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Absolute gravimetry in Antarctica: Status and prospects

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Abstract

Twenty-three absolute gravity measurements at 12 stations have been performed in the Antarctic up to 2004. We review the measurements, and present a catalogue of gravity values. Four of the sites have repeated occupations. Gravity is sensitive both to elevation change and to changes in density distribution caused by past and present changes in the Antarctic ice mass. Thus, repeated absolute gravity measurements, especially when collocated with observations of vertical displacement from precise positioning systems, can provide information on the time evolution of the Antarctic ice sheet. We compare the observed gravity change with observed vertical motion, and with predictions from various models of the glacial isostatic adjustment and of present glacier mass balance.

Keywords: Antarctica; Absolute gravity; GPS; DORIS; VLBI; Glacial isostatic adjustment (GIA); Postglacial rebound (PGR); Glacier balance

1. Introduction

Gravity surveys in the Antarctic started in the 1950s. Reference stations for them were obtained by long-range relative ties from outside the Antarctic, using pendulums or spring gravimeters. Some early examples: Amalvict (2004) describes the tie from the BIPM site in Sèvres to Port-Martin and Pointe-Géologie in Adélie Land in 1952. Sledźinski (2001) gives an account on the pendulum measurement at Dobrolowski in 1958. Harada et al. (1963) report on the pendulum work at Syowa in 1962.

Absolute gravity measurements in the Antarctic began in 1990 when transportable instruments had become available. Apart from providing reference values for relative surveys, the purpose from the beginning has been to obtain information about gravity change and through that about earth dynamics.

Gravity value at a surface point depends both on the distance from the centre of mass of the Earth and on the density distribution. Variation in gravity can be caused by changes in the first, in the latter or in both. As a method of monitoring changes in height, absolute gravity has the drawback that density changes unrelated to the phenomenon under study may dominate the result. The advantage is that the measurement refers to the Earth's center of mass (Carter et al., 1989), independently of reference frame issues (Blewitt, 2003).

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Best results are achieved when both position and gravity change are monitored and jointly interpreted. During the last 20 yr several projects around the world have striven to obtain such co-located data. The target has often been the postglacial rebound (PGR), i.e., the viscoelastic response of the Earth to past changes in ice mass (glacial isostatic adjustment GIA), or the elastic response of the Earth to present-day deglaciation. The accuracy of modern absolute gravimeters is about $m_0 = 2\ \mu\text{Gal}$ (one-sigma) (Niebauer et al., 1995; Francis et al., 2005). Assuming independent annual measurements, a trend in gravity can be determined in N years with the precision $(12/(N(N-1)(N+1)))^{1/2}\, m_0$ or in 10 yr to 0.22 μGal/yr. Such studies are carried out in Laurentia since 1988 (Lambert et al., 2001), in Greenland since 1996 (Wahr et al., 2001), in Svalbard since 1998 (Sato et al., 2006), in Fennoscandia with absolute gravity since 1988 (Bilker et al., 2004; Wilmes et al., 2004); with relative gravity methods since 1966 (Ekman and Mäkinen, 1996; Mäkinen et al., 2005).

In many parts of the world, the Pleistocene and Holocene deglaciations have left a rich geological record. The contemporary PGR has, e.g., in Fennoscandia, been studied for more than 100 yr, starting with tide gauges and repeated leveling. Using these data, reasonably well-constrained models of the ice history and of the Earth rheology have been constructed. In the Antarctic, the geological record is scarcer and little contemporary PGR data exist. Large uncertainties are connected with the different scenarios of Antarctic ice history, and with its contribution to the global sea level and its climatic and paleoclimatic implications. While models of Antarctic ice history and present-day mass balance differ considerably among themselves (Wahr et al., 1995; James and Ivins, 1995, 1998; Nakada et al., 2000), they predict measurable changes of gravity at bedrock and of elevation of bedrock in some cases as large as −15 μGal/yr and 10 cm/yr (Huybrechts and Le Meur, 1999). Thus, observations of gravity and elevation change pan be used to shed light on the validity of the models.

In this paper, of which preliminary oral versions were presented by Amalvict (2003) and Amalvict and de Linage (2004), we catalogue and review all absolute gravity measurements in Antarctica from 1990 to the austral summer 2003/2004. As gravity change and vertical motion are closely related, we discuss this relationship and review observations of vertical motion at the gravity sites. Finally, we compare the observations with predictions of gravity change and vertical motion, derived from different scenarios of ice history and present-day mass balance.

2. Absolute gravity measurements

2.1. Chronology

Table 1 lists in chronological order all absolute gravity measurements in the Antarctic known to us. The stations are shown in Fig. 1. Their coordinates are in Table 2. Acronyms of institutions are in Table 3, and information about gravimeters in Table 4.

2.2. Results

Table 5 summarizes the published absolute gravity results and the documentation on them. Complete information is not always available. As the measurements span a long period and were processed independently by different groups, it is important to ascertain whether the same corrections have been applied to the raw observations of the momentary acceleration of the free fall. We will review the corrections and the measurements, using the processing standards of the International Absolute Gravity Base Station Network (IAGBN) by Boedecker (1988) as a guideline.

2.2.1. Earth tides

The major question is the treatment of the permanent tide. According to the Resolutions of the International Association of Geodesy (IAG) in 1983 (Tscherning, 1984) the influence of the permanent tidal yielding of the Earth should be retained in gravity, while the time average of the tide-generating force itself should be eliminated, i.e., the amplitude factor δ for the zero-frequency wave M_0S_0 in the tidal correction should be $\delta = 1$ ("zero tidal gravity"). If the effect of the permanent yielding is removed (say, using $\delta = 1.16$) we get "non-tidal" or "tide-free" gravity; if both permanent yielding and the tide-generating force are retained ($\delta = 0$) we get "mean tidal gravity" (Ekman, 1989). The transformation from non-tidal to mean gravity was historically done with the Honkasalo correction (Honkasalo, 1964). In some early data at hand the transformation from tide-free gravity to zero-tidal gravity was done with the formula of the Standard Earth Tide Committee (Rapp, 1983), which Boedecker (1988) also refers to. The formula is calculated

Table 1
Absolute gravity measurements in the Antarctic known to us, in chronological order

#	Station	Instrument	Expedition or organizer or project	Operating institute	Season	Reference
1	Terra Nova Bay IAGS (Italy)	IMGC	CNR, ENEA	IMGC	1990/1991	Cerutti et al. (1992)
2	Syowa (Japan)	GA60	JARE-33	GSI	1991/1992	Fujiwara et al. (1993, 1994)
3	Syowa	NAOM2	JARE-34	NAOM	1992/1993	Tsubokawa and Hanada (1994)
4		AGVRP		NAOM	1992/1993	Hanada and Tsubokawa (1994)
5	Aboa (Finland)	JILAg#5	FINNARP 1993	FGI	1993/1994	Mäkinen (1994)
6	Syowa	FG5#104	JARE-36	GSI	1994/1995	Yamamoto (1996)
7	McMurdo (United States)	FG5#102	USGS	NOAA	1995/1996	Sasagawa et al. (1997)
8	Terra Nova Bay AB	FG5#102	USGS	NOAA	1995/1996	Sasagawa et al. (1997)
9	McMurdo	FG5#102	USGS	NOAA	1997/1998	Sasagawa et al. (1997)
10	Terra Nova Bay AB	FG5#102	USGS	NOAA	1997/1998	Sasagawa et al. (1997)
11	Cape Roberts (United States)	FG5#102	USGS	NOAA	1997/1998	Sasagawa et al. (1997)
11	Mount Coates (United States)	FG5#102	USGS	NOAA	1997/1998	Sasagawa et al. (1997)
13	General Bernardo O'Higgins (Chile)	FG5#101		BKG	1997/1998	Lothhammer et al. (submitted for publication)
14	Jubany (Argentina)	FG5#101		BKG	1997/1998	Lothhammer et al. (submitted for publication)
15	Dumont d'Urville (France)	FG5#206	IPEV	IPGS/EOST	1999/2000	Amalvict et al. (2001)
16	Syowa	FG5#203	JARE-42	GSI	2000/2001	Kimura (2002)
17	Aboa	JILAg#5	FINNARP2000	FGI	2000/2001	Mäkinen (2002)
18	Syowa	FG5#203	JARE-45	GSI	2003/2004	Fukuda et al. (2005)
19		FG5#210	JARE-45	Kyoto University	2003/2004	Fukuda et al. (2005)
20	Sanae IV (South Africa)	FG5#221	FINNARP 2003	FGI	2003/2004	Mäkinen et al. (2004)
21	Aboa	FG5#221	FINNARP 2003	FGI	2003/2004	Mäkinen et al. (2004)
22	Novolazarevskaya (Russia)	FG5#221	FINNARP 2003	FGI	2003/2004	Mäkinen et al. (2004)
23	Maitri (India)	FG5	23rd IAE	NGRI	2003/2004	Anonymous (2005)

A summary of instrument types is given in Table 4. Acronyms of expeditions and institutes are explained in Table 3. All measurements were made by summer expeditions; italics in season description indicate the observation year. The reference is the earliest note in literature we have located, not necessarily the one from which the final results (Table 5) come. On the measurement at Maitri we have no further information, and it will not be treated in the continuation. During the field season 2005/2006 new measurements were performed at Dumont d'Urville (FG5#206), and Aboa, Sanae IV and Novolazarevskaya (all FG5#221). They are not treated in this paper.

on the assumption that the tide-free gravity was obtained using for M_0S_0 the amplitude factor of low-frequency tides in the Wahr (1981) theory. Thus, it may not in each case exactly restore zero-tidal gravity, as the amplitude factor that was used to get the non-tidal gravity in the first place may be different. However, in this connection the difference can be neglected.

For the measurements #2 and #3 the first publications provide tide-free or mean tide values. This is explained by Nakagawa et al. (1994) who give the zero-tide values we use.

For measurements #7 and #8, Sasagawa et al. (2004) provide the processing records. From them it is obvious that the Earth tide correction is tide-free. We therefore add $0.16 \times M_0S_0$ to #7 and #8, i.e., +9.1 and +8.7 μGal, respectively.

2.2.2. *Ocean tidal loading*

Analyzing ocean tidal models around the Antarctic is beyond the scope of this paper. In many cases, shortcomings of the global models are evident in the residual variation in the set-by-set absolute gravity time series where the models are used. Regional models have recently become available (Padman et al., 2002). The only site where gravimetrically observed tidal parameters were applied is Syowa (Ogawa et al., 1991; Shibuya and Ogawa, 1993).

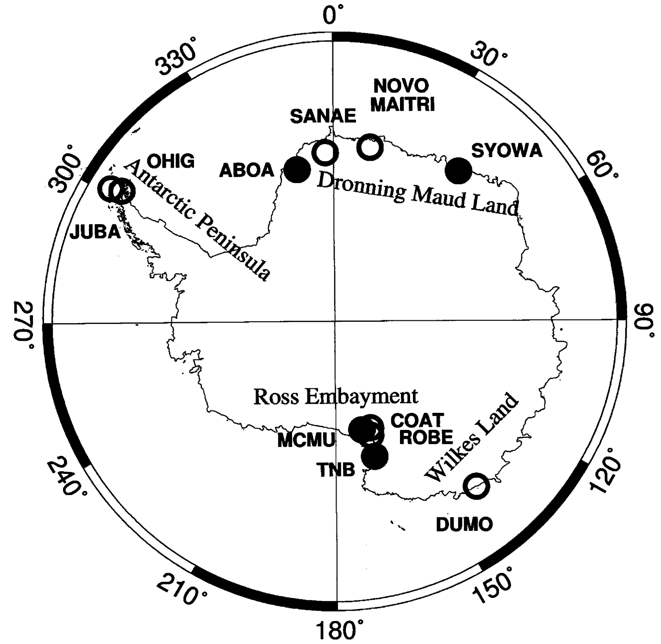

Fig. 1. Absolute gravity sites in the Antarctic, and the region names used to group them. Repeated absolute gravity sites are shown by a solid circle, others by open circles. The station abbreviations are starting eastwards from zero meridian—NOVO: Novolazarevskaya; DUMO: Dumont d'Urville; TNB: Terra Nova Bay; ROBE: Cape Roberts; COAT: Mt. Coates; MCMU: McMurdo; JUBA: Jubany; OHIG: O'Higgins. The rest have their full names shown.

However, the experience is that since absolute gravity data is usually taken over an extended period of time, model errors for the diurnal and semidiurnal waves are largely averaged out. Table 6 gives the ocean tidal models used in the computations.

2.2.3. Correction for polar motion

The sign of the correction in Boedecker (1988) is ambiguous and is known to have caused confusion at the time. Thus, it is worthwhile to check the correction in early papers when possible. Nakagawa et al. (1994) provide the computed corrections that show the correct sign.

Table 2
Coordinates of absolute gravity stations, used in the original computations

Station	Coordinates	Source
Aboa	73.0550°S, 13.4067W, 449.6 m	J. Mäkinen (personal information)
Cape Roberts	77.035°S, 163.179°E, 10 m	T. van Dam (personal information)
Dumont d'Urville	66.67°S, 140.17°E, 35 m	Amalvict et al. (2001)
Jubany	62.2333°S, 58.6600°W, 2 m	Lothhammer et al. (submitted for publication)
McMurdo (Satgrav) 1995	77°50′49″S, 166°40′05″E, 30 m	Sasagawa et al. (2004)
McMurdo (Satgrav) 1997	77.8469°S, 166.6681°E, 30 m	T. van Dam (personal information)
Mt. Coates	77.8058°S, 161.9967°E, 2207 m	T. van Dam (personal information)
Novolazarevskaya	70.7762°S, 11.8350°E, 118 m	J. Mäkinen (personal information)
O'Higgins	63.32103°S, 57.90011°W, 8.40 m	Lothhammer et al. (submitted for publication)
Sanae IV	71.6742°S, 2.8459°W, 855 m	J. Mäkinen (personal information)
Syowa (IAGBN)	69°00′5S, 39°35′5E, 21.492 m	Fujiwara et al. (1994)
Syowa (IAGBN)	69°0027.035″S, 39°35′06.372″E, 21.492 m	Nakagawa et al. (1994)
Terra Nova Bay (IAGS)	74°41′36.13″S, 164°05′59.26″E, 54.3 m	Cerutti et al. (1992)
Terra Nova Bay (AB)	74°41′36″S, 164°05′59″E, 30 m	Sasagawa et al. (2004)
Terra Nova Bay (AB)	74.6933°S, 164.0559°E, 30 m	T. van Dam (personal information)

Elevations refer to the mean sea level, to the ellipsoid, or to a local datum.

Table 3
Acronyms of institutions, programs and expeditions

BKG	Bundesamt für Kartographie und Geodäsie; Frankfurt/Main, Germany
CNR	Italian National Research Council
ENEA	Italian National Agency for New Technologies, Energy and the Environment
FGI	Finnish Geodetic Institute, Masala, Finland
FINNARP	Finnish Scientific Antarctic Expedition
GSI	Geographical Survey Institute, Japan
IAE	Indian Antarctic Expedition
IMGC	Istituto di Metrologia G. Colonnetti, Torino, Italy
IPEV	French Polar Institute
IPGS/EOST	Institut de Physique du Globe de Strasbourg, France
JARE	Japanese Antarctic Research Expedition
Kyoto Univ	Kyoto University, Japan
NAOM	National Astronomical Observatory of Japan, Mizusawa
NGRI	National Geophysical Research Institute, India
NOAA	National Oceanic and Atmospheric Administration, USA
USGS	United Stated Geological Survey

2.2.4. Correction for the gravity effect of the atmosphere

The main question here is the standard atmosphere for the reduction. Strictly speaking, the IAGBN standards do not specify a standard atmosphere, they only specify the standard atmospheric pressure for the station, depending on its height. This is the pressure according to DIN 5450, which differs insignificantly from, say, the U.S. Standard Atmosphere. Further, following the resolution no. 8 of the IAG in 1983 (Tscherning, 1984), IAGBN processing requests that the coefficient −0.30 μGal/hPa should be used, unless special investigations are available. Nowadays for highest accuracy the attraction and deformation effects are integrated using a full grid of surface pressures, sometimes even 3-D atmospheric density information.

In the Antarctic, long-term average pressures are typically well below the pressures according to a standard atmosphere. This causes a large constant negative part in the correction when the target is the standard atmosphere, and makes it attractive to use the average pressure instead. For example, at Syowa the average pressure (1957–1987) was 986.7 hPa, i.e., 24.0 hPa below the standard pressure 1010.67 hPa. In the measurement #2 the average pressure was used (Nakagawa et al., 1994), together with the empirical factor −0.32 μGal/hPa. We therefore make the correction $-0.32 \times (1010.67 - 986.7) = -7.7$ μGal to bring #2 in line with other measurements at Syowa.

Measurement #15 was reduced to 984.9 hPa, which is the mean pressure at Dumont d'Urville at the station height 35 m, from 40 yr of observations (Amalvict et al., 2001). The standard pressure at this height is 1009.0 hPa. Therefore, a correction of $-0.3 \times (1009.0 - 984.9) = -7.2$ μGal is added to the reported value.

2.2.5. Instrumental corrections

One particular instrumental correction concerns us here, namely the correction for the slow comparator of the zero crossing detector (ZCD) in early FG5 gravimeters (Niebauer et al., 1995). The processing tables by Sasagawa et al. (2004) show that the correction −12.5 μGal for this effect was applied for measurement #8, but not for #7, which consists of two measurements performed immediately before and after #8. We therefore assume that the correction for measurement #8 is accidental and eliminate it by adding 12.5 μGal to the value in Table 5.

Table 4
The types of absolute gravimeters used in the Antarctic

Gravimeter	Method	Description
IMGC	Rise and fall	Alasia et al., 1982
GA60	Rise and fall	Sakuma (1983), Murakami (1989)
NAOM#2	Free fall	Tsubokawa and Hanada (1986)
AGVRP	Free fall	Hanada et al. (1987)
JILAg	Free fall	Zumberge et al. (1982), Faller et al. (1983), Niebauer et al. (1986)
FG5	Free fall	Niebauer et al. (1995)

Table 5
The published results of Antarctic AG measurements

#	Station	Instrument	Date	Vertical gradient (μGal/cm)	AG value and uncertainty (one-sigma) (μGal)	Drop S.D. (μGal)	Level (m)	Source(s)
1	Terra Nova Bay (IAGS)	IMGC	20–27 December 1990		982854919 ± 3.7[a] 982855244 ± 5		0.91 0	Cerutti et al. (1992)
2*	Syowa (IAGBN)	GA60	4–28 January 1992	−3.34 ± 0.01	982523851 982524252	30	1.200	Nakagawa et al. (1994)
3	Syowa (IAGBN)	NAOM2	27 December 1992 26 January 1993	−3.34	982523825 982524152	40	0.980	Nakagawa et al. (1994)
4	Syowa (IAGBN)	AGRVP	3–10 January 1993 4–5 February 1993	−3.34	982523839 982524113	40	0.820	Nakagawa et al. (1994)
5	Aboa	Jilag#5	13–23 January 1994	−4.248 ± 0.03	982623069.8 ± 5		0	Koivula and Mäkinen (2005) Mäkinen et al. (in preparation)
6	Syowa (IAGBN)	FG5#104	20 January–11 February 1995	−3.34	982524326.9 ± 2.0	15	0	Kaminuma et al. (1997) Fukuda et al. (2005)
7*	McMurdo (Satgrav)	FG5#102	4–7 November 1995 1–3 December 1995	−3.28 + 0.03	982972759.9 ± 2.1 982972758.0 ± 2.2		1.000 1.000	Sasagawa et al. (2004)
8*	Terra Nova Bay (AB)	FG5#102	11–16 November 1995	−3.12 ± 0.03	982865642.9 ± 2.1		1.000	Sasagawa et al. (2004)
9	McMurdo (Satgrav)	FG5#102	22 and 25–26 November 1997	−3.28	982972777.5	6.9	1.000	T. van Dam (personal information)
10*	Terra Nova Bay (AB)	FG5#102	28 November–2 December 1997	−3.12	982865663.4	6.7	1.000	T. van Dam (personal information)
11	Cape Roberts	FG5#102	7–8 December 1997	−3.20	982905602.7	12.5	1.000	T. van Dam (personal information)
12	Mt. Coates	FG5#102	10 December 1997	−3.68	982431034.2	13.5	1.000	T. van Dam (personal information)
13	O'Higgins	FG5#101	12–14 December 1997	−3.52 + 0.04	982225537 ± 5		1.000	Lothhammer et al. (submitted for publication)
14	Jubany	FG5#101	18–20 December 1997	−3.09 ± 0.02	982199136 ± 4		1.000	Lothhammer et al. (submitted for publication)
15*	Dumont d'Urville	FG5#206	26 February–2 March 2000	−3.82 ± 0.03	982387174.2 ± 11.1[b]	57.5	0	Hinderer et al. (2002)
16	Syowa (IAGBN)	FG5#203	29 December 2000–25 January 2001	−3.34	982524328.2		0	Fukuda et al. (2005)
17	Aboa	Jilag#5	15–27 January 2001	−4.248	982623078.2 ± 5		0	Koivula and Mäkinen (2005), Mäkinen et al. (in preparation)
18	Syowa (IAGBN)	FG5#203	28 December 2003–17 January 2004	−3.34	982524322.8 ± 2.0	31.0	0	Fukuda et al. (2005)
	Syowa (45G1)	FG5#203	17–31 January 2004	−3.34	982524323.6 ± 2.0	34.0	0	
19	Syowa (IAGBN)	FG5#210	17 January–1 February 2004	−3.34	982524324.5 ± 2.0	14.2	0	Fukuda et al. (2005)
	Syowa (45G1)	FG5#210	28 December 2003–17 January 2004	−3.34	982524327.0 ± 2.0	12.5	0	
20	Sanae IV	FG5#221	25–27 January 2004	−4.40 ± 0.06	982449282.5 ± 1.9		1.200	Mäkinen et al. (2004, in preparation)
21	Aboa	FG5#221	5–7 February 2004	−4.248	982622565.9 ± 2.0		1.200	Mäkinen et al. (2004, in preparation)
22	Novolazarevskaya	FG5#221	10–11 February 2004	−3.55 ± 0.06	982579007.8 ± 2.0		1.200	Mäkinen et al. (2004, in preparation)

The numbers refer to Tables 1 and 5. The observations are numbered in the same way as in Table 1. Asterisk show measurements where we have modified or recomputed some correction(s) in Section 2.2. More explanations in text.

[a] Summing statistical scatter to error budget.

[b] Single-set scatter.

Table 6
Ocean tidal models used in the absolute measurements

#	Station	Ocean tidal model
1	Terra Nova Bay (IAGS)	N/A
2	Syowa (IAGBN)	Observed tidal parameters (Ogawa et al., 1991; Shibuya and Ogawa, 1993)
3	Syowa (IAGBN)	Observed tidal parameters
4	Syowa (IAGBN)	Observed tidal parameters
5	Aboa	Schwiderski
6	Syowa (IAGBN)	Observed tidal parameters
7	McMurdo (Satgrav)	Schwiderski
8	Terra Nova Bay (AB)	Schwiderski
9	McMurdo (Satgrav)	FES95.2
10	Terra Nova Bay (AB)	Schwiderski
11	Cape Roberts	FES95.2
12	Mt. Coates	FES95.2
13	O'Higgins	Schwiderski
14	Jubany	Schwiderski
15	Dumont d'Urville	FES95.2
16	Syowa (IAGBN)	Observed tidal parameters
17	Aboa	Schwiderski
18	Syowa (IAGBN) Syowa (IAGBN B)	Observed tidal parameters
19	Syowa (IAGBN) Syowa (IAGBN B)	Observed tidal parameters
20	Sanae IV	FES95.2
21	Aboa	Schwiderski
22	Novolazarevskaya	FES95.2

2.2.6. The vertical gradient

The value of the vertical gradient of gravity is used for two purposes. The gradient over the drop range is needed in the rigorous equation of motion. The gradient is also used to transfer the result to some conventional reference height above the station marker. In order to decouple the error in the gradient from the absolute result as far as possible, it would obviously be preferable to quote the absolute value close to the drop range. In Table 5 we therefore give the results both at a conventional height, and at the original observation height when published. Some of the stations have massive piers, because to prevent snow accumulation the laboratory is raised high above the ground. The attraction of the pier produces a height-dependent gradient. At present this is known to be an issue at Aboa, where the time series includes measurements with the JILAg#5 (at about 0.84 m) and with the FG5 (at about 1.20 m), and the available gradient was measured over the first 1 m above the pier.

2.2.7. Relative ties between the stations

At Terra Nova Bay the measurement #1 was performed at the site IAGS, and the measurements #8 and #10 at the site AB. No direct relative ties between the IAGS and AB have been reported but both have been connected to a third station, the IRGS. The result of #l (Cerutti et al., 1992), transferred to IRGS is 982 863 890 ± 33 μGal. In 1995, the relative tie from AB (at level 0.000 m) to IRGS gave −2040.9 ± 12.4 μGal (Sasagawa et al., 2004). From this it can be calculated that measurement #1 transferred to the site and level (1 m) of measurements #8 and #10 has the value $982863890 + 2040.9 - 312 = 982865619$ μGal and the standard error $(33^2 + 12.4^2 + 3^2)^{1/2} = 35$ μGal.

2.3. Summary of results at repeated stations

2.3.1. Terra Nova Bay

There are three measurements 1992–1997. The corrected and transferred values at AB (1 m height: #1 is 982865619 ± 35 μGal, #8 is 982865664.1 ± 2.1 μGal, and #10 is 982865663.4 μGal. It is reasonable to assign to

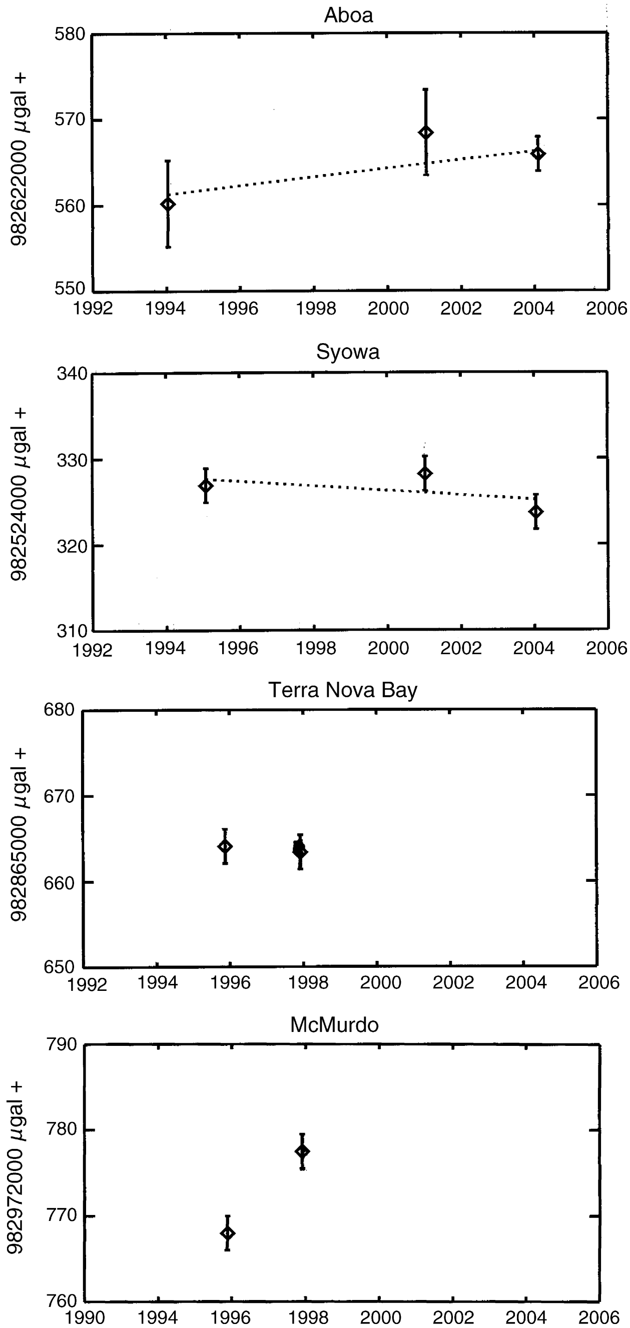

Fig. 2. Results of repeated absolute gravity measurements at four Antarctic sites (Aboa, Syowa, Terra Nova Bay, McMurdo). Comments in text.

#10 the same uncertainty 2.1 μGal as to #8. The #1 has a high uncertainty due to the long chain of relative transfers. Using only #8 and #10, the rate of gravity change from 1995 to 1997 is -0.4 ± 1.5 μGal/yr (Fig. 2a).

2.3.2. Syowa

Syowa has seven absolute measurements 1992–2004, where we have considered the 2003/2004 measurements on the two piers IAGBN and 45G1 to be a single measurement for each instrument. Nakagawa et al. (1994) and Fukuda et al. (2005) discuss some problems in the early observations 1992–1993. We follow Fukuda et al. (2005) who use only #6,

#16, and the mean of #18 and #19 for trend determination. The resulting rate of gravity change is −0.3 ± 0.4 μGal/yr (Fig. 2b).

2.3.3. Aboa

Aboa has three measurements 1994–2004. We reduce #5 and #17 to the level of #21 (1.20 m) and get 982622560.0 ± 5 and 982622568.4 ± 5 μGal, respectively. The weighted regression results in the gravity rate 0.5 ± 0.5 μGal/yr (Fig. 2c).

2.3.4. McMurdo

The corrected (see 2.2.1) average of the two occupations in #7 is (982972769.0 + 982972767.1)/2 = 982972768.0 μGal, and the measurement #9 is 982972777.5 μGal. We assign to both the uncertainty 2.0 μGal. The change + 8.5 μGal is rather large. It gives a gravity change rate +4.2 ± 1.4 μGal/yr (Fig. 2d).

3. Observations of vertical motion

In Table 7 we have collected information on techniques and available results at the absolute gravity stations.

3.1. GPS

Recent studies report Global Positioning System (GPS) observations leading to vertical velocities in various Antarctic regions: Donnellan and Luyendyk (2004) report vertical velocities as large as 12 ± 4 mm/yr in Marie Byrd Land, in accordance with predictions. Dietrich et al. (2004) focus on GPS in Antarctic Peninsula with 9.5 ± 5.6 mm/yr at O'Higgins and 2.4 ± 5.6 mm/yr at Palmer. They conclude that "10 yr of campaign-type observations are needed to separate vertical signals at the millimeter level from noise".

There are four International GPS Service (IGS) stations among our sites. Their vertical motion results in Table 7 are from M.B. Heflin's daily time series at http://sideshow.jpl.nasa.gov/mbh/series.html (retrieved February 22, 2005;

Table 7
Positioning techniques at the absolute gravity stations, starting year or time span of observations used, and observed rates of vertical motion, in mm/yr, with standard error (one-sigma)

Region	Station	CGPS	EGPS	DORIS	VLBI	ITRF2000
Dronning Maud Land	Aboa	2003– N/A	SCAR	–	–	–
	Sanae IV	IGS 1998– −1.59 ± 0.23	SCAR	–	–	−1.4 ± 1.1
	Novolazarevskaya	–	SCAR	–	–	–
	Syowa	IGS 1995– +1.75 ± 0.32	SCAR	1993–2005 +4.03 ± 0.21	1998– +4.6 ± 2.2	+2.1 ± 1.9
Wilkes Land	Dumont d'Urville	1997– −0.56[a]/0.43[b]	SCAR	1993–2005 +0.73 ± 0.15		−0.9 ± 1.4
Ross Sea	Terra Nova Bay	1998– +0.4 ± 0.1	SCAR	–	–	–
Embayment	Mt. Coates	1996– +4.5 ± 2.3	–	–	–	–
	Cape Roberts	–	–	–	–	–
	McMurdo	IGS 1995– −1.23 ± 0.33	SCAR	–	–	+0.8 ± 1.3
Antarctic	Jubany	1997–	SCAR	–	–	–
Peninsula	O'Higgins	IGS 1995– +6.53 ± 0.20	SCAR +9.5 ± 5.6	–	1992– + 5.1 ± 1.0	+ 9.5 ± 1.1

CGPS: continuous GPS; EGPS: Episodic GPS. Positive rates mean uplift. Explanations in text.
[a] Bouin.
[b] TIGA.

see Heflin et al., 2002). The more variable solutions from individual analysis centers can be inspected at http://www-gpsg.mit.edu/~tah/MIT_IGS_AAC/ maintained by T.A. Herring.

Bouin and Vigny (2000) processed the 1995–1998 data from the IGS stations and from Dumont d'Urville but did not publish the vertical velocities. The Dumont d'Urville data has however been used in the ITRF2000 (see Section 3.4). Bouin (personal information) calculated a vertical velocity for the 1998–2003 period of time, and TIGA (GPS Tide Gauge Benchmark Monitoring-Pilot Project) provides a weekly solution (ftp.sonel.org/pub/gps/tiga/neuseries). The Mt. Coates result is from Raymond et al. (2004). The rest of the CGPS stations in the table rely on annual downloads only, and the time series have either not been published or are still too short for conclusions. The preliminary result at Terra Nova Bay (Negusini et al., 2005) was provided by M. Negusini (personal communication 2004).

Several sites have participated in the SCAR GPS Epoch campaigns. For up-to-date listing see http://www.tu-dresden.de/ipg/service/scargps/database.html. Campaigns 1995–1998 were analysed by Dietrich et al. (2001). They refrained from publishing the vertical velocities, as from the 3-yr time span the uncertainty in them was quite high.

3.2. DORIS

Early Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) vertical velocities were published by Soudarin et al. (1999) using data 1993–1997. The values of velocity at Syowa and Dumont d'Urville (1993–2005) presented in Table 7 were provided by P. Willis (personal information). They were computed in the same way as the results (1993.0–2003.2) described by Willis and Heflin (2004), i.e., using the GGM01C geopotential model and aligned to ITRF2000 with a 14-parameter transformation. It is interesting to note that a free network DORIS solution has vertical rates 3–4 mm/yr smaller at the Antarctic sites (personal information by P. Willis; Willis and Heflin, 2004). This is mostly due to its translation drift in z relative to the ITRF2000 (op. cit.).

In addition to the table, there were two months of measurements at Terra Nova Bay in 1995. Obviously, in such a short time no velocity estimates could be obtained.

3.3. VLBI

Our dataset comprises the two Antarctic Very Long Baseline Interferometry (VLBI) sites. The velocity at Syowa comes from Fukuzaki et al. (2005) and the velocity at O'Higgins from Schlüter et al. (2004).

3.4. ITRF2000

The ITRF2000 (International Terrestrial Reference Frame) vertical velocities in Table 7 were computed from (x, y, z) rates available at ftp://lareg.ensg.ign.fr/pub/itrf/itrf2000/. The ITRF2000 solution combines results from different techniques and different analysis centers in an optimal way (Altamimi et al., 2002). The relatively large uncertainties at our sites may thus reflect the discrepancies between them.

4. Expected relationship between gravity change and vertical motion

The two major factors causing vertical bedrock motion in the Antarctic are thought to be the ongoing viscoelastic response of the Earth to past deglaciation(s) (GIA), and the instantaneous elastic response to contemporary variation in the ice balance.

In the context of the Fennoscandian GIA, two simple models were proposed in the 1960's for the ratio of gravity change at the solid surface and elevation change $\dot{g}/\dot{h}$ (Ekman and Mäkinen, 1996). Assume first that the uplift is due to decompression with no additional mass. This leads heuristically to the "free air model" $\dot{g}/\dot{h} = -2g/a = -0.31\ \mu\text{Gal/mm}$ where a is the radius of the Earth. If, on the other hand, there is no decompression, only additional mass in the upper mantle (density $\rho = 3300\ \text{kg/m}^3$), the Bouguer approximation leads to the ratio $\dot{g}/\dot{h} = -2g/a + 2\pi G\rho = -0.17\ \mu\text{Gal/mm}$, where G is the Newtonian constant of gravitation.

This latter figure is close to the ratio $\dot{g}/\dot{h} = -2g/a + (1/6.5) = -0.154\ \mu\text{Gal/mm}$ found numerically by Wahr et al. (1995). They applied Maxwell rheology of the mantle with various two-layer viscosity models. The discovery leads them to propose that absolute-gravity measurements could be used to remove the GIA contribution from observed $\dot{h}$ to leave only the elastic part due to contemporary ice balance. Fang and Hager (2001) found that such a Bouguer ratio is

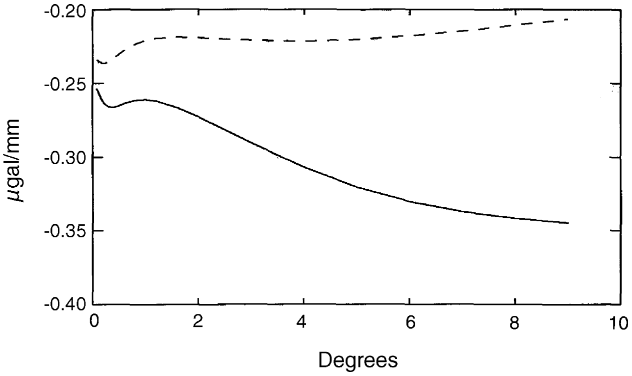

Fig. 3. Ratios of surface loading Green's functions from Farrell (1972), Gutenberg-Bullen Earth model. The dashed line is the ratio of elastic gravity (i.e., deformation effect only, no Newtonian term) and vertical displacement. In the solid line gravity includes the attraction of the load, approximated by a layer at station elevation. Gravity is positive down and displacement is positive up. More comments in text.

almost independent of the radial viscosity profile, as the viscous response of a Maxwell earth is nearly incompressible. Peltier (2004) points out that (as a consequence of an approximate relationship between viscoelastic load Love numbers) $\dot{g} \approx (-2g/a + g/a)\dot{h} = (-g/a)\dot{h}$; the ratio $-g/a$ then equals the number of Wahr et al. (1995) cited above.

Using repeated relative gravity (1966–1993) in Fennoscandia, Ekman and Mäkinen (1996) found empirically the ratio $\dot{g}/\dot{h} = -0.20 \pm 0.06\,\mu\text{Gal/mm}$, where the uncertainty is a 95% confidence interval. Recently Mäkinen et al. (2005), using longer gravity series and various new datasets of $\dot{h}$ quoted updated ratios -0.16 ± 0.04 to -0.18 ± 0.06 (two-sigma).

For the elastic influence of the present-day ice load it is more difficult to generalize about the ratio, as the direct attraction of the load is potentially a major contributor and it depends on local conditions like the mass variation and topography close to the station (James and Ivins, 1998; Le Meur and Huybrechts, 2001). As gravity change and vertical motion due to a surface load are typically computed by convoluting the corresponding Green's functions with the load, some guidance can, in any case, be obtained by comparing them. Fig. 3 shows the ratio of the Green's functions for gravity change and vertical motion. The ratio is about -0.23 μGal/mm when the attraction of the load is not included and around -0.27 μGal/mm when it is included.

In the Green's functions of Fig. 3, the load is approximated by a layer at station elevation, and thus only produces a gravity effect due to the curvature of the Earth. This is all right for far zones in flat topography but inappropriate near the station. In addition, the delta-function-like local attraction (with gravity effect $2\pi G\sigma$, where G is the Newtonian gravity constant, and σ is the surface density) is not at all represented in the Green's function (Pekeris, 1978). A rough calculation shows that it could overshadow the other two. Suppose the load is a spherical cap with radius 300 km and water-equivalent 0.5 m. In its center the vertical displacement is 11 mm, the elastic gravity effect 2.4 μGal, and the Newtonian part 0.4 μGal. The total is 3.0 μGal. The local attraction approximated by a Bouguer plate produces 21 μGal. This will not materialize, as the gravimeter is mounted on rock and not on the ice or snow, but depending on local geometry the local attraction could easily be 20% of the Bouguer plate or 4.2 μGal. Moreover, the near-field variation in ice and snow mass could be different from the regional average which determines the deformation.

5. Predictions of gravity and elevation change

5.1. Glacial isostatic adjustment

5.1.1. General considerations

The global sea level history continues to be one of the major constraints in modeling Antarctic deglaciation, and it is customary to characterize the ice models in terms of their contribution to the eustatic sea level (ESL). To get an idea of the size of the rebound signals expected, a back-of-the-envelope calculation follows, with caveats in parentheses. Recent models tend to produce around 15 m in ESL. This corresponds to an ice layer about 500 m thick if spread uniformly over the present-day grounded ice area (but in several places the ice has earlier extended even to the continental shelf edge). Assuming local isostasy, and a density of 3300 kg m^{-3} for the mantle and 917 kg m^{-3}

for the ice, the equilibrium response of bedrock height is 917/3300 × 500 = 140 m (but of course local isostasy is a simplification, and as the absolute gravity stations are close to the ice edge, complicated forebulge phenomena can be expected). Suppose that the rebound can be characterized by exponential decay with a relaxation time of 3 kyr, which in view of the decay times observed in Fennoscandia and Laurentia (Mitrovica, 1996) is rather on the short side. Then if the 500 m ice layer was removed linearly between 10 and 5 kyr before present, we would today expect a vertical velocity of 4.3 mm/yr and a gravity rate of −0.66 μGal/yr. It would thus seem that even in this minimum estimate (using primitive calculations) the Antarctic deglaciation is expected to produce an observable present-day rebound.

Of course, the actual scenarios do not include a constant-thickness deglaciation model. Typically a large loss of ice is shown in West Antarctica, while the East Antarctica has been considered more stable. In the sequel we will discuss published deglaciation models and the predictions of $\dot{g}$ and $\dot{h}$ they provide at the absolute gravity sites.

5.1.2. Published deglaciation models and postglacial rebound predictions

Predictions of contemporary $\dot{g}$ and/or $\dot{h}$ for the whole Antarctic are available from several models of ice history. James and Ivins (1998) provide numerical values of both $\dot{g}$ and $\dot{h}$ at five of our sites, plus maps with isolines from which values can be estimated for the remaining ones. The models are labeled LC79, ICE-3G, and D91. The rheological parameters are: lithospheric thickness 120 km, upper mantle viscosity 1×10^{21} Pa s, lower mantle 2×10^{21} Pa s. In addition, they have results from ICE-4G ($\dot{h}$ only) from preliminary maps. Nakada et al. (2000) produce maps of $\dot{g}$ and $\dot{h}$ for models ANT3, ANT4, ICE-3G, HB, D91, ANT5 and ANT6. Their rheology is: lithosphere 100 km, upper mantle viscosity 5×10^{20} Pa s, lower mantle 1×10^{22} Pa s.

Kaufmann et al. (2005) give maps of $\dot{h}$ for models ANT3, ICE-3G, and HUY. The 1-D rheology appears to be (their Fig. 2a) lithosphere 100 km, upper mantle viscosity about 3×10^{20} Pa s, lower mantle 1×10^{22} Pa s. They also have predictions from a model with lateral viscosity variations. Their maps have isolines only at 5 mm/yr, which makes the interpolation of values for our sites difficult. Huybrechts and Le Meur (1999) provide a map of $\dot{h}$; in this paper we call their model HULM. The rheology is lithosphere 100 km, upper mantle viscosity 5×10^{20} Pa s, lower mantle 1×10^{21} Pa s. HULM is remarkable in that it is couples a dynamic 3-D model of the ice sheet with the GIA response of the bedrock. All the other computations use a prescribed ice model as an input to the GIA computation. Ivins et al. (2002) make detailed predictions of $\dot{h}$ for the Antarctic Peninsula (O'Higgins and Jubany stations in our data) from a number of ice scenarios and rheological models. They are too extensive to be summarized here. Ivins and James (2005) provide colour-coded maps of $\dot{h}$ predictions using their deglaciation model IJ05 and different mantle rheologies. In addition, there are a number of recent models of Antarctic ice history that have so far not been used to predict contemporary $\dot{g}$ and/or $\dot{h}$ rates.

Given the close relationship of $\dot{g}$ and $\dot{h}$ in GIA predictions, it does not matter much if only $\dot{h}$ is given. We have verified that multiplying the $\dot{h}$ predictions of James and Ivins (1998) by the coefficient −0.154 μGal/mm reproduces their $\dot{g}$ predictions always better than 0.18 μGal/yr, in 80% of the cases to better than 0.10 μGal/yr. As to the maps of $\dot{g}$ and $\dot{h}$ by Nakada et al. (2000), inspection shows that they are identical save for the scale.

In order to put the PGR predictions into perspective, and to keep the exposition self-contained, some information on the ice models is needed here. The central factors for the prediction are (James and Ivins, 1998): (a) the total amount of ice removed, usually expressed in terms of the contribution to ESL (b) the timing of the deglaciation, and (c) its spatial pattern. Table 8 shows the main features of the ice models, and the predictions they provide. Since the spatial pattern of the deglaciation within each area is not always well constrained by observations, we have grouped the absolute-gravity stations according to the region: Dronning Maud Land (Aboa, Sanae, Novolazarevskaya, Syowa), Wilkes Land (Dumont d'Urville), Ross Embayment (Terra Nova Bay, Mt. Coates, Cape Roberts, McMurdo), Antarctic Peninsula (O'Higgins, Jubany). We give the predictions in terms of $\dot{h}$; predictions of $\dot{g}$ are approximately obtained by multiplying them with −0.154 μGal/mm.

The majority of the ice models derive in some way from the CLIMAP reconstruction (Hughes et al., 1981; Stuiver et al., 1981) at LGM. The CLIMAP does not include any scenario for the deglaciation timing. The ANT3 was obtained as a difference between the CLIMAP and the present-day ice-sheet and timed to explain far-field sea level data (Nakada and Lambeck, 1988). Though the deglaciation is early, the large masses produce appreciable uplift signals at all our sites. ANT4 (Nakada and Lambeck, 1989) was obtained from ANT3 by scaling down the amount of ice. Nevertheless, as the timing was moved closer to the present, ANT4 provides nearly the same predictions as ANT3. The model ANT5

(Nakada et al., 2000) was obtained by keeping ANT4 in the interior of the ice sheet, and modifying coastal parts to fit RSL histories at eight sites. Model ANT6 (Nakada et al., 2000) is a minimum model to satisfy only those eight RSL histories and shows little loss of mass elsewhere.

The model LC79 derives from Lingle and Clark (1979), digitization and timing is by James and Ivins (1998). The D91 model (Denton et al., 1991) is a revision of the CLIMAP, based on new geological and glaciological evidence. In East Antarctica, the mass reduction in D91 is mostly along the coasts, which produces large rates at some absolute sites.

The model ICE-3G (Tushingham and Peltier, 1991) is based on the CLIMAP, and on RSL histories from four sites. The ICE-4G (Peltier, 1994) values in Table 8 are from James and Ivins (1998) and come from preliminary maps; numerical values for O'Higgins and McMurdo from a revised ICE-4G (Peltier, 1998) are available at http://maia.usno.navy.mil/conventions/chapter7/pgr.model and differ slightly from those in Table 8. A further revision of ICE-4G (Peltier, 2002) has 17.3 m in ESL rise and main deglaciation between 10 and 4 ky BP. ICE-5G (Peltier, 2004) is in the Antarctic essentially identical with it.

The model HB (Nakada et al., 2000) is based on the glaciological 3-D modeling by Huybrechts (1990), but the deglaciation is assumed to have taken place between 12 and 6 kyr B.P. such that all sites have the same time history. In the original model by Huybrechts (1990) deglaciation mostly took place after 6 BP and is continuing until today. This scenario (HUY in Kaufmann et al., 2005) produces quite different rates.

The coupled glaciological-isostatic model by Huybrechts and Le Meur (1999) called HULM in Table 8 has the deglaciation still continuing today. It produces very large vertical rates, more than 100 mm/yr in West Antarctica (where there are no absolute sites).

The most recent model IJ05 (Ivins and James, 2005) draws extensively on geological and glaciological evidence, using Denton and Hughes (2002) as an initial guide. The deglaciation in East Antarctica takes place in the coastal zones.

Nakada et al. (2000) provide isolines of ice thickness removed since LGM for ANT3, ANT4, ICE-3G, HB, D91, ANT5, and ANT6. Kaufmann et al. (2005) have snapshots of ANT3, ICE-3G, and HUY at three epochs, as do Ivins and James (2005) for IJ05. We may summarize them and Table 8 as follows:

(1) All models except ANT5 and ANT6 have substantial deglaciation in the Ross Sea Embayment, but due to differences in spatial distribution and timing can produce either negligible rates, large rates, or a gradient between McMurdo and Terra Nova Bay. Interestingly, ANT5 and ANT6, which are controlled by RSL histories at both these sites, have little deglaciation and small rates.

Table 8
Models of Antarctic deglaciation from which predictions of vertical motion or surface gravity change are available

Model acronym	ESL (m)	Start (kyr)	End (kyr)	Region and vertical motion (mm/yr)			
				DML	WL	Ross	AP
LC79	29	9	4	0–1	0	1–7	7
D91	24.5	12	4	1–6	4	4–5	−1
ANT3	37	17	6	1–2	2	4–6	2
ANT4	24	12	6	1–2	2	4–6	2
ANT5	16.7	12	6	2	2	1	1
ANT6	6.6	12	6	0–1.5	0	1	1.5
HB	12	12	6	0–2	2	6–8	2
HUY	13	6	C	(0–2)	(7)	(2)	(2)
ICE-3G	26	9	4	0–1	0	−2 to 0	4
ICE-4G	22	12	5	1–2	0	−1 to 0	4
HULM	19	9	C	1	2	5	0–2
IJ05	11	15	C	(0–2)	(2)	(0–1)	(3)

The models are described in the text. Here they are characterized by the equivalent change in eustatic seal level (ESL), and by start and end of deglaciation in kyr. "C" means the deglaciation is still going on. The vertical motion predictions give the range for absolute gravity sites in Dronning Maud Land (DML; Aboa, Sanae, Novolazarevskaya, Syowa), in Wilkes Land (WL; Dumont d'Urville), in the Ross Sea Embayment (Ross; McMurdo, Mt. Coates, Cape Roberts, Terra Nova Bay), and in the Antartic Peninsula (AP; O'Higgins, Jubany). The rates in model HUY and IJ05 are in parentheses as they were estimated from isolines with 5 mm/yr intervals (HUY) and colour-coded maps (IJ05).

(2) Relatively small rates are predicted for Dronning Maud Land throughout, except by D91, which has a large deglaciation in the area of the Riiser-Larsen ice-shelf and large positive rate (at Aboa).
(3) The predictions for the Antarctic Peninsula sites are highly variable, and obviously detailed modeling (Ivins et al., 2002) is required.
(4) In Wilkes Land, glaciological modelling (HUY, HULM) produces past ice domes that in the case of HUY predict a large rate at the Dumont d'Urville.
(5) Most models predict large rates in the interior of the West Antarctic ice sheet, where there are no absolute gravity sites.

5.2. Present-day mass imbalance

Note that the models HUY, HULM and IJ05 described in the previous section in principle contain also the prediction from present-day mass imbalance. James and Ivins (1998) show predictions from four scenarios, developed by James and Ivins (1997), from estimates by Bentley and Giovinetto (1991) and by Jacobs et al. (1992). We do not go into the models in detail, but we will comment on them in the next chapter in connection with the observations.

6. Comparison of observations and predictions

Observed and predicted gravity change and vertical motion at the four 'repeat' sites are collected in Table 9.

6.1. Dronning Maud Land

At Syowa, both gravity and vertical motion observations indicate uplift, in harmony with the minor uplift predicted from the PGR modeling and with small predicted present-day effects. At Aboa gravity results prefers subsidence, although the rate does not significantly differ from zero. Clear subsidence is not predicted by any of the PGR models; on the contrary, the D91 with a large deglaciation at the Riiser-Larsen ice shelf predicts appreciable uplift with gravity change −1.1 μGal/yr (James and Ivins, 1998). One of the contemporary scenarios of James and Ivins (1998) does predict subsidence (+0.5 μGal/yr) at Aboa, but then it does that for most of coastal Antarctica. In any case it is interesting to note that the CGPS at Sanae IV supports minor subsidence (Table 7).

6.2. Ross Sea Embayment

Neither at Terra Nova Bay nor at McMurdo do the gravity results and vertical motion observations (Table 9) support the large PGR uplift predicted by many of the models in Table 8. It is noteworthy that ANT5, which is constrained by RSL histories at both sites, predicts only minor uplift in the area. The contemporary scenarios predict stability or

Table 9
Observed and modelled gravity change and vertical velocity, for the four stations with repeated absolute gravity

Region	Station	Observed	Modelled PGR	Modelled elastic
Dronning Maud Land	Aboa $\dot{g}$	+0.5 ± 0.5 μGal/yr	0 to −1.1 μGal/yr	+0.5 to −0.7 μGal/yr
	Aboa $\dot{h}$	N/A	−0.1 to +6.6 mm/yr	−2.0 to +2.6 mm/yr
	Syowa $\dot{g}$	−0.3 ± 0.4 μGal/yr	−0.1 to −0.3 μGal/yr	+0.2 to −0.2 μGal/yr
	Syowa $\dot{h}$	+1.8 ± 0.3 to +4.6 ± 2.2 mm/yr	+0.7 to +1.6 mm/yr	−0.7 to +0.6 mm/yr
Ross Sea Embayment	TNB[a] $\dot{g}$	−0.4 ± 1.4 μGal/yr	+0.3 to −1.0 μGal/yr	+0.5 to 0.0 μGal/yr
	TNB[a] $\dot{h}$	+0.4 ± 0.1 mm/yr	−2.0 to +6 mm/yr	−1.6 to −0.1 mm/y
	McMurdo $\dot{g}$	+4.5 ± 1.4 μGal/yr	+0.1 to −1.2 μGal/yr	+0.3 to 0.0 μGal/yr
	McMurdo $\dot{h}$	−1.2 ± 0.3 to +0.8 ± 1.1 mm/yr	−0.1 to +8 mm/yr	−1.0 to 0.0 mm/yr

Error estimates are one-sigma. The column "Modelled PGR" gives the range of predictions from the models discussed in Section 5.1. and Table 8. In the units given, the $\dot{g}$ and $\dot{h}$ predictions are roughly related by $\dot{g} = -0.154 \times \dot{h}$. The column "Modelled elastic" gives the range of predictions by James and Ivins (1998) from their 4 scenarios of present-day ice sheet evolution. The $\dot{g}$ and $\dot{h}$ predictions are roughly related by $\dot{g} = -0.27 \times \dot{h}$.
[a] TNB: Terra Nova Bay.

minor subsidence. On the other hand, none of this agrees with the larger uplift measured by CGPS (Table 7) at Mt. Coates near McMurdo. Further, the gravity results at McMurdo are baffling: the gravity increase is much larger than the minor subsidence from CGPS would lead us to expect.

7. Summary and discussion

We have collected 23 absolute gravity measurements at 12 Antarctic sites, reviewed them, and aligned the results to the IAGBN processing standards. Repeated measurements are available at four sites. We have compiled information on vertical motion observed with various techniques, and reviewed the corresponding predictions from 12 GIA models for all existing absolute gravity sites, grouped regionally. While the observational data is still much too scarce for definite conclusions, the following preliminary assessment can be made: (1) in Dronning Maud Land, observed $\dot{g}$ and $\dot{h}$ are roughly consistent with each other and with GIA and contemporary ice mass scenarios that predict only minor vertical motion. (2) At the sites in the Ross Sea Embayment, observed $\dot{g}$ and $\dot{h}$ do not support the large uplift predicted by many GIA models. (3) Observed $\dot{g}$ and $\dot{h}$ appear inconsistent at McMurdo and around it.

The majority of the sites are situated in coastal areas of East Antarctica, in regions where most models predict only minor PGR. The reason is obviously the geographical distribution of Antarctic bases on bedrock, as absolute gravity measurements up to now have required almost laboratory conditions. Large PGR rates are predicted in the Ross Sea Embayment, in the Antarctic Peninsula, and in the interior of West Antarctica. In these areas the differences among models are large, too, and they should be specially targeted in future measurements. Of particular interest are the history and current balance of the West Antarctic ice sheet, where there are nunataks but no bases. The ongoing development of portable absolute gravimeters may facilitate the collection of repeated absolute gravity data to support such studies.

The new satellite missions are obviously having a large impact on Antarctic glaciology and Earth sciences (Fukuda et al., 2002). The Gravity Recovery and Climate Experiment (GRACE) satellite mission is currently collecting a time series of variation in the gravity field of the Earth that can be inverted for variation in total regional mass, including both GIA and the present-day ice mass (Velicogna and Wahr, 2006). The Ice, Cloud, and Land Elevation Satellite (ICESat; Zwally et al., 2002) and the CryoSat-2 mission (Drinkwater, 2003) will provide time series of Antarctic surface elevations, to continue and areally expand the series from ERS-1 and ERS-2 altimetry (Wingham et al., 1998; Zwally et al., 2005). The simulations by Velicogna and Wahr (2002) based on pre-mission error models show considerable improvement in the recovery of PGR and ice mass signals if pointwise vertical motion observations are added to the combination of GRACE and ICESat.

Most of the discussion in this paper has been about the use of repeated absolute gravity measurements for geodynamics. In view of the discrepancies between different velocity solutions (cf. Section 3) they may also prove useful for resolving reference frame issues. Finally it should be pointed out that for the gravity mapping of the Antarctic, whether airborne or from the surface, there is a continued need of more high precision (i.e., absolute) reference sites, and there a single measurement usually suffices.

Several absolute gravity measurements are already planned for the coming International Polar Year (IPY, March 2007–March 2009) In addition to bedrock sites, measurements on the ice sheets, carefully monitored by GPS, are considered. New portable absolute gravimeters could provide easier measurements, but with a lower precision and accuracy.

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