Associated Legendre polynomials (normalized)
(r,θ,λ)	Spherical coordinates of mass element
dM	Mass element
dV	Volume element
ρ	Density
q	Surface load (mass per surface)
dS	Surface element

Introducing volume elements, it can be seen that the density distribution becomes a factor in the integral over the complete Earth. Density variations mainly occur in the hydrosphere (atmosphere and oceans) and acts as a variable loading effect on the solid Earth surface (Gegout and Cazenave, 1993). Surface loads are represented as mass per surface element q. Because we are on the Earth surface the variable radius r can be set to the spherical radius a. Then, the coefficients are determined by:

$$\begin{aligned} C_{nm} &= \frac{a^2}{(2n+1)M} \iint_{Earth} q P_{nm}(\cos\theta) \cos m\lambda dS \\ S_{nm} &= \frac{a^2}{(2n+1)M} \iint_{Earth} q P_{nm}(\cos\theta) \sin m\lambda dS \end{aligned} \tag{3-4}$$

The surface load is defined by:

$$q = \frac{P_S}{g} = \rho_W h \tag{3-5}$$

where

P_S	Surface pressure
g	Mean gravity acceleration
ρ_W	Density of water (salt water 1040 (in case of PPHA), continental water 1000 kg/m^3)
h	Height of water column (1mm = 1kg/m^2)

Introducing the surface pressure the gravity coefficients are determined by:

$$\begin{aligned} C_{nm} &= \frac{a^2}{(2n+1)Mg} \iint_{Earth} P_S P_{nm}(\cos\theta) \cos m\lambda dS \\ S_{nm} &= \frac{a^2}{(2n+1)Mg} \iint_{Earth} P_S P_{nm}(\cos\theta) \sin m\lambda dS \end{aligned} \tag{3-6}$$

Taking into account the elastic deformation of the solid Earth under the variable load via the load Love number k_n for loading harmonic of degree n we get the final formula:

$$\begin{aligned} C_{nm} &= \frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} P_S P_{nm}(\cos\theta) \cos m\lambda dS \\ S_{nm} &= \frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} P_S P_{nm}(\cos\theta) \sin m\lambda dS \end{aligned} \tag{3-7}$$

Because in the current approach the de-aliasing product is represented by a spherical harmonic series of degree and order 100 the following loading Love numbers are used (Dong et al, 1996, Farrel, 1972):

$k_0 = 0; \quad k_1 = 0; \quad k_2 = -0.308; \; k_3 = -0.195; \; k_4 = -0.132$

$k_5 = -0.103; \; k_6 = -0.089; \; k_7 = -0.082; \; k_8 = -0.078; \; k_9 = -0.073$

for k_{10} to k_{17}: $-\dfrac{0.682 + 0.27(n-10)/8}{n}$

for k_{18} to k_{31}: $-\dfrac{0.952 + 0.288(n-18)/14}{n}$

for k_{32} to k_{55}: $-\dfrac{1.24 + 0.162(n-32)/24}{n}$

for k_{56} to k_{100}: $-\dfrac{1.402 + 0.059(n-56)/44}{n}$

3.2.1.2 Processing Sequence

Starting point are point values of surface pressure on a regular equiangular grid. Before numerical integration the point values have to be transformed to block-mean values representing the pressure for the block. As for the point values, blocks are defined on an equiangular grid. To analyze gravity variations caused by atmospheric surface pressure variations a mean surface pressure field covering at least one year of data has to be subtracted (in order to eliminate seasonal effects in the mean field) in above equation 3-7 (see also chapter 3.3). After subtraction of the mean pressure field residual pressure data, which represent mass variations with respect to the mean field are available.

$$\begin{aligned} C_{nm} &= \frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} \left(P_S - \overline{P}_S\right) P_{nm}(\cos\theta)\cos m\lambda \, dS \\ S_{nm} &= \frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} \left(P_S - \overline{P}_S\right) P_{nm}(\cos\theta)\sin m\lambda \, dS \end{aligned} \tag{3-8}$$

Then numerical integration starts row by row computing the integrals of associated Legendre polynomials in latitude direction and integrals of trigonometric functions in longitude direction. After completion the residual gravity spherical harmonic series is available. This gravity series corresponds to the deviation of the gravity field from the mean gravity field due to atmospheric mass variations.

3.2.2 Vertical Integration of Atmospheric Column

3.2.2.1 Fundamental Formulas

If the vertical structure of the atmosphere shall be taken into consideration the vertical integration of the atmospheric masses has to be performed. For this case we start again with the basic formulas (3-1) and (3-2) from chapter 3.2.1 and introduce the volume elements defined in formula (3-3).

$$\begin{aligned} C_{nm} &= \frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_0^\infty r^{n+2} \rho \, dr \right] P_{nm}(\cos\theta)\cos m\lambda \sin\theta \, d\theta \, d\lambda \\ S_{nm} &= \frac{1}{(2n+1)Ma^n} \iint_{Earth} \left[\int_0^\infty r^{n+2} \rho \, dr \right] P_{nm}(\cos\theta)\sin m\lambda \sin\theta \, d\theta \, d\lambda \end{aligned} \tag{3-9}$$

Using the hydrostatic equation:

$$\rho dr = -\frac{dP}{g_r} \tag{3-10}$$

we get:

$$\begin{aligned} C_{nm} &= -\frac{1}{(2n+1)Ma^n}\iint_{Earth}\left[\int_{P_S}^{0}\frac{r^{n+2}}{g_r}dP\right]P_{nm}(\cos\theta)\cos m\lambda\,\sin\theta d\theta d\lambda \\ S_{nm} &= -\frac{1}{(2n+1)Ma^n}\iint_{Earth}\left[\int_{P_S}^{0}\frac{r^{n+2}}{g_r}dP\right]P_{nm}(\cos\theta)\sin m\lambda\,\sin\theta d\theta d\lambda \end{aligned} \tag{3-11}$$

The gravity acceleration in height r (g_r) can be approximated from the mean gravity acceleration g by:

$$g_r = g\left(\frac{a}{r}\right)^2 \tag{3-12}$$

Then we get:

$$\begin{aligned} C_{nm} &= -\frac{1}{(2n+1)Ma^{n+2}g}\iint_{Earth}\left[\int_{P_S}^{0}r^{n+4}dP\right]P_{nm}(\cos\theta)\cos m\lambda\,\sin\theta d\theta d\lambda \\ S_{nm} &= -\frac{1}{(2n+1)Ma^{n+2}g}\iint_{Earth}\left[\int_{P_S}^{0}r^{n+4}dP\right]P_{nm}(\cos\theta)\sin m\lambda\,\sin\theta d\theta d\lambda \end{aligned} \tag{3-13}$$

The radial coordinate r is composed of (see figure 3-2 and (Wahr and Svensson, 1999)):

$$r = r_s + \delta r = a + \xi + h + \delta r = a + \xi + z \tag{3-14}$$

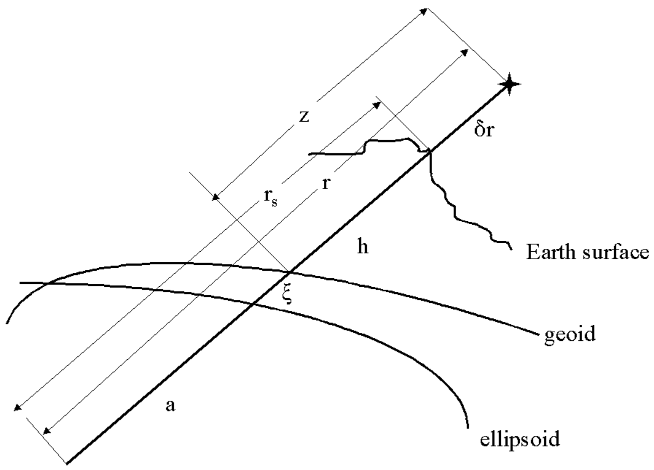

Figure 3-3: Radial component r used in vertical integration

ξ is the height of the mean geoid above the mean sphere r = a., h is the elevation of the Earth´s surface above the mean geoid (Earth´s surface topography). The geopotential height Φ at a point * above the Earth´s surface r = a + z is defined by:

$$\Phi = \frac{1}{g}\int_0^z g_r dz = a\left(\frac{z}{a+z}\right) \tag{3-15}$$

After transformation we get:

$$\Phi = a\left(\frac{z}{a+z}\right) \Rightarrow \frac{\Phi}{a} = \frac{z}{a+z} \Rightarrow z = \frac{(a+z)\Phi}{a} \Rightarrow z = \frac{\Phi a}{a} + \frac{\Phi z}{a} \Rightarrow$$
$$\Phi = z - \frac{\Phi z}{a} \Rightarrow \Phi = z\left(1 - \frac{\Phi}{a}\right) \Rightarrow z = \frac{\Phi}{\left(1 - \frac{\Phi}{a}\right)} \tag{3-16}$$

Then it follows:

$$r = a + \frac{\Phi}{\left(1 - \frac{\Phi}{a}\right)} + \xi = \frac{a\left(1 - \frac{\Phi}{a}\right) + \Phi}{\left(1 - \frac{\Phi}{a}\right)} + \xi = \frac{a}{\left(1 - \frac{\Phi}{a}\right)} + \xi \tag{3-17}$$

This expression is substituted in (3-13):

$$C_{nm} = -\frac{1}{(2n+1)Ma^{n+2}g} \iint_{Earth} \left[\int_{P_S}^{0} \left(\frac{a}{1 - \frac{\Phi}{a}} + \xi \right)^{n+4} dP \right] P_{nm}(\cos\theta) \cos m\lambda \, \sin\theta d\theta d\lambda$$
$$S_{nm} = -\frac{1}{(2n+1)Ma^{n+2}g} \iint_{Earth} \left[\int_{P_S}^{0} \left(\frac{a}{1 - \frac{\Phi}{a}} + \xi \right)^{n+4} dP \right] P_{nm}(\cos\theta) \sin m\lambda \, \sin\theta d\theta d\lambda \tag{3-18}$$

After including the degree dependent term into the integral (for numerical reasons) and introducing again the elastic deformation of the solid Earth (see equation 3-7) we get the following final formulas for determination of the gravity coefficients using the vertical integration approach:

$$C_{nm} = -\frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} \left[\int_{P_S}^{0} \left(\frac{a}{a - \Phi} + \frac{\xi}{a} \right)^{n+4} dP \right] P_{nm}(\cos\theta) \cos m\lambda \, \sin\theta d\theta d\lambda$$
$$S_{nm} = -\frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} \left[\int_{P_S}^{0} \left(\frac{a}{a - \Phi} + \frac{\xi}{a} \right)^{n+4} dP \right] P_{nm}(\cos\theta) \sin m\lambda \, \sin\theta d\theta d\lambda \tag{3-19}$$

From the meteorological analysis centers usually not the geopotential height Φ, but temperature and specific humidity are available on the model or half levels. Therefore, before the integration with formula (3-19) can be performed numerically, the geopotential heights for all levels have to be computed. This computation can be done in the following way (White, 2001, formula 2.21; Schrodin 2000, page 51) (N_{Level} represents the lowest level).

$$\Phi_{k+1/2} = \Phi_S + \frac{1}{g} \sum_{j=k+1}^{N_{level}} R_{dry} T_v \ln \frac{P_{j+1/2}}{P_{j-1/2}} \tag{3-20}$$

with
- $\Phi_{k+1/2}$ Geopotential height at half level (layer interfaces)
- Φ_S Geopotential height at surface (if provided as potential divide by g_0)
- R_{dry} Gas constant for dry air = 287 $m^2/(s^2K)$ = 287 J/(kgK)
- T_v Virtual temperature

$P_{k+1/2}$ Pressure at half level (layer interface)

$$T_v = (1 + 0.608H)T \tag{3-21}$$

H specific Humidity
T Temperature

$$P_{k+1/2} = a_{k+1/2} + b_{k+1/2} P_S \tag{3-22}$$

$a_{k+1/2}$ Model dependent coefficient
$b_{k+1/2}$ Model dependent coefficient
Both coefficients are provided in ECMWF GRIB files, for DWD see Schroding 2000, p.51)

The geopotential heights at pressure levels finally can be used to compute the inner integral in (3-19). In the second term ξ/a, the mean geoid above the sphere r=a can be approximated by the geopotential height at the Earth´s surface which is available at ECMWF.

3.2.2.2 Processing Sequence

Starting points are point values of surface pressure and geopotential height grids on the Earth's surface and point values of temperature and specific humidity at all model levels of the atmospheric model in the same global grid. All these equiangular point grids are transformed to block mean grids by applying a mean value operator to the 4 corner points. Then the pressure at all model levels (formula 3-22) is computed by using the atmospheric model specific interpolation coefficients (a, b). These pressure values, the virtual temperature, which is computed from the real temperature and the specific humidity in each model level (3-21) and the surface geopotential heights are used to compute the geopotential heights for all levels. For this also a mean gravity acceleration has to be used, which is computed from the reference ellipsoid WGS84. In our case the normal gravity at the equator is used. Then the integration is done numerically for each degree separately using the geopotential heights of the model levels. These intermediate results are stored in a three dimensional array with longitude, latitude and degree as indices. Finally the spherical harmonic analysis is performed for each degree of the spherical harmonic series separately, in order to take into account the degree dependent exponent in equation (3-19). Finally the complete spherical harmonic series is written on a binary spherical harmonic series file.

To analyze gravity variations caused by atmospheric vertical integrated pressure variations a corresponding mean field covering at least one year of data has to be subtracted (in order to eliminate seasonal effects in the mean field) from the inner integral of above equation 3-19 (see also chapter 3.3). After subtraction of the mean pressure field residual pressure data, which represent mass variations with respect to the mean field are available:

$$\begin{aligned} C_{nm} &= -\frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} \left(\left[\int_{P_S}^{0} \left(\frac{a}{a-\Phi} + \frac{\zeta}{a} \right)^{n+4} dP \right] - \overline{P}_{VI} \right) P_{nm}(\cos\theta) \cos m\lambda \sin\theta d\theta d\lambda \\ S_{nm} &= -\frac{a^2(1+k_n)}{(2n+1)Mg} \iint_{Earth} \left(\left[\int_{P_S}^{0} \left(\frac{a}{a-\Phi} + \frac{\zeta}{a} \right)^{n+4} dP \right] - \overline{P}_{VI} \right) P_{nm}(\cos\theta) \sin m\lambda \sin\theta d\theta d\lambda \end{aligned} \tag{3-23}$$

For a better clarification of this processing sequence a pseudo code is provided below.

Read global surface pressure from GRIB file
IMET_ECMWF_IFS_PSFC_A_YYYY_MM_DD_HH.grb
Read global surface geopotent. height from GRIB file
IMET_ECMWF_IFS_PHISFC_A_YYYY_MM_DD_HH.grb

```
Read global model level temperatures from GRIB file
        IMET_ECMWF_IFS_TEMP_A_YYYY_MM_DD_HH.grb
Read global model level specific humidity from GRIB file
        IMET_ECMWF_IFS_SHUM_A_YYYY_MM_DD_HH.grb
Compute for all global data sets block mean values
Do for all block means in the global grid files
        Do for all model levels
                Compute pressure at model level (3-22)
                Compute virtual temperature a model level (3-21)
                Compute geopotential height of model level by summing up individual heights and
                        add surface geopotential height (3-20)
                Compute expression in large brackets of inner integral in (3-19)
                Do for all degrees of spherical harmonic series
                        Apply exponent and do numerical integration by multiplication with pressure
                                difference of model levels and summation of all model levels
                        Store result in temporary 3-D field with long., latitude and degree as indices
                End Do
        End Do
End Do
Do for all degrees of spherical harmonic series
        Subtract mean contribution for this degree by reading it from a separate file
        Perform spherical harmonic analysis for this degree using the temporary 3-D field (3-19)
        Store coefficients of this degree in result vector
End Do
Write spherical harmonic series to output file
```

The processing time for a 1 day processing on a SUN Ultra 450 using one (out of 4) 400 MHz CPU is approximately 2 hours.

3.3 Mean Ocean and Atmospheric Pressure Fields

To calculate residual barotropic or baroclinic sea level or residual atmospheric pressure fields (see equation 3-8 for surface pressure resp. equation 3-23 for vertical integration) corresponding mean fields have to be computed.

For RL01 this is a 2001 mean field, RL02 and RL03 are calculated with a 2001+2002 mean (see also chapter 4 and 5). Examples of this mean fields are shown below.

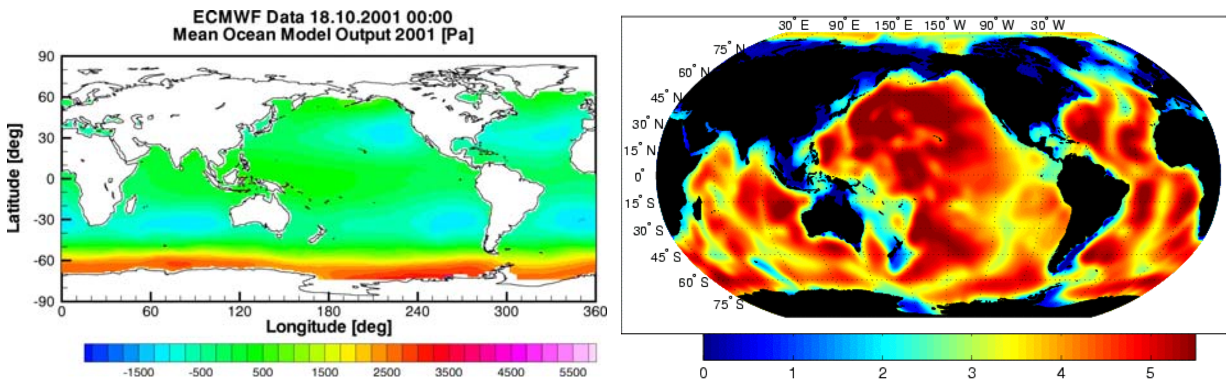

Figure 3-4: Barotopic sea level mean field [Pa] derived from PPHA 6h output for 2001 (left) and baroclinic sea level mean field [10^5 hPa] derived from 6h bottom pressure fields for 2001+2002 (right)

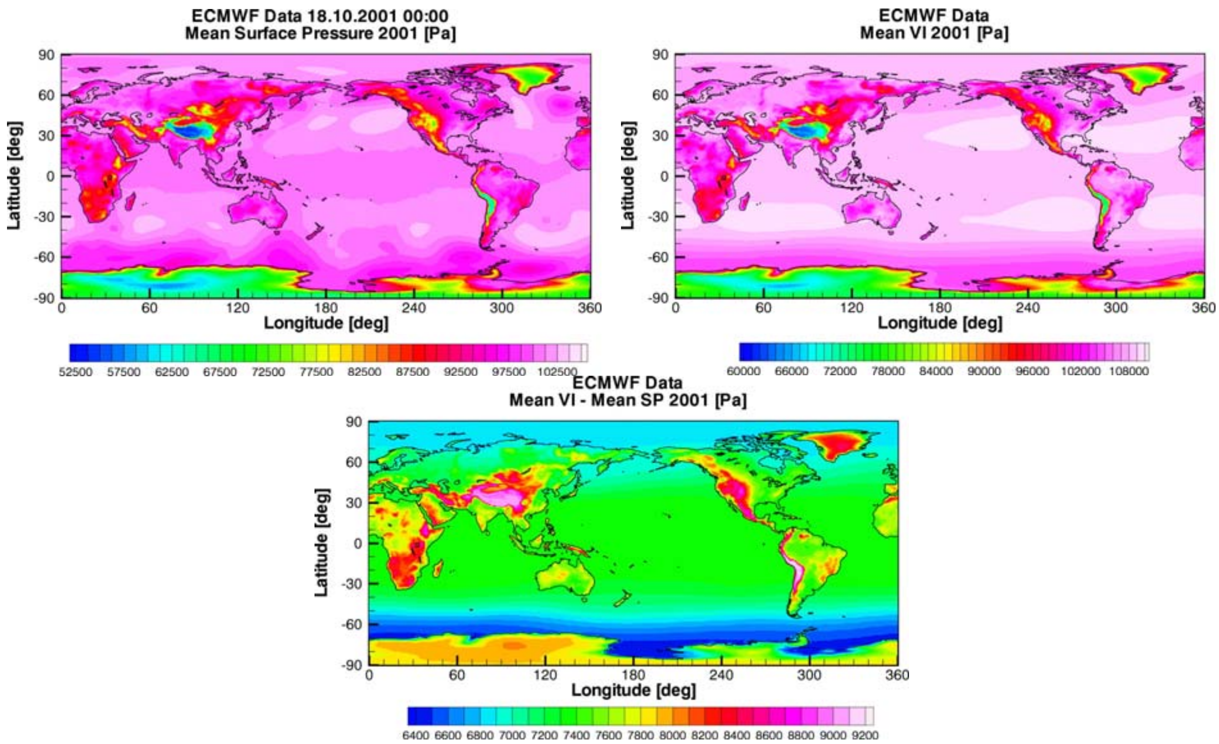

Figure 3-5: Surface pressure (upper left) and vertical integrated mean field for 2001 [Pa] (upper right) and their difference (lower middle) [Pa]

The bias of about 7000 Pascal between the surface and vertical integrated mean fields is due to the different mean heights.

3.4 Combination of Atmosphere and Ocean

To get the global residual pressure field, used as input for calculation of the spherical harmonic series, the ocean and atmosphere actual and mean fields are combined in the following way (example see figure 3-5):

1. Build the difference between the actual 6h barotropic sea level (chapter 3.1) and the mean barotropic sea level (chapter 3.3) which defines the residual barotropic sea level (see figure 3-6)
2. In case of PPHA, undefined ocean areas (e.g. ocean areas above 65° and -75° latitude) are filled with 0 values.
3. Build the difference between the actual 6h surface or vertical integrated pressure (chapter 3.2) and the atmospheric mean field (chapter 3.3) which defines the residual atmospheric pressure (example see figure 3-7)
4. Over the oceans the residual barotropic sea level and the residual atmospheric pressure are added
5. The land and ocean residual pressure values are the input to calculate spherical harmonic series, which are stored in an ASCII file (the AOD1B product, see chapter 5)

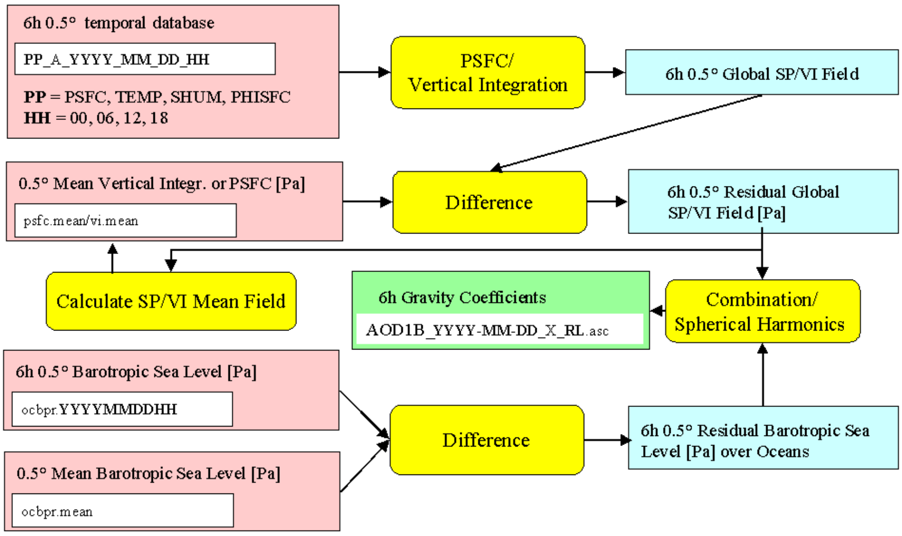

Figure 3-6: Processing strategy combination of ocean and atmosphere (red: input, yellow: processing step, light blue and green: output)

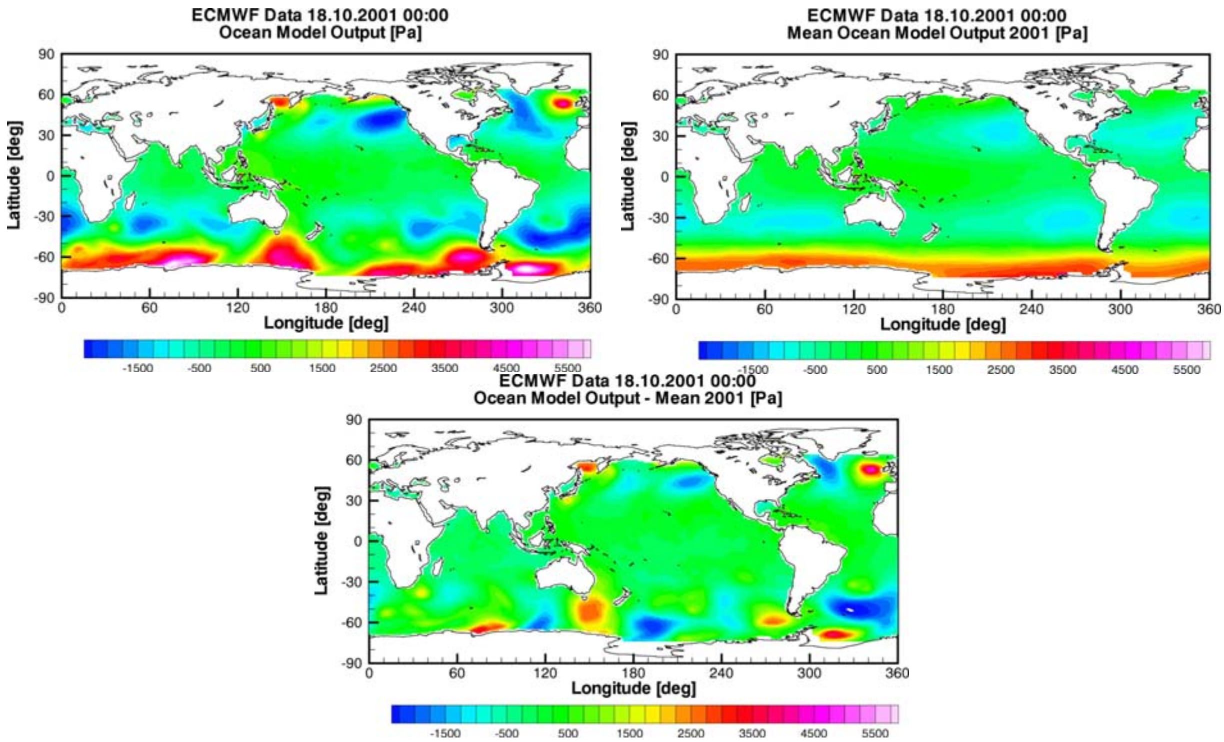

Figure 3-7: PPHA barotopic sea level on October 18, 2001, 00:00 (upper left), 2001 mean field (upper right) and corresponding residual field (lower middle) [Pa]

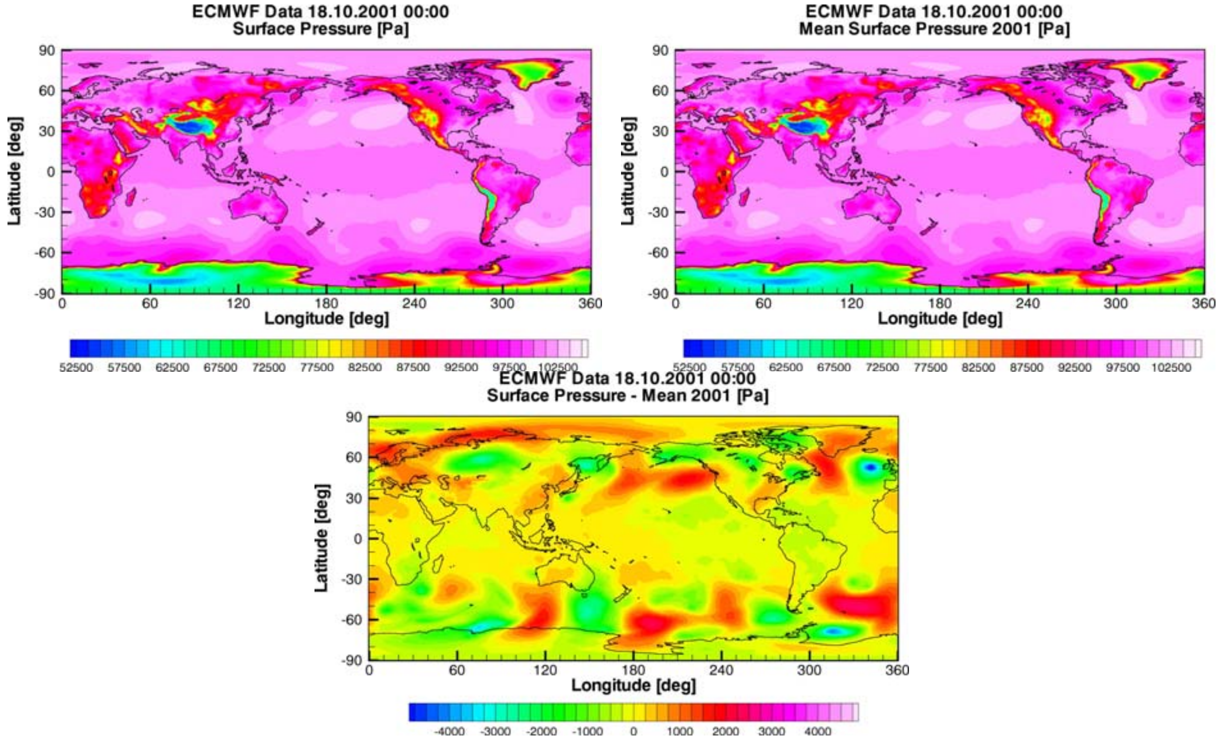

Figure 3-8: Surface pressure on October 18, 2001, 00:00 (upper left), 2001 mean field (upper right) and corresponding residual field (lower middle) [Pa]

4 Available Releases of the AOD1B Product

The following releases are available:

Release	Period	Ocean Model	Mean Field	S2 Tide Atmosphere [(3)]	S2 Tide Ocean
RL00	June 2000-April 2003 [(1)]	PPHA	2001	Included	Included
RL01	June 2000-today [(7)]	PPHA	2001	Included	Included
RL02	[(2)]	PPHA	2001+2002	Included	Removed [(4)]
RL03	Jan 2002-today [(7)]	OMCT[(5)]	2001+2002	Included	Removed [(4)]
RL04	Jan 2001-today	OMCT[(6)]	2001+2002	Included	Removed [(4)]

Comments:

(1) RL00 generation stopped in April 2003 and substituted by RL01. Both AOD products are exactly the same, except that besides the global combined mass variation also the atmospheric and oceanic contributions are provided in the RL01 AOD1B product

(2) Only available for May 2003, July 2003, August 2003, September 2003, November 2003, February 2004, December 2004 and January 2005

(3) The S2 atmospheric tide is still included in the atmospheric part of the AOD1B products. When using an atmospheric tide model in POD users might have to avoid a double book-keeping by reduction of the S2 part from the AOD1B using their atmospheric tide model prior to POD.

(4) The S2 atmospheric tide was removed from surface pressure before forcing PPHA or OMCT using a strategy described in Ponte and Ray (2002). This is done to avoid double-modeling, once in the ocean's response to pressure variations and once in the altimetric ocean tide models. **Consequently, users should take care to use an ocean tide model which has the total (gravitational plus atmospheric) S2 tide in!**

(5) The RL03 OMCT outputs were calculated with the condition of vanishing net freshwater fluxes during the period Jan 2002 to December 2004. Since January 2005 this condition is replaced by a condition that instantaneously conserves mass. As a consequence, gravity field products of the period January 2002 to December 2004 corrected with this version of OMCT show artificial slopes over land which has to be corrected by the corresponding GAB products (for definition see chapter 7).

GRACE users which are analyzing GFZ RL03 or JPL RL02 time-series are strongly recommended to read GRACE Technical Note #04!

(6) To overcome the RL03 problems, all RL04 OMCT outputs were calculated by a condition that instantaneously conserves mass. Additionally, the OMCT RL04 bathymetry was adjusted to the AOD1B software land-ocean mask (used to combine atmospheric and oceanic contributions), the thermodynamic sea ice model was updated and a new data set for surface salinity relaxation was taken into account. Besides the 6-hourly atmosphere, ocean and combined mass variations, RL04 also provides OMCT ocean bottom pressure variation ("oba"-marked coefficients, for further details see chapter 6).

(7) It is planned to stop the generation of RL01 and RL03 within 2007 and to continue with the routine generation of RL04 only.

5 Long-term Statistics of the AOD1B Product

The 6-hourly residual spherical harmonic coefficients (AOD1B product) are routinely transformed to corresponding atmospheric, oceanic and combined geoid height variations. The minimum, maximum, mean and rms values are used to check the AOD1B product on consistency. Minimum and maximum atmospheric values of RL01 and RL03 are in the range of ±10-20 mm, the mean is nearly 0 mm, the rms is usually around 2-5 mm. Same holds true for the ocean part of the barotropic PPHA model which is mass conserving. Since variations in total ocean mass due to freshwater fluxes were allowed in RL03 OMCT simulations for the period January 2002 to December 2004, the long-term mean shows a trend until January 2005, when again mass conserving was applied (see chapter 4 for details). The long-term statistic including degree 0 and 1 terms for July 1, 2002 until July 31, 2005 for RL01 and RL03 is shown in the following Figure 5-1. Figure 5-2 shows statistics for RL04, where, besides the usual atmospheric, oceanic and combined mass variations, also the OMCT-derived ocean bottom pressure variations (see chapter 6) are shown.

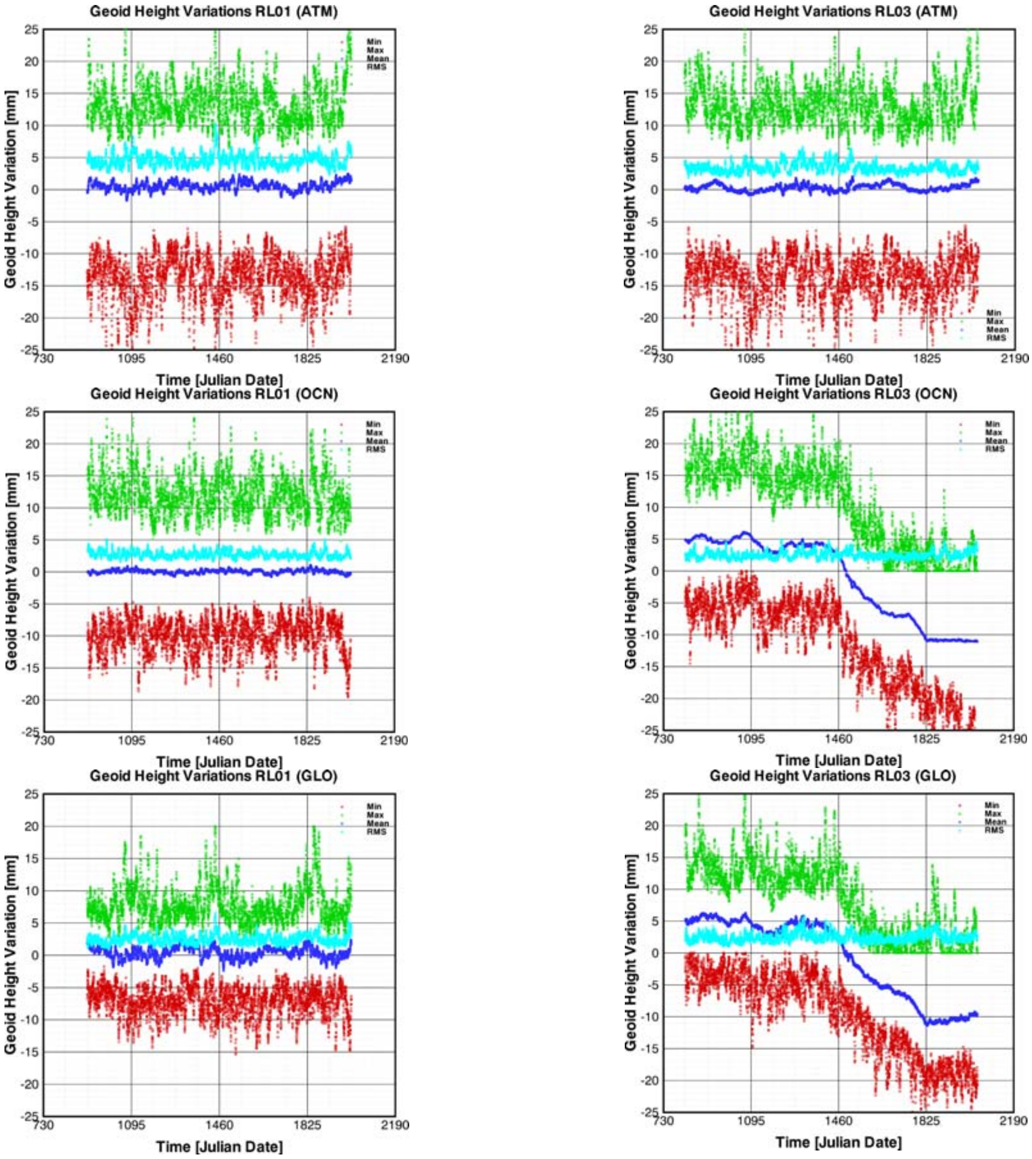

Figure 5-1: AOD1B derived geoid height variation statistics (minimum (red), maximum (green), mean (blue) and rms (light blue)) including degree 0 and 1 terms for July 1, 2002 until July 31, 2005 for atmosphere (top), ocean (middle) and global combination (bottom) for RL01 (using PPHA model) and RL03 (using OMCT).

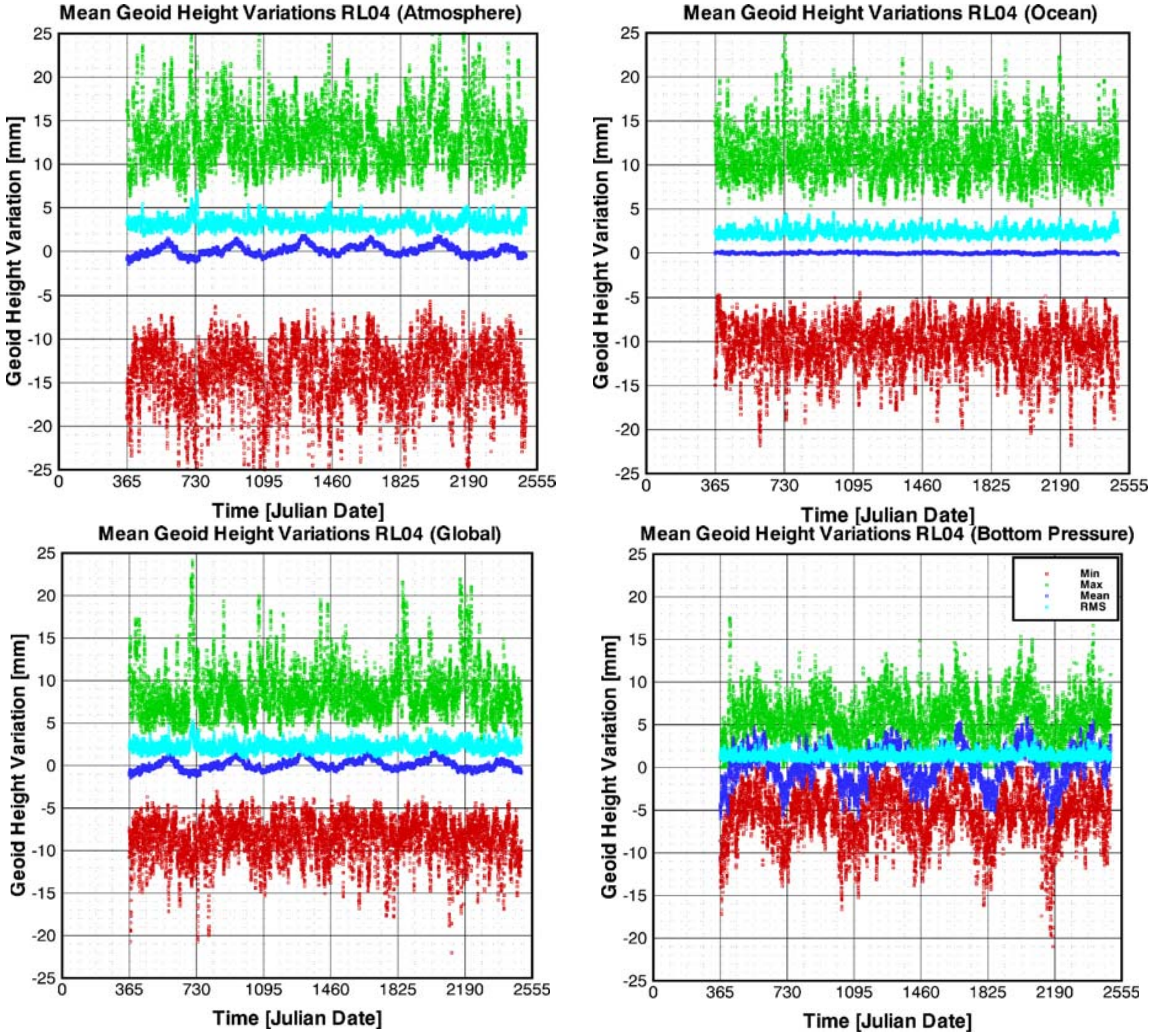

Figure 5-2: AOD1B RL04 derived geoid height variation statistics (minimum (red), maximum (green), mean (blue) and rms (light blue)) including degree 0 and 1 terms for January 1, 2001 until October 31, 2006 for atmosphere (top left), ocean (top right), global combination (top left) and ocean bottom pressure (bottom right).

6 AOD1B and OCN1B Format and Content Description

In the following chapters the output format and the content of the atmosphere and ocean de-aliasing product (AOD1B) and the ocean model output (OCN1B) are described.

6.1 Format of the Atmosphere and Ocean De-aliasing Product (AOD1B)

The AOD1B products will be available in the GRACE ISDC on a daily basis using the GRACE level-1 filename convention "AOD1B_YYYY-MM-DD_S_RL.EXT.gz" (Case *et al*., 2002) where "YYYY-MM-DD" is the corresponding date, the GRACE satellite identifier "S" is fixed to X (meaning product cannot be referred to GRACE-A or GRACE-B), RL is an increasing release number and EXT is fixed to asc (ASCII data). For data transfer simplification the products are gnu-zipped (suffix "gz").

Each file consists of a header with a dedicated number of lines (NUMBER OF HEADER RECORDS) and ends with a constant header line (END OF HEADER). The first part of the header is based on the level-1 instrument product header convention (Case *et al*., 2002) and gives more general information on the product (header lines PRODUCER AGENCY to PROCESS LEVEL). These lines are accomplished by a certain number of header lines describing the de-aliasing product more precisely like

`PRESSURE TYPE (SP OR VI)`	:	Surface Pressure or Vertical Integration approach
`MAXIMUM DEGREE`	:	The maximum degree of the spherical harmonic series
`COEFFICIENT ERRORS (YES/NO)`	:	Yes, if errors are added to the coefficients
`COEFF. NORMALIZED (YES/NO)`	:	YES, if the coefficients are normalized
`CONSTANT GM [M^3/S^2]`	:	GM value used for computation
`CONSTANT A [M]`	:	semi-major axis value used for computation
`CONSTANT FLAT [-]`	:	flattening value used for computation
`CONSTANT OMEGA [RAD/S]`	:	Earth rotation rate used for computation
`NUMBER OF DATA SETS`	:	Number of data fields per product
`DATA FORMAT (N,M,C,S)`	:	Format to read the data (depending on header line " COEFFICIENT ERRORS (YES/NO)"

The NUMBER OF DATA SETS is 12 or 16 (RL04) because for each 6-hours 3 or 4 (RL04) different spherical harmonic series (incl. degree 0 and 1) up to a MAXIMUM DEGREE (defined in the header, 100 for all releases) are provided. Before calculation of these spherical harmonic series the 0.5º block means are defined as follows (also depending on PRESSURE TYPE (SP OR VI) defined in the header):

1. DATA SET TYPE "glo" (GLObal atmosphere and ocean combination):
Land: [SP-SP(mean)] or [VI-VI(mean)]
Defined ocean area: [ocean-ocean(mean) + SP-SP(mean)] or [ocean-ocean(mean) + VI-VI(mean)]
Undefined ocean area: 0

2. DATA SET TYPE "atm" (global ATMosphere):
Land area: [SP-SP(mean)] or [VI-VI(mean)]
Defined ocean area: [SP-SP(mean)] or [VI-VI(mean)]
Undefined ocean area: [SP-SP(mean)] or [VI-VI(mean)]

3. DATA SET TYPE "ocn" (OCeaN area):
Land: 0
Defined ocean: ocean-ocean(mean)
Undefined ocean: 0

4. DATA SET TYPE "oba" (Ocean Bottom pressure Analysis, only RL04):
Land: 0
Defined ocean: [ocean-ocean(mean) + SP-SP(mean)] (see Note 2 below!)
Undefined ocean: 0

Note 1: Due to the undefined ocean pixels in the PPHA barotropic ocean model (pixels outside the 75°S/65°N latitude band) the sum of the “ocn” and “atm” coefficients is **not** the “glo” coefficient!

Note 2: The S2 atmospheric tide was removed from the “oba” surface pressure data (SP-SP(mean)) using a strategy described in Ponte and Ray (2002).

The following is an example for the AOD1B_2002-05-01_X_01.asc product, where for simplification only the two first and last coefficients of each data set are given:

```
PRODUCER AGENCY               : GFZ
PRODUCER INSTITUTION          : GFZ
FILE TYPE ipAOD1BF            : 999
FILE FORMAT 0=BINARY 1=ASCII  : 1
NUMBER OF HEADER RECORDS      : 29
SOFTWARE VERSION              : atm_ocean_dealise.01
SOFTWARE LINK TIME            : Not Applicable
REFERENCE DOCUMENTATION       : GRACE De-aliasing ADD
SATELLITE NAME                : GRACE X
SENSOR NAME                   : Not Applicable
TIME EPOCH (GPS TIME)         : 2000-01-01 12:00:00
TIME FIRST OBS(SEC PAST EPOCH):  73483148.816000 (2002-04-30 23:59: 8.82)
TIME LAST OBS(SEC PAST EPOCH) :  73569548.816000 (2002-05-01 23:59: 8.82)
NUMBER OF DATA RECORDS        :    61812
PRODUCT CREATE START TIME(UTC): 2003-02-25 15:49:57.000
PRODUCT CREATE END TIME(UTC)  : 2003-02-25 17:50:18.000
FILESIZE (BYTES)              :  2474676
FILENAME                      : AOD1B_2002-05-01_X_01.asc
PROCESS LEVEL (1A OR 1B)      : 1B
PRESSURE TYPE (SP OR VI)      : VI
MAXIMUM DEGREE                : 100
COEFFICIENT ERRORS (YES/NO)   : NO
COEFF. NORMALIZED (YES/NO)    : YES
CONSTANT GM [M^3/S^2]         :  0.39860050000000E+15
CONSTANT A [M]                :  0.63781370000000E+07
CONSTANT FLAT [-]             :  0.29825722356300E+03
CONSTANT OMEGA [RAD/S]        :  0.72921150000000E-04
NUMBER OF DATA SETS           : 12
DATA FORMAT (N,M,C,S)         : (2(I3,X),E15.9,X,E15.9)
END OF HEADER
DATA SET 01:   5151 COEFFICIENTS FOR 2002-05-01 00:00:00 OF TYPE glo
  0   0 -.135435996E-09 0.000000000E+00
  1   0 -.696238601E-10 0.000000000E+00
...
100  99 -.828253859E-14 -.175293932E-13
100 100 0.126298458E-13 0.554480726E-14
DATA SET 02:   5151 COEFFICIENTS FOR 2002-05-01 00:00:00 OF TYPE atm
  0   0 0.401898514E-10 0.000000000E+00
  1   0 0.225522283E-09 0.000000000E+00
...
100  99 0.722601553E-15 0.393424767E-16
100 100 0.179852658E-14 -.165148489E-14
DATA SET 03:   5151 COEFFICIENTS FOR 2002-05-01 00:00:00 OF TYPE ocn
  0   0 0.207567297E-11 0.000000000E+00
  1   0 -.209127879E-09 0.000000000E+00
...
100  99 0.510387838E-14 0.729377169E-14
100 100 0.155247629E-14 0.949324291E-14
DATA SET 04:   5151 COEFFICIENTS FOR 2002-05-01 06:00:00 OF TYPE glo
  0   0 -.960557189E-10 0.000000000E+00
  1   0 -.210970460E-10 0.000000000E+00
...
100  99 -.425918879E-14 -.166074453E-13
100 100 0.545089132E-14 -.561110987E-14
DATA SET 05:   5151 COEFFICIENTS FOR 2002-05-01 06:00:00 OF TYPE atm
  0   0 0.803510591E-10 0.000000000E+00
  1   0 0.258349385E-09 0.000000000E+00
```

```
...
100  99 -.176526235E-14 0.662645347E-15
100 100 0.524793984E-14 -.199281818E-16
DATA SET 06:   5151 COEFFICIENTS FOR 2002-05-01 06:00:00 OF TYPE ocn
  0   0 0.233590924E-11 0.000000000E+00
  1   0 -.191746994E-09 0.000000000E+00
...
100  99 0.465385317E-14 0.840468478E-14
100 100 0.218720802E-14 -.147296184E-14
DATA SET 07:   5151 COEFFICIENTS FOR 2002-05-01 12:00:00 OF TYPE glo
  0   0 -.130867539E-09 0.000000000E+00
  1   0 -.622117836E-11 0.000000000E+00
...
100  99 -.980827450E-14 -.264733486E-13
100 100 0.172324071E-13 0.133860780E-13
DATA SET 08:   5151 COEFFICIENTS FOR 2002-05-01 12:00:00 OF TYPE atm
  0   0 0.855524540E-10 0.000000000E+00
  1   0 0.290702845E-09 0.000000000E+00
...
100  99 0.406549558E-14 0.128476038E-14
100 100 0.643893462E-15 0.811294313E-14
DATA SET 09:   5151 COEFFICIENTS FOR 2002-05-01 12:00:00 OF TYPE ocn
  0   0 0.427502478E-11 0.000000000E+00
  1   0 -.204739061E-09 0.000000000E+00
...
100  99 0.487412982E-14 0.562979458E-14
100 100 0.801392000E-14 0.728205814E-14
DATA SET 10:   5151 COEFFICIENTS FOR 2002-05-01 18:00:00 OF TYPE glo
  0   0 -.129505962E-09 0.000000000E+00
  1   0 -.599107951E-11 0.000000000E+00
...
100  99 -.128849962E-14 -.120559974E-13
100 100 0.407529528E-15 0.970380292E-14
DATA SET 11:   5151 COEFFICIENTS FOR 2002-05-01 18:00:00 OF TYPE atm
  0   0 0.959166080E-10 0.000000000E+00
  1   0 0.279274424E-09 0.000000000E+00
...
100  99 -.178242566E-14 0.329597760E-14
100 100 0.161335787E-14 0.604664766E-14
DATA SET 12:   5151 COEFFICIENTS FOR 2002-05-01 18:00:00 OF TYPE ocn
  0   0 0.752176099E-11 0.000000000E+00
  1   0 -.195272771E-09 0.000000000E+00
...
100  99 0.673919890E-14 0.106280308E-13
100 100 -.122003463E-14 0.409984557E-14
```

6.2 Format of the Ocean Model Output (OCN1B)

The OCN1B products is available in the GRACE ISDC on a daily basis using the level-1 filename convention (Case *et al*., 2002) "OCN1B_YYYY-MM-DD_S_RL.EXT.gz" where "YYYY-MM-DD" is the corresponding date, the GRACE satellite identifier "S" is fixed to X (meaning product can not be referred to GRACE-A or GRACE-B), RL is an increasing release number and EXT is fixed to asc (ASCII data). For data transfer simplification the products are gnu-zipped (suffix "gz").

Note: At present, this product is only available for the RL01 PPHA product, but, if requested by users also OMCT-based OCN1B products may be made available in the future. Please refer to the SDS monthly newsletters.

Each OCN1B file consists of a header with a dedicated number of lines (NUMBER OF HEADER RECORDS) and ends with a constant header line (END OF HEADER). The first part of the header is based on the level-1 instrument product header convention (Case *et al*., 2002) and gives more general information on the product (header lines PRODUCER AGENCY to INPUT FILE NAME). These lines are accomplished by a certain number of header lines which are derived from the original ocean model output header like

OCEAN MODEL NAME	:	The name of the ocean model
FORCING	:	Data set used for the forcing model
WIND STRESS	:	The name of the wind stress model
UNITS	:	Unit of barotropic sea level
LATITUDE SOUTH [DEG]	:	Southern latitude border of ocean model
LATITUDE NORTH [DEG]	:	Southern latitude border of ocean model
LATITUDE GRID SPACING [DEG]	:	Latitude grid spacing
LONGITUDE WEST [DEG]	:	Western longitude border of ocean model
LONGITUDE EAST [DEG]	:	Eastern longitude border of ocean model
LONGITUDE GRID SPACING [DEG]	:	Longitude grid spacing
NUMBER OF DATA SETS	:	Number of data fields per product (24 means hourly fields)

The following is an example for the header of the OCN1B_2001-10-31_X_00.asc product:

```
PRODUCER AGENCY               : GFZ
PRODUCER INSTITUTION          : GFZ
FILE TYPE ipOCN1BF            : 998
FILE FORMAT 0=BINARY 1=ASCII  : 0
NUMBER OF HEADER RECORDS      : 31
SOFTWARE VERSION              : V1.1c
SOFTWARE LINK TIME            : Not Applicable
REFERENCE DOCUMENTATION       : TBD
SATELLITE NAME                : GRACE X
SENSOR NAME                   : Not Applicable
TIME EPOCH (GPS TIME)         : 2000-01-01 12:00:00
TIME FIRST OBS(SEC PAST EPOCH):  57826748.816000 (2001-10-31 18:59: 8.81)
TIME LAST OBS(SEC PAST EPOCH) :  57909548.816000 (2001-11-01 17:59: 8.81)
NUMBER OF DATA RECORDS        :   967680
PRODUCT CREATE START TIME(UTC): 2002-04-28 00:13:09.000
PRODUCT CREATE END TIME(UTC)  : 2002-04-28 00:13:09.000
FILESIZE (BYTES)              :  3872384
FILENAME                      : OCN1B_2001-10-31_X_00.DAT
PROCESS LEVEL (1A OR 1B)      : 1B
INPUT FILE NAME               : pressol.20011101
OCEAN MODEL NAME              : BTPPHA
FORCING                       : ECMWF_0.5_DEGREE
WIND STRESS                   : LKB
UNITS                         : CM
LATITUDE SOUTH [DEG]          :  -75.375
LATITUDE NORTH [DEG]          :   65.250
LATITUDE GRID SPACING [DEG]   :    1.125
LONGITUDE WEST [DEG]          :    0.000
LONGITUDE EAST [DEG]          :  358.875
LONGITUDE GRID SPACING [DEG]  :    1.125
NUMBER OF DATA SETS           :  24
END OF HEADER
```

This header is followed by the binary original output of the barotropic or baroclinic ocean model. To read this binary data a software package is provided at the two GRACE data archives at ISDC and PO.DAAC.

7 Averaged AOD1B products: GAA, GAB, GAC and GAD

As stated in chapter 6.1, the daily AOD1B products provide three or four (RL04) sets of spherical harmonic coefficients from degree 0 up to a maximum degree (100 for all releases) for 6 hourly intervals:

DATA SET TYPE ATM: Spherical harmonic coefficients describing the global atmospheric variability in terms of gravity.

DATA SET TYPE OCN: Spherical harmonic coefficients describing the variability of the barotropic or baroclinic ocean model in terms of gravity.
Note: This is not ocean bottom pressure because the atmosphere is excluded (see chapter 6.1)!

DATA SET TYPE GLO: This is the sum of the global atmospheric variability plus the oceanic pressure variability in terms of gravity.

Note: The sum of the ATM and OCN spherical harmonics gives exactly the GLO data set for AOD1B-RL03 and RL04. However, because PPHA has undefined ocean areas, GLO is not exactly the sum of ATM plus OCN in case of RL01 products.

DATA SET TYPE OBA: Only for RL04 spherical harmonic coefficients are provided describing the ocean bottom pressure variability as derived from OMCT runs. Here, surface pressure (SP) instead of vertical integrated (VI) pressure variability is used to distinguish between what is observed (and subtracted) from GRACE (VI) and what is observed by ocean bottom pressure recorders (SP).
Special care has to be taken, because the S2 atmospheric tide was removed from the “oba” surface pressure data (SP-SP(mean)) using a strategy described in Ponte and Ray (2002).
Additionally, leakage from land is avoided because land pixels are set to zero before calculation of the spherical harmonics.

The 6-hourly AOD1B GLO-coefficients have to be applied (e.g. by linear or spline interpolation) to the static background mean gravity field during GRACE POD or calculation of gravity field partial derivatives in order to obtain short-term mass variation corrected monthly GRACE gravity field products. As a result, over land areas the GRACE monthly solutions describe (beside un-modeled signals such as post-glacial rebound) the continental water cycle or land ice mass variations.

Note: Although provided within the AOD1B products, the degree 0 and 1 terms are not used during determination of GRACE products!

For ocean applications the subtracted AOD1B signal has to be re-added to the GRACE monthly fields. Therefore, the Level-2 centers also provide the averaged AOD1B products used to generate their individual monthly fields (monthly GSM gravity fields and averaged AOD1B of each center’s release have the same time span!). The monthly mean values of the GLO-coefficients are the Level-2 GAC-products which are provided in the same format as the GSM gravity field solutions (see GRACE Level-2 Gravity Field Product User Handbook). The averaging of the GAx products is carried out over a whole number of days - regardless of whether full or partial day's data were used in creating the GRACE monthly solution.
Additionally, for RL04, also the GAD-products are provided (mean of the 6-hourly OBA products) because these products are free from continental leakage and directly provide monthly ocean bottom pressure variability (except a negligible small non-zero monthly mean atmospheric S2 tide).

In principal the GAC or GAD products are sufficient for GRACE gravity field analysis. But, as stated above and in TN04 the artificial leakage of the non-mass-conserving OMCT output to land areas has to be corrected for land applications. Therefore, the OCN data sets of the AOD1B products are also provided as monthly means. These products are labeled GAB and have to be added to the GFZ RL03 and JPL RL02

Level-2 products for land applications, because this gravity releases are both based on OMCT RL03 products. For further details it is recommended to read TN04!

For completeness also the monthly mean of the ATM coefficients are provided as GAA-products.

Note: As with the daily AOD1B products the GAA to GAD products include degree 0 and 1 terms. Users shall be aware not to apply these coefficients in their calculations!

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9 Acronyms

AOD1B	Atmosphere and Ocean De-aliasing level-1B product
ECMWF	European Center for Medium Weather Forecast
DWD	Deutscher Wetterdienst
GFZ	GeoForschungsZentrum Potsdam
GRACE	Gravity Recover And Climate Experiment
ISDC	Integrated System and Data Center
NCEP	National Center for Environmental Predictions
OCN1B	Ocean level-1B product
OMCT	Ocean Model for Circulation and Tides
PO.DAAC	Physical Oceanographic Distributed Active Archive Center
PPHA	Pacanowski, Ponte, Hirose and Ali