

第11回森羅万象学校

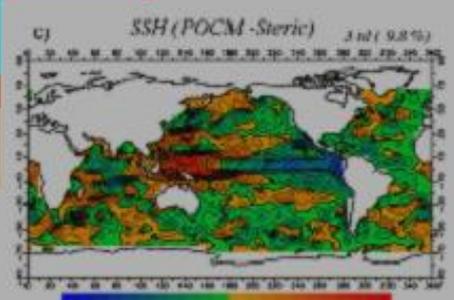
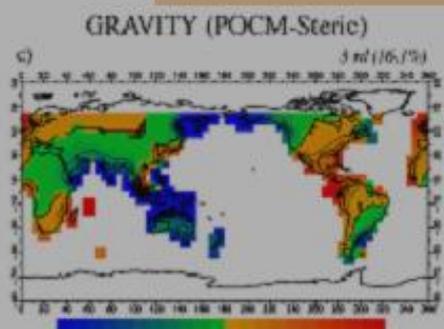
「リモートセンシングは地球をどこまで斬ったか」

休暇村支笏湖・2011年2月13-14日

# 地上および衛星重力測定による 地球変動モニタリング(1)



地球惑星科学専攻 福田洋一



# 内容1 (13日午後)

## ✓ イントロダクション

- 自己紹介を兼ねた研究歴
- 精密測地計測

## ✓ 衛星重力ミッション

- 衛星重力ミッション概要
- 地球重力場の決定
- 衛星で見る重力場

## ✓ GRACEの応用研究

- GRACEデータの利用
- 陸水変動
- 氷床変動
- 地震

# 内容2(14日午前)

## ✓ 地上での重力測定

- 重力計の原理
- 超伝導重力計の応用
- 野外重力測定

## ✓ 衛星高度計

- 衛星高度計の原理
- 海域の重力場
- 海面形状とGOCE
- 海水準変動

## ✓ 展望

- 精密測位による地球環境監視
- 将来ミッション

# 略歴1

1955年 兵庫県生まれ

1977年 京都大学理学部卒業

必須の卒業研究はなかった

ラコスト重力計による精密重力測定

1979年 京都大学大学院修士課程修了(地球物理学専攻)

ラコスト重力計による**重力の時間変化の測定**

コンピューター・グラフィックスによる測地データの時空間表示

1980年 弘前大学理学部

LANDSATデータ解析(石油資源開発)、PCによる画像解析

青函トンネルでの重力測定

1985年 第27次南極地域観測隊に参加(夏隊)

1986年 第28次南極地域観測隊に参加(夏隊)

しらせによる船上重力測定

1987年 東京大学海洋研究所

**衛星高度計(GEOSAT)による海域重力場の研究**

学位論文(1990年):

Precise determination of local gravity field using

both the satellite altimeter data and the surface gravity data

超伝導重力計観測

1991年 第33次南極地域観測隊に参加(夏隊)

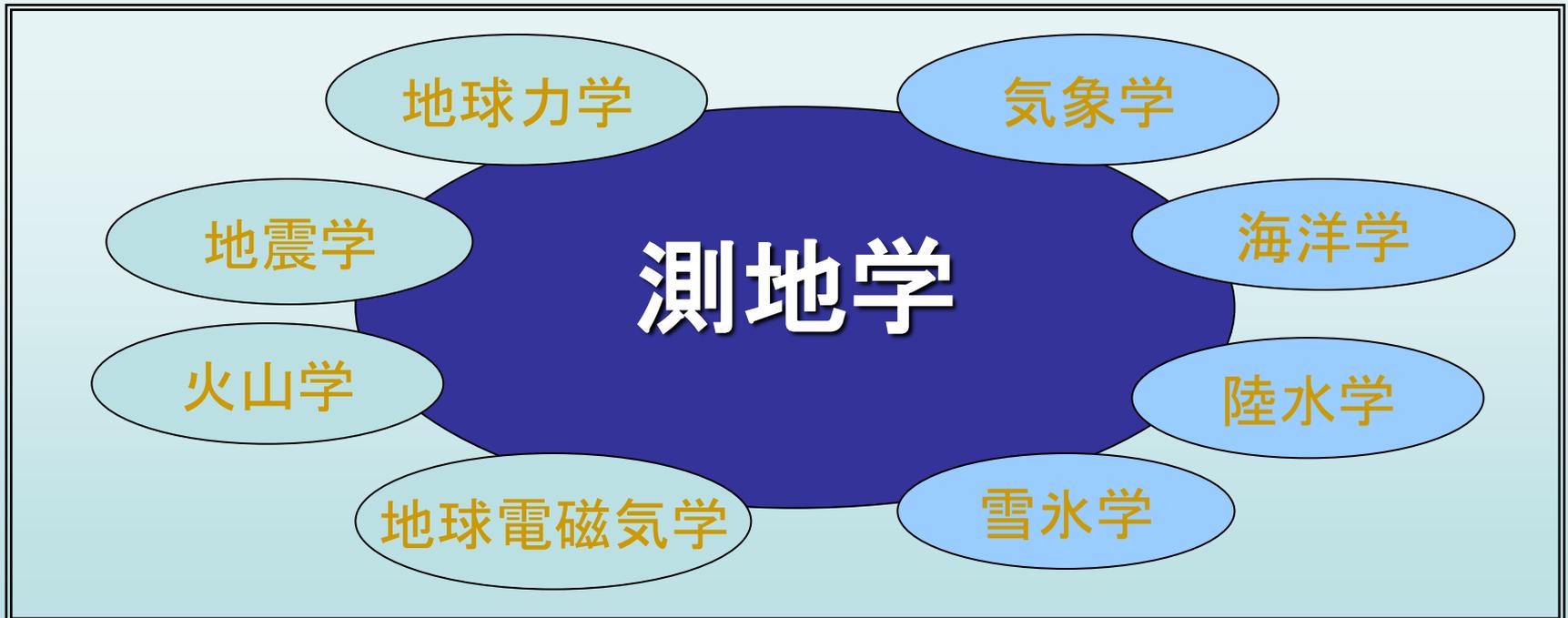
船上重力、超伝導重力観測、絶対重力測定

# 略歴2

- 1992年 京都大学理学部附属地球物理学研究施設(大分県別府市)  
重力測定による別府地域の**地下水(温泉水)変動**の検出  
衛星高度計(TOPEX/Poseidon)データによる**海面荷重変化**
- 1996年 京都大学大学院理学研究科
- 1997-2004年: インドネシア・バンドンでの超伝導重力計観測
- 1999年- : FG-5絶対重力計、国内外での測定  
インドネシアでの絶対重力測定(2002)
- 2003年 第45次南極地域観測隊に参加(夏隊)  
昭和基地での絶対重力測定、超伝導重力計観測
- 2002-2004年: 科振費「**精密衛星測位技術による地球環境モニター**」  
サブテーマ1: GPS掩蔽法を用いた地球大気・電離圏のモニター(津田:代表)  
サブテーマ2: 衛星重力ミッションの基礎技術開発・評価(福田)
- 2004年- : **GRACEデータ**の一般公開  
陸水変動、氷床変動、地震などへの応用
- 2006-2010年: 地球研(RIHN)プロジェクト  
都市の地下環境に残る人間活動の影響(代表:谷口)  
**GRACEデータの応用、野外用絶対重力計A10の応用(2007-)**
- 2008年- : インドネシア・チビノンでの超伝導重力計観測
- 2010年: **GOCEデータ**の一般公開  
南極での局所重力場決定

# 測地学とは

- ✓地球の形状、重力場、地球回転およびそれらの時間変化を決める科学分野
  - それらを記述するための理論を提供する
  - それらを計測するための道具を提供する
- ✓地球システムの様々なサブ・システム間の相互作用を解く鍵を与える
  - 地球惑星科学の様々な分野との関わり



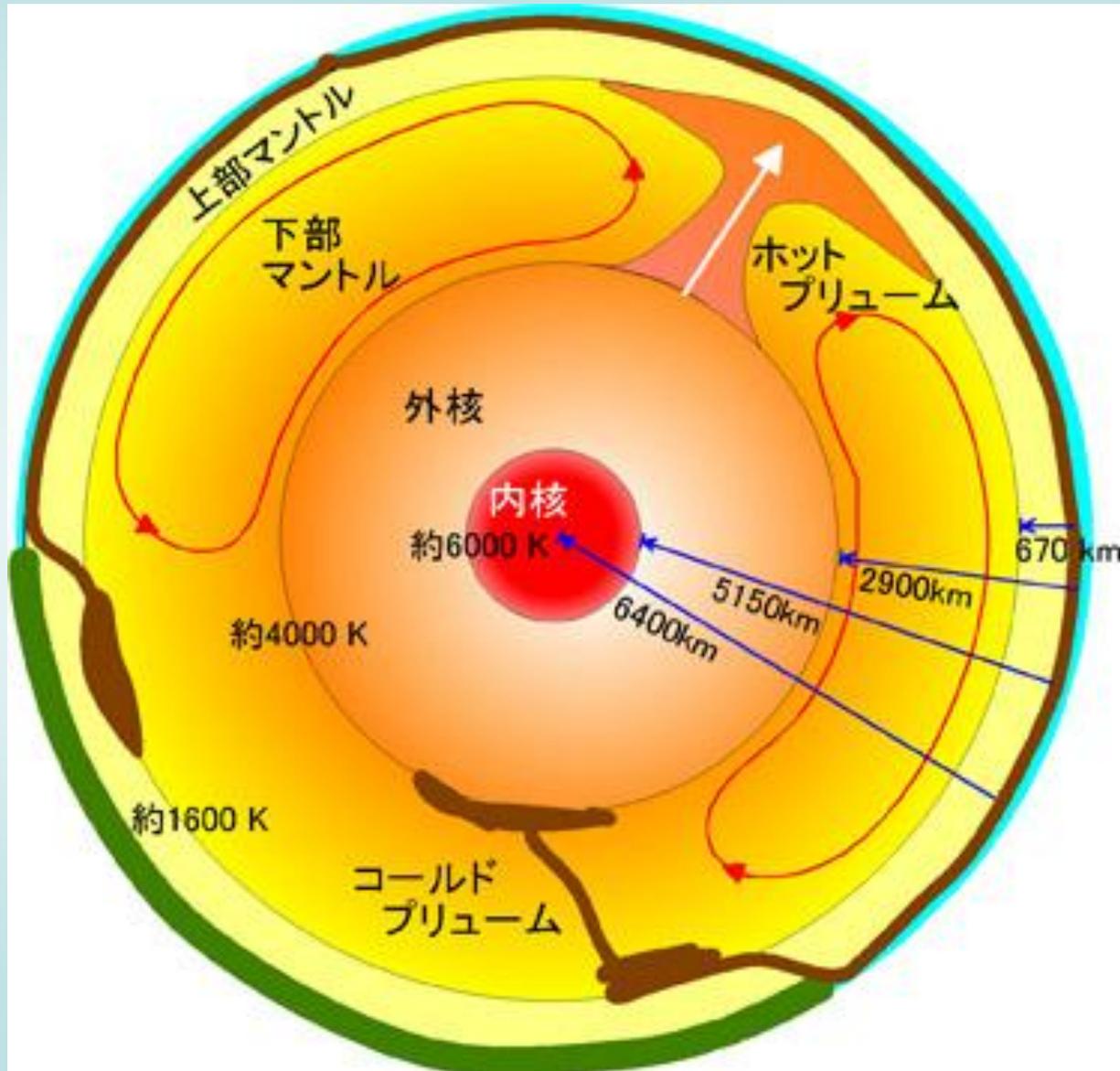
# 現代測地学のポイント

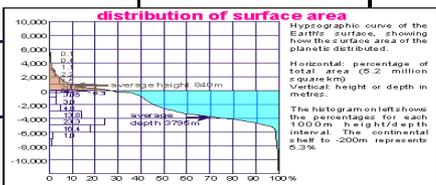
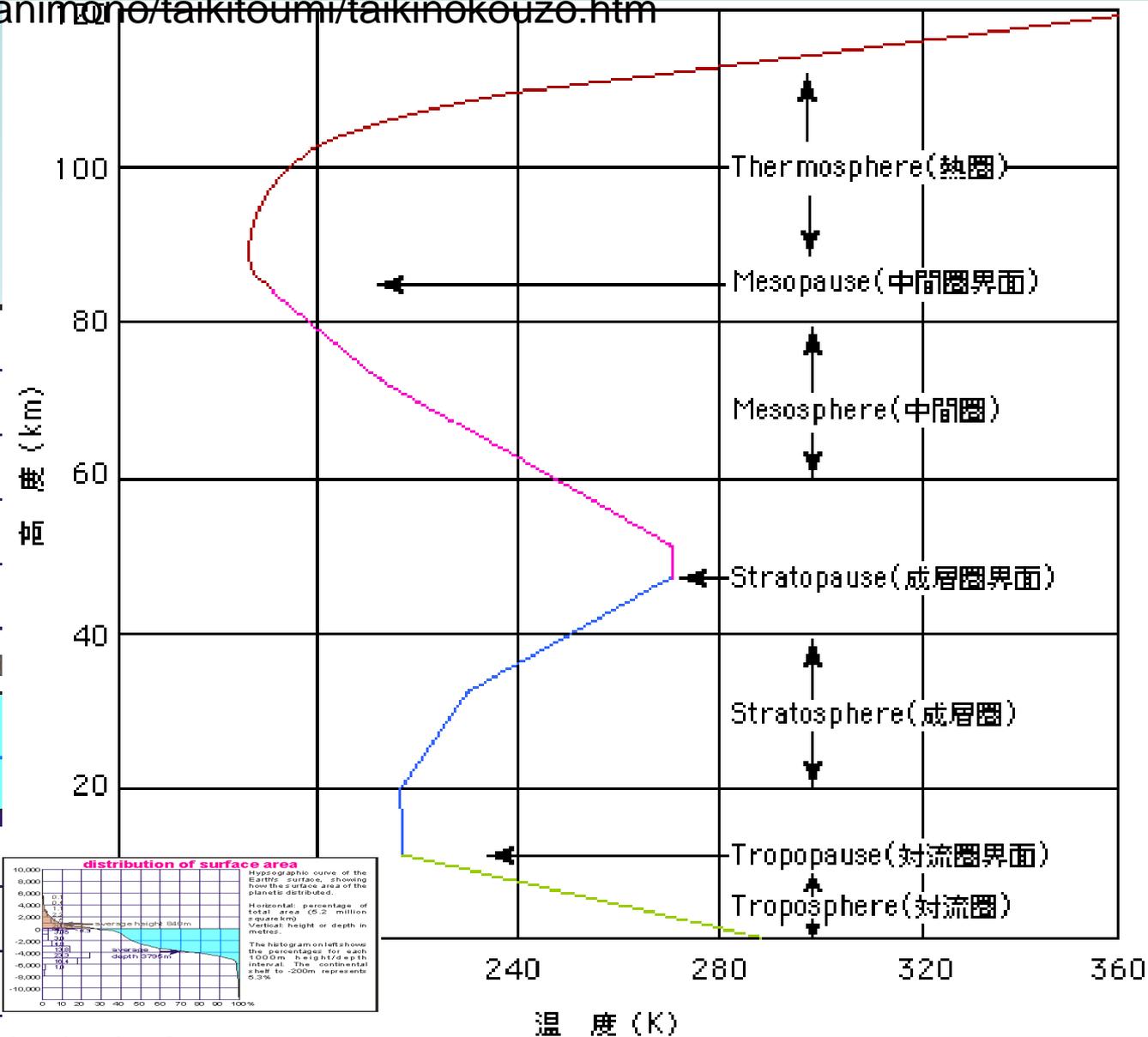
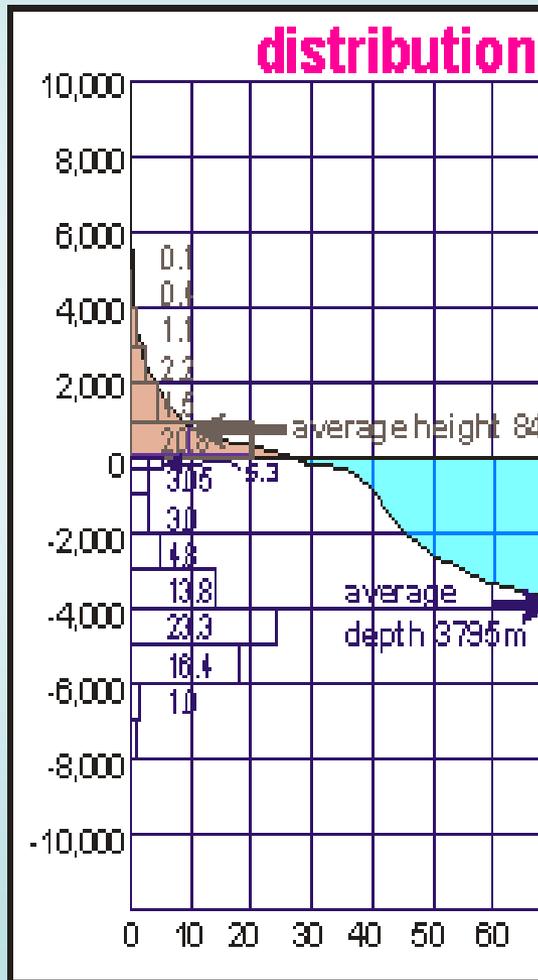
- 極めて高い測定精度
  - mm で地球の形状を決める
  - $\mu\text{gal}$  ( $10^{-8}\text{ms}^{-2}$ ) で地球の重力場を決める
  - 0.01 mas (milli arc second) で地球の回転を決める
- 精度を達成するために
  - 測定技術
    - 宇宙(測地)技術
      - VLBI, SLR, GPS, SAR, ALT, GRV
    - ハイテク
      - 絶対重力計(AG), 超伝導重力計(SG), レーザー技術
  - 高精度なレファレンス・フレーム(Geodetic Reference Frame)
    - ITRF (International Terrestrial Reference Frame),
    - IERS (International Earth Rotation and Reference Systems Service )
    - GRS80 (Geodetic Reference System1980)

# 測地基準系

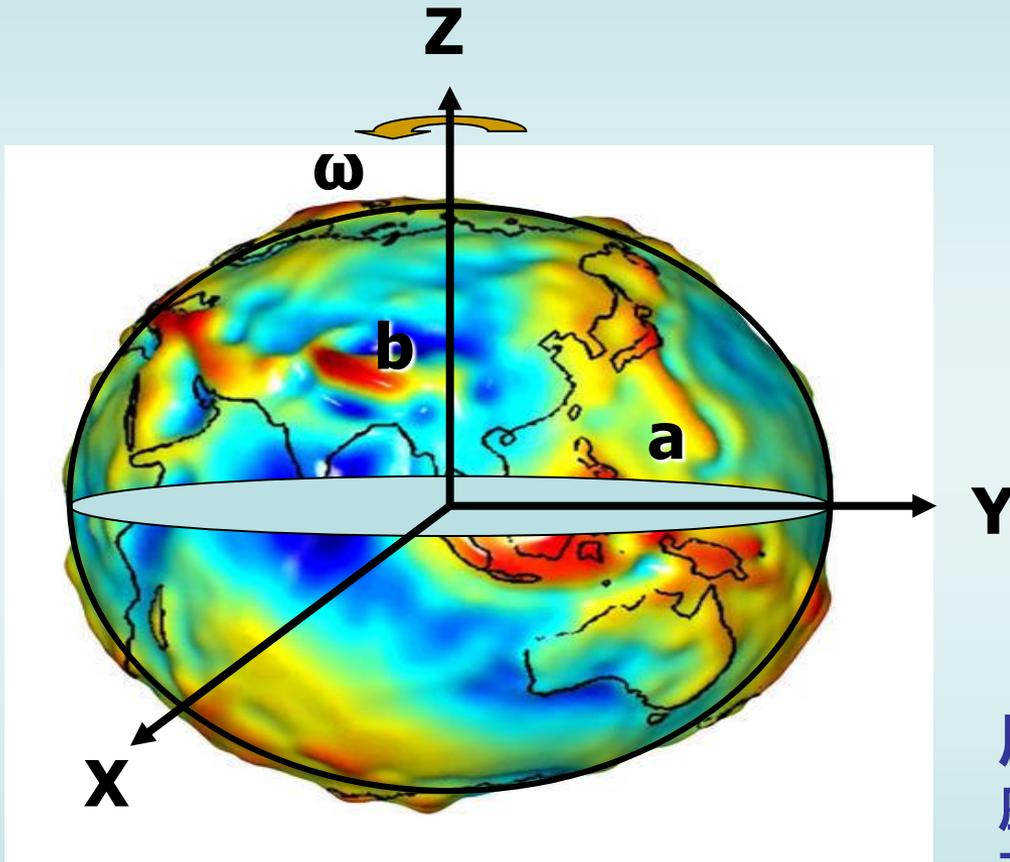
- 回轉楕円体(地球楕円体)
- 座標系
  - ITRF
- 地球回轉
  - 地球潮汐、歳差・章動、極運動、LOD
- 高さと重力・ジオイド
  - 楕円体高、正標高

# 地球の構造とダイナミクス





# 地球楕円体



GRS80 ellipsoid

$$a=6378137 \quad \text{m}$$

$$b=6356752.314 \quad \text{m}$$

$$f=(a-b)/a=1/298.257222101$$

$$\omega=7292115 \times 10^{-11} \text{rad/s}$$

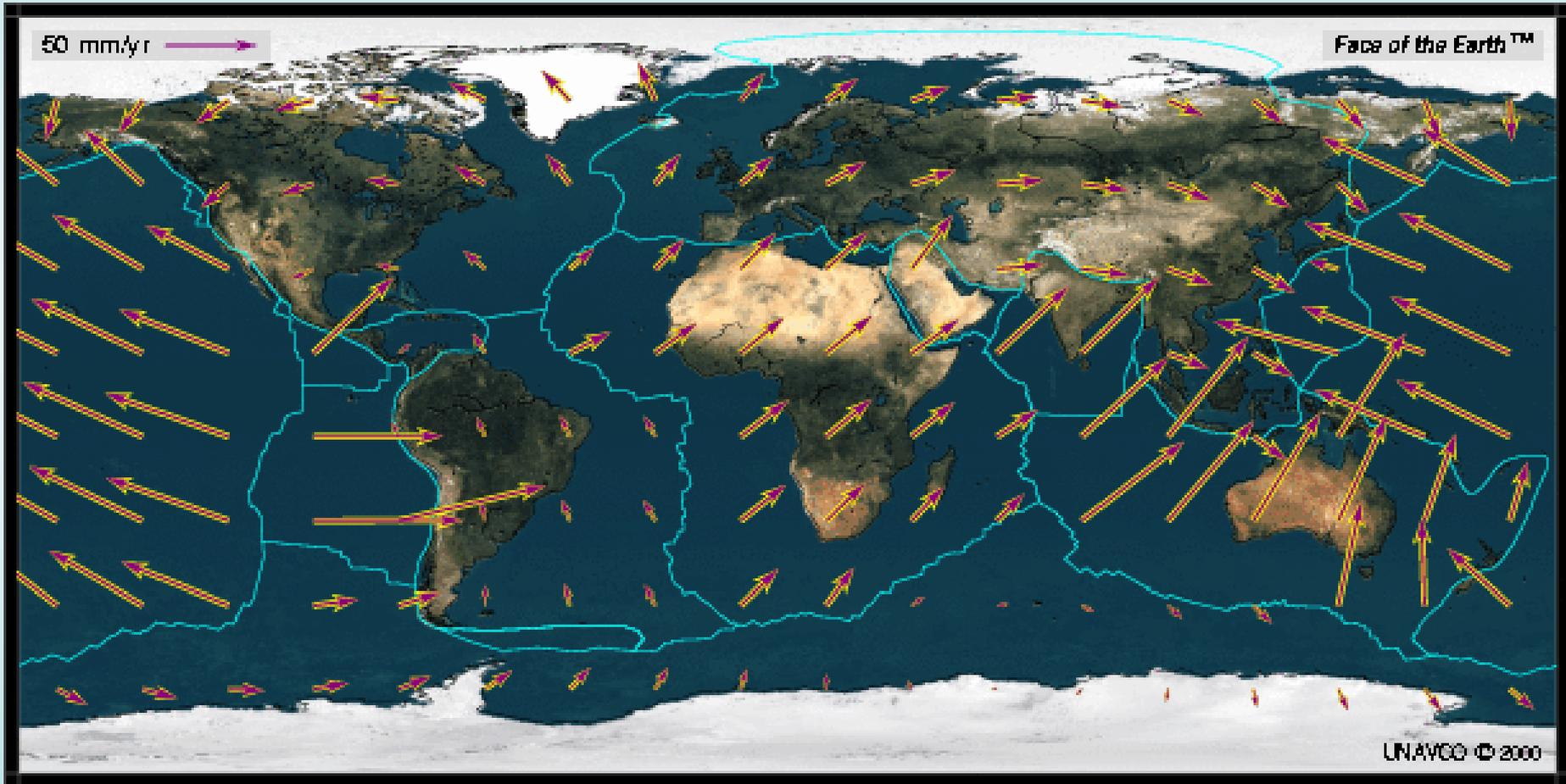
座標をどのように決めるか？

座標原点  $\rightarrow$  重心

Z-軸  $\rightarrow$  自転軸

X,Y軸

# プレート運動



[http://sps.unavco.org/crustal\\_motion/dxdt/images/nuvel1a\\_nnr.gif](http://sps.unavco.org/crustal_motion/dxdt/images/nuvel1a_nnr.gif)

# ITRF (from <http://itrf.ensg.ign.fr/>)

## Definitions

**A Terrestrial Reference System (TRS)** is a spatial reference system co-rotating with the Earth in its diurnal motion in space. In such a system, positions of points anchored on the Earth solid surface have coordinates which undergo only small variations with time, due to geophysical effects (tectonic or tidal deformations).

**A Terrestrial Reference Frame (TRF)** is a set of physical points with precisely determined coordinates in a specific coordinate system (cartesian, geographic, mapping...) attached to a Terrestrial Reference System. Such a TRF is said to be a realization of the TRS.

# ITRF2005 Map

[http://itrf.ensg.ign.fr/ITRF\\_solutions/2005/doc/ITRF2005\\_GPS.SSC.txt](http://itrf.ensg.ign.fr/ITRF_solutions/2005/doc/ITRF2005_GPS.SSC.txt)

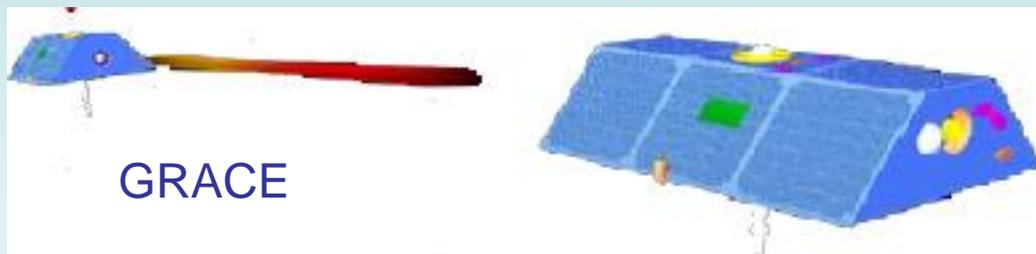
ITRF2005\_GPS.SSC.txt

## ITRF2005 STATION POSITIONS AT EPOCH 2000.0 AND VELOCITIES GPS STATIONS

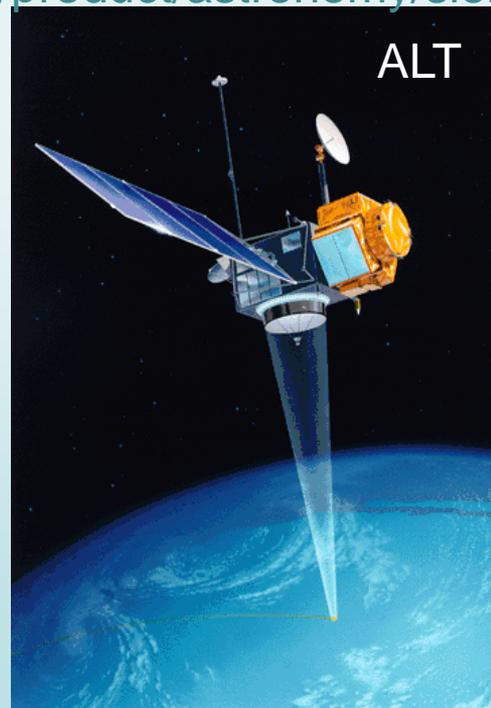
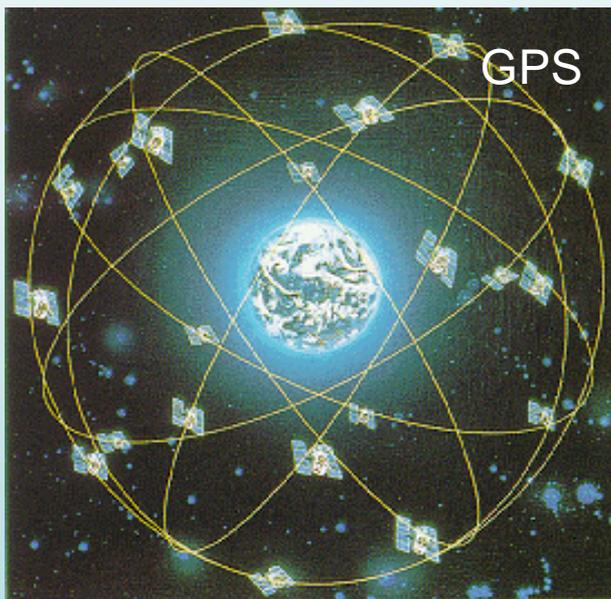
DOMES NB.	SITE NAME	TECH.	ID.	X/Vx	Y/Vy	Z/Vz	Sigmas			SOLN	DATA_START
				-----m/m/y-----							
10001S006	PARIS	GPS	OPMT	4202777.434	171367.913	4778660.147	0.005	0.002	0.006		
10001S006				-.0118	0.0170	0.0111	.0011	.0004	.0012		
10002M006	GRASSE	GPS	GRAS	4581690.969	556114.738	4389360.731	0.001	0.000	0.001	1	00:000:00000
10002M006				-.0139	0.0186	0.0116	.0001	.0001	.0001		
10002M006	GRASSE	GPS	GRAS	4581690.975	556114.741	4389360.734	0.001	0.000	0.001	2	03:113:00000
10002M006				-.0139	0.0186	0.0116	.0001	.0001	.0001		
10002M006	GRASSE	GPS	GRAS	4581690.974	556114.744	4389360.739	0.001	0.001	0.001	3	04:295:43200
10002M006				-.0139	0.0186	0.0116	.0001	.0001	.0001		
10003M004	TOULOUSE	GPS	TOUL	4627846.086	119629.236	4372999.754	0.001	0.000	0.001		
10003M004				-.0111	0.0191	0.0117	.0003	.0001	.0003		
10003M009	TOULOUSE	GPS	TLSE	4627851.889	119639.921	4372993.492	0.001	0.001	0.001		
10003M009				-.0111	0.0191	0.0117	.0003	.0001	.0003		
10004M004	BREST	GPS	BRST	4231162.638	-332746.764	4745130.859	0.004	0.001	0.004		
10004M004				-.0111	0.0162	0.0134	.0009	.0003	.0009		
10023M001	La Rochelle	GPS	LROC	4424632.623	-94175.321	4577544.022	0.003	0.001	0.003		
10023M001				-.0106	0.0183	0.0123	.0006	.0002	.0006		
10090M001	SAINT JEAN DES	GPS	SJDV	4433469.919	362672.729	4556211.652	0.002	0.001	0.002	1	00:000:00000
10090M001				-.0118	0.0186	0.0121	.0008	.0002	.0008		
10090M001	SAINT JEAN DES	GPS	SJDV	4433469.921	362672.729	4556211.656	0.001	0.000	0.001	2	99:071:57600
10090M001				-.0118	0.0186	0.0121	.0008	.0002	.0008		
10202M001	REYKJAVIK	GPS	REYK	2587384.422	-1043033.508	5716563.995	0.001	0.000	0.001	1	00:000:00000
10202M001				-.0216	-.0028	0.0059	.0001	.0001	.0002		
10202M001	REYKJAVIK	GPS	REYK	2587384.410	-1043033.501	5716563.980	0.006	0.003	0.012	2	00:169:56460
10202M001				-.0216	-.0028	0.0059	.0001	.0001	.0002		
10202M001	REYKJAVIK	GPS	REYK	2587384.415	-1043033.509	5716564.003	0.001	0.000	0.001	3	00:173:03120
10202M001				-.0216	-.0028	0.0059	.0001	.0001	.0002		
10202M003	REYKJAVIK	GPS	REYZ	2587383.736	-1043032.722	5716564.472	0.001	0.001	0.001		
10202M003				-.0216	-.0028	0.0059	.0001	.0001	.0002		
10204M002	HOFN	GPS	HOFN	2679689.983	-727951.292	5722789.189	0.001	0.000	0.001	1	00:000:00000
10204M002				-.0046	0.0144	0.0177	.0001	.0001	.0003		

# 宇宙測地技術

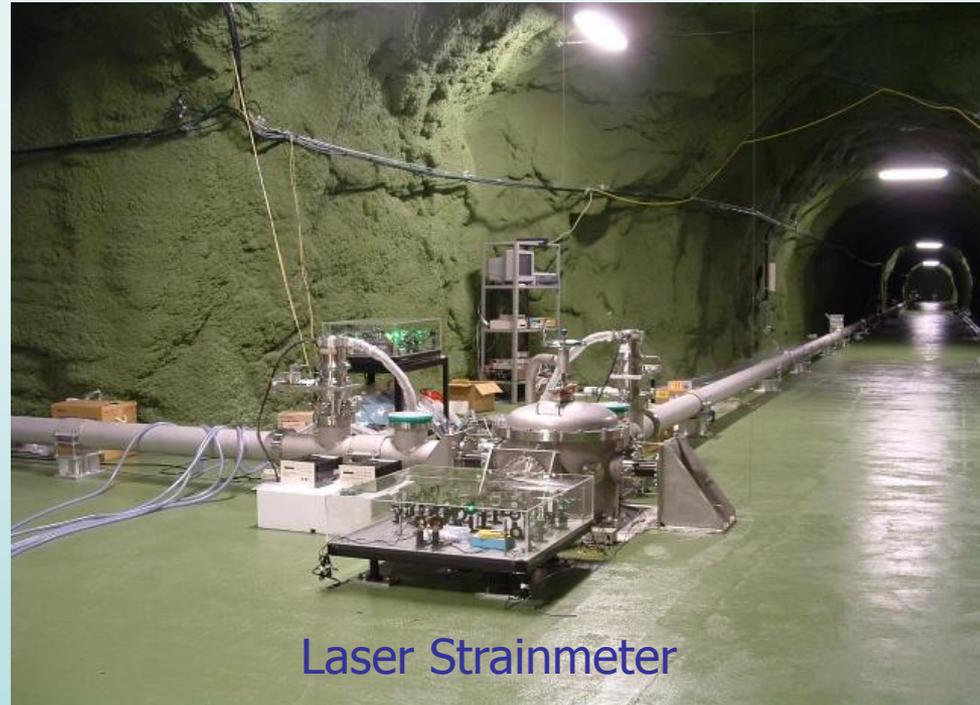
[http://solarsystem.nasa.gov/scitech/display.cfm?ST\\_ID=186](http://solarsystem.nasa.gov/scitech/display.cfm?ST_ID=186)



<http://www.aes.co.jp/product/astronomy/sien.html>

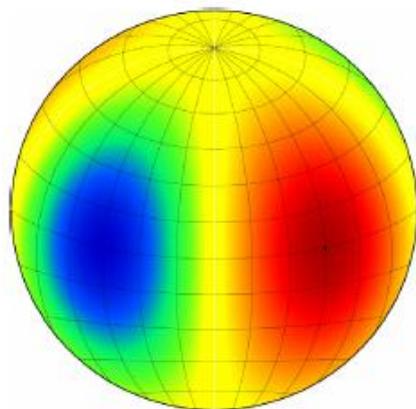
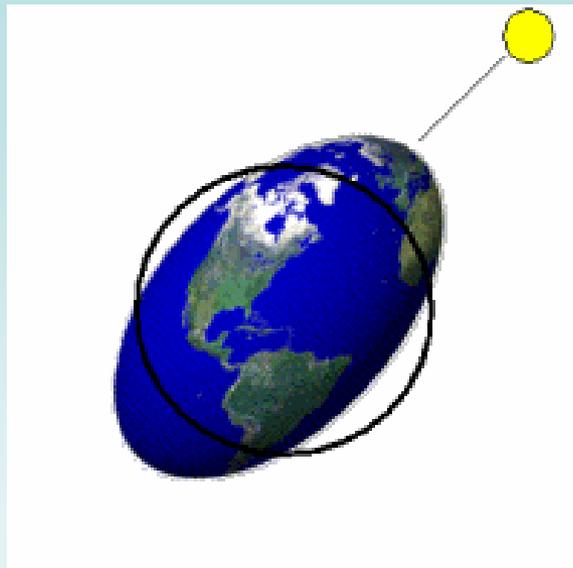


# ハイテク測定

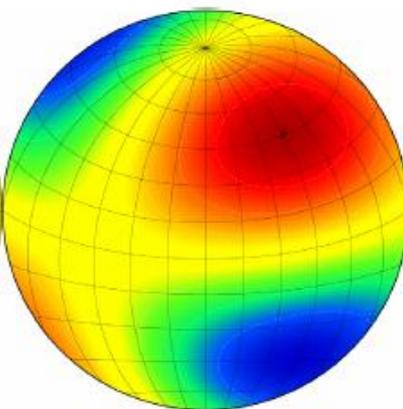


# 地球潮汐

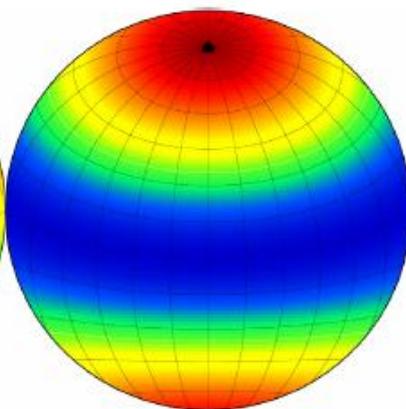
月



Sectorial



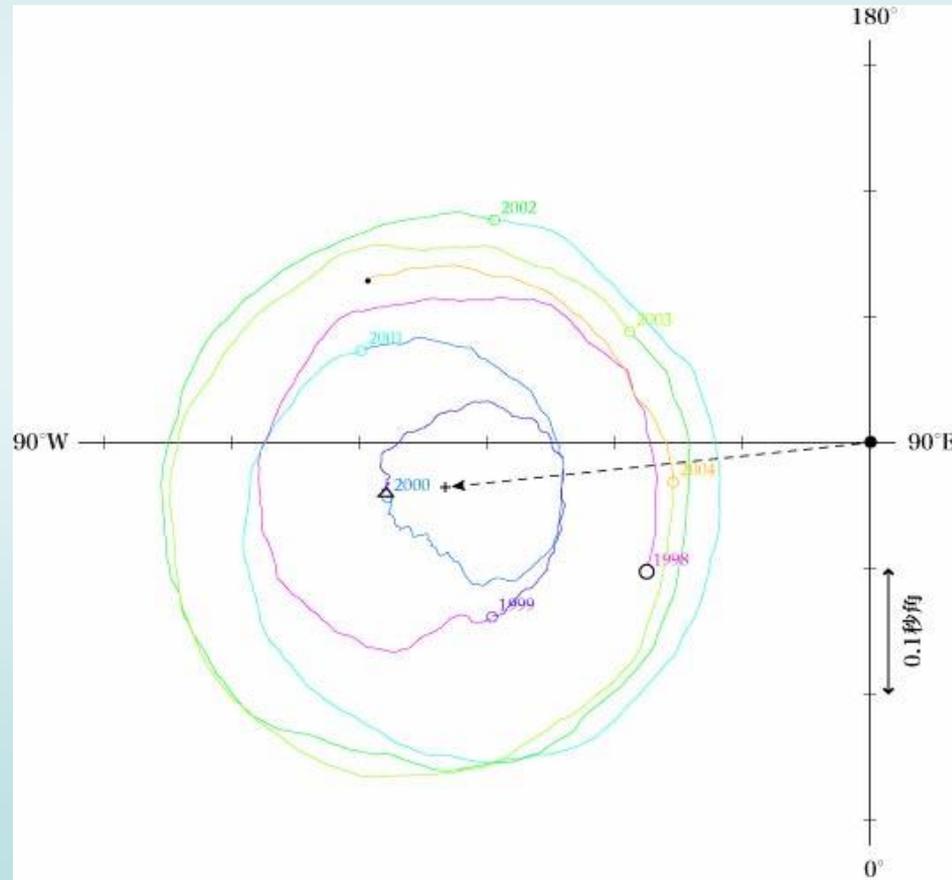
Tesseral



Zonal

# 極運動

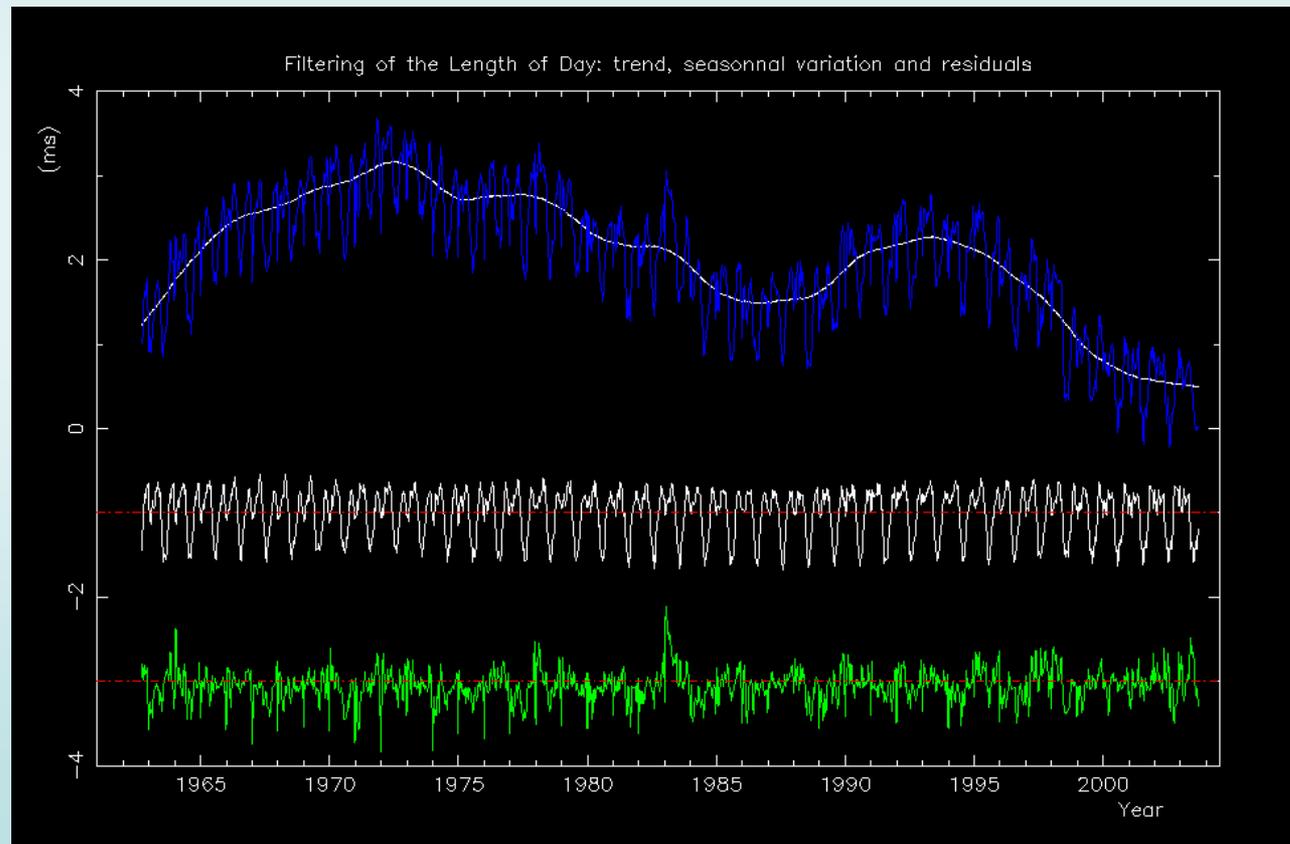
極運動は、固体地球に対して自転軸が変動する現象であり、地球の形状軸と瞬間の自転軸とがずれている場合に生じる。極運動は一種の自由振動で、19世紀末、チャンドラーはおよそ430日の周期で地球が半径数mの極運動していることを発見した。この極運動はチャンドラー極運動(チャンドラーウォブル)と呼ばれる。



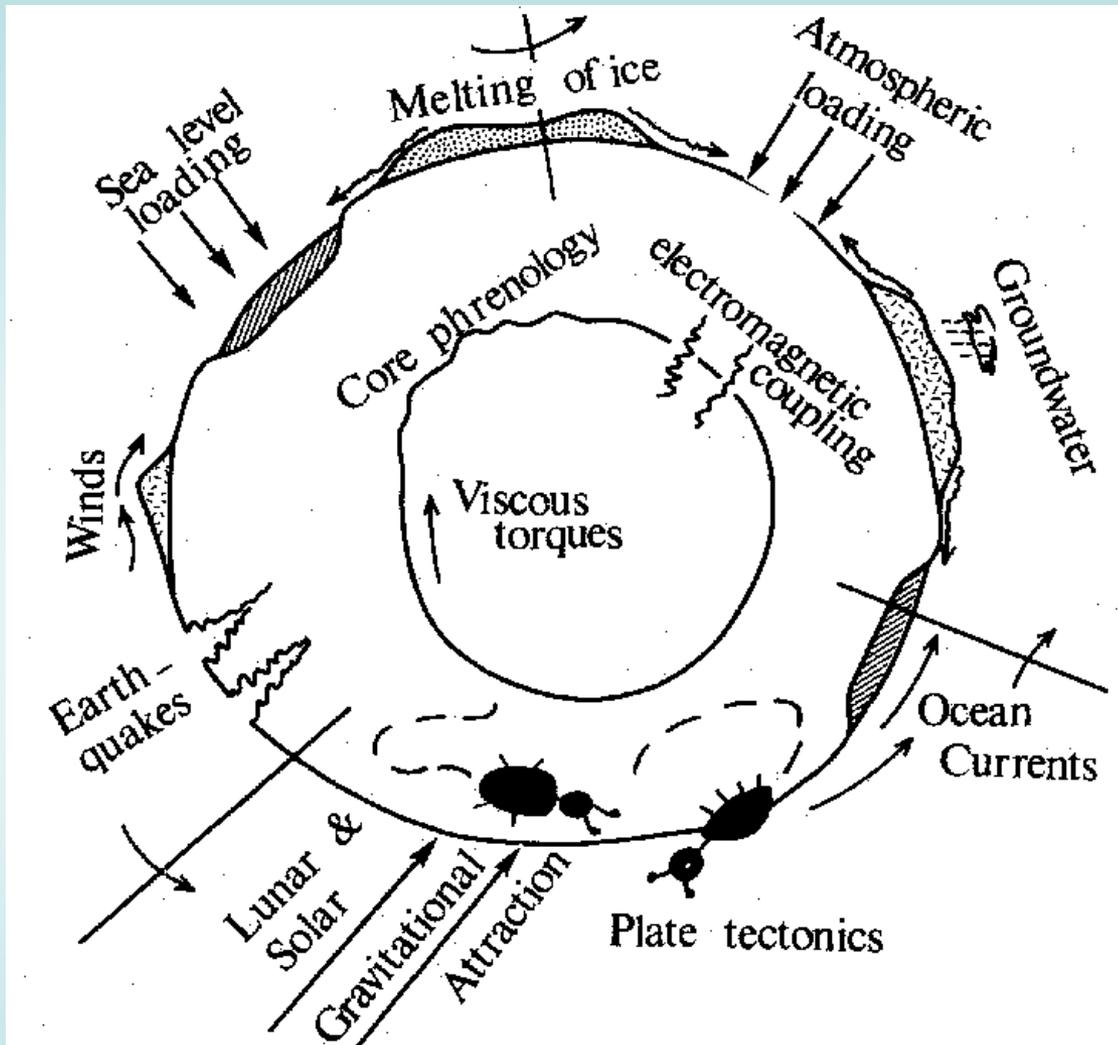
(<http://wwwsoc.nii.ac.jp/geod-soc/web-text/part3/furuya/furuya-1.html>)

# Length of day (LOD)

一般に、閉じた系では、その系内の角運動量(角速度と慣性モーメントの積)の総和は変化しないという角運動量保存則が成り立つ。地球の持つ角運動量の大部分は、固体地球の自転による角運動量であるが、そのほかに大気を持つ角運動量の変化は、地表面での摩擦をとおして固体地球との角運動量の交換が起こり、結果として地球の自転速度に変化をもたらす。



(<http://hpiers.obspm.fr/eop-pc/>)



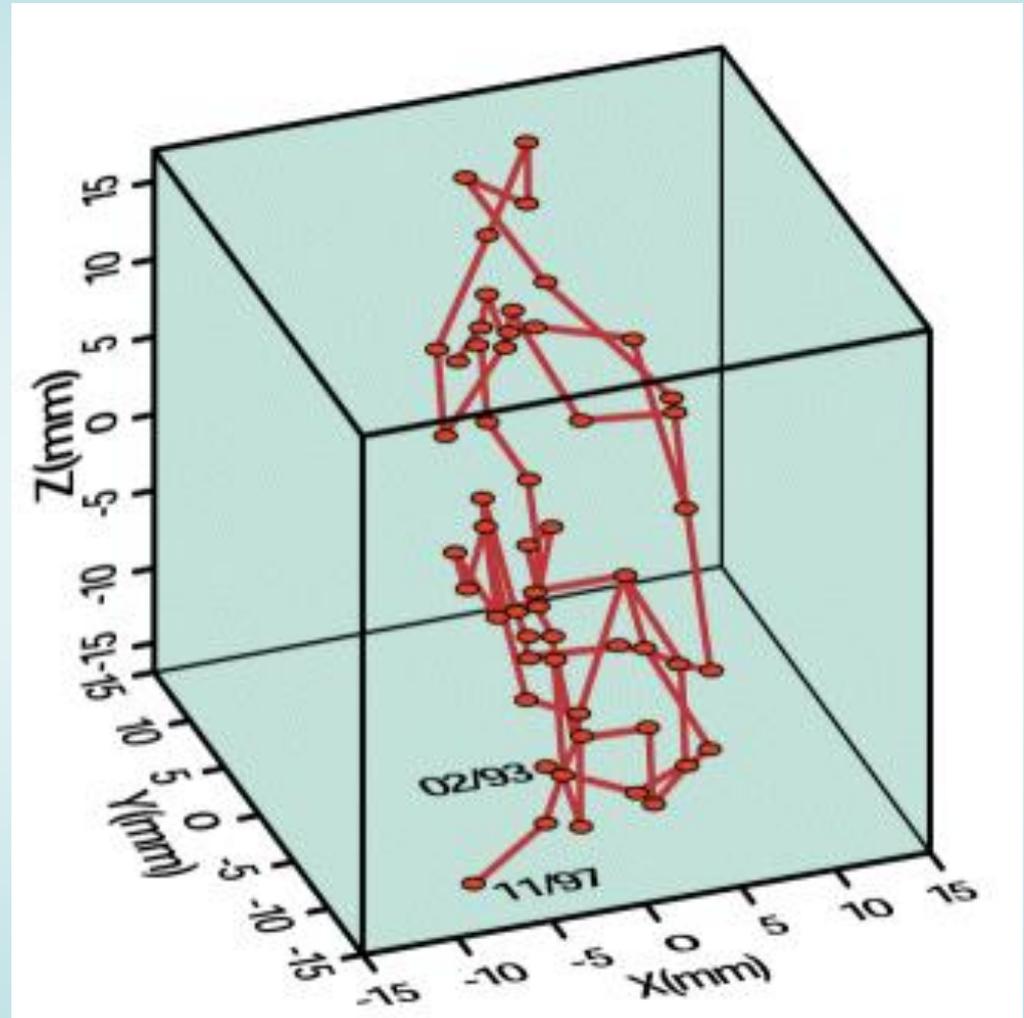
大気と地球間での  
角運動量の交換

*Changes in length-of-day and atmospheric circulation*  
Kurt Lambeck, *Nature*, 1980

# 地球の重心

地球の重心位置は、海洋、土壌水分、降雪、陸水など地球上での水循環による質量の再配分の結果として、3cm程度の範囲で常に変化している。

=> 1次の重力場球面調和関数



<http://www.avisioceanobs.com/fr/applications/geodesie-et-geophysique/autres-applications-geophysiques/index.html>

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## ✓ イン트로ダクション

- 自己紹介を兼ねた研究歴
- 精密測地計測

## ✓ 衛星重力ミッション

- 衛星重力ミッション概要
- 地球重力場の決定
- 衛星で見る重力場

## ✓ GRACEの応用研究

- GRACEデータの利用
- 陸水変動
- 氷床変動
- 地震

# 衛星重力ミッション概要

# 衛星重力ミッション

## CHAMP (2000.7.15)- (2010.9.19)

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

## GRACE (2002. 3.17)- (201x)

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

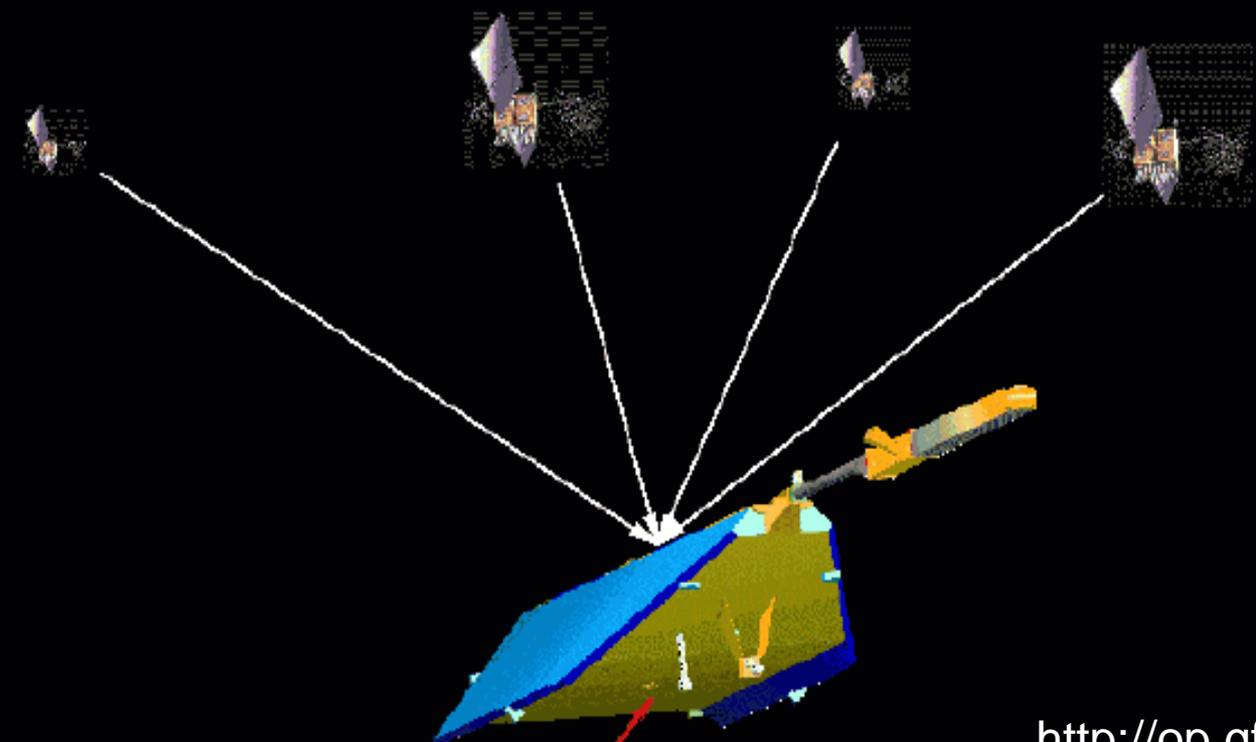
## GOCE (2009.03.17 ) - (2012.12 + ??)

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

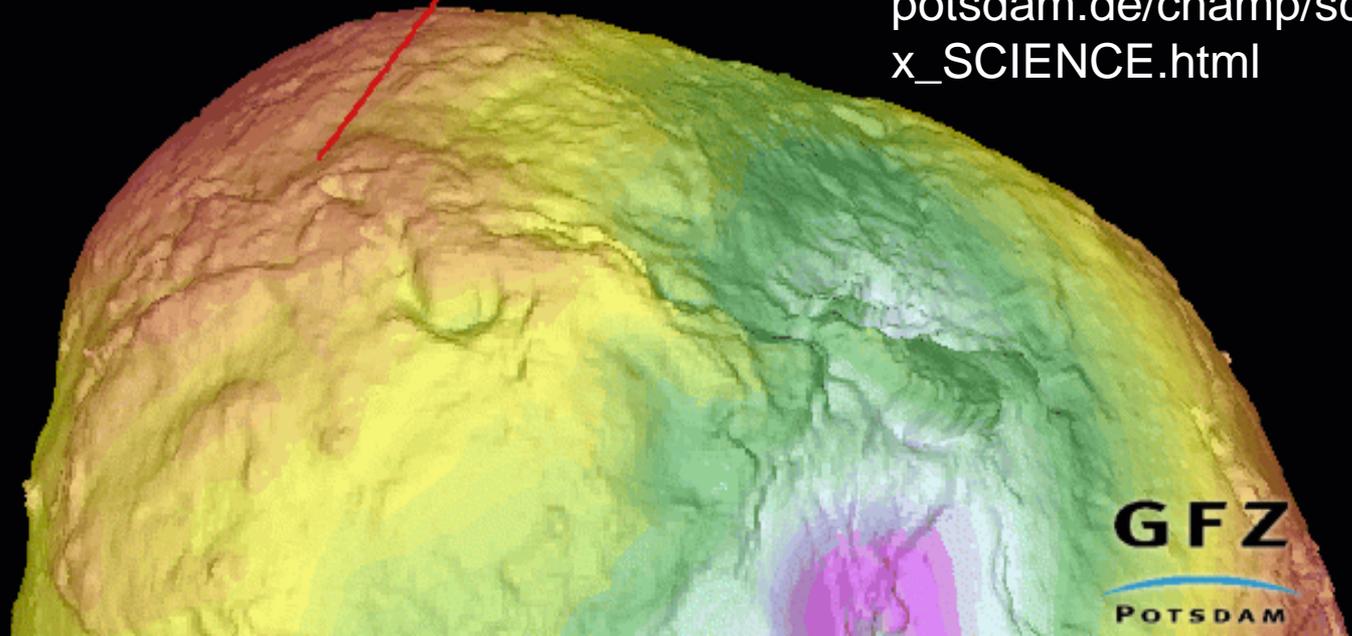
## GRACE-FO , GRACE-II (20??)

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

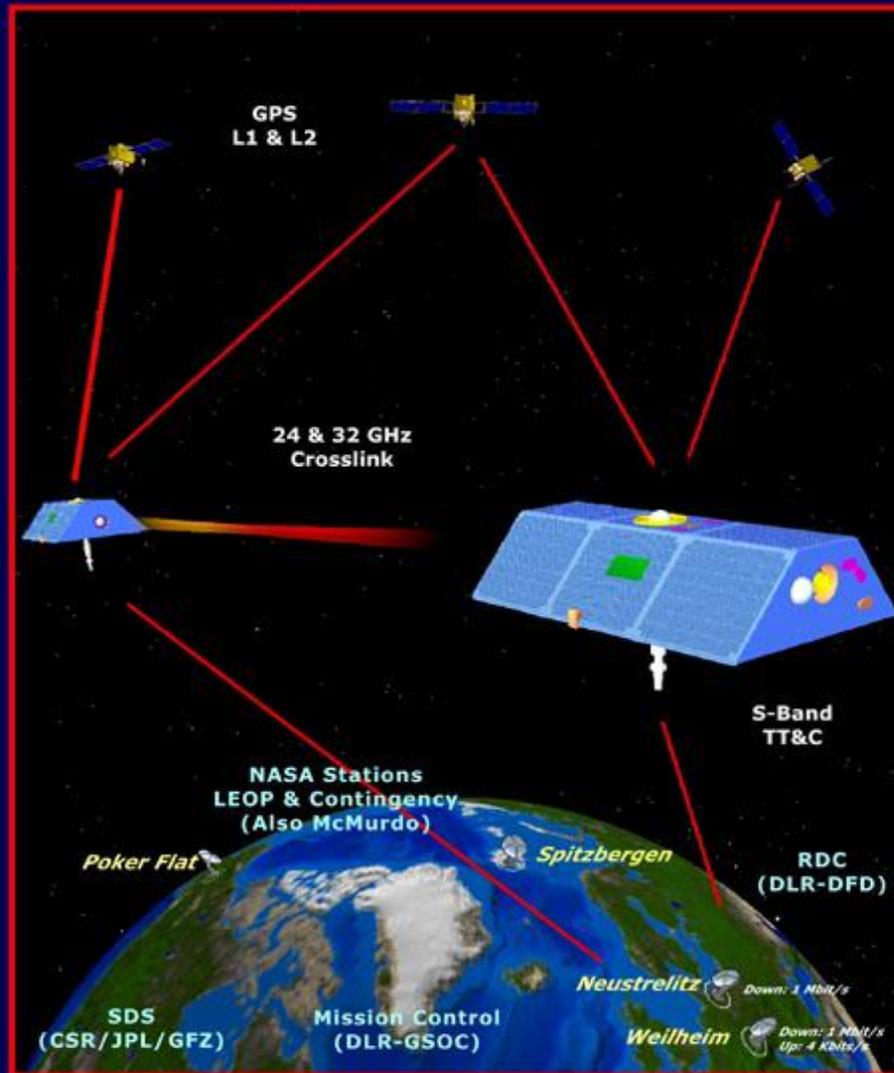
# CHAMP



[http://op.gfz-potsdam.de/champ/science/index\\_SCIENCE.html](http://op.gfz-potsdam.de/champ/science/index_SCIENCE.html)



# GRACE



## 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

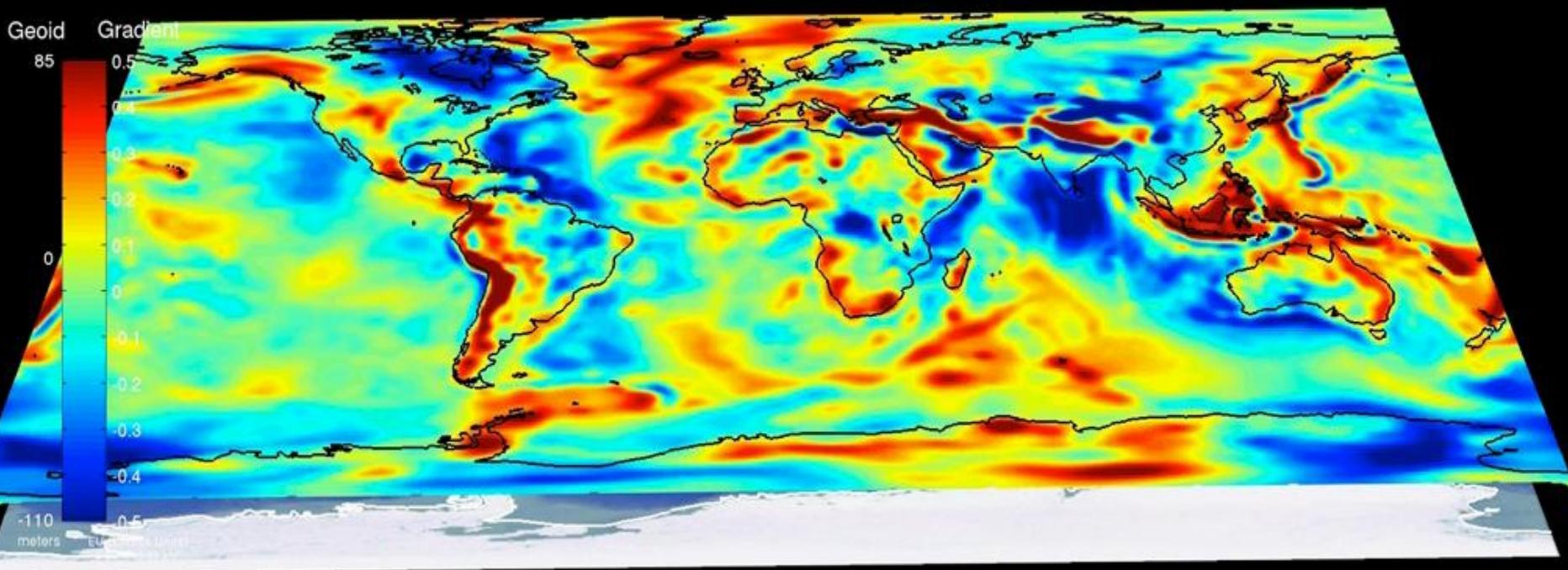
Non-Repeat Ground Track

Earth Pointed, 3-Axis Stable

# GOCE



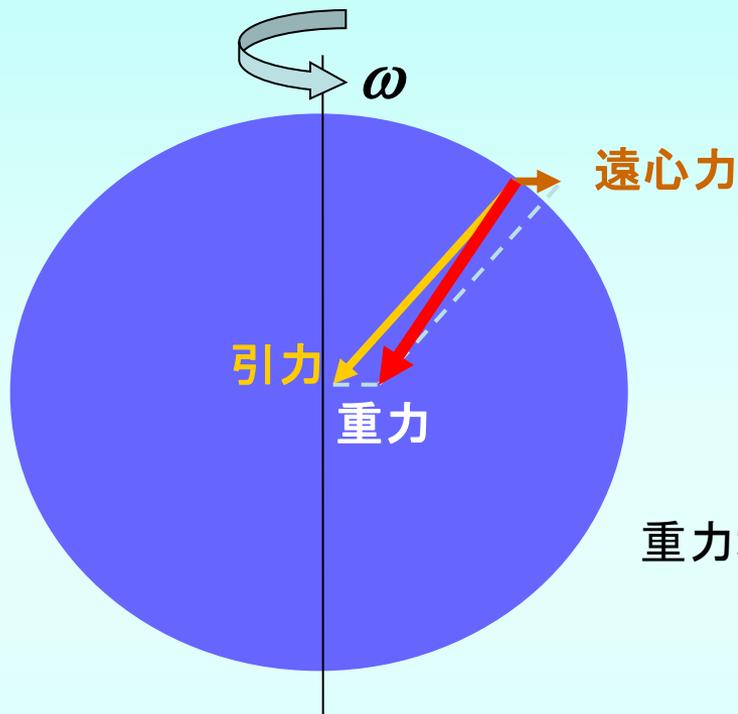
[http://www.esa.int/esaLP/ESA1MK1VMOC\\_LPgoc\\_e\\_0.html](http://www.esa.int/esaLP/ESA1MK1VMOC_LPgoc_e_0.html)



[http://www.esa.int/esaMI/Operations/SEMNRNKIWZE\\_1.html](http://www.esa.int/esaMI/Operations/SEMNRNKIWZE_1.html)

# 地球重力場の決定

# 地球の重力場



$$\text{重力} = \text{引力} + \text{遠心力}$$

$$\text{grad } W = \text{grad } V + \text{grad } \Phi$$

↑                    ↑                    ↑  
重力ポテンシャル   引力ポテンシャル   遠心力ポテンシャル

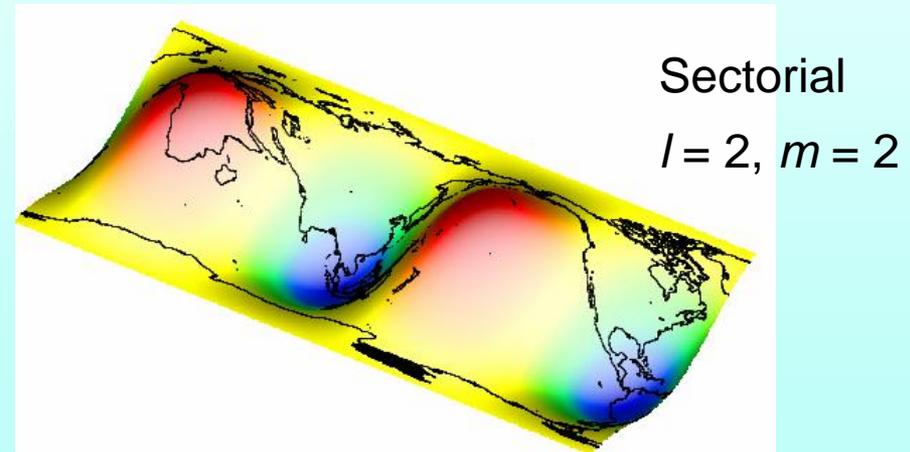
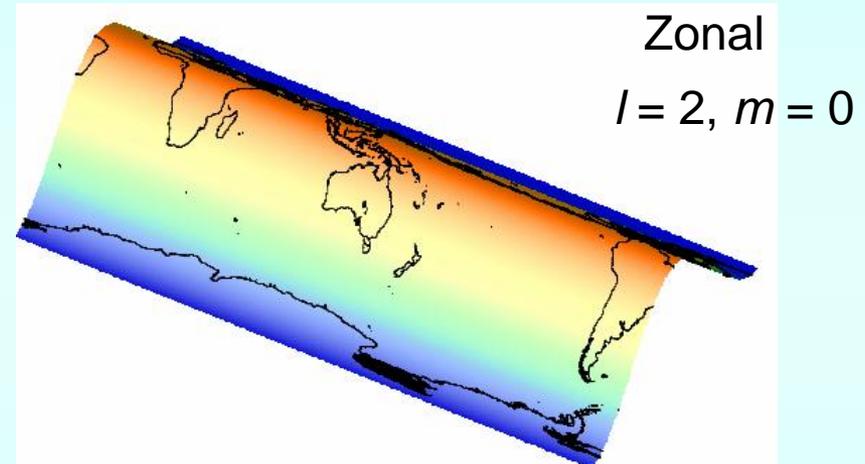
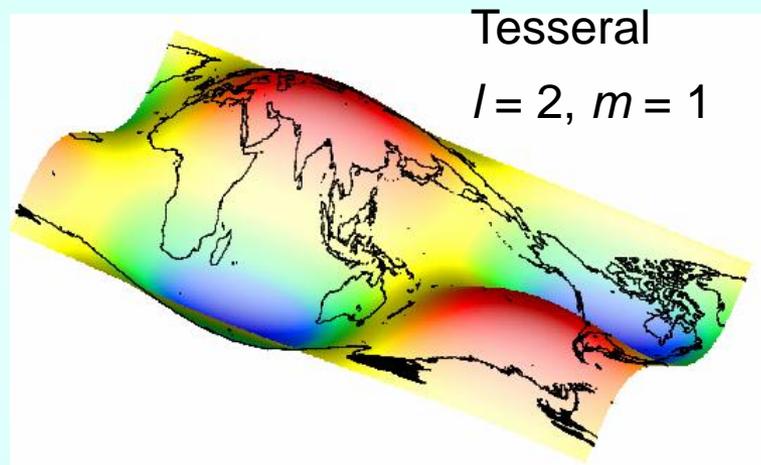
$$V = G \iiint_{\text{earth}} \frac{\rho(\mathbf{x}) d^3 \mathbf{x}}{|\mathbf{r} - \mathbf{x}|}$$

$$\Phi = \frac{1}{2} \omega^2 (x^2 + y^2)$$

ジオイド: 平均的な海面に近い等重力ポテンシャル面

# Vの球面調和関数展開

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



Degree  $l$  Order  $m$ の成分  
節の数

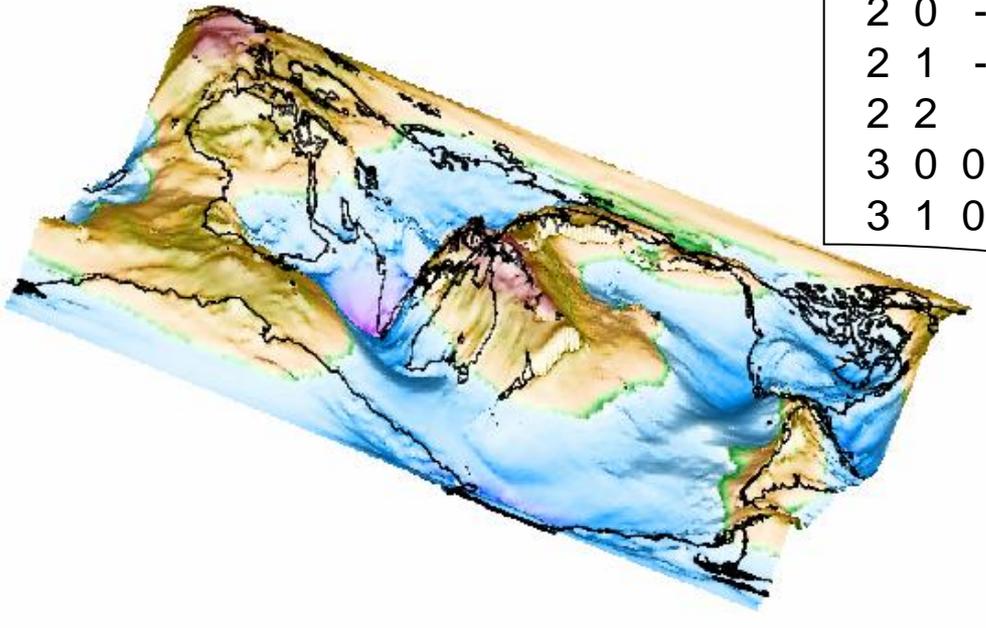
南北方向  $l - m$  個

東西方向  $2m$  個

# Stokes係数

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

CHAMP  
EIGEN-2 model



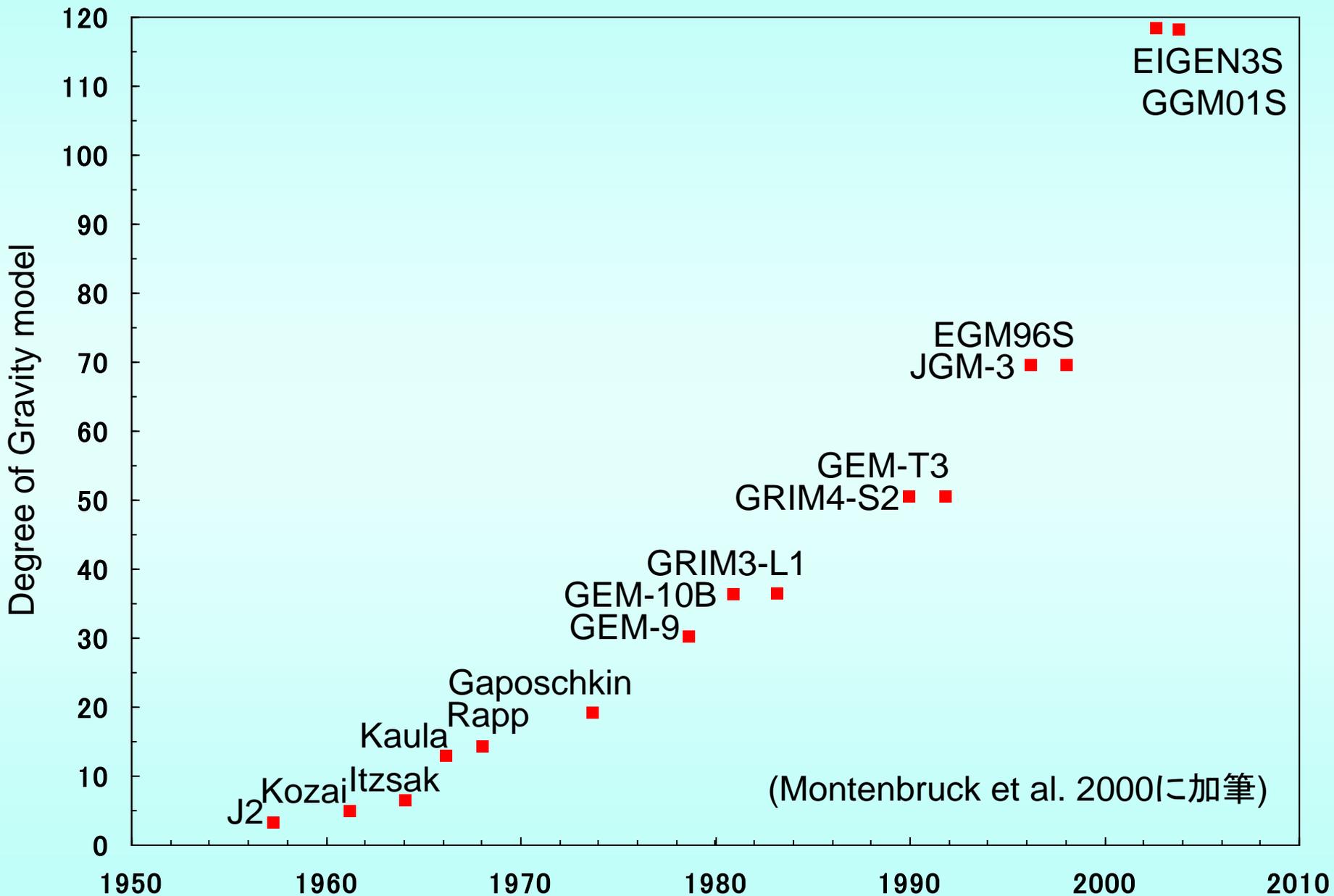
$l$	$m$	$C_{lm}$	$S_{lm}$
0	0	0.1000000000000D+01	0.0000000000000D+00
1	0	0.0000000000000D+00	0.0000000000000D+00
1	1	0.0000000000000D+00	0.0000000000000D+00
2	0	-.484165815935D-03	0.0000000000000D+00
2	1	-.139274044771D-09	0.141275625216D-08
2	2	.243930491835D-05	-.140027520233D-05
3	0	0.957730216460D-06	0.0000000000000D+00
3	1	0.203054457836D-05	0.248146553306D-06
			⋮

Up to Degree 120 / Order 120

精密な地球重力場の決定

= 高次までの  $\bar{C}_{lm}$ 、 $\bar{S}_{lm}$  を高精度で決定すること

# 地球重力場モデルの変遷



# 人工衛星による地球重力場決定

## 衛星の軌道



地球の中心に質量が集中していると考える（質点の力学）

Keplerの第1法則：地球を焦点の一つとする楕円軌道

Keplerの第2法則：面積速度一定の法則

Keplerの第3法則：公転周期の2乗は軌道の半長径の3乗に比例

実際の地球は密度が均一でない

衛星軌道の摂動

不均質な重力場を反映

衛星自体が重力計センサー

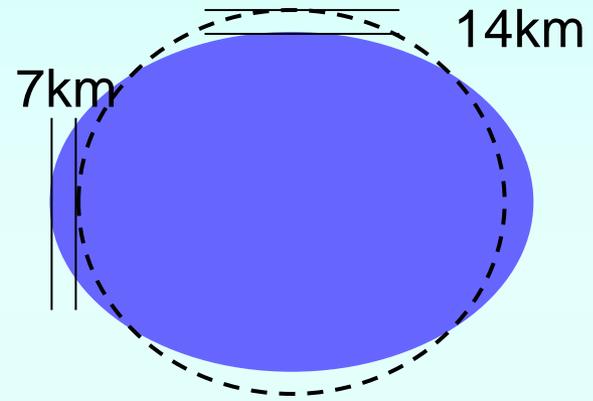
# 初期の成果

バンガード1号衛星の軌道追跡結果

## $J_2 (= -C_{20})$ の決定

地球は楕円型

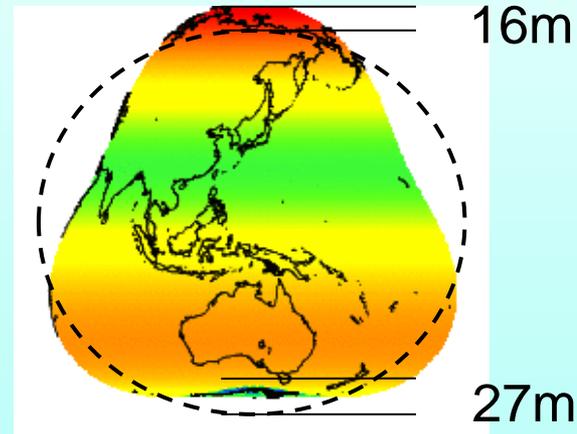
扁平率  $1/297 \rightarrow 1/298.25$



## $J_3 (= -C_{30})$ の決定

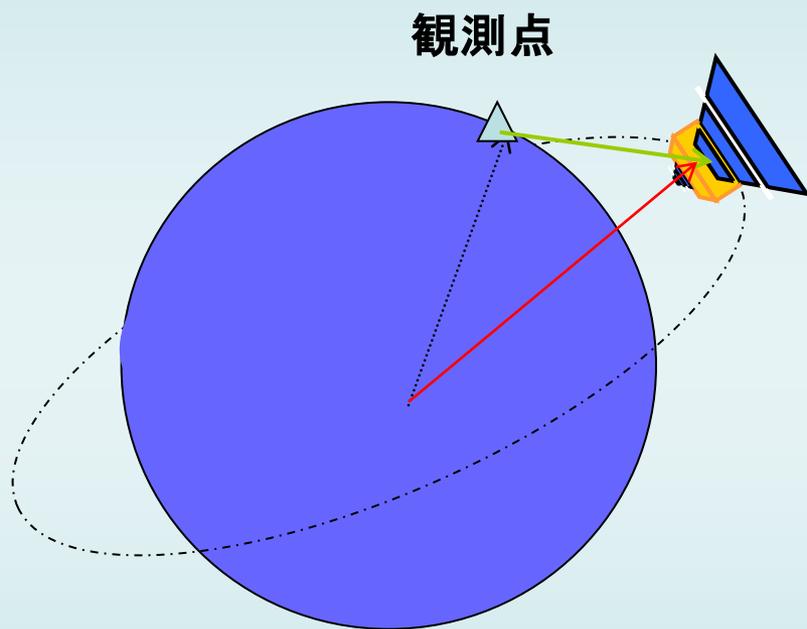
古在由秀

地球は西洋梨型



# 軌道解析による $C_{lm}$ , $S_{lm}$ の決定

精密な衛星軌道決定と密接な関係



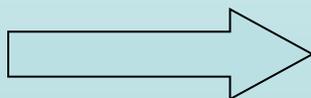
地球の引力による加速度  
 $grad(V_0 + \Delta V)$

大気の抵抗 月の引力  
太陽の引力 太陽輻射圧  
...

運動方程式

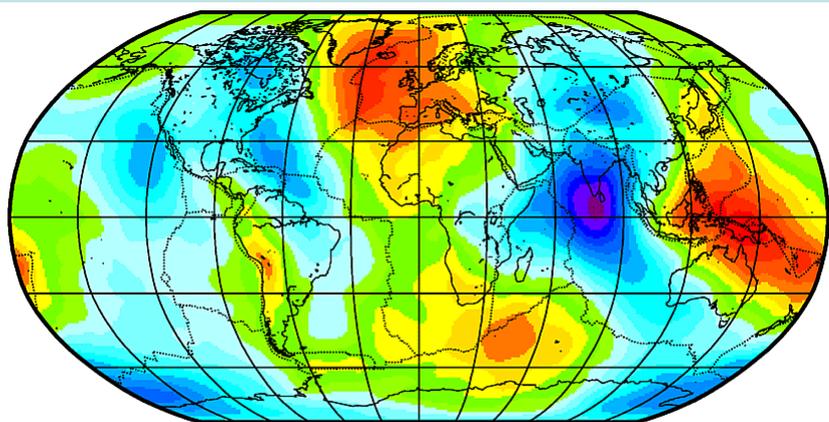
$$\frac{m_s d^2 \mathbf{r}_I}{dt^2} = \mathbf{F}_I \left( t; \mathbf{r}_I, \frac{d\mathbf{r}_I}{dt} \right)$$

数値積分

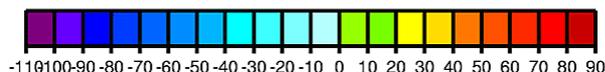


衛星の位置

# GRIM5-S1 model (2000)



GRIM5-S1 Geoid (a=6378136.46m, 1/f=298.25765) in meter



Up to Degree 99 and Order 95  
の地球重力場モデル

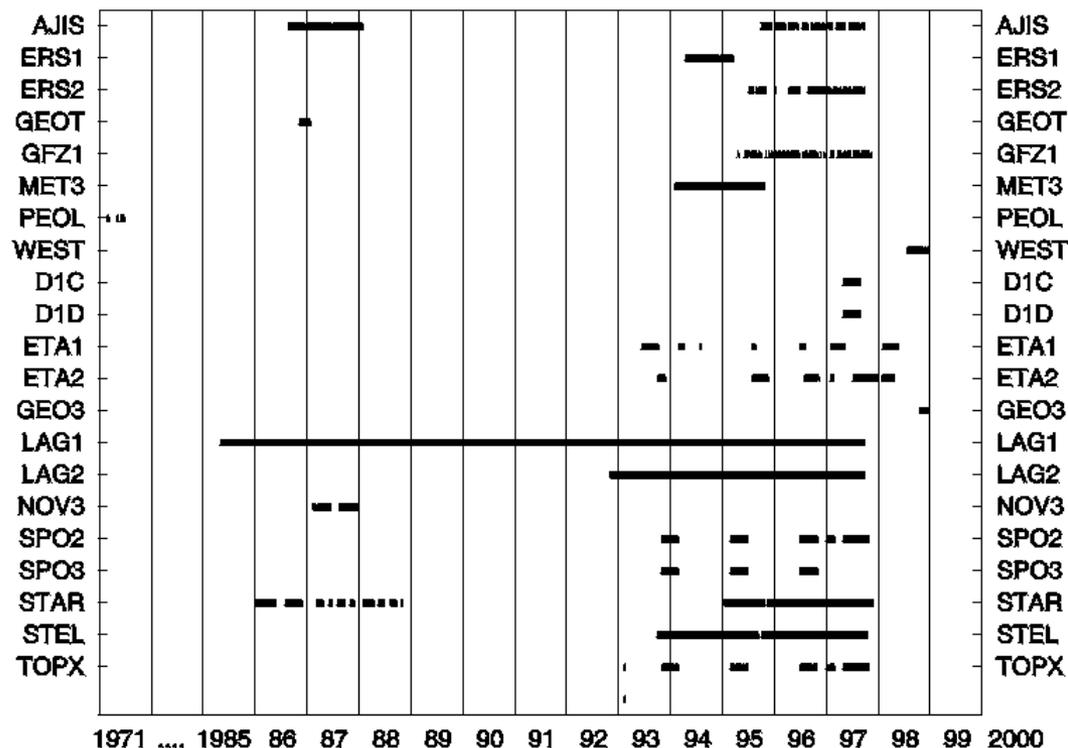
30年にわたる21衛星の軌道を使用  
膨大なデータ解析

アルゴリズム

計算機資源

人的資源

→重力場を決定できるのは  
世界の一部のグループ

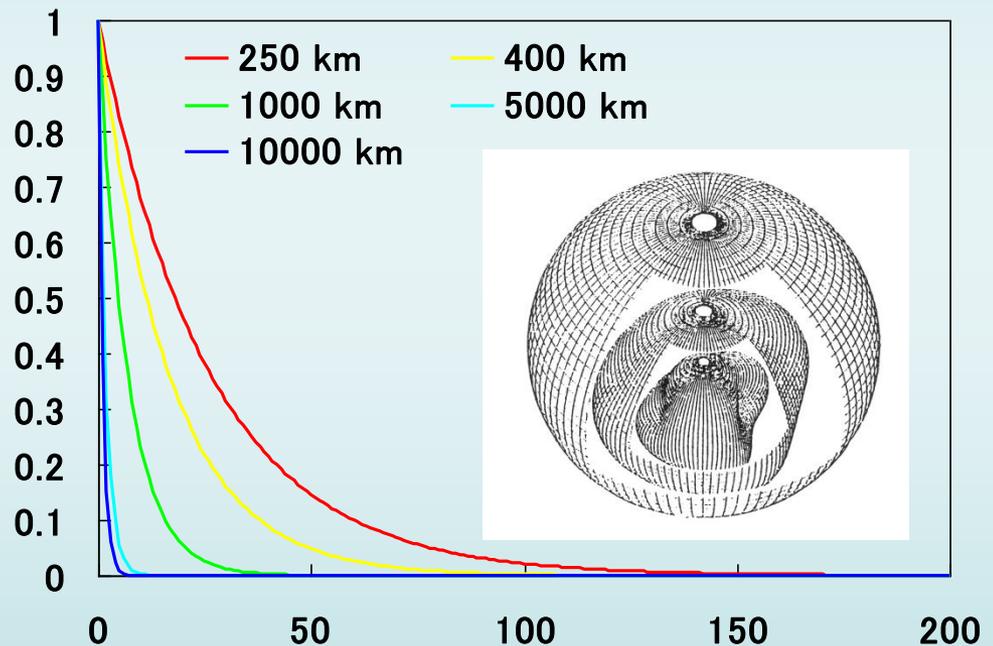


# 地上からの軌道追跡による 重力場決定の限界

## ①モデルの精度



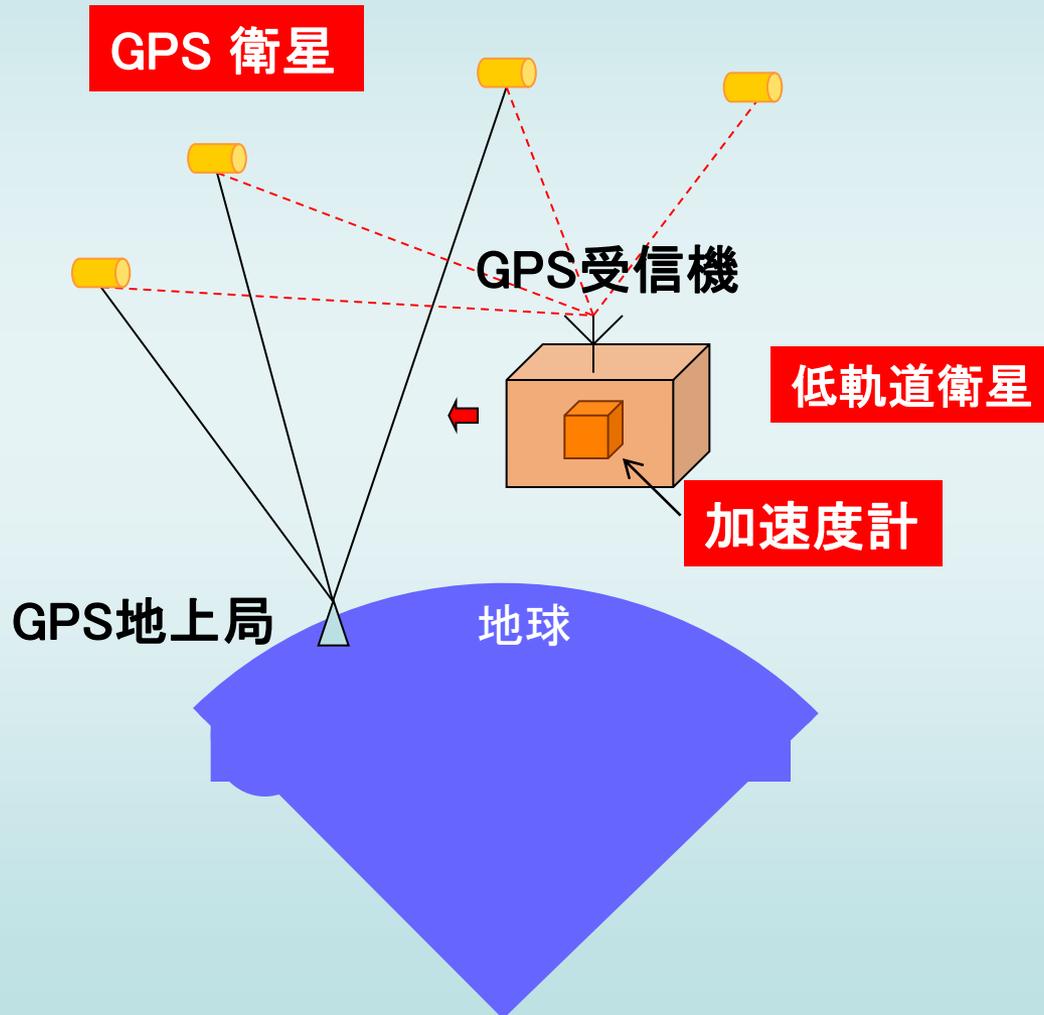
## ②軌道追跡の連続性



## ③高度による重力場の減衰

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

# CHAMPミッション



CHAMP (GFZ, 2000)



# CHAMPデータによる地球重力場決定

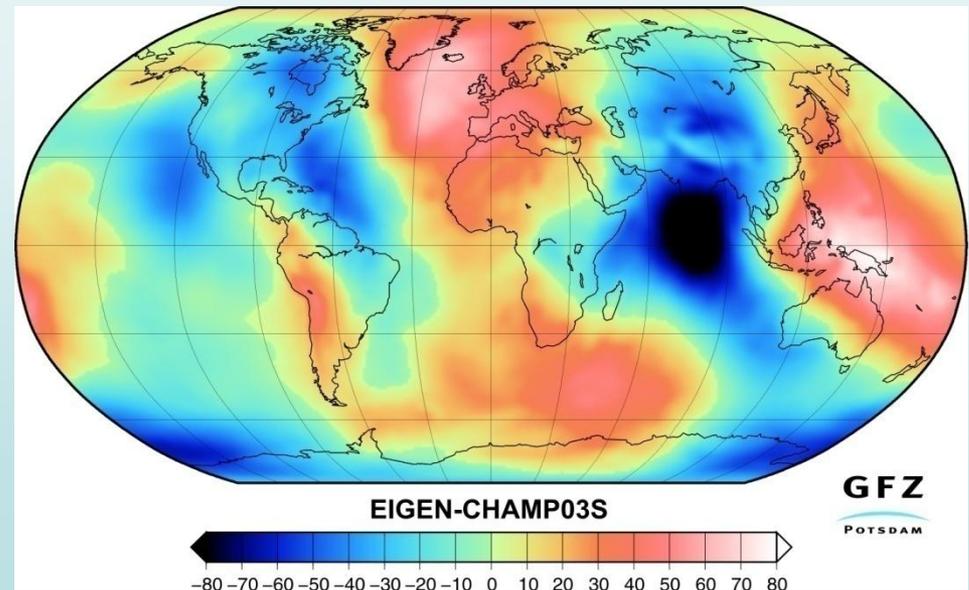
基本的な手順はこれまでと同じ

GPS衛星データからの軌道決定  
加速度データの扱い

→重力場決定に使われるデータの質の向上

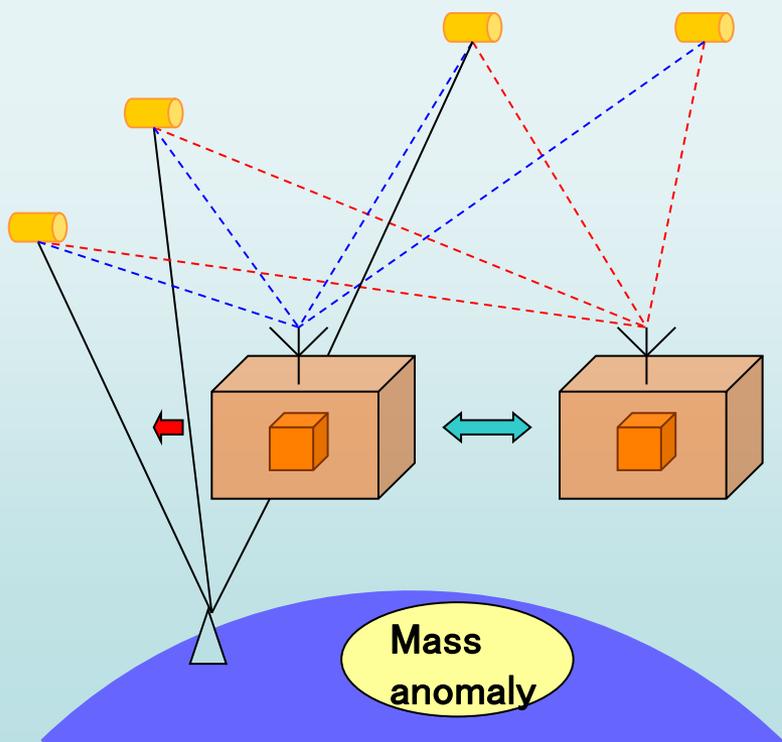
**EIGEN-CHAMP03S**

33ヶ月間のCHAMP衛星データのみ  
120次まで

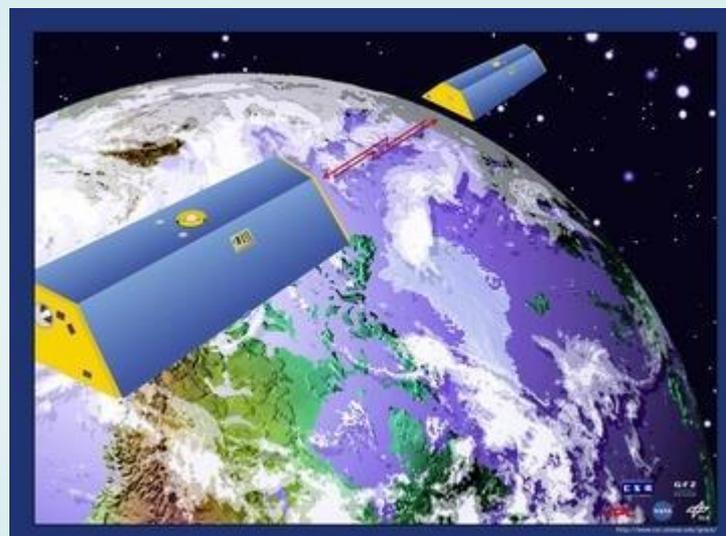


# GRACEミッション

L-L SST  
2衛星間の距離を測定

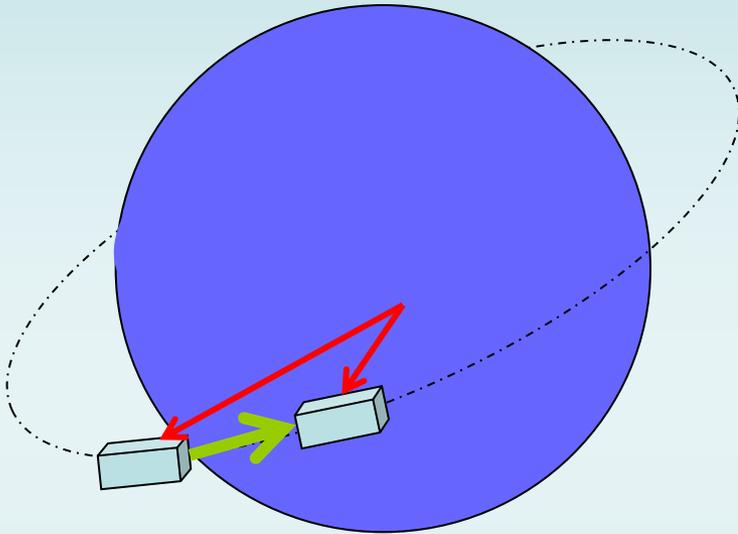


GRACE(2002)



1ヶ月ごと、120次の重力場を提供  
↓  
時間変動する重力シグナルの検出

# GRACEからの重力場決定



$$\mathbf{R} = \mathbf{x}_q - \mathbf{x}_p$$

観測量

range

$$R = \mathbf{R} \cdot \hat{\mathbf{R}}$$

range rate

$$\dot{R} = \dot{\mathbf{R}} \cdot \hat{\mathbf{R}}$$

range acceleration

$$\ddot{R} = \ddot{\mathbf{R}} \cdot \hat{\mathbf{R}} + \dot{\mathbf{R}} \cdot \left( \frac{\dot{\mathbf{R}}}{R} - \frac{\dot{\mathbf{R}}\dot{\mathbf{R}}}{R} \right)$$

$$\ddot{\mathbf{R}} = \mathbf{a}_q - \mathbf{a}_p + \ddot{\mathbf{R}}_d$$

# GRACEによる重力場モデル

GGM01S 120次まで 111日間

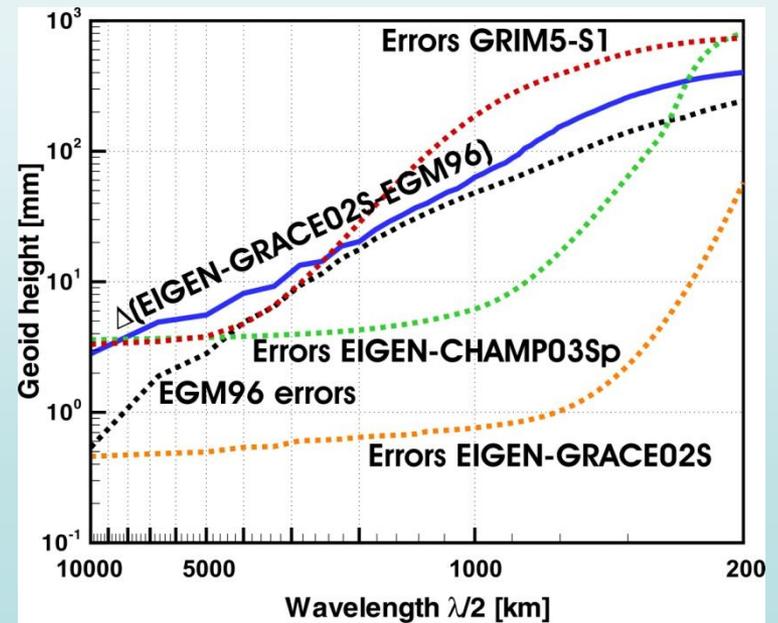
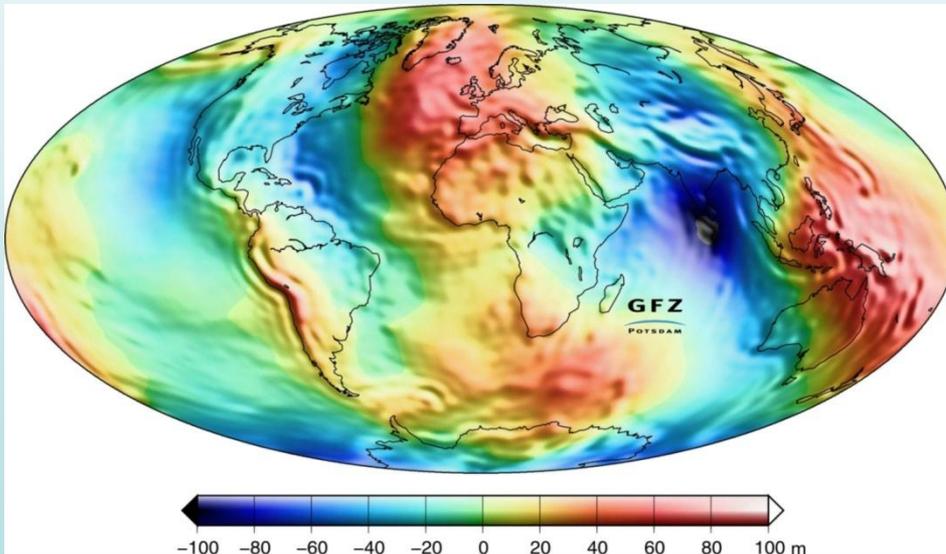
GGM02S 160次まで 363日間

No Kaula constraint

EIGEN-GRACE01S 120次まで 39日間

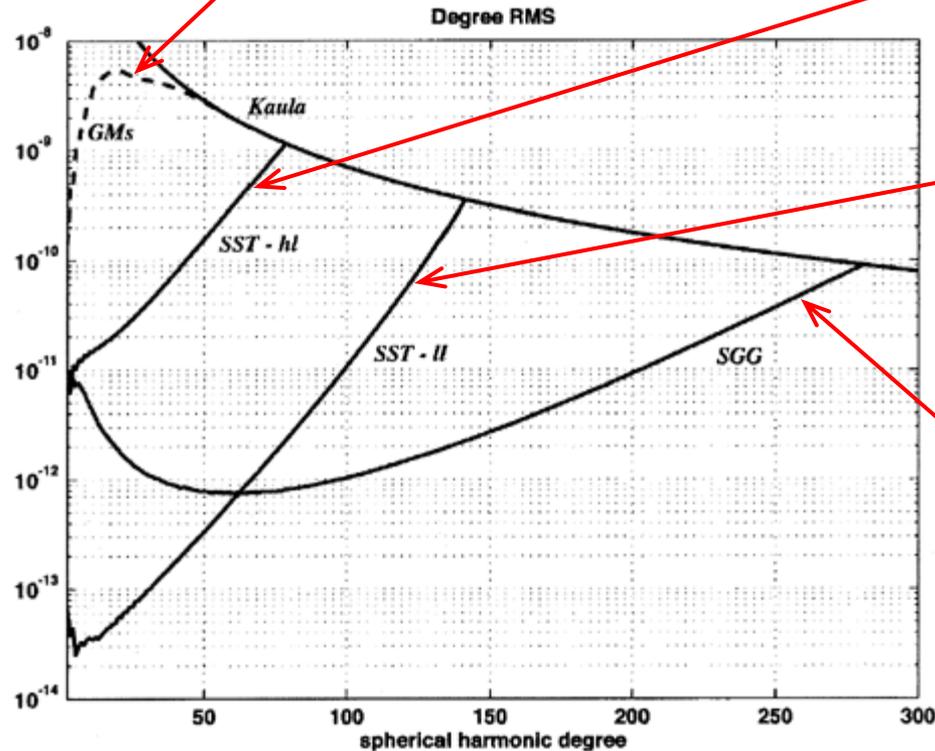
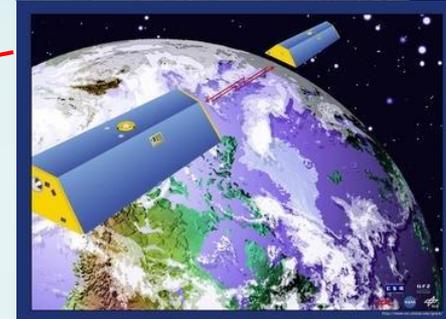
EIGEN-GRACE02S 160次まで 110日間

...



# 衛星による重力モデルの改良

これまでの重力モデル



European Space Agency (1999)

GOCE



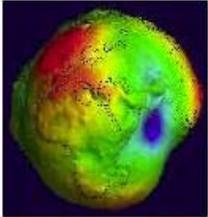
→ 3つの衛星データの使用でより精度の高い重力場モデルに

# 最新の地球重力場データ

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

ICGEM Homepage

<http://icgem.gfz-potsdam.de/ICGEM/Main.html>



**ICGEM**

GFZ Potsdam

ICGEM Home

Table of Available Models

Evaluation of Models

Model References Table

Visualization of Geoid Models

Tutorial

Service for Computing Data from Models

Models from Dedicated Time Periods

Latest Changes

Guest Book

Evaluation Service

Software Download Service



ICGEM

## International Centre for Global Earth Models (ICGEM)

ICGEM is one of six centres of the [International Gravity Field Service \(IGFS\)](#) of the [International Association of Geodesy \(IAG\)](#).

The other five Centres are

- [Bureau Gravimetrique International \(BGI\)](#) at CNES / CRGS, Toulouse, France
- [Digital Elevation Model Centre \(DEM\)](#) at Montfort University, UK
- [International Centre for Earth Tides \(ICET\)](#) at Obs. Royal de Belgique, Brussels, Belgium
- [International Geoid Service \(IGeS\)](#) at Politecnico di Milano, Milan, Italy
- [Technical Support Centre of IGFS](#) at NGA, Saint Louis, USA

## Global Gravity Field Models

Model	Year	Degree	Data	Reference	download
<a href="#">GO_CONS_GCF_2_DIR</a>	2010	240	S(GOCE)	Bruinsma et al, 2010	X
<a href="#">GO_CONS_GCF_2_TIM</a>	2010	224	S(GOCE)	Pail et al, 2010a	X
<a href="#">GO_CONS_GCF_2_SPW</a>	2010	210	S(GOCE)	Migliaccio et al, 2010	X
<a href="#">GOCO01S</a>	2010	224	S(GOCE,Grace)	Pail et al, 2010b	X
<a href="#">EIGEN-51C</a>	2010	359	S(Grace,Champ),G,A	Bruinsma et al, 2010	X
<a href="#">AIUB-CHAMP03S</a>	2010	100	S(Champ)	Prange, L. et al, 2010	X
<a href="#">EIGEN-CHAMP05S</a>	2010	150	S(Champ)	Flechtner et al, 2010	X
<a href="#">ITG-Grace2010s</a>	2010	180	S(Grace)	Mayer-Gürr et al, 2010	X
<a href="#">AIUB-GRACE02S</a>	2009	150	S(Grace)	Jäggi et al, 2009	X
<a href="#">GGM03C</a>	2009	360	S(Grace),G,A	Tapley et al, 2007	X
<a href="#">GGM03S</a>	2008	180	S(Grace)	Tapley et al, 2007	X
<a href="#">AIUB-GRACE01S</a>	2008	120	S(Grace)	Jäggi et al, 2008	X
<a href="#">EIGEN-5S</a>	2008	150	S(Grace,Lageos)	Förste et al, 2008	X
<a href="#">EIGEN-5C</a>	2008	360	S(Grace,Lageos),G,A	Förste et al, 2008	X
<a href="#">EGM2008</a>	2008	2190	S(Grace),G,A	Pavlis et al, 2008	X
<a href="#">ITG-Grace03</a>	2007	180	S(Grace)	Mayer-Gürr et al, 2007	X
<a href="#">AIUB-CHAMP01S</a>	2007	90	S(Champ)	Prange, L. et al, 2007	X
<a href="#">ITG-Grace02s</a>	2006	170	S(Grace)	Mayer-Gürr et al, 2006	X
<a href="#">EIGEN-GL04S1</a>	2006	150	S(Grace,Lageos)	Förste et al, 2006	X
<a href="#">EIGEN-GL04C</a>	2006	360	S(Grace,Lageos),G,A	Förste et al, 2006	X
<a href="#">EIGEN-CG03C</a>	2005	360	S(Champ,Grace),G,A	Förste et al, 2005c	X
<a href="#">GGM02C</a>	2004	200	S(Grace),G,A	UTEX CSR, 2004	X
<a href="#">GGM02S</a>	2004	160	S(Grace)	UTEX CSR, 2004	X
<a href="#">EIGEN-CG01C</a>	2004	360	S(Champ,Grace),G,A	Reigber et al, 2006	X

# 衛星で見る重力場変化

# 重力場変動成分の見積もり

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

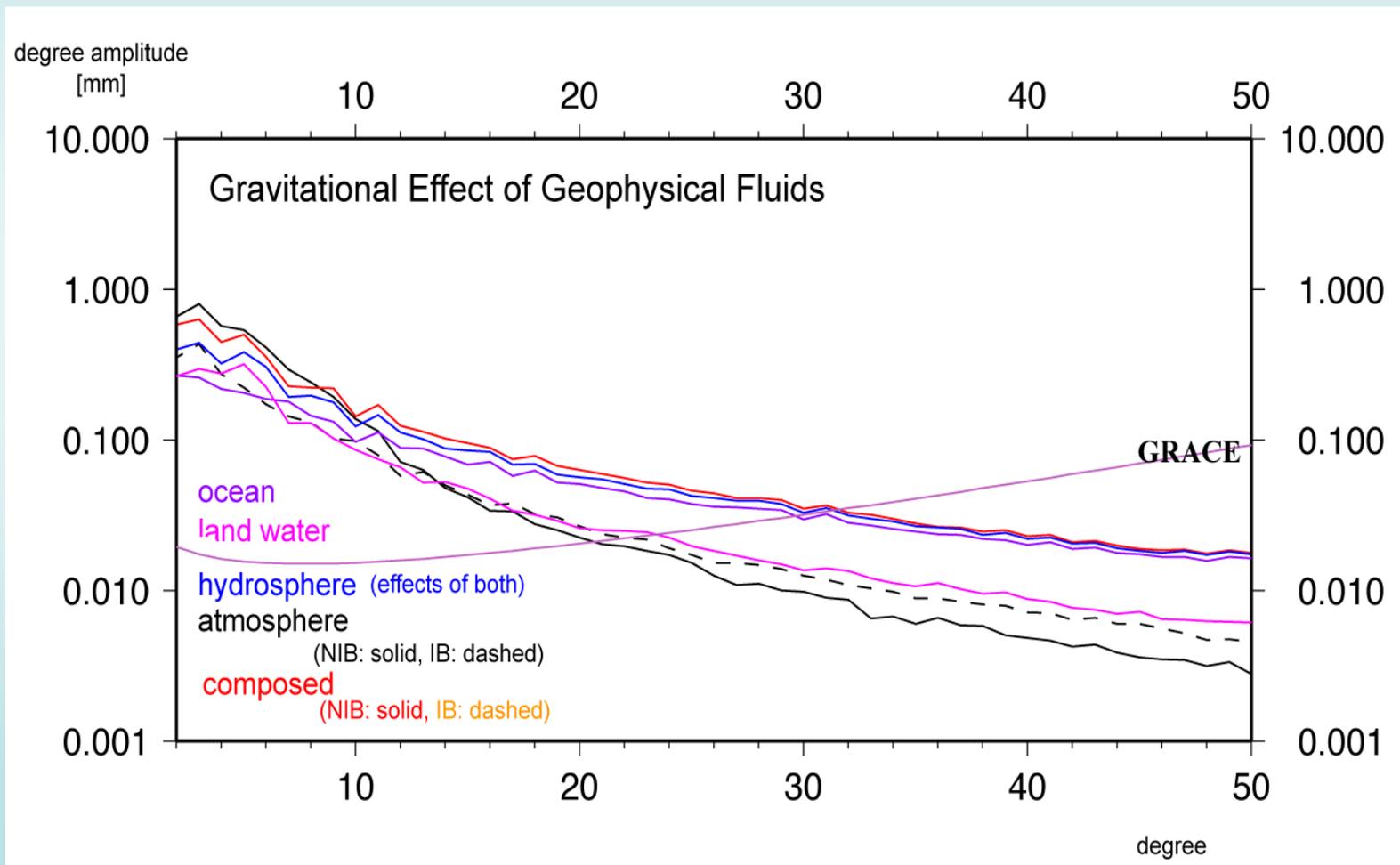
$$\begin{pmatrix} \Delta \bar{C}_{l,m}(t) \\ \Delta \bar{S}_{l,m}(t) \end{pmatrix} = \frac{3}{4\pi} \frac{1+k_l'}{2l+1} \frac{1}{R\rho_{ave\ Earth}} \iint \Delta\rho(\theta, \lambda, t) P_{l,m}(\cos\theta) \begin{pmatrix} \cos m\lambda \\ \sin m\lambda \end{pmatrix} d\sigma.$$

$\Delta\rho$ : 面密度の変化

⇒ 大気、海洋、陸水などの量変化を $\Delta\rho$ であらわす

# Degree Varianceによる精度の見積もり

測定誤差の伝播と重力場の打ち切り誤差の影響に基づく統計的な評価  
(Jekeli and Rapp, 1980)



# 重力場変動による衛星の速度変化

$$\frac{1}{2} \hat{v}^2 - V = E$$

全運動エネルギーと位置エネルギー

$$\hat{v} = v_m + v$$

$$V = U + T$$

変動成分と平均成分に分解、  
速度の2次の項を無視する

$$\frac{1}{2} v_m^2 - U = E$$

$$v = \frac{T}{v_m} = \frac{\gamma N}{v_m} = \frac{T}{R} \sqrt{\frac{r}{\gamma}} = \frac{\sqrt{r\gamma}}{R} N \cong 1.28 \times 10^{-3} N (m/s)$$

@450km

$$1\text{mmジオイド} = 1.28 \mu\text{m/s}$$

# 衛星軌道に沿ったデータのシミュレーション

## ー 衛星軌道位置の計算

ケプラー軌道を仮定

軌道傾斜角89度, 離心率0.005, 平均高度450km

## ー 軌道上でのジオイド(衛星速度)の計算

グローバルモデル: EGM-96から軌道位置のジオイドを計算

ローカルモデル(日本周辺):

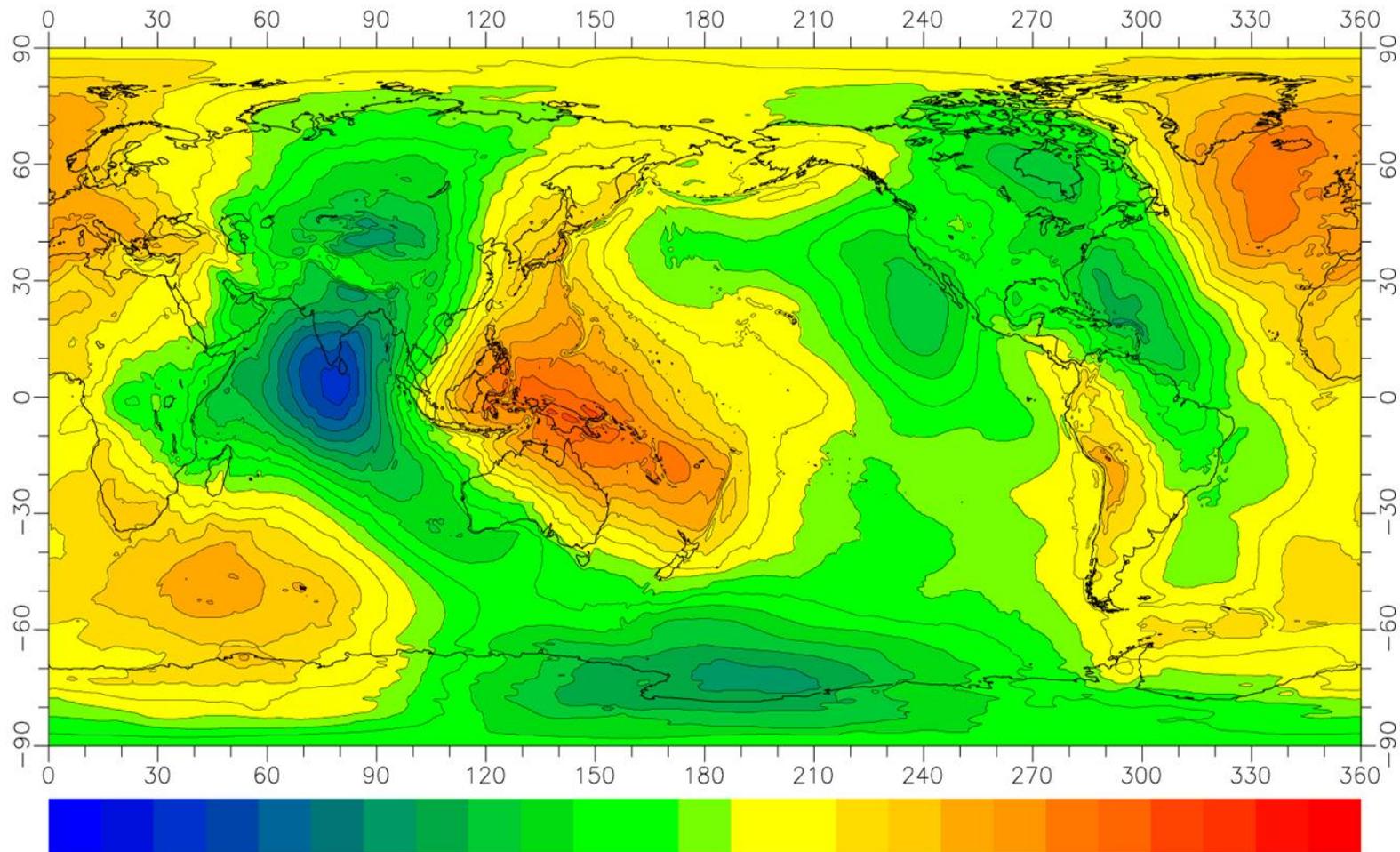
地表重力異常データ(S&S)を用い球面FFT法で軌道高度でのジオイドを計算

時間変動成分

表面気圧(1999年ECMWF, 6時間毎)データ軌道上のジオイドへの影響を計算

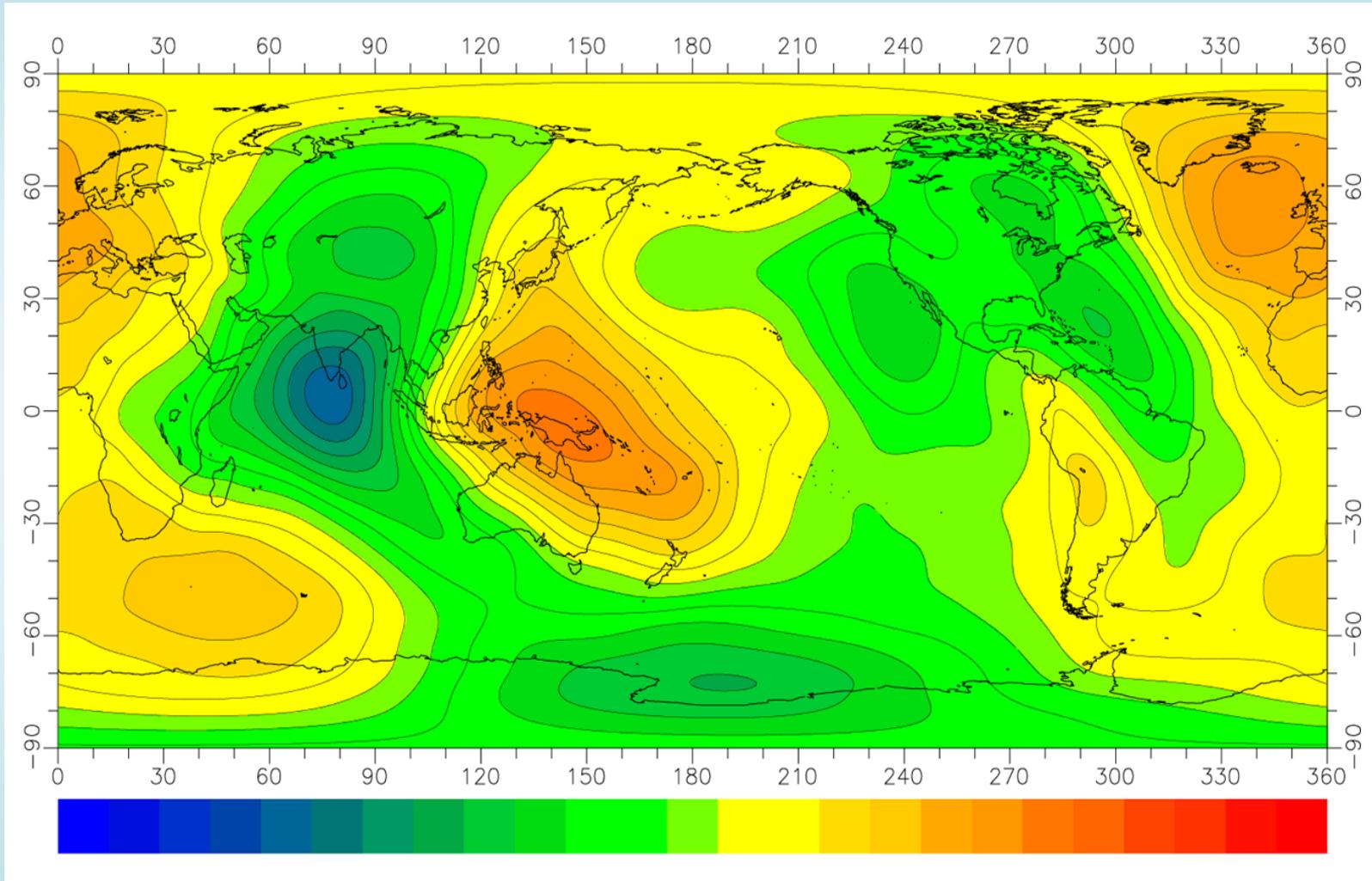
# EGM96ジオイド(地表)

CI : 10m



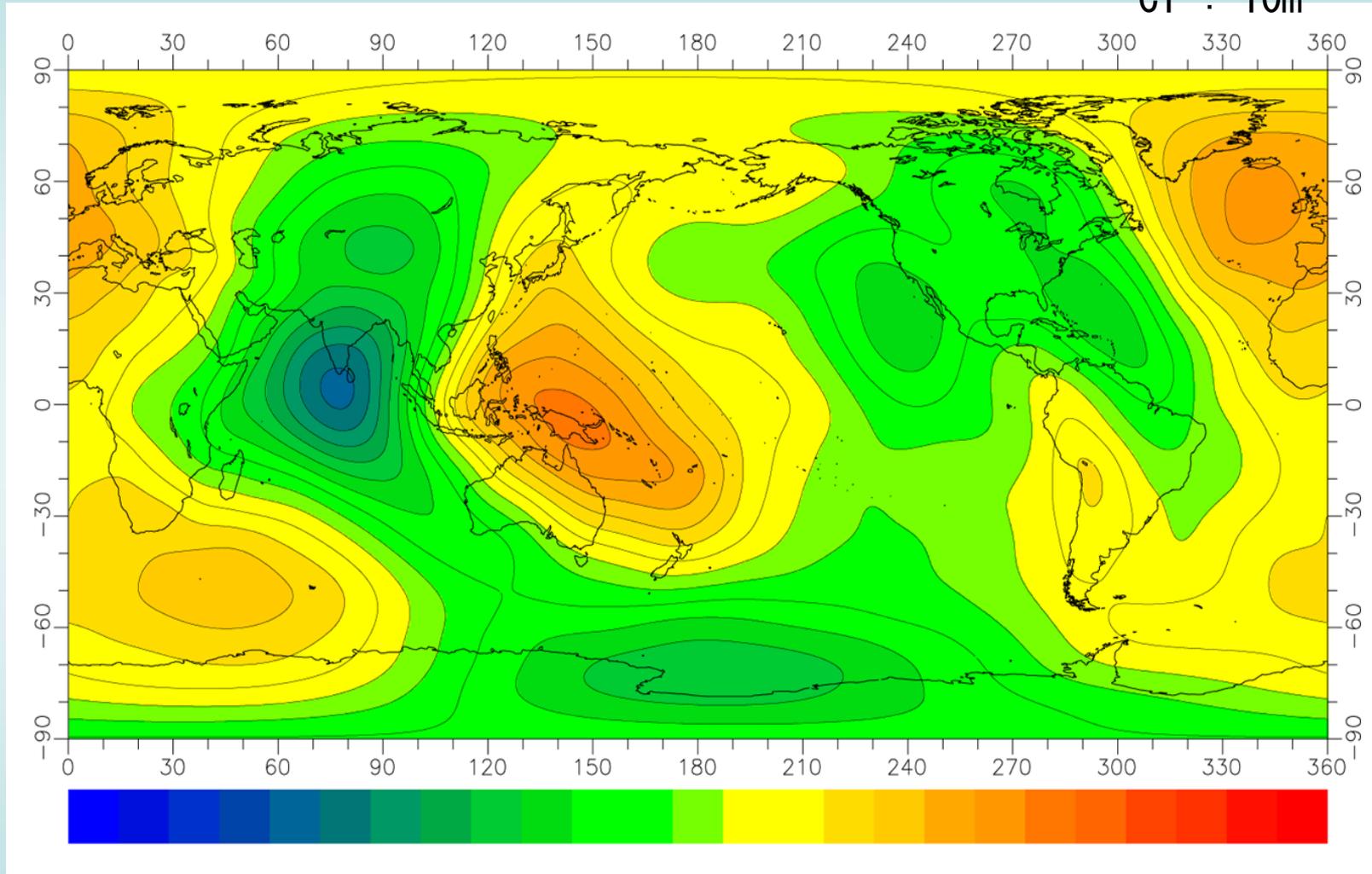
# EGM96ジオイド ( $h=450\text{km}$ )

CI : 10m

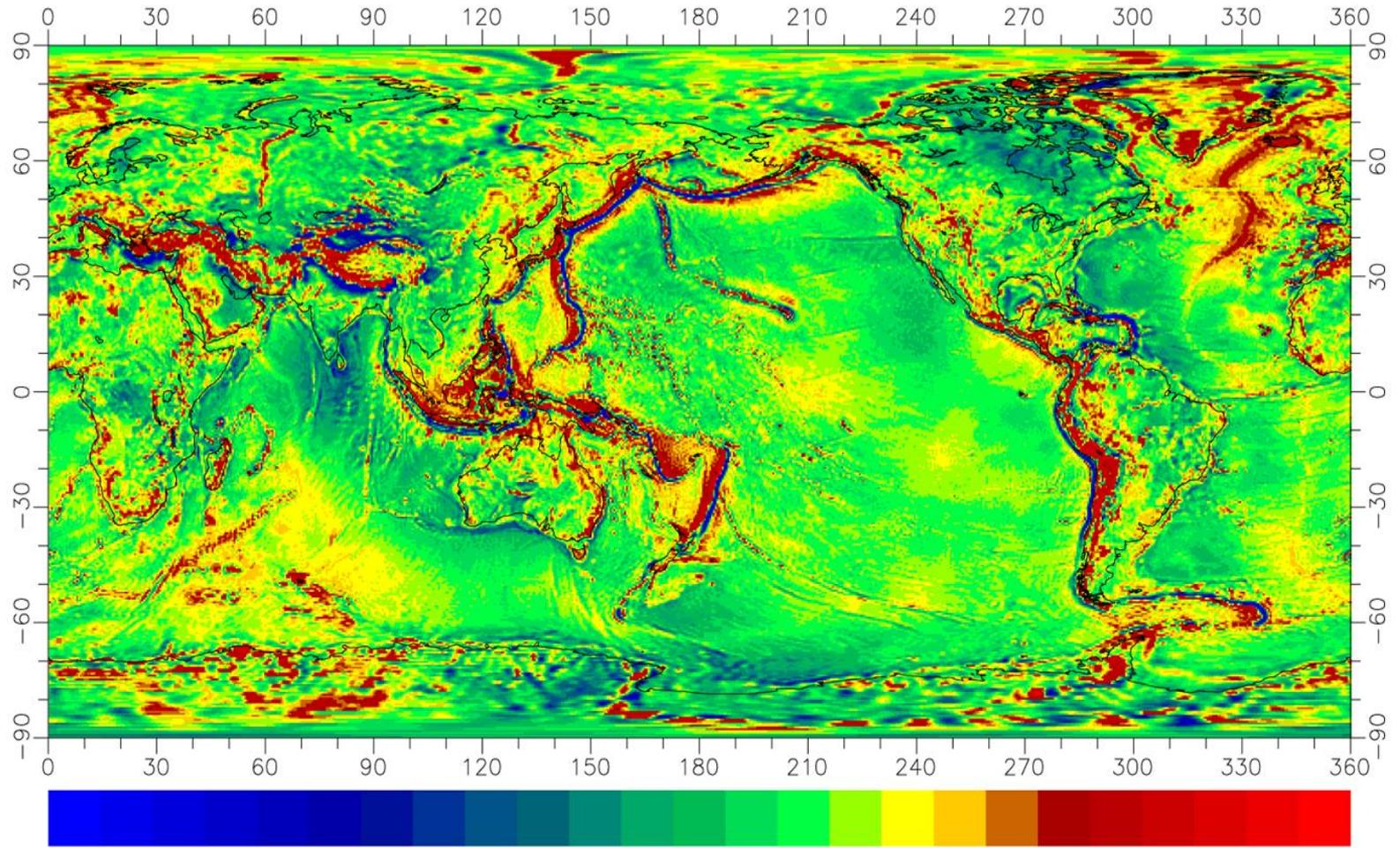


# EGM96ジオイド ( $h=600\text{km}$ )

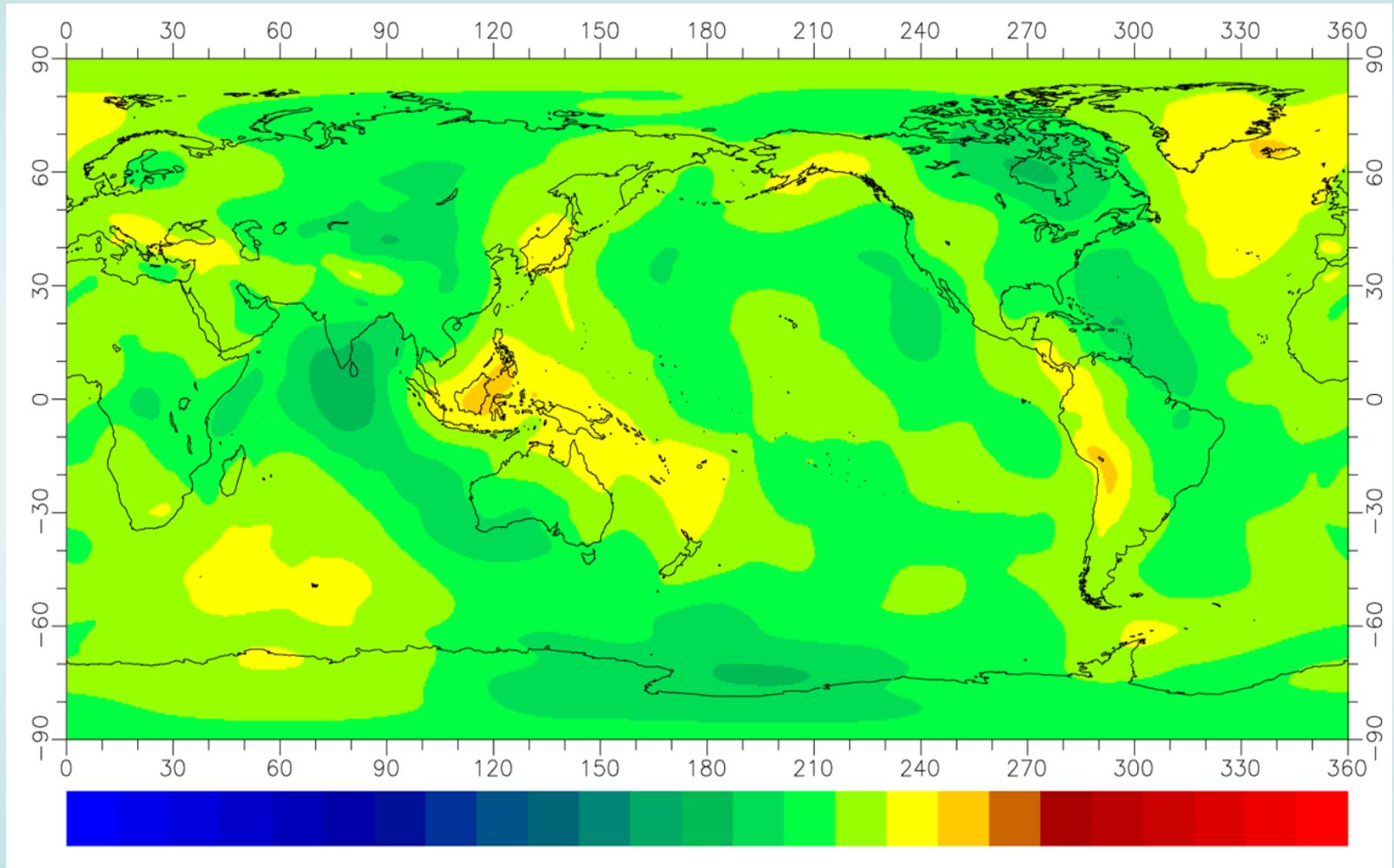
CI : 10m



# EGM96重力異常(地表)

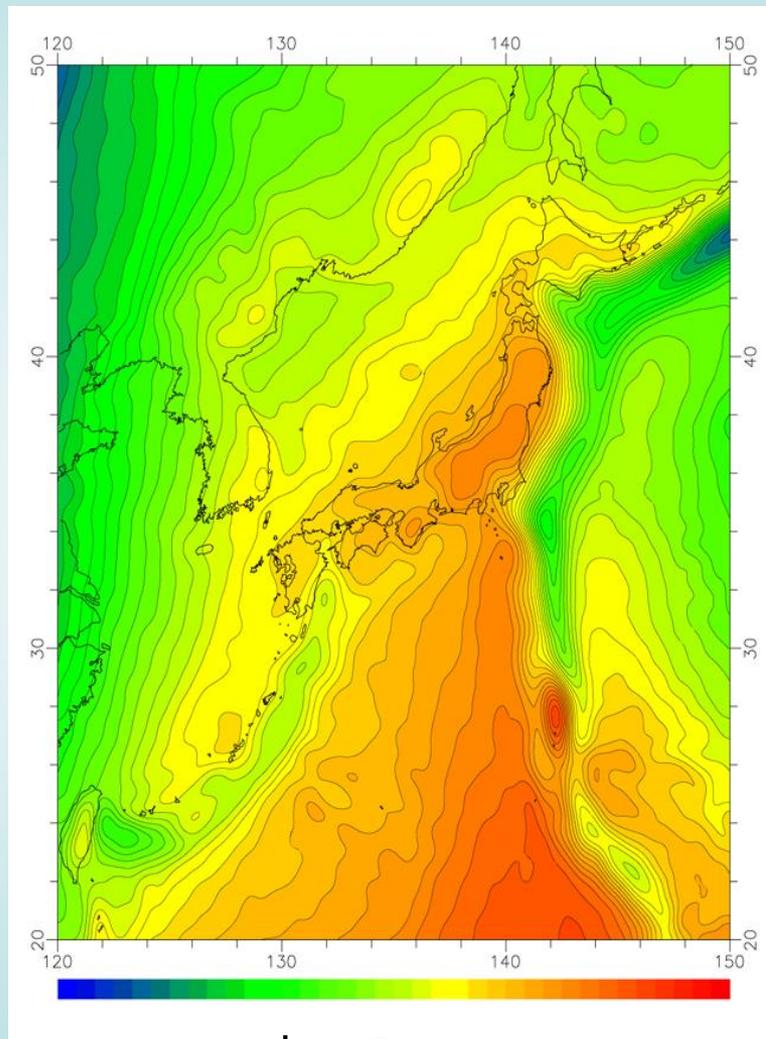


# EGM96重力異常 ( $h=450\text{km}$ )

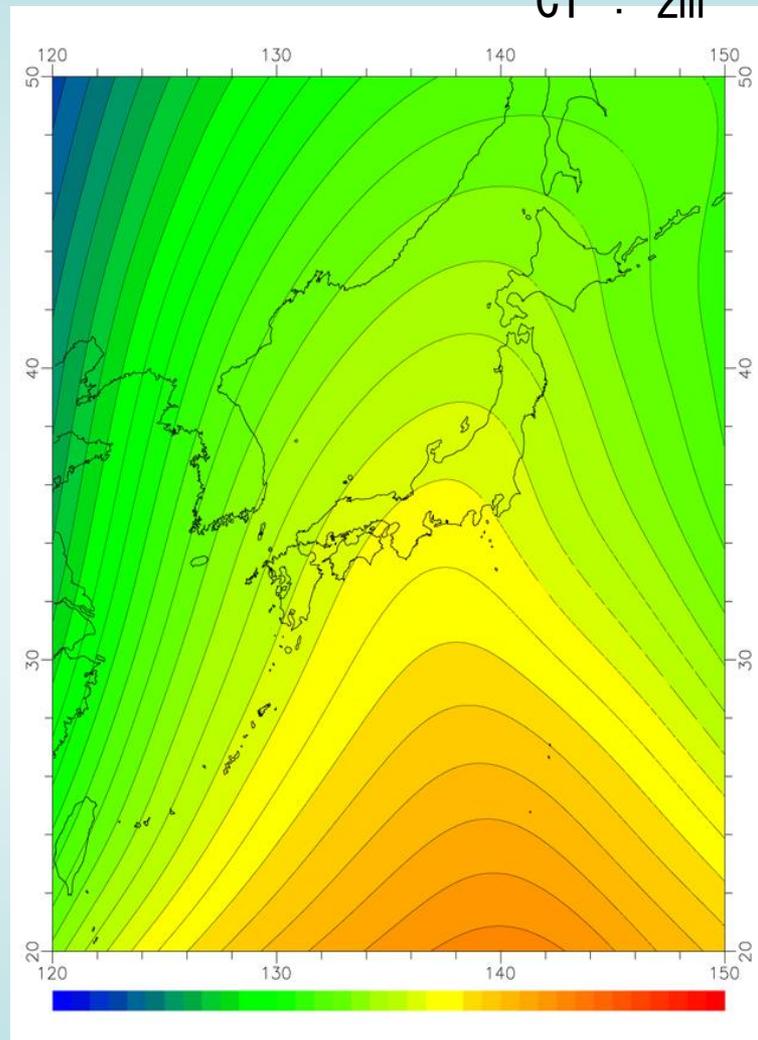


# EGM96ジオイド(日本周辺)

CI : 2m



$h=0\text{km}$

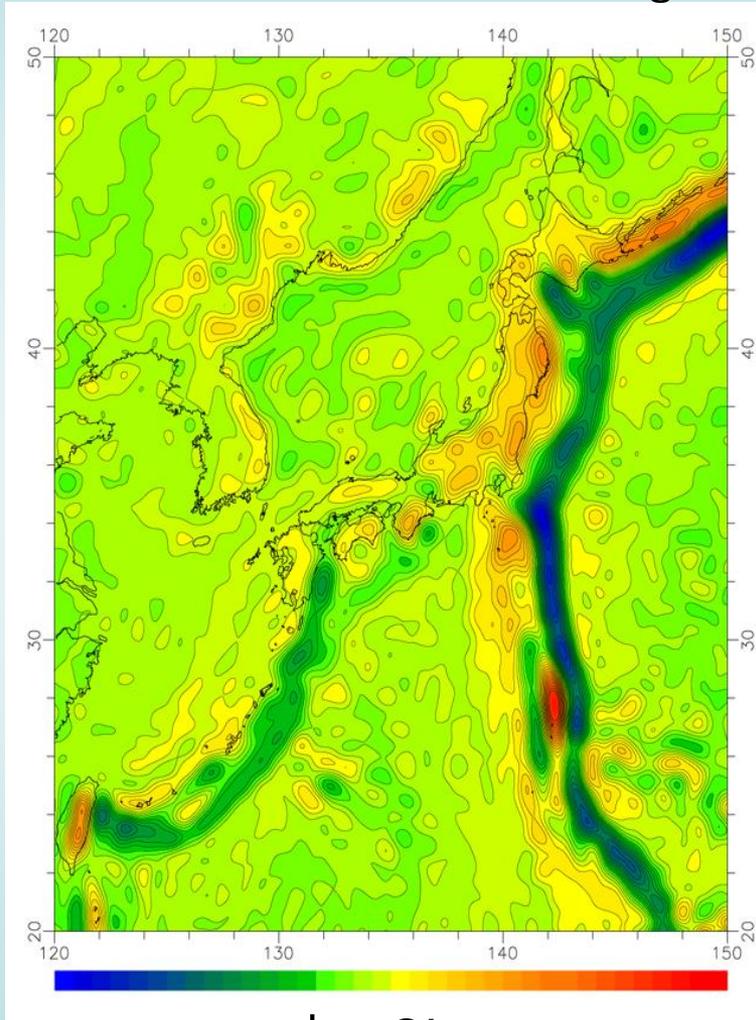


$h=450\text{km}$

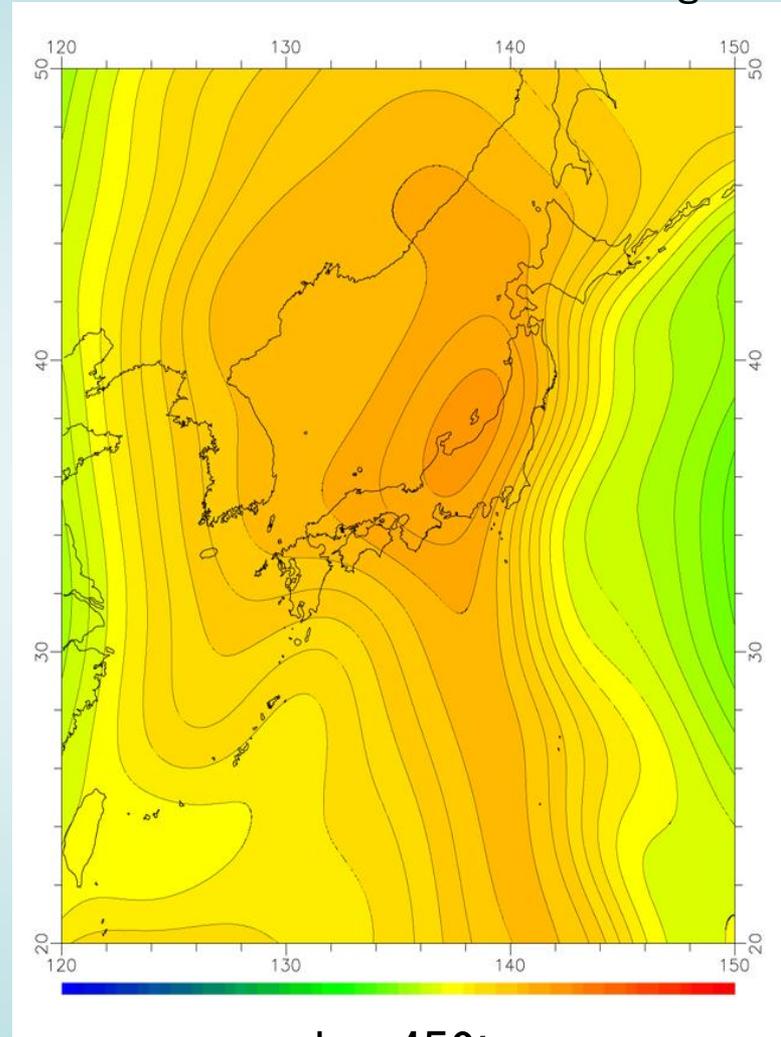
# EGM96重力異常(日本周辺)

CI : 50mgal

CI : 1mgal

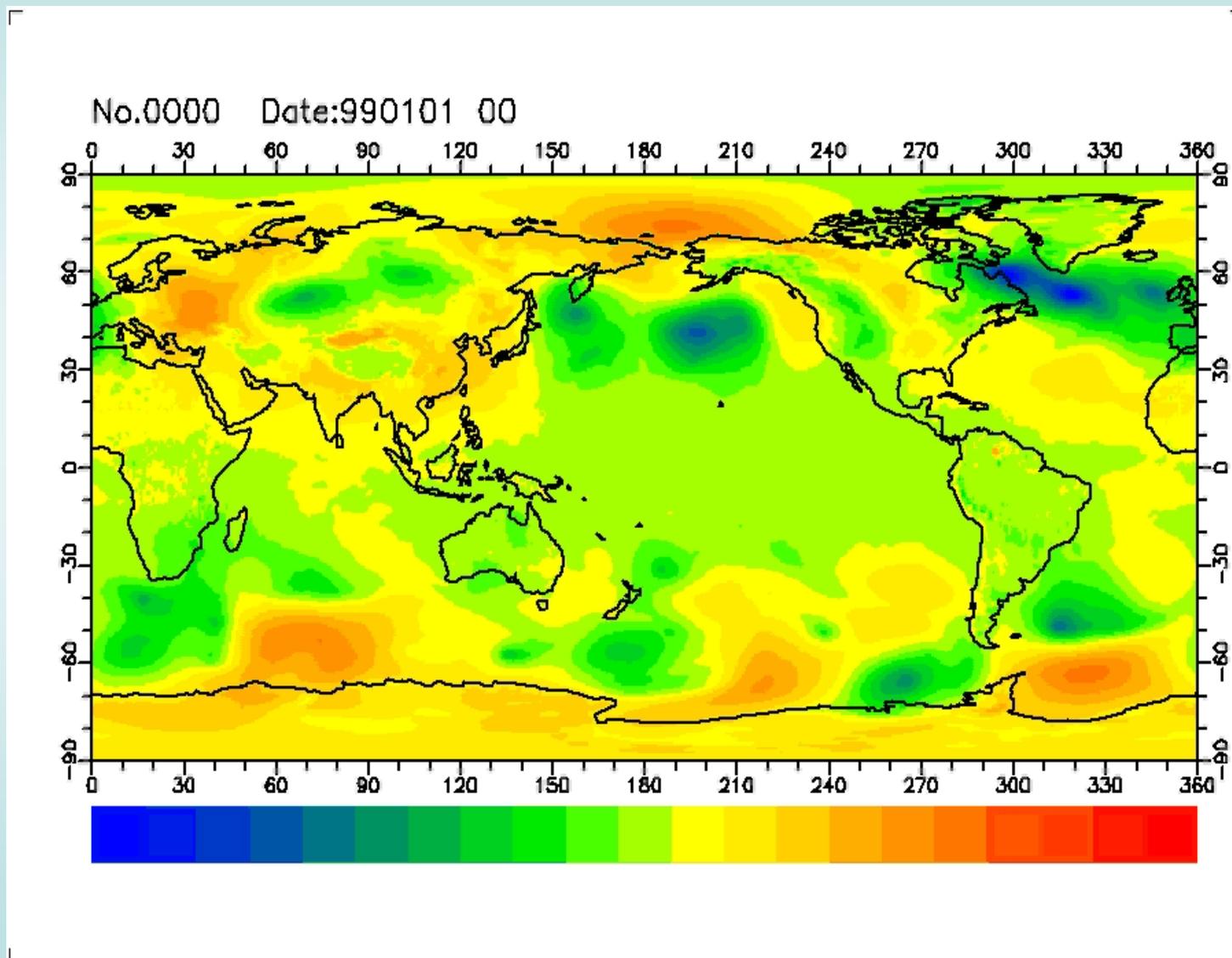


$h=0\text{km}$

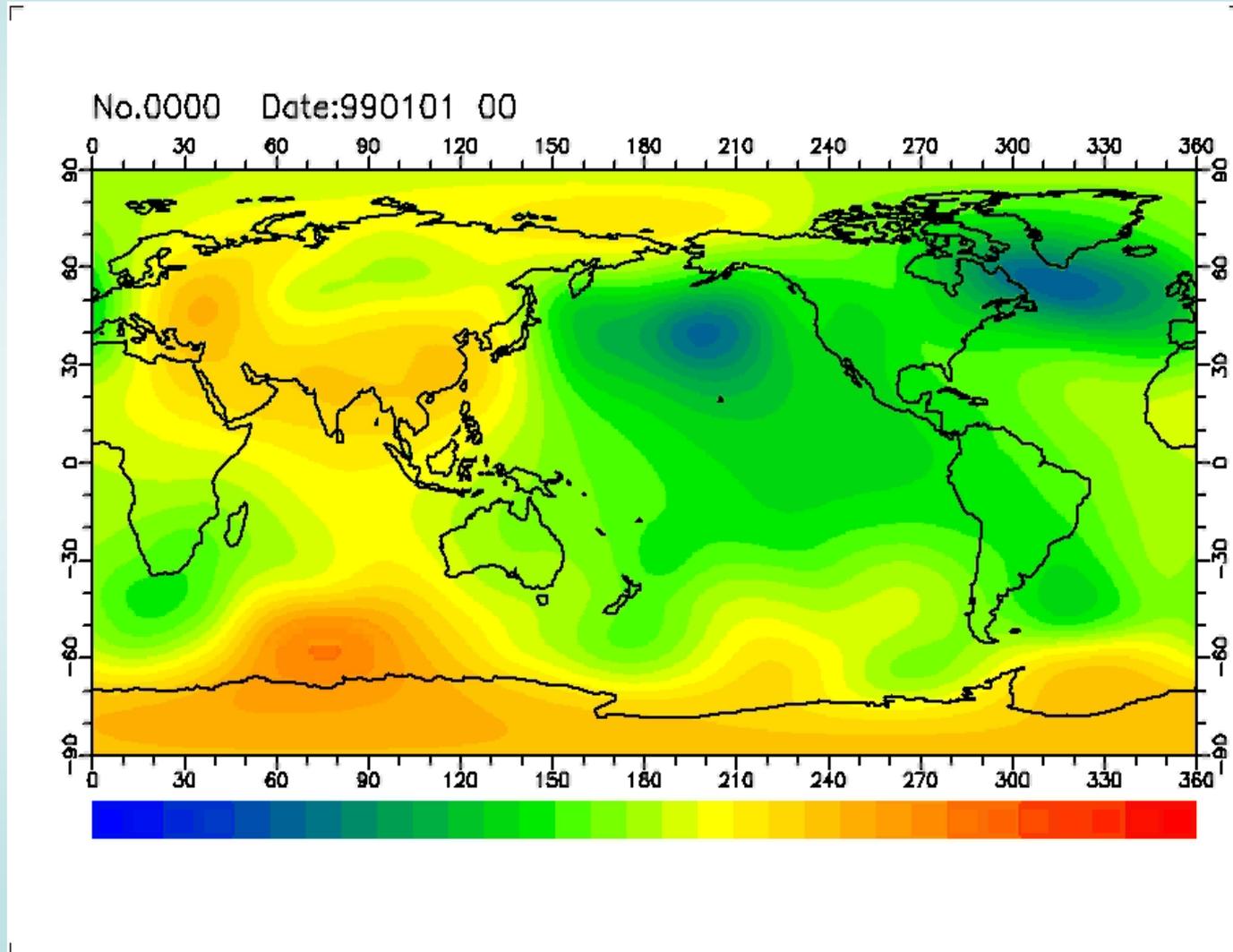


$h=450\text{km}$

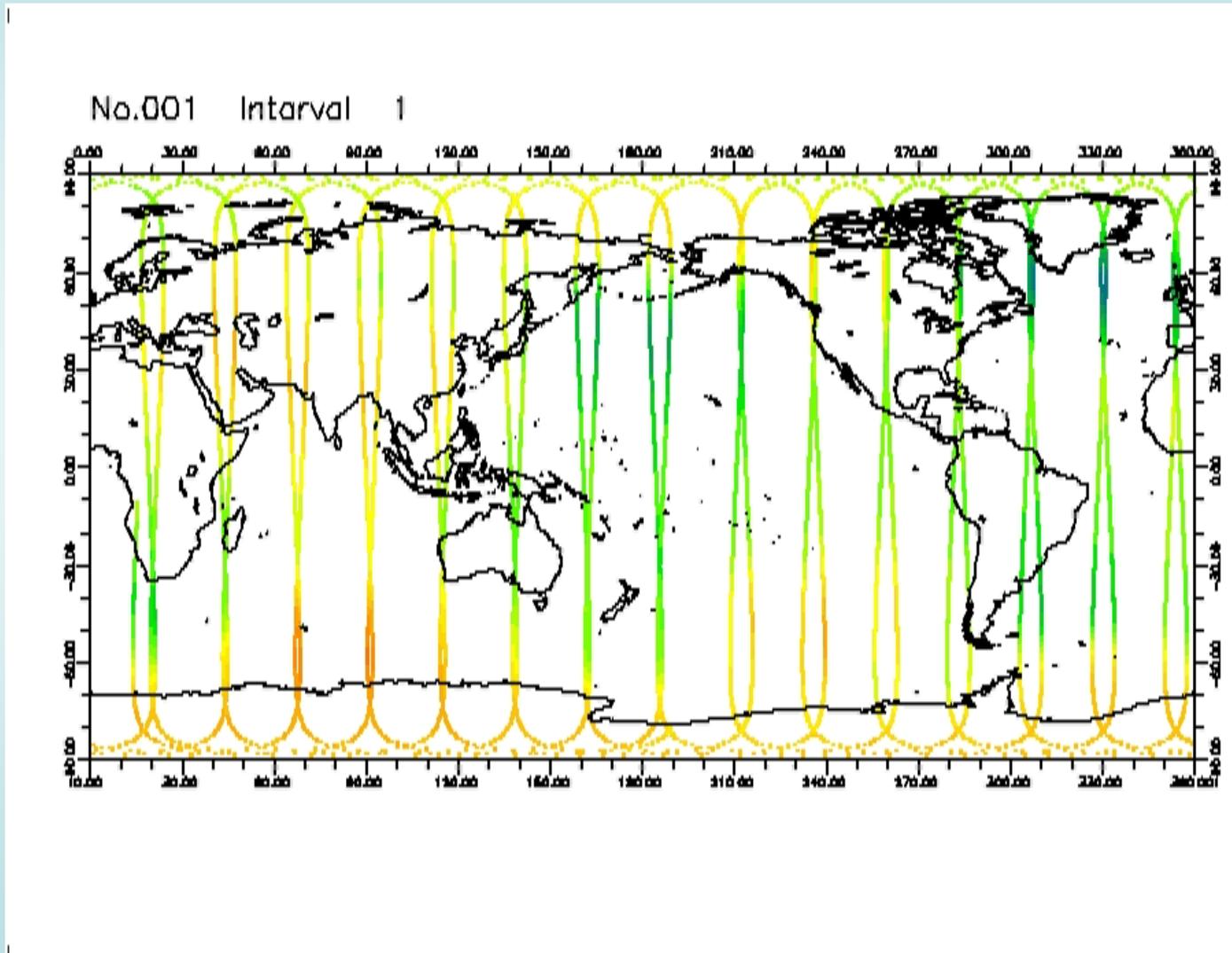
# 表面気圧(変動成分)



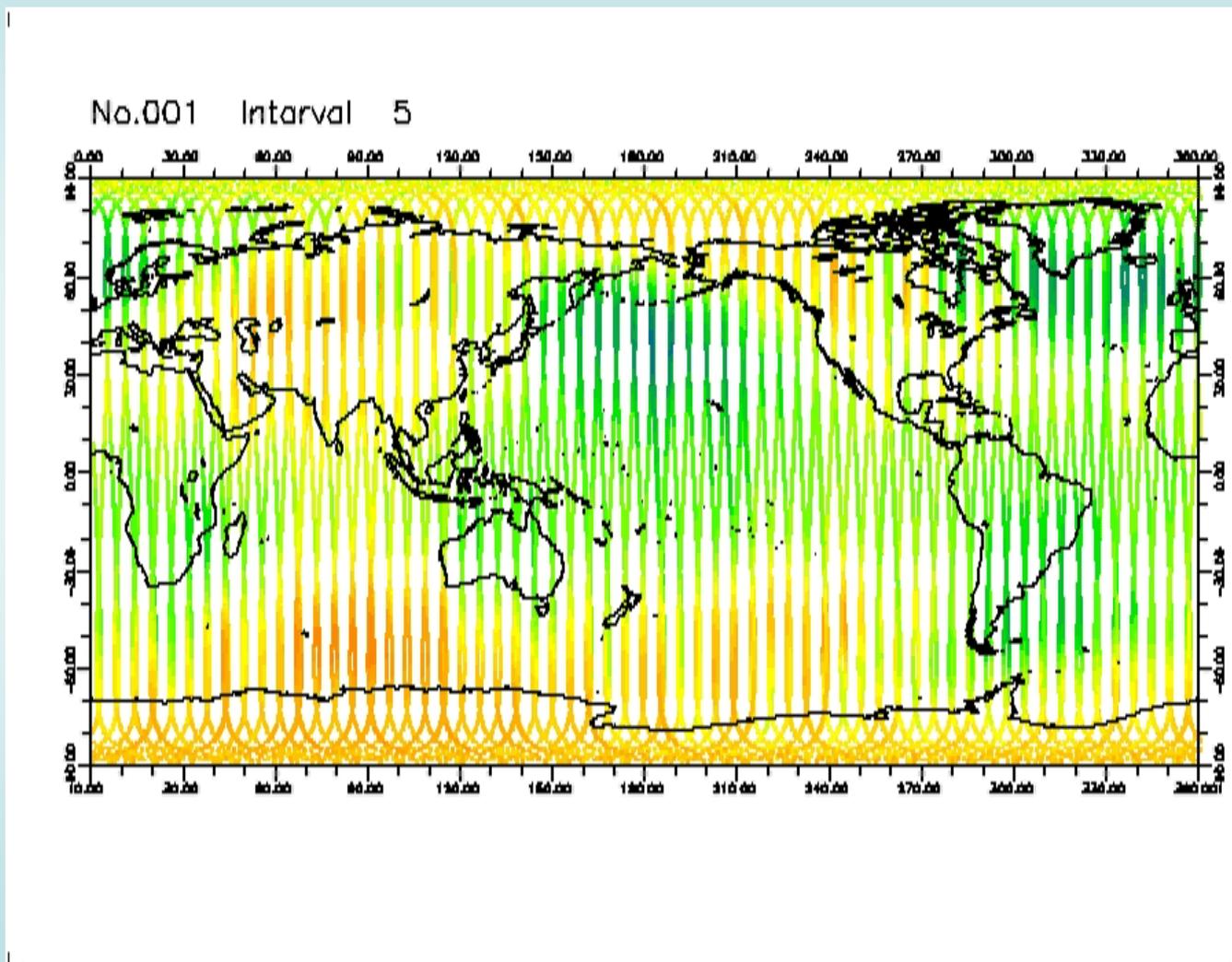
# 気圧によるジオイド高変化(450km-NIB)



# GRACE軌道での気圧の影響(1日毎)

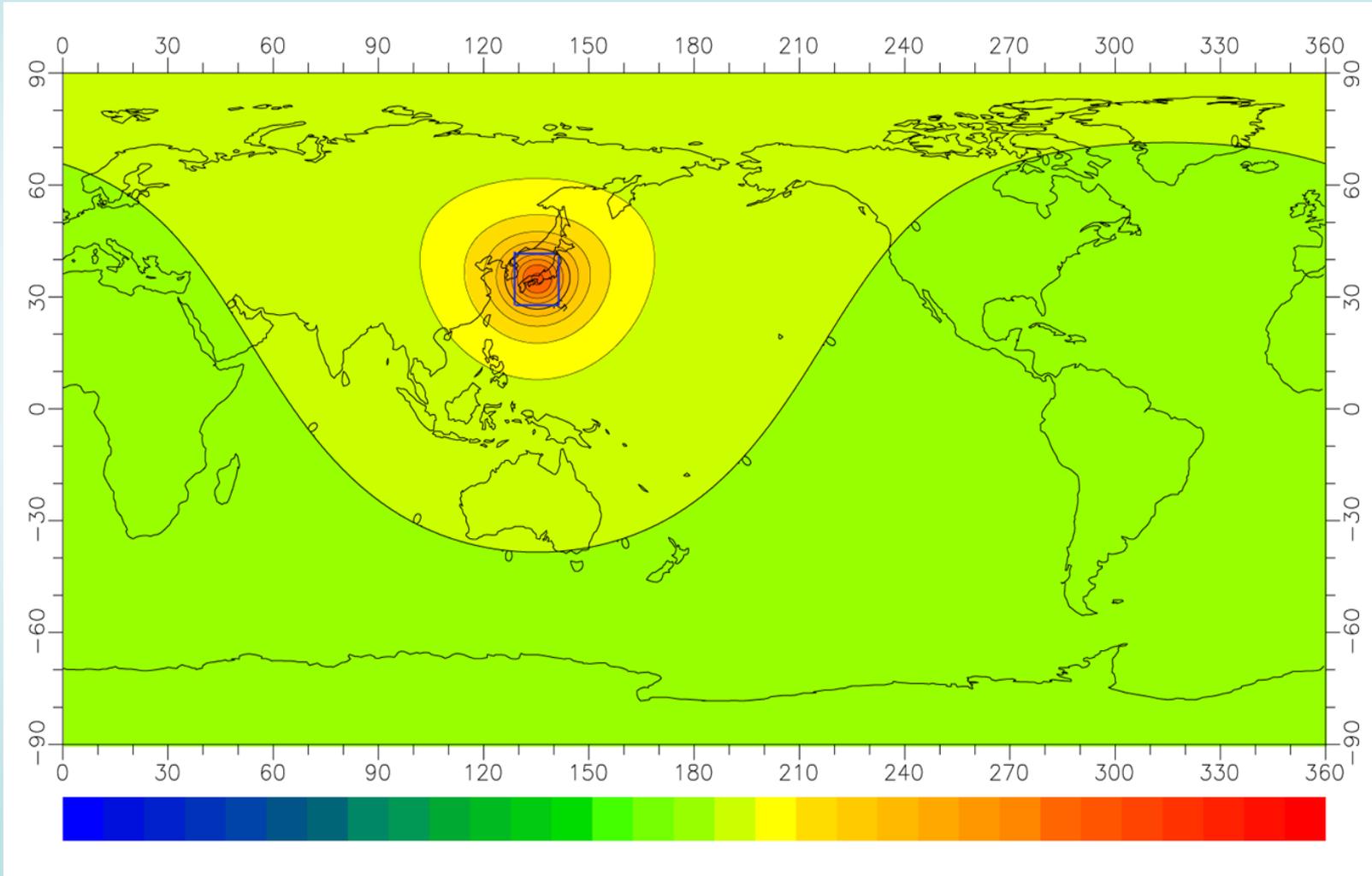


# GRACE軌道での気圧の影響(5日毎)



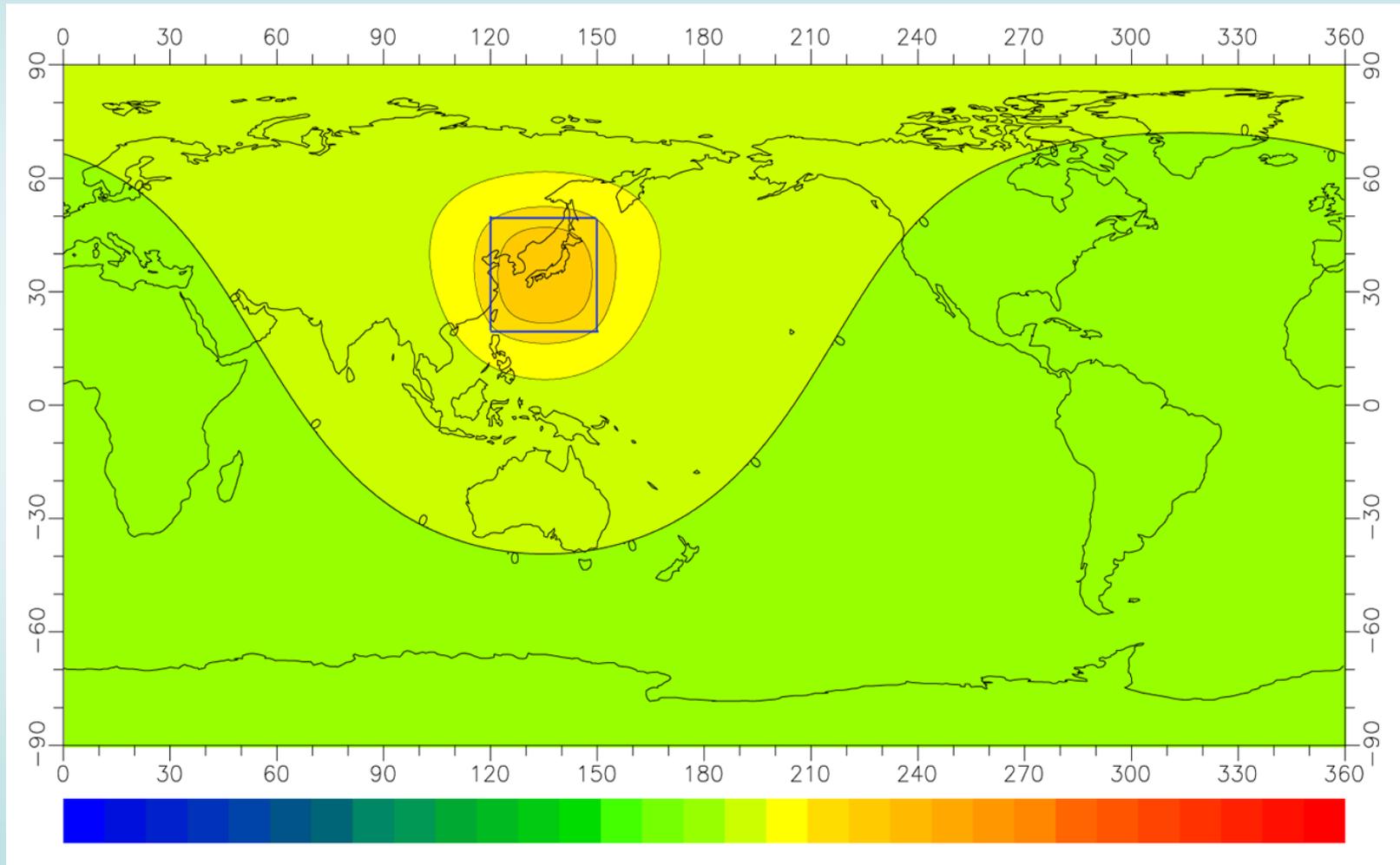
# 水荷重によるジオイドの変化(1)

10° x10° 100cm厚の水過重 CI : 1mm @ 450km



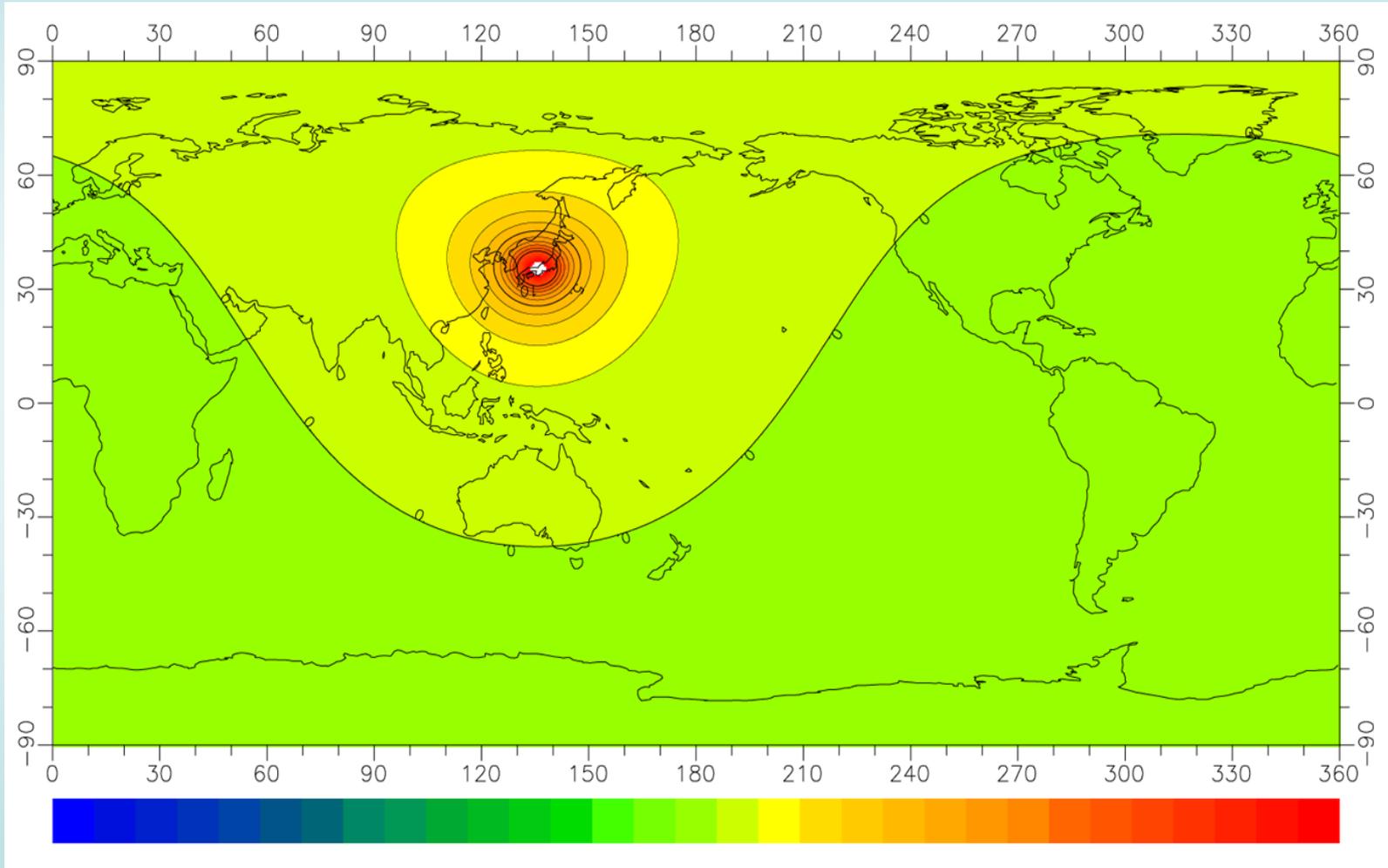
# 水荷重によるジオイドの変化(2)

30° x30° 10cm厚の水過重 CI : 1mm @ 450km



# 水荷重によるジオイドの変化(3)

1° x 1° 10cm厚の水過重 CI : 1  $\mu$ m @ 450km (Max=0.017mm)



# 内容1 (13日午後)

## ✓ イントロダクション

- 自己紹介を兼ねた研究歴
- 精密測地計測

## ✓ 衛星重力ミッション

- 衛星重力ミッション概要
- 地球重力場の決定
- 衛星で見る重力場

## ✓ GRACEの応用研究

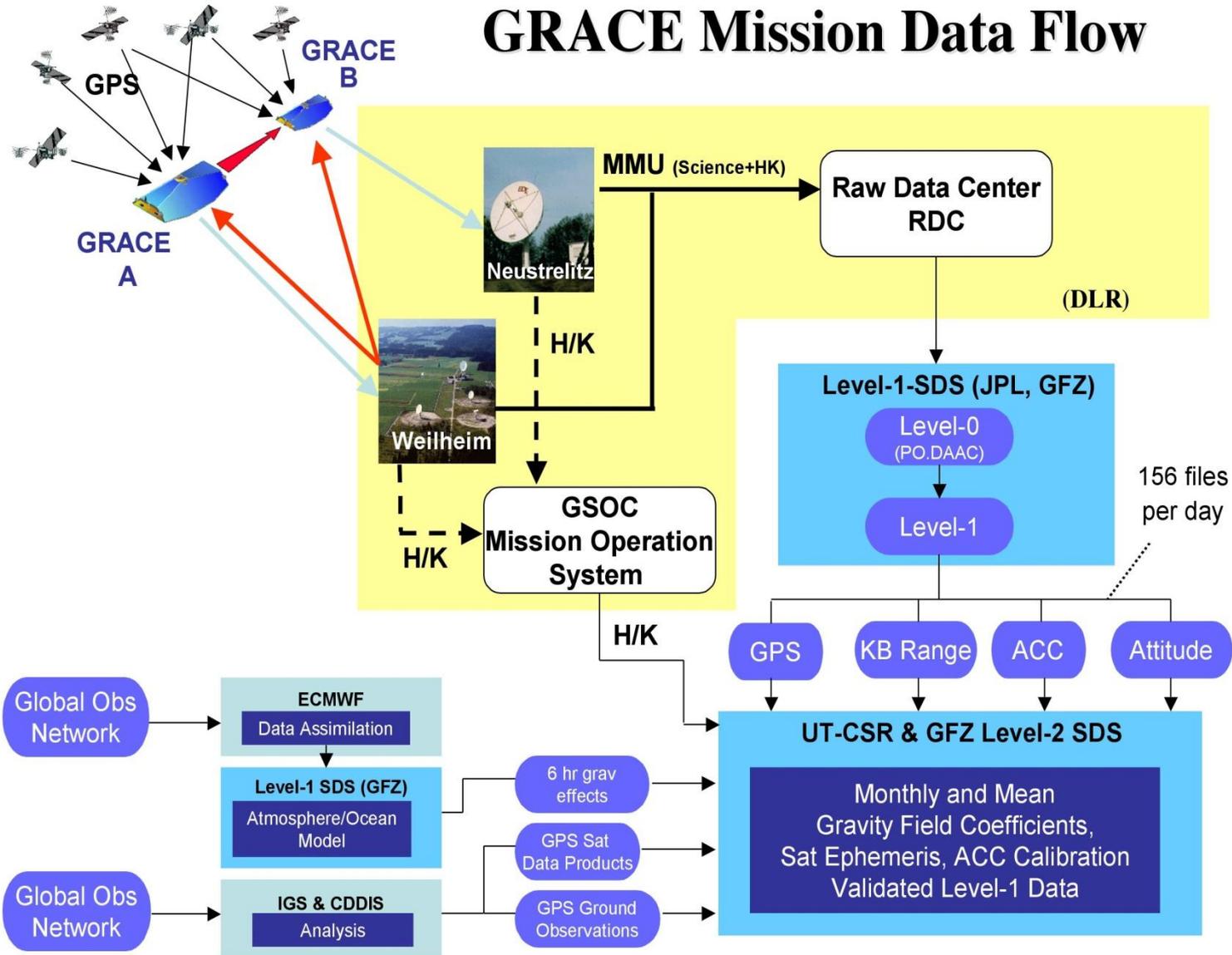
- GRACEデータの利用
- 陸水変動
- 氷床変動
- 地震

# GRACEデータの利用

# GRACEのデータ

- Level 0 data センサーデータ
  - K-Band Phase Data 10Hz sampling
  - GPS Data(Orbit Det.) 1Hz sampling
  - GPS Data(Occultation) 50 Hz sampling
- Level 1 data
  - K-Band Ranging (Biased Range & Derivatives) ~  
5s sample rate
  - Geophysical Corrections(データ、ソフト)  
地球潮汐、海洋潮汐、大気、...
- Level 2 data
  - 重力場球面調和関数係数 (Stokes係数) 時系列  
120次／1ヶ月

# GRACE Data作成の流れ





**Jet Propulsion Laboratory**  
California Institute of Technology

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# GRACE

## Gravity Recovery and Climate Experiment



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### **NEW** GRACE Tellus web site

GRACE Science Team Meeting  
December 8 & 9, 2006  
San Francisco, California

Questions and comments concerning the GRACE Science Data Products should be directed to [grace@podaac.jpl.nasa.gov](mailto:grace@podaac.jpl.nasa.gov)

**GRACE is a joint partnership between the National Aeronautics and Space Administration (NASA) in the United States and Deutsches Zentrum Für Luft und Raumfahrt (DLR) in Germany. Prof. Byron Tapley of The University of Texas Center for Space Research (UTCSR) is the Principal Investigator (PI), and Prof. Christoph Reigber of the GeoForschungsZentrum (GFZ) Potsdam is the Co-Principal Investigator (Co-PI). The Jet Propulsion Laboratory carries out project management and systems engineering activities.**

The twin GRACE satellites were launched on March 17, 2002. Since that time, the GRACE Science Data System (SDS) has produced and distributed estimates of the Earth gravity field on an ongoing basis. These estimates, in conjunction with other data and models, have provided observations of terrestrial water storage changes, ice-mass variations, ocean bottom pressure changes and sea-level variations. This portal, together with ISDC, is responsible for the distribution of the data and documentation for the GRACE project. A brief overview of the science data flow is given at <http://www.csr.utexas.edu/grace/asdp.html> and more details are provided in the project documents. A complete list of relevant project documents has been made available ([click here](#)). Users are strongly urged to read these documents before proceeding with data analysis.

**A Guide To Available Data**

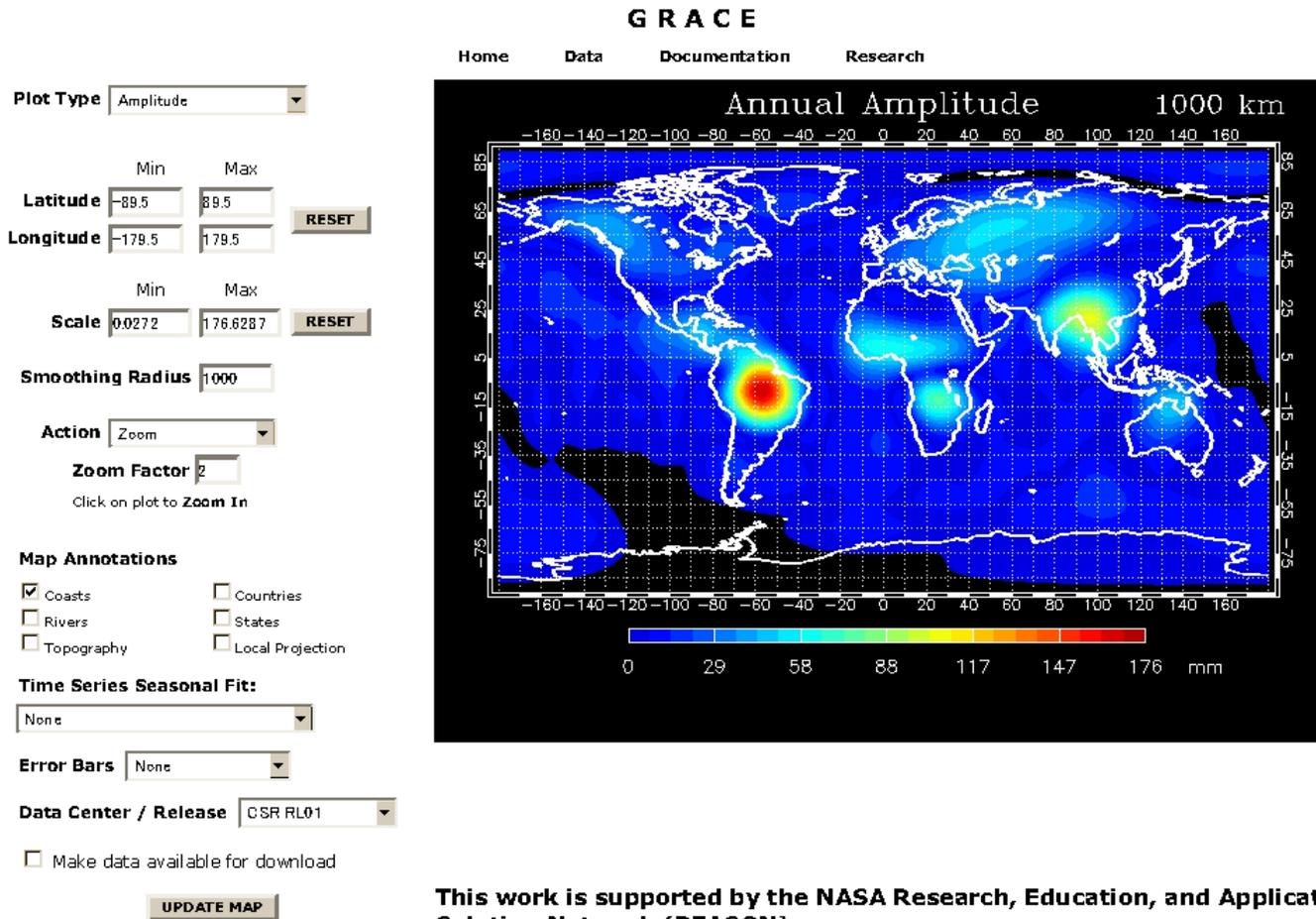
(May 10, 2006)

# Level-2データの計算サイト

<http://geoid.colorado.edu/grace/grace.php>

GRACE

<http://geoid.colorado.edu/grace/grace.php>



This work is supported by the NASA Research, Education, and Applications Solution Network (REASON)

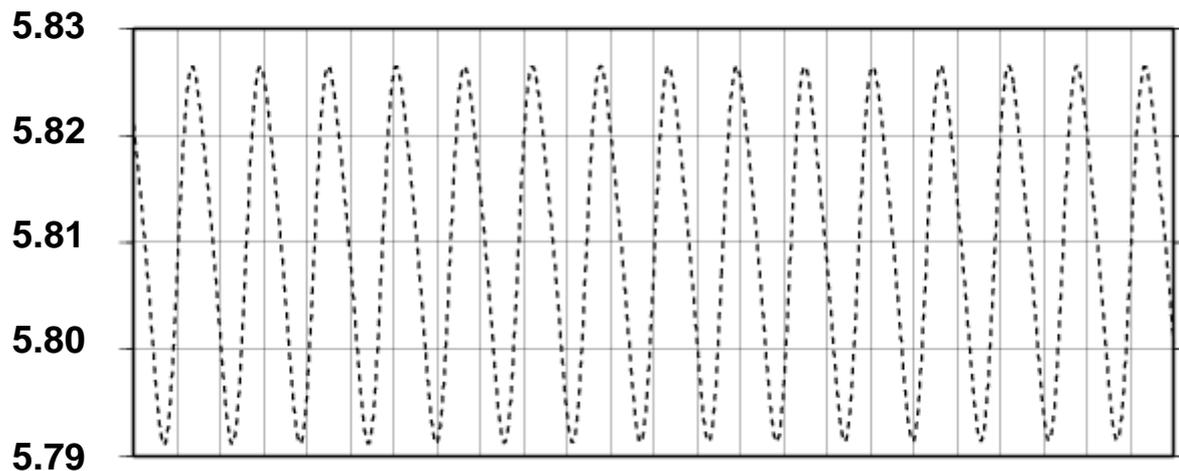
GRACE-1

縦軸 単位[m<sup>2</sup>/s<sup>2</sup>]

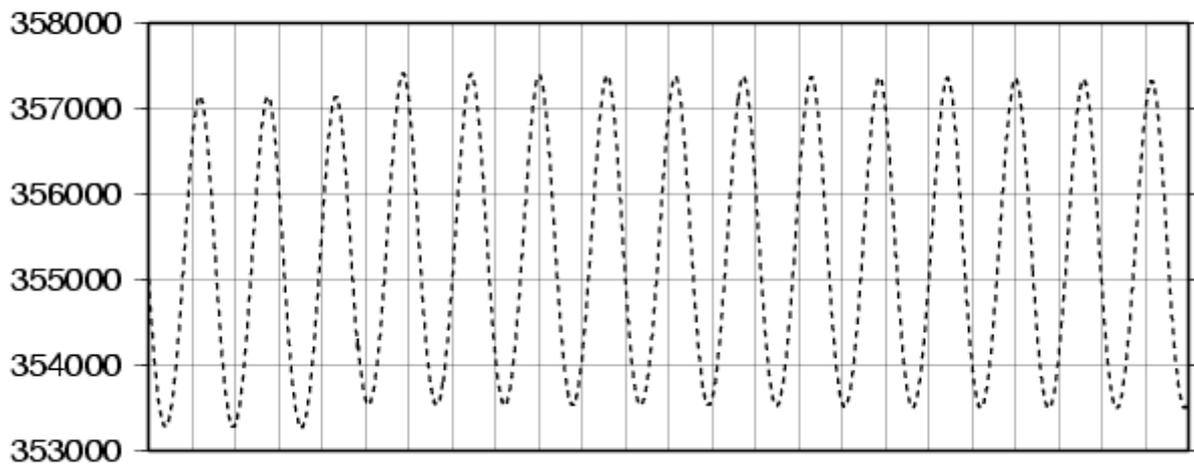
横軸 1目盛 1時間

× 10<sup>4</sup>

# Potential



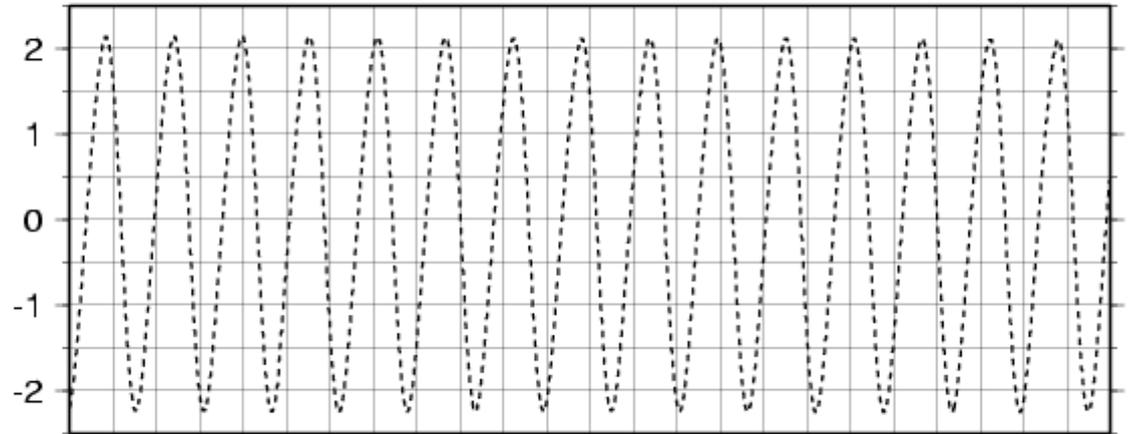
# Range



縦軸 単位[m]

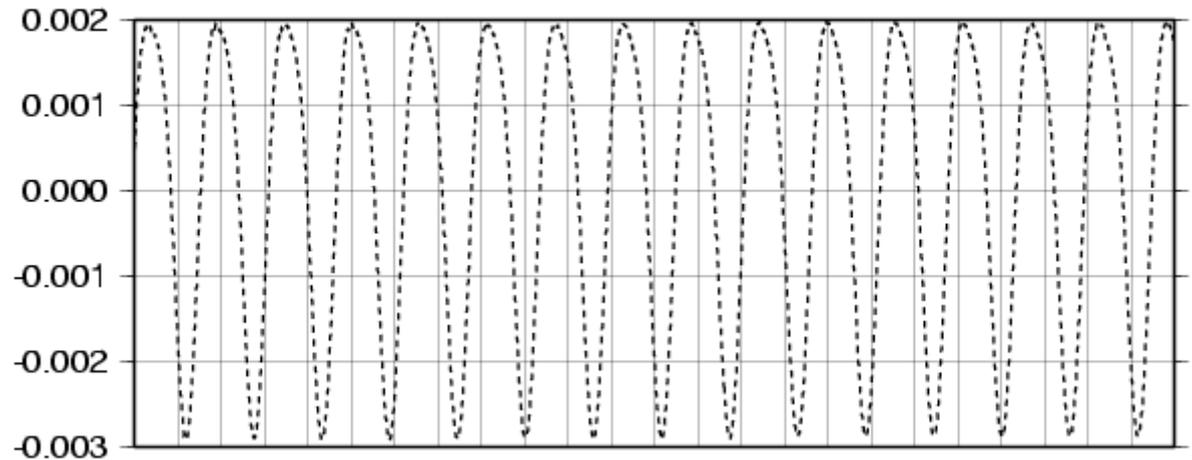
横軸 1目盛 1時間

# Rangerate



縦軸 単位[m/s]  
横軸 1目盛 1時間

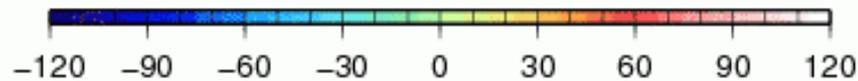
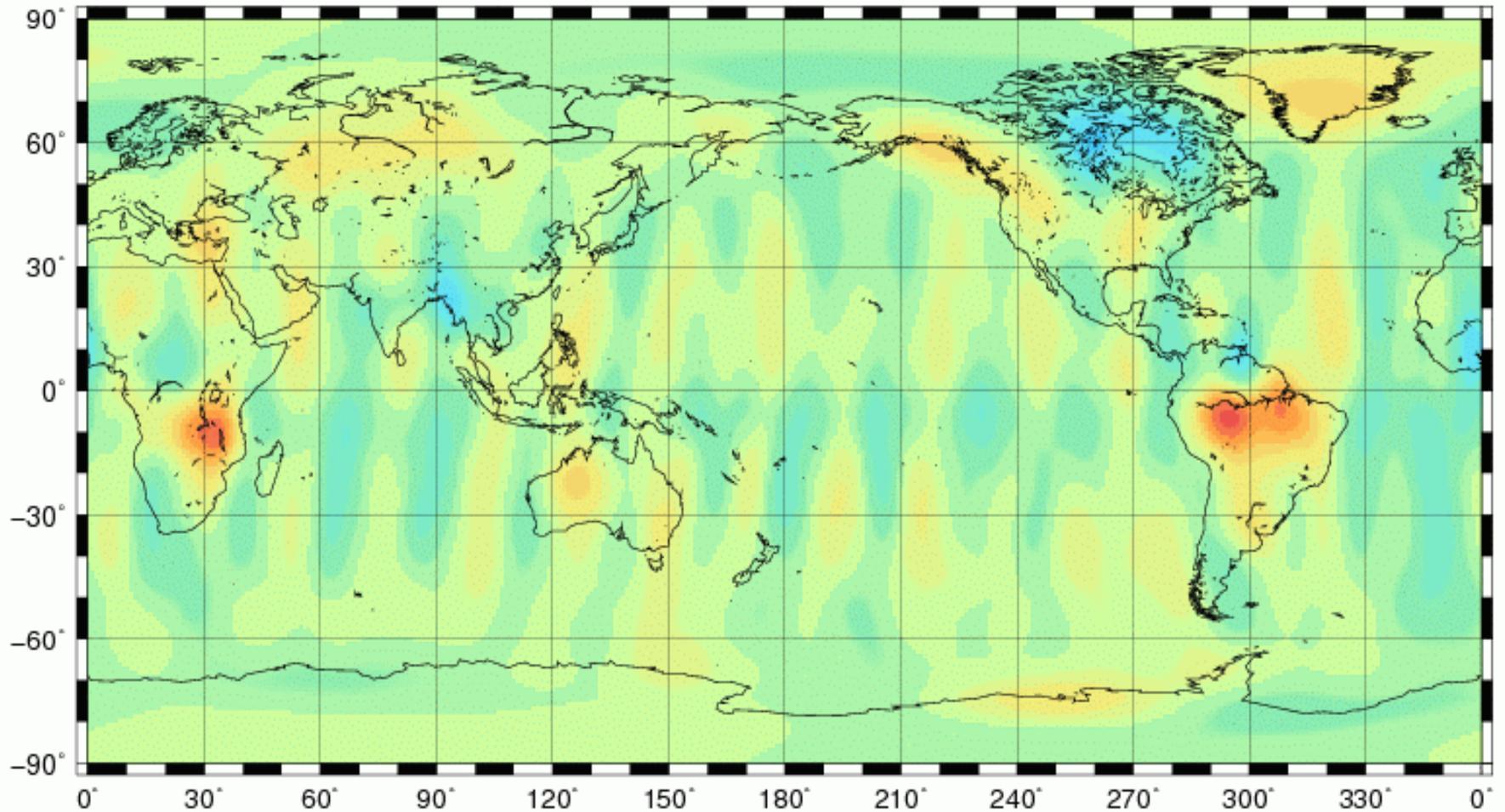
# Rangeacc



縦軸 単位[m/s<sup>2</sup>]  
横軸 1目盛 1時間

# 重力場の時間変化

d001-2002-102



Water Equivalence (mm)

# 入手可能なLevel-2データ

- GRACE SDS(Science Data System)

- JPL-RL04.1

- UTCSR-RL04

- GFZ-RL04

- [http://podaac.jpl.nasa.gov/grace/data\\_access.html#Level2](http://podaac.jpl.nasa.gov/grace/data_access.html#Level2)

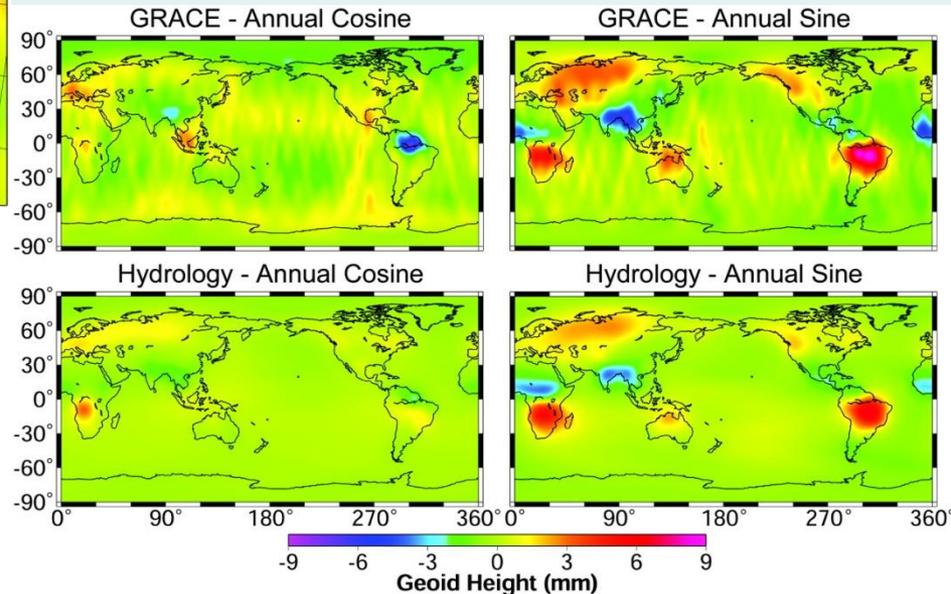
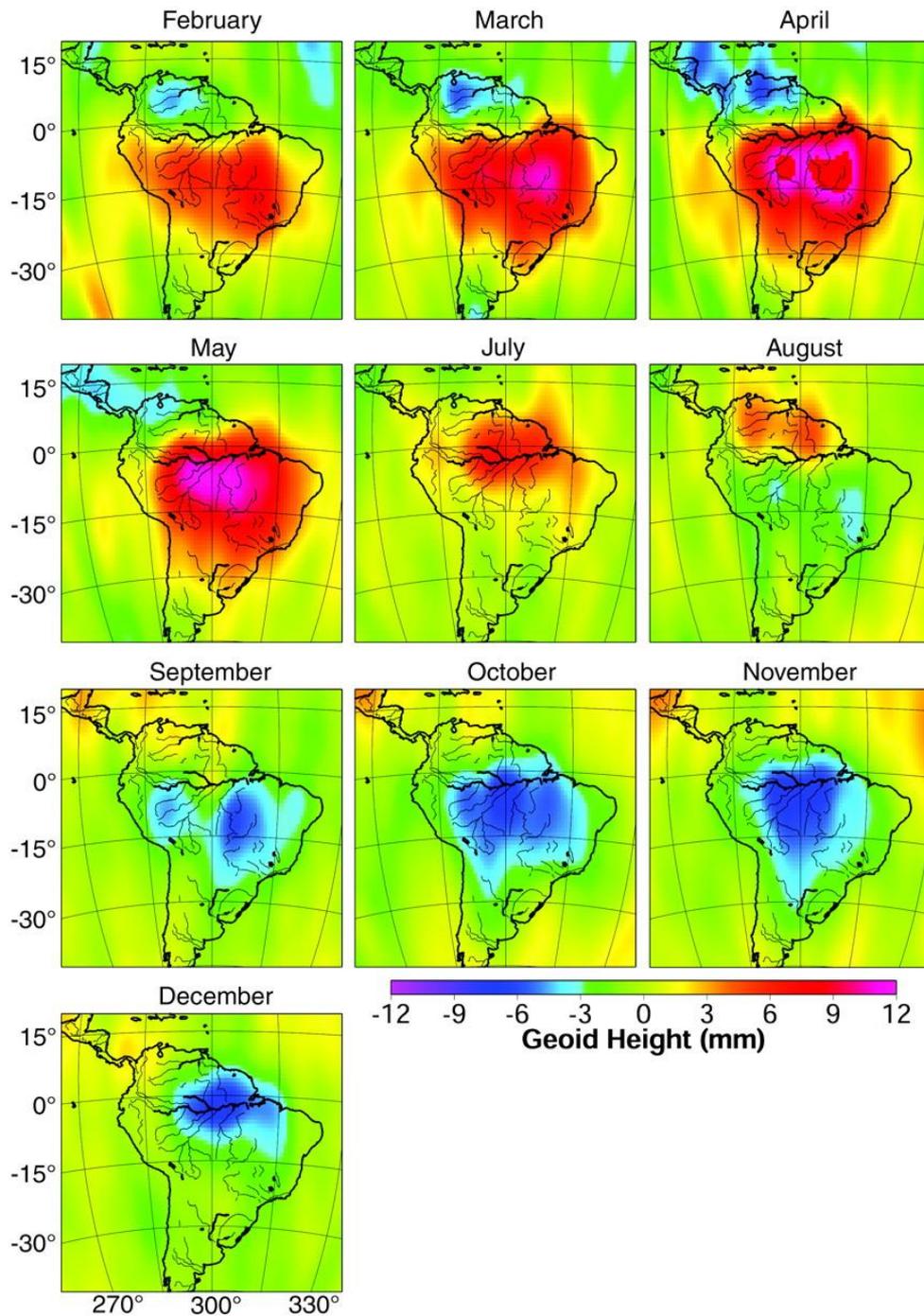
- GRGS 10-day Solution RL02

- <http://grgs.obs-mip.fr/index.php/fre/Donnees-scientifiques/Champ-de-gravite/grace/release02>

# 陸水變動

# GRACE Measurements of Mass Variability in the Earth System

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



# 水循環研究へのGRACEの適用



$$P = \underline{E} + R + \underline{G} + \triangle S$$

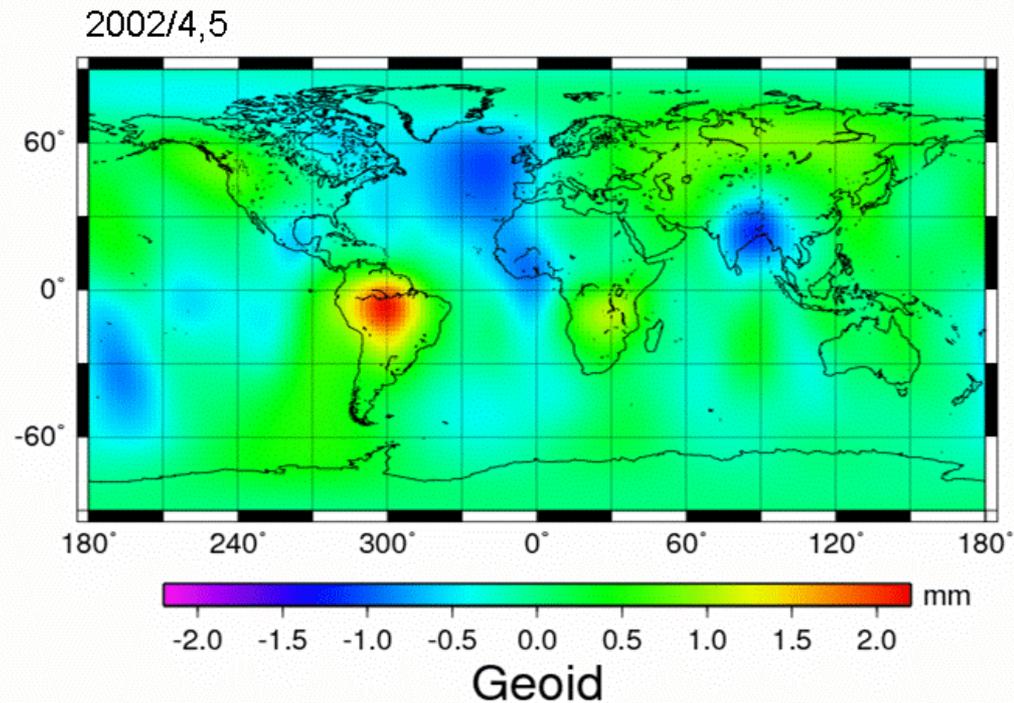
P:降水量

E:蒸発散量

R:河川流出量

G:地下水流出量

$\triangle S$ :地下水貯留量 ←  
(土壤水分含む)



# グローバル・フィルタ

$$\Delta N(\theta, \lambda) = a \sum_{l=0}^{l_{trunc}} W_l \sum_{m=0}^l P_{lm}(\cos \theta) (\Delta C_{lm} \cos m\lambda + \Delta S_{lm} \sin m\lambda)$$

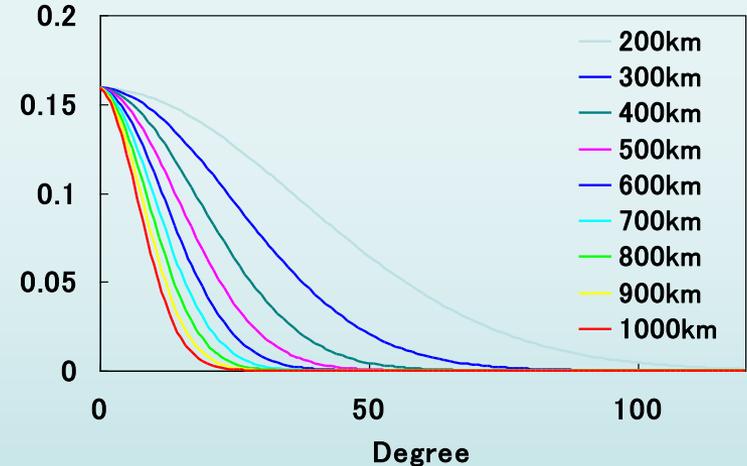
Gaussian filter (Jekeli 1981, Wahr 1998)

$$W(\alpha) = \frac{b}{2\pi} \frac{\exp[-b(1 - \cos \alpha)]}{1 - \exp(-2b)}$$

$$b = \frac{\ln 2}{1 - \cos(r/a)}$$

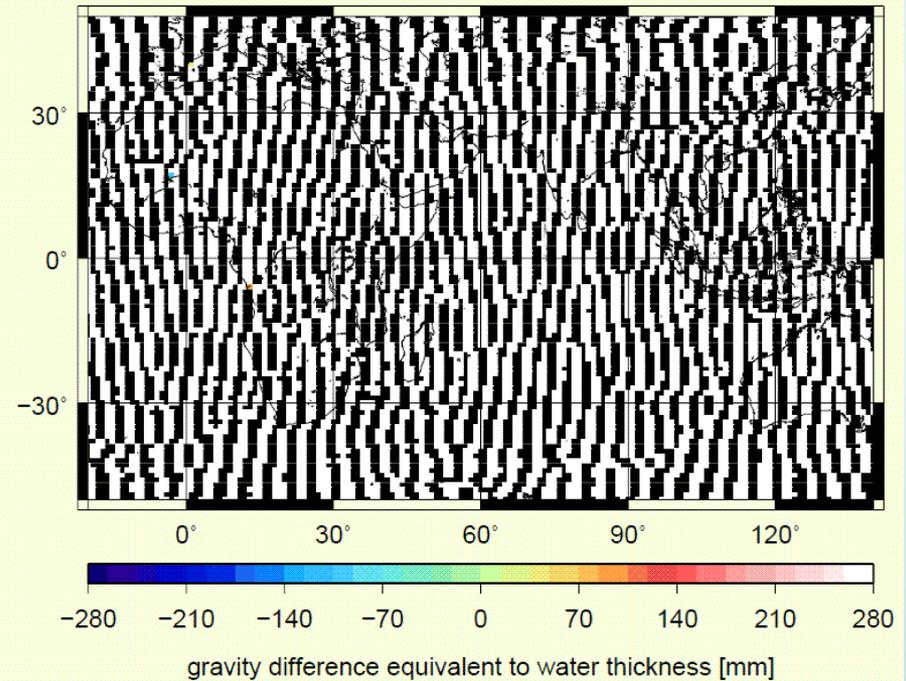
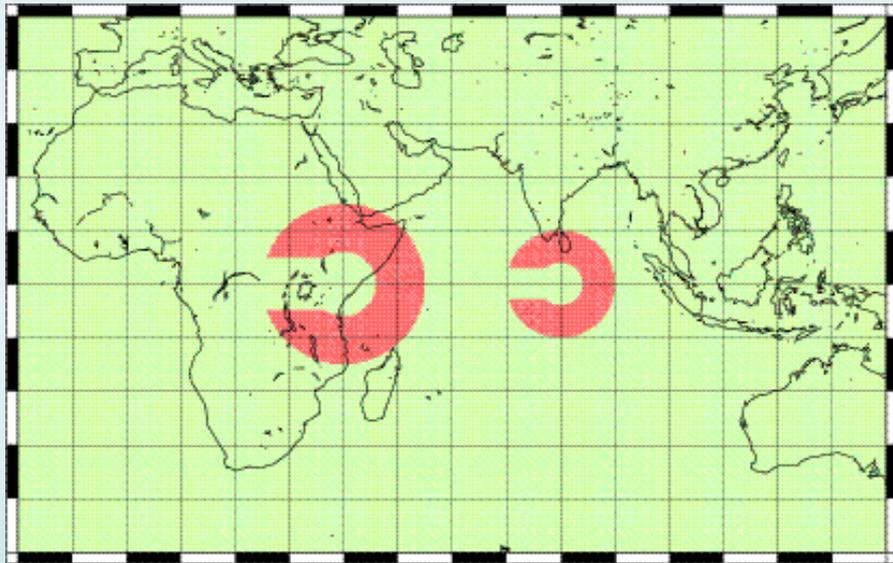
$$W_l = \int_0^\pi W(\alpha) P_l(\cos \alpha) \sin \alpha d\alpha$$

Spectrum domain



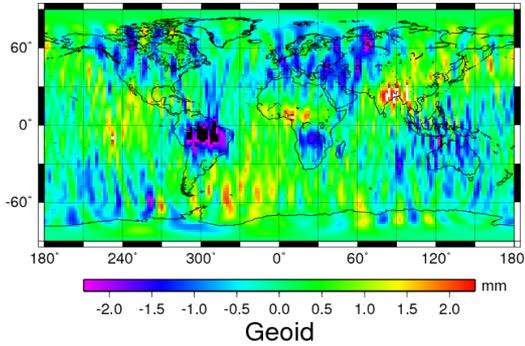
# 空間フィルタの効果

Gaussian filter 0km

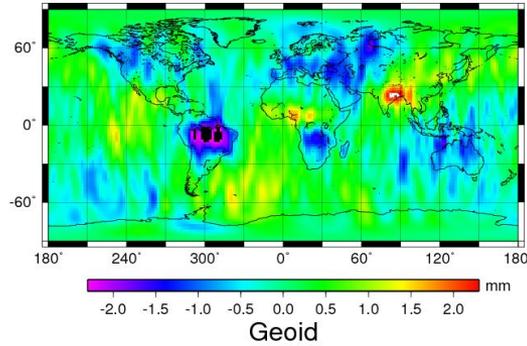


# 空間フィルタの効果

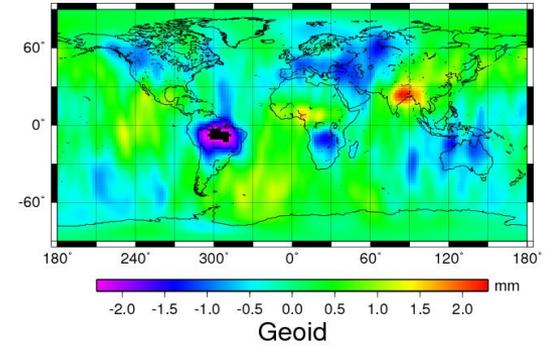
200km



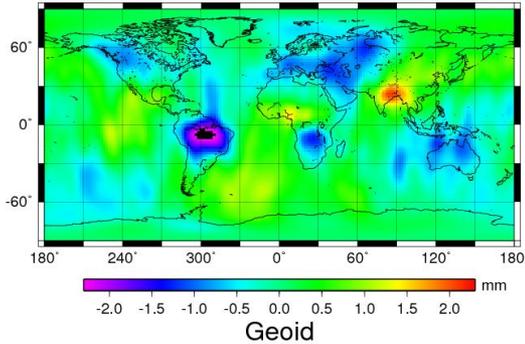
300km



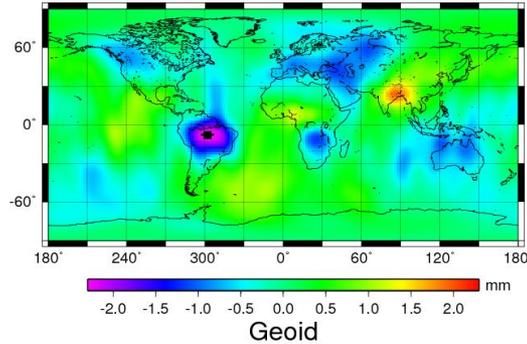
400km



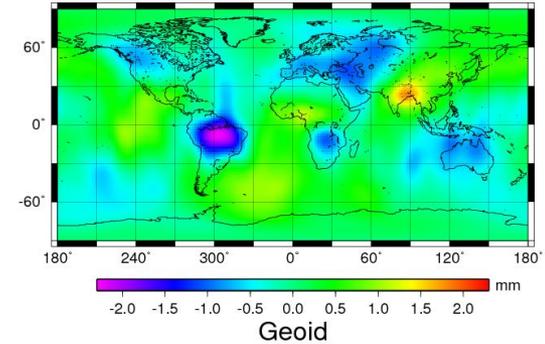
500km



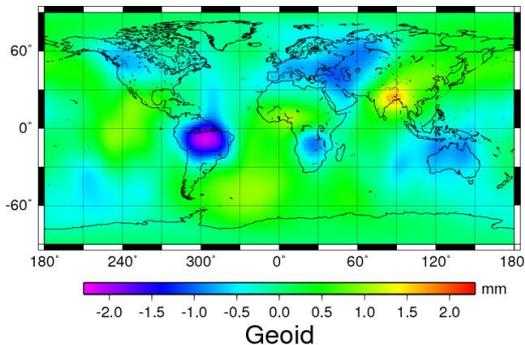
600km



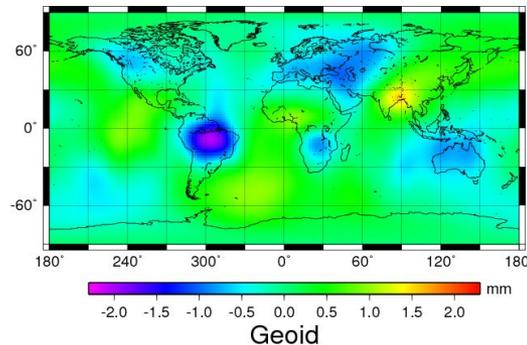
700km



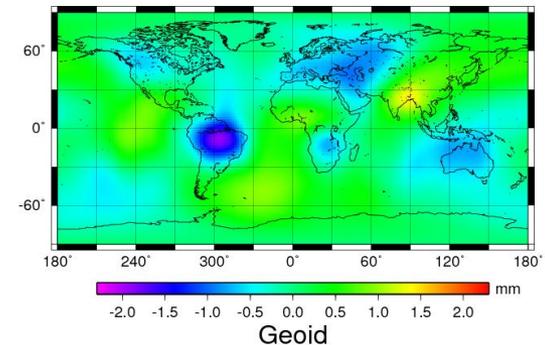
800km



900km



1000km



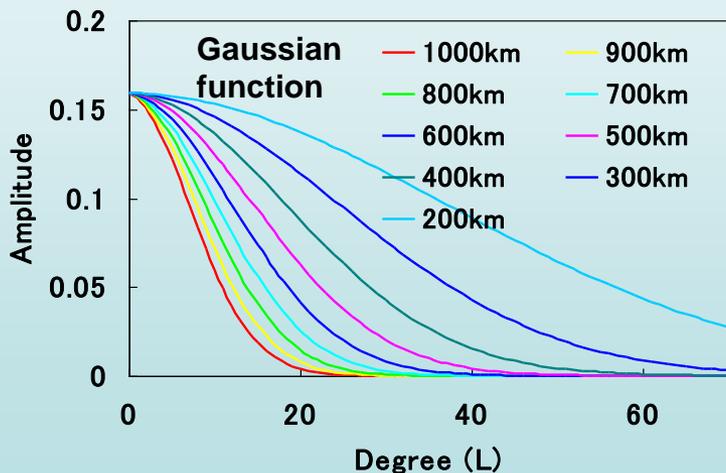
# Regional Filterの設計

(Swenson et al., 2004)

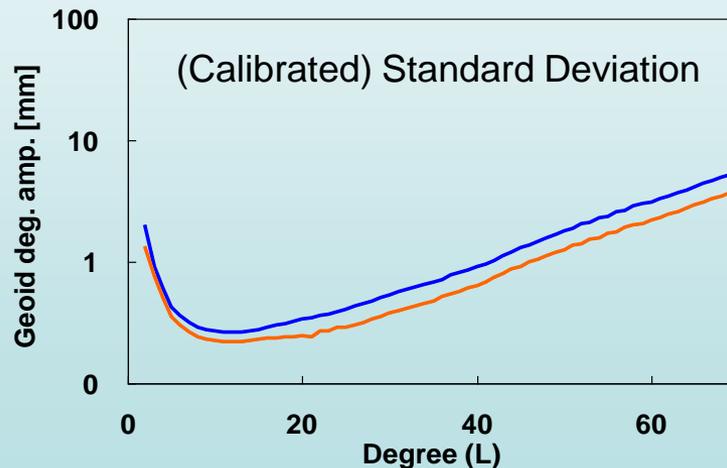
Gaussian filterをbaseとし、LSMにより  
Leakage error + measurement error → minimize

重み係数  $\begin{Bmatrix} W_{lm}^C \\ W_{lm}^S \end{Bmatrix} = \left[ 1 + \frac{2(2l+1)B_l^2}{\sigma_0^2 G_l (1+k_l)^2} \left( \frac{a\rho_E}{3} \right)^2 \right]^{-1} \begin{Bmatrix} g_{lm}^C \\ g_{lm}^S \end{Bmatrix}$  領域の形状

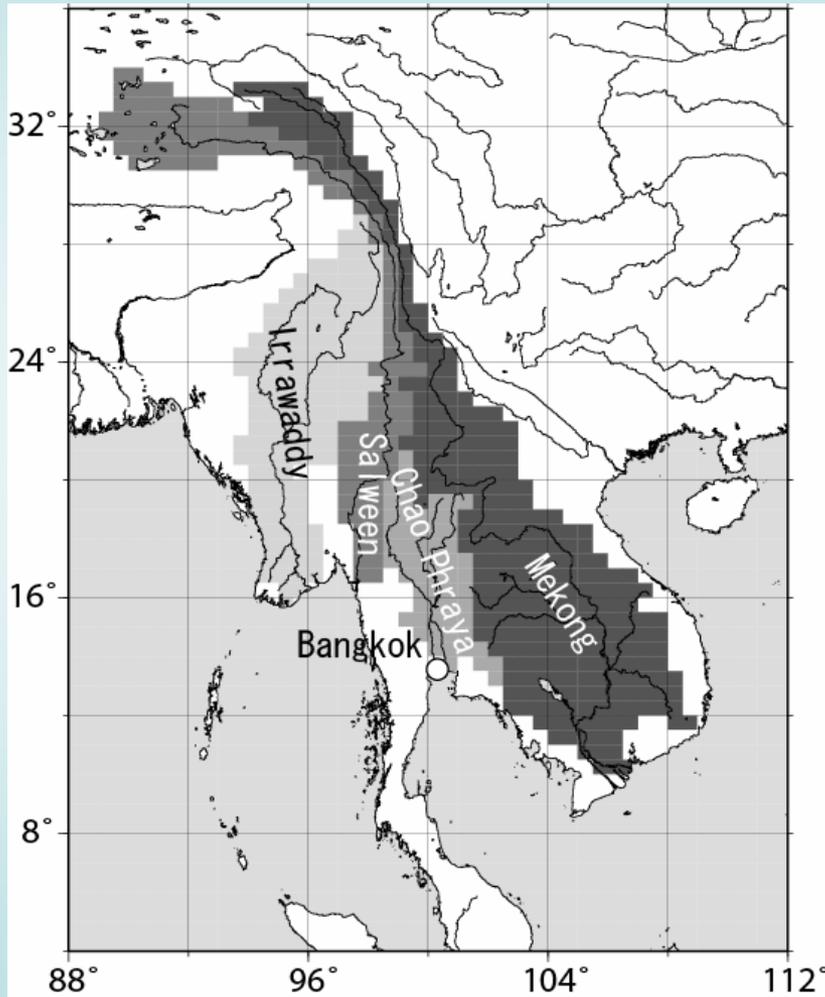
相関関数とその相関長



衛星の観測誤差



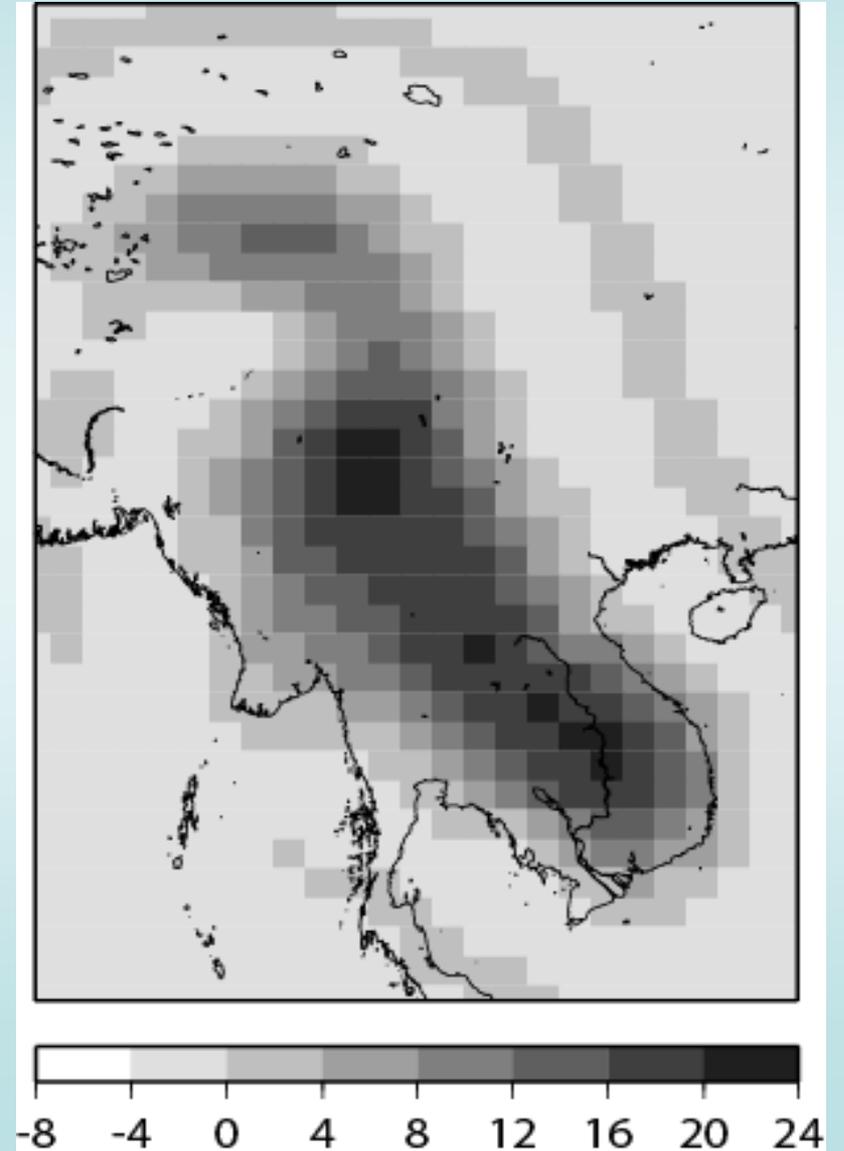
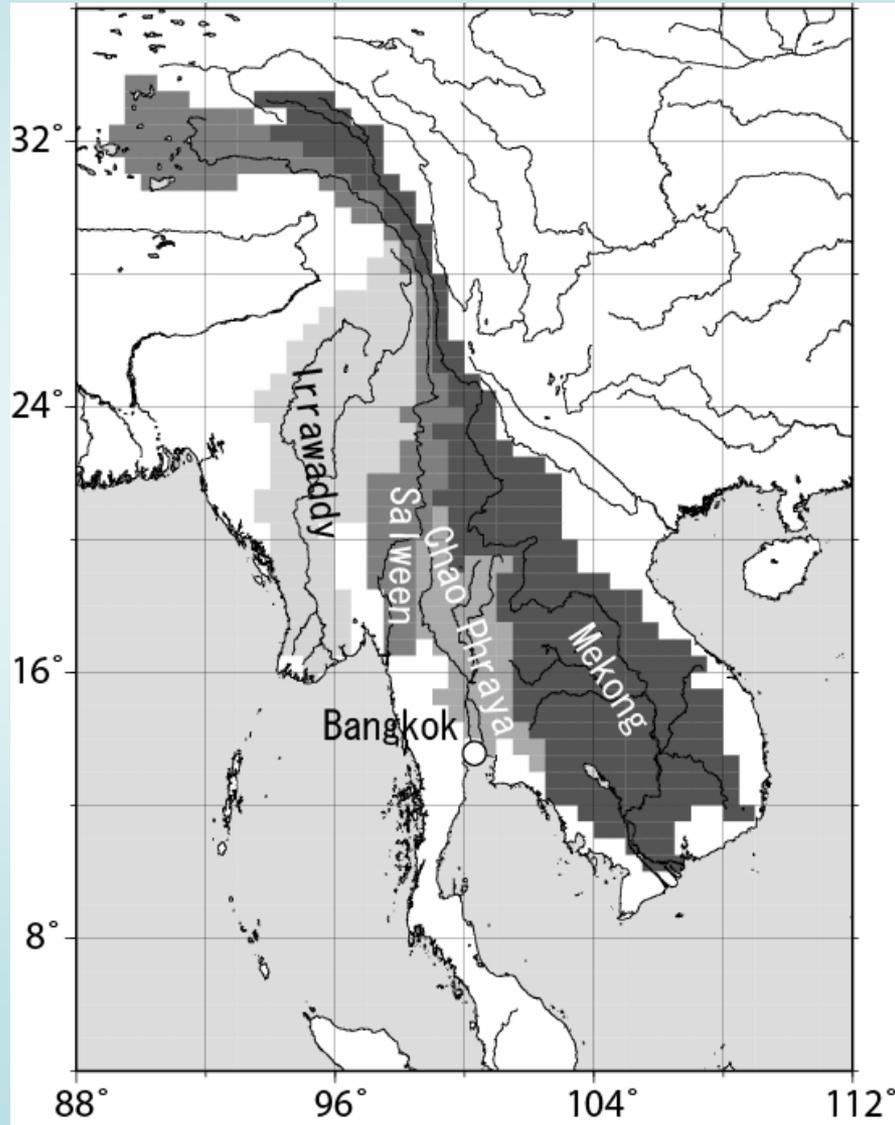
# インドシナ半島における解析例



## •流域面積

River	Drainage Area (km <sup>2</sup> )
Salween	330 000
Chao Phraya	178 000
Irrawaddy	425 000
Mekong	814 000
Total	1 750 000

# Regional Filterの例



2002/4,5

2002/8

2002/9

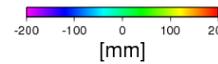
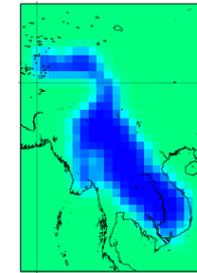
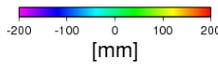
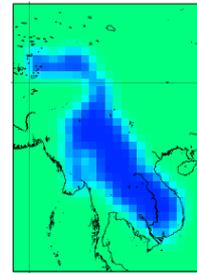
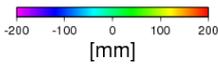
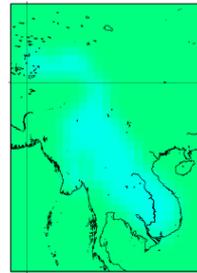
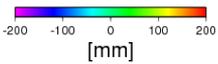
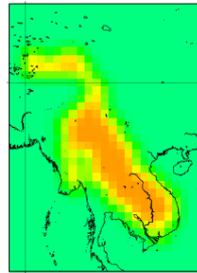
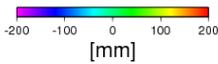
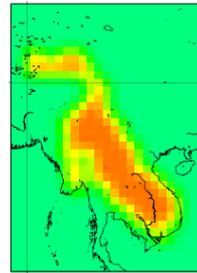
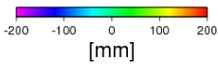
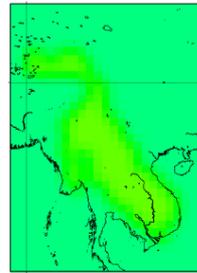
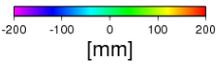
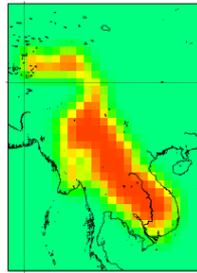
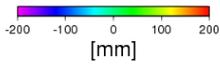
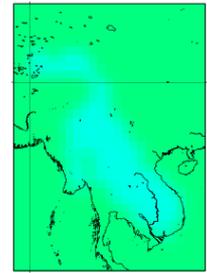
2002/10

2002/11

2003/2

2003/3

2003/4



2003/5

2003/7

2003/8

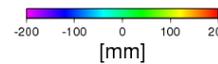
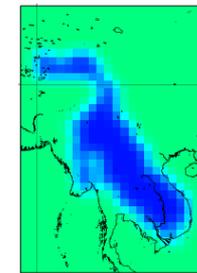
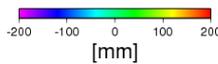
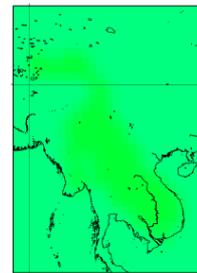
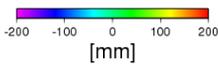
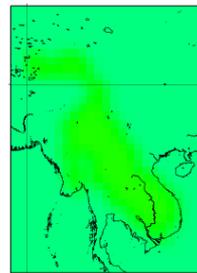
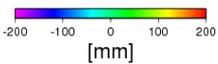
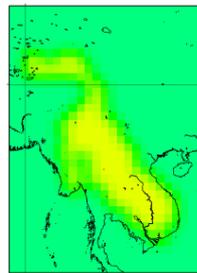
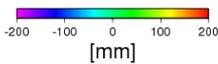
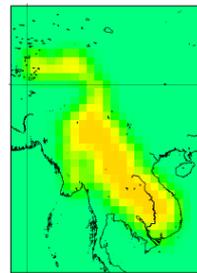
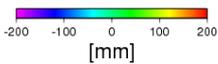
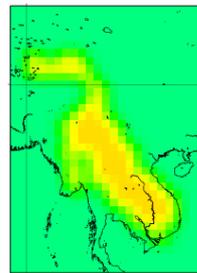
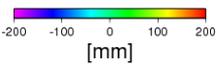
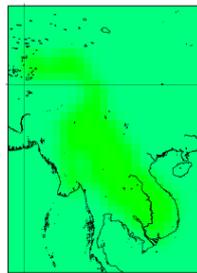
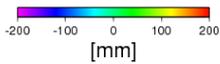
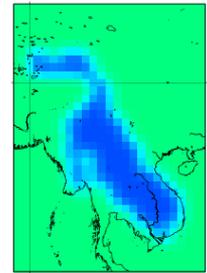
2003/9

2003/10

2003/11

2003/12

2004/1



2004/2

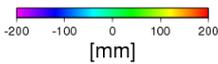
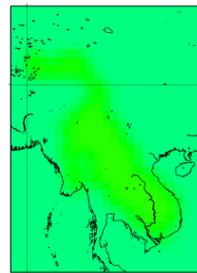
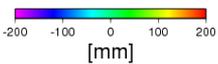
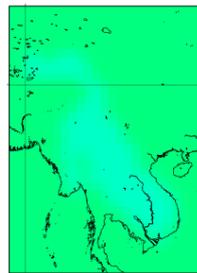
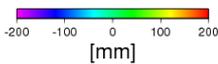
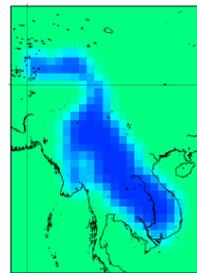
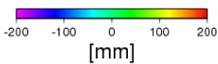
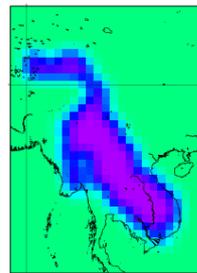
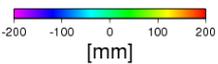
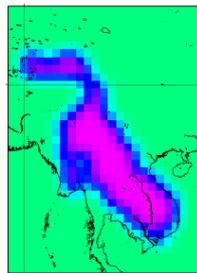
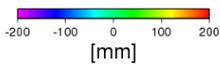
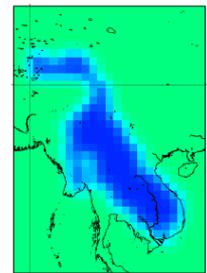
2004/3

2004/4

2004/5

2004/6

2004/7

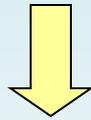


Mass variations detected by GRACE

# 陸水貯留量算定

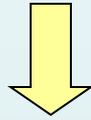
大気客観解析値(GANAL)

地上大気データ



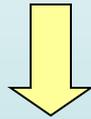
オフライン陸面モデル(SiB)

流出量



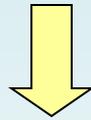
オフライン河川モデル(GRivet)

河川流量



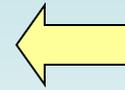
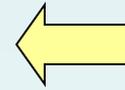
陸水貯留量

観測値

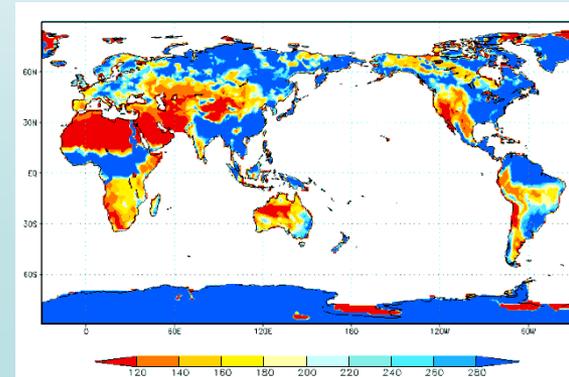


積雪深析値

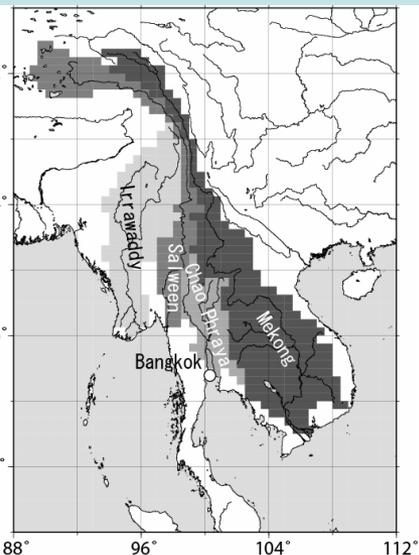
積雪深データ



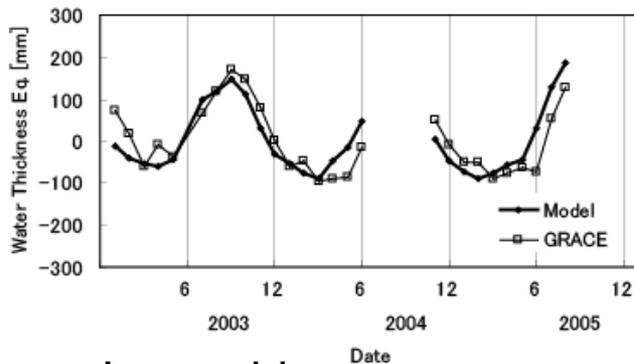
土壌水分、積雪水当量



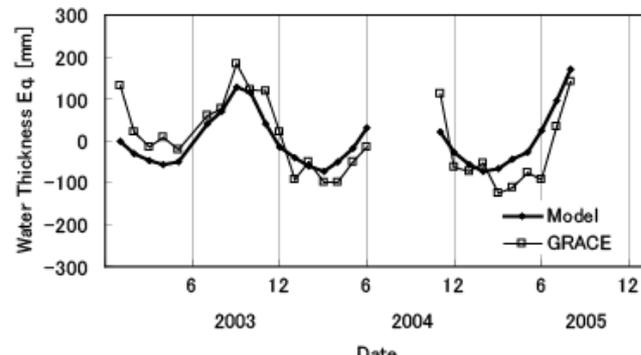
# 流域毎のGRACEとモデル比較(1)



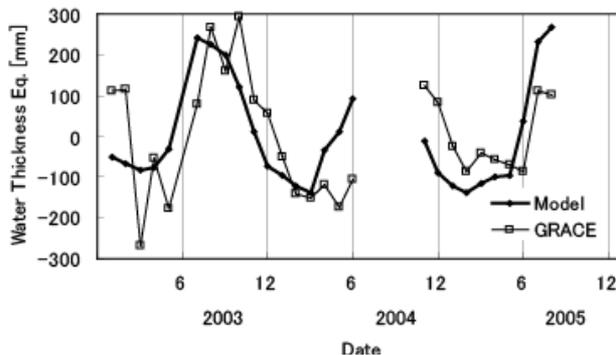
(a) 4 rivers combined



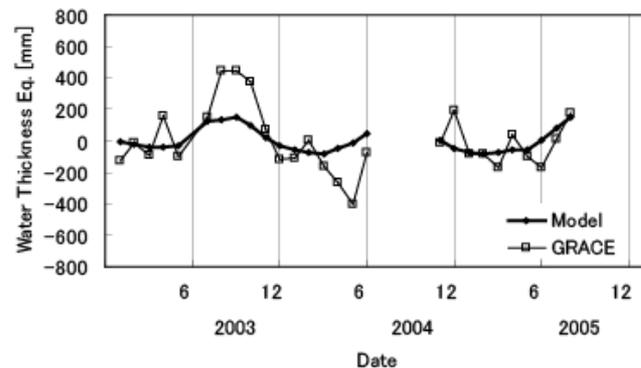
(b) Mekong



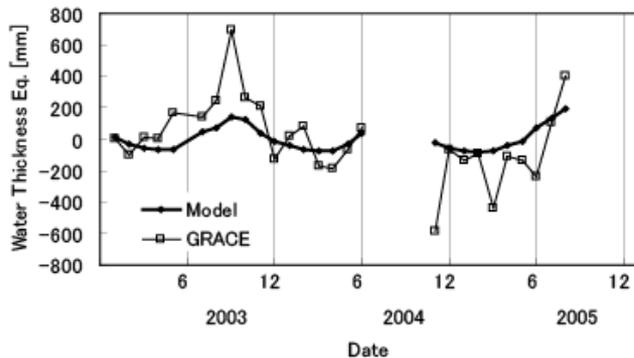
(c) Irrawaddy



(d) Salween

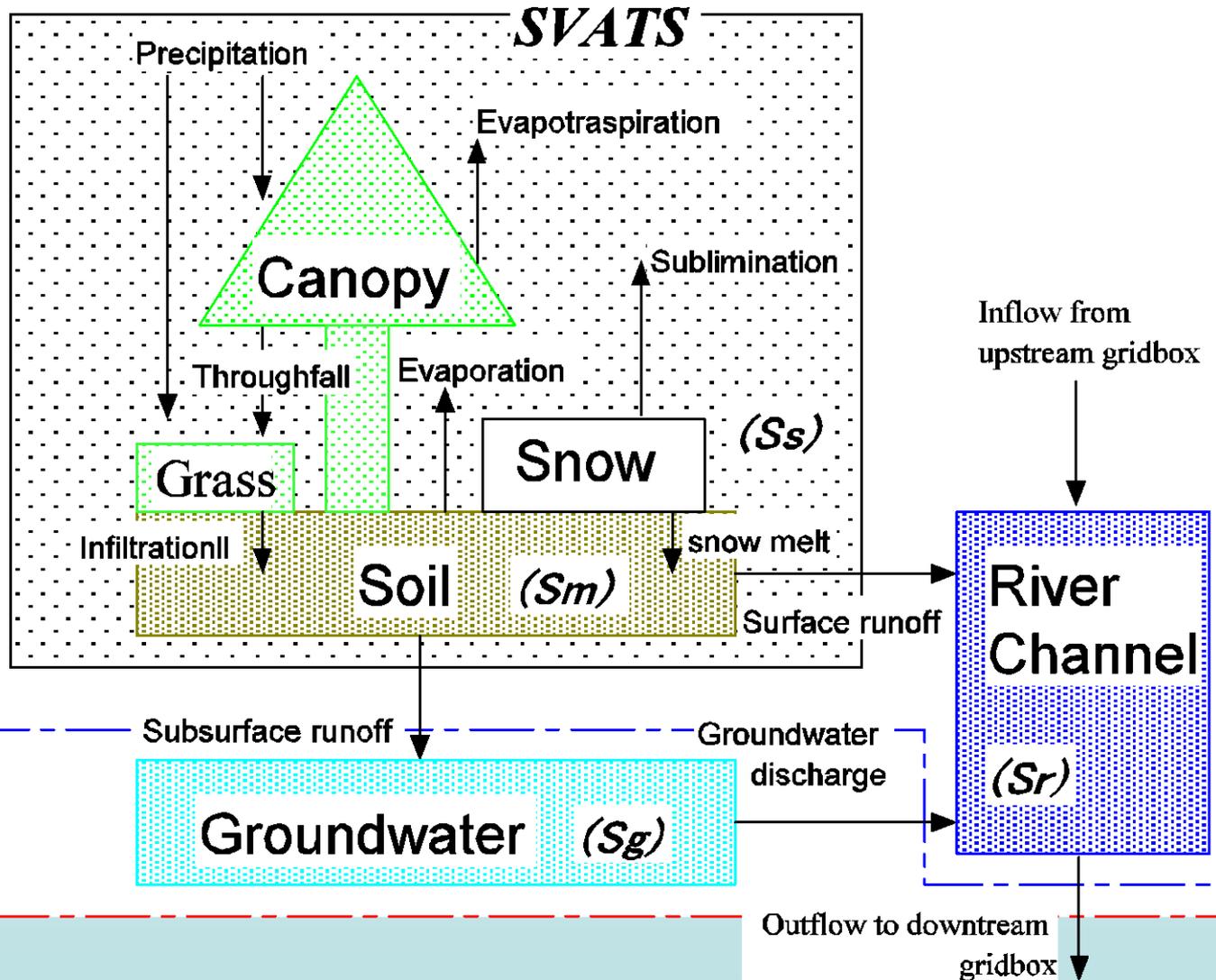


(e) Chao Phraya

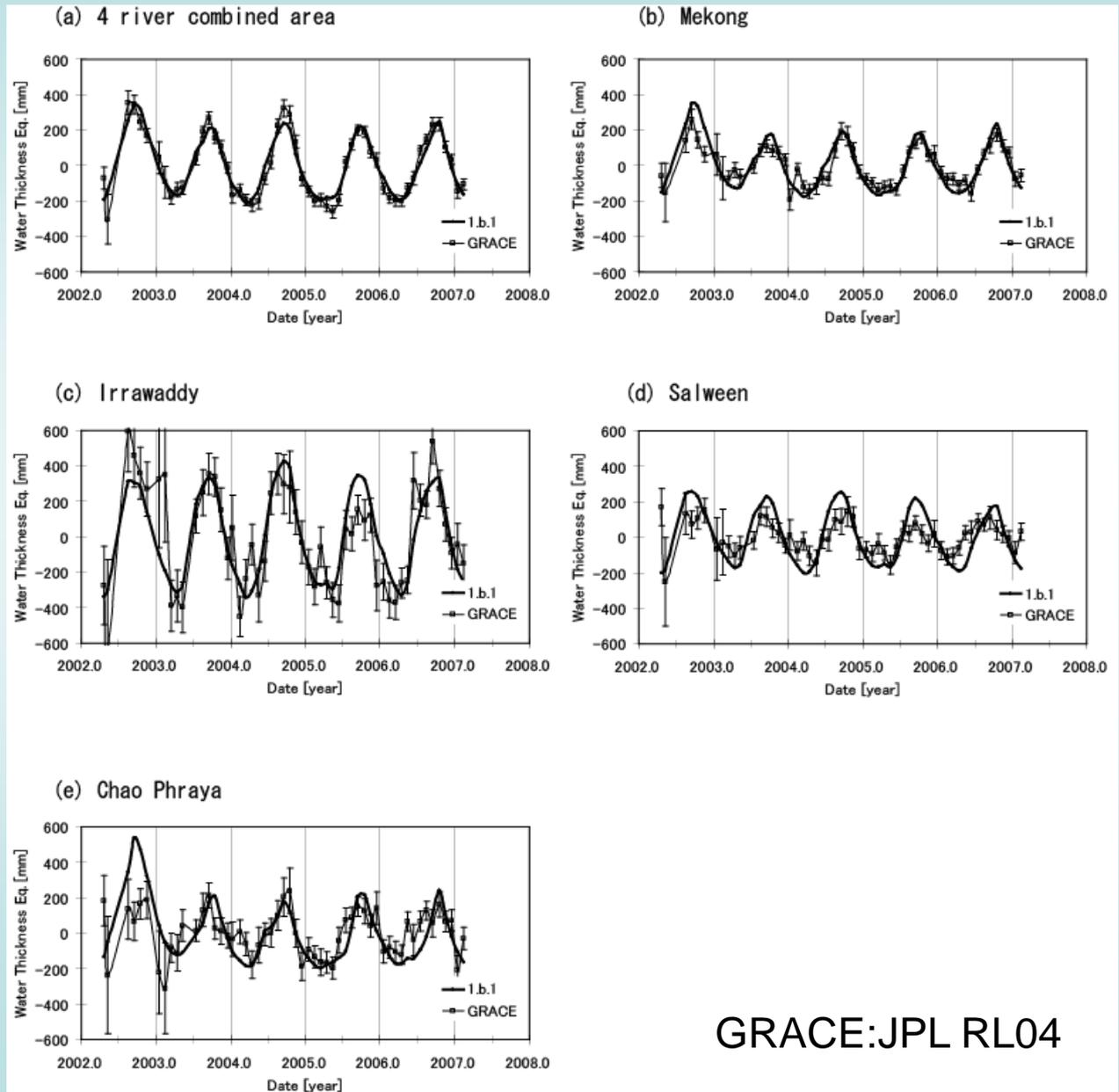
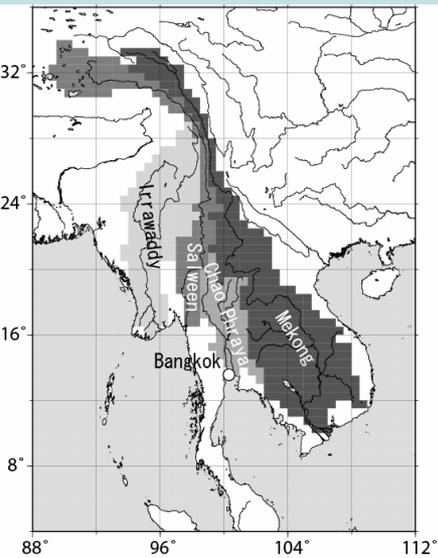


1.b.x ( $S_m + S_s + S_r + S_g$ )

1.a.x ( $S_m + S_s + S_r$ )



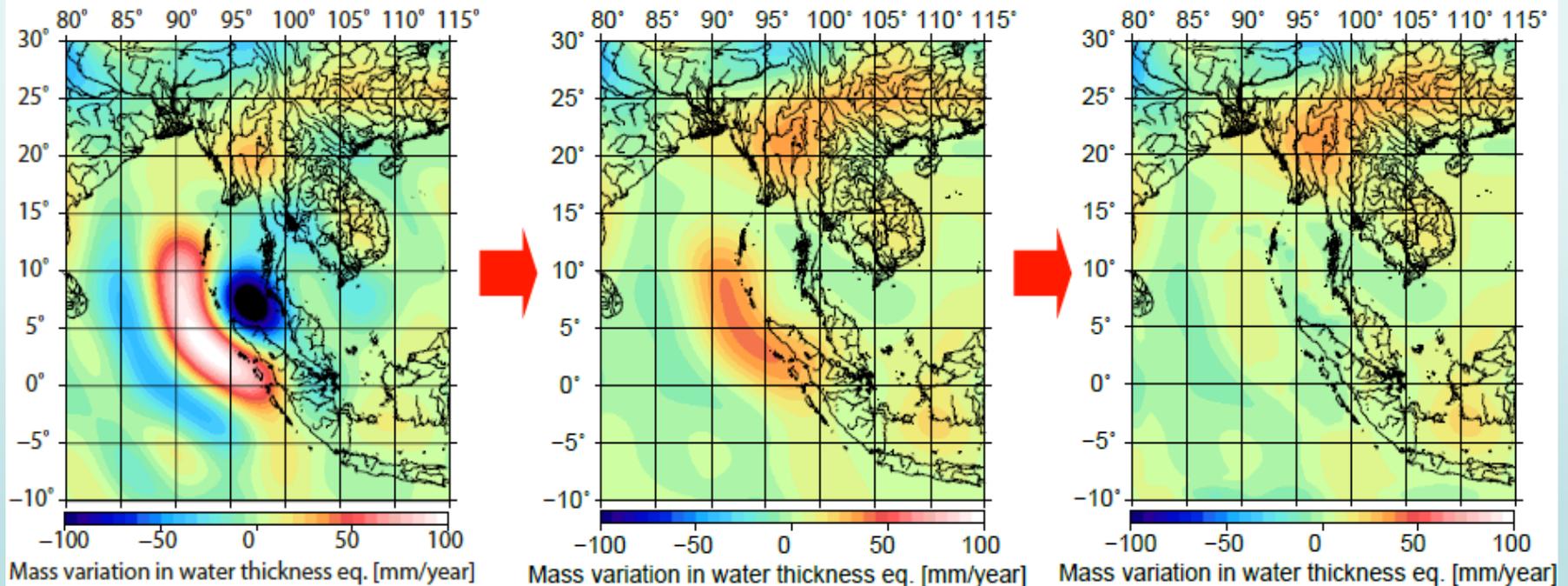
# 流域毎のGRACEとモデル比較(2)



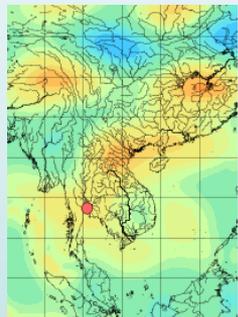
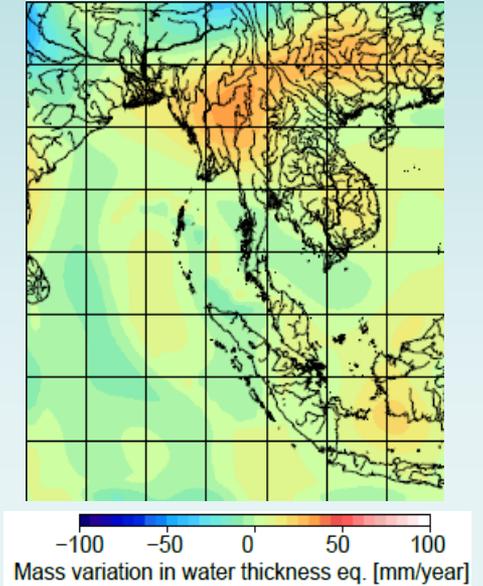
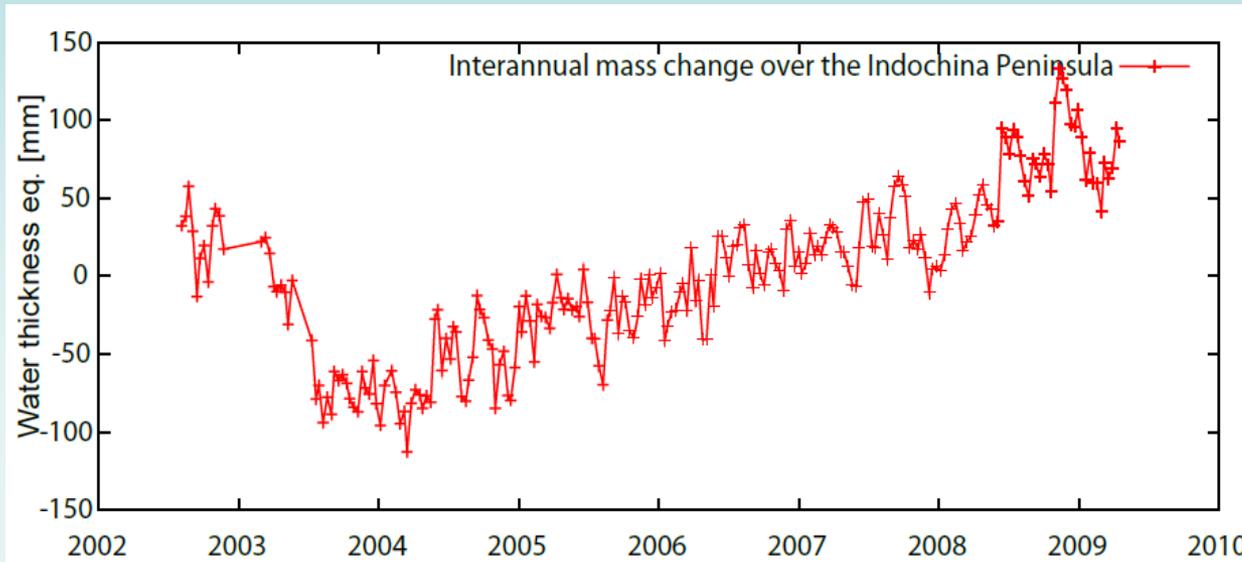
# GRACEデータ処理

使用データ: CNES/GRGS every 10 day gravity field solutions (v02)  
(up to degree/order 50, July 2002 to April 2009)

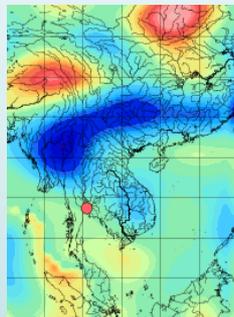
- スマトラ地震のシグナルの除去 (co-seismic, after seismic)
  - PGRのトレンドの除去 (-1.5 mm/yr)
  - 年周・半年周成分の除去
- <http://grgs.obs-mip.fr/index.php/fre/Donnees-scientifiques/Champ-de-gravite/grace/release02>



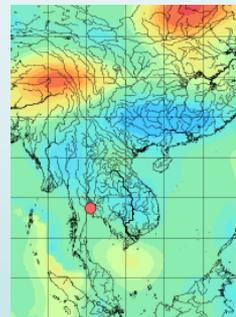
# 陸水質量の経年変動



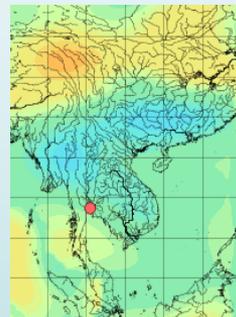
2002



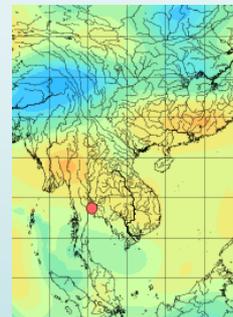
2003



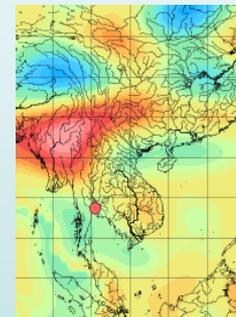
2004



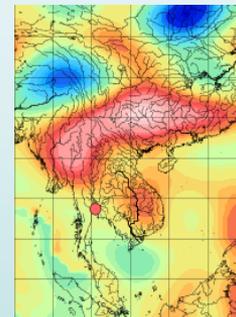
2005



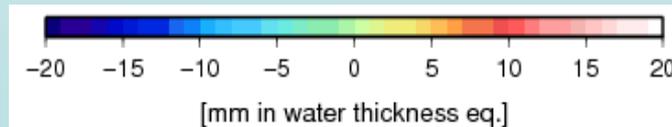
2006



2007



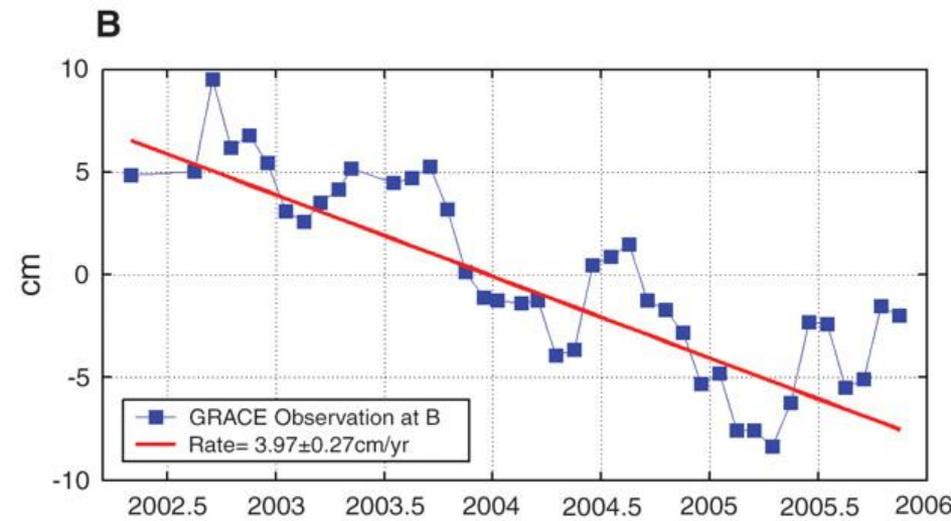
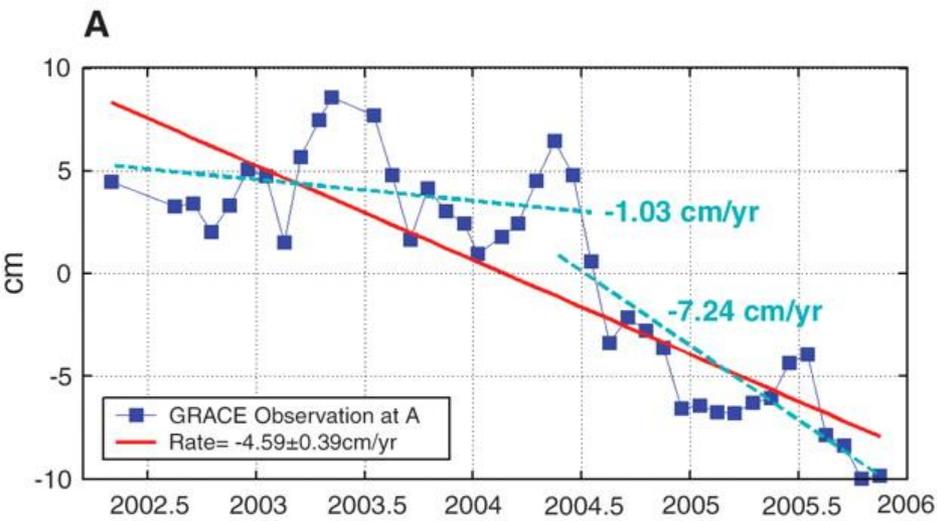
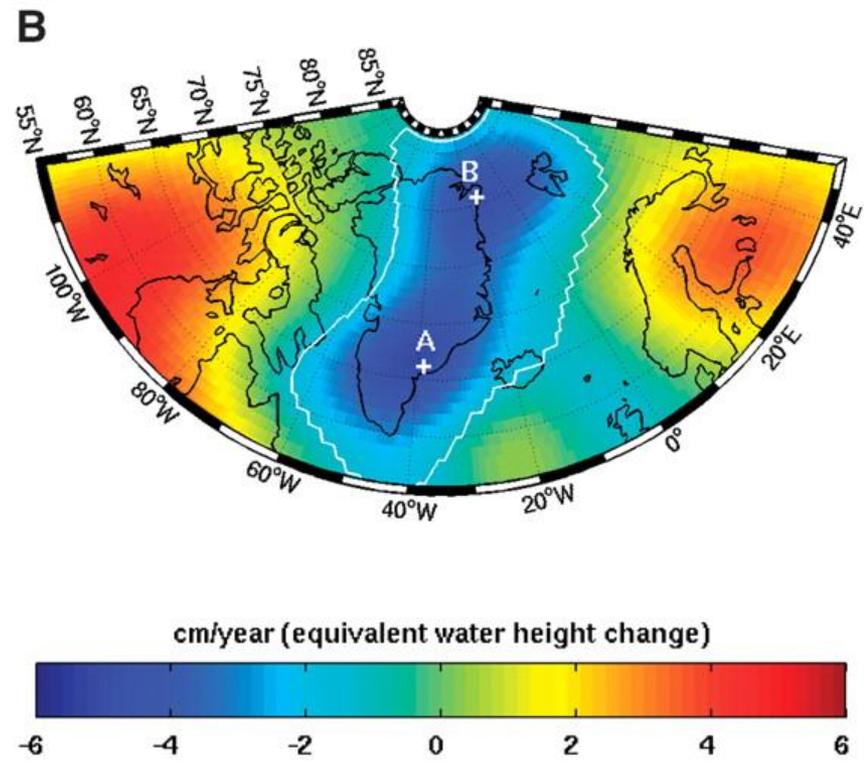
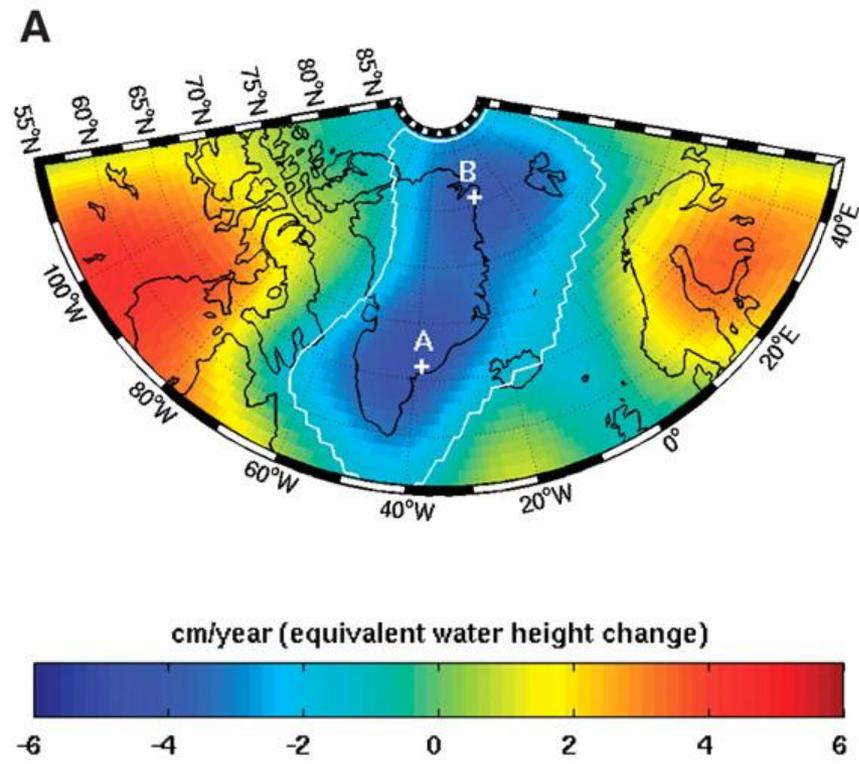
2008



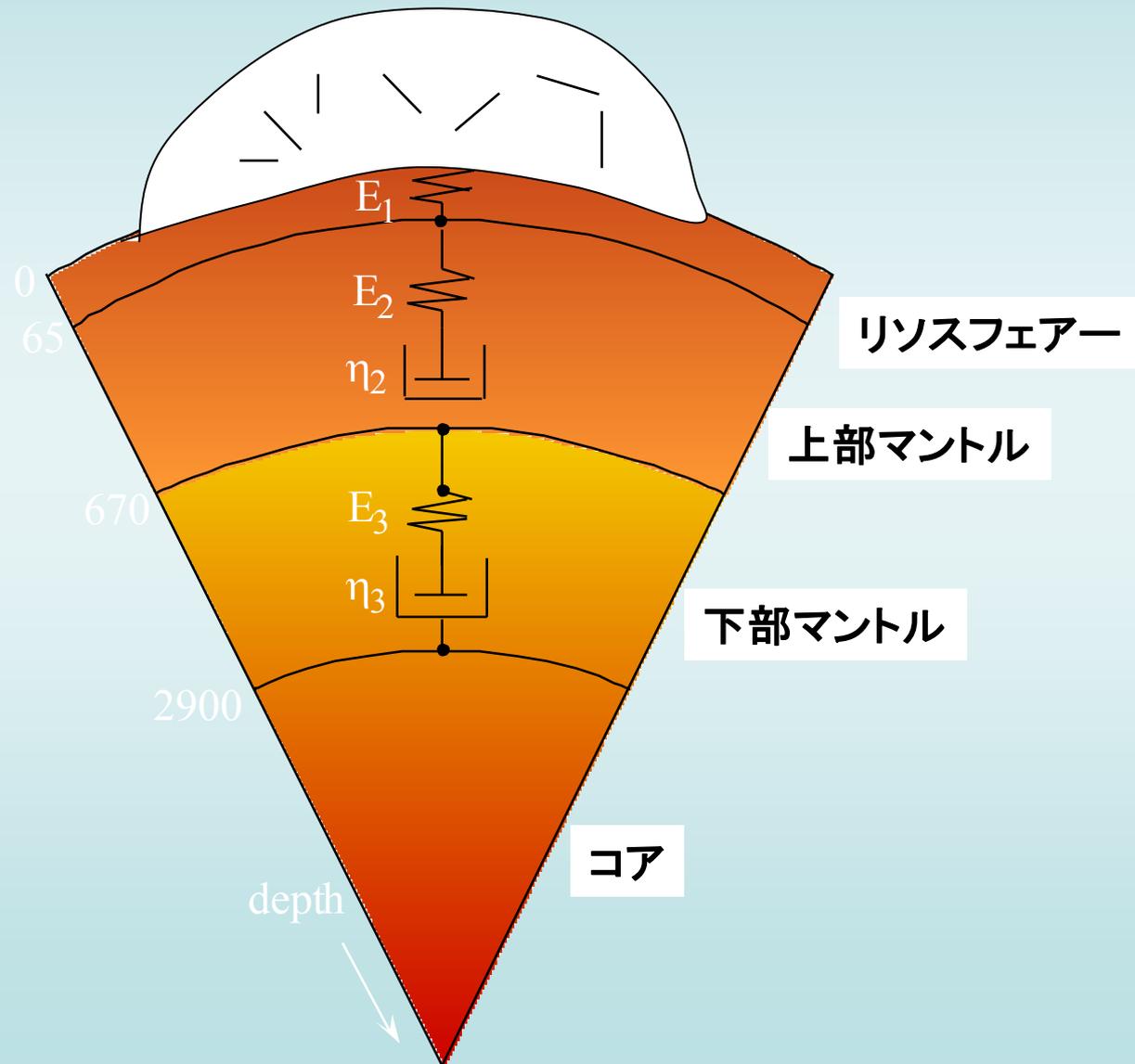
# 氷床変動

# Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet

Chen, Wilson, Tapley, Science, 313, 2006

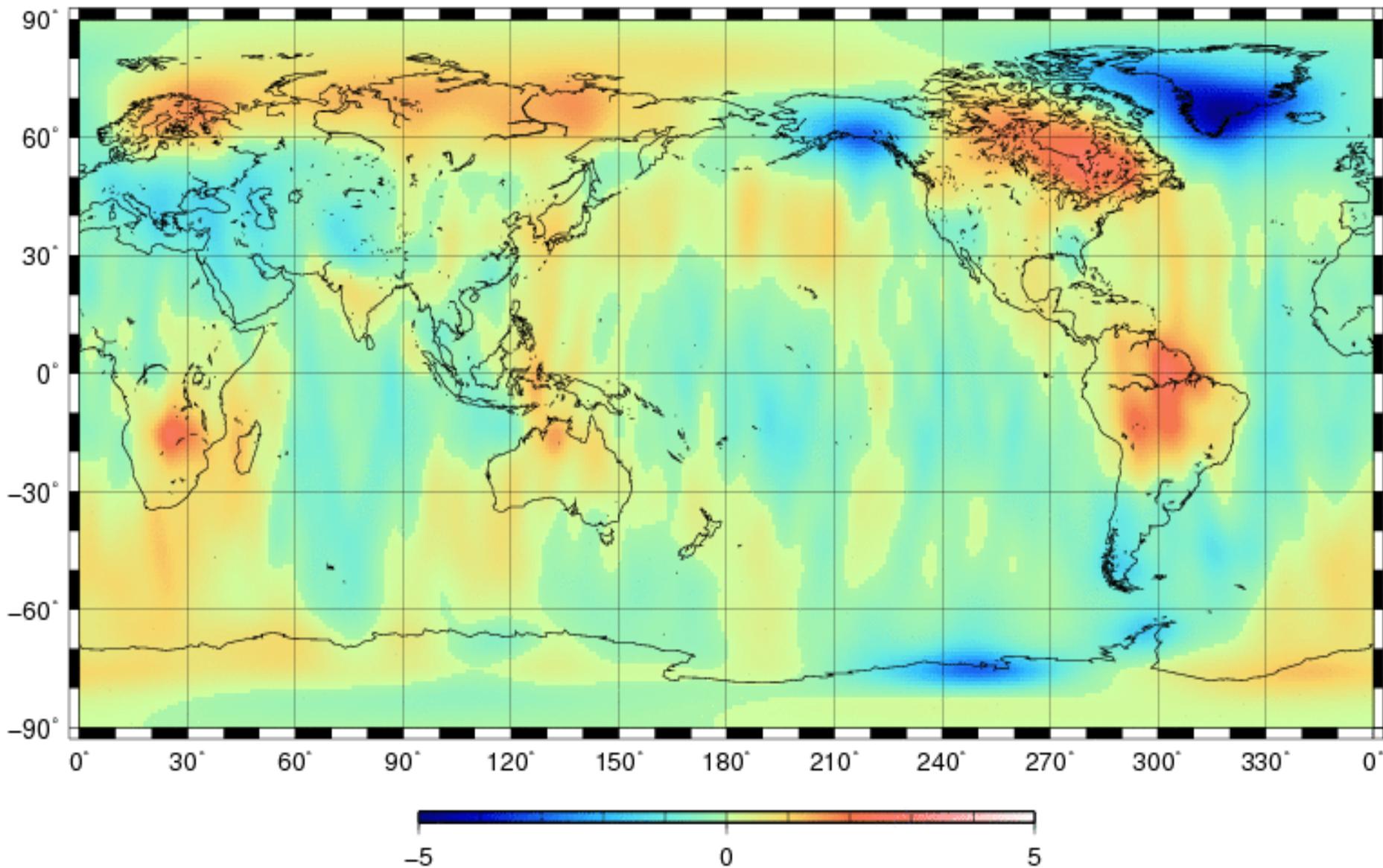


# 氷床変動とPGR (GIA)



# GRACEによるジオイドの経年変化

Geoid Trend (mm/year)



# 南極氷床の質量変動



- グローバルな水循環・水収支
- 環境モニタリング

- 観測データが少ない
- 正確なモデルがない
- シグナルが小さい

# 氷床変動の研究手法

## (1) 質量収支法

(Total net input from snow accumulation)

- (losses by melting and ice discharge)

- ice-core measurements
- ice thickness + velocity (by GPS, InSAR)

## (2) 氷床表面の高度変化の測定

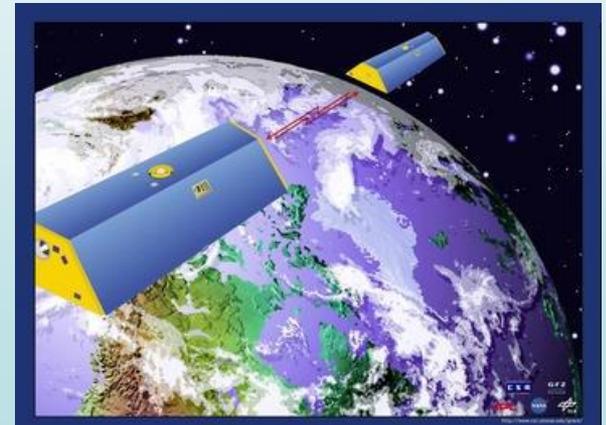
- air-borne altimetry
- satellite altimetry (ERS1 & 2, ICESat, ...)

## (3) 質量変化の測定

- GRACE (2002 - )

約1ヶ月ごとに地球重力場の解を提供

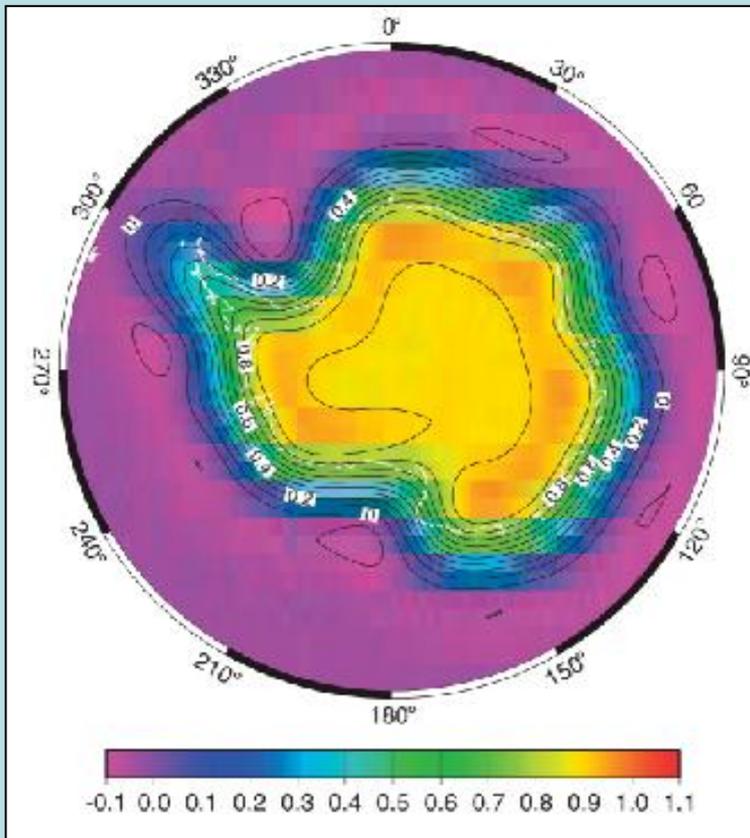
→ 質量分布の時間変化



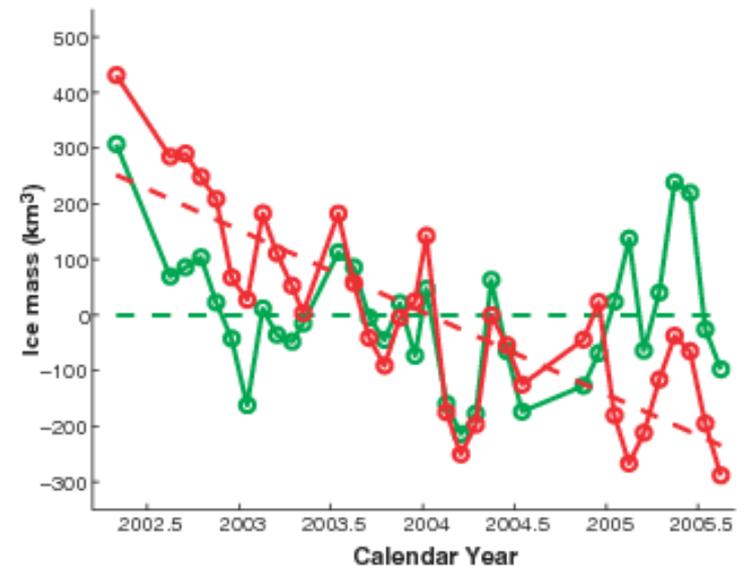
# GRACEを使った南極氷床変動の研究

Velicogna and Wahr (Science, 311, 2006)

(34 months data from April 2002 to August 2005)



**Fig. 3.** Monthly ice mass changes and their best-fitting linear trends for WAIS (red) and EAIS (green) for April 2002 to August 2005. The GRACE data have been corrected for hydrology leakage and for PGR.



# 南極氷床変動の特徴

Filchner-Ronne

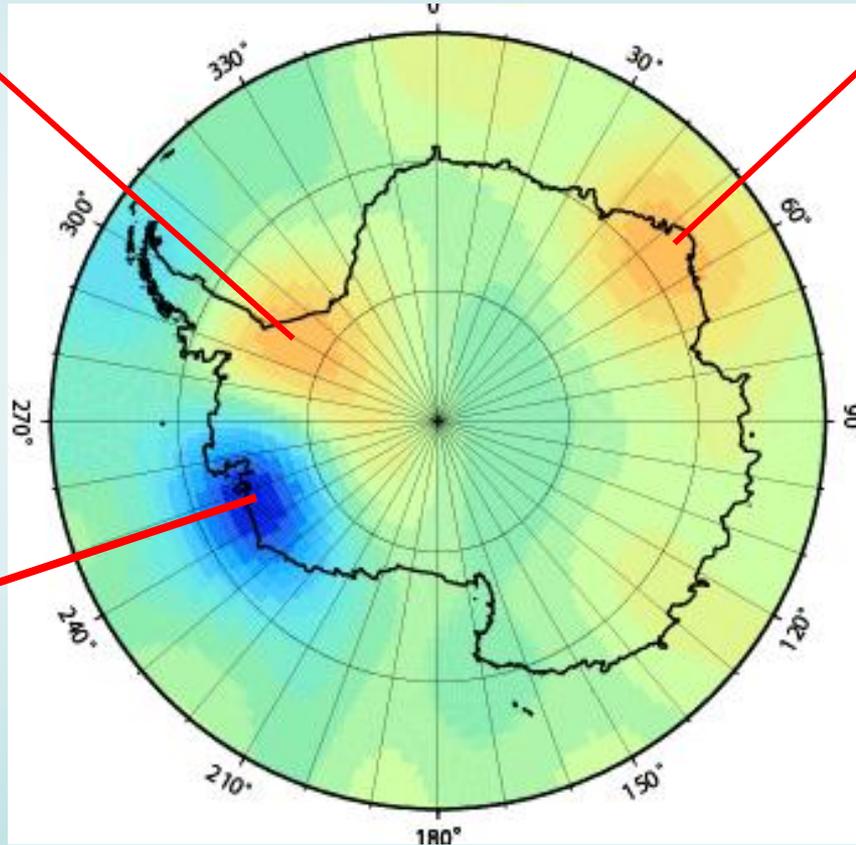
降雪, PGR

Pine

融解

白瀬氷河

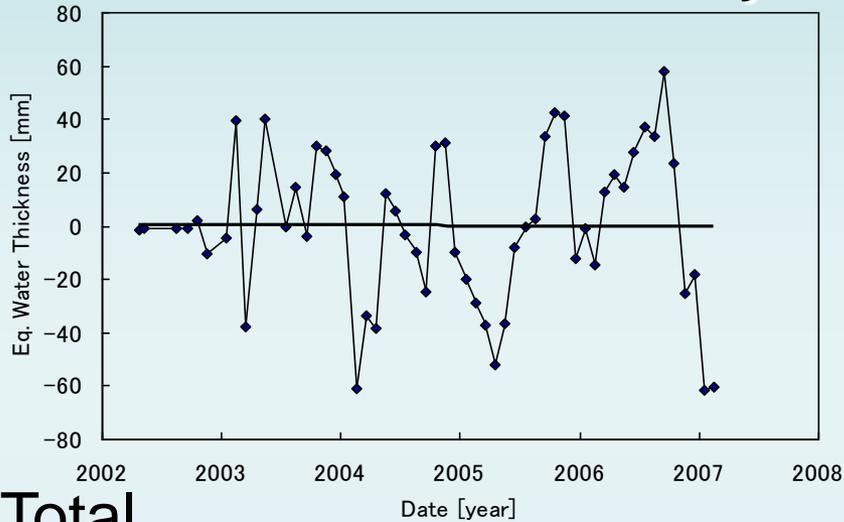
PGR ?  
Error ?  
降雪



# 大陸スケールでの質量変動

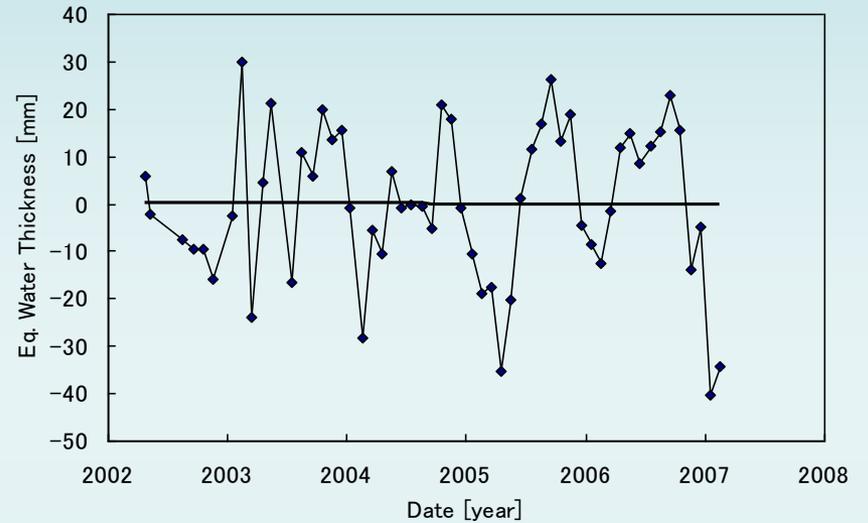
WAIS

-0.2mm/y



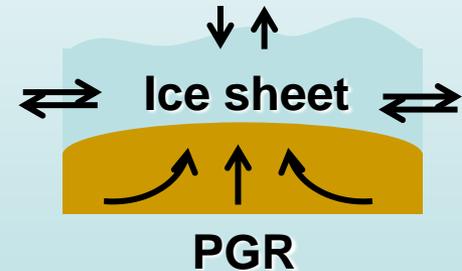
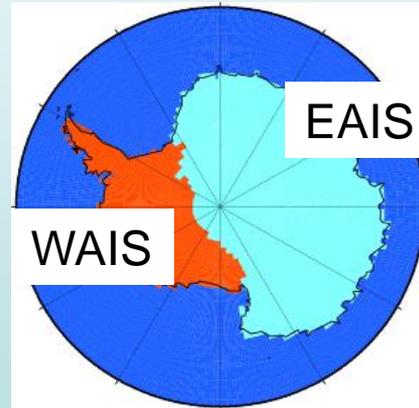
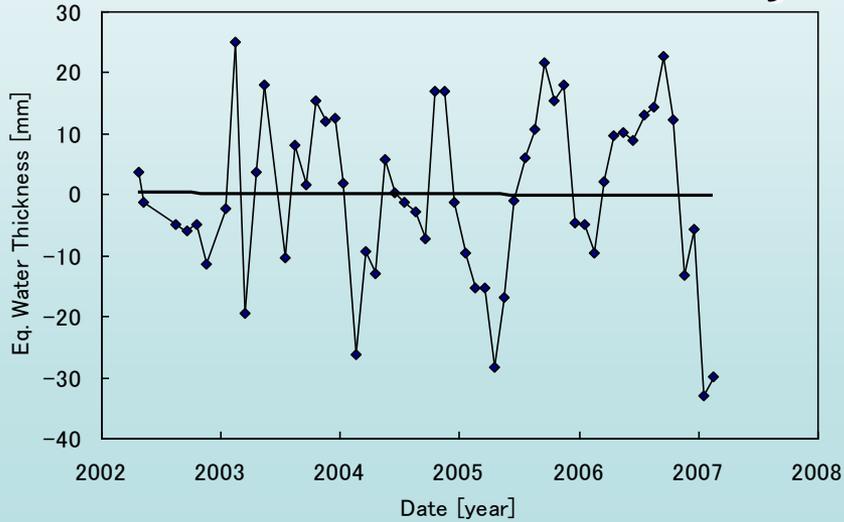
EAIS

-0.1mm/y



Total

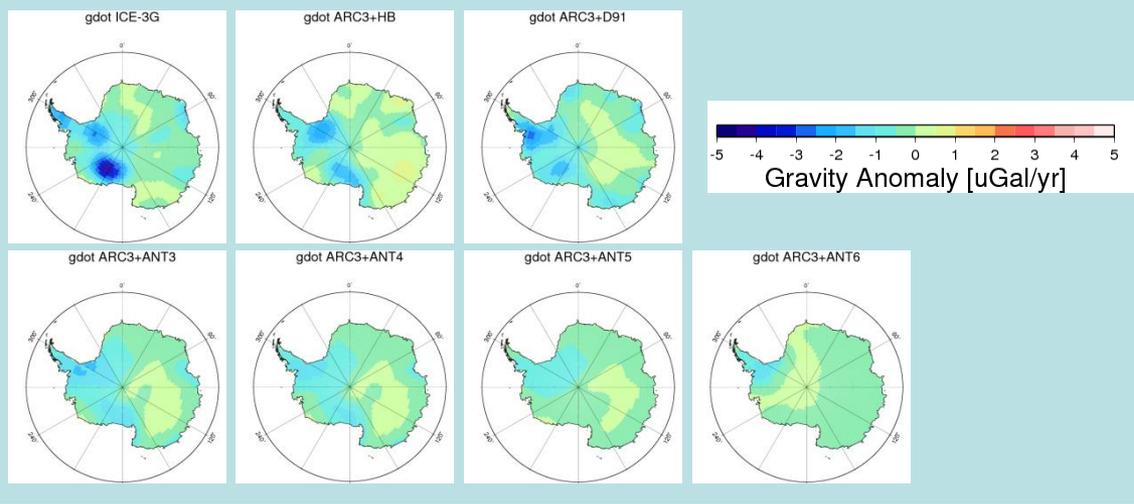
-0.1mm/y



UTCSR RL04

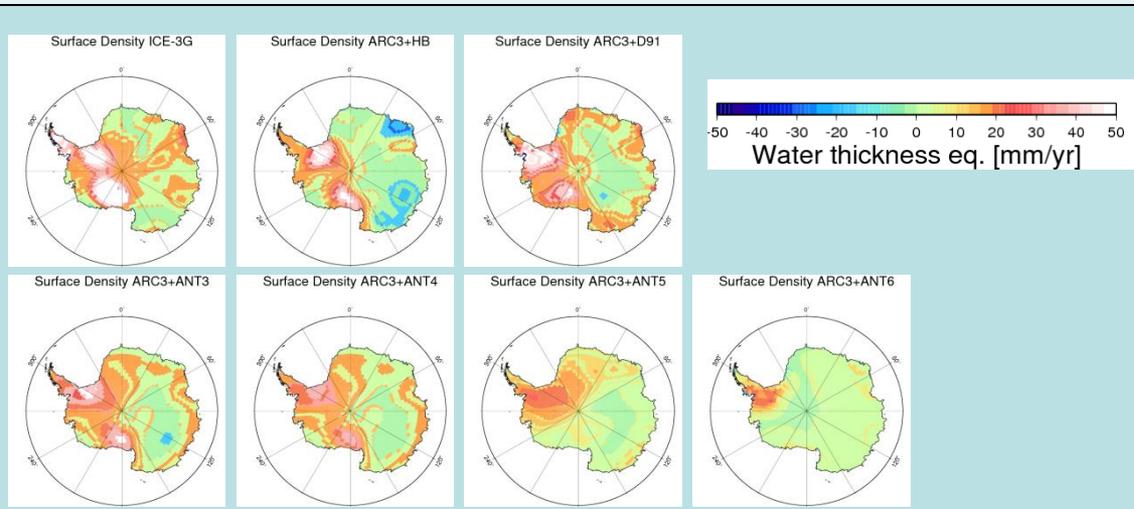
[mm/yr] (water thickness eq.)

# PGR Models

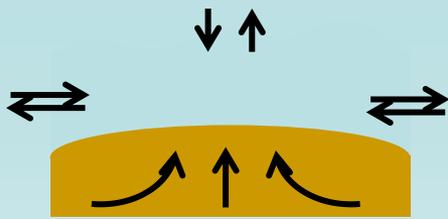


PGR Model	WAIS	EAIS	Total
ICE-3G	34.1	9.1	15.7
ARC3+HB	20.2	0.3	5.5
ARC3+D91	25.6	6.9	11.9
ARC3+ANT3	21.6	7.1	10.9
ARC3+ANT4	18.1	6.3	9.4
ARC3+ANT5	10.5	5.3	6.6
ARC3+ANT6	5.4	1.7	2.7

Nakada et al. (2000) Water thickness eq.



[mm/yr] (water thickness eq.)



## GRACE



## Post Glacial Rebound

— )



## Ice Mass Changes

	WAIS	EAIS	Total
UTCSR	-0.2	-0.1	-0.1
GFZ	10.1	9.5	7.1
JPL	1.4	-1.7	-0.7

PGR Model	WAIS	EAIS	Total
ICE-3G	34.1	9.1	15.7
ARC3+HB	20.2	0.3	5.5
ARC3+D91	25.6	6.9	11.9
ARC3+ANT3	21.6	7.1	10.9
ARC3+ANT4	18.1	6.3	9.4
ARC3+ANT5	10.5	5.3	6.6
ARC3+ANT6	5.4	1.7	2.7

	WAIS	EAIS	Total
UTCSR	-34.3 ~ -5.6	-9.2 ~ -1.8	-15.8 ~ -2.8
GFZ	-24 ~ +4.7	+0.5 ~ +7.8	-8.6 ~ +4.4
JPL	-32.7 ~ -4.0	-10.7 ~ -3.3	-16.3 ~ -3.4

[mm/yr] (water thickness eq.)

GIA (Glacial Isostatic Adjustment)

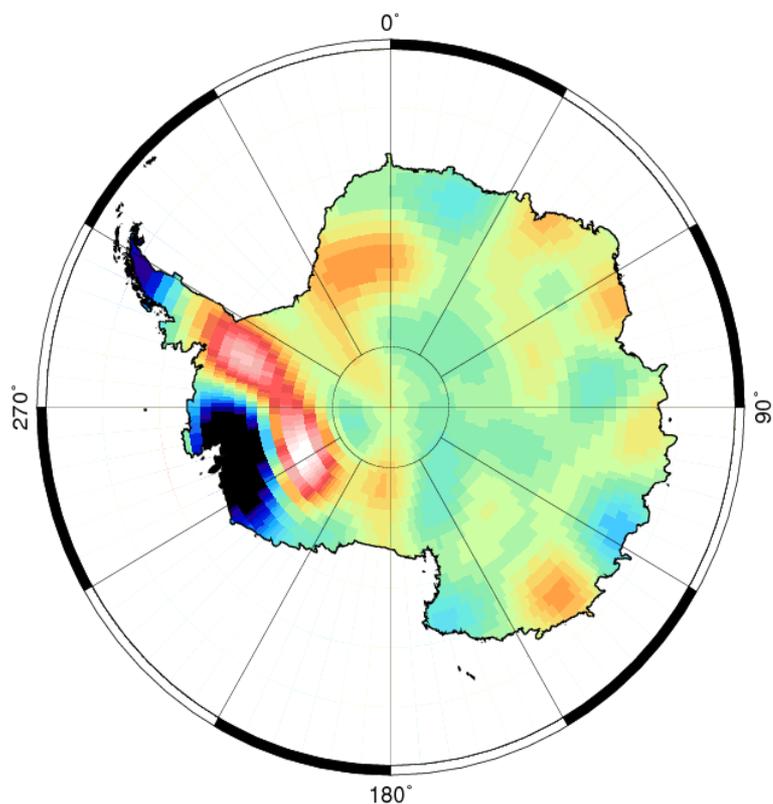
≡ PGR

トレンドの見積もり

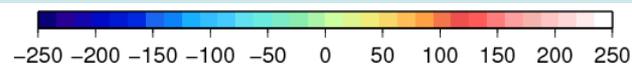
# GRACEデータから得られた 質量の経年変化のトレンド



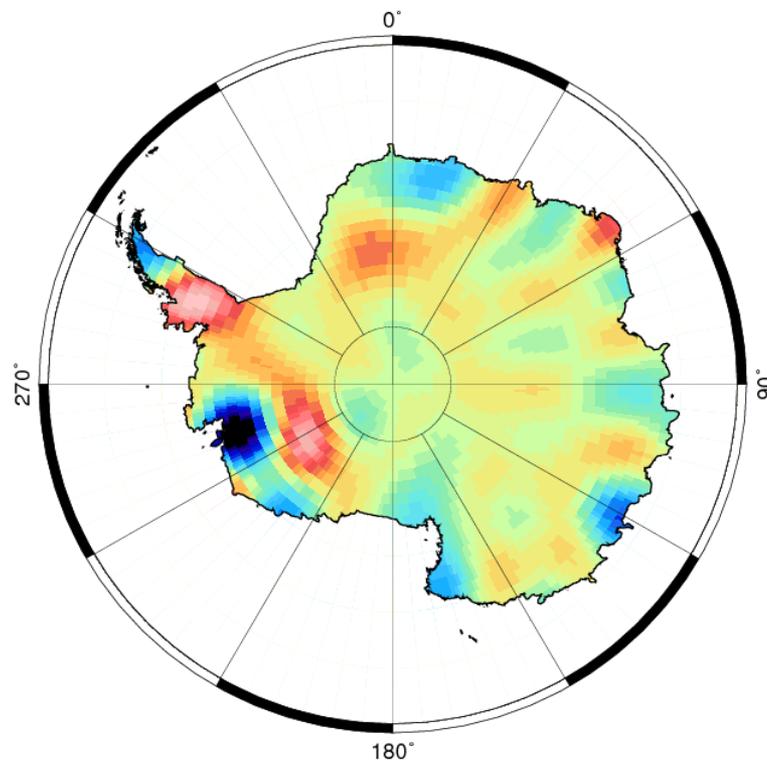
Mass change in water thickness equivalence [mm/yr]



# ICESatデータから得られた 高度の経年変化のトレンド



Elevation change [mm/yr]



# GIAトレンドの算出

GRACEのトレンド(質量変化); GIA、氷床  
ICESatのトレンド(高度変化); 氷床のみ検出と仮定

GRACE

-

ICESat × 氷床密度

=

GIAの質量変化

GIA質量変化  
+  
氷床質量変化

氷床質量変化

空間分布が未知

典型的な密度を使ってGIATレンドを作成してみると、

新雪

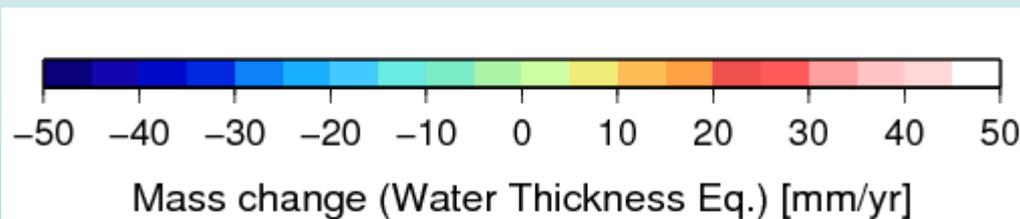
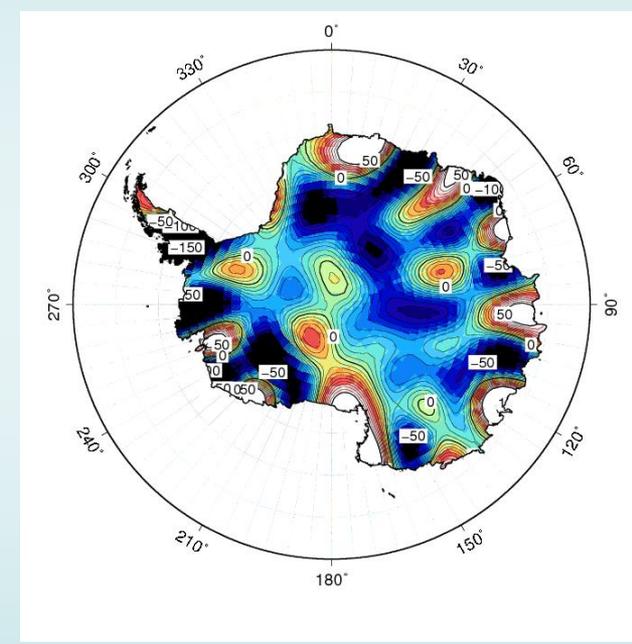
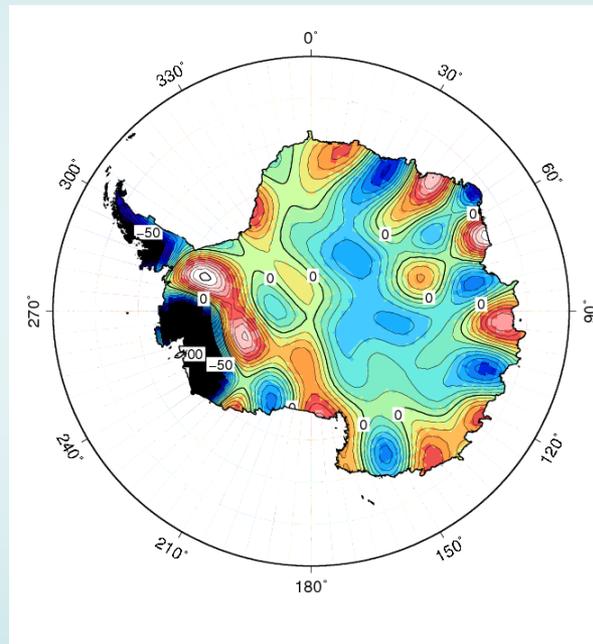
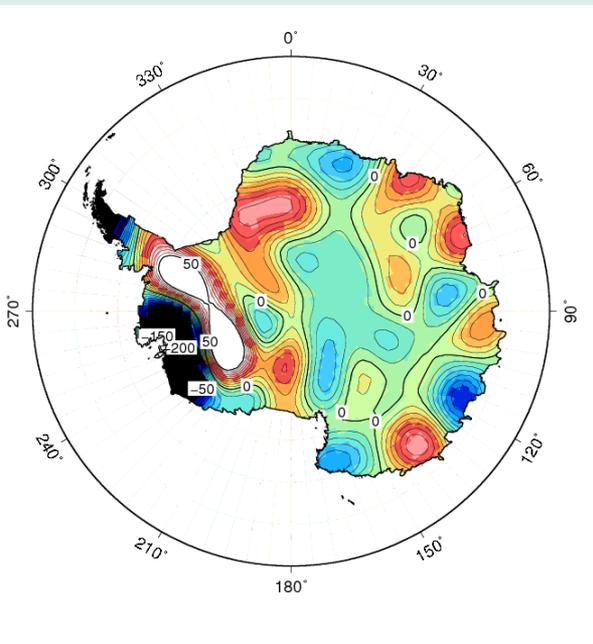
20 kg/m<sup>3</sup>

フィルン

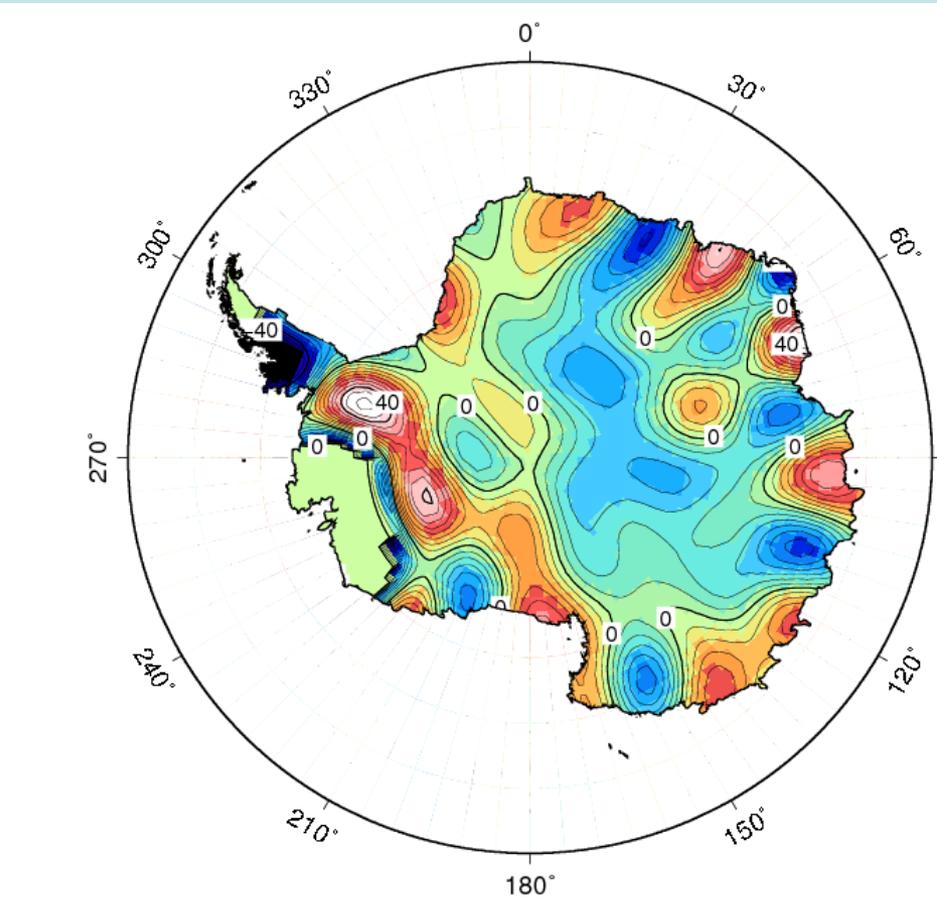
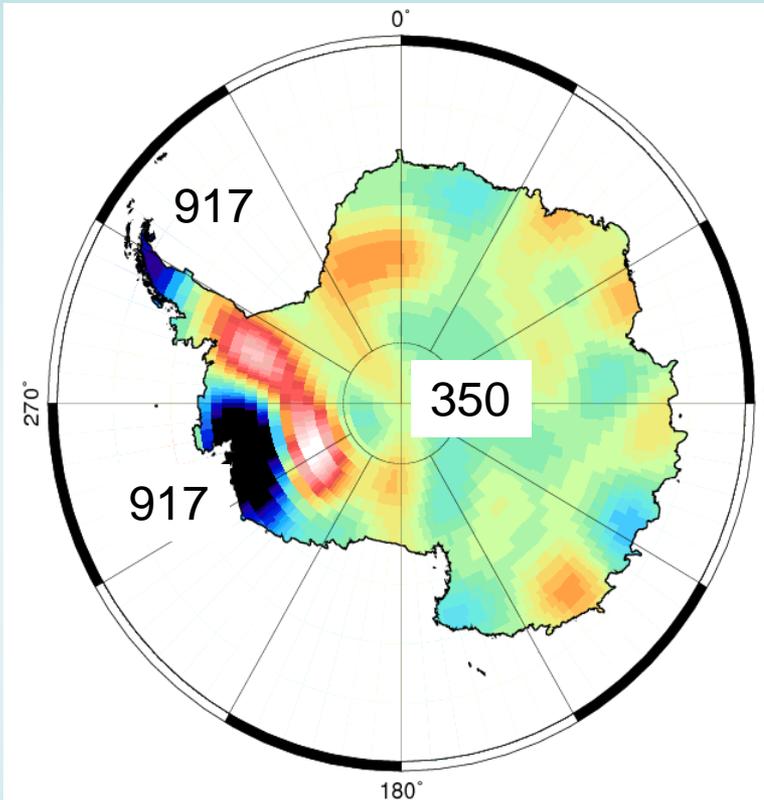
350 kg/m<sup>3</sup>

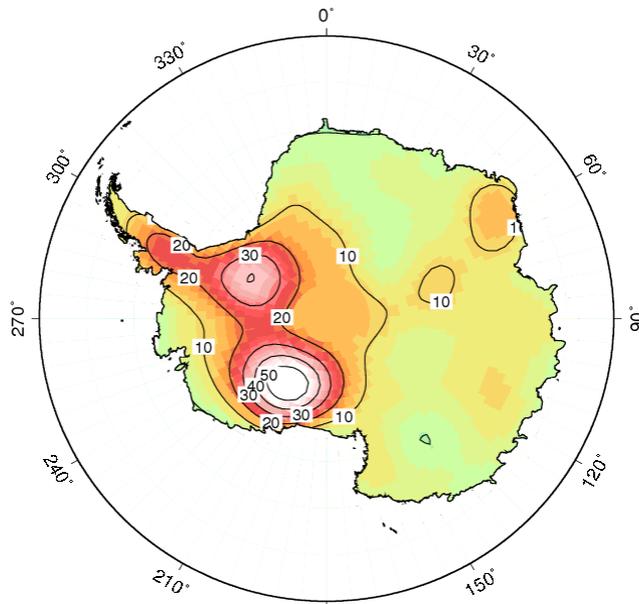
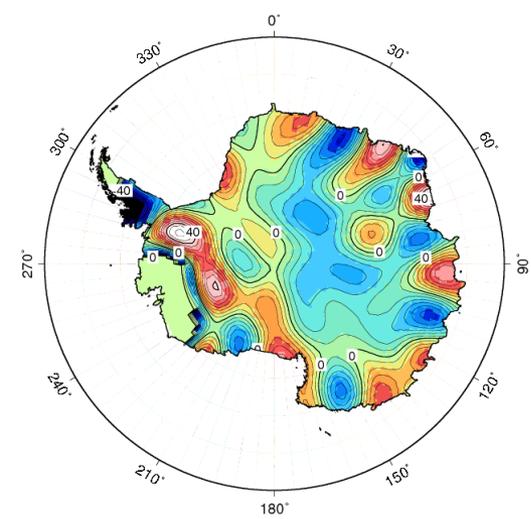
氷床の最大密度

917 kg/m<sup>3</sup>

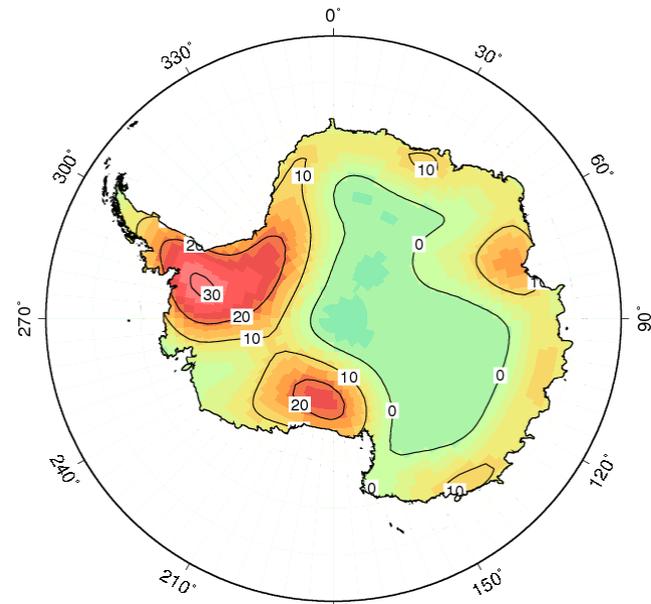


# PIGと南極半島で最大氷床密度、残りはフィルンとしてみると

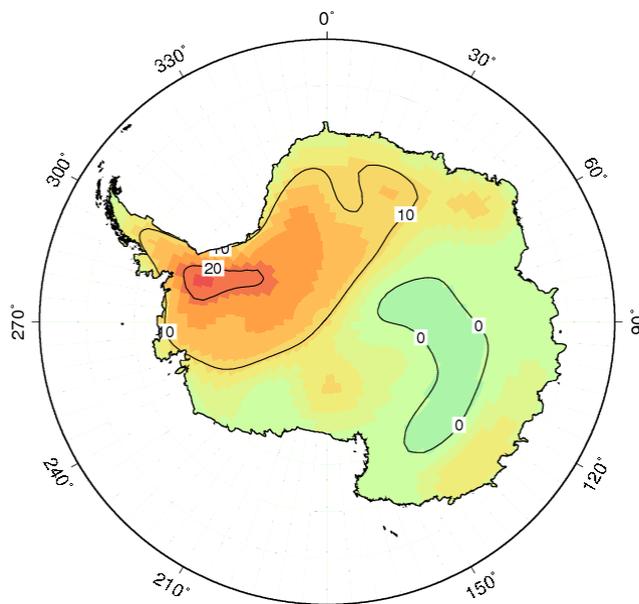




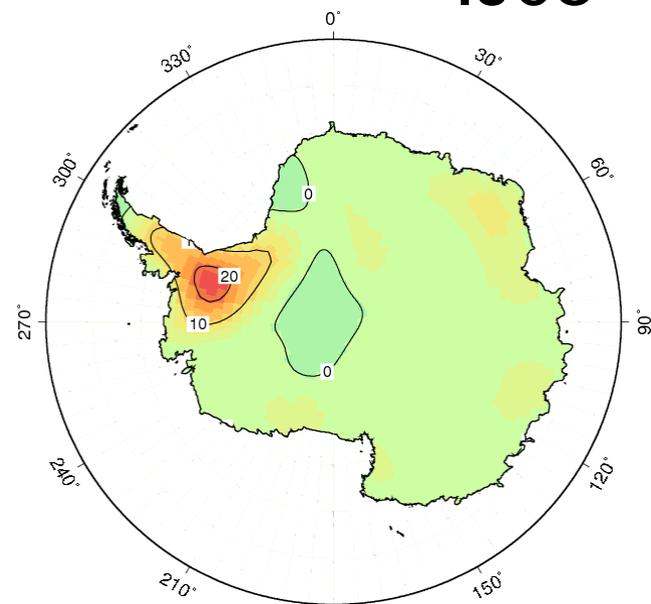
**ICE-5G**



**IJ05**



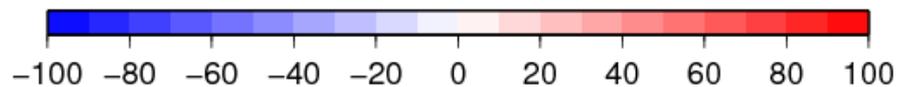
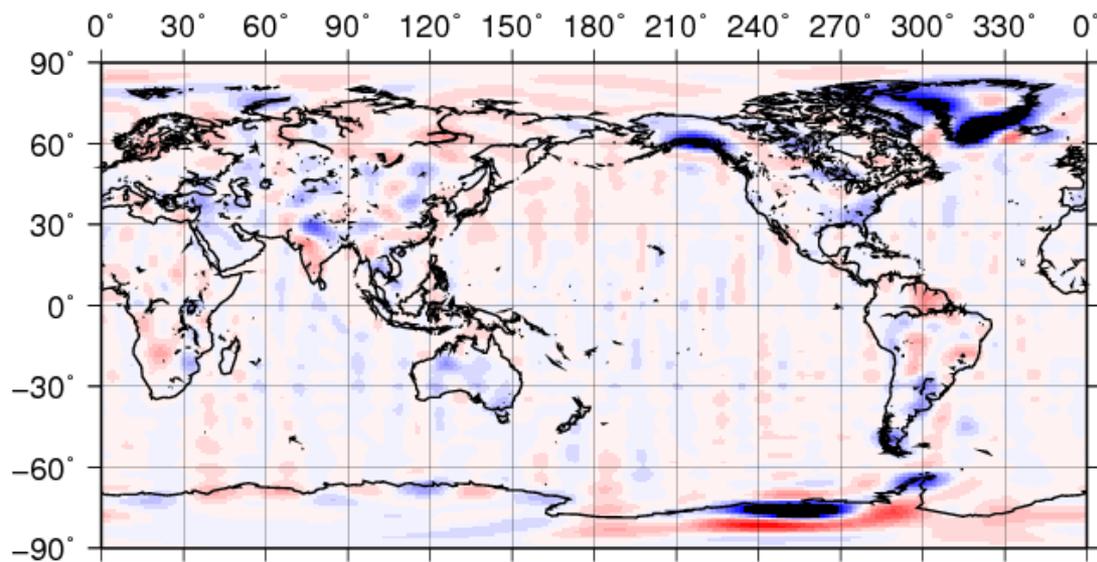
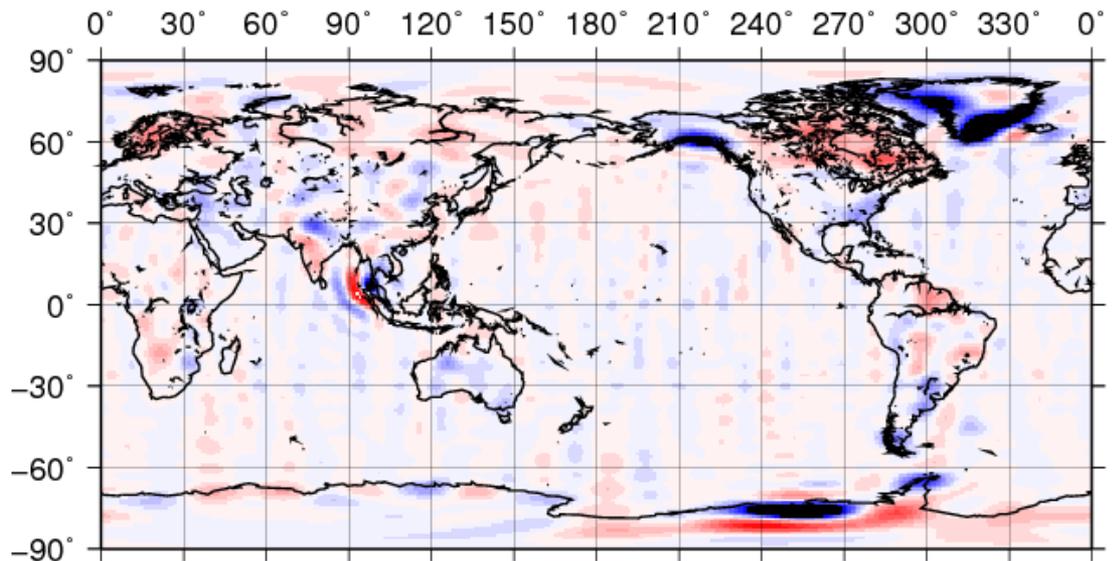
**ARC3+ANT5**



**ARC3+ANT6**

# GRACEによる 質量変化トレンド

スマトラ地震、  
南極以外のGIA  
(ICE-5G)を除去



Mass variation in water thickness equivalence [mm]

# 水質量バランスとGIAトレンド

海洋変動: 391 Gt/yr

(海水準変動との関連)

南極以外の陸水変動: -207 Gt/yr

南極の氷床変動: -185 Gt/yr

南極のGIA+氷床変動: -34 Gt

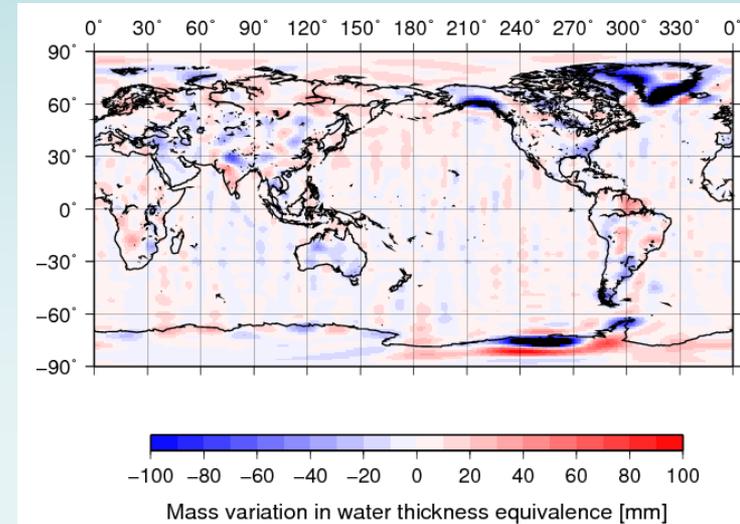
予想される南極のGIAトレンド:  $-34 - (-185) = 151$  Gt

ICE5G: 162 Gt

IJ06: 4 Gt

ARC3+ANT5: 99 Gt

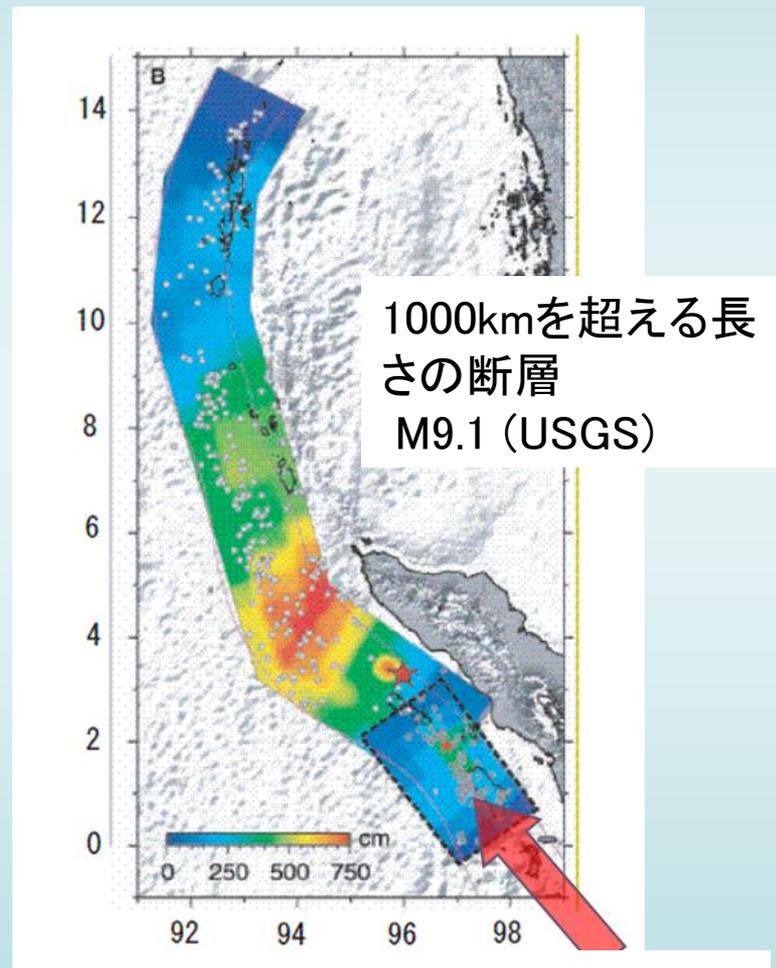
ARC3+ANT6: 40 Gt



# 地 震

# 2004年スマトラ・アンダマン地震

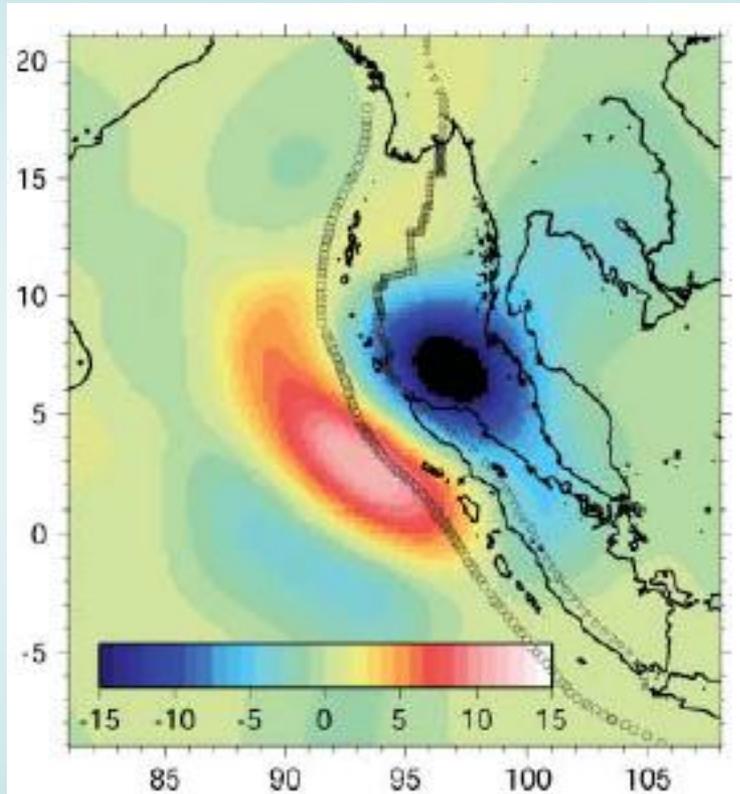
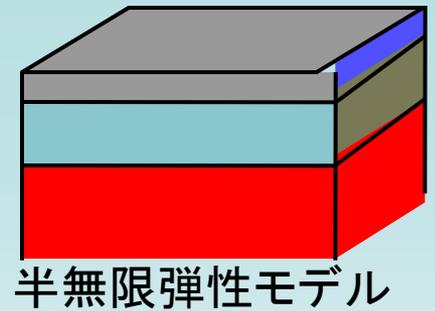
Ammon et al., 2005



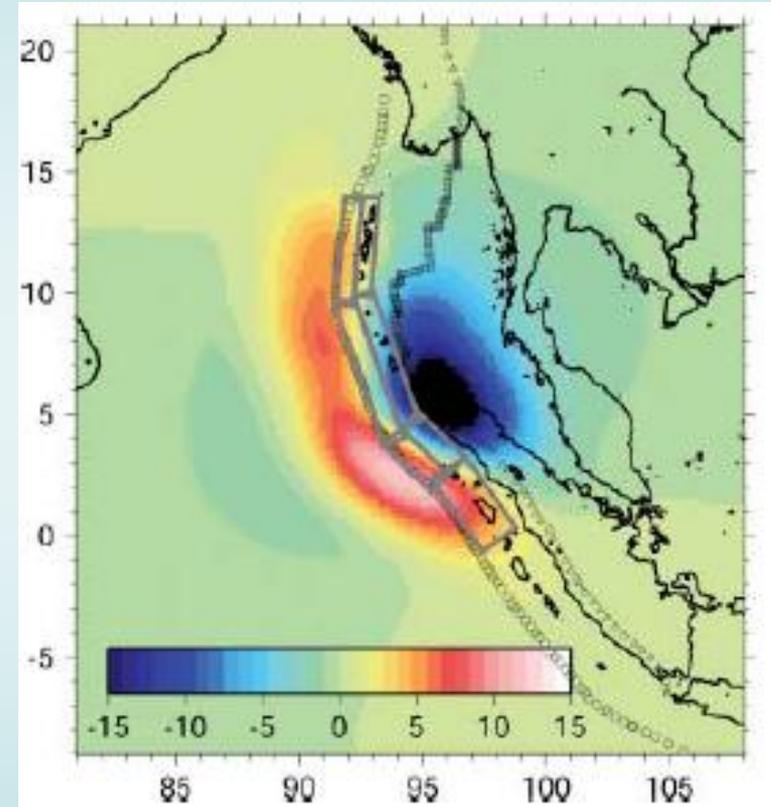
2005年3月  
ニアス地震

# GRACE Level 1データを用いた研究

Crustal Dilatation Observed by GRACE  
After the 2004 Sumatra-Andaman Earthquake  
Chan *et al.* (2006)

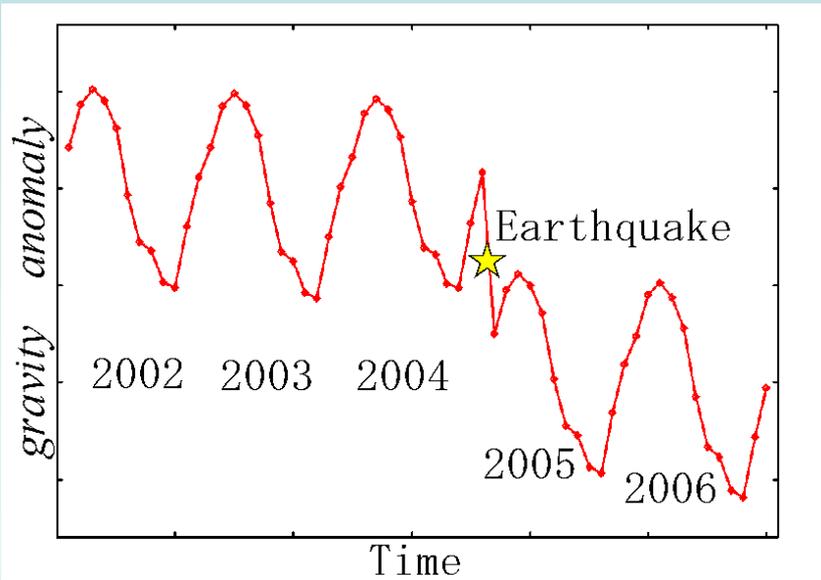


Gravity changes (in  $\mu\text{Gal}$ ) after the Sumatra-Andaman earthquake computed from GRACE Level-1 data.



Predicted coseismic gravity changes (in  $\mu\text{Gal}$ ), inferred by combining vertical displacement and dilatation.

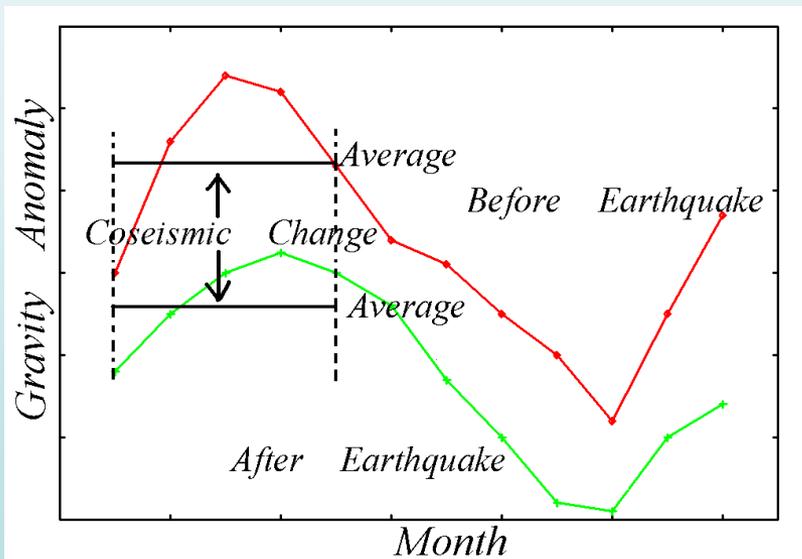
# 検出方法



- 1) 地震による重力変化は、突然起こり、そのまま永久に残る
- 2) 陸水や海洋変動などに伴う重力変化は、季節変動のような周期的なものが主である

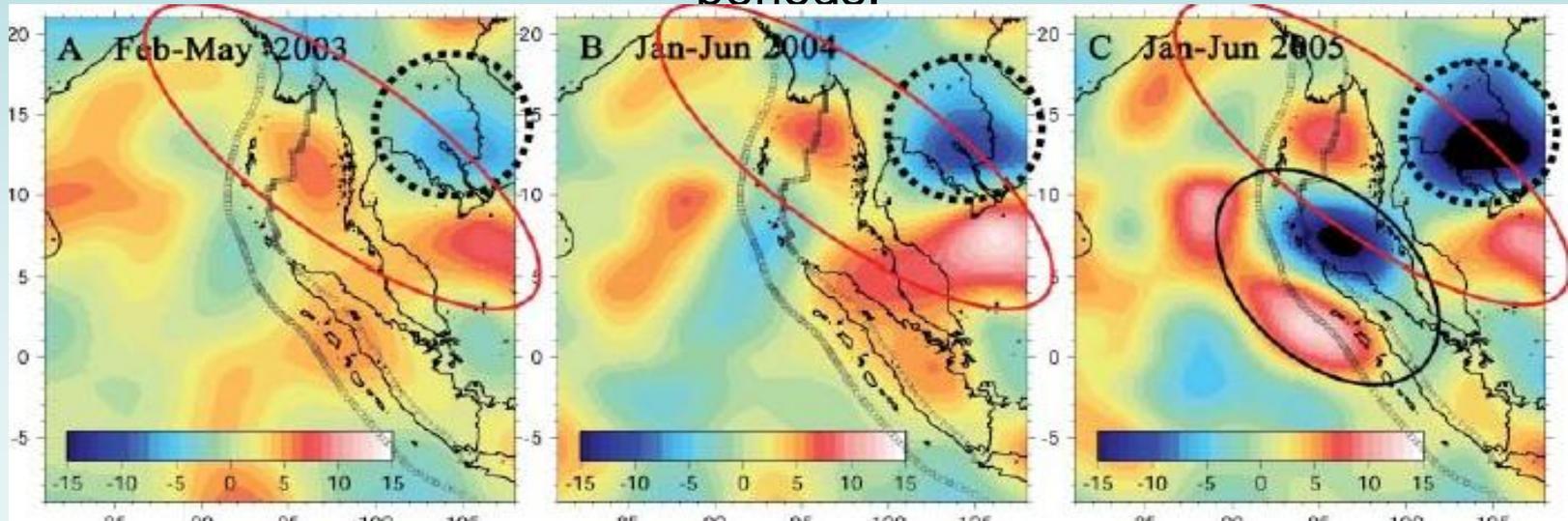


同じ月のデータの差をとったり、地震の前後での長期間の平均の差をとると、2)によるシグナルは消えて、地震の影響だけが残る。

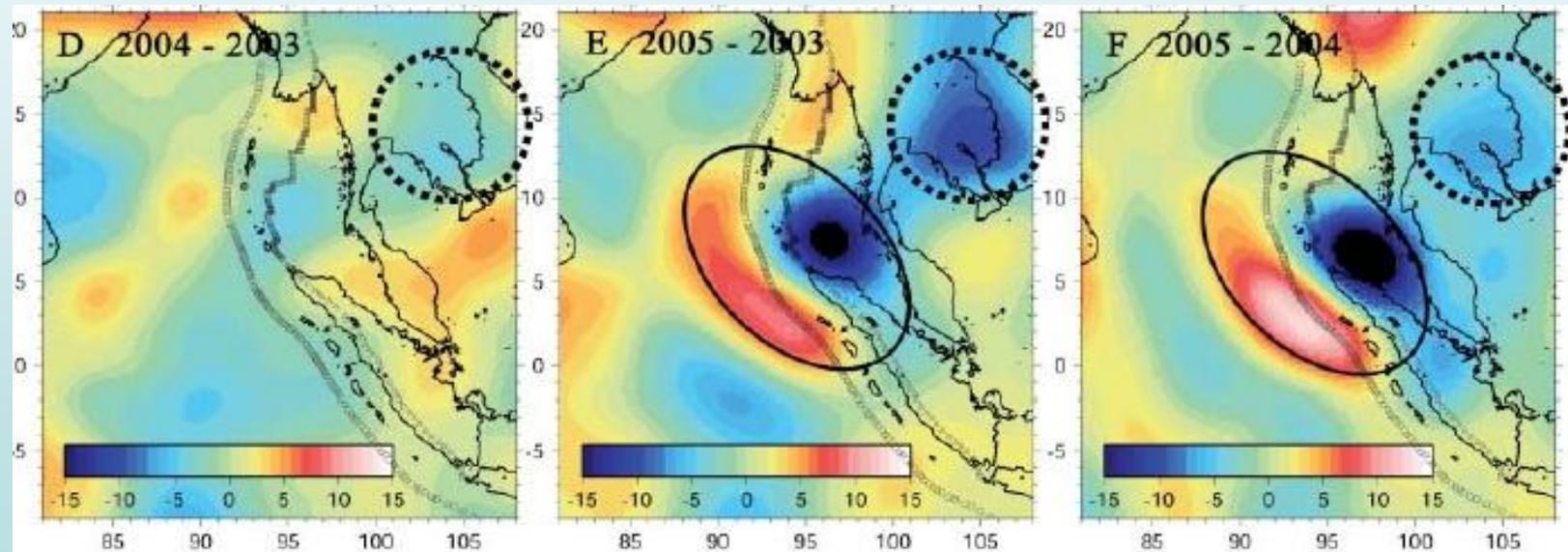


# Chan *et al.* (2006)

Cumulated gravity anomaly with respect to a reference model for the periods.

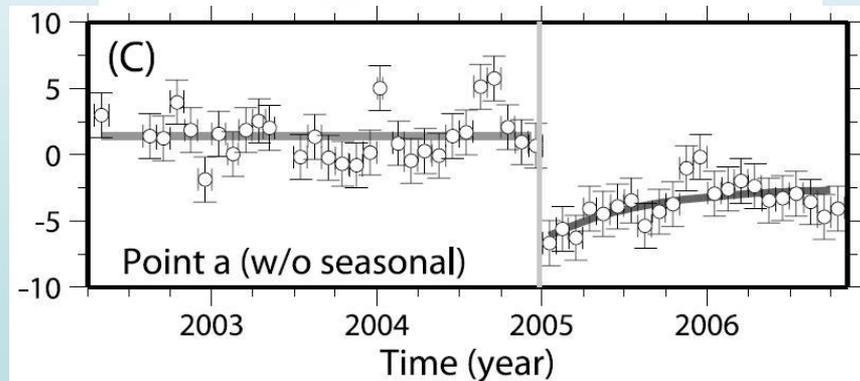
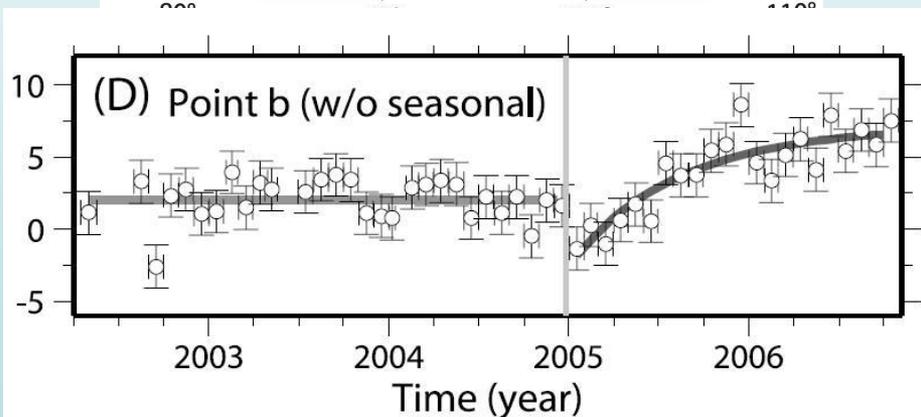
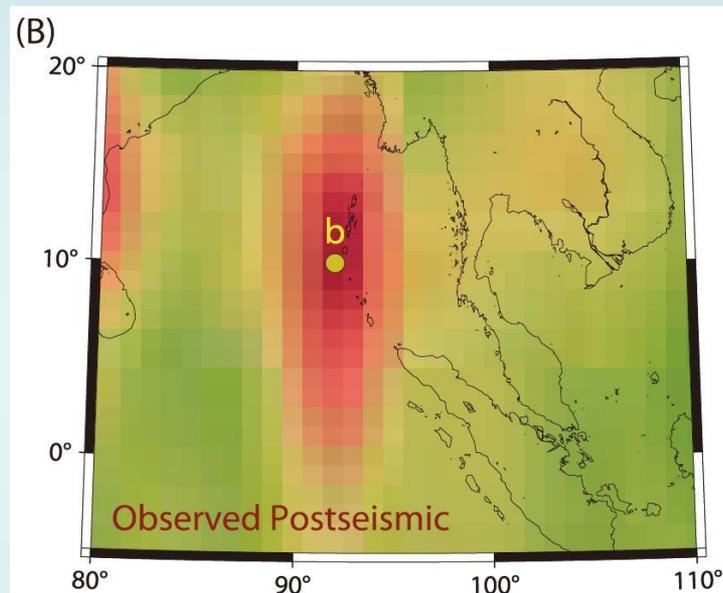
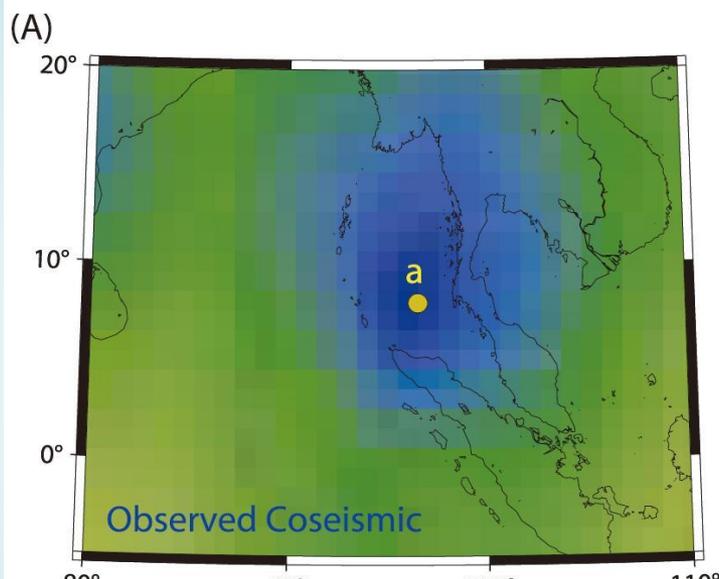


Gravity changes between two year, inferred by differencing (A),(B) and (C).



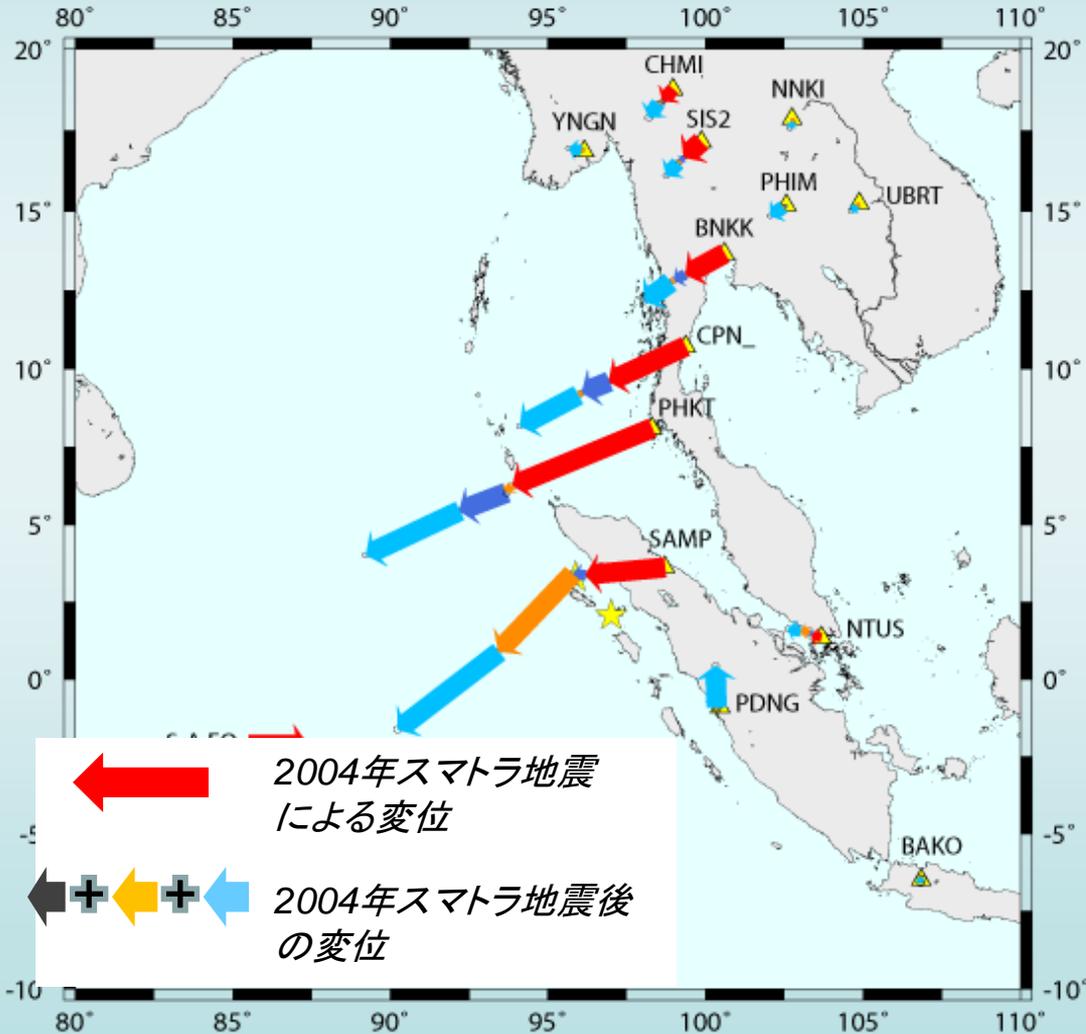
# Postseismicな 重力変化

This cannot be explained with simple afterslip or viscous relaxation of Maxwellian upper mantle. It suggests the relaxation of coseismic dilatation and compression by the diffusion of supercritical H<sub>2</sub>O abundant in the upper mantle. (Ogawa and Heki, GRL, 2007)



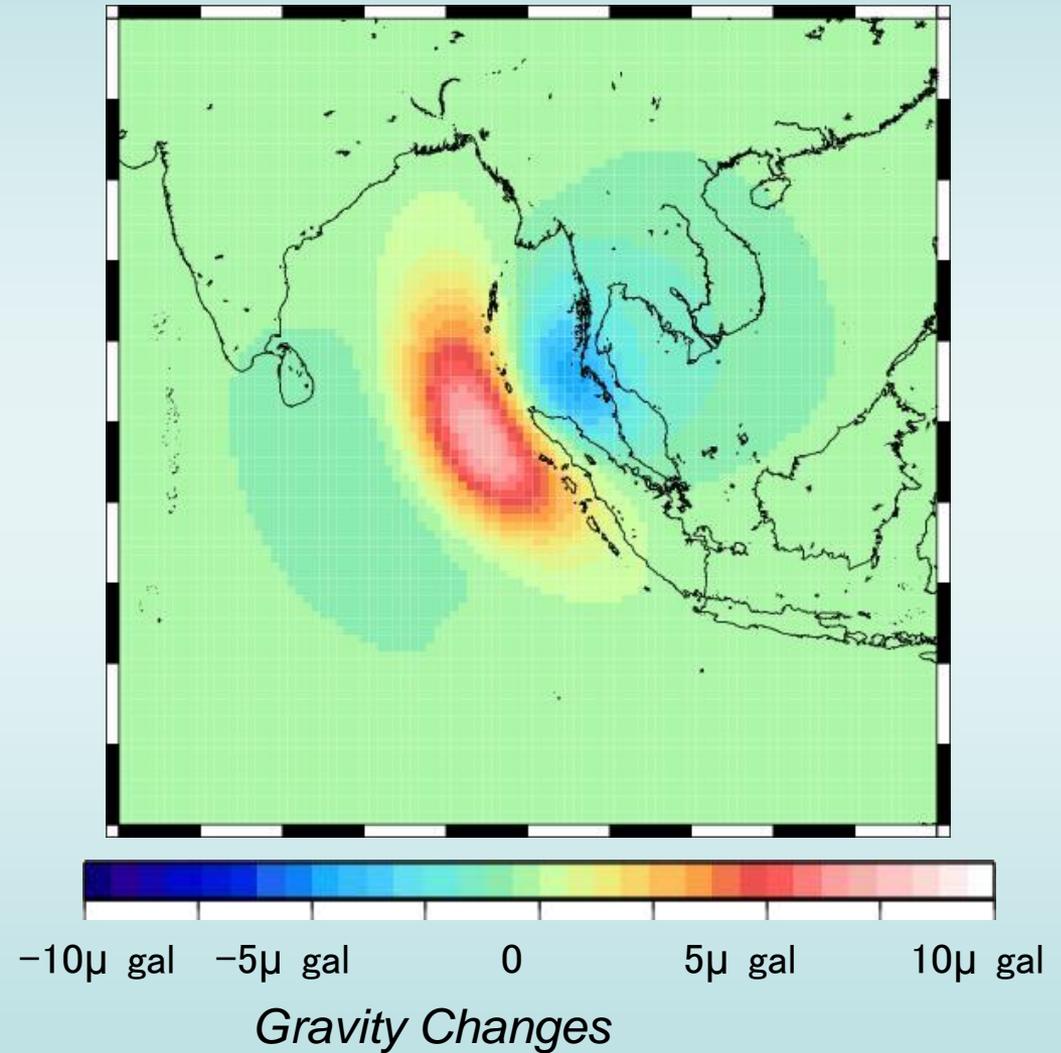
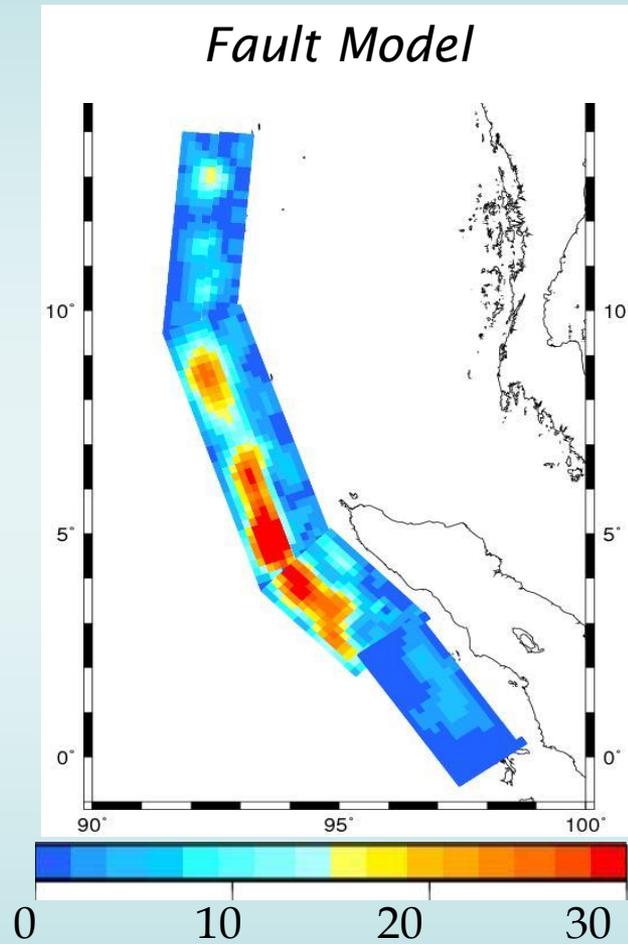
# 余効すべりが重力変化に及ぼす影響

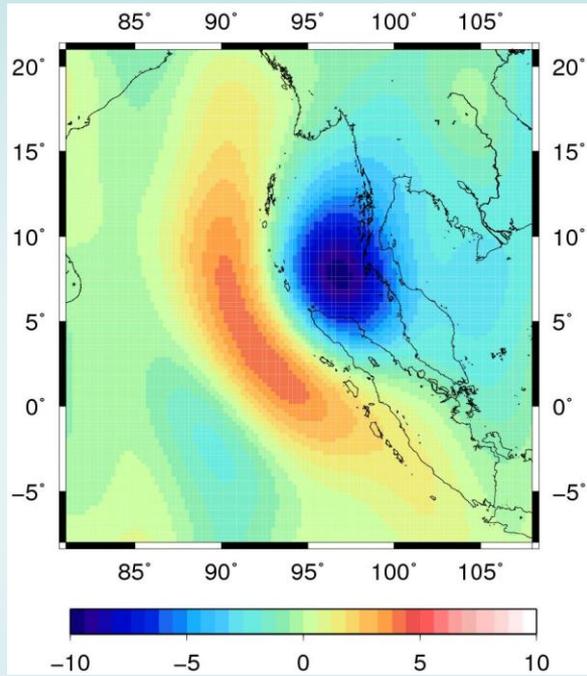
*Cumulative displacements*  
After Sumatra-Andaman EQ



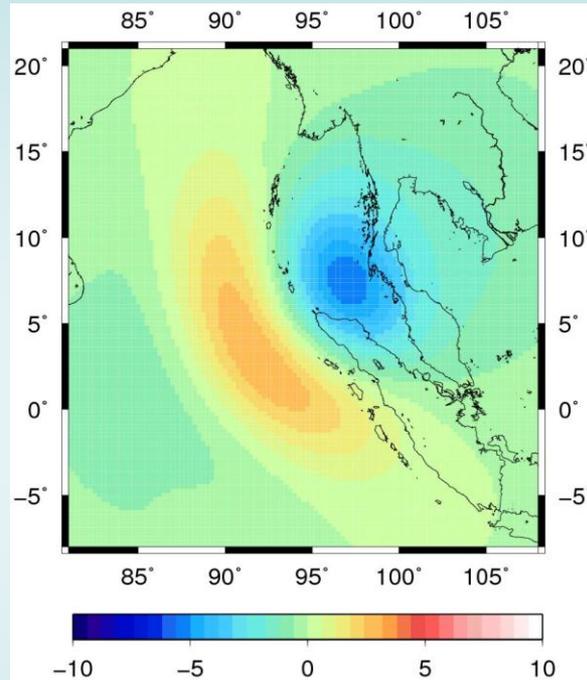
連続GPS観測による2004年スマトラ地震とそれ以降の余効変動,  
*Katagi (2008)*

# 球成層構造モデル(PREM)で計算される重力変化

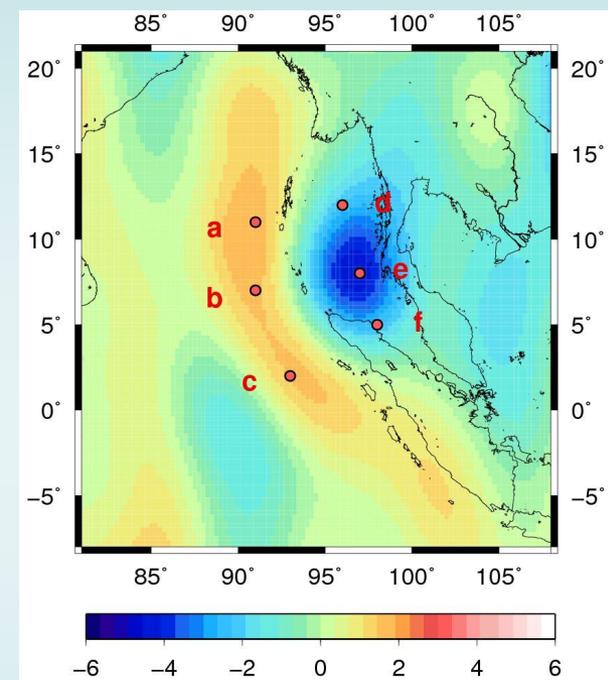




**GRACE  
(Obs)**

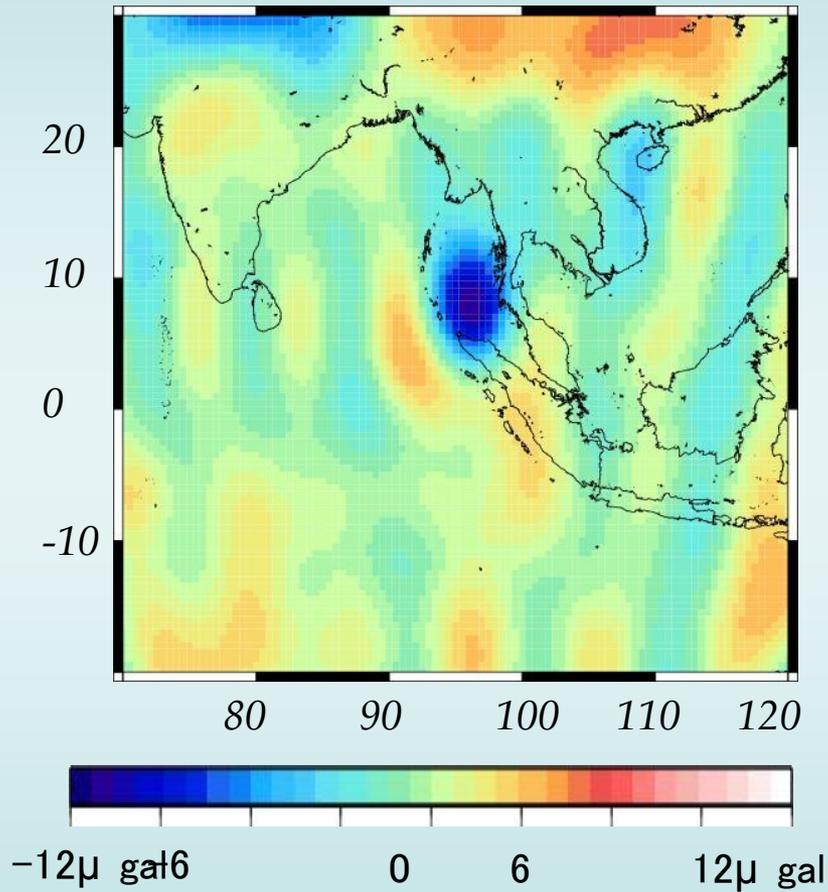


**Coseismic  
(Model)**

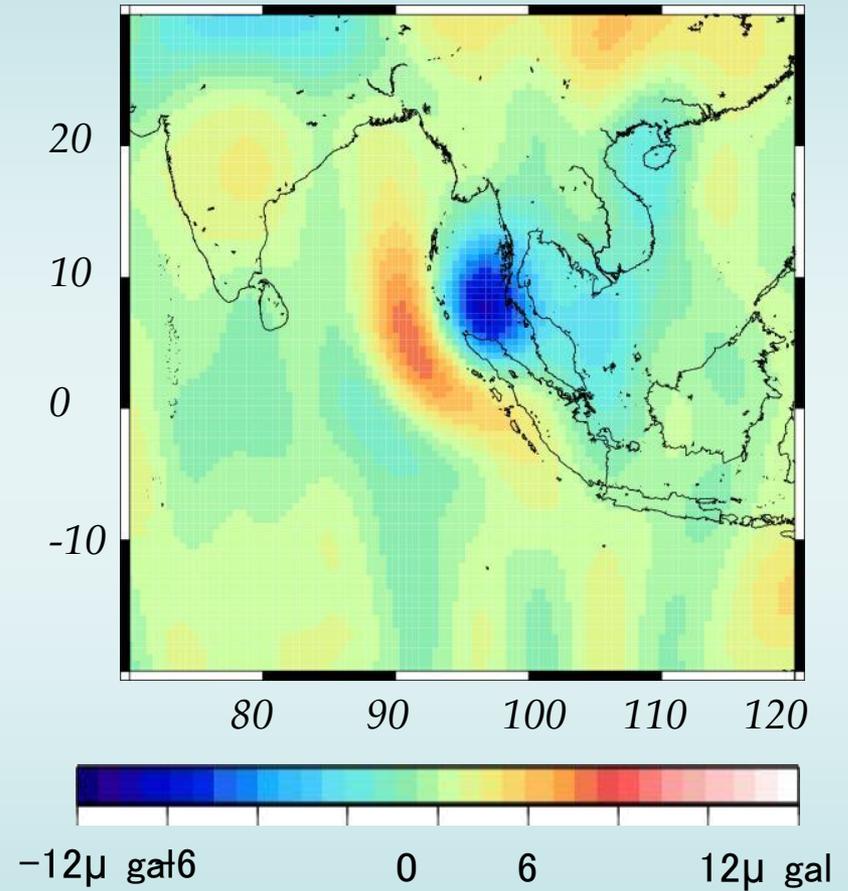


**Postseismic**

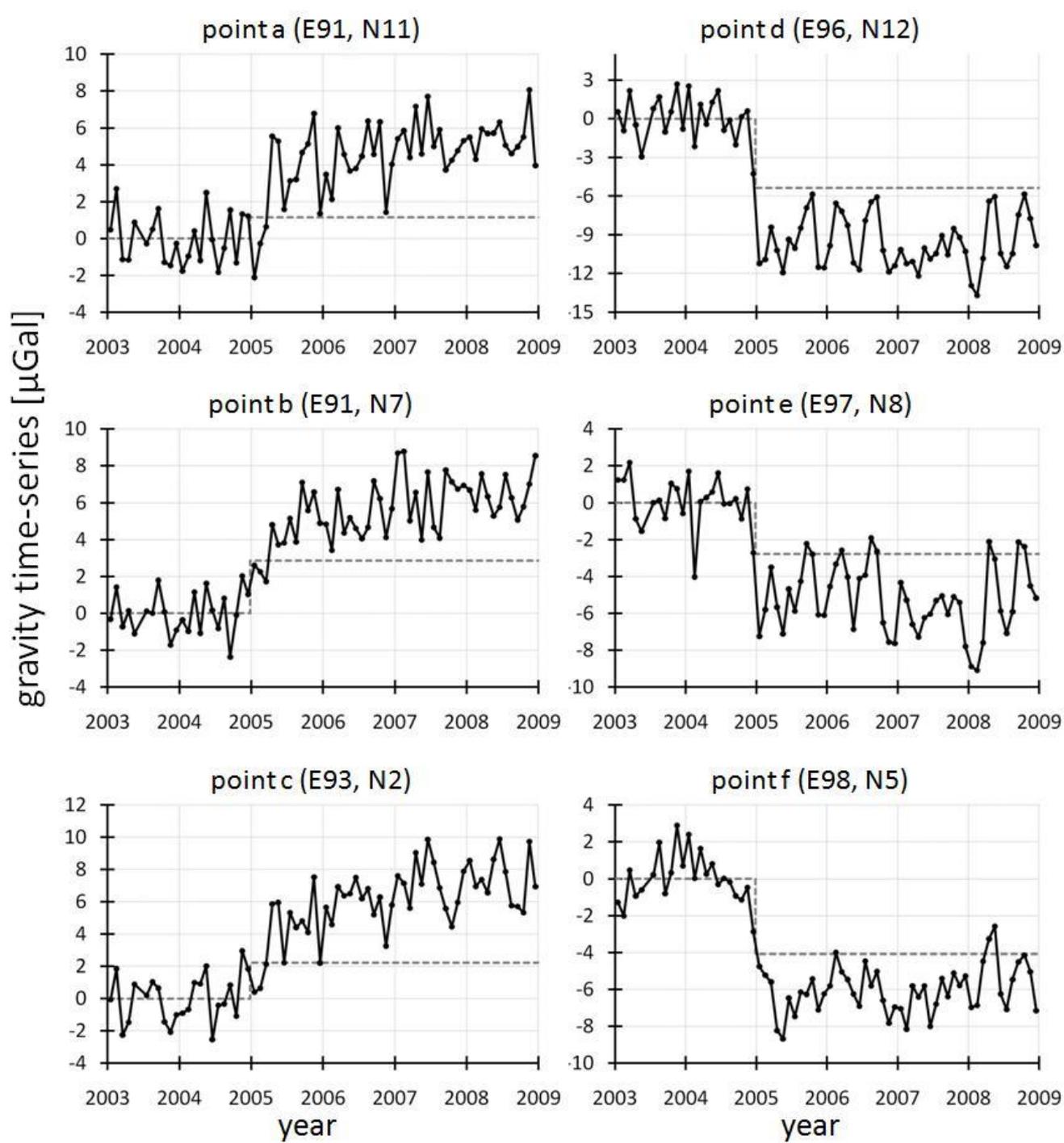
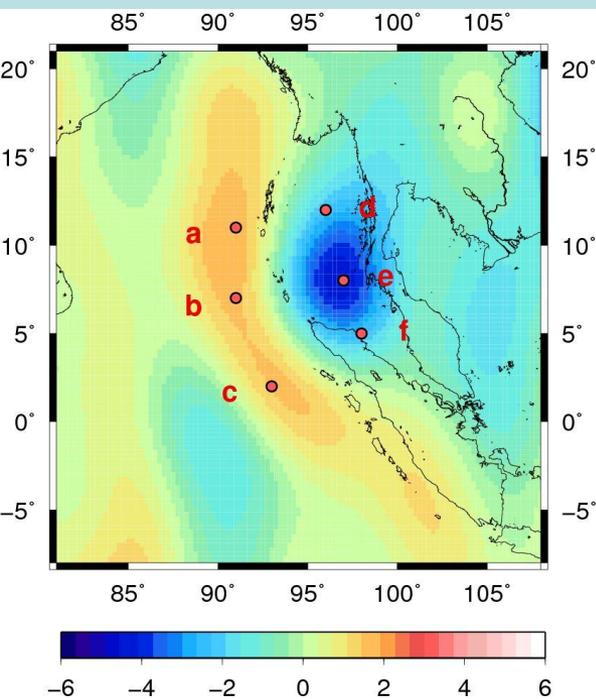
# Postseismicな重力変化

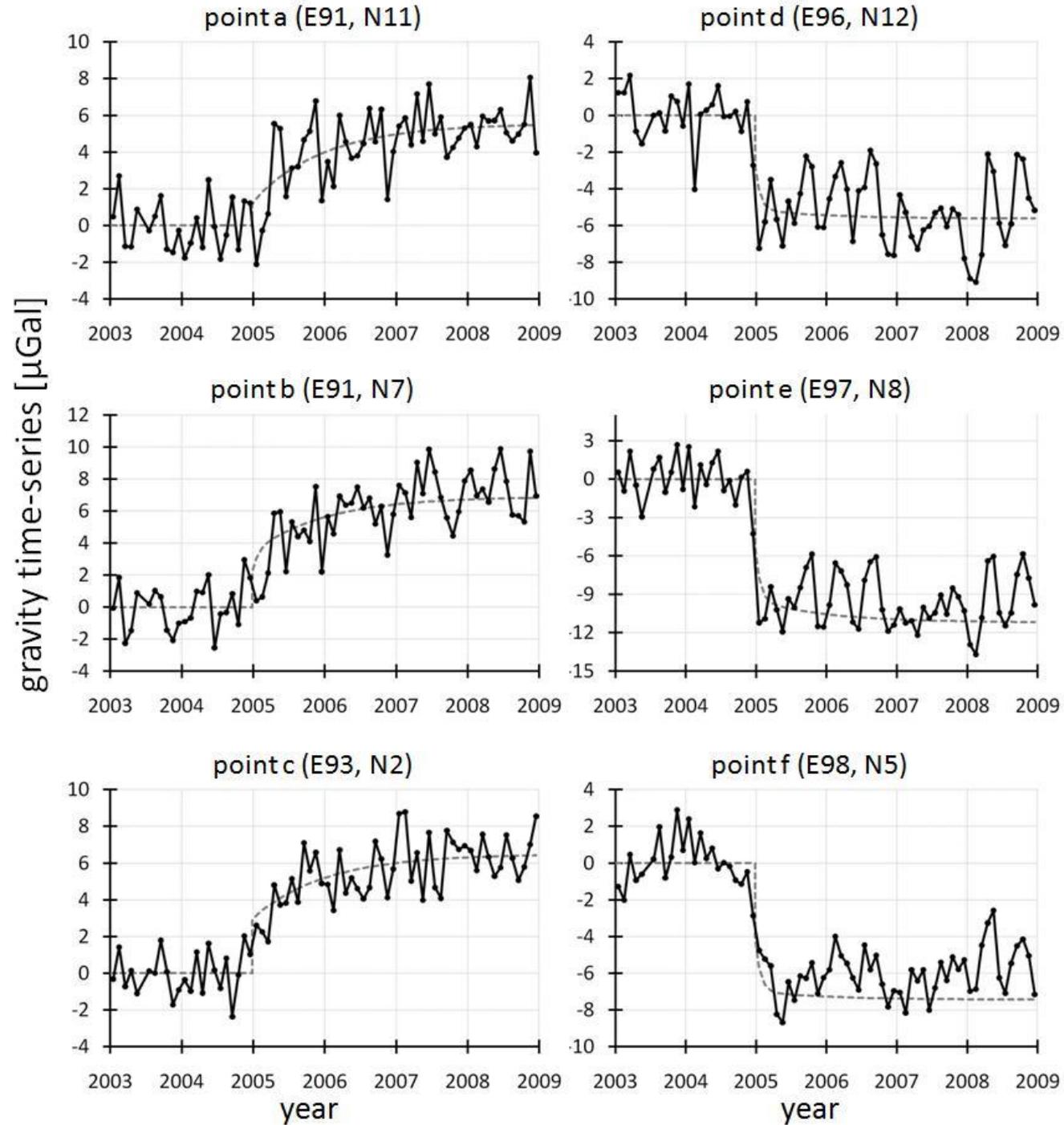
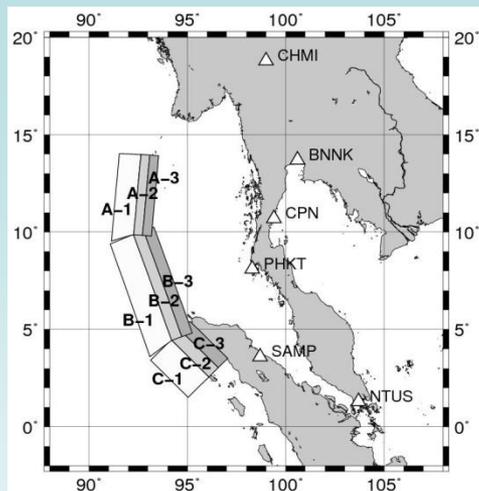


地震後4ヶ月まで

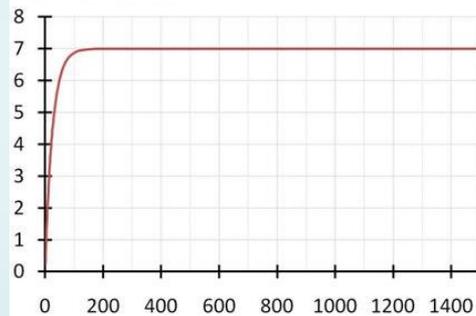


地震後2年まで

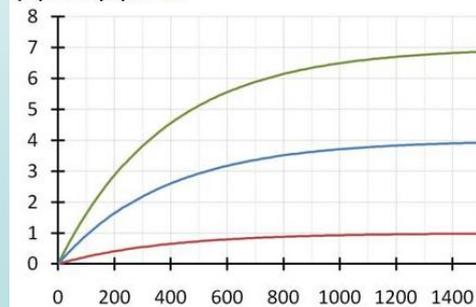




(a) Sallow parts

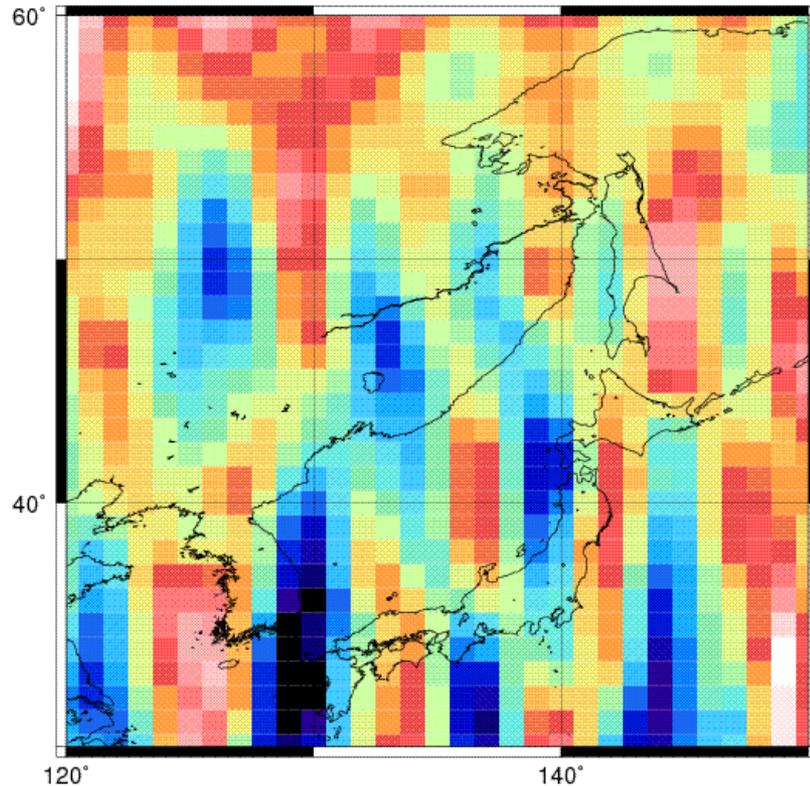


(b) Deep parts



# 他の地震は検出できるか？ 十勝沖地震、パキスタン北部地震

Gravity difference (Smoothing Radius=0300km) L2

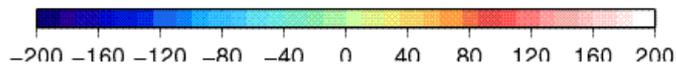


This gravity map is the difference between

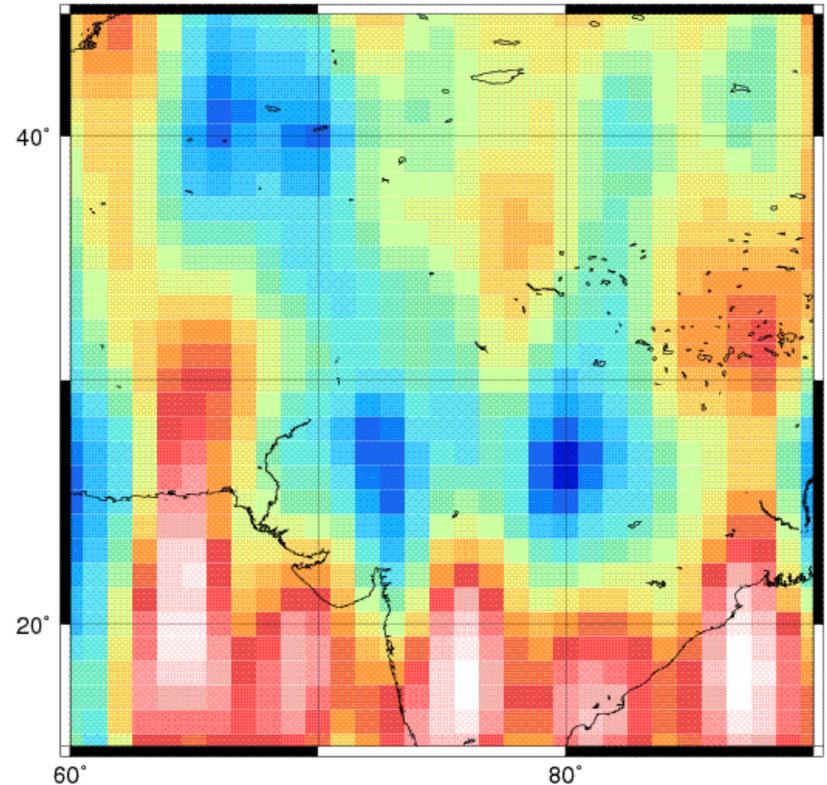
Average(yr03- 1, 2, 3, 4, 5, 7, 8, 9\_JPL\_GSM\*GAC-2)

to (minus)

Average(yr05- 1, 2, 3, 4, 5, 7, 8, 9\_JPL\_GSM\*GAC-2)



Gravity difference (Smoothing Radius=0350km) L2

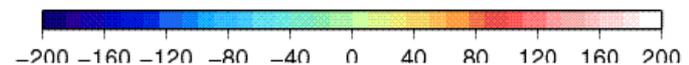


This gravity map is the difference between

Average(yr03-11,12yr04- 2, 3, 4, 5, 6, 7,11,12yr05- 1, 2, 3, 4, 5, 6, 7\_GFZ\_GSM+

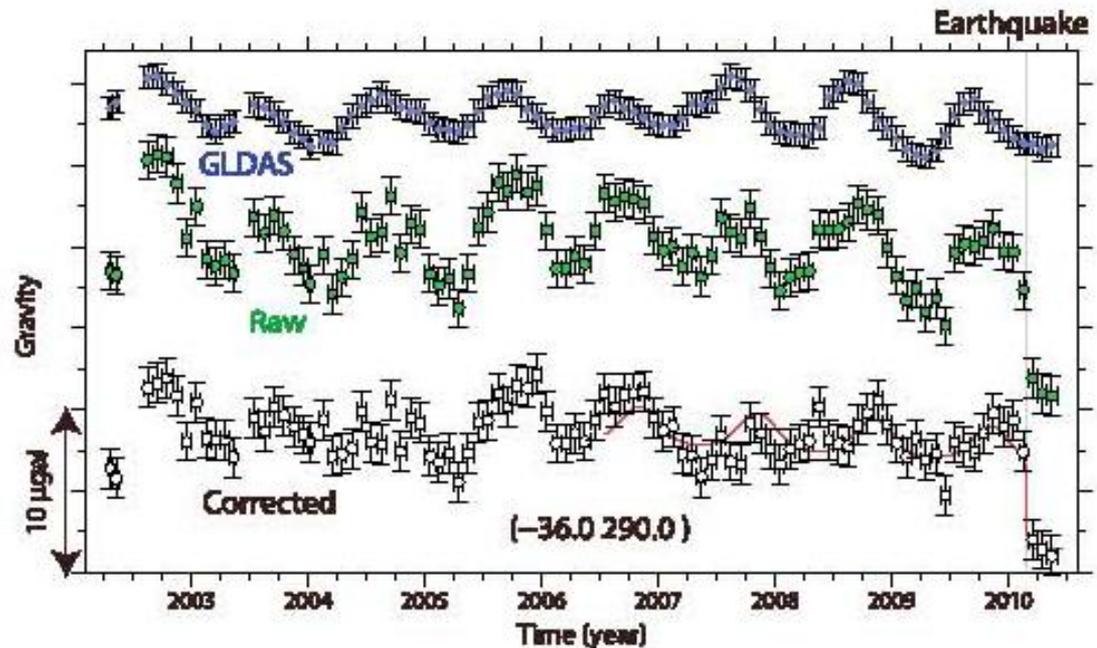
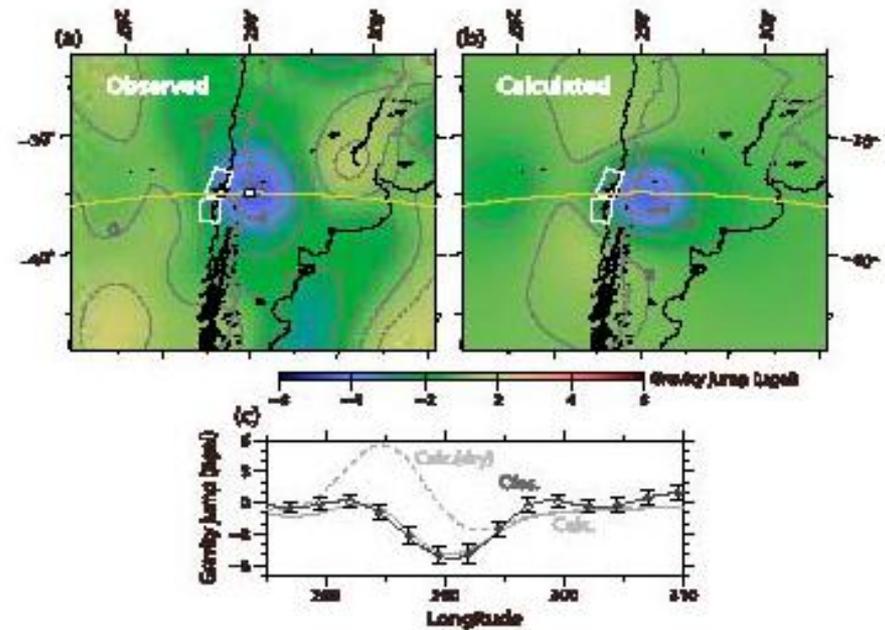
to (minus)

Average(yr05-11,12yr06- 1, 2, 3, 4, 5, 6, 7\_GFZ\_GSM+GAB-2)



# 2例目、 2010チリ地震

Heki, K. and K. Matsuo,  
*GRL*, 37, 2010



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