12th DECIGO Workshop
東京大学理学部4号館1220室
2013年10月27日

今後の衛星重力ミッションの動向

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京都大学大学院理学研究科

話　題

- 衛星重力ミッションの概要

- これまでの成果
  - 時間変動地球重力場(GRACE)
  - 静的（平均）地球重力場(GOCE)

- 将来ミッション

衛星重力ミッション

CHAMP (2000.07.15)- (2010.09.19)

- CHAllenging Mini-satellite Payload for geophysical research applications
- H-L Satellite-to-Satellite Tracking

GRACE (2002.03.17)- (2017 ??)

- Gravity Recovery And Climate Experiment
- L-L Satellite-to-Satellite Tracking (Microwave Link)

GOCE (2009.03.17) - (2013.10.21)

- Gravity field and steady-state Ocean Circulation Explorer
- Gravity Gradiometer

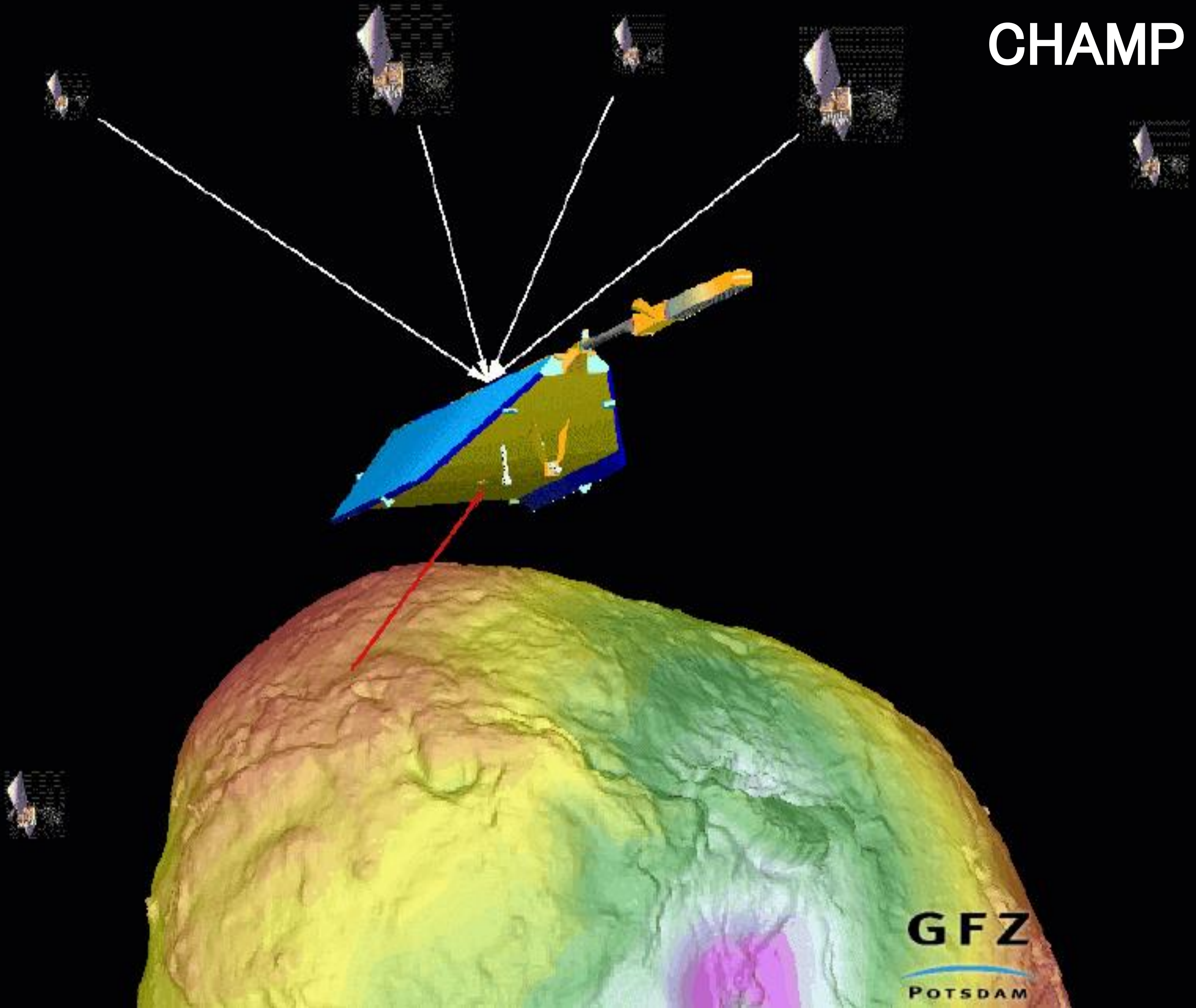
Swarm(2013.11.14 scheduled)

- ESA's magnetic field mission
- H-L Satellite-to-Satellite Tracking (CHAMP like 3 satellites)

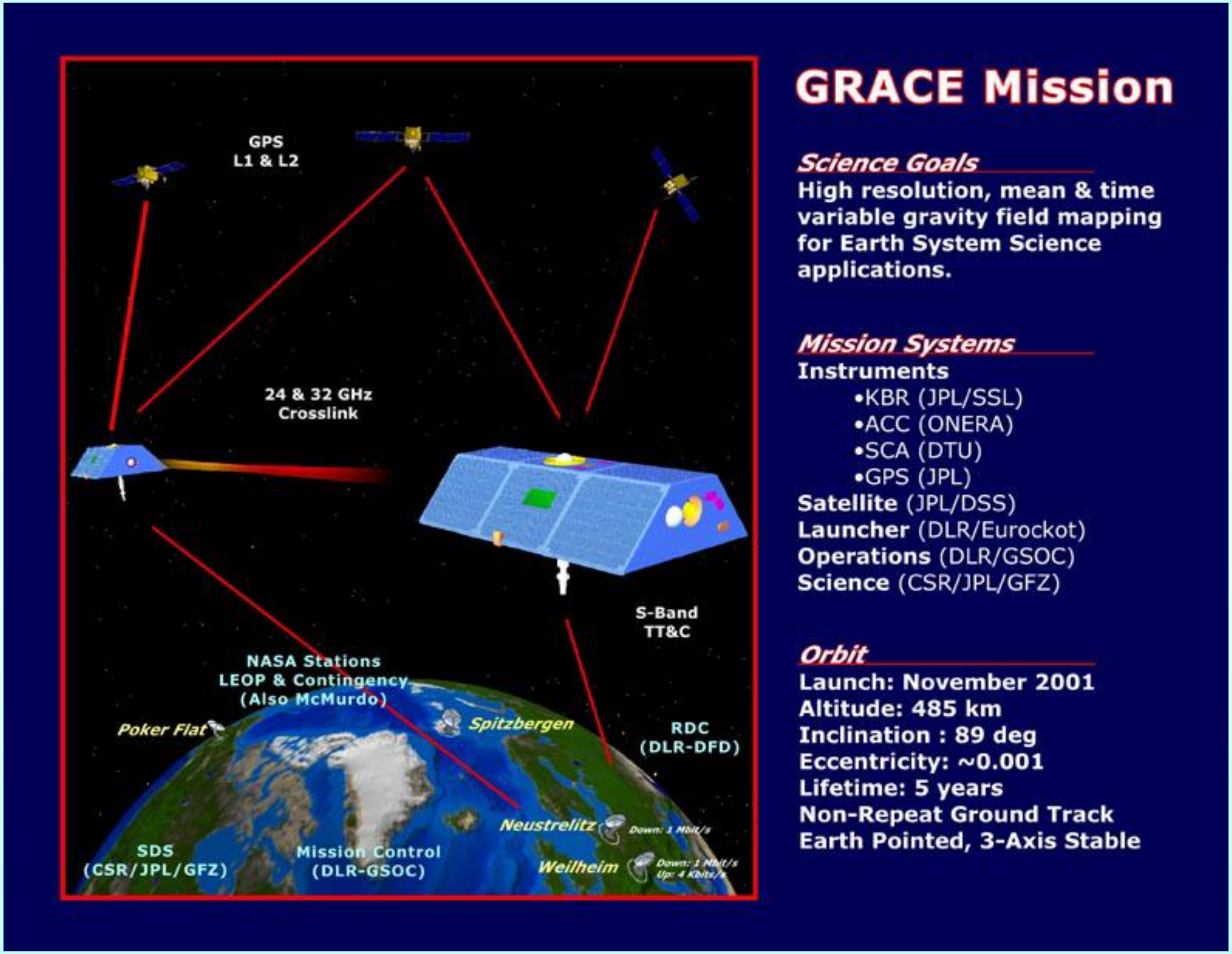
GRACE-FO (2017), GRACE-II (202?)

- GRACE GAP Filler (Microwave Radar)
- L-L Satellite-to-Satellite Tracking (Laser Link)

CHAMP



GRACE Mission



GRACE Mission

Science Goals

High resolution, mean & time variable gravity field mapping for Earth System Science applications.

Mission Systems

Instruments

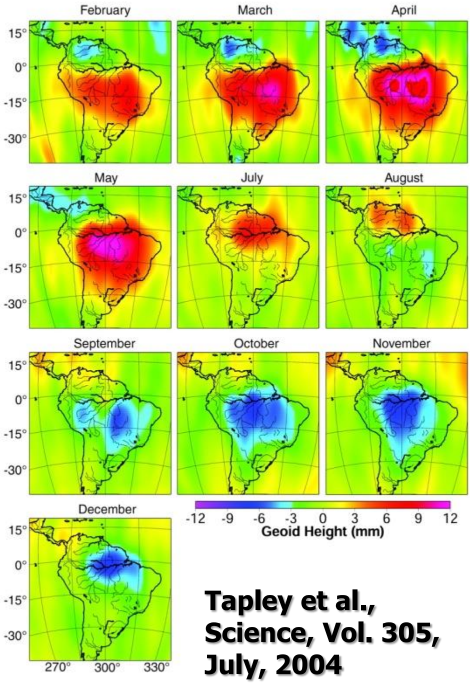
- KBR (JPL/SSL)
- ACC (ONERA)
- SCA (DTU)
- GPS (JPL)

Satellite (JPL/DSS)
Launcher (DLR/Eurockot)
Operations (DLR/GSOC)
Science (CSR/JPL/GFZ)

Orbit

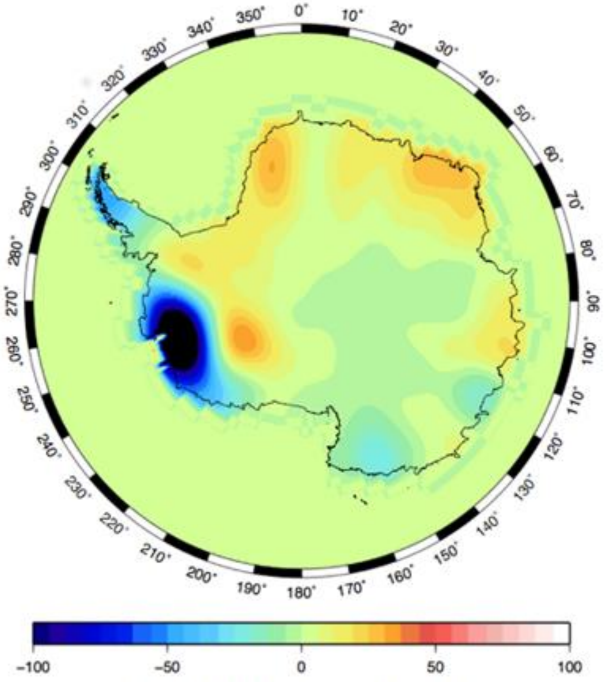
Launch: November 2001
Altitude: 485 km
Inclination : 89 deg
Eccentricity: ~0.001
Lifetime: 5 years
Non-Repeat Ground Track
Earth Pointed, 3-Axis Stable

GRACE Applications



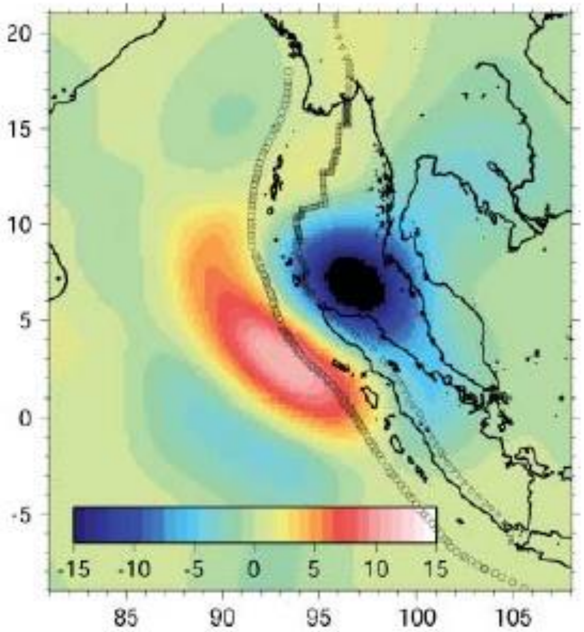
Tapley et al., Science, Vol. 305, July, 2004

Landwater Changes



CSR RL04 in mmH2O/yr
2003/01 ~ 2010/12

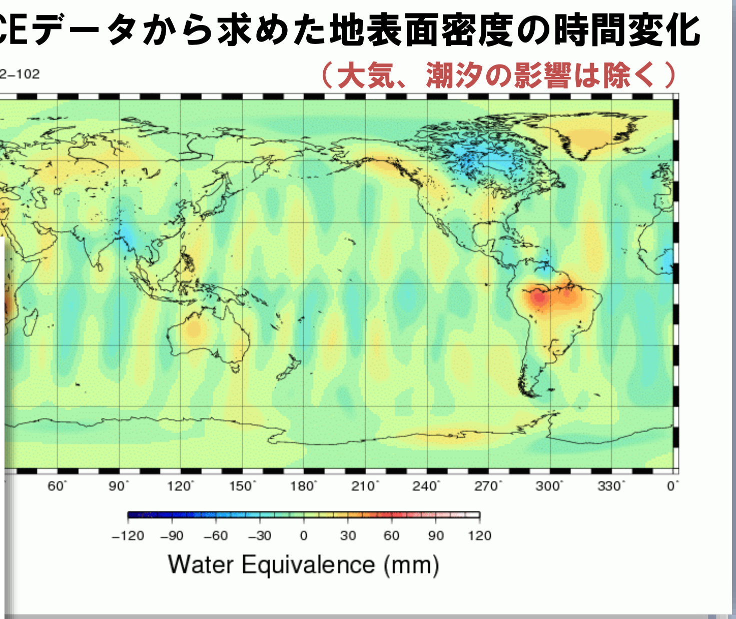
Ice Sheet Mass Changes



Chan *et al.* (2006)

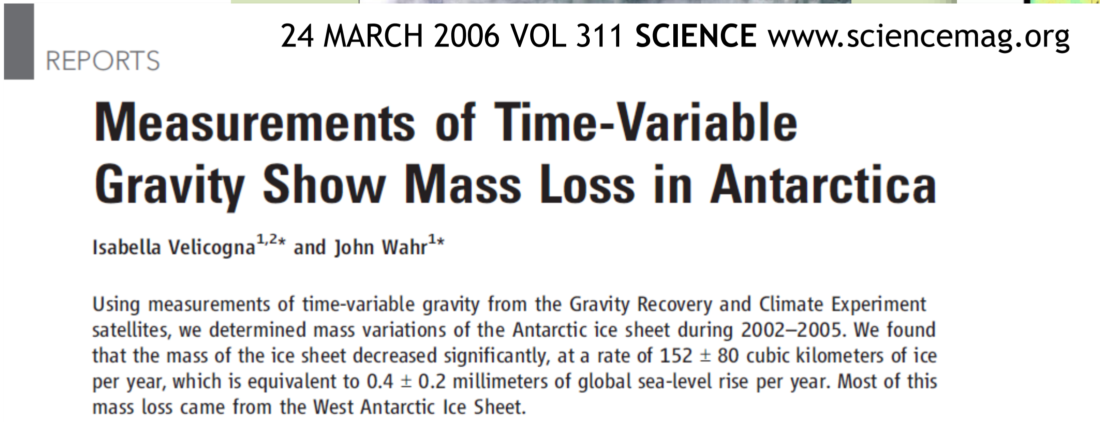
Earthquakes

現行の衛星重力ミッション～ GRACE (2002~)



GRACEデータから求めた地表面密度の時間変化

（大気、潮汐の影響は除く）



REPORTS

24 MARCH 2006 VOL 311 **SCIENCE** www.sciencemag.org

Measurements of Time-Variable Gravity Show Mass Loss in Antarctica

Isabella Velicogna[1,2]* and John Wahr[1]*

Using measurements of time-variable gravity from the Gravity Recovery and Climate Experiment satellites, we determined mass variations of the Antarctic ice sheet during 2002–2005. We found that the mass of the ice sheet decreased significantly, at a rate of 152 ± 80 cubic kilometers of ice per year, which is equivalent to 0.4 ± 0.2 millimeters of global sea-level rise per year. Most of this mass loss came from the West Antarctic Ice Sheet.

南極氷床の減少を初めて明らかに

２００２～２００５年のＧＲＡＣＥデータから、南極全体で１５２±８０km^3/yrで質量が減少していることを報告

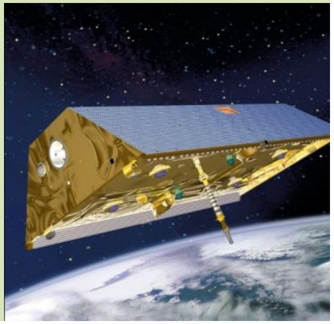
✓ 地上観測が困難な環境での大陸全体での氷床質量の減少量を

→ 衛星観測の有効性

精度：10^{-8} m/s^{2}の精度の全球解を、1カ月間隔

→ 地表での水の変化に換算して数cm

現行の衛星重力



REPORTS

24 MARCH 2006 VOL 311 SCI

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Isabella Velicogna[1,2]* and John Wahr[1]*

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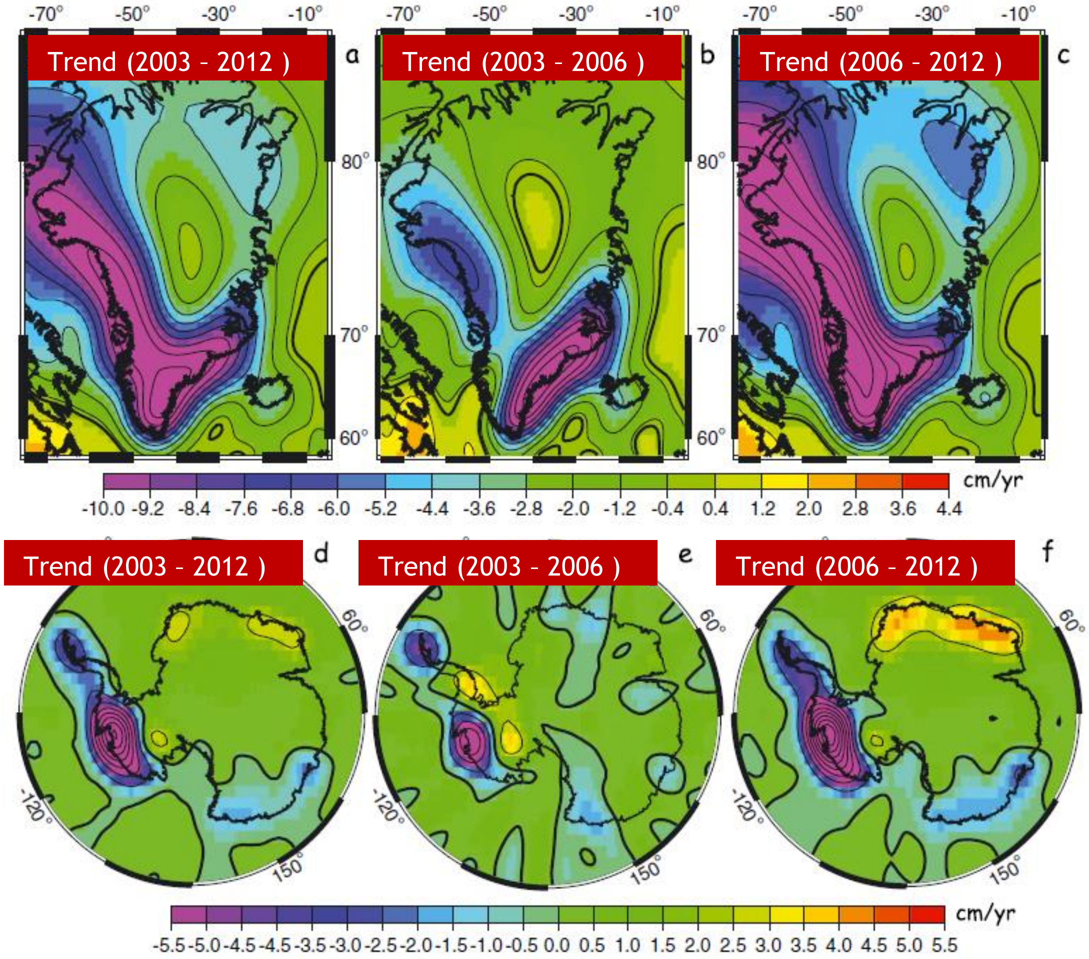
南極氷床の減少を初めて

２００２～２００５年のＧＲＡＣＥデータ
２±８０km³/yrで質量が減少していること

- ✓ 地上観測が困難な環境での大陸全体での
  - → 衛星観測の有効性

GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 3055–3063, doi:10.1002/grl.50527, 2013

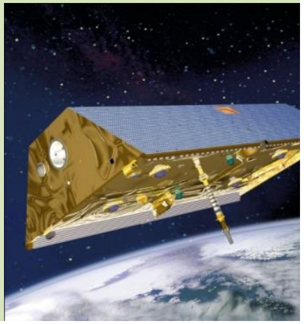


近年の氷床融解の加速

大陸で平均すると、質量減少が加速

地域別には、氷床融解が加速する地域と
積雪により質量が増加した地域の両方がある

現行の衛星重力



REPORTS

24 MARCH 2006 VOL 311 S

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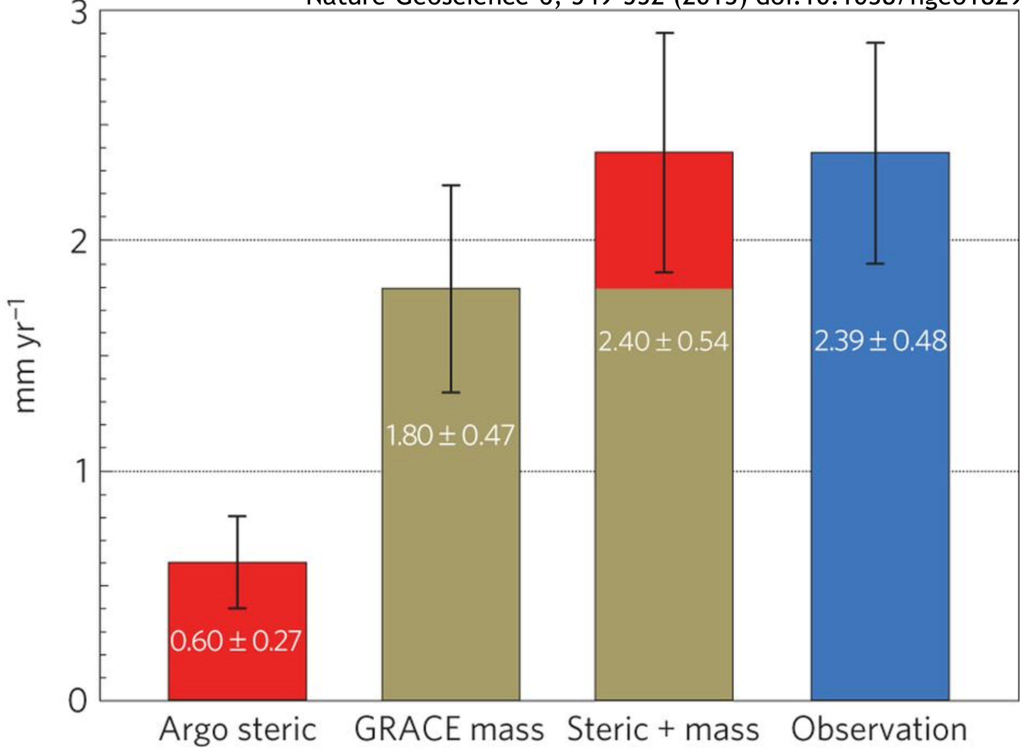
南極氷床の減少を初めて

２００２～２００５年のＧＲＡＣＥデータ
２±８０km³/yrで質量が減少していること

✓ 地上観測が困難な環境での大陸全体での

→ 衛星観測の有効性

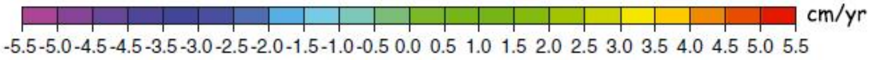
Nature Geoscience 6, 549-552 (2013) doi:10.1038/ngeo1829



氷床融解と海水準変動　（2005-2011）

GRACEから得られた極域氷床と山岳氷河の融解量が、海水面の上昇値と整合する。（海水の熱塩膨張の効果はArgo観測から）

2013



近年の氷床融解の加速

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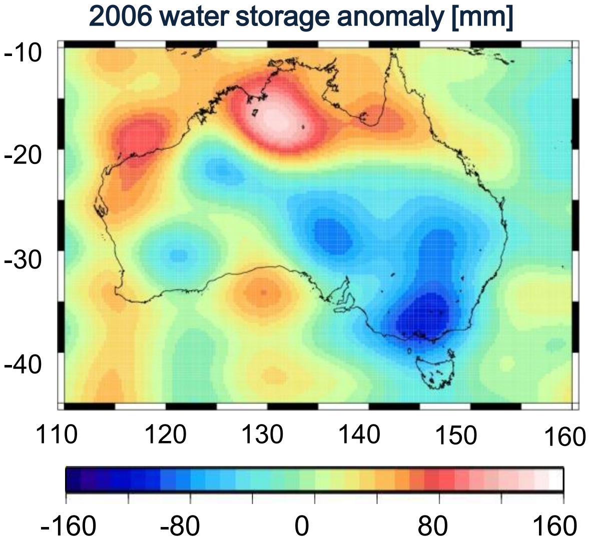
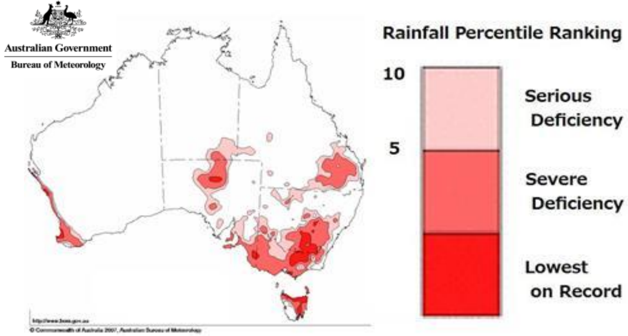
現行の衛星重力ミッション GRACE (2002-)

2006年のオーストラリア大旱魃

Hasegawa *et al.*, ***EGU General Assembly 2010***



Historic drought struck in 2006
(2006 Drought statement)



Vol 460|20 August 2009|**doi:10.1038/nature08238**

Satellite-based estimates of groundwater depletion in India

Matthew Rodell[1], Isabella Velicogna[2,3,4] & James S. Famiglietti[2]

インド北部での灌漑による地下水減少

インド北部の地下水が、灌漑により、2002-2008間で 17.7±4.5 km^3/yr 減少

→ 地上モニタリングが困難な地下水変化の衛星観測に成功

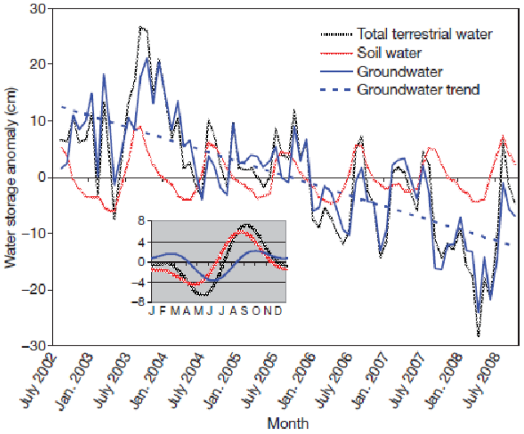


Figure 3 | Monthly time series of water storage anomalies in northwestern India. Monthly time series of anomalies of GRACE-derived total TWS, modelled soil-water storage and estimated groundwater storage, averaged over Rajasthan, Punjab and Haryana, plotted as equivalent heights of water in centimetres. Also shown is the best-fit linear groundwater trend. Inset, mean seasonal cycle of each variable.

基

外

空間

応

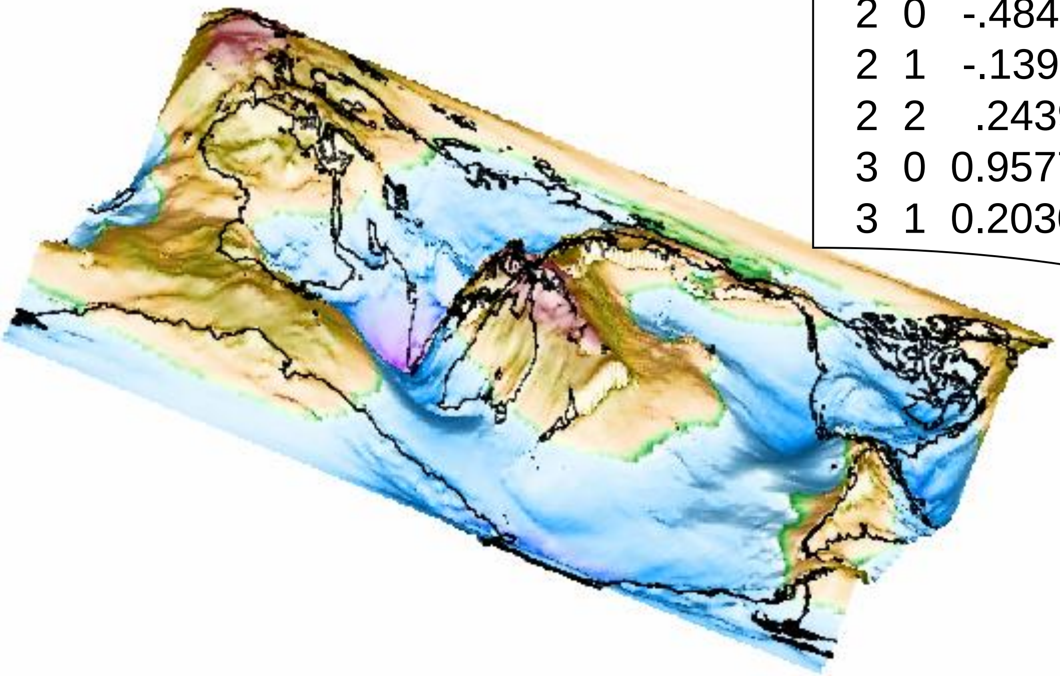
の全球解を、

化に換算して数cm

重力場データ

$$V = \frac{GM}{R}\sum_{l=0}^{L}\sum_{m=0}^{l}\left(\frac{R}{r}\right)^{l+1}\overline{P}_{lm}(\sin\phi)(\overline{C}_{lm}\cos(m\lambda)+\overline{S}_{lm}\sin(m\lambda))$$

CHAMP
EIGEN-2 model

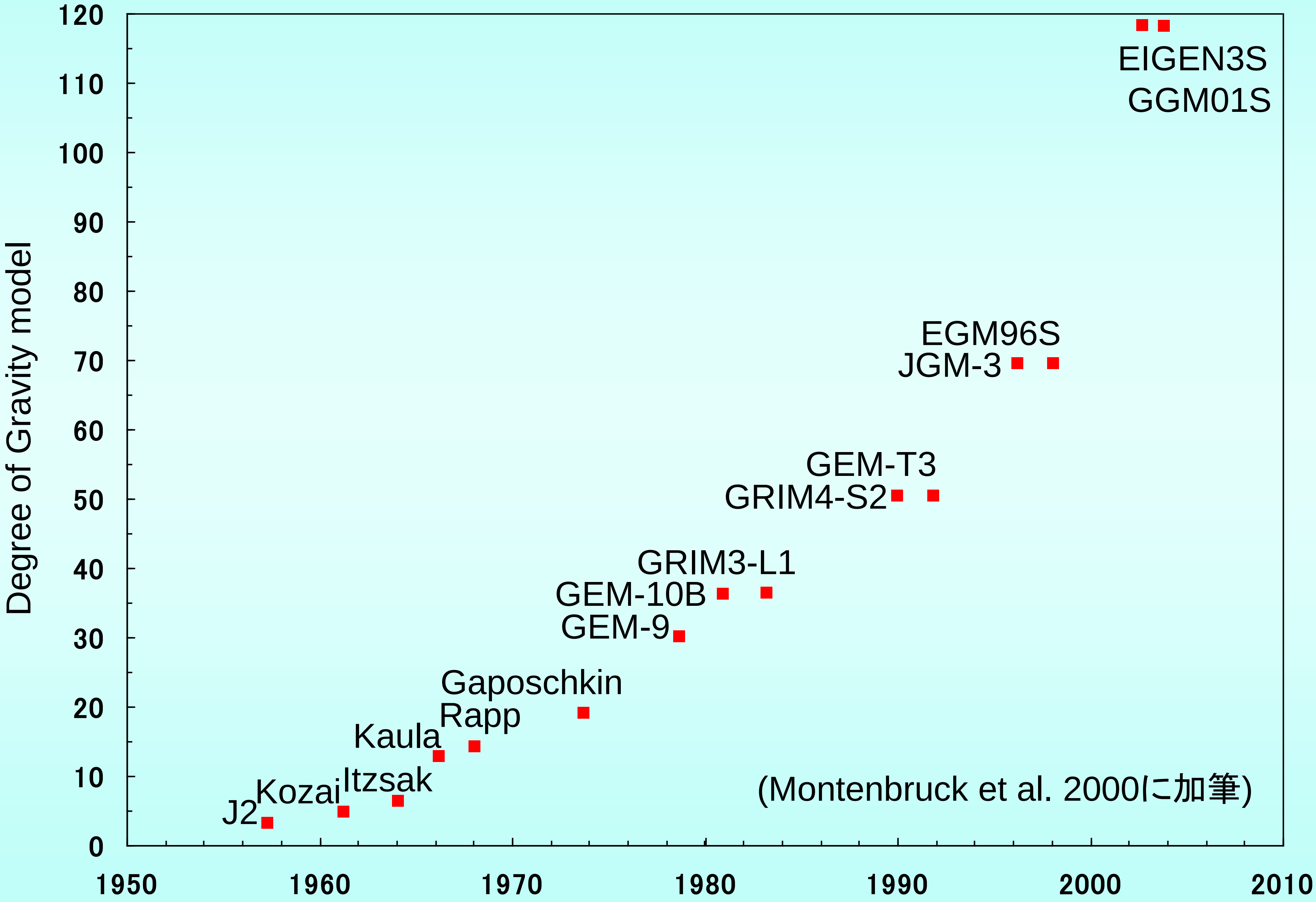


l	*m*	C_{lm}	S_{lm}
0	0	0.100000000000D+01	0.000000000000D+00
1	0	0.000000000000D+00	0.000000000000D+00
1	1	0.000000000000D+00	0.000000000000D+00
2	0	-.484165815935D-03	0.000000000000D+00
2	1	-.139274044771D-09	0.141275625216D-08
2	2	.243930491835D-05	-.140027520233D-05
3	0	0.957730216460D-06	0.000000000000D+00
3	1	0.203054457836D-05	0.248146553306D-06

⋮

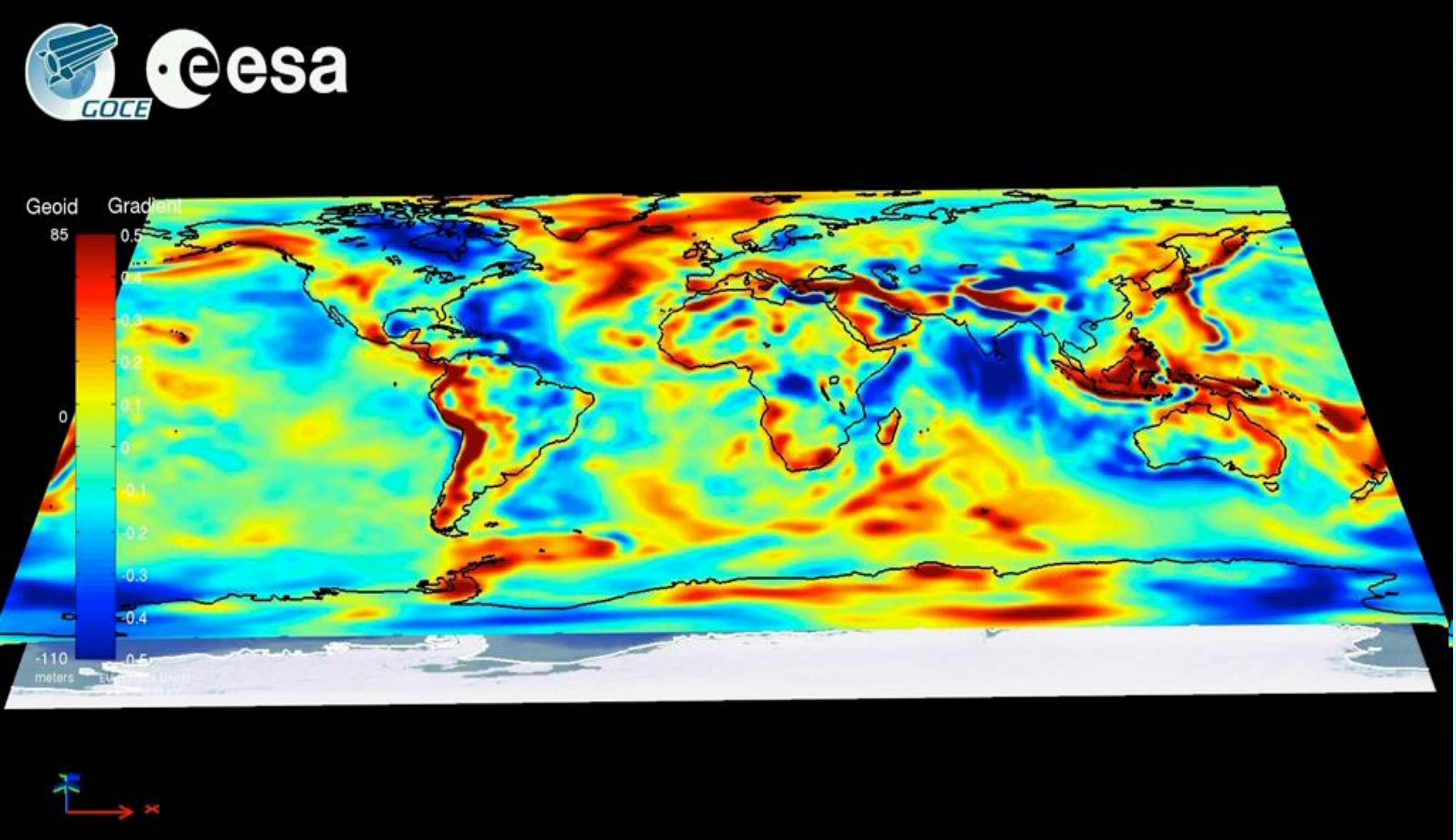
Up to Degree 120 / Order 120

衛星による地球重力場モデルの発展

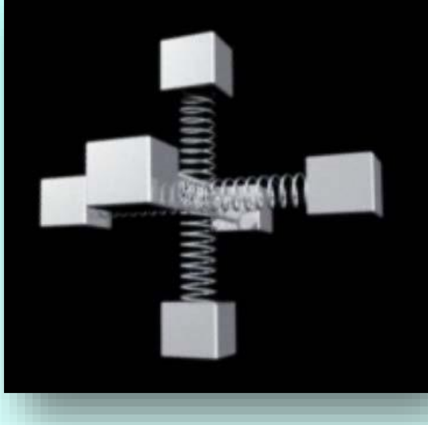


(Montenbruck et al. 2000に加筆)

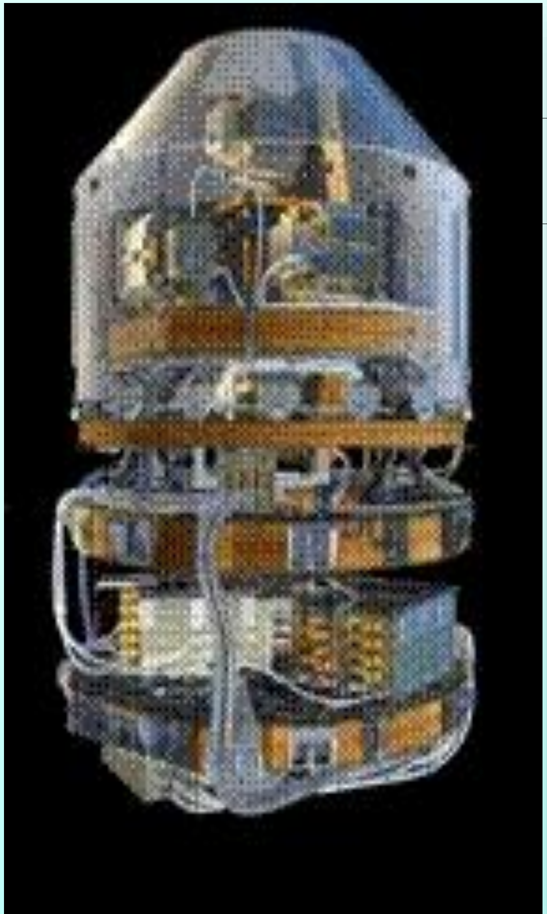
GOCE

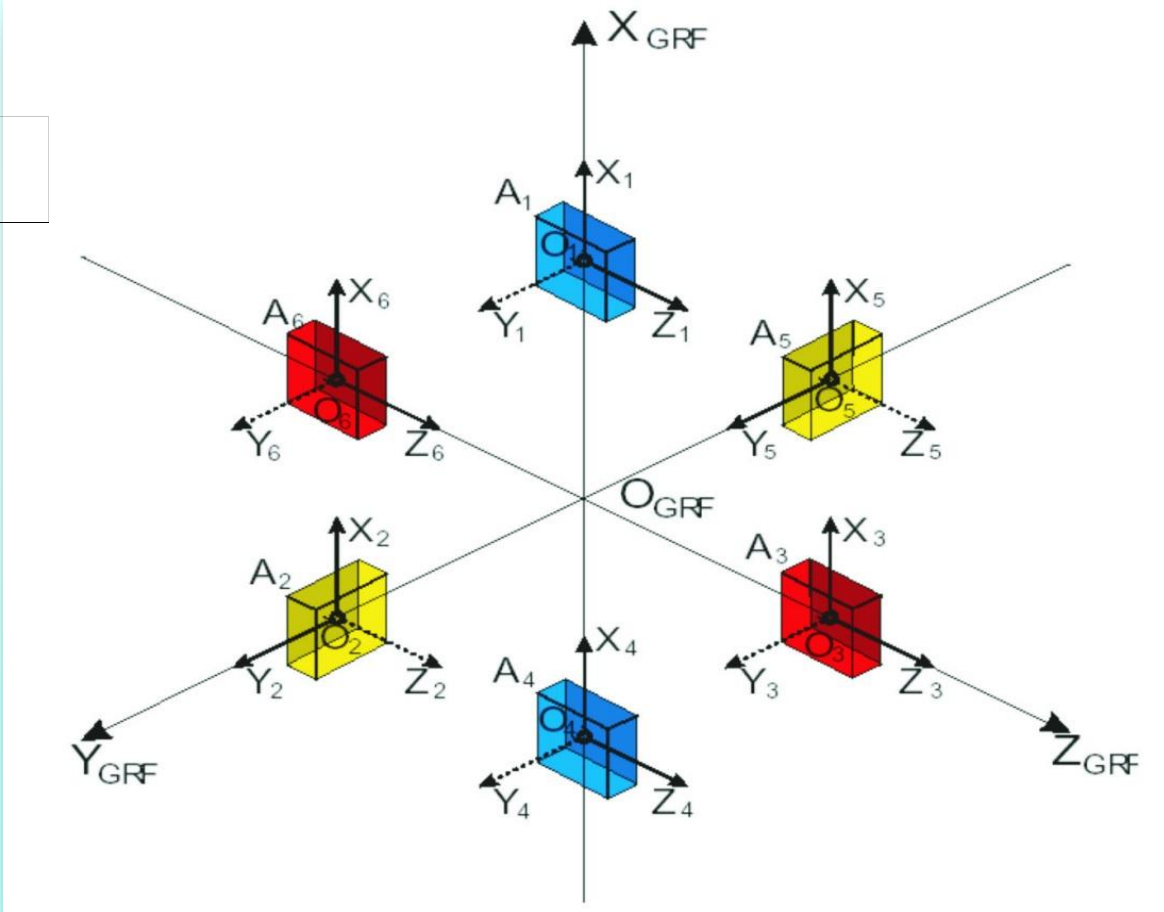

GOCE
esa
Geoid
Gradient
85
0
-110
meters
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
x

EGG



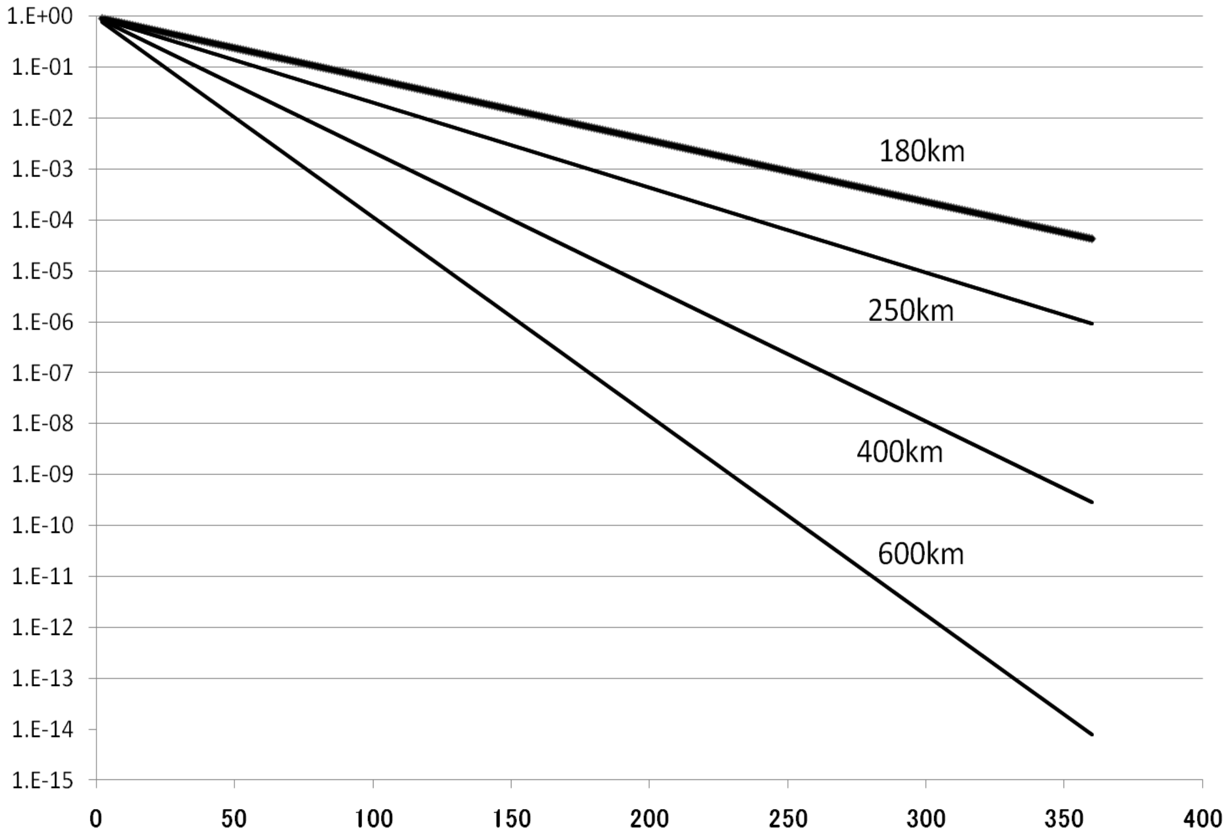
$$[W_{ij}] = \mathrm{grad}\,\mathbf{g} = \mathrm{grad}(\mathrm{grad}\,W) = \begin{pmatrix} W_{xx} & W_{xy} & W_{xz} \\ W_{yx} & W_{yy} & W_{yz} \\ W_{zx} & W_{zy} & W_{zz} \end{pmatrix}$$





軌道高度(h)による重力場(V)の減衰

$$V = \frac{GM}{a+h}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\left(\frac{a}{a+h}\right)^{l} P_{lm}(\sin\phi)(C_{lm}\cos(m\lambda)+S_{lm}\sin(m\lambda))$$



軌道高度による重力場決定精度

Figure 2.3: 200 km Altitude

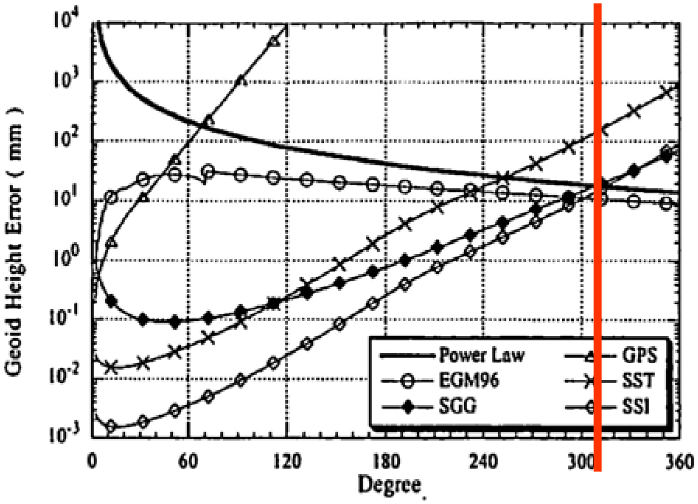


Figure 2.4: 300 km Altitude

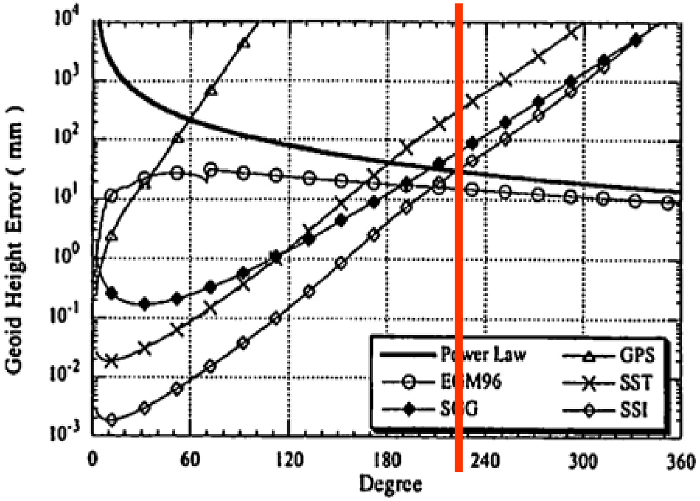


Figure 2.5: 400 km Altitude

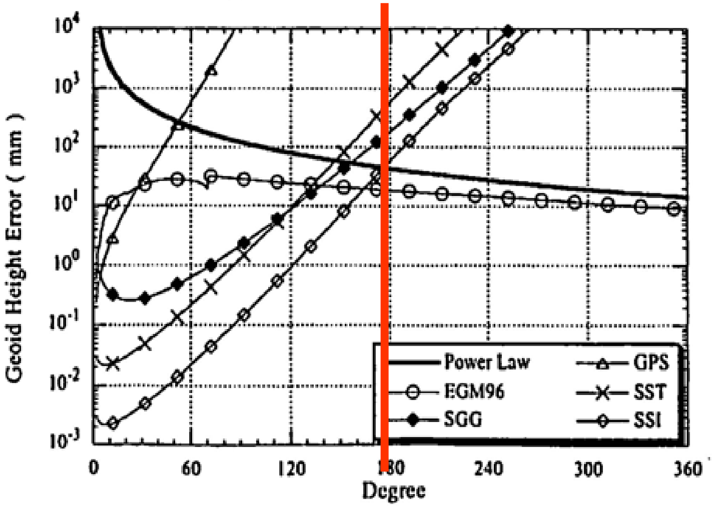
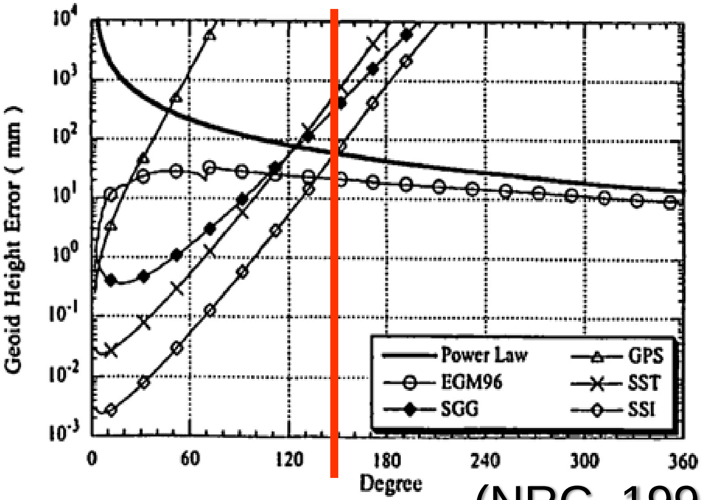


Figure 2.6: 500 km Altitude



(NRC, 1997)

地球物理学的応用

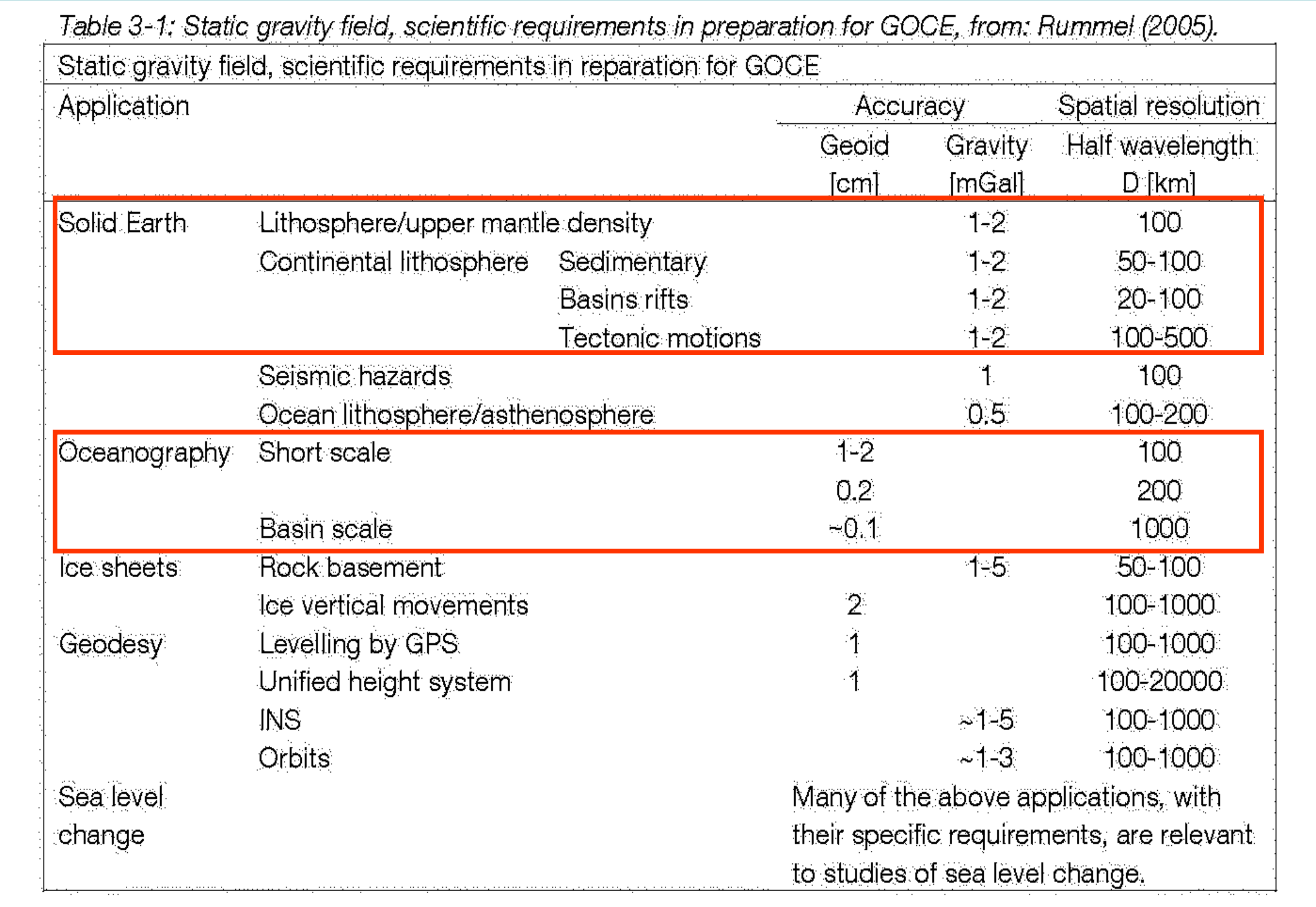
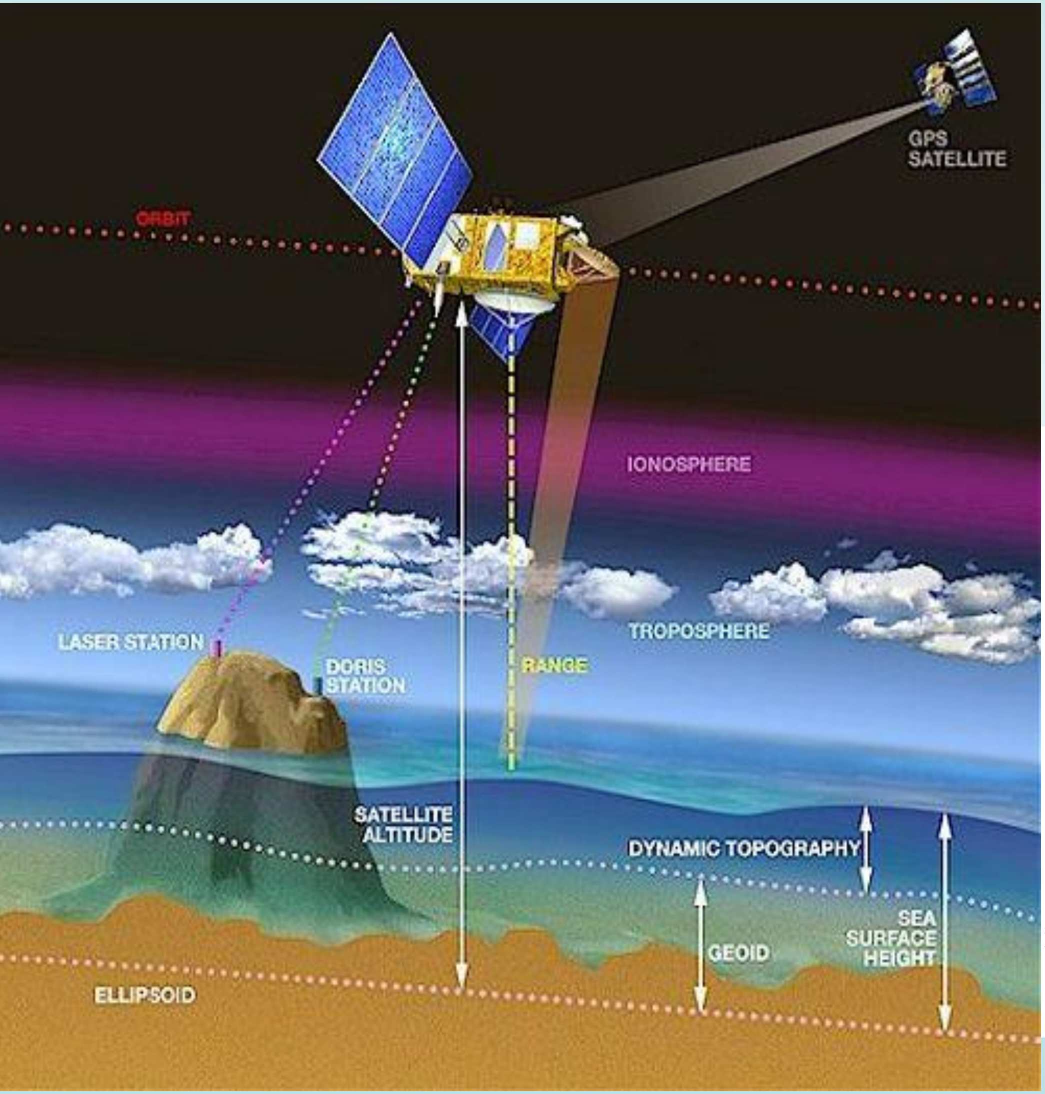


Table 3-1: Static gravity field, scientific requirements in preparation for GOCE, from: Rummel (2005).

Static gravity field, scientific requirements in reparation for GOCE

Application			Accuracy		Spatial resolution
			Geoid [cm]	Gravity [mGal]	Half wavelength D [km]
Solid Earth	Lithosphere/upper mantle density			1-2	100
	Continental lithosphere	Sedimentary		1-2	50-100
		Basins rifts		1-2	20-100
		Tectonic motions		1-2	100-500
	Seismic hazards			1	100
	Ocean lithosphere/asthenosphere			0.5	100-200
Oceanography	Short scale		1-2		100
			0.2		200
	Basin scale		~0.1		1000
Ice sheets	Rock basement			1-5	50-100
	Ice vertical movements		2		100-1000
Geodesy	Levelling by GPS		1		100-1000
	Unified height system		1		100-20000
	INS			~1-5	100-1000
	Orbits			~1-3	100-1000
Sea level change			Many of the above applications, with their specific requirements, are relevant to studies of sea level change.		

海面形状と海流



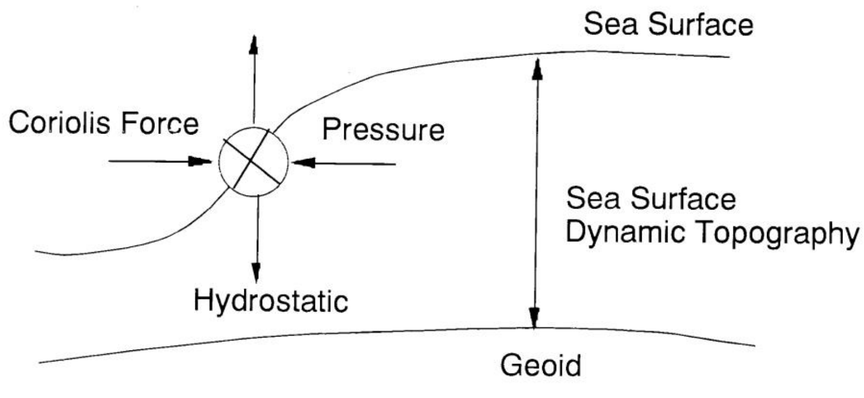
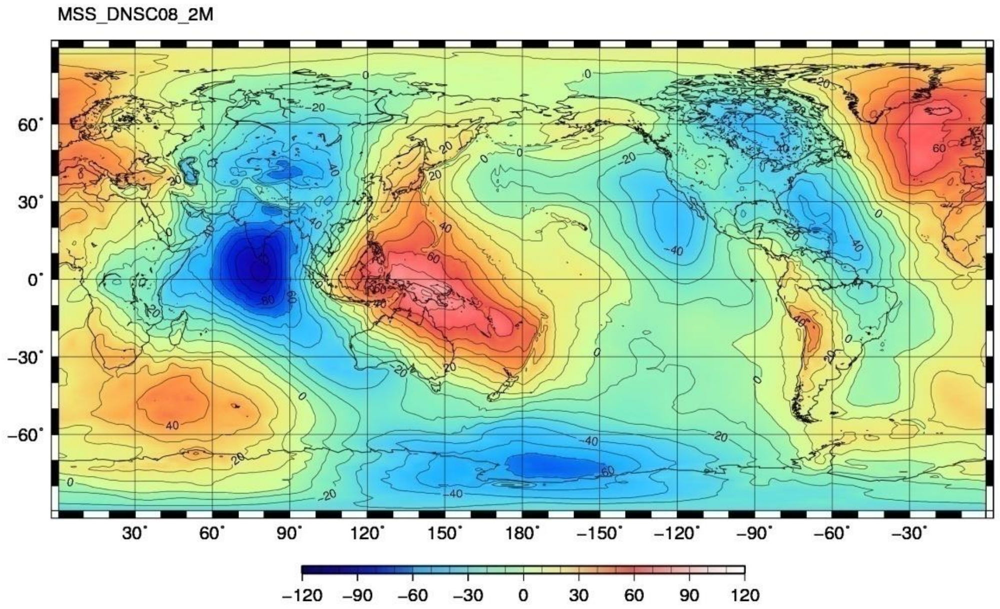


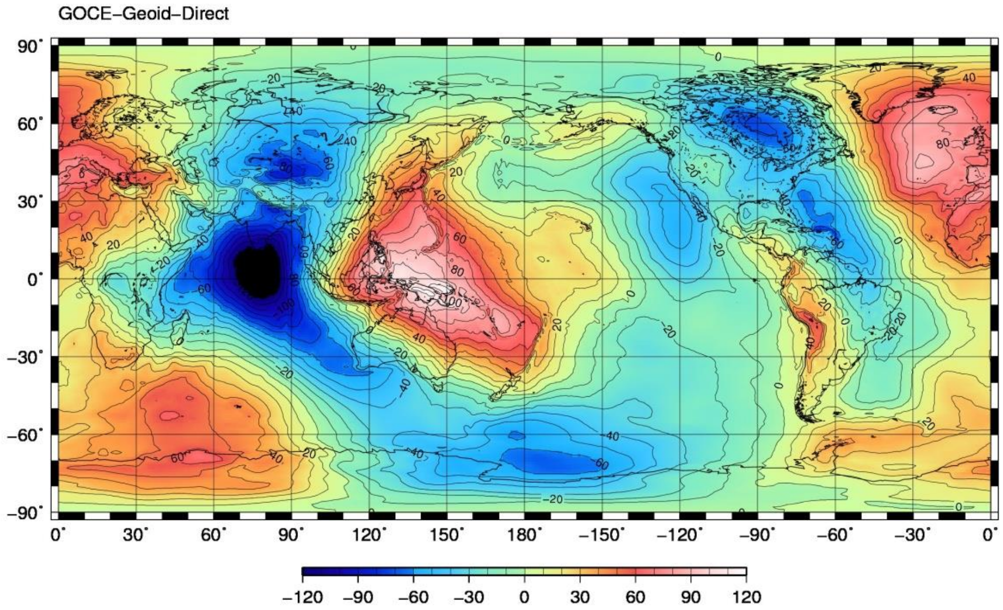
Fig. 2. A schematic view of the sea surface dynamic topography which is caused by geostrophic balance between ocean current and the slope of the sea surface.

SSH



Mean Sea Surface

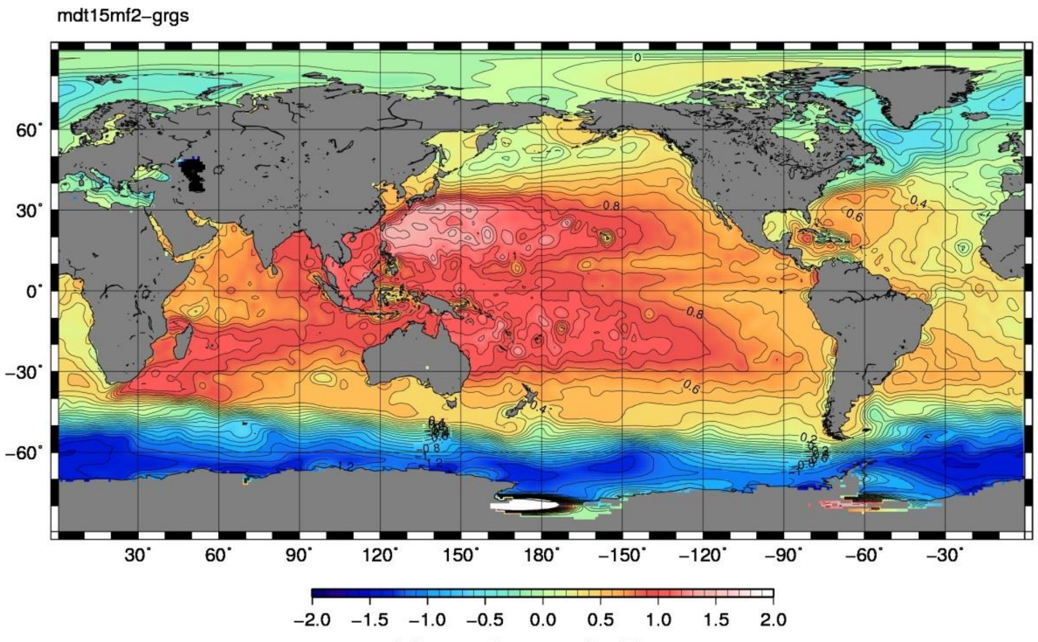
GEOID



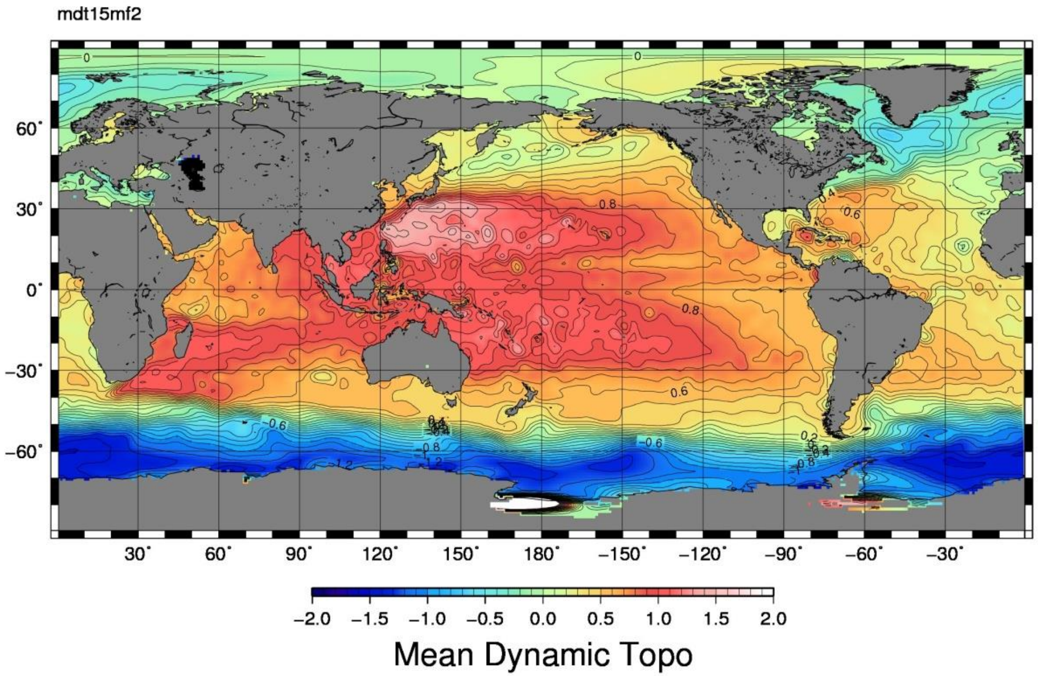
Global Geoid

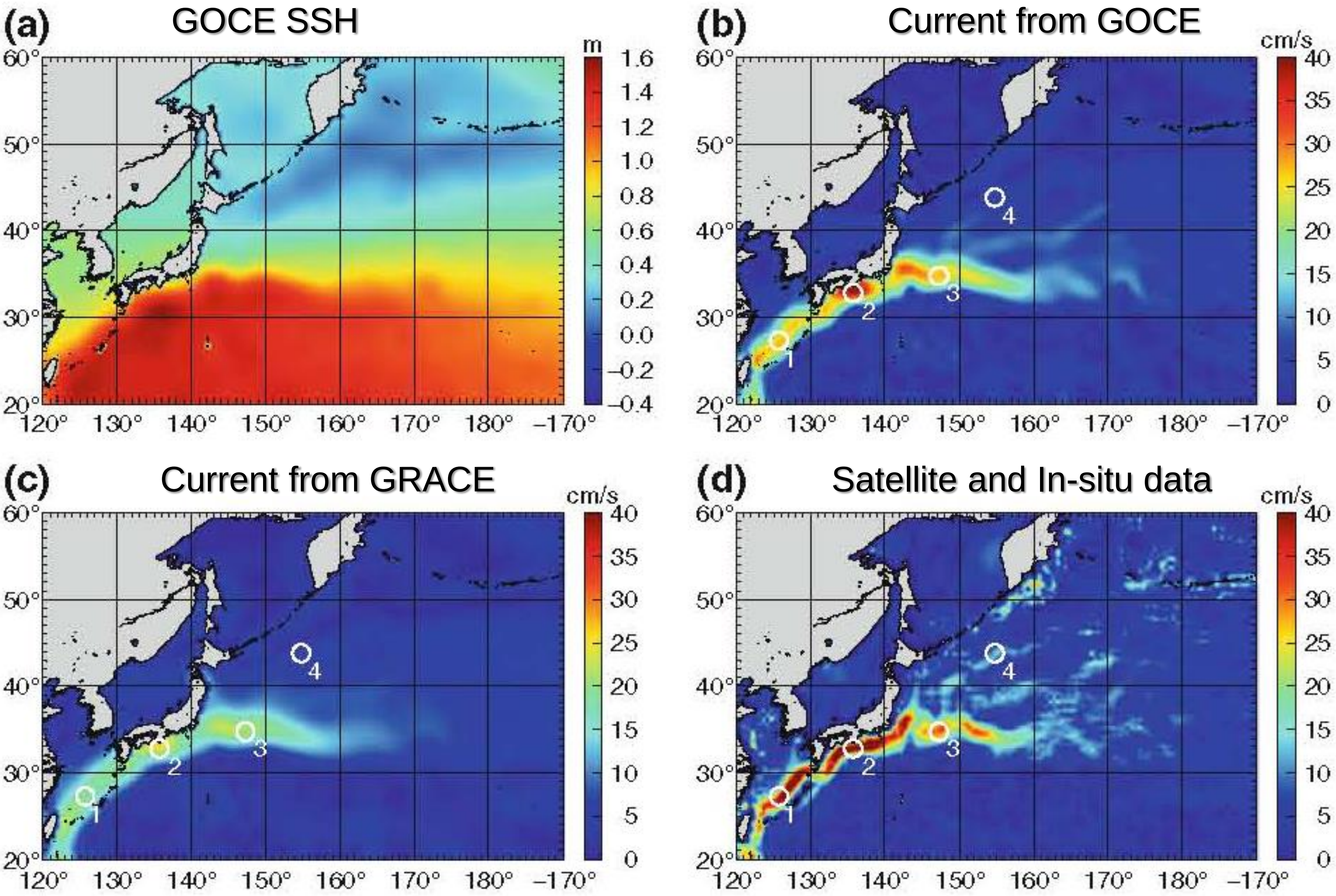
SSDT

GRACE



GOCE





After Knudsen et al., 2011

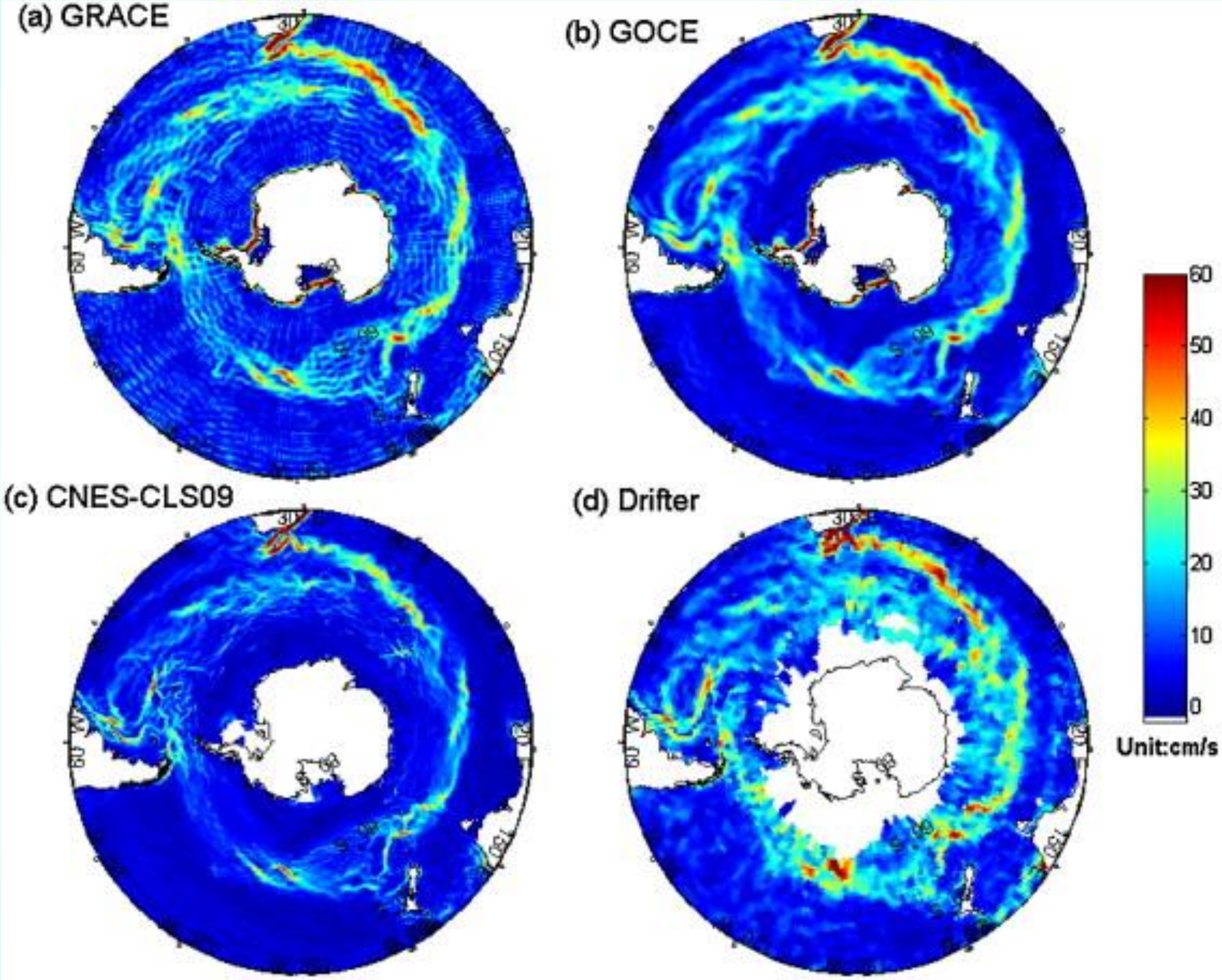
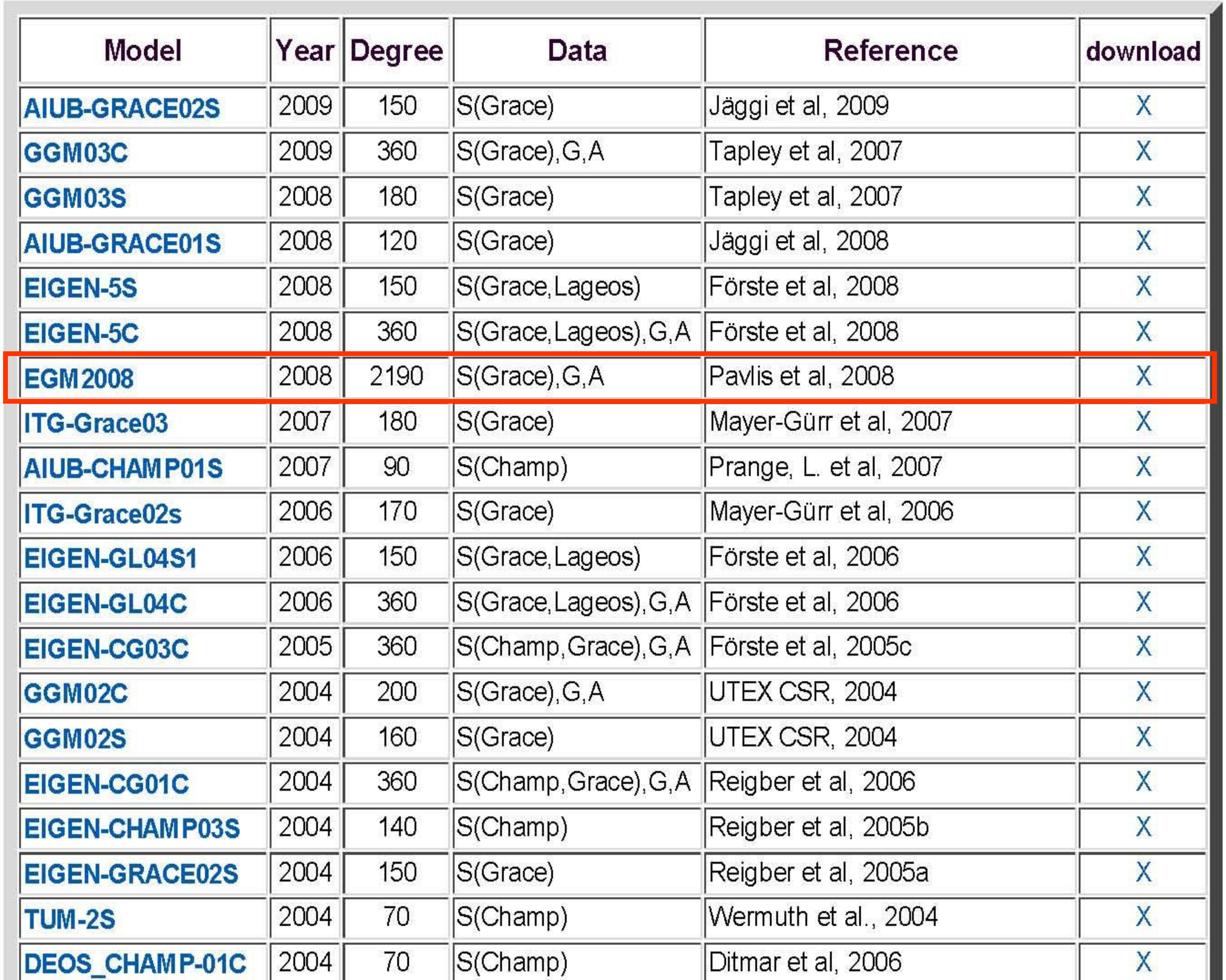


Fig. 5. Magnitude of the geostrophic velocities in the Antarctic circumpolar area. The velocity estimates from GRACE-derived geoid (ITG-Grace2010) (a), GOCE-derived geoid (GOCE-TIM3) (b), the CNES-CLS09 model (c) and the in situ drifters' measurements (d)

(Feng et al., J. Geodyn., 2013)

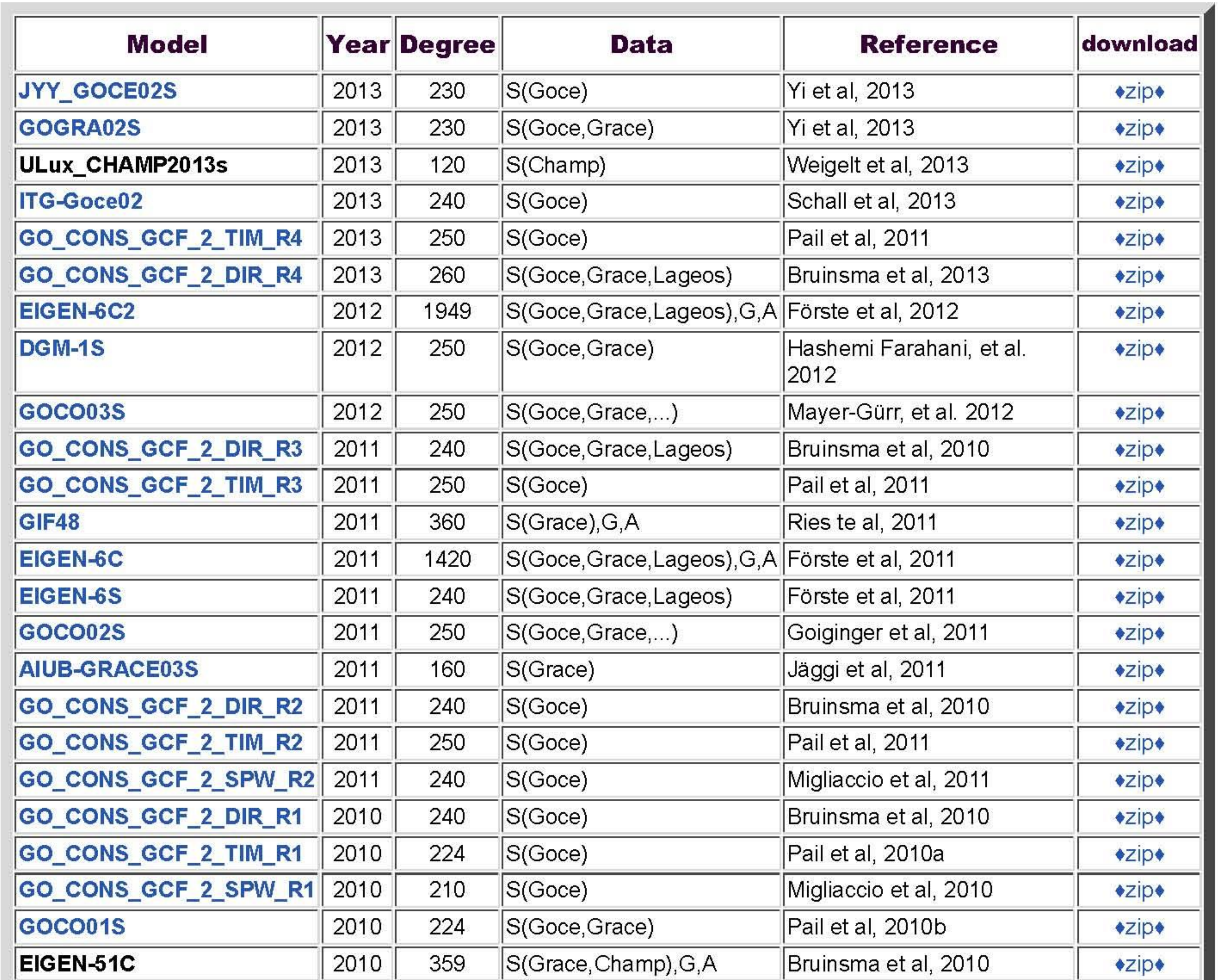
Global Gravity Field Models

http://icgem.gfz-potsdam.de/ICGEM/ICGEM.htm



Model	Year	Degree	Data	Reference	download
AIUB-GRACE02S	2009	150	S(Grace)	Jäggi et al, 2009	X
GGM03C	2009	360	S(Grace),G,A	Tapley et al, 2007	X
GGM03S	2008	180	S(Grace)	Tapley et al, 2007	X
AIUB-GRACE01S	2008	120	S(Grace)	Jäggi et al, 2008	X
EIGEN-5S	2008	150	S(Grace,Lageos)	Förste et al, 2008	X
EIGEN-5C	2008	360	S(Grace,Lageos),G,A	Förste et al, 2008	X
EGM2008	2008	2190	S(Grace),G,A	Pavlis et al, 2008	X
ITG-Grace03	2007	180	S(Grace)	Mayer-Gürr et al, 2007	X
AIUB-CHAMP01S	2007	90	S(Champ)	Prange, L. et al, 2007	X
ITG-Grace02s	2006	170	S(Grace)	Mayer-Gürr et al, 2006	X
EIGEN-GL04S1	2006	150	S(Grace,Lageos)	Förste et al, 2006	X
EIGEN-GL04C	2006	360	S(Grace,Lageos),G,A	Förste et al, 2006	X
EIGEN-CG03C	2005	360	S(Champ,Grace),G,A	Förste et al, 2005c	X
GGM02C	2004	200	S(Grace),G,A	UTEX CSR, 2004	X
GGM02S	2004	160	S(Grace)	UTEX CSR, 2004	X
EIGEN-CG01C	2004	360	S(Champ,Grace),G,A	Reigber et al, 2006	X
EIGEN-CHAMP03S	2004	140	S(Champ)	Reigber et al, 2005b	X
EIGEN-GRACE02S	2004	150	S(Grace)	Reigber et al, 2005a	X
TUM-2S	2004	70	S(Champ)	Wermuth et al., 2004	X
DEOS_CHAMP-01C	2004	70	S(Champ)	Ditmar et al, 2006	X

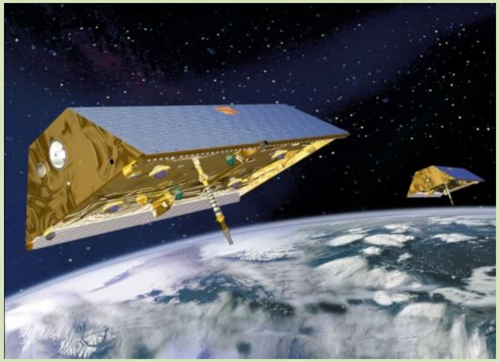
http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html

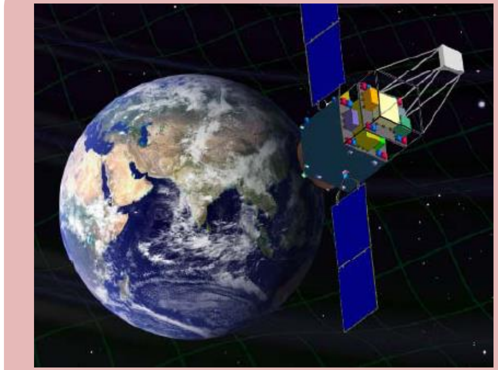


Model	Year	Degree	Data	Reference	download
JYY_GOCE02S	2013	230	S(Goce)	Yi et al, 2013	♦zip♦
GOGRA02S	2013	230	S(Goce,Grace)	Yi et al, 2013	♦zip♦
ULux_CHAMP2013s	2013	120	S(Champ)	Weigelt et al, 2013	♦zip♦
ITG-Goce02	2013	240	S(Goce)	Schall et al, 2013	♦zip♦
GO_CONS_GCF_2_TIM_R4	2013	250	S(Goce)	Pail et al, 2011	♦zip♦
GO_CONS_GCF_2_DIR_R4	2013	260	S(Goce,Grace,Lageos)	Bruinsma et al, 2013	♦zip♦
EIGEN-6C2	2012	1949	S(Goce,Grace,Lageos),G,A	Förste et al, 2012	♦zip♦
DGM-1S	2012	250	S(Goce,Grace)	Hashemi Farahani, et al. 2012	♦zip♦
GOCO03S	2012	250	S(Goce,Grace,...)	Mayer-Gürr, et al. 2012	♦zip♦
GO_CONS_GCF_2_DIR_R3	2011	240	S(Goce,Grace,Lageos)	Bruinsma et al, 2010	♦zip♦
GO_CONS_GCF_2_TIM_R3	2011	250	S(Goce)	Pail et al, 2011	♦zip♦
GIF48	2011	360	S(Grace),G,A	Ries te al, 2011	♦zip♦
EIGEN-6C	2011	1420	S(Goce,Grace,Lageos),G,A	Förste et al, 2011	♦zip♦
EIGEN-6S	2011	240	S(Goce,Grace,Lageos)	Förste et al, 2011	♦zip♦
GOCO02S	2011	250	S(Goce,Grace,...)	Goiginger et al, 2011	♦zip♦
AIUB-GRACE03S	2011	160	S(Grace)	Jäggi et al, 2011	♦zip♦
GO_CONS_GCF_2_DIR_R2	2011	240	S(Goce)	Bruinsma et al, 2010	♦zip♦
GO_CONS_GCF_2_TIM_R2	2011	250	S(Goce)	Pail et al, 2011	♦zip♦
GO_CONS_GCF_2_SPW_R2	2011	240	S(Goce)	Migliaccio et al, 2011	♦zip♦
GO_CONS_GCF_2_DIR_R1	2010	240	S(Goce)	Bruinsma et al, 2010	♦zip♦
GO_CONS_GCF_2_TIM_R1	2010	224	S(Goce)	Pail et al, 2010a	♦zip♦
GO_CONS_GCF_2_SPW_R1	2010	210	S(Goce)	Migliaccio et al, 2010	♦zip♦
GOCO01S	2010	224	S(Goce,Grace)	Pail et al, 2010b	♦zip♦
EIGEN-51C	2010	359	S(Grace,Champ),G,A	Bruinsma et al, 2010	♦zip♦

地球重力観測衛星としてのDPFのスペック

～　GOCE, GRACEとの比較





	GRACE	DPF	GOCE
手法	2機の衛星間の距離を測定	1 軸の重力偏差計	3 軸の重力偏差計
基線長	220km	0.3m	0.5m
感度	1 μm/s/$Hz^{1/2}$	3.1×10^{-15} /s^2/$Hz^{1/2}$	5×10^{-12} /s^2/$Hz^{1/2}$
高度	500km	500km	270km

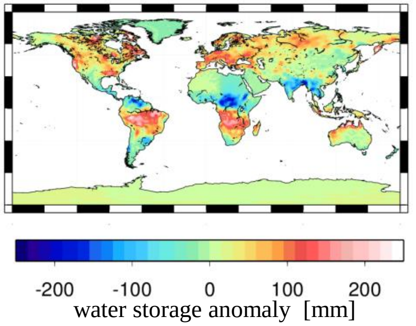
NUMERICAL SIMULATION

	Measurement error	AOD model error
Case 1	Considered	Considered
Case 2	Considered	Ignored
Case 3	Ignored	Considered

３つのケーススタディ

目的：　DPFデータの陸水モニタリングへの応用

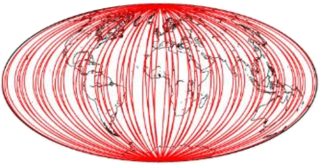
行程：　90次までの重力場を1カ月間隔で推定



真の重力場

GLDAS陸水モデルから計算される時間変化する重力場

衛星軌道の**真値**



forward 計算

重力偏差・衛星の位置の**真値**

（５秒間隔でサンプリング）

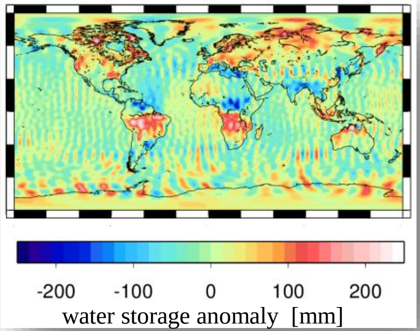
計測誤差
- 重力偏差
- 衛星姿勢
- 衛星位置

大気海洋シグナルの補正誤差
- 大気：ECMWF - NCEP
- 海洋：OMCT - MOG2D

重力偏差・衛星の位置の計測値**（誤差を含む）**

Filtering
Inversion 計算

重力場の**推定値**



NUMERICAL SIMULATION

	Measurement error	AOD model error
Case 1	Considered	Considered
Case 2	Considered	Ignored
Case 3	Ignored	Considered

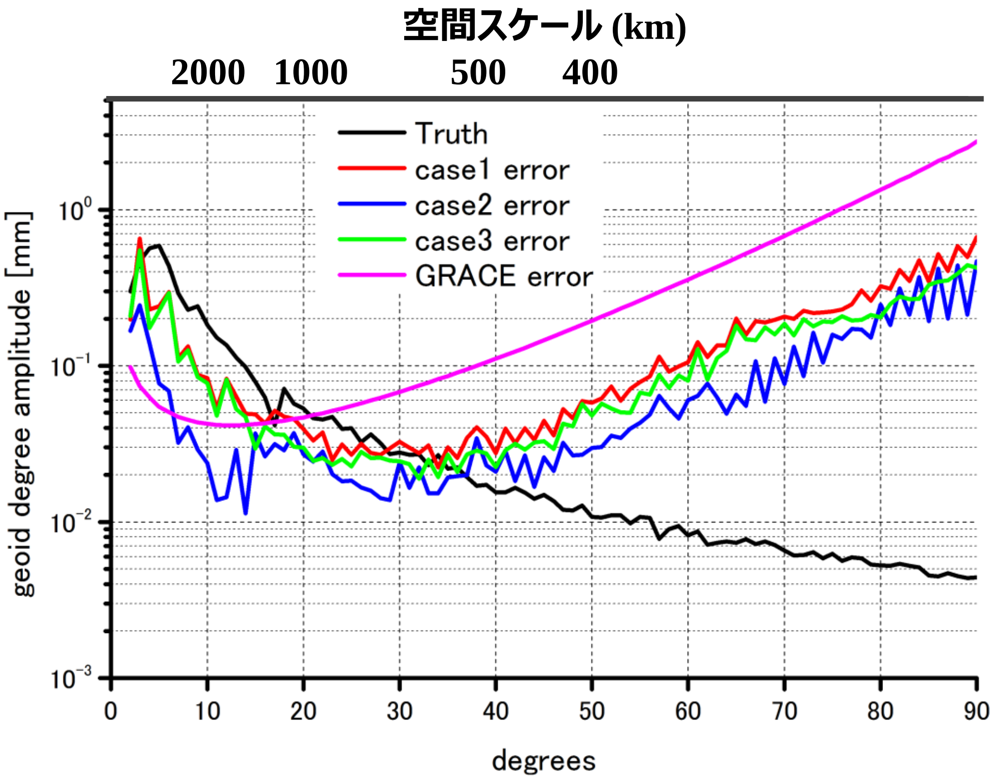


Fig. 入力した陸水シグナル、DPF観測から得られた重力場の誤差、GRACEのformal error のパワースペクトル（geoid degree amplitude）

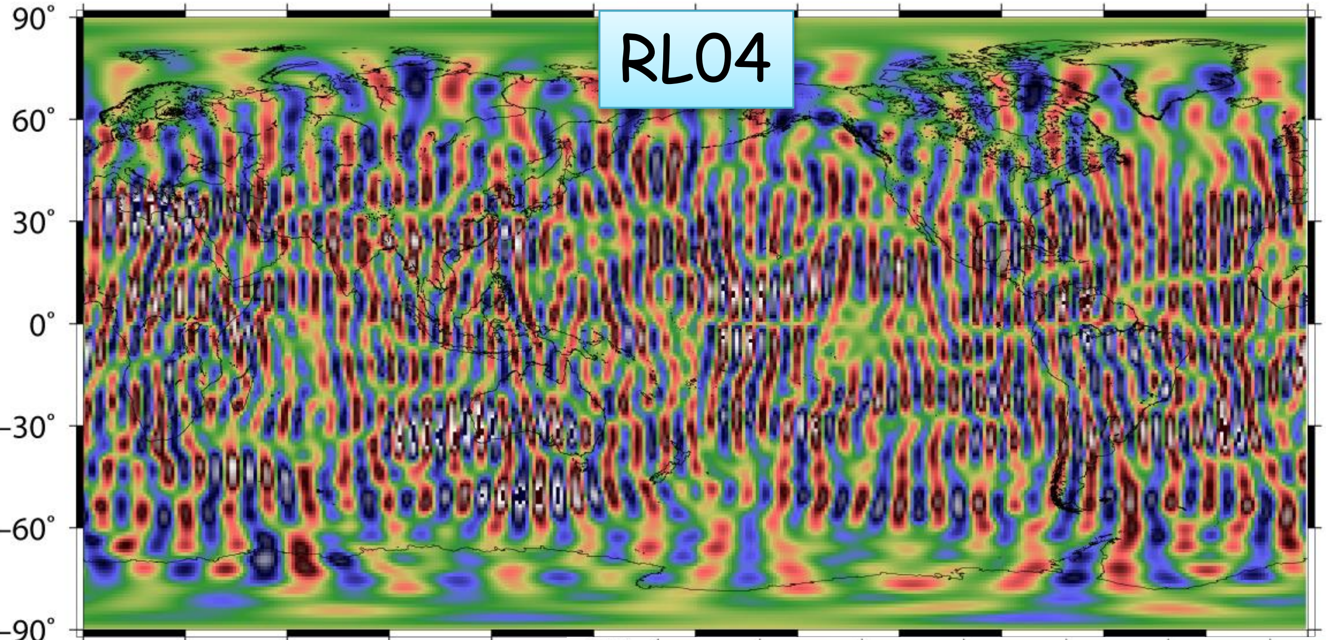
- 1000km以上の空間スケールでは、 DPFから得られる重力場の誤差は、GRACE解の誤差より１桁程度小さい
- 陸水シグナルに対するSN比>1となる次数はGRACEの20次（1000km）に対し、DPFは30次（~660km）まで上昇
- AODモデルの誤差がDPF重力観測の主要な誤差ソース

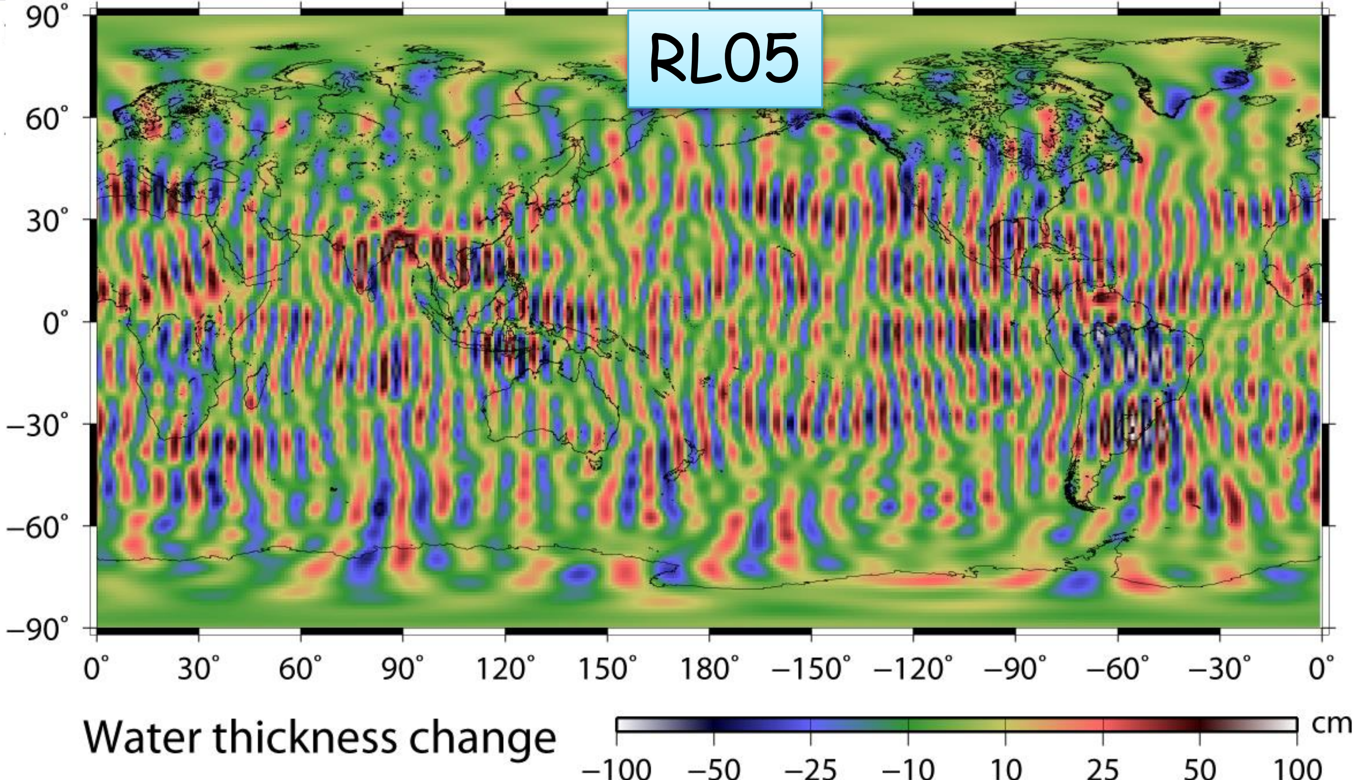
→ 低周波帯域の計測誤差に少し余裕がある

- *10次以下でDPF解の誤差がGRACE formal errorより大きいのはGRACE formal errorが実際のGRACE解の誤差を過小評価しているためと思われる*

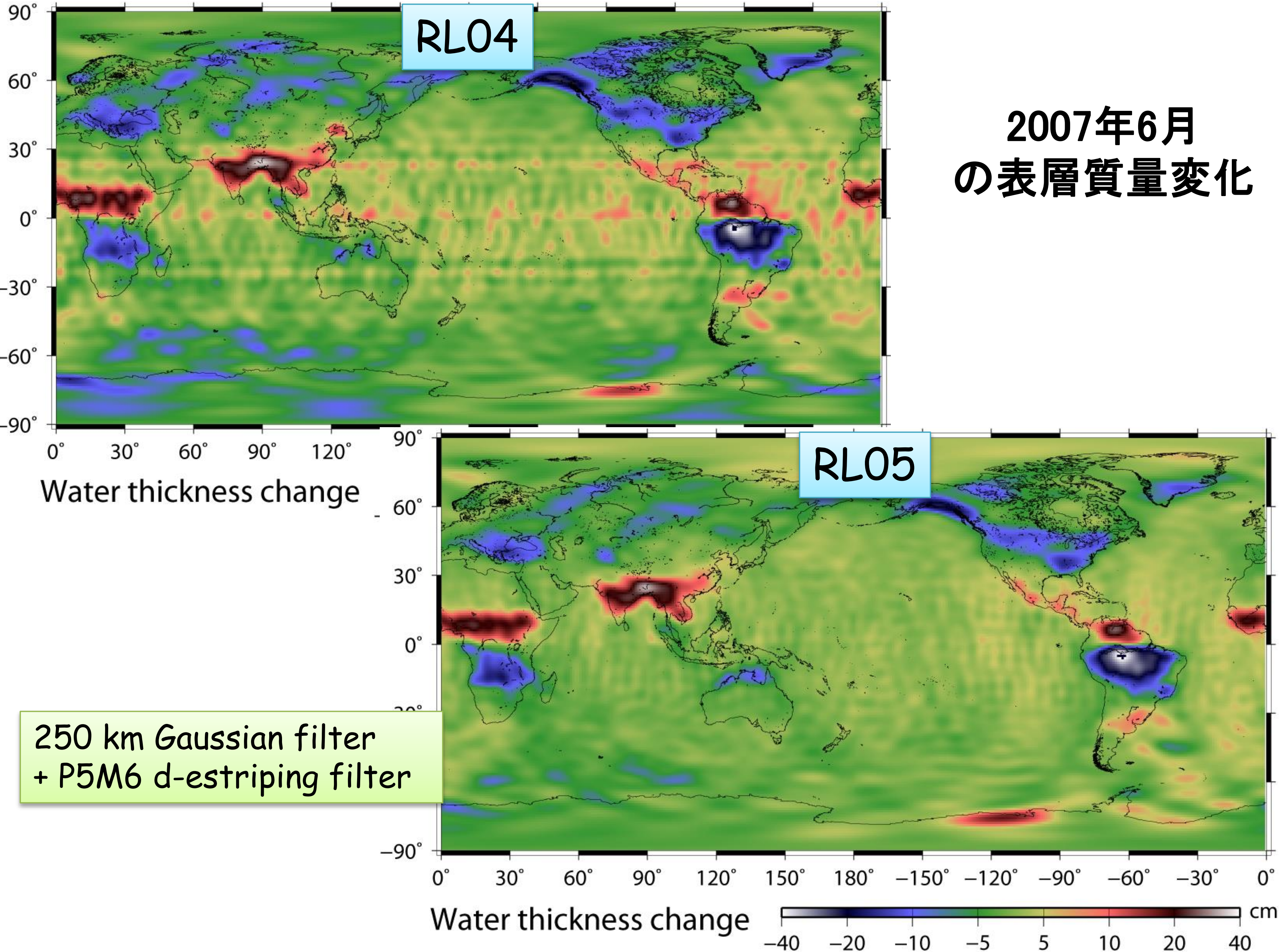
GRACE再解析

2007年6月
の表層質量変化



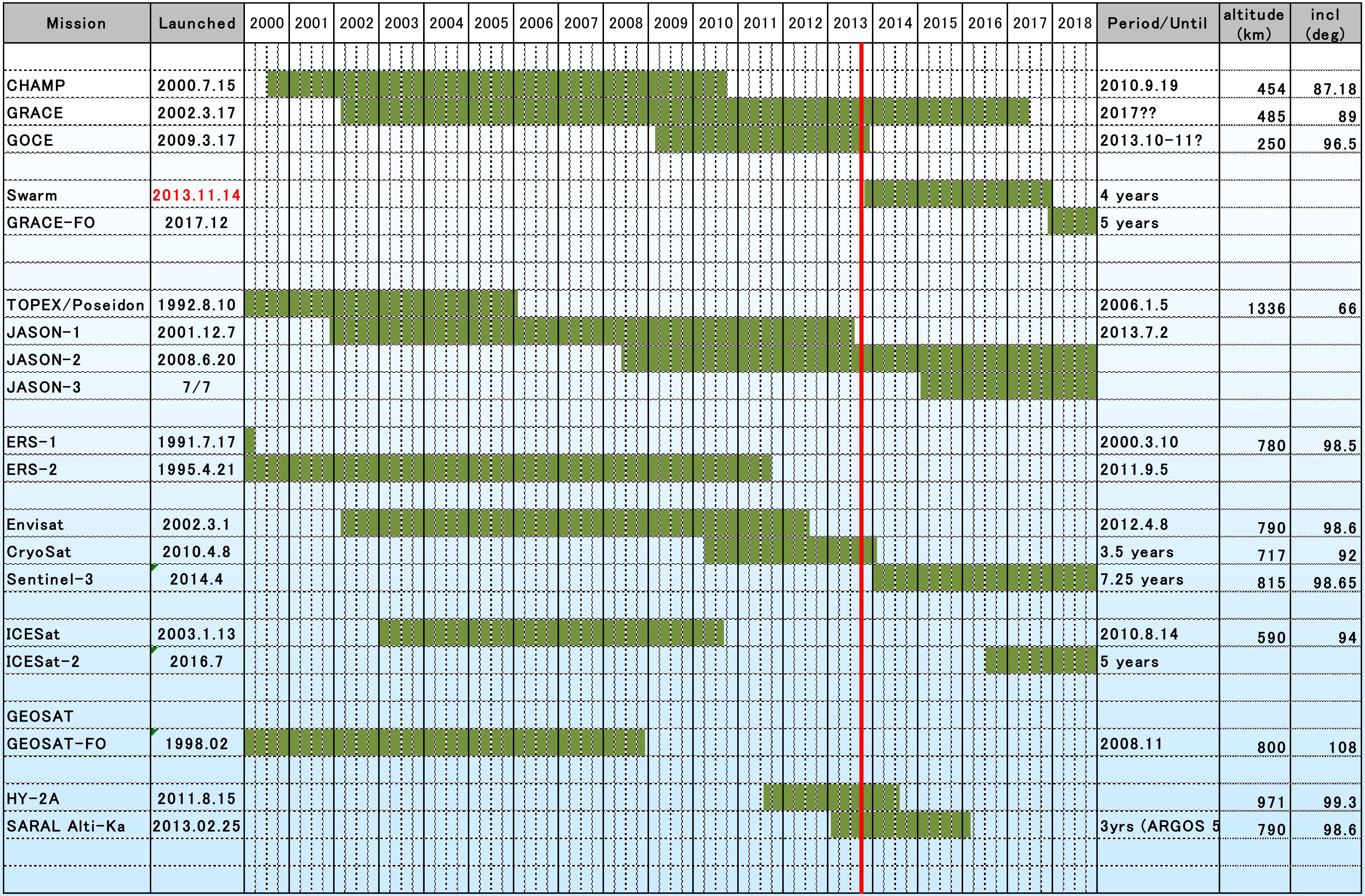


2007年6月
の表層質量変化



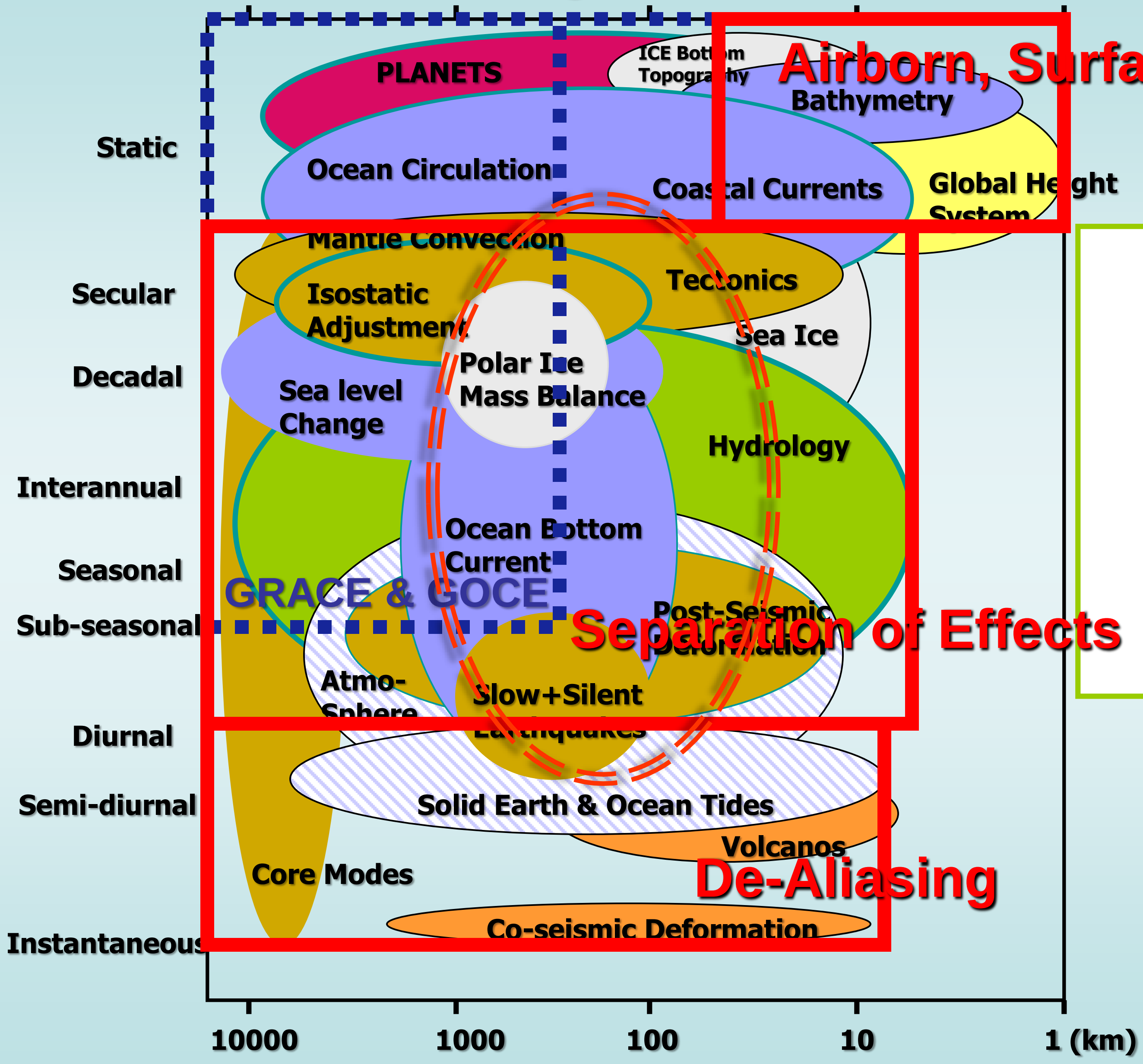
250 km Gaussian filter
+ P5M6 d-estriping filter

Gravity, Altimeter Missions



Mission	Launched	Period/Until	altitude (km)	incl (deg)
CHAMP	2000.7.15	2010.9.19	454	87.18
GRACE	2002.3.17	2017??	485	89
GOCE	2009.3.17	2013.10-11?	250	96.5
Swarm	2013.11.14	4 years		
GRACE-FO	2017.12	5 years		
TOPEX/Poseidon	1992.8.10	2006.1.5	1336	66
JASON-1	2001.12.7	2013.7.2		
JASON-2	2008.6.20			
JASON-3	7/7			
ERS-1	1991.7.17	2000.3.10	780	98.5
ERS-2	1995.4.21	2011.9.5		
Envisat	2002.3.1	2012.4.8	790	98.6
CryoSat	2010.4.8	3.5 years	717	92
Sentinel-3	2014.4	7.25 years	815	98.65
ICESat	2003.1.13	2010.8.14	590	94
ICESat-2	2016.7	5 years		
GEOSAT				
GEOSAT-FO	1998.02	2008.11	800	108
HY-2A	2011.8.15		971	99.3
SARAL Alti-Ka	2013.02.25	3yrs (ARGOS 5	790	98.6

Challenges for Future Missions



Solid Earth
Oceans
Ice
hydrology
Geodesy
Planets

After Haagmans & Rummel
(GGSM 2004, Port)

GFZ
Helmholtz Centre
POTSDAM

HELMHOLTZ CENTRE POTSDAM
GFZ GERMAN RESEARCH CENTRE
FOR GEOSCIENCES

Development, Operation and Analysis of Gravity Field Satellite Missions

- **GRACE-FO**
  - Science Data System
  - News
  - Literature
- GRACE
- Gravity Missions Studies
- Satellite Payload Development and Integration
- Satellite Receiving Station Ny-Ålesund

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Global Geomonitoring and Gravity Field Topics
Development, Operation and Analysis of Gravity Field Satellite Missions GRACE-FO

Gravity Recovery and Climate Experiment-Follow-On (GRACE-FO) Mission

The Gravity Recovery and Climate Experiment-Follow-On (GRACE-FO) Mission, due for launch in August 2017, is a NASA directed mission to continue the goals of the original GRACE mission and provide continuity for the GRACE data set.

The primary goal of the GRACE-FO Mission is to obtain accurate global and high-resolution models for both the static and the time variable components of the Earth's gravity field. As in the original GRACE mission, this goal is achieved by making accurate measurements of the inter-satellite range between two co-planar, low altitude polar orbiting twin satellites using a K/Ka-Band microwave tracking system. Additionally, each satellite carries geodetic quality Global Navigation Satellite System (GNSS) receivers, a Laser Retro-Reflector (LRR) for ground station ranging, and high accuracy accelerometers to precisely measure the non-gravitational accelerations acting on the satellite.

As a secondary goal, GRACE-FO will carry a Laser Ranging Interferometer (LRI) as a technology demonstration. It will provide laser interferometry measurements of inter-satellite range changes in orbit to demonstrate laser-ranging technology in support of future GRACE-like missions. Another secondary objective is the continuation of GRACE radio occultation measurements.

The GRACE-FO project will be executed in the US under the direction of the NASA Earth Science Division (ESD) within the NASA Science Mission Directorate (SMD) and the Earth Systematic Missions Program Office at Goddard Space Flight Center (GSFC). The Jet Propulsion Laboratory (JPL) is assigned responsibility for the GRACE-FO project.

The GRACE-FO mission has significant German participation managed by the German

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GRACE-FO Mission

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- The primary goal of the GRACE-FO Mission is **to obtain accurate global and high-resolution models for both the static and the time variable components** of the Earth's gravity field.

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将来ミッション（まとめ）

- 時間変化モニタリング（氷床、陸水）
  - GRACE-FO (2017～）
  - GRACE-2 (2020以降）
  - Formation Flight Missions
- 静的な重力場
  - 空間分解能
  - 超低高度衛星
  - GOCEを超えるのは難しい
  - Cold Atom Interferometry ？