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EXTRACTING THE SPATIO-TEMPORAL VARIATIONS IN THE GRAVITY FIELD RECOVERED FROM GRACE SPATIAL MISSION: METHODS AND GEOPHYSICAL APPLICATIONS

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RÉSUMÉ

L'estimation des variations spatio-temporelles du champ de gravité terrestre à partir des mesures de la mission satellitaire Gravity Recovery and Climate Experiment (GRACE) ont permis de mieux comprendre les redistributions de masse à des échelles de temps mensuelle, saisonnière ou décennale. Les solutions GRACE produites par différents centres, adoptant des stratégies de traitement différentes, conduisent à des résultats cohérents. Cependant, ces solutions présentent aussi des erreurs aléatoires et systématiques, celles-ci pouvant avoir une structure spatio-temporelle spécifique.

Afin de réduire le bruit et améliorer la qualité des signaux géophysiques présents dans les données GRACE, plusieurs méthodes ont été proposées mais nécessitent en général des informations a priori sur la structure spatio-temporelle du bruit pourtant mal connue. Malgré les efforts considérables effectués pour améliorer la qualité des données GRACE pour des applications géophysiques de plus en plus fines, le filtrage du bruit reste une question problématique comme exposé dans le Chapitre 1.

Dans cette thèse, nous proposons une approche différente, utilisant une technique de filtrage spatio-temporel, la Multichannel Singular Spectrum Analysis (M-SSA) décrite dans le Chapitre 2. La M-SSA est une méthode s'adaptant aux données, à variables multiples et non-paramétrique, qui exploite simultanément les corrélations spatiales et temporelles d'un champ géophysique. Nous utilisons la M-SSA sur 13 ans de données GRACE en harmoniques sphériques distribuées par cinq centres de calculs. Nous montrons que cette méthode permet d'extraire les modes de variabilité communs aux différentes solutions, et de réduire significativement les erreurs spatio-temporelles spécifiques à chaque solution et liées aux différentes stratégies de calculs. En particulier, cette méthode filtre efficacement les stries Nord-Sud dues, entre autres, aux imperfections des modèles de corrections des phénomènes connus.

Dans le Chapitre 3, nous comparons notre solution GRACE à d'autres solutions en harmoniques sphériques et à des solutions basées sur des blocs de concentration de masse (mascons) utilisant des a priori sur la structure spatio-temporelle du signal géophysique. Nous comparons également les performances de notre solution M-SSA GRACE par rapport à d'autres solutions en calculant la déformation de surface induite par les variations de masse déduites des mesures GRACE et en la comparant avec des mesures indépendantes de déplacement provenant des stations du Global Navigation Satellite System (GNSS).

Enfin, nous discutons dans le Chapitre 4 d'une application possible d'une solution GRACE améliorée pour répondre à des questions encore débattues liées au rebond post-glaciaire. Plus précisément, nous nous intéressons à la séparation du signal du rebond post-glaciaire, lié à la fonte ancienne, du signal de fonte récente des glaces dans la région de la Géorgie du Sud.

Mots clefs : GRACE – gravité – M-SSA.

ABSTRACT

Measurements of the spatio-temporal variations of Earth's gravity field recovered from the Gravity Recovery and Climate Experiment (GRACE) mission have led to unprecedented insights into large spatial mass redistribution at secular, seasonal, and sub-seasonal time scales. GRACE solutions from various processing centers, while adopting different processing strategies, result in rather coherent estimates. However, these solutions also exhibit random as well as systematic errors, with specific spatial and temporal patterns in the latter.

In order to dampen the noise and enhance the geophysical signals in the GRACE data, several methods have been proposed. Among these, methods based on filtering techniques require a priori assumptions regarding the spatio-temporal structure of the errors. Despite the large effort to improve the quality of GRACE data for always finer geophysical applications, removing noise remains a problematic question as discussed in Chapter 1.

In this thesis, we explore an alternative approach, using a spatio-temporal filter, namely the Multichannel Singular Spectrum Analysis (M-SSA) described in Chapter 2. M-SSA is a data-adaptive, multivariate, and non-parametric method that simultaneously exploits the spatial and temporal correlations of geophysical fields to extract common modes of variability. We perform an M-SSA simultaneously on 13 years of GRACE spherical harmonics solutions from five different processing centers. We show that the method allows for the extraction of common modes of variability between solutions, and removal of the solution-specific spatio-temporal errors arising from each processing strategies. In particular, the method filters out efficiently the spurious North-South stripes, most likely caused by aliasing of the imperfect geophysical correction models of known phenomena.

In Chapter 3, we compare our GRACE solution to other spherical harmonics solutions and to mass concentration (mascon) solutions which use a priori information on the spatio-temporal pattern of geophysical signals. We also compare performance of our M-SSA GRACE solution with respect to others by predicting surface displacements induced by GRACE-derived mass loading and comparing results with independent displacement data from stations of the Global Navigation Satellite System (GNSS).

Finally, in Chapter 4 we discuss the possible application of a refined GRACE solution to answer debated post-glacial rebound questions. More precisely, we focus on separating the post-glacial rebound signal related to past ice melting and the present ice melting in the region of South Georgia.

Key words: GRACE – gravity – M-SSA.

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1.1 Contexte général

La mesure des variations spatio-temporelles du champ de gravité terrestre par satellite est précieuse pour l'étude de nombreux phénomènes en Sciences de la Terre. Tous les processus physiques engendrant une redistribution de masse significative s'étalant sur plusieurs centaines de kilomètres peuvent être observés. De ce point de vue, la mission spatiale Gravity Recovery And Climate Experiment (GRACE, [Tapley et al., 2004](#)), en orbite de 2002 à 2017, a été un succès. En donnant accès à des cartes du champ de gravité terrestre avec une résolution temporelle de 10 jours et spatiale de ~ 400 km, GRACE a permis une avancée importante dans la compréhension de nombreux processus géophysiques.

Tout d'abord, GRACE a donné un accès sans précédent aux redistributions de masses liées aux variations climatiques : mouvements des masses d'eau et de glace sur les continents et dans les océans, à des échelles de temps allant du mois à la dizaine d'année. Notamment, GRACE a permis d'estimer les variations du stock d'eau continentale (neige, glace, eaux de surface, humidité du sol et eaux souterraines), paramètre clé du bilan hydrologique global et jouant un rôle majeur dans les modèles de climat du système Terre, mais difficilement mesurable in situ ([Famiglietti, 2004](#)). Cette information s'est avérée précieuse en hydrologie ([Ramillien et al., 2008](#)). De plus, GRACE a permis une meilleure compréhension de l'évolution récente de la cryosphère en rendant possible la réalisation de bilans de masse de glace des calottes et systèmes glaciaires ([Velicogna and Wahr, 2013](#)). L'étude des variations de masses océaniques, essentielle notamment à la quantification de la montée du niveau des mers impactant directe-

ment les populations, a également largement bénéficié de la mission GRACE ([Johnson and Chambers, 2013](#), [Chambers and Bonin, 2012](#), [Blazquez et al., 2018](#)).

Ensuite, la mission GRACE a aidé à la compréhension de mouvements de masse de la Terre solide. D’abord, pour le cycle sismique, en mettant en avant les signatures co-sismiques et post-sismiques des méga-séismes ([Chen et al., 2007c](#), [Panet et al., 2007, 2018](#)). Puis, pour quantifier l’érosion des continents et les dépôts de sédiments ([Mouyen et al., 2018](#)) ou étudier les mouvements du pôle ([Chen et al., 2013](#), [Adhikari and Ivins, 2016](#)). Finalement, GRACE a aussi permis de placer des contraintes sur des paramètres rhéologiques du manteau terrestre ([Panet et al., 2010](#), [Chanard et al., 2018b](#)).

Afin de continuer à améliorer notre compréhension des phénomènes physiques présentés ci-dessus ainsi que d’étudier des processus physiques de plus en plus fins, il est nécessaire de raffiner le traitement des données GRACE. En effet, le bruit de mesure, mais aussi les erreurs associées aux stratégies de traitement des données GRACE polluent les signaux géophysiques. La motivation première de cette thèse est donc de proposer une nouvelle méthode de post-traitement des données GRACE, réduisant considérablement le bruit spécifique associé au traitement, sans a priori sur sa structure, et permettant un degré de filtrage moins important. La seconde motivation de ce travail est de proposer de nouvelles applications géophysiques possibles d’une solution GRACE moins bruitée et moins filtrée.

1.2 Variations spatio-temporelles du champ de gravité par gravimétrie spatiale

1.2.1 La mission GRACE

La mission GRACE : généralités

La mission Gravity Recovery and Climate Experiment (GRACE, [Tapley et al. \(2004\)](#)) est une mission spatiale germano-américaine développée conjointement par la NASA (National Aeronautics and Space Administration) et le DLR (Deutsches Zentrum für Luft- und Raumfahrt).

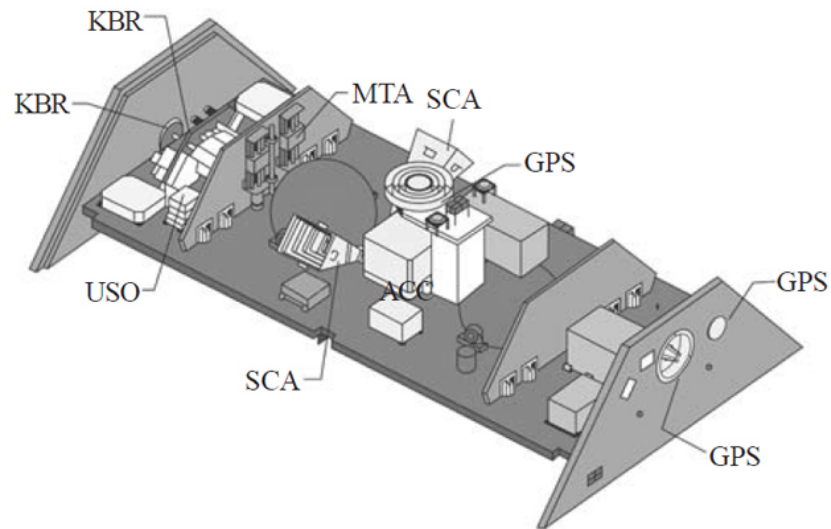


Figure 1.1 – Instruments de mesure embarqués sur les satellites GRACE (NASA, 2003). K-Band Ranging (KBR) : télémétrie en bande K pour mesurer précisément la distance inter-satellites ($10 \mu\text{m}$ à 220 km). Ultra Stable Oscillator (USO) : oscillateur ultra stable pour la télémétrie en bande K. ACC : accéléromètre mesurant les accélérations non-gravitationnelles agissant sur les satellites (précision de 10^{-10} m/s^2). Star Camera Assembly (SCA) : traqueurs stellaires déterminant l'attitude du satellite. Coarse Earth Sun and Sensor (CES) : capteur suivant de façon robuste la Terre et le Soleil. Center of Mass Trim Assembly (MTA) : mesure la position du centre de masse du satellite et l'ajuste si nécessaire en vol. BlackJack GPS Receiver and Instrument Processing Unit (GPS) : récepteurs GPS mesurant les déplacements relatifs à la constellation GPS. Globalstar Silicon Solar Cell Arrays (GSA) : système d'énergie de fonctionnement.

Débutée en mars 2002 et décommissionnée en octobre 2017, cette mission a permis une estimation des variations spatio-temporelles du champ de gravité terrestre avec une résolution sans précédent. En effet, la résolution obtenue est d'1 cm de géoïde pour une distance de 275 km contre 5 cm pour une distance de 400 km avec Challenging Minisatellite Payload (CHAMP).

Instrumentation

La mission GRACE est constituée de deux satellites identiques travaillant en tandem sur la même orbite quasi polaire à 500 km au dessus du sol terrestre et à environ 220 km l'un de l'autre. Ces satellites sont équipés d'accéléromètres en leurs centres de masse qui vont mesurer les forces non-gravitationnelles subies par les satellites en orbite (frottements atmosphériques,

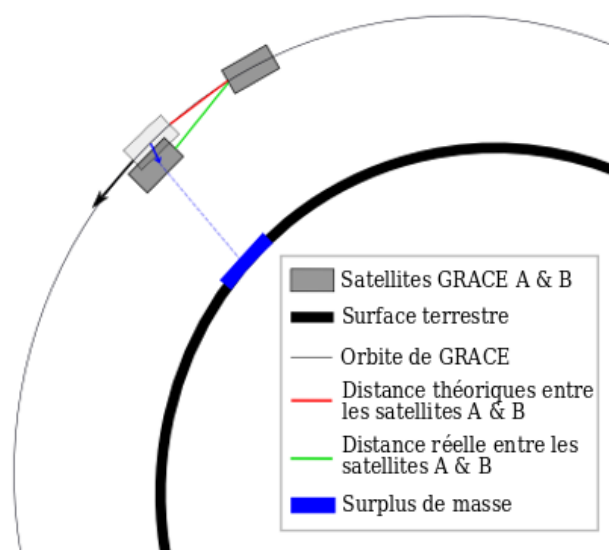


Figure 1.2 – Principe de mesure de la mission GRACE. L'effet du surplus de masse est largement exagéré pour faciliter la représentation.

pression de radiation solaire, etc.). La mission utilise également un système de mesure de distance reposant sur des émissions micro-ondes, le "K-Band Ranging" (KBR). Le KBR utilise l'information de la phase des signaux inter-satellites et est assez sensible pour détecter des variations de la distance entre les deux satellites de l'ordre $10\ \mu\text{m}$. Les satellites sont également équipés, entre autres, de récepteurs GPS pour suivre leur positionnement, de caméras stellaires qui permettent de déterminer l'attitude des satellites, e.g. leur orientation, ainsi que de réflecteurs laser qui permettent de contrôler l'orbite des satellites grâce au réseau de stations laser terrestre. La Figure 1.1 illustre l'instrumentation embarquée sur les satellites GRACE.

Principe

Lors de leurs 16 révolutions quotidiennes autour de la Terre, les variations spatiales de gravité vont influencer la trajectoire des satellites GRACE et donc la distance qui les sépare. Une région avec une gravité plus importante (un excès de masse) va attirer le premier satellite lors de son passage au dessus de la zone, et donc l'éloigner du second satellite. Après avoir dépassé cette zone, le premier satellite va reprendre sa vitesse normale alors que l'orbite du second

satellite va être modifiée à son tour.

Alors, lorsque deux satellites sont situés sur la même orbite, la distance qui les sépare varie en fonction des masses qu'ils survolent. Mesurer précisément et continuellement la distance inter-satellites donne donc accès aux variations spatiales et temporelles du champ de gravité terrestre. La Figure 1.2 illustre ce principe. La mission GRACE permet de cartographier le champ de gravité terrestre avec une résolution spatiale d'environ 400 km et temporelle de 10 jours.

Corrections

Le champ de gravité est sensible à tous les phénomènes engendrant un mouvement de masses. En première approximation, les mesures des anomalies du champ de gravité par GRACE sont affectées par les variations de l'hydrologie continentale, des masses océaniques et atmosphériques, ainsi que des processus tectoniques (volcans, séismes, convection, etc.) et astronomiques. Dans le but d'accéder à des quantités pour lesquelles il n'existe pas de mesure *in situ* à l'échelle globale (bilans hydrologiques, transports de masse tectonique, etc.), il est donc important de corriger les mesures GRACE des effets bien connus et modélisés. Parmi eux, on retrouve les marées solides et océaniques, les effets de marées polaires, les perturbations liées à d'autres corps astronomiques (comme la Lune, le Soleil ou les autres planètes), les processus atmosphériques et leur impact sur les transferts de masse océanique ([Flechtner et al., 2013](#)).

Une fois ces phénomènes corrigés, les mesures GRACE donnent accès aux anomalies du champ de gravité de la Terre dont l'amplitude annuelle pic-à-pic, représentée sur la Figure 1.3a montre, au premier ordre, les variations de masse liées à l'hydrologie continentale (cycle hydrologique du bassin amazonien, glaciers d'Alaska, etc.). De plus, la Figure 1.3b représentant la tendance des mesures gravimétriques GRACE entre 2002 et 2017 montre l'amplitude importante de certains effets tectoniques (séismes de Sumatra, Maule, Tohoku Oki), assèchement de bassins hydrologiques (mer Caspienne), ou encore fonte des glaces

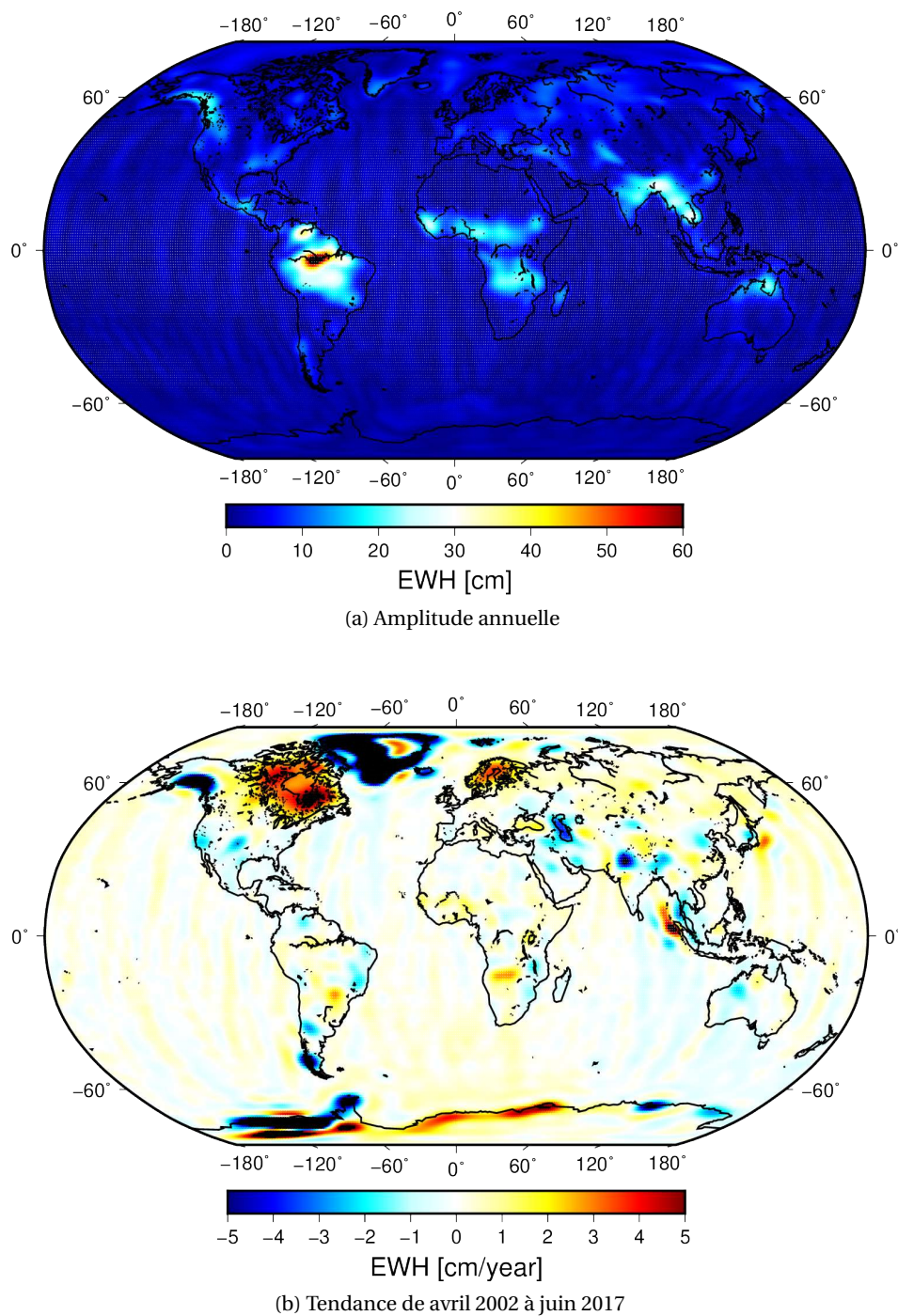


Figure 1.3 – Cartes d'amplitude annuelle et de tendance calculées à partir des données en harmoniques sphériques du GFZ filtrées avec un filtre de décorrélation DDK5.

(Antarctique, Groenland).

1.2.2 Solutions en harmoniques sphériques

La plupart des solutions GRACE sont fournies à l'utilisateur sous forme de coefficients en harmoniques sphériques. Cette partie va présenter le principe sur lequel s'appuient ces solutions.

Principe

Les mesures des satellites GRACE (accélération, orbite, distance KBR...) sont utilisées pour inverser, par moindres carrés, l'équation de mouvement 1.1 de l'orbite des satellites :

$$\ddot{\vec{r}} = \vec{f}_g + \vec{f}_{ng} + \vec{f}_{emp} \quad (1.1)$$

où l'indice "g" désigne les accélérations gravitationnelles, "ng" l'accélération liée aux forces non-gravitationnelles ou de surface et "emp" certaines forces empiriques à modéliser.

Les accélérations gravitationnelles sont la somme des perturbations directes des planètes et des perturbations du géopotentiel. Le vecteur des perturbations directes des planètes est calculé à partir de leurs éphémérides. Les accélérations géopotentielles sont décomposées en harmoniques sphériques variant temporellement jusqu'à un degré et ordre donnés. Le potentiel de pesanteur vérifie l'équation de Laplace :

$$\Delta U = \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} = 0 \quad (1.2)$$

Son développement à un temps t en un point de coordonnées géographiques de colatitude ϕ et longitude λ peut être exprimé comme :

$$U_s(r, \phi, \lambda, t) = \frac{GM}{a_e} + \frac{GM}{a_e} \sum_{l=2}^{L_{max}} \left(\frac{a_e}{r}\right)^l \sum_{m=0}^l P_{lm}(\sin \phi) [C_{lm}(t) \cos(m\lambda) + S_{lm}(t) \sin(m\lambda)] \quad (1.3)$$

où a_e est le rayon équatorial terrestre, L_{max} le degré maximum du développement, r la distance au point de calcul, P_{lm} le polynôme de Legendre associé, et C_{lm} et S_{lm} les coefficients de Stokes.

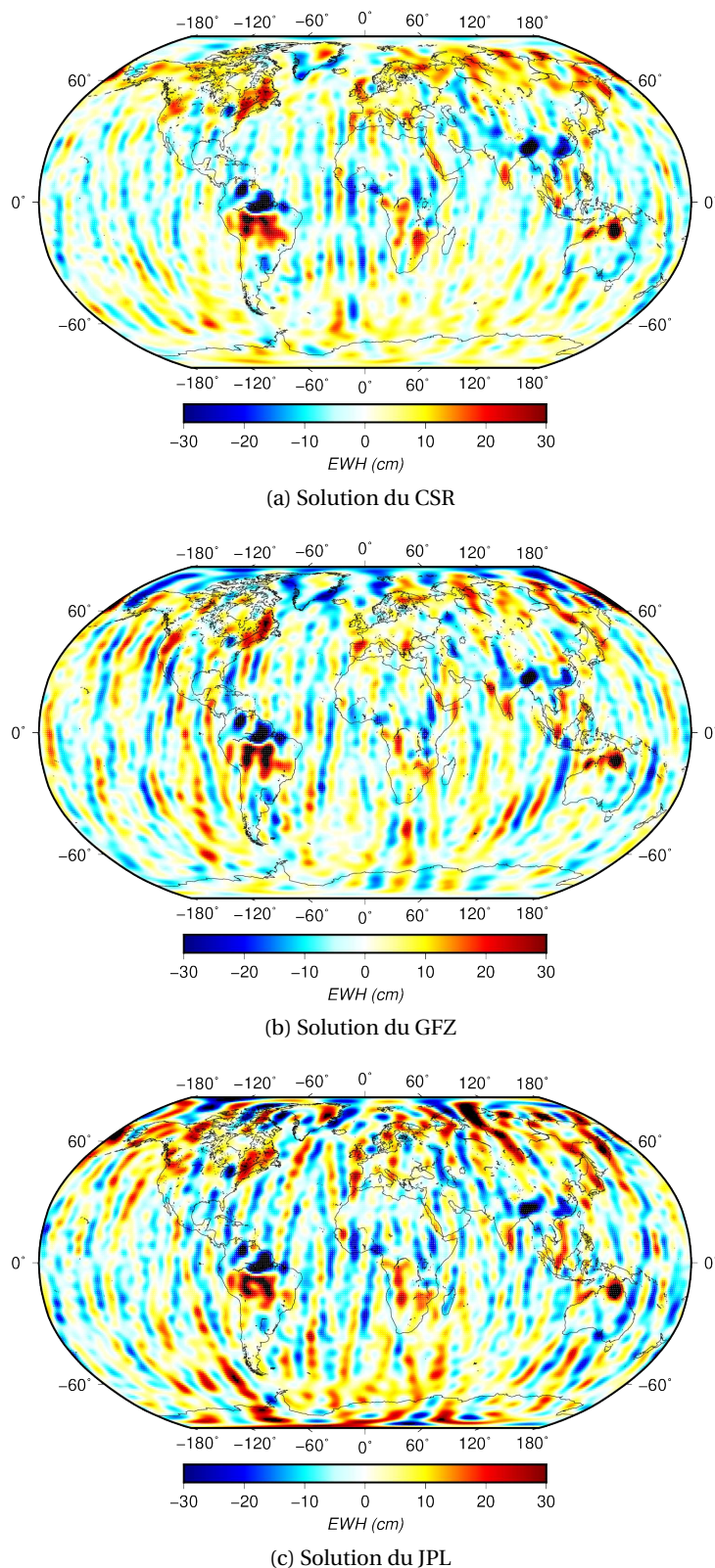


Figure 1.4 – Solutions d’anomalies de masse de surface pour janvier 2006 par rapport à juillet 2005, exprimées en équivalent hauteur d’eau (cm) à partir des données GRACE filtrées avec un filtre de décorrélation DDK5.

1.2. Variations spatio-temporelles du champ de gravité

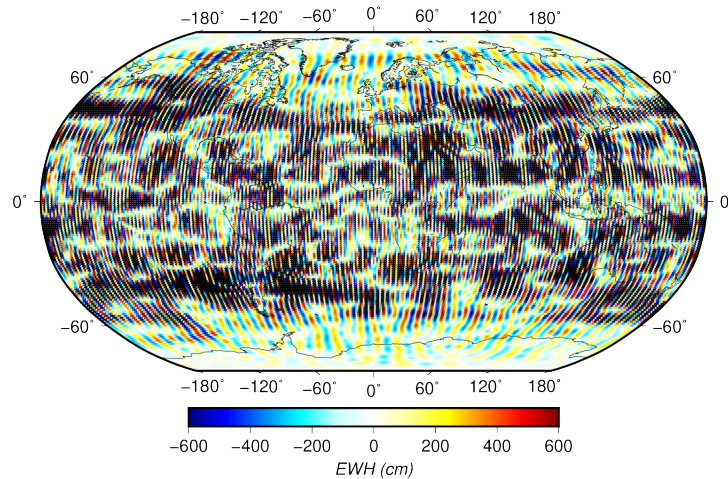


Figure 1.5 – Solution d’anomalies de masse de surface pour janvier 2006 par rapport à juillet 2005, exprimées en équivalent hauteur d’eau (cm) depuis les données GRACE du GFZ sans filtre.

Solutions officielles

Trois centres de calcul officiels des données GRACE fournissent chacun une solution GRACE non contrainte en harmoniques sphériques (Bettadpur, 2007, Dahle et al., 2013, Watkins and Yuan, 2012). Il s’agit du centre pour la recherche spatiale de l’Université du Texas (CSR), du centre de recherche allemand pour les géosciences (GFZ) et du centre de recherche spatiale de la NASA (JPL).

Ces trois centres effectuent des calculs similaires, mais n’utilisent pas les mêmes stratégies de traitement : modèles de forces, degré maximum de développement en harmoniques sphériques différents, etc. Ces solutions sont présentées dans la figure 1.4 pour une date donnée (les dates ont été choisies arbitrairement, à six mois d’écart pour avoir une idée de l’amplitude annuelle, mais d’autres dates n’auraient pas changer les interprétations). On peut voir que le signal est, en première approximation, similaire mais présente cependant des différences visibles.

Post-traitements

Les solutions en harmoniques sphériques présentent des erreurs liées au bruit observationnel ainsi qu’aux méthodes de calcul qui limitent leur précision. On peut voir sur la Figure 1.5

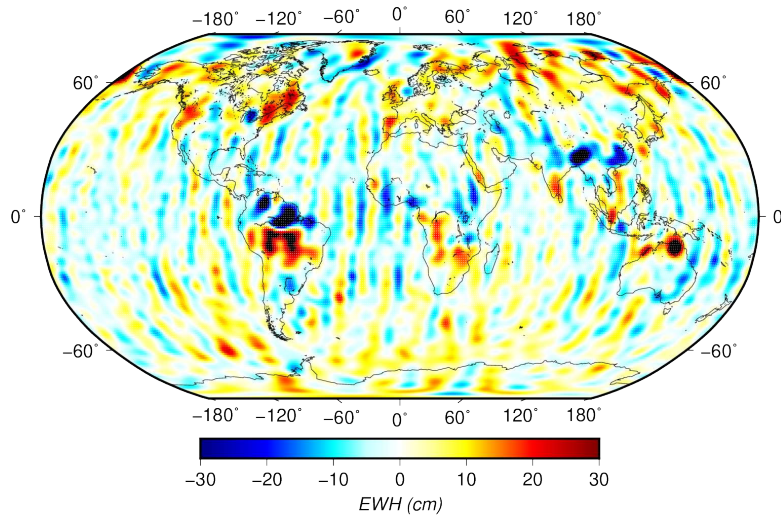


Figure 1.6 – Moyenne des solutions GRACE d’anomalies de masse de surface des trois centres officiels (CSR, GFZ et JPL) filtrés par DDK5 pour janvier 2006 par rapport à juillet 2005, exprimées en équivalent hauteur d’eau (cm).

que le signal est très largement dominé par du bruit orienté nord-sud en lien avec l’orbite quasi-polaire des satellites. Ces erreurs sont principalement causées par le bruit dans les mesures d’accélérométrie à bord des satellites ([Flechtner et al., 2016](#)), et/ou par l’utilisation de modèles de correction non parfaits des effets atmosphériques et océaniques (de marées ou non) avec des périodes d’une heure à quelques jours ([Han et al., 2004](#), [Thompson et al., 2004](#), [Seo et al., 2008](#)).

Avant de pouvoir utiliser ces données pour des applications géophysiques, il est donc nécessaire de les filtrer. De nombreuses méthodes ont été mises en place pour réduire le bruit dans ces données dont :

- des filtres gaussiens ([Jekeli, 1981](#), [Schrama et al., 2007](#)) ;
- des filtres dépendant de l’ordre et du degré ([Swenson and Wahr, 2002](#), [Guo et al., 2010](#)) ;
- un filtre variant temporellement ([Seo et al., 2006](#)) ;
- des filtres de décorrélation ([Swenson and Wahr, 2006b](#), [Kusche, 2007](#), [Kusche et al., 2009](#));
- ACI (Analyse en Composantes Indépendantes, [Frappart et al., 2010](#), [Seoane et al., 2013](#));
- ACP (Analyse en Composantes Principales, [Forootan et al., 2012](#));
- SSA (Singular Spectrum Analysis, [Wouters and Schrama, 2007](#)).

1.2. Variations spatio-temporelles du champ de gravité

Ces approches de filtrage permettent de réduire efficacement le bruit, particulièrement les stries nord-sud, présent dans les données mais causent également un étalement spatial du signal, i.e. une perte d'information à petites longueurs d'onde ([Chen et al., 2007a](#), [Landerer and Swenson, 2012](#)). Il est donc important de choisir un filtre approprié à l'utilisation que l'on va faire des données pour retirer un maximum de bruit tout en gardant une bonne résolution spatiale du signal.

Les filtres de décorrélation du GFZ, appelé DDK, sont les plus largement utilisés car ils sont facilement accessibles en ligne et permettent d'adapter facilement le niveau de filtrage à l'utilisation souhaitée. Il s'agit de filtres non-isotropes de décorrélation basés sur une régularisation des équations normales et utilisant en a priori une matrice de covariance des erreurs issues des calculs GRACE. Les différents niveaux de filtrage vont de DDK1, le plus fort, à DDK8, le plus faible. Quand la force du filtrage diminue, le signal géophysique est mieux préservé mais les erreurs deviennent plus grandes. Pour des études géophysiques globales, DDK5 est celui le plus fréquemment utilisé.

[Sakumura et al. \(2014\)](#) a proposé d'utiliser la moyenne de plusieurs solutions pour réduire le bruit. La moyenne des trois solutions officielles filtrées par DDK5 est représentée sur la Figure 1.6.

Particularité des solutions contraintes

Une autre façon de réduire le bruit dans les solutions GRACE consiste à utiliser une régularisation lors du traitement des données initiales ([Lemoine et al., 2007, 2013](#), [Bruinsma et al., 2010](#), [Save et al., 2012](#), [Eshagh et al., 2013](#)). La régularisation est appliquée lors de la procédure d'inversion par moindres carrés et consiste à ajouter une contrainte a priori empirique sur les coefficients de Stokes afin de réduire les stries nord-sud.

Par exemple, la solution GRACE du CNES/GRGS présentée en Figure 1.7, dès sa première

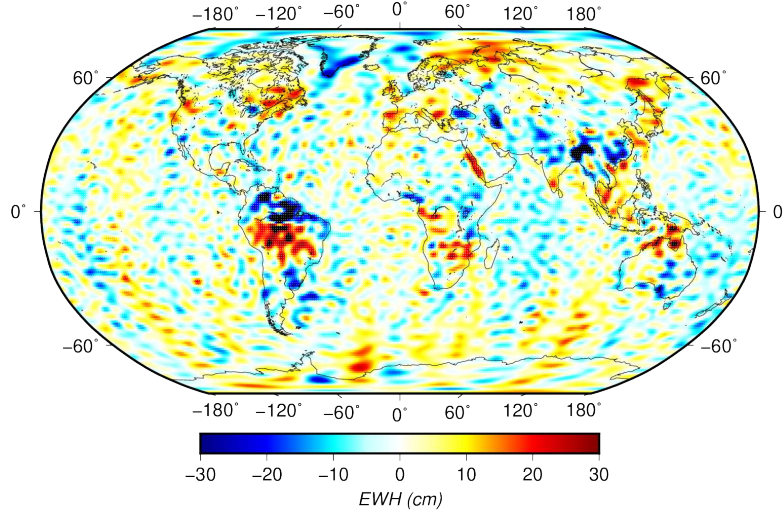


Figure 1.7 – Solution GRACE régularisée d’anomalies de masse de surface du GRGS pour janvier 2006 par rapport à juillet 2005, exprimées en équivalent hauteur d’eau (cm).

version, est contrainte (Lemoine et al., 2007). Les solutions à 10 jours de la version RL01 présentent des coefficients en harmoniques sphériques contraints pour les degrés 31 à 50 à se rapprocher du champ statique EIGEN-GL04S, alors que ceux du champ statique ont remplacé les coefficients de degrés 51 à 150. Les coefficients temporels $c_{n,m}$ de degré n et ordre m sont contraints vers les coefficients statiques $C_{n,m}$ via la relation :

$$c_{n,m} = C_{n,m} \pm \sigma_n \quad (1.4)$$

$$\sigma_n = \frac{e^{-(n+264)/10.91}}{\sqrt{2.5}}$$

Si cette méthode permet de réduire efficacement les stries nord-sud observées dans les solutions classiques, les solutions produites ne sont pas totalement objectives puisqu’il est nécessaire d’avoir une information a priori sur le champ pour déterminer les contraintes à appliquer. De plus, le signal dans les régions où il y a une forte variabilité est potentiellement atténué par la contrainte, tout comme dans les zones où le signal est restreint spatialement (Bruinsma et al., 2010, Save et al., 2012).

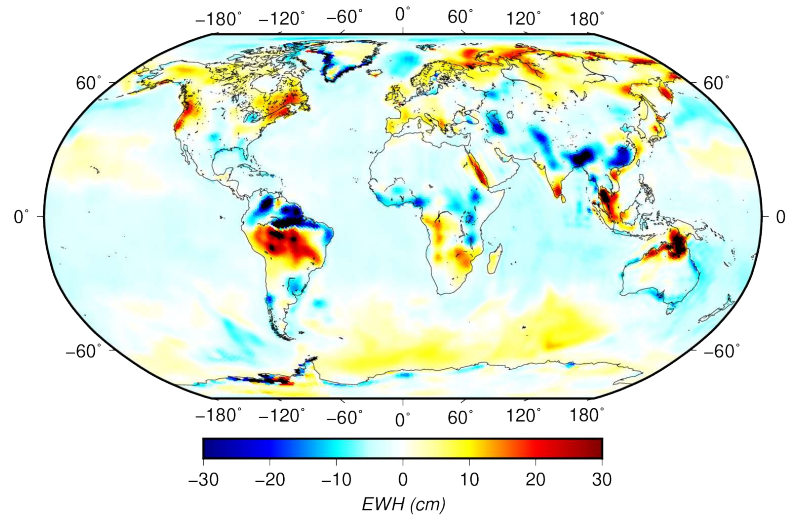


Figure 1.8 – Solution mascons GRACE d’anomalies de masse de surface du CSR pour janvier 2006 par rapport à juillet 2005, exprimées en équivalent hauteur d’eau (cm).

1.2.3 Solutions mascons

Les solutions en harmoniques sphériques ne sont pas les seules proposées par les différents centres de calculs. Récemment, l’utilisation de blocs de concentration de masses, appelés mascons, a permis de fournir des solutions présentant moins de bruit et un signal géophysique mieux localisé, en particulier à la limite océan/continent ([Save et al., 2016](#), [Watkins et al., 2015](#), [Luthcke et al., 2013](#)).

Les solutions mascons sont une approche spatio-temporelle pour décrire les signaux temporels de gravité dans laquelle l’espace est divisé en parcelles de concentration de masses de surfaces égales. Les contributions au signal gravimétrique de chaque parcelle sont calculées directement à partir des observations de distance ou vitesse KBR.

Les fonctions de base des mascons permettent d’utiliser des informations a priori pour limiter les stries nord-sud présentes dans les solutions en harmoniques sphériques. Ces informations a priori peuvent être dérivées de modèles géophysiques quasi-globaux, de modèles hydrologiques, de données altimétriques, ou bien directement de solutions GRACE en harmoniques sphériques.

Par construction, ces solutions ne contiennent donc pas de bruit à géométrie de stries nord-

sud comme on peut le voir sur la Figure 1.8 représentant la solution mascons du CSR. Contrairement aux solutions en harmoniques sphériques, ces solutions ne présentent pas non plus d'étalement spatial du signal autour des grandes sources de variabilité, ne nécessitent pas d'utilisation de filtre et présentent une meilleure résolution spatiale – en particulier dans les régions où le signal est peu étendu, relativement à la résolution spatiale de GRACE.

Cependant, ces solutions — utilisant des modèles géophysiques pour contraindre spatialement le signal — ne sont pas objectives et peuvent atténuer certains signaux.

Les difficultés de filtrage des solutions GRACE en harmoniques sphériques, ainsi que les informations a priori nécessaires à la réalisation des solutions mascons ont motivé mon travail de thèse. En effet, afin de s'affranchir au maximum de contraintes non-objectives de traitement, j'ai travaillé au développement d'une méthode de filtrage prenant avantage d'une méthode d'analyse spectrale appelée : Multichannel Singular Spectrum Analysis.

1.3 Multichannel Singular Spectrum Analysis

La Multichannel Singular Spectrum Analysis (M-SSA) est une méthode d'analyse de séries temporelles dite "non paramétrique" qui ne nécessite l'utilisation d'aucune information a priori sur la structure spatiale et/ou temporelle d'un champ géophysique à étudier ou du bruit qu'il contient. La M-SSA est une généralisation de la Singular Spectrum Analysis (SSA) pour l'analyse de séries temporelles multivariées ([Vautard et al., 1992](#), [Ghil et al., 2002](#)).

Comparée aux autres méthodes de développement sur base de fonctions orthogonales utilisées sur les données GRACE comme l'ACI et l'ACP ([Frappart et al., 2010](#), [Seoane et al., 2013](#), [Forootan et al., 2012](#)), la M-SSA permet plus de liberté dans les composantes et la mise en évidence des signaux périodiques via des paires de composantes. Par exemple, la M-SSA permet contrairement à l'ACP, l'utilisation de copie décalées dans le temps des séries temporelles, utiles par exemple pour l'étude de signaux hydrologiques présentant un temps de transfert dans les bassins.

Cette méthode s'appuie sur les corrélations spatio-temporelles dans un jeu de séries temporelles pour en extraire une base empirique de fonctions représentant les modes communs de variabilité spatio-temporelle du jeu de données et fournit donc une méthode de filtrage adaptée aux données. Le principal avantage de la M-SSA est qu'elle permet de distinguer des oscillations et des tendances – avec des pentes non-constantes – présentes dans les séries temporelles sans utiliser d'information à priori sur leurs périodes ou amplitudes.

Développée au départ pour des applications climatologiques, la M-SSA a d'abord été utilisée pour étudier des oscillations basse fréquence de l'atmosphère à partir de données de hauteur du géopotential ([Plaut and Vautard, 1994](#), [Keppenne and Ghil, 1993](#)), le niveau des mers ([Unal and Ghil, 1995](#)), ou encore pour étudier conjointement les vents et températures de surface ([Jiang et al., 1995](#)).

Plus récemment, [Walwer et al. \(2016\)](#) se sont intéressés à l'utilisation de cette méthode pour des données géodésiques, et en particulier sur un ensemble de séries temporelles de positionnements GPS, en montrant son intérêt pour l'étude de déformations volcaniques.

Les données d'anomalie de gravité obtenues par la mission GRACE sont corrélées dans le temps et dans l'espace, alors que le bruit qui les pollue – principalement sous la forme de stries nord-sud – est distribué aléatoirement dans le temps et corrélé spatialement seulement à très petite échelle. La M-SSA est donc adaptée à l'étude, et particulièrement au filtrage de ces données. Elle a d'ailleurs déjà été utilisée sur 6 ans de données GRACE hebdomadaires du GFZ par [Rangelova et al. \(2012\)](#). Contrairement à cette étude, nous utilisons plusieurs solutions mensuelles GRACE et ne prenons pas en compte les corrélations connues entre les différents harmoniques sphériques. Notre méthodologie est explicitée dans la Partie 2.2.

Développer de nouvelles méthodes de filtrage objectif efficaces des données GRACE est un paramètre clé pour augmenter la résolution spatiale des signaux géophysiques, et possible-

ment raffiner certaines applications géophysiques décrites dans ce qui suit.

1.4 GRACE : applications géophysiques

Les données d'anomalies de gravité GRACE ont permis d'avoir accès à des informations plus précises que par le passé sur les variations des masses terrestres, utiles à de nombreux domaines des Sciences de la Terre. Sans vouloir rendre compte de la totalité des applications possibles des données GRACE en géosciences, nous discutons dans ce qui suit quelques exemples de leur utilisation qui montrent l'importance d'une estimation précise des variations spatio-temporelles du champ de gravité.

1.4.1 Hydrologie

Une des plus grandes contributions à la variabilité de la gravimétrie observée par GRACE est liée au stock d'eau continentale. Par exemple, la Figure 1.3a montre l'amplitude annuelle pic à pic de la hauteur de l'anomalie de masse exprimée en hauteur d'eau équivalente mesurée par GRACE, où l'on voit en première approximation les contributions des grands bassins hydrologiques. L'eau continentale s'infiltre ensuite dans le sol ou bien reste à sa surface sous forme d'eau ou de glace, mais contribue également au bilan de masse océanique. Bien que les mesures de gravimétrie spatiale ne puissent pas distinguer ces différentes sources, elles permettent un accès unique à la variation totale du stock d'eau continentale à l'échelle de quelques centaines de km dans le cas de la mission GRACE.

Les estimations du stock d'eau continentale par GRACE sont particulièrement intéressantes lorsqu'elles sont combinées à des modèles d'hydrologie de surface. En effet, elles peuvent être comparées aux prédictions de ces modèles afin d'en évaluer la précision et possiblement d'en proposer des améliorations ([Frappart et al., 2006](#), [Hinderer et al., 2006](#), [Ramillien et al., 2005](#), [Swenson and Milly, 2006](#), [Syed et al., 2008](#)), ou bien à des mesures humidité du sol, d'eau souterraine, et/ou de neige pour mieux comprendre ces données ([Frappart et al., 2006](#), [Swenson and Wahr, 2006a](#), [Yeh et al., 2006](#)). Par exemple, la Figure 1.9 montre les différences entre le stock d'eau moyen dans le bassin amazonien et les prédictions du modèle GLDAS/Noah

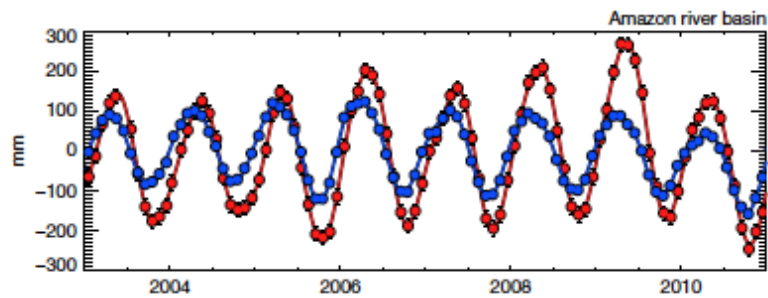


Figure 1.9 – Stock d’eau moyen dans le bassin Amazonien vu par GRACE (rouge) et par le modèle hydrologique GLDAS/Noah (bleu, [Rodell et al., 2004](#)).

([Rodell et al., 2004](#)), ne contenant pas de contribution des eaux souterraines, et les estimations GRACE ([Swenson and Wahr, 2006b](#)). La mise en lumière de ces différences a par la suite conduit à l’assimilation des données GRACE dans certains modèles d’hydrologie (e.g., [Forman et al., 2012](#), [Li et al., 2012](#)).

[Landerer et al. \(2010\)](#), [Longuevergne et al. \(2010\)](#) ont cependant montré l’importance du choix de la méthode de filtrage appliquée aux données GRACE pour pouvoir les comparer à d’autres données d’hydrologie, qui présentent en général une meilleure résolution spatiale, ce qui a motivé un des objectifs de cette thèse.

Les données GRACE se sont également montrées utiles dans l’étude des épisodes de sécheresse ([Houborg et al., 2012](#)) et dans l’estimation du risque de crue à grande échelle spatiale ([Reager and Famiglietti, 2009](#)), paramètre essentiel à la mitigation de ces catastrophes naturelles. En effet, les variations du stock d’eau continentale mesurées par GRACE, en comparaison à leurs variations passées, sont un indicateur important des conditions climatiques actuelles et utiles à la prévention de certains risques.

1.4.2 Cryosphère

Une des plus grandes conséquences du réchauffement climatique est l’augmentation du niveau des mers liée à l’accélération de la fonte des glaces en Antarctique et au Groenland. En

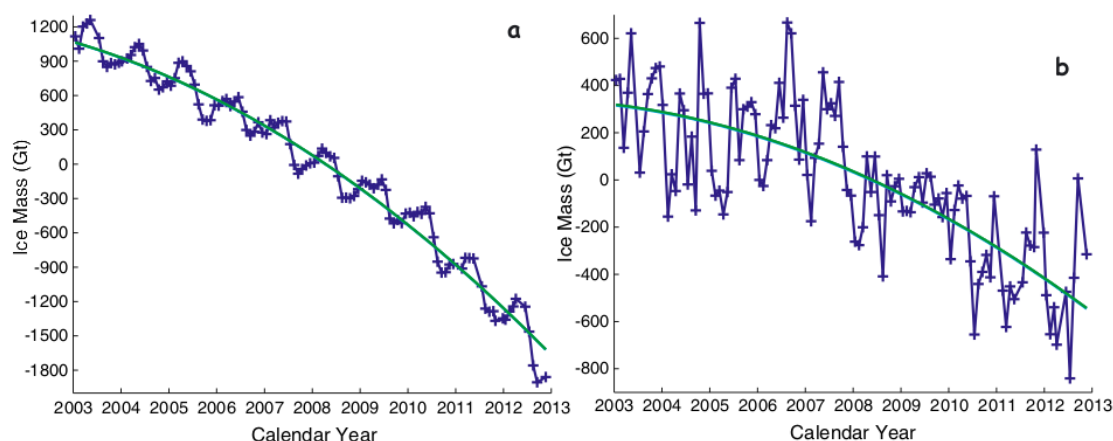


Figure 1.10 – Figure issue de [Velicogna and Wahr \(2013\)](#). Séries temporelles d'évolutions de la masse de glace en Gigatonnes (1 Gt = 10¹² kg) pour (a) le Groenland et (b) l'Antarctique estimé à partir des données GRACE de janvier 2003 à novembre 2012. La tendance quadratique correspondant le mieux est tracée en vert.

plus d'une surveillance des zones polaires via altimètres radar et laser mesurant les variations d'élévation des calottes, la gravimétrie spatiale présente quelques avantages dont l'estimation directe des variations de masse ainsi que l'accès à des données moyennées régionalement dues à l'altitude des satellites de la mission. Bien entendu, ces avantages sont contrebalancés par des inconvénients : une résolution spatiale faible ainsi qu'une difficulté importante à séparer la fonte récente des glaces du signal de rebond crustal post-glaciaire.

GRACE a donc permis d'estimer des variations de masse de glace au Groenland ([Chen et al., 2006](#), [Luthcke et al., 2006](#)), en Antarctique ([Velicogna and Wahr, 2013](#)), en Alaska ([Tamisiea et al., 2005](#)), en Himalaya ([Matsuo and Heki, 2010](#)) ou encore en Patagonie ([Chen et al., 2007b](#)). Par exemple, [Velicogna and Wahr \(2013\)](#) utilisent les données GRACE pour estimer les variations dans les masses de glace au Groenland et en Antarctique. Sur la Figure 1.10, on constate une accélération conséquente de la perte de masse dans les deux régions sur toute la période de données disponibles. Toutes les études publiées arrivent au même constat, quelque soit la solution GRACE utilisée. Cependant, la méthode de filtrage utilisée pour s'affranchir du bruit de traitement ainsi que le modèle de rebond post-glaciaire (RPG) impactent grandement l'estimation des bilans de masse de glace ([Velicogna and Wahr, 2013](#)).

1.4.3 Terre Solide

Bien que le champ de gravité terrestre moyen soit principalement causé par des changements de masses de la Terre solide, leurs variations sont souvent trop lentes et/ou de trop faible amplitude pour être mesurables par GRACE. Quelques exceptions sont cependant à noter.

Rebond Post-Glaciaire

Le signal de rebond post-glaciaire (RPG) est clairement visible, notamment au nord de l'Amérique du Nord dans les données GRACE et s'est montré utile pour contraindre le profil rhéologique, e.g. le profil de viscosité, du manteau (Paulson et al., 2007). La Figure 1.11 montre par exemple (a) la tendance linéaire des données GRACE en Amérique du Nord pendant la période 2002-2012, (b) un modèle de RPG (A et al., 2012) utilisant le modèle de glaces ICE-5G et le profil de viscosité VM2 (Peltier, 2004), (c) la différence des deux. Le modèle explique bien les observations GRACE au dessus de la baie de l'Hudson, les observations GRACE permettant de valider les hypothèses combinées du modèle de glace et du profil de viscosité. Une différence importante persiste en Alaska et est attribuée à la fonte récente des glaciers. Le signal de RPG reste un paramètre important à déterminer pour le Groenland et l'Antarctique mais la question demeure ouverte à cause de la difficulté à séparer le RPG du signal de fonte récente dans ces régions.

Les modèles de RPG présentent encore une grande variabilité car ils restent difficiles à contraindre par manque de données historiques sur la glace, son épaisseur, sa localisation et son âge. Ces modèles peuvent cependant bénéficier de nouvelles contraintes utilisant les données GRACE (Riva et al., 2009). Dans le Chapitre 4, nous nous essaierons par exemple à séparer le signal lié au RPG du signal de fonte récente dans la région de Géorgie du Sud.

Méga-séismes

Au cours de la période d'activité de la mission GRACE, les trois méga-séismes : 2004 Sumatra-Andaman (Océan Indien), 2010 Maule (Chili) et 2011 Tohoku-Oki (Japon) ont été imagés par la mission (Cambiotti and Sabadini, 2012, Chen et al., 2007c, Han et al., 2006, 2008, 2010, Matsuo

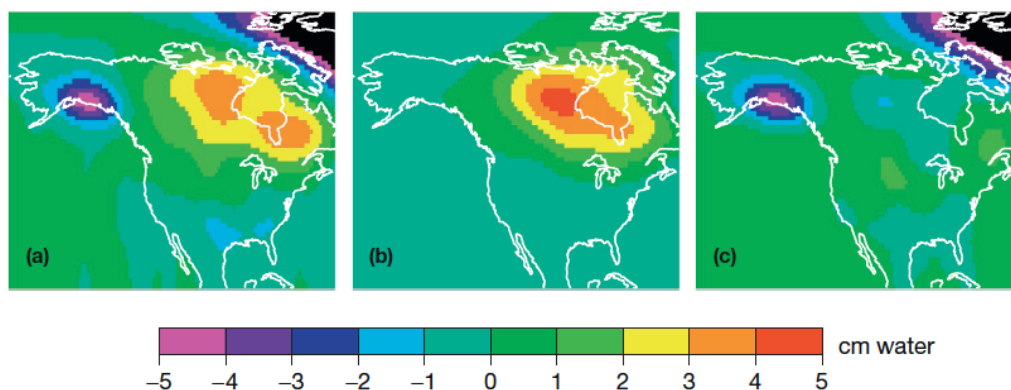


Figure 1.11 – Figure de (Wahr, 2015). (a) tendance linéaire des données GRACE en Amérique du Nord pendant la période 2002-2012, (b) un modèle de RPG (A et al., 2012) utilisant le modèle de glaces ICE-5G et le profil de viscosité VM2 (Peltier, 2004), (c) la différence des deux.

and Heki, 2011, Panet et al., 2007, Wang et al., 2012). Les signaux co-sismiques (sauts dans les données) ainsi que post-sismiques (signaux s'atténuant dans le temps après le séisme) ont été étudiés en utilisant les données GRACE, souvent combinées à des mesures GPS, apportant une information importante en mer en zone de subduction. Par exemple, les changements de gravité liés aux séismes de Sumatra-Andaman (2004 - Mw 9.3) et Nias (2005 - Mw 8.7) ont pu être observés (Panet et al., 2007) et sont représentés sur la Figure 1.12 (Chen et al., 2007c). Han et al. (2010) se sont intéressés aux changements de gravité liés au séisme de Maule (2010 - Mw 8.8) et ont montré que les données GRACE pouvaient être utilisées pour contraindre les paramètres des modèles sismiques. Pour aller encore plus loin, Panet et al. (2018) ont montré l'utilité des données GRACE dans la compréhension des mouvements de masses asismiques en profondeur et son importance pour l'évaluation du risque sismique.

Modèles de surcharge

Les mesures des variations spatio-temporelles du champ de gravité par GRACE ont également joué un rôle clé dans la modélisation des déformations non-tectoniques de la surface terrestre induites par les variations des charges hydrologiques, océaniques et atmosphériques. Les mesures GRACE, associées à un modèle de Terre sphérique, élastique stratifié ont en effet été utilisées pour prédire les déplacements verticaux et horizontaux observés par les stations GNSS (Davis et al., 2004, Bettinelli et al., 2008, Fu and Freymueller, 2012, Fu et al., 2012, 2013,

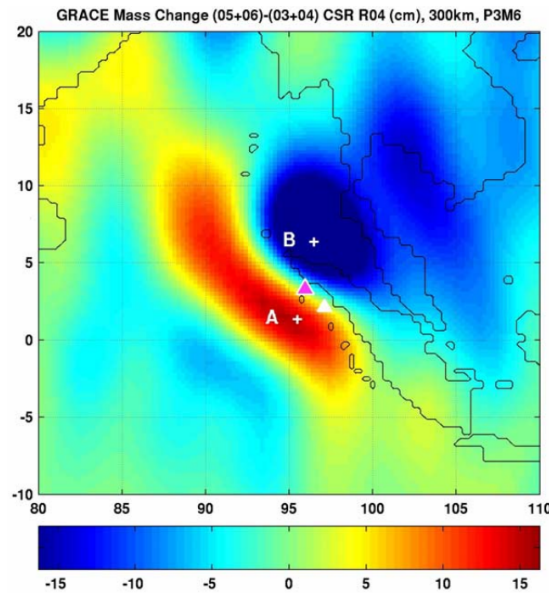


Figure 1.12 – Figure de [Chen et al. \(2007c\)](#). Changements de masse à partir de données GRACE entre la moyenne de 2005 et 2006 et la moyenne de 2003 et 2004 (sans décembre 2004) dans la région des séismes de Sumatra-Andaman du 26 décembre 2004 (Mw 9.3) et de Nias du 28 mars 2005 (Mw 8.7) dont les épicentres sont représentés respectivement par les triangles rose et blanc.

[Nahmani et al., 2012](#), [Chanard et al., 2018b](#)). La Figure 1.13 représente une série temporelle de positions journalière GNSS (en gris) pour la station LHAZ, Chine (Tibet) ainsi que les déplacements calculés à partir de GRACE (en rouge)([Chanard et al., 2018b](#)). Les données GRACE se sont avérées mieux prédire les déformations observées par GNSS, en partie pour les raisons invoquées en section 1.4.1, comme l'ont montré [Dong et al. \(2002\)](#), [Jiang et al. \(2013\)](#), [Li et al. \(2016\)](#).

Proposer un modèle précis des déplacements liés aux redistributions de charge est important pour mieux comprendre les effets non-tectoniques de surcharge et corriger de leurs effets sur les séries temporelles GNSS. En conséquence, ceci permettrait de mettre en évidence de potentiels signaux tectoniques de petite amplitude comme certains glissements lents ([Vergnolle et al., 2010](#)) ou d'améliorer la précision des estimations de vitesses de déformation tectonique ([Blewitt and Lavallée, 2002](#)).

Un des facteurs actuellement limitant des modèles de surcharge utilisant GRACE est la

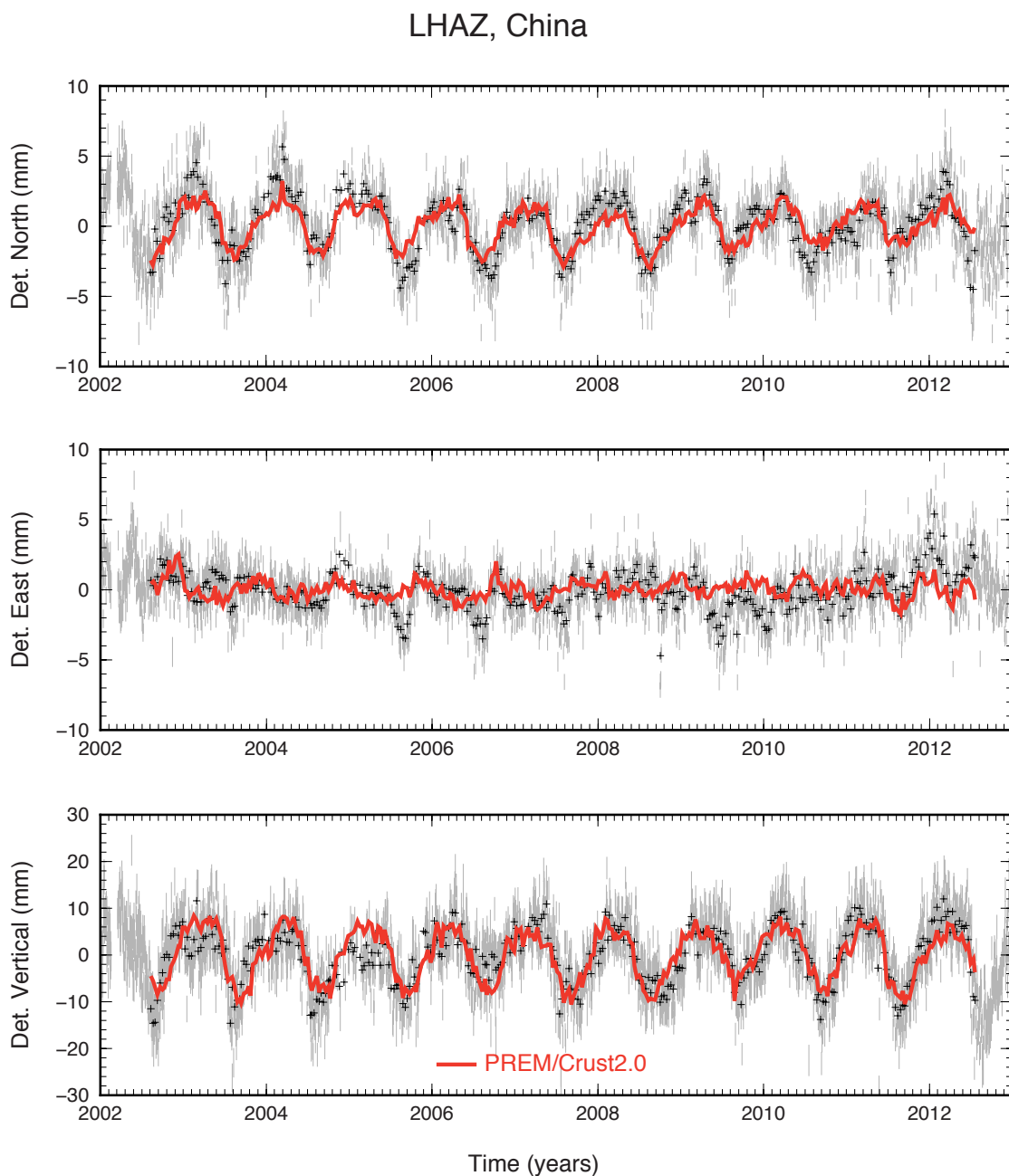


Figure 1.13 – Figure de [Chanard et al. \(2018b\)](#). Séries temporelles journalières de positions GNSS – sans la tendance – et barres d’erreurs $1 - \sigma$ associées (gris) pour la station LHAZ, China (Tibet). Les croix noires sont les moyennes glissantes sur 10 jours des observations journalières. Les courbes rouges montrent les déplacements calculés à partir de GRACE.

présence de stries nord-sud dans les données qui rendent possiblement difficile la modélisation des déformations est-ouest. La Figure 1.13 montre en effet des déplacements verticaux et horizontaux sur la composante nord-sud relativement bien prédits à partir des données GRACE, mais la composante est-ouest reste difficile à expliquer. Nous verrons dans la partie 3.3 comment un meilleur filtrage permet de réduire ces écarts entre déplacements mesurés et déplacements calculés à partir de données GRACE.

Ces mesures de déformation liées aux charges de surface peuvent également fournir des informations intéressantes sur la rhéologie de la Terre, rejoignant l'utilisation plus classique des charges de surface pour placer des contraintes sur la viscosité du manteau dans des problèmes de rebond post-glaciaire. Par exemple, [Chanard et al. \(2018a\)](#) ont utilisé les données GRACE pour tester l'adéquation des déformations terrestres liées aux charges atmosphériques, océaniques et hydrologiques avec les viscosités transitoires proposées dans différentes études post-sismiques, plaçant ainsi des contraintes intéressantes sur la relaxation post-sismique.

1.4.4 Mouvements du pôle

Le pôle terrestre, point de croisement dans l'hémisphère nord entre la surface et l'axe de rotation, est en mouvement. Mesuré depuis plus d'une centaine d'années à l'aide de données astrométriques, ce mouvement est principalement circulaire à une période proche de l'année mais présente également une dérive à long terme.

Les données GRACE sont utiles pour différencier les causes des changements du mouvement basse fréquence de la position du pôle. [Adhikari and Ivins \(2016\)](#) ont montré que les oscillations décennales du mouvement du pôle peuvent être expliquées par la variabilité du signal de variations globales dans les stocks d'eau. Les données GRACE ont également permis de montrer que plus de 90% du changement long terme observé depuis 2005 dans le mouvement du pôle est explicable par l'accélération de la fonte des glaces et de son impact sur le niveau des mers ([Chen et al., 2013](#)).

1.4.5 Océanographie

Même si les variations de gravité en domaine océanique sont bien plus faibles que celles de l'hydrologie continentale, certains signaux océanographiques ont été clairement identifiés dans les données GRACE. Combinées aux hauteurs de la surface de la mer mesurées par altimétrie, les données GRACE permettent notamment de séparer les contributions des effets stériques (variation de volume liée à la variation de température) des effets non-stériques aux variations de la hauteur de la surface océanique ([Chambers, 2006](#), [Willis et al., 2008](#)). Quantifier l'effet stérique est fondamental pour la compréhension de la montée du niveau moyen des mers suite au changement climatique qui est un problème sociétal majeur.

Les anomalies de masse en domaine océanique sont également proportionnelles à la pression au plancher des océans, et peuvent être utilisées pour améliorer les modèles de circulation océanique ([Zlotnicki et al., 2007](#)), et/ou être comparées à des mesures ponctuelles pour séparer les effets locaux des effets régionaux ([Morison et al., 2007](#)). La mission GRACE a par exemple permis de cartographier les variations de la pression de plancher des océans ([Chambers and Bonin, 2012](#)) ou de mettre en évidence des signaux anormaux de cette pression dans l'océan Austral ([Boening et al., 2011](#)).

La large utilisation des données GRACE ainsi que la nécessité d'avoir des solutions toujours plus raffinées ont motivé le développement d'une méthode plus objective de filtrage de ces données présentée dans le chapitre suivant.

DATA-ADAPTIVE SPATIO-TEMPORAL FILTERING OF GRACE DATA

In this chapter, we combine GRACE solutions expressed in terms of SHs from five analysis centers and use M-SSA to isolate geophysical signals and minimize processing errors. This combination allows to use a filter which damps small wavelengths less than the commonly used filters. After describing in Section 2.1 the GRACE data used in this study, we introduce briefly the M-SSA method in Section 2.2 and describe the procedure that we have used to clean up the GRACE dataset and test it out on synthetic dataset and hydrological model.

2.1 GRACE Level-2 Solutions

The GRACE satellite mission, launched in 2002 and decommissioned in 2017, has provided maps of the Earth's gravity field with a spatial resolution of a few hundred kilometers and a temporal resolution of 1 month ([Bettadpur, 2012](#), [Dahle et al., 2013](#), [Mayer-Gürr et al., 2016](#), [Watkins and Yuan, 2012](#)) to 10 days ([Tapley et al., 2004](#), [Lemoine et al., 2013](#)). Several processing centers have released constrained and/or unconstrained solutions in terms of SHs ([Wahr et al., 1998](#)) and surface mass density grids usually expressed in equivalent water height (EWH) with a given water density. Although processing strategies differ, solutions are consistent within ± 50 mm EWH, but also exhibit both systematic and random noise ([Sakumura et al., 2014](#)). The raw GRACE data are called Level-1, while the processed data are called Level-2.

In this study, we use monthly solutions expressed in SHs from five analysis centers for which specifications are given in Table 2.1; these centers are listed below:

1. CSR – the Center for Space Research of the University of Texas;
2. GFZ – the German Research Centre for Geosciences;

Chapter 2. Data-adaptive spatio-temporal filtering of GRACE data

#	Center	Version	Max. deg.	Start	End	Dealiasing
1	CSR	RL05	90	04/2002	06/2017	AOD1B RL05
2	GFZ	RL05a	90	04/2002	12/2016	AOD1B RL05
3	GRAZ	ITSG2016	90	04/2002	12/2016	AOD1B RL05
4	JPL	RL05	60	04/2002	06/2017	AOD1B RL05
5	GRGS	RL03	80	08/2002	05/2016	ERA-Interim and TUGO

Table 2.1 – GRACE datasets used in this study, with the truncation degree of the spherical harmonics (SH) decomposition, the starting and ending dates of data availability for each solution, and the dealiasing models used for the atmosphere and ocean masses. AOD1B is the Atmosphere and Ocean De-aliasing Level-1B model developed by the GFZ ([Flechtner et al., 2013](#)), TUGO is the Toulouse Unstructured Grid Ocean model ([Lyard, 2010](#)), and ERA-Interim is a reanalysis of the global atmosphere using a fixed version of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric model and data assimilation method, along with atmospheric observations that start in 1979 ([Dee et al., 2011](#)).

3. GRAZ – the Institute of Geodesy of the University of Graz;
4. JPL – NASA’s Jet Propulsion Laboratory; and
5. GRGS – the French Research Group for Spatial Geodesy.

Four of the gravity solutions in Table 2.1, namely (1)–(4), are unconstrained, and therefore require — prior to any geophysical application — post-processing to remove noise in the higher SH coefficients of the gravity field, including striping artifacts. We also use the regularized solution (5) but apply the same post-processing filters to all 5 solutions for consistency. Note also that solution (5) is based on a dealiasing approach different from that of solutions (1)–(4), as described in Table 2.1.

The noise is huge in unconstrained solutions and our attempts to proceed directly, i.e. without prefiltering these solutions was unsuccessful. We decided then to apply a filter to all the solutions. To filter and de-stripe the GRACE solutions used in this study, we adopt first the largely used DDK filter ([Kusche, 2007](#), [Kusche et al., 2009](#)). DDK is a non-isotropic decorrelation filter based on a regularization of the normal equation; it uses a priori error covariance matrices derived from GRACE processing. The DDK filter offers several levels of smoothing, with DDK1 being the strongest one, and DDK8 the weakest. As the smoothing intensity decreases, the

geophysical signal is better preserved but the errors become larger and manifest themselves mainly as North–South stripes.

For geophysical applications, the processing centers recommend an average of solutions from the official processing centers (CSR, GFZ and JPL), to which the DDK5 spatial filter has been applied (Sakumura et al., 2014). This recommendation is meant to insure a good compromise between signal retained and noise removed. Figure 2.1a shows, as an example, the mean of GRACE mass anomaly DDK5-filtered solutions from CSR, GFZ and JPL for the month of January 2006, relative to July 2005. Figure 2.1b presents, for the same period, the mean of the data provided by all 5 centers used in this study, filtered with the weaker DDK7 filter.

The variations recorded by the mean, DDK5-filtered GRACE solution over a 6-month interval exhibits North–South stripes characteristic of the error pattern of the GRACE data. Also visible are regions of smoothed geophysical signal that correspond to known large annual hydrological variations, in the Amazon basin or Southeast Asia, for example. Figure 2.2 shows the maps of mean mass rates from January 2003 to December 2014 for the official solution, based on the mean of the three official centers filtered with DDK5 and for the mean of the five centers used in this study, filtered with the weaker DDK7 filter.

In this study, in order to more accurately locate such geophysical signals in the GRACE solutions, we apply the DDK7 filter, a weaker degree of filtering than DDK5, to all five Level-2 GRACE solutions.

2.2 Methodology

2.2.1 Multichannel Singular Spectrum Analysis (M-SSA)

Starting from GRACE Level-2 solutions, post-processed with the DDK7 filter, we developed a methodology that is as objective as possible — i.e., that makes use of the smallest amount of a priori information — to preserve geophysical signals while removing the spurious random and processing noise. As the GRACE dataset exhibits correlations in both time and space,

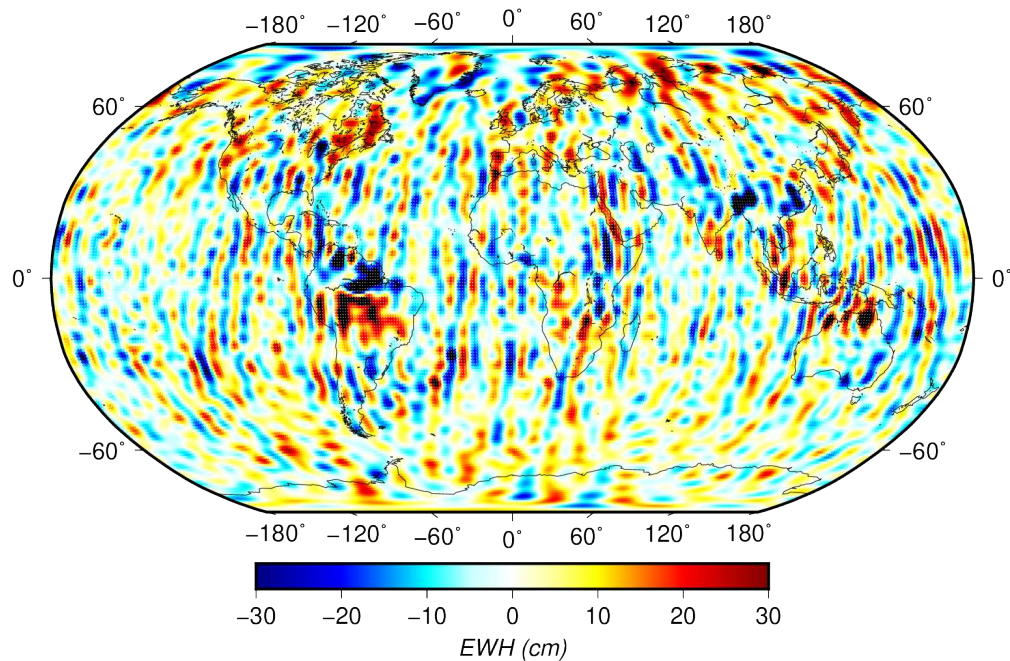
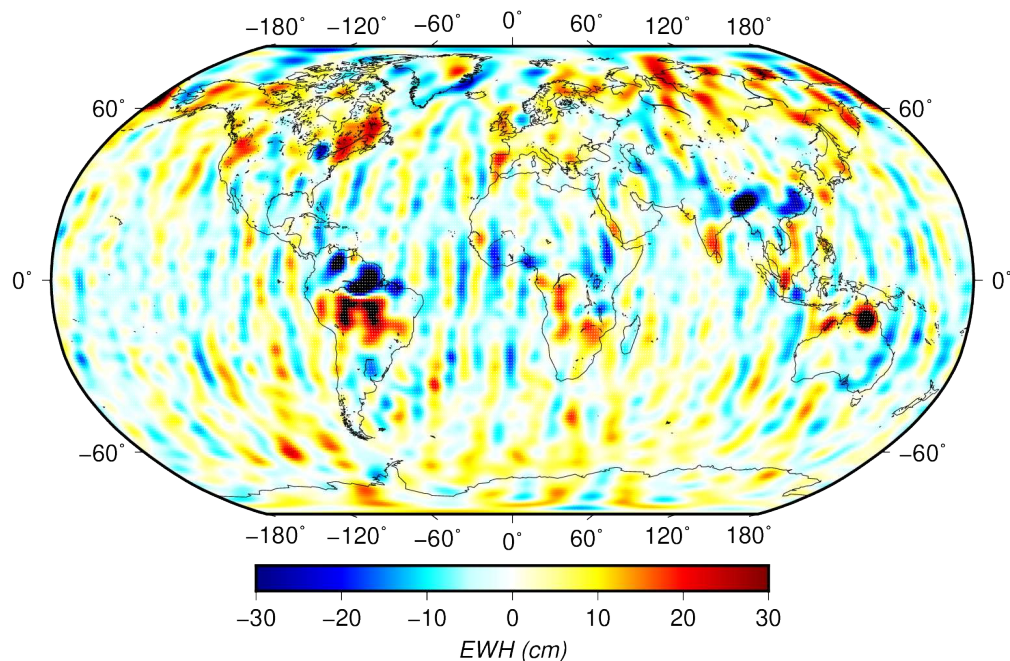


Figure 2.1 – Surface mass density anomaly solutions for January 2006, relative to July 2005, expressed in equivalent water height (EWH, in cm).

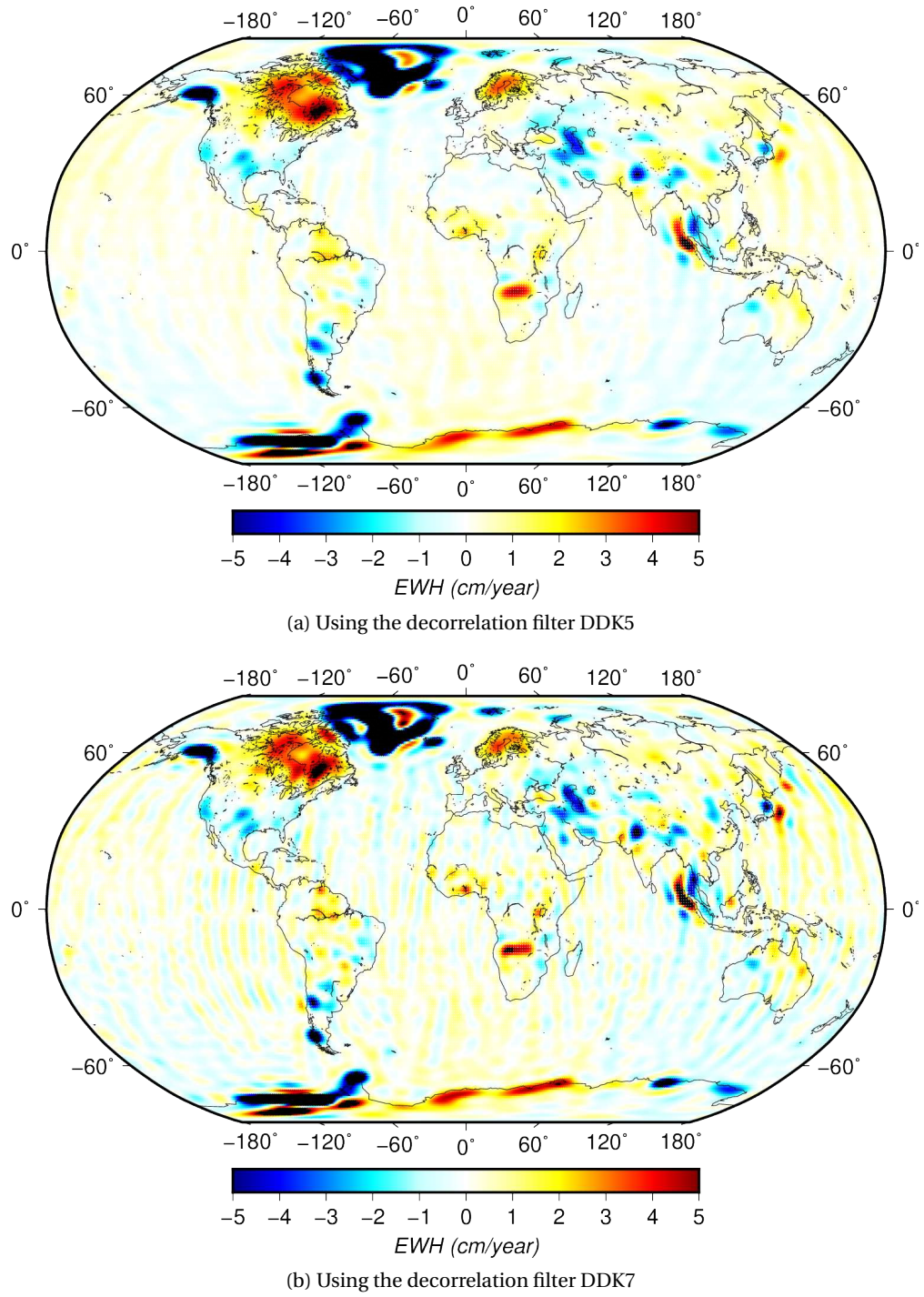


Figure 2.2 – Mean of JPL, GFZ and CSR surface mass density rates from 2003 to 2015 expressed in equivalent water height per year (in cm/year), derived from GRACE.

we adopt a data-adaptive method that simultaneously exploits these correlations, namely the Multichannel Singular Spectrum Analysis (M-SSA) ([Vautard and Ghil, 1989](#), [Ghil and Vautard, 1991](#), [Vautard et al., 1992](#), [Ghil et al., 2002](#), [Alessio, 2016](#)). The Singular Spectrum is the spectrum of singular values, which equal the square roots of the positive eigenvalues of a covariance matrix, and are obtained by singular-value decomposition of the matrix. The term Multichannel or, alternatively, Multivariate refers to the simultaneous use of several time series.

We present here the general M-SSA methodology which will be applied twice hereafter, first on an ensemble of time series consisting of the coefficients from the five centers for a given spherical harmonic (step 1: see Section 2.2.2), and second on the EWH time series at seven given points (step 2: see Section 2.2.3).

M-SSA extracts from the data a set of empirical orthogonal functions (EOFs) representing the common spatio-temporal modes of variability of the time series being analysed ([Ghil et al., 2002](#), [Walwer et al., 2016](#), and references therein). The M-SSA and its advantages over usual methods like univariate SSA or PCA are well described by [Walwer et al. \(2016\)](#).

The time series one wants to study can then be projected onto these EOFs, and thus provide a decomposition into components that correspond either to trends with variable slope, oscillations or noise. Because the EOFs are directly deduced from the data, the M-SSA does not require a priori information on the spatio-temporal characteristics of the time series.

Let us take an ensemble of L time series

$$\{\mathbf{X}_l(t) : l = 1, \dots, L; t = 1, \dots, N\}, \quad (2.1)$$

N being the number of data points in each. In the cases treated here, all the time series need to have the same constant sampling interval Δt .

The main idea of M-SSA is to exploit the covariance information contained in series of M lagged copies of all the $\mathbf{X}_l(t)$'s ([Ghil et al., 2002](#), [Walwer et al., 2016](#)). The choice of the window length M must be made according to the dataset to optimize the quantity of information extracted, while maintaining satisfactory statistical confidence. On the one hand, increasing

M allows to extract signals with larger periods because the extracted signals have periods that are at most $M * \Delta T$. On the other hand, larger M leads to lower values for the ratio N/M which implies lower statistical significance of the signals extracted with the M-SSA.

We start by constructing the matrix $\widetilde{\mathbf{X}}_l$ that includes M time-delayed copies of the original time series $\mathbf{X}_l(t)$ as its columns:

$$\widetilde{\mathbf{X}}_l = \begin{pmatrix} \mathbf{X}_l(1) & \mathbf{X}_l(2) & \cdots & \mathbf{X}_l(M) \\ \mathbf{X}_l(2) & \mathbf{X}_l(3) & \cdots & \mathbf{X}_l(M+1) \\ . & . & \cdots & . \\ . & . & \cdots & . \\ \mathbf{X}_l(N') & \mathbf{X}_l(N'+1) & \cdots & \mathbf{X}_l(N) \end{pmatrix}, \quad (2.2)$$

where $N' = N - M + 1$.

The covariance matrix $\mathbf{T}_{l,l'}$ between two time series $\mathbf{X}_l(t)$ and $\mathbf{X}_{l'}(t)$ has a $(M \times M)$ size and is given by:

$$(\mathbf{T}_{l,l'})_{j,j'} = \frac{1}{\tilde{N}} \sum_{n=\max(1,1+j-j')}^{\min(N,N+j-j')} \mathbf{X}_l(n) \mathbf{X}_{l'}(n+j'-j), \quad (2.3)$$

with

$$\tilde{N} = \min(N, N+j-j') - \max(1, 1+j-j') + 1. \quad (2.4)$$

These matrices are the blocks of a grand covariance matrix $\tilde{\mathbf{T}}$ of size $(L \times M) \times (L \times M)$:

$$\tilde{\mathbf{T}} = \begin{pmatrix} \mathbf{T}_{1,1} & \mathbf{T}_{1,2} & . & . & . & \mathbf{T}_{1,L} \\ \mathbf{T}_{2,1} & \mathbf{T}_{2,2} & . & . & . & \mathbf{T}_{2,L} \\ . & . & . & . & . & . \\ . & . & . & \mathbf{T}_{l,l'} & . & . \\ . & . & . & . & . & . \\ \mathbf{T}_{L,1} & \mathbf{T}_{L,2} & . & . & . & \mathbf{T}_{L,L} \end{pmatrix}. \quad (2.5)$$

The eigenvalues λ_k and eigenvectors $\mathbf{E}^k$ diagonalize the matrix $\tilde{\mathbf{T}}$, cf.

$$\tilde{\mathbf{T}}\mathbf{E}^k = \lambda_k \mathbf{E}^k. \quad (2.6)$$

The eigenvectors $\mathbf{E}^k$ are called spatio-temporal EOFs (ST-EOFs) and are concatenations of L segments $\mathbf{E}_l^k$ of length M . The projection of the rows of the matrix $\tilde{\mathbf{X}} = (\tilde{\mathbf{X}}_1, \tilde{\mathbf{X}}_2, \dots, \tilde{\mathbf{X}}_L)$ onto the eigenvectors $\mathbf{E}_k$ gives the corresponding spatio-temporal principal components (ST-PCs) $\mathbf{A}^k(t)$:

$$\mathbf{A}^k(t) = \sum_{j=1}^M \sum_{l=1}^L \mathbf{X}_l(t+j-1) \mathbf{E}_l^k(j). \quad (2.7)$$

The ST-PCs $\{\mathbf{A}^k(t) : k = 1, \dots, L \times M\}$ can be thought of as temporal modes of variability that are shared across the time series being analysed. The eigenvalues $\{\lambda_k\}$ constitute the eigenspectrum; each of them equals the fraction of the variance of the entire dataset that is captured by the corresponding ST-PC. We shall also refer to the ST-PCs as simply PCs, for brevity.

Given the eigendecomposition above, one can partially reconstruct the time series $\mathbf{X}_l(t)$ using the ST-PCs and ST-EOFs (Ghil and Vautard, 1991, Vautard et al., 1992). The partially reconstructed signal $\mathbf{R}_l^k(t)$ associated with the ST-EOF $\mathbf{E}^k$ and ST-PC $\mathbf{A}^k$ is given by:

$$\begin{cases} \mathbf{R}_l^k(t) = \frac{1}{M} \sum_{j=1}^M \mathbf{A}^k(t-j+1) \mathbf{E}_l^k(j) & \text{for } M \leq t \leq N-M+1, \\ \mathbf{R}_l^k(t) = \frac{1}{t} \sum_{j=1}^t \mathbf{A}^k(t-j+1) \mathbf{E}_l^k(j) & \text{for } 1 \leq t \leq M-1, \\ \mathbf{R}_l^k(t) = \frac{1}{N-t+1} \sum_{j=t-N+M}^M \mathbf{A}^k(t-j+1) \mathbf{E}_l^k(j) & \text{for } N-M+2 \leq t \leq N. \end{cases} \quad (2.8)$$

These partial reconstructions (RC) $\{\mathbf{R}_l^k\}$ are filtered versions of the original time series that contain only the spatio-temporal modes selected. The original time series can be reconstructed by summing the entire set of $\mathbf{R}_l^k(t)$'s:

$$\mathbf{X}_l(t) = \sum_{k=1}^{L \times M} \mathbf{R}_l^k(t). \quad (2.9)$$

Note that the ST-PCs $\mathbf{A}^k(t)$ have length N' , while the RCs $\mathbf{R}_l^k(t)$ have full length N .

2.2.2 Step 1

We simultaneously apply M-SSA to the five time series of each of the 8277 SH coefficients of GRACE Level-2 solutions DDK7-filtered from the five processing centers described in Section 2.1, over the time interval August 2002–March 2016, i.e., $N = 164$ months and $L = 5$. We use a lag window of size $M = 13$ months in order to capture the annual signal that dominates the GRACE time series. This first step of our filtering procedure is somewhat related to the filtering in the time-domain of each SH proposed by [Wouters and Schrama \(2007\)](#) except that we involve here the data from five processing centers and use then the M-SSA rather than a simple SSA.

Data gaps exist in the GRACE time series and need to be filled prior to the M-SSA analysis. To do so, we used a data-adaptive gap-filling algorithm based on single-channel singular spectrum analysis (SSA gap filling: [Kondrashov et al., 2005](#), [Kondrashov and Ghil, 2006](#)). First, we linearly interpolate the n missing data $\{d_k : 1 \leq k \leq n\}$, with $n \ll N$, in each SH coefficient time series $\mathbf{X}_l(t)$ independently. Next, we perform an SSA analysis iteratively until the χ^2 ,

$$\chi^2 = \left\{ \frac{\sum_{k=1}^n (d_k^{(p-1)} - d_k^{(p)})^2}{\sigma_{(p-1)} \cdot \sigma_p} \right\}^{1/2}, \quad (2.10)$$

between the reconstructed missing signal at iteration p , $\{d_k^{(l,p)} : 1 \leq k \leq n\}$, with associated least-square error $\sigma^{(p,l)}$, and its previous iteration $p - 1$, satisfies $\chi^2 < 0.1$. In the above equation we dropped the index l of the time series being interpolated for simplicity.

Figure 2.3 shows the normalized 65 leading eigenvalues obtained from all the M-SSA analyses of the SH coefficient series from the five GRACE analysis centers used in this work. One observes a rapid decrease in the normalized eigenvalues, with a low plateau starting roughly at rank 8. The first 8 corresponding ST-EOFs capture, therefore, most of the variance of the original dataset, while the other ST-EOFs represent what we shall consider as noise in the data. These 8 leading ST-EOFs capture around 83% of the total variance up to degree 20, around 60% for degrees 21 to 40, and around 50% for degrees 41 to 90.

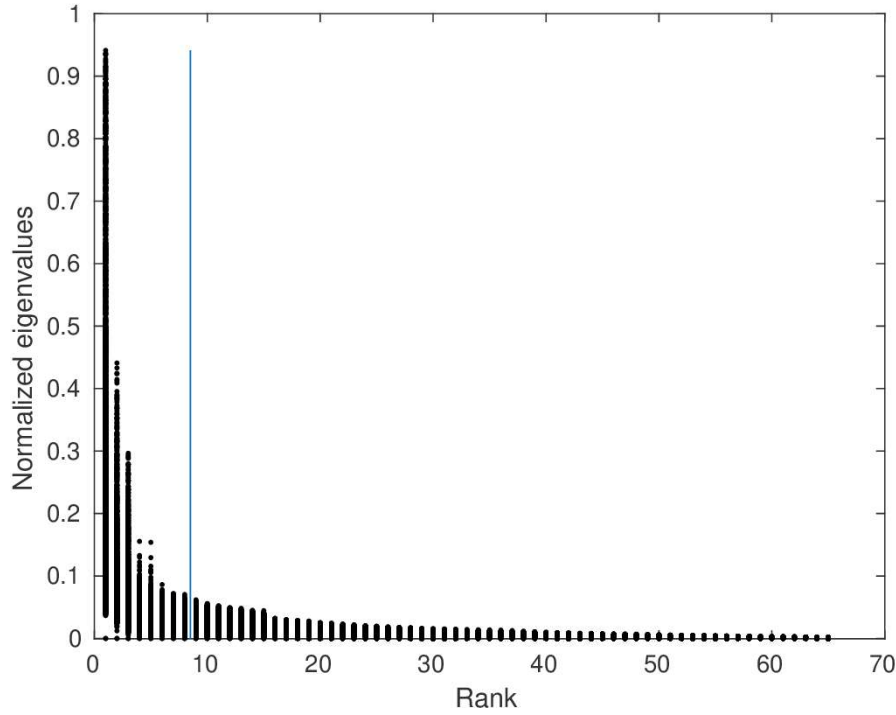


Figure 2.3 – Normalized 65 leading eigenvalues from all 8277 M-SSA analyses performed on the spherical harmonics (SH) coefficients available in the GRACE solutions from the 5 analysis centers in Table 2.1 (one spectrum per SH i.e. one per M-SSA analyses). The blue line is placed after rank 8, the rank at which the eigenvectors are not used in our reconstructions.

Figure 2.4 shows as an example visually made combinations of the RCs obtained from the M-SSA spatio-temporal decomposition of the time series of SH coefficients $C_{3,1}$ from the 5 processing centers ; note that for this coefficient, some of the noise may be due its resonance with the Earth rotation. Here we use the standard notation $C_{l,m}$ for SHs, with l the degree and m the order. The RCs of other SH coefficients are given in appendix Figure A.1.

In this particular case, the first 8 ST-PCs capture about 80% of the total variance of the dataset. Here RCs 1–8 in panels (a)–(c) of Figure 2.4 represent a long-term nonlinear trend (RCs 1+7), annual (RCs 2+3), and semi-annual (RCs 4–6+8) signals and they show a strong correlation among all five GRACE solutions, but RC 9 in panel (d) does not. We discarded, therefore, this component from the analysis. In panel (e), moreover, we notice that the reconstructed signal based on the first 8 ST-PCs is generally consistent among all 5 analysis centers, but may sometimes differ for one of them, as seen during year 2003 or in late 2011–early 2012.

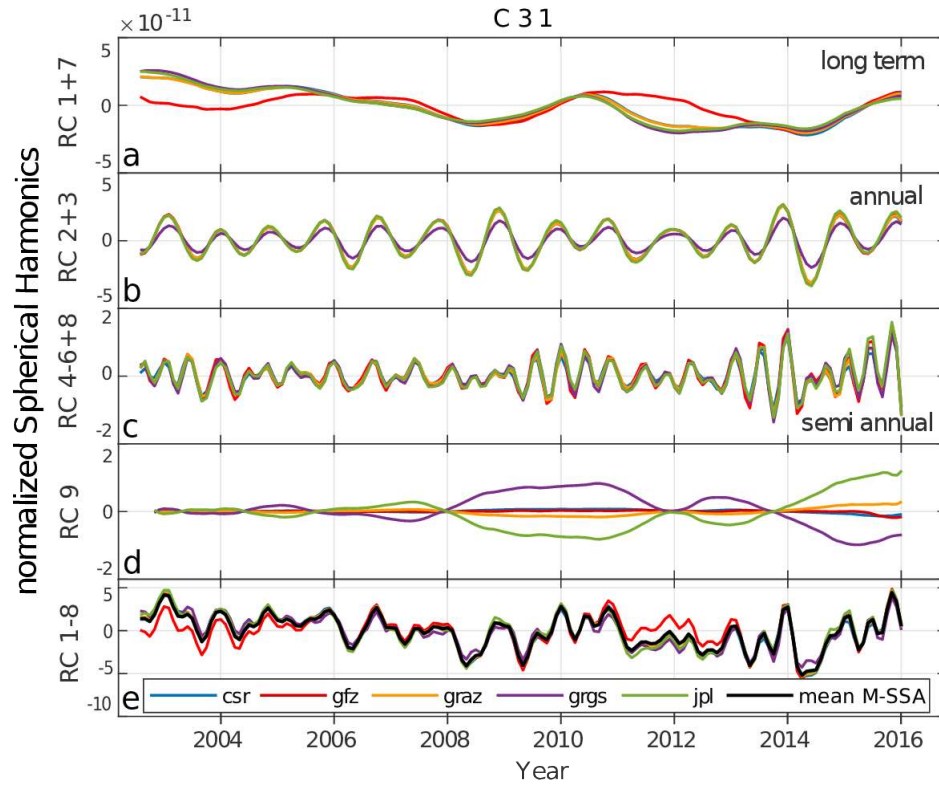


Figure 2.4 – Multichannel Singular Spectrum Analysis (M-SSA) decomposition of GRACE SH $C_{3,1}$. The source of the Level-2 data is shown by colors: CSR (blue), GFZ (red), GRAZ (yellow), CNES/GRGS (purple), and JPL (green). The first 3 panels, (a)–(c), show a visually made combinations of partial reconstructions (RCs) of similar nature for each processing center. These RC combinations correspond to (a) long-term trend, along with (b) annual, and (c) semi-annual signals that are all three coherent between processing centers, while the 9th RC in panel (d) shows discrepancies between centers; the latter are most likely due to differences in processing strategies. The bottom panel (e) shows the signal reconstructions using the first 8 RCs for each of the 5 GRACE solutions, as well as their mean (black).

We similarly computed an M-SSA decomposition for each of the 8277 SH coefficients (up to degree 90) from the 5 GRACE processing centers, and reconstructed a filtered signal by retaining RCs 1–8 only, considering that after the eighth component, noise becomes larger than the retrieved geophysical signal. We finally average these 5 reconstructions, as shown by the black curve in Figure 2.4e. This procedure amounts to a “smart mean” that exploits the coherent signals from the 5 independent GRACE processing centers, while filtering out the noise (which of course contributes to the signal variance) — without using a priori information or any hypothesis on the structure of the noise. Note that when a center doesn’t provide a SH

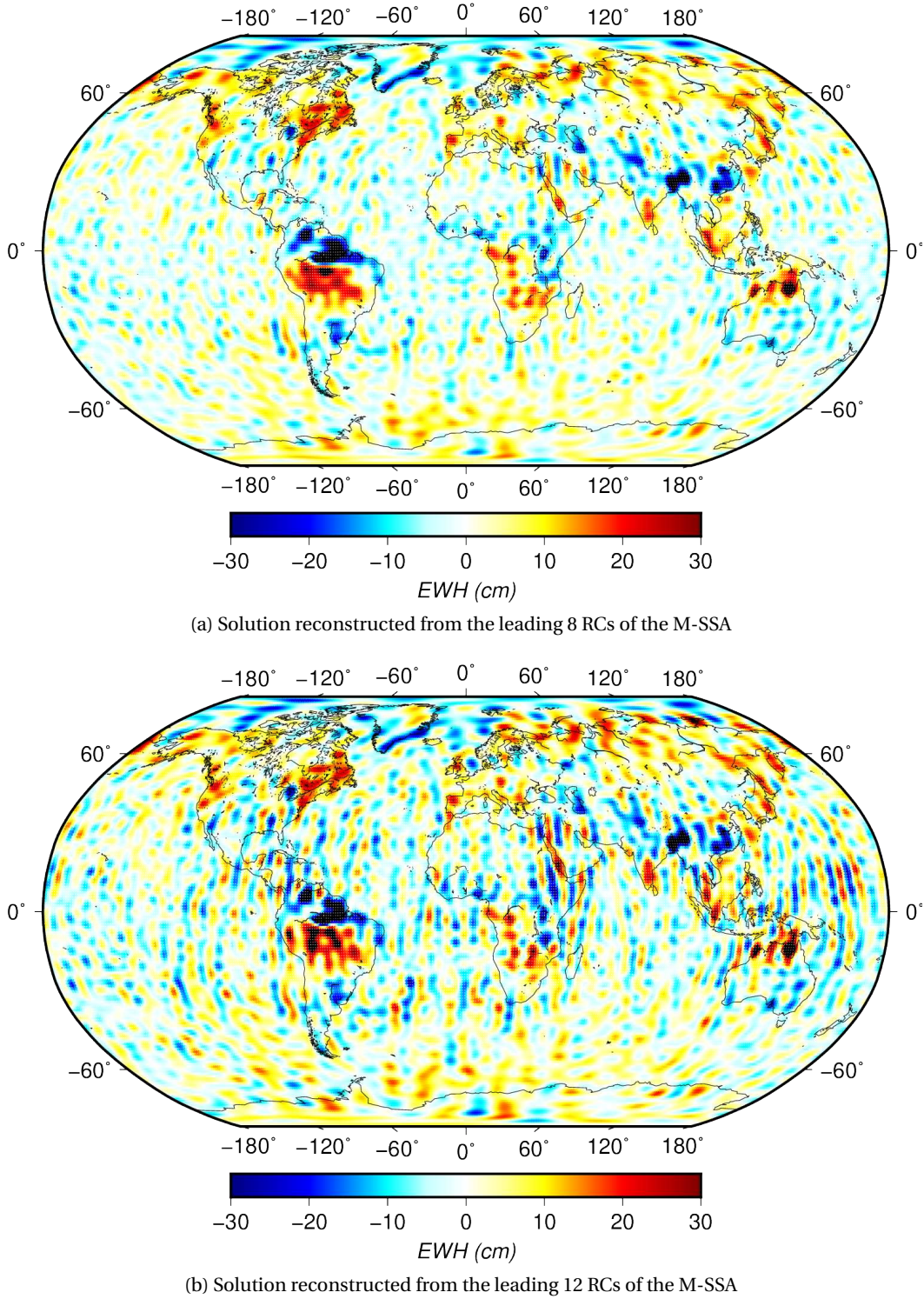


Figure 2.5 – Surface mass density anomalies solutions for January 2006 relative to July 2005, expressed in equivalent water height (EWH, in cm), from the intermediate M-SSA GRACE solution obtained from the mean of all 5 processing centers' signals filtered with DDK7 and reconstructed with 8 or 12 RCs of the M-SSA applied to SHs.

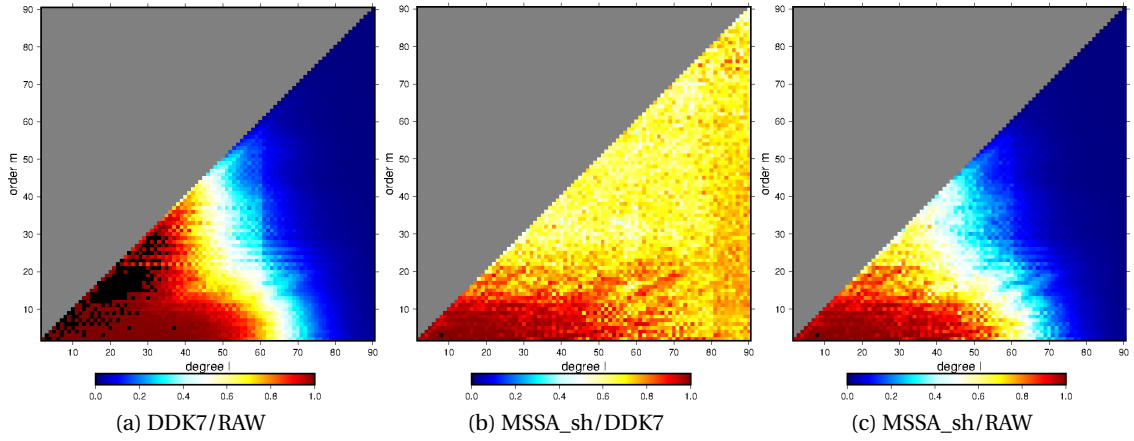


Figure 2.6 – Standard deviation ratio of time dependent spherical harmonics $Y_{lm}(t)$ between (a) the mean of the five centers filtered with DDK7 and the mean of the raw ones; (b) M-SSA filtered (step 1) and the mean of the DDK7 filtered ones; (c) M-SSA (step 1) filtered and the mean of the raw ones.

coefficient, due to the difference in maximum degree, we apply our M-SSA analysis to all the available time series for this SH coefficient.

The resulting, filtered and averaged SH coefficients are then transformed to $1^\circ \times 1^\circ$ gridded maps of EWH. Figure 2.5a shows, as an example, a map of the EWH for the month of January 2006, relative to July 2005. As can be seen in Figure 2.5a, adding more PC essentially adds stripes (i.e. noise). The comparison with the widely used mean of the CSR, GFZ and JPL EWH solutions, after application of the DDK5 filter (Figure 2.1a), shows that the intermediate M-SSA GRACE solution, obtained after this step, in Figure 2.5a here reduces considerably the North–South stripes, while preserving the location and shape of geophysical signals. The amplitude ratio of the spherical harmonics before and after filtering with the DDK7 filter and before and after applying the M-SSA on the SH are presented in Figure 2.6. It can be seen that the M-SSA reduces significantly the amplitude of large order spherical harmonics (by a factor close to 2) in view of the fact that they are the one containing the North-South information. However, the effect of M-SSA is very different from that of a classical (gaussian, DDK) spatial filter. M-SSA removes the erratic part of the time-dependent signal but not the coherent part.

2.2.3 Step 2

To further improve the intermediate M-SSA GRACE solution described in the previous section, by keeping 8 modes of the M-SSA filtered spherical harmonics coefficients, and to reduce the residual spatial noise, we now apply the M-SSA method to the time series of EWH gridded maps based on the M-SSA-derived SHs, such as the one in Figure 2.5a. To do so, we apply M-SSA to the EWH time series at each point of the $1^\circ \times 1^\circ$ grid, simultaneously with EWH time series at 6 neighboring points that are located at the same latitude and spaced 2° apart, see Figure 2.7f. The choice of the localisation and of the number of points is linked to the shape and width of the North–South stripes, and it takes into account the rapid increase in computing time as the number of time series considered increases.

The final GRACE M-SSA solution is given by the RCs of the EWH decomposition, where we retain the eight leading components that allow us to reconstruct the dominant part of the signal, while reducing the noise. Figure 2.7(a–e) shows the M-SSA decomposition of the EWH time series at latitude 41° N and longitude 51° E, in the Caspian Sea. Similar times series are given at other grid points in appendix Figure A.2.

For the point in Figure 2.7, by applying M-SSA to the EWH time series, we retrieve (a) a long-term variation, (b) a strong annual mode, (c) a long-term oscillating mode, and (d) a semi-annual mode. All four components are statistically robust, i.e. statistically significant for a window length between a year and a decade. Therefore, they are likely to be geophysical signals of interest.

The amplitude ratio of the spherical harmonics after applying M-SSA on the SH and after applying M-SSA on the spatial grids, and before any filtering and after applying M-SSA on the spatial grids are presented in Figure 2.8.

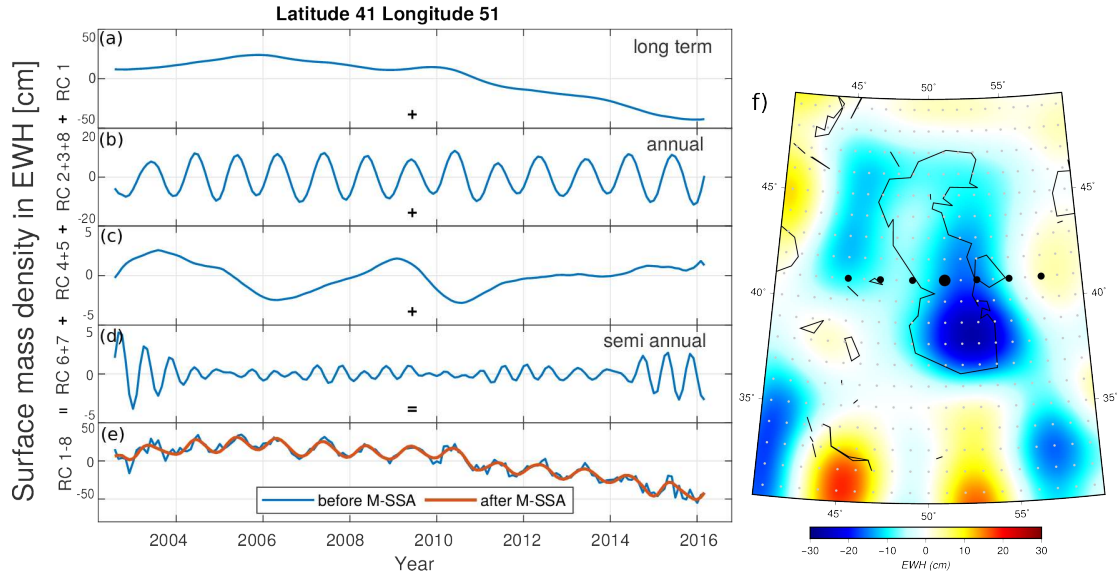


Figure 2.7 – (a - e) M-SSA-based spatio-temporal decomposition of GRACE data-derived surface mass density anomalies time series at latitude 41° N and longitude 51° E, in the Caspian Sea. The first 4 panels show a single RC, in panel (a), or a sum thereof, in panels (b)–(d). The bottom panel shows the time series prior to the final M-SSA (blue) and the signal reconstructed using the leading 8 RCs of the gridded EWH values (red). (f) Surface mass density anomalies around the Caspian Sea for January 2006 relative to July 2005, expressed in equivalent water height (EWH, in cm) from the intermediate M-SSA GRACE solution obtained from the mean of all 5 processing centers' signals reconstructed from the leading 8 RCs of the M-SSA applied to SHs. In black, the points of the seven time series used in the M-SSA spatio-temporal decomposition presented in panels (a - e)

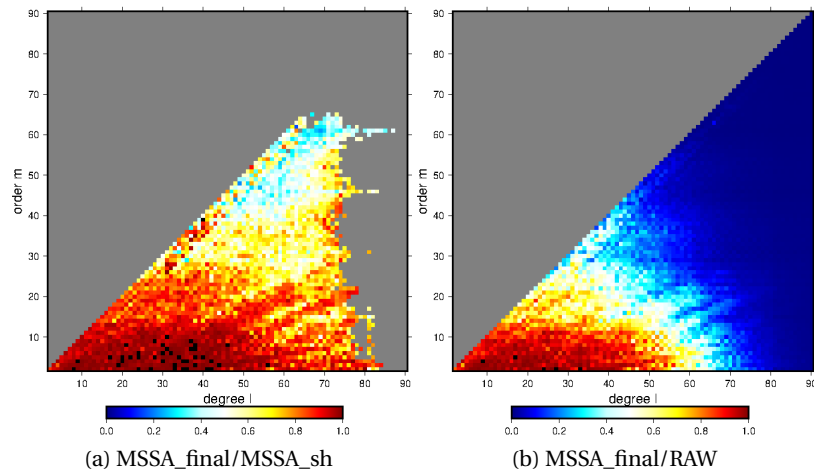


Figure 2.8 – Standard deviation ratio of time dependent spherical harmonics $Y_{lm}(t)$ between (a) M-SSA (step 2) filtered and M-SSA (step 1) filtered ones; and (b) M-SSA (step 2) filtered and the mean of the raw ones.

2.2.4 Synthetic tests

In order to evaluate the methodology used here to retrieve the physical signal from GRACE, we ran two kinds of tests:

A test on North-South stripes

With this first test, we seek to determine how the M-SSA method erases or preserves North-South stripes depending upon their temporal modulation. Because spurious NS stripes in GRACE data are caused by dealiasing errors in model predictions and accelerometer noise, they are expected to appear at random times in a given area. On the opposite, an actual geophysical signal that would also have a spatial pattern elongated in a NS direction would be correlated in time with the surrounding areas at the GRACE data spatial scale. Because of the very different temporal characteristics of noise and signal, the M-SSA should be able to remove a NS stripe that appears at random times but preserve a NS stripe that corresponds to an actual geophysical signal.

We tested this by adding a NS stripe in South America to our final solutions, which consist of one realization per month from 2002 to 2016, with two temporal patterns represented schematically at the top of Figure 2.9. In the first case, the NS stripe is introduced into one of the months only (Figure 2.9b). This is meant to simulate a spurious NS stripe that one seeks to filter out. In a second case, the NS stripe is modulated in amplitude through time with an annual period across the 162 realizations. This is meant to simulate a geophysical signal of interest elongated in the NS direction. The maximum amplitude of the stripe is 10 cm EWH in both cases, as shown in Figure 2.9a.

As shown on Figure 2.9, the M-SSA method effectively removes the spurious NS stripe (Figure 2.9b) but preserves the simulated annual geophysical signal (Figure 2.9c). This is due to the fact that the annual mode of variability introduced is one of the leading ones in the actual geophysical signal that surrounds the NS stripe. It is therefore preserved by the M-SSA, while the one-time stripe, which is not correlated in time with its surroundings, is removed.

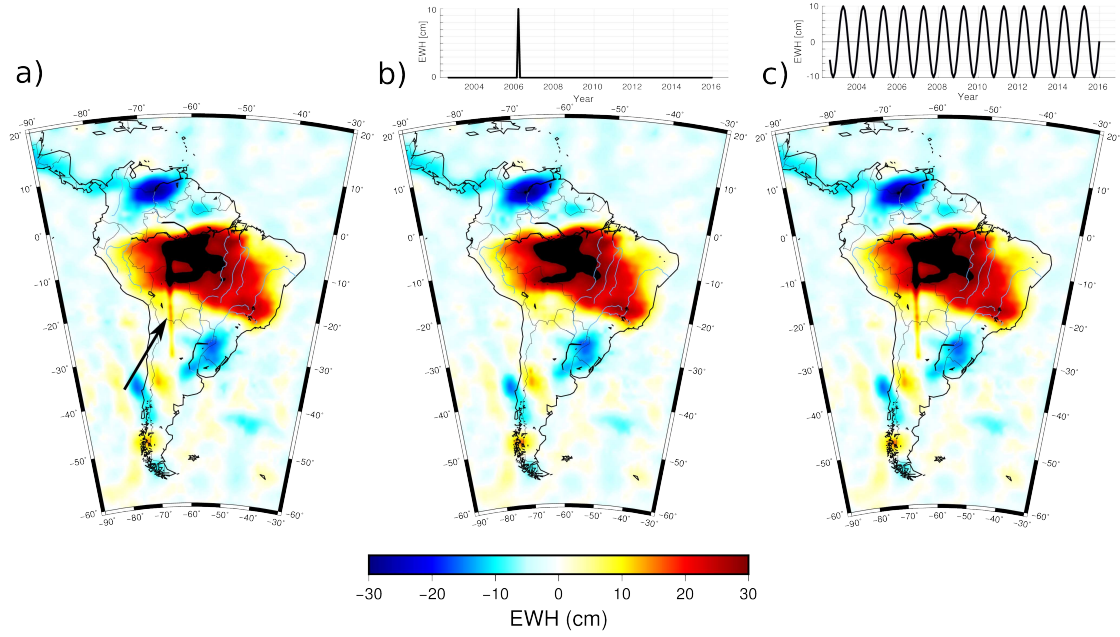


Figure 2.9 – Surface mass density anomalies solutions for March 2006, expressed in equivalent water height (EWH, in cm). (a) The M-SSA GRACE solution in South America with a North-South stripe of 10 cm amplitude (shown by the black arrow); (b) the solution obtained using the M-SSA on a signal with one-time stripe inserted in March 2006; and (c) the solution obtained using the M-SSA on a signal with a stripe modulated in amplitude through time with an annual period.

This simple test shows that the M-SSA can efficiently eliminate spurious stripes while preserving geophysical signals whose temporal patterns are present in the surroundings. However, if erratic local peaks were present in the hydrological signal, they would also be suppressed by the M-SSA procedure.

A test on the GLDAS model data

With this second test, we seek to determine whether the M-SSA method preserves the actual spatial and temporal modulations of the global hydrological signal. To do so, we use version 2.1 of the Global Land Data Assimilation System (GLDAS), which is based on land surface modeling and data assimilation (Rodell et al., 2004, Beaudoin and Rodell, 2016). We expect such a model to contain the same space- and time-dependent features as the actual hydrological

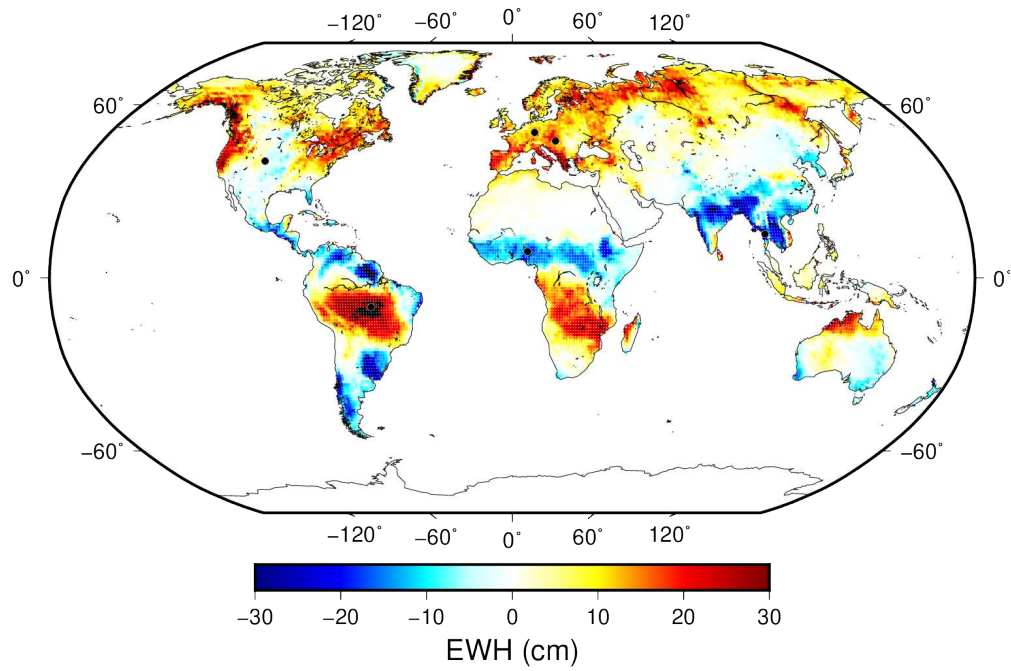
signal we seek to retrieve from GRACE, without being affected by erratic NS stripes of course.

We build the input signal by adding the monthly $1^\circ \times 1^\circ$ GLDAS grids for terrestrial water storage corresponding to snow, canopy and soil water between the surface and 2 m depth (Figure 2.10a, GLDAS model data from https://giovanni.gsfc.nasa.gov/giovanni/#service=TmAvMp&starttime=&endtime=&dataKeyword=GLDAS_NOAH10_M). We then apply to the resulting grids (1) the DDK7 filter only, and (2) the second step of the M-SSA method from August 2002 to March 2016. As described above the M-SSA method uses the DDK7-filtered signal as starting point. Figure 2.10 shows the result in terms of the EWH difference between the months of January 2006 and July 2005.

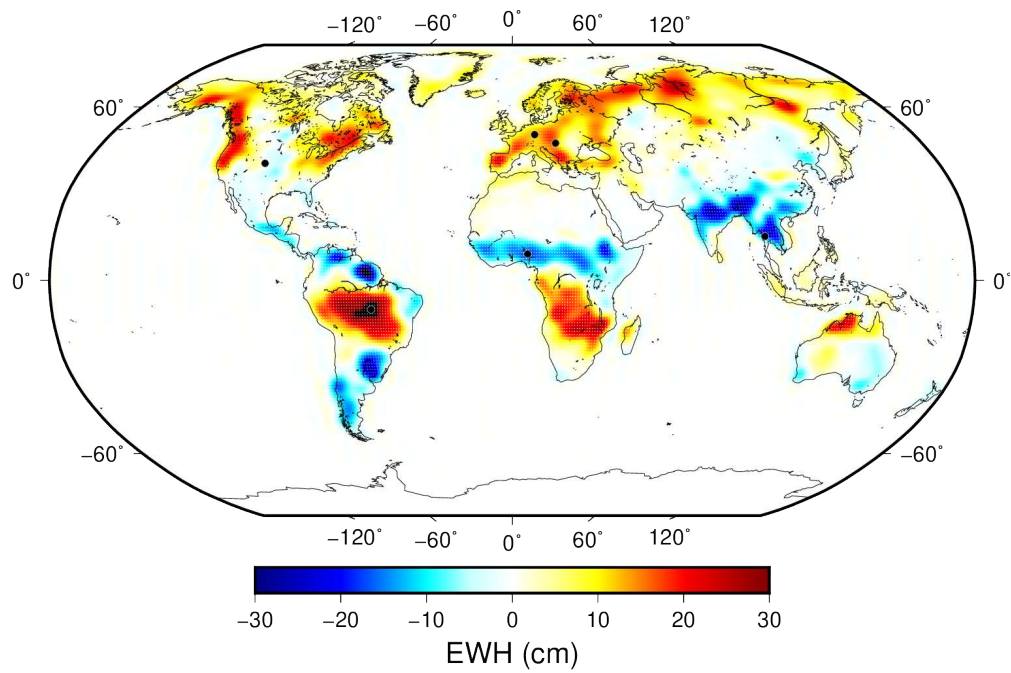
The DDK7-filtered solution, displayed in Figure 2.10b, simply smoothes the input signal. A small amplitude spurious signal elongated in the North-South direction is visible in the oceans: this is an expected consequence of the filtering of a high amplitude spot on a continent by a decorrelating filter (see figure 4 of [Swenson and Wahr, 2006b](#)). The general shape and amplitude of the original signal are otherwise well preserved.

The M-SSA solution, displayed in Figure 2.10c, is very similar to the DDK7-filtered one of Figure 2.10b. Indeed, the 8 leading ST-PCs of the M-SSA used here retrieve more than 98% of the input signal. Therefore, in the likely hypothesis that the actual hydrological signal has the same spatial and temporal characteristics as the GLDAS model data, it is appropriate to apply the M-SSA procedure to retrieve hydrological signals from GRACE data.

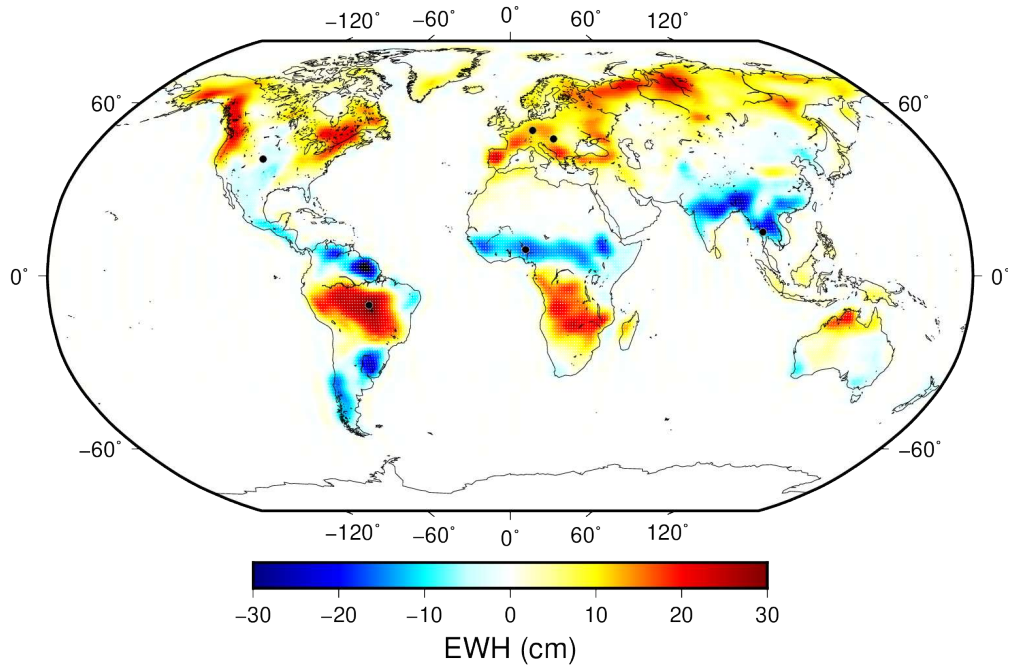
We also compare in Figure 2.11 the EWH time series at 6 locations of where the hydrological signal is important, one in North America, one in South America, two in Europe, one in Asia, and one in Africa. We observe that the 8 leading components used for the M-SSA reconstructions allows for an accurate reproduction of the input GLDAS signal, except for a few sharp peaks that mostly appear at the Colorado location (Figure 2.11a). There, the M-SSA reconstruction reproduces well the 2012 drought but misses spikes present in the GLDAS input signal in 2009



(a) GLDAS before filtering



(b) GLDAS after the DDK7 filter



(c) GLDAS after M-SSA on the data filtered with DDK7

Figure 2.10 – Total water storage from GLDAS data for January 2006 relative to July 2005, expressed in equivalent water height (EWH, in cm). The black dots are the points for which we plotted the time-series before and after M-SSA in Figure 2.11.

and 2015, for instance. This may result from the fact that the M-SSA method, by construction, removes information that is not correlated in time and space. When we add a few more RCs, the sharp peaks are still poorly reproduced as shown in Figure 2.11a.

The other locations displayed on Figure 2.11 show a very good agreement between the input GLDAS model data and the M-SSA reconstructions. This is expected for the quasi-sinusoidal time series at a location in Brazil (panel b) but also visible for more irregular ones. For instance, the summer droughts of 2003 and 2015 in Europe are well-reproduced at a location in Germany (panel c). Also, the Danube basin wet summers of 2005, 2010, and 2014, associated with elevated soil water content, are visible at a location near Budapest (panel d). We also chose a coastal location in Thailand (panel f) in order to detect potential artifacts that may be caused at the interface between signal and no signal, but find that the input time series at that location is also well reproduced by the M-SSA method.

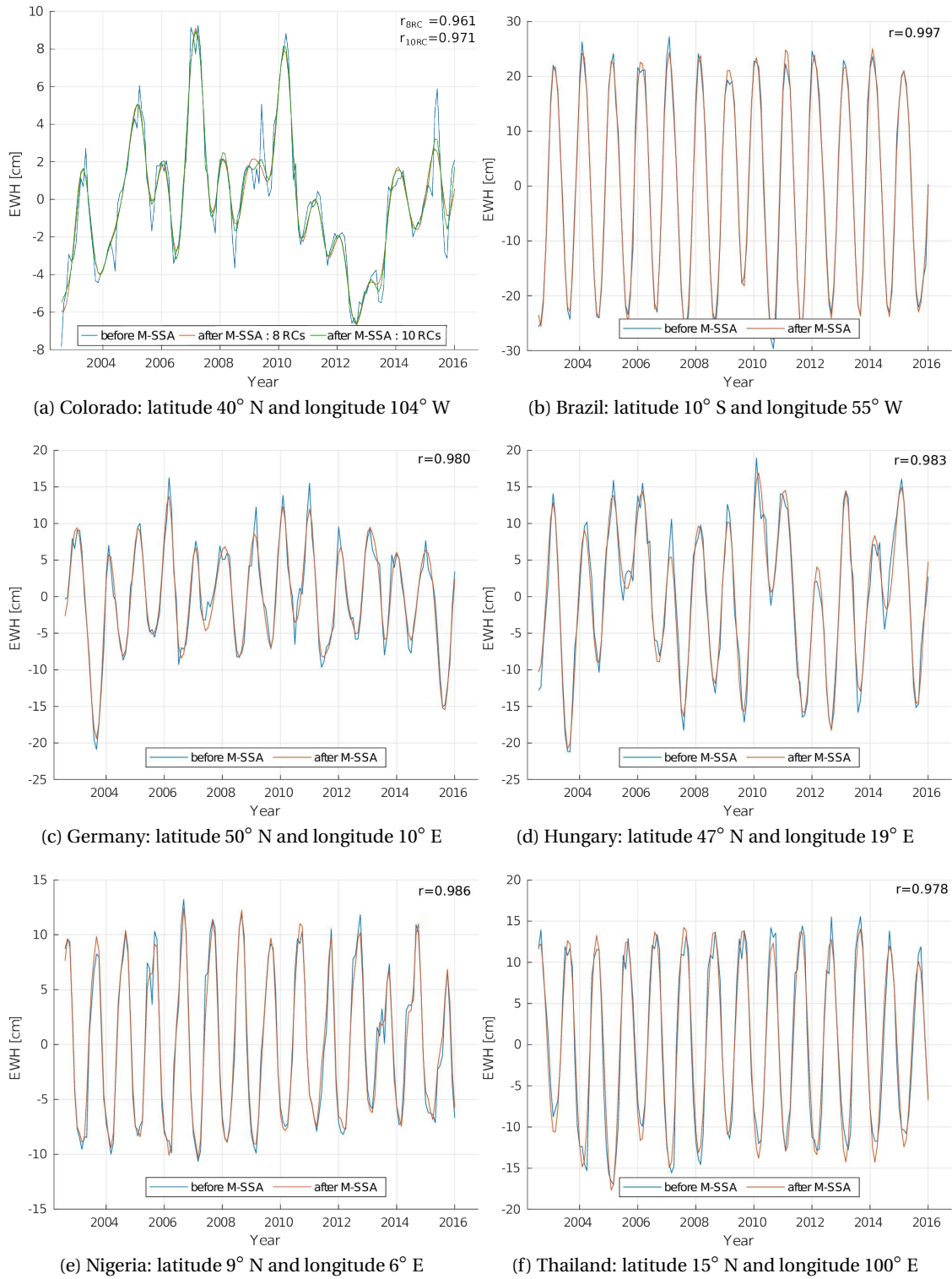


Figure 2.11 – Time series of total water storage from GLDAS data before (blue) and after (red) the M-SSA with 8 RCs, and r the correlation coefficient between these time series.

2.3 Resulting GRACE solution

2.3.1 Results using GRACE Level 2 RL05 data

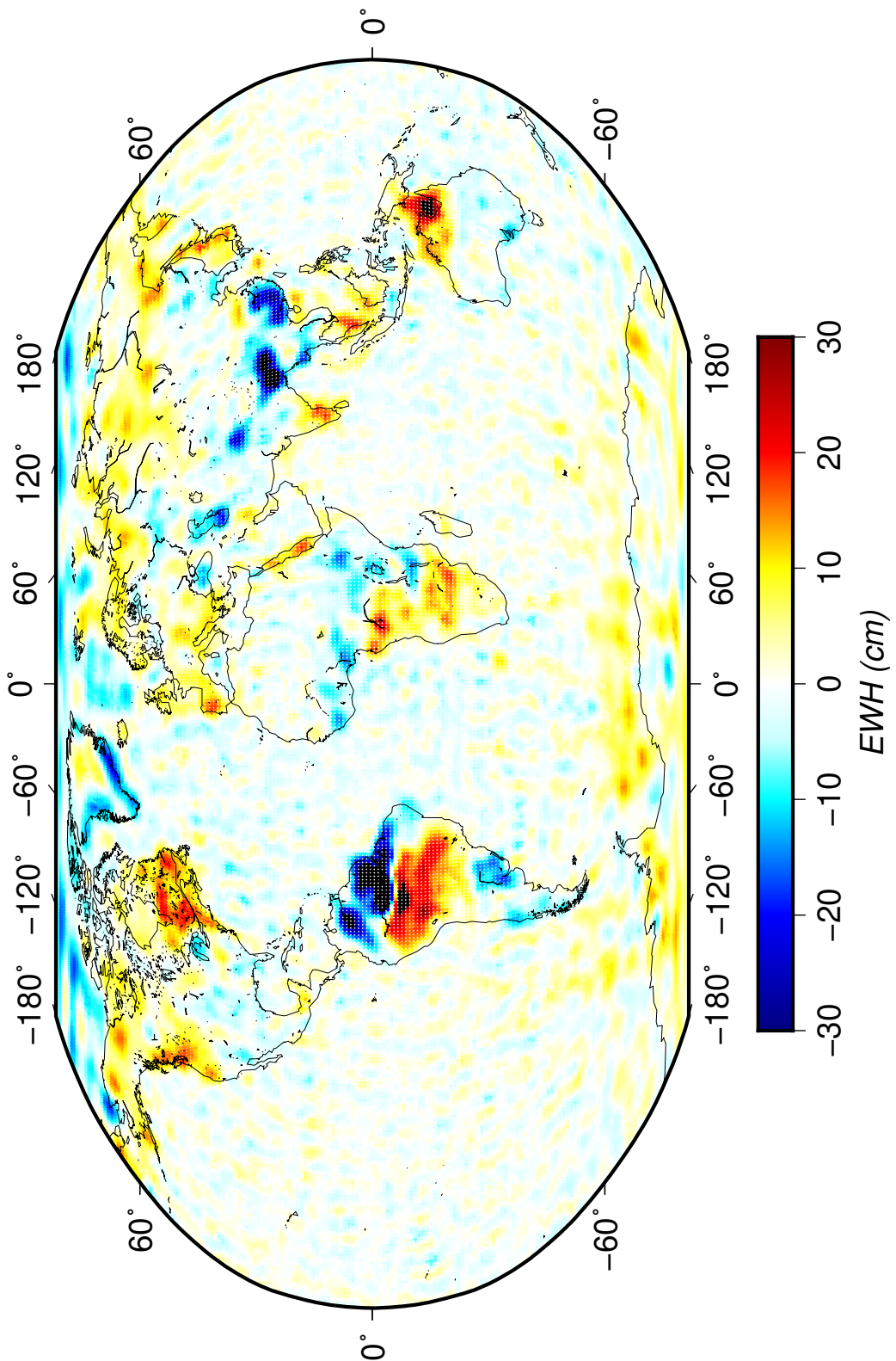
Figure 2.12a shows the final M-SSA v1 solution of GRACE mass anomaly for the month of January 2006 relative to July 2005 and Figure 2.12b shows the mean rate of mass variations from January 2003 to December 2014. North-South stripes have been efficiently reduced and coherent signals are preserved in terms of location and shape in regions in which a geophysical signal is expected — whether due, for instance, to post-seismic deformation or to surface loading. For example, in terms of continental hydrology, the signal in the M-SSA solution of Figure 2.12a is more compact in the Amazon basin and in West and South Africa than in the standard SH solution of Figure 2.1a.

2.3.2 Results using GRACE Level 2 RL06 data

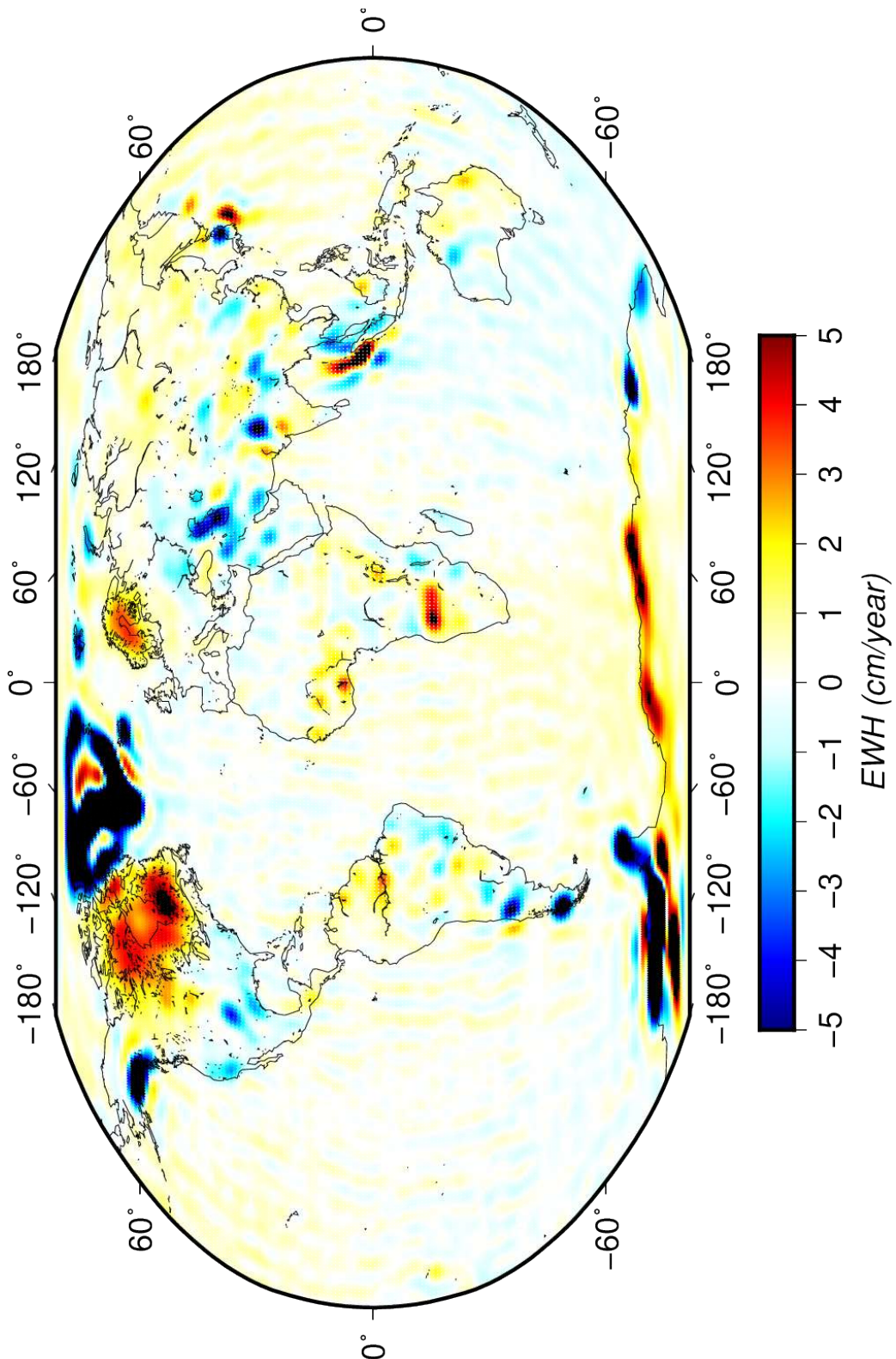
In 2018, the Star Camera and K-Band Range Level-1B GRACE products were reprocessed and published in the Level-1B RL03 dataset. This was used, along with other updates and improvements, to release new GRACE Level-2 data – called RL06 for the official calculation centers. This new version of the Level-2 data uses improved parameterizations and updated background models like the Atmosphere and Ocean De-aliasing Level-1B (AOD1B) RL06 model developed by the GFZ ([Dobslaw et al., 2017](#)).

Out of the five centers producing the data we used in the previous part, only the GRGS didn't release a new dataset using the L1B RL03 data. Therefore, to make a new M-SSA GRACE solution, the v2, we used only four datasets – presented in Table 2.2 – to which we applied the same methodology as the one presented in Section 2.2.

Figure 2.13a shows the final M-SSA v2 solution of GRACE mass anomaly for the month of January 2006 relative to July 2005 and Figure 2.13b shows the mean rate of mass variations from January 2003 to December 2013.



(a) the final M-SSA GRACE v1 solution for January 2006 relative to July 2005.



(b) Mean rate from January 2003 to December 2014 given in cm/year for the M-SSA GRACE v1 solution.

Figure 2.12 – Surface mass density anomalies and mean rate of M-SSA GRACE v1 solution expressed in equivalent water height.

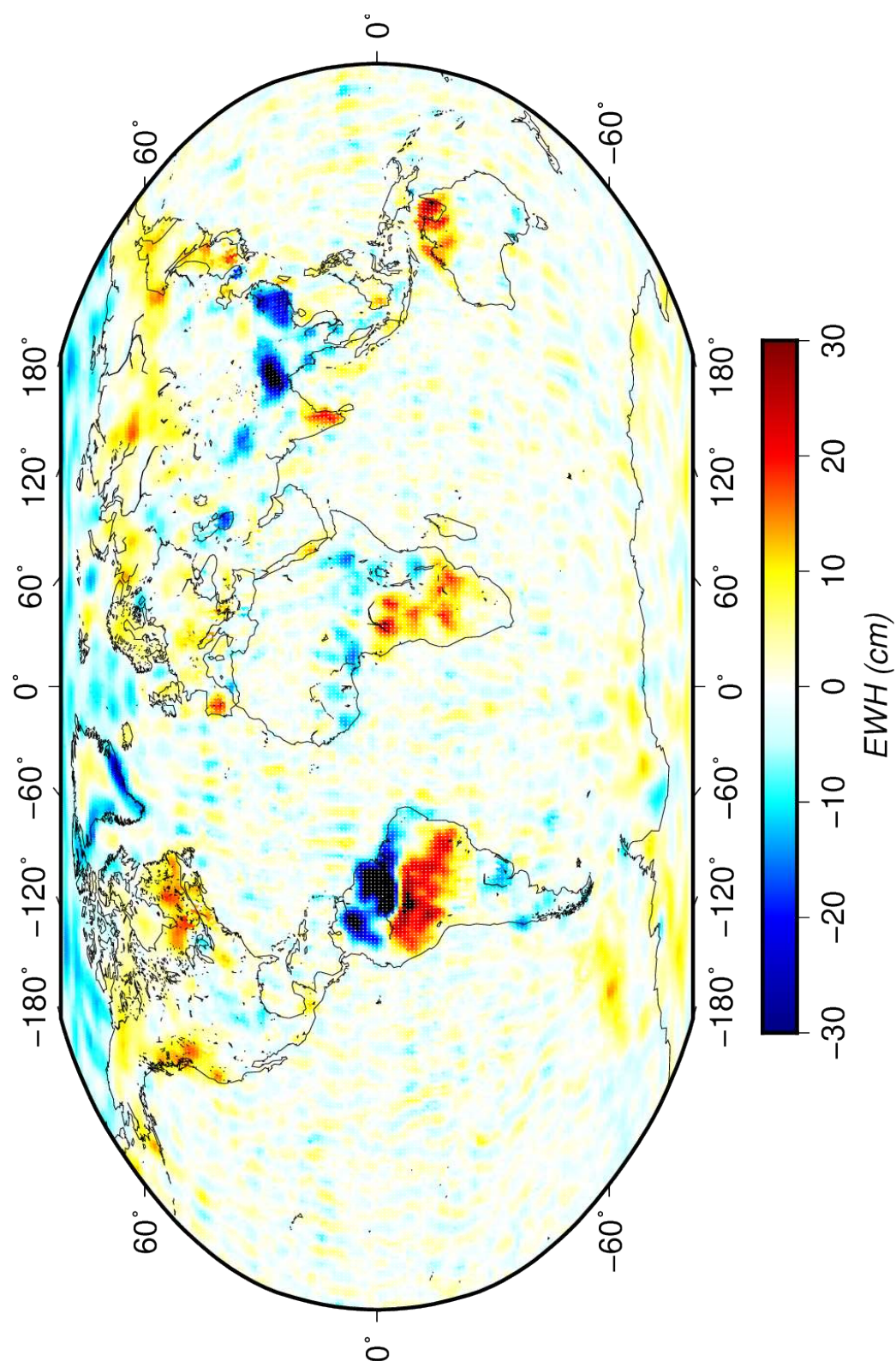
2.3. Resulting GRACE solution

#	Center	Version	Max. deg.	Start	End	Dealiasing
1	CSR	RL06	96	04/2002	08/2016	AOD1B RL06
2	GFZ	RL06	96	01/2003	08/2016	AOD1B RL06
3	GRAZ	ITSG2018	96	04/2002	08/2016	AOD1B RL06
4	JPL	RL06	96	04/2002	08/2016	AOD1B RL06

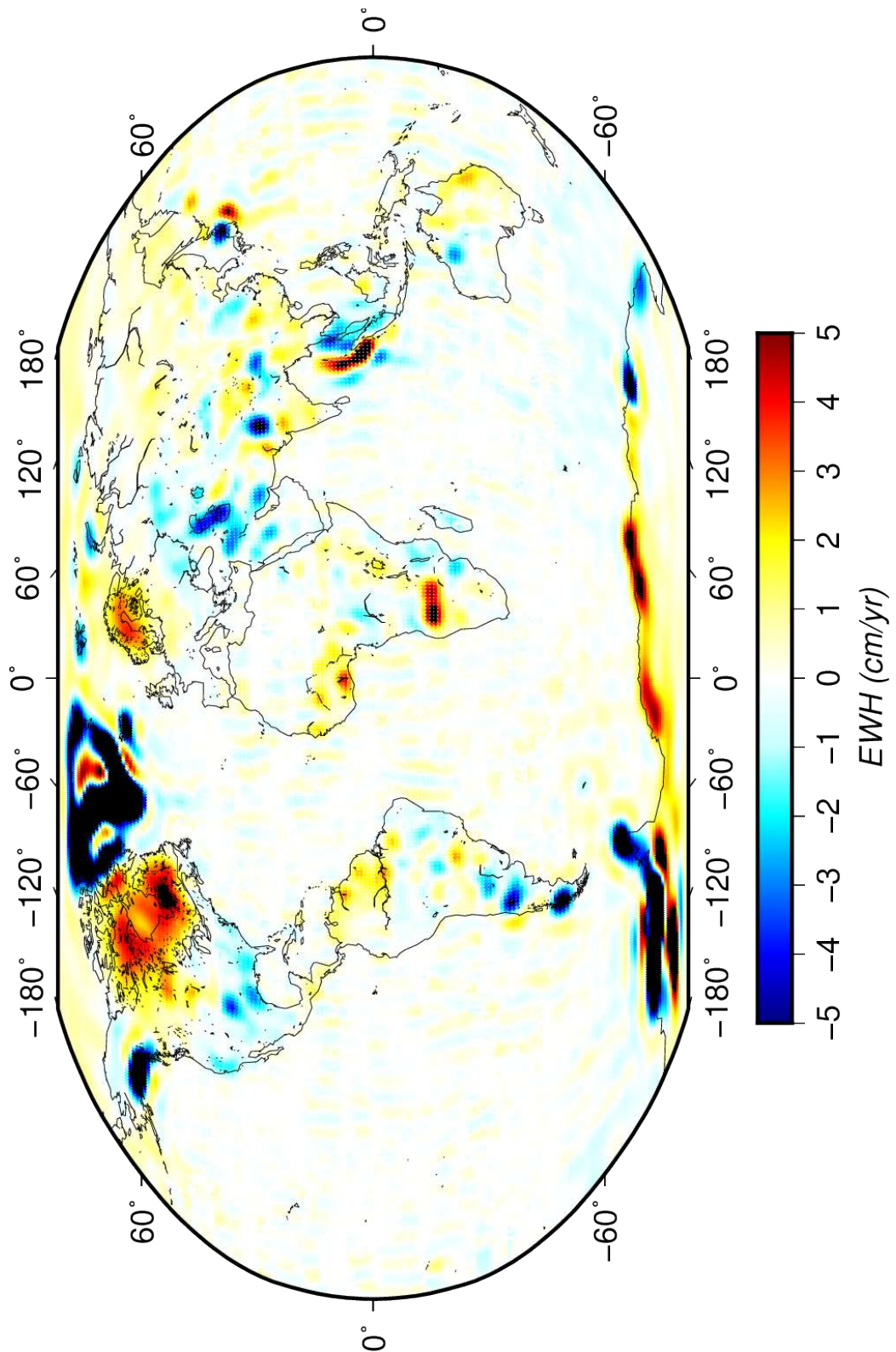
Table 2.2 – GRACE datasets used for this M-SSA GRACE v2 solution, with the truncation degree of the spherical harmonics (SH) decomposition, the starting and ending dates of data availability for each solution at the moment of the study, and the dealiasing models used for the atmosphere and ocean masses. AOD1B is the Atmosphere and Ocean De-aliasing Level-1B model developed by the GFZ ([Dobslaw et al., 2017](#)).

If we compare M-SSA solutions v1 from Figure 2.12 and v2 from Figure 2.13, we see that the noise level in the ocean is substantially similar but a slightly smaller in South Atlantic in the latest results. In continental hydrology, the noise is smaller in the v2 and the geophysical signal presents less leakage.

In the next chapter, we compare our GRACE M-SSA solutions to other published GRACE solutions.



(a) the final M-SSA GRACE v2 solution for January 2006 relative to July 2005.



(b) Mean rate from January 2003 to December 2013 given in cm/year for the M-SSA GRACE v2 solution.

Figure 2.13 – Surface mass density anomalies and mean rate of M-SSA GRACE v2 solution expressed in equivalent water height.

COMPARISON OF THE M-SSA GRACE SOLUTION TO OTHER SOLUTIONS

3.1 Global comparison with other GRACE solutions

3.1.1 Comparison with other SH solutions

Here, we compare, the M-SSA GRACE v1 solution with two other SH solutions. The first one is the average of the solutions from the three official GRACE processing centers (CSR, GFZ and JPL), where the DDK5 filter is applied ([Sakumura et al., 2014](#)). This solution, recommended by the official centers and largely used, is plotted in Figure 2.1a. The second one is the mean of the 5 solutions used in this study, filtered with the weaker DDK7 filter, which is the starting filter applied before implementing the M-SSA analysis described in the previous chapter.

Figure 3.1 shows the differences between the mean of all 5 GRACE solutions, each filtered by DDK7, and the M-SSA solution on the one hand, and between the mean of the DDK5-filtered solutions of the 3 official centers (CSR, JPL and GFZ) and the M-SSA solution on the other hand ; once more, the plot is for the month of January 2006, relative to July 2005. Similar maps for difference with the 5 GRACE SH solutions are given in appendix Figure B.3 and for mass rate differences between January 2003 and December 2014 in Figure 3.2.

These maps show that the M-SSA methodology, as used in this study, is efficient at removing North–South stripe artefacts from GRACE SH solutions, whether compared to solutions filtered with DDK5 or DDK7. The M-SSA method allows one to start with the DDK7-filtered solutions therefore producing a less smoothed geophysical signal than the one present after DDK5

3.1. Global comparison with other GRACE solutions

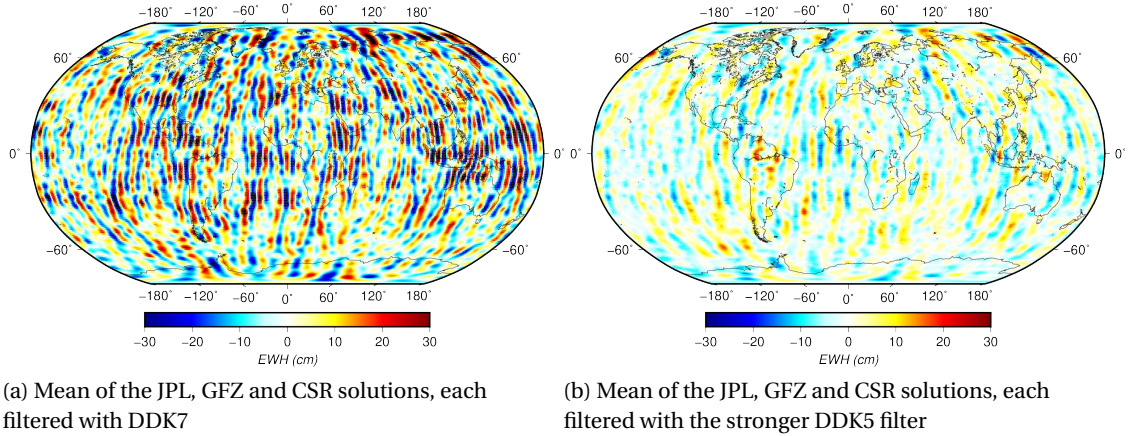


Figure 3.1 – Surface mass density anomalies differences for January 2006 relative to July 2005, expressed in EWH (in cm), between a solution and the solution obtained herein after M-SSA step 2.

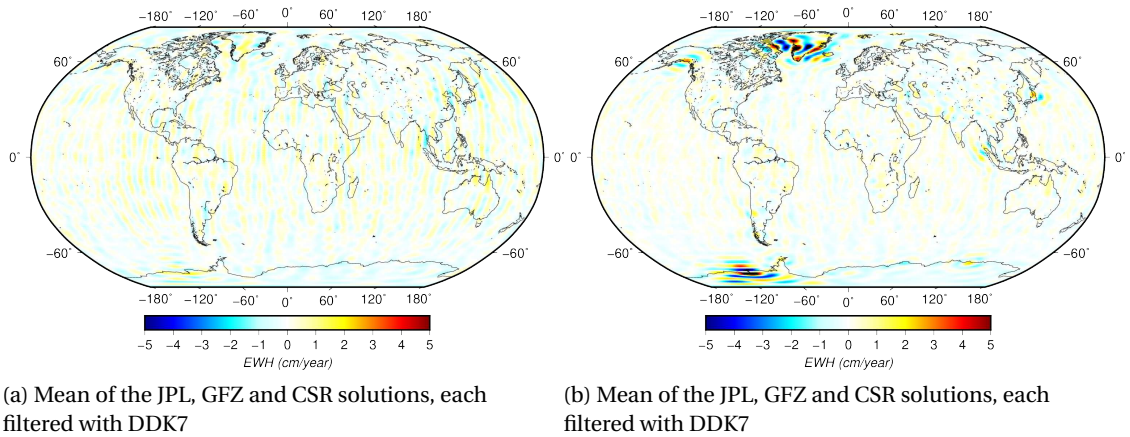


Figure 3.2 – (a) Surface mass density rates from 2003 to 2015 differences expressed in equivalent water height per year (in cm/year), between a solution and the M-SSA solution.

filtering (Figures 2.1a and 2.12a).

The final M-SSA GRACE solution, as illustrated in Figure 2.12a, contains limited spurious noise and more localized signals than the recommended 3-center average of GRACE SH solutions in Figure 2.1a. Excellent localization is apparent, for example, in the Amazon basin, in West and South Africa, and around the Caspian Sea.

3.1.2 Comparison with mascons solutions

Mascons are mass concentration blocks, onto which GRACE ranging observations are fitted (Luthcke et al., 2013, Watkins et al., 2015, Save et al., 2016). Mascon solutions require for geophysical constraints to be implemented within the GRACE processing, contrary to the standard SH approach. A priori geophysical constraints help reduce GRACE Level-2 noise compared to the standard post-processing by DDK filtering. By construction, mascon solutions do not allow North–South stripes and exhibit well-localized hydrological signals with no significant leakage effect, as seen, for instance, in Figure 3.3a for the Amazon basin or the Greenland ice mass loss.

In this comparison, we use the mascons solutions from CSR, JPL and the NASA Goddard Space Flight Center (GSFC). Figure 3.3 shows maps of the amplitude of mass anomalies for January 2006 relative to July 2005, for these three solutions. They all use a division of the Earth in equal surface mass concentration parcels, but the processing differs between the three solutions. The CSR solution (Save et al., 2016) and the GSFC solution (Luthcke et al., 2013) both represent each mascon function by finite spherical harmonics expansion while the JPL solution (Watkins et al., 2015) represent them by analytical expression. Furthermore, the CSR solution uses a regularization process and GRACE spherical harmonics as a priori information ; the GSFC solution uses spatial and temporal constraints based on previous mascons solutions as well as a spatial restriction to ground ice area in high latitude ; and the JPL solution uses near-global geophysical model and altimetric data as a priori.

To compare the M-SSA solution to the mascon ones, the ocean and atmospheric de-aliasing models had to be restored over the ocean. The de-aliasing models presented in Table 2.1 are average and added to the final M-SSA GRACE solution; this corrected solution is illustrated in Figure 3.4. The differences between this solution and the mascons ones are illustrated in Figure 3.5.

The same maps for mass rates are in Figures 3.6. Note that the huge differences around Green-

3.1. Global comparison with other GRACE solutions

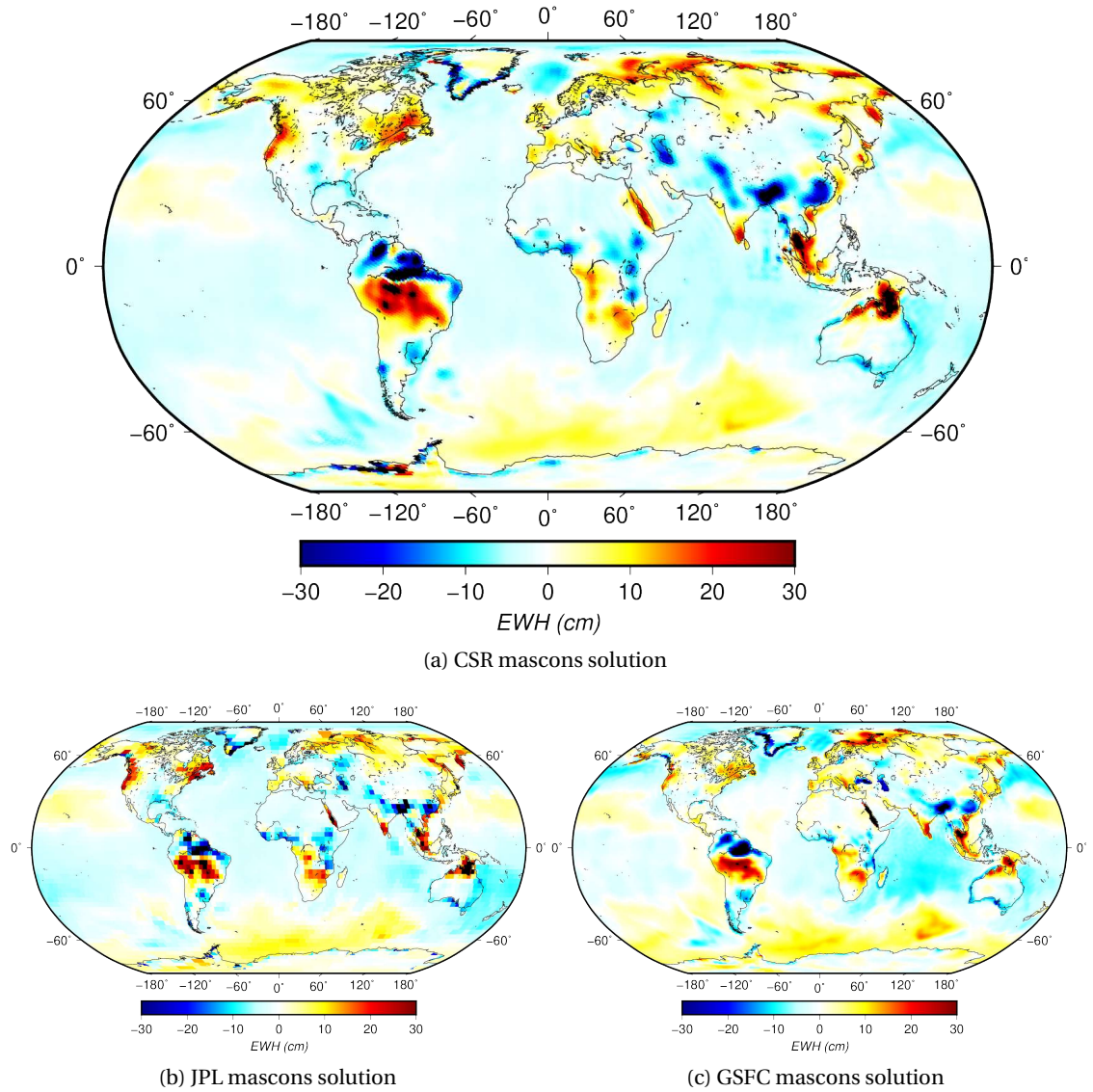


Figure 3.3 – Surface mass density anomalies for January 2006 relative to July 2005 expressed in equivalent water height (in cm) from 3 mascons solutions.

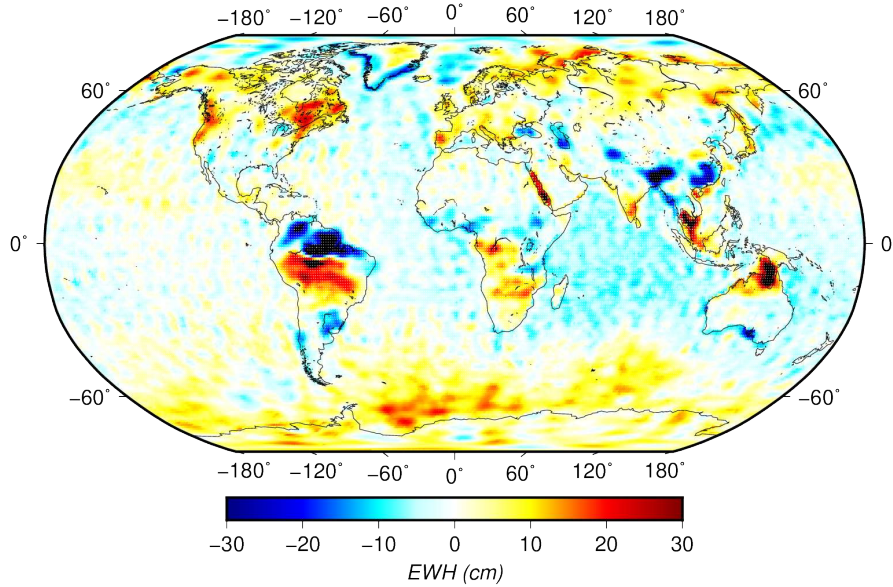


Figure 3.4 – M-SSA surface mass density anomalies solution for January 2006 relative to July 2005, expressed in equivalent water height (in cm), after restoration of the ocean and atmospheric model over oceans (from AOD1B, ERA-Interim and TUGO) that is removed during the processing of GRACE spherical harmonics data. We need to add them back to compare the M-SSA solution to mascon solution that do not use this correction.

land and West Antarctica are due to the leakage over the ocean of the large mass variations associated with ice melting in the spherical harmonics solutions while, in the mascons solutions, the inversion favors mass variations over the continents.

As expected, the difference between the mascons and M-SSA solutions shows residual North–South stripes in the latter. In addition, this difference also appears to include some geophysical signals, which we address in the following subsection by studying in greater detail the regional maps for the Caspian and Aral Seas, along with those for recent mega-earthquakes. We also note that the differences between the mascon and M-SSA solutions are of the same order of magnitude as the differences between mascon solutions from different analysis centers, as shown in Figure 3.7.

3.1. Global comparison with other GRACE solutions

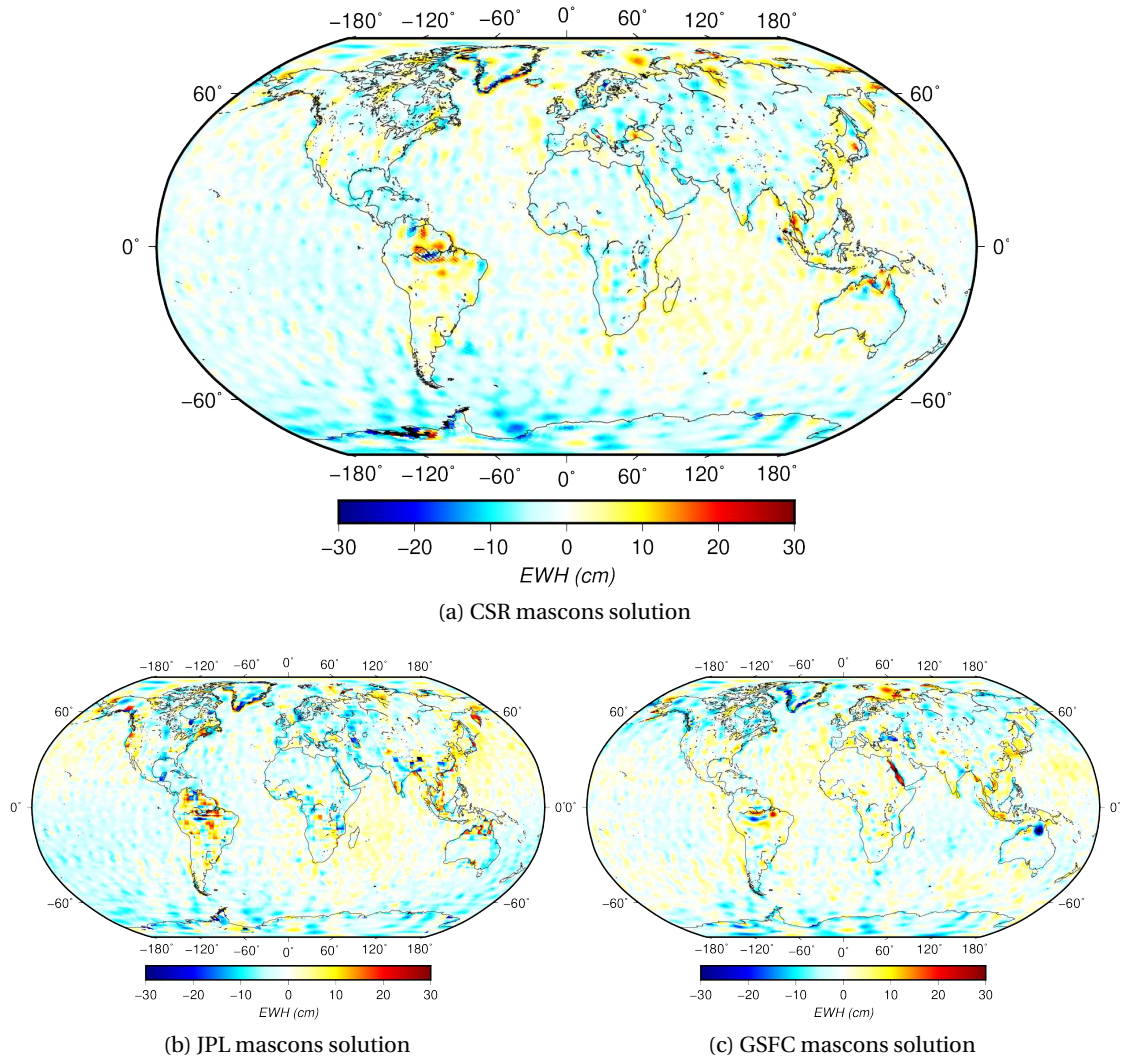


Figure 3.5 – Surface mass density anomalies differences for January 2006 relative to July 2005, expressed in equivalent water height (in cm), between a mascon solution and the M-SSA solution.

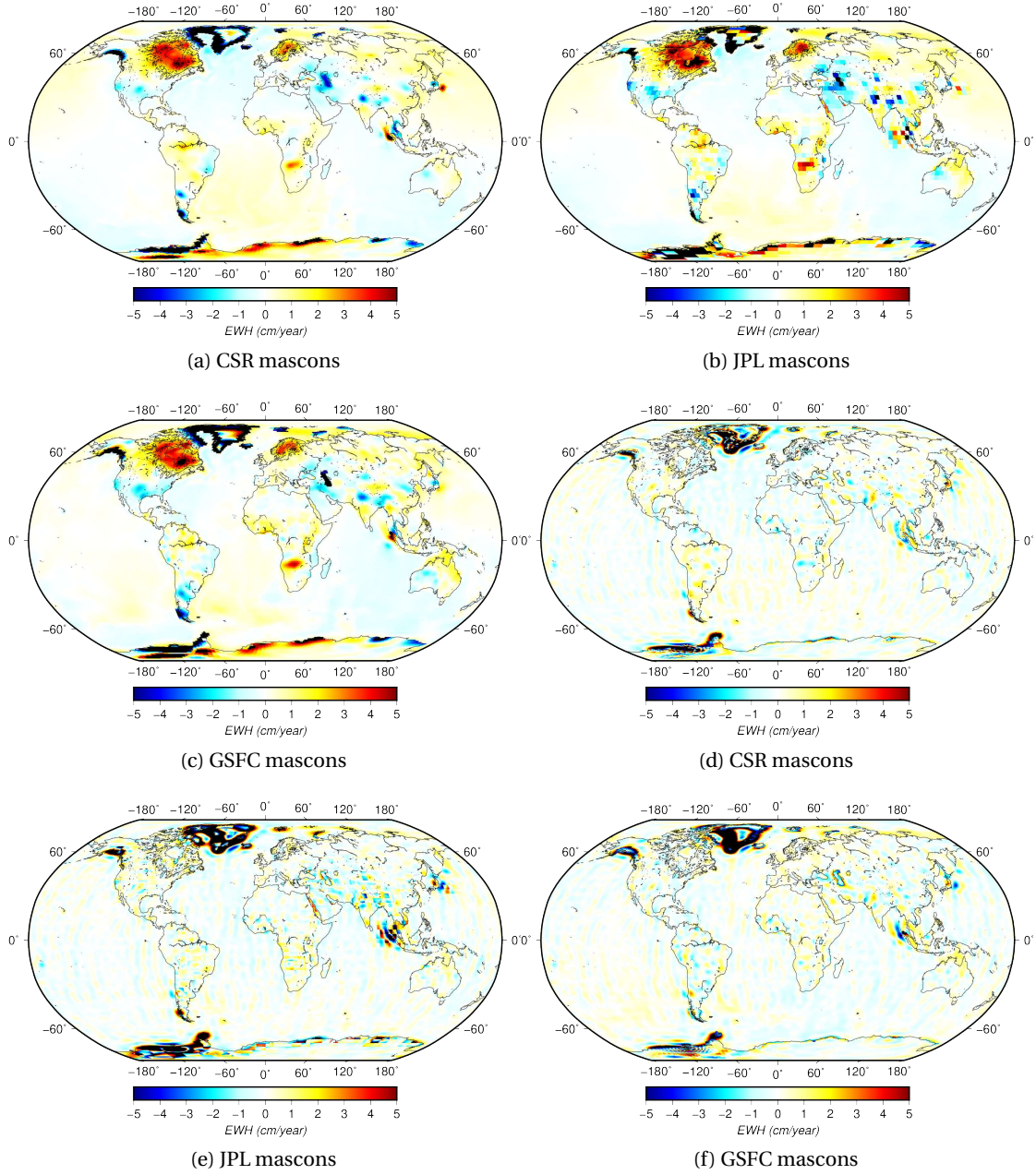


Figure 3.6 – (a-c) Mascon surface mass density rates from 2003 to 2015 expressed in equivalent water height per year (in cm/year). (d-f) Surface mass density rates from 2003 to 2015 difference expressed in equivalent water height per year (in cm/year) between a mascons solution and the M-SSA solution.

3.2. Regional comparisons with other GRACE solutions

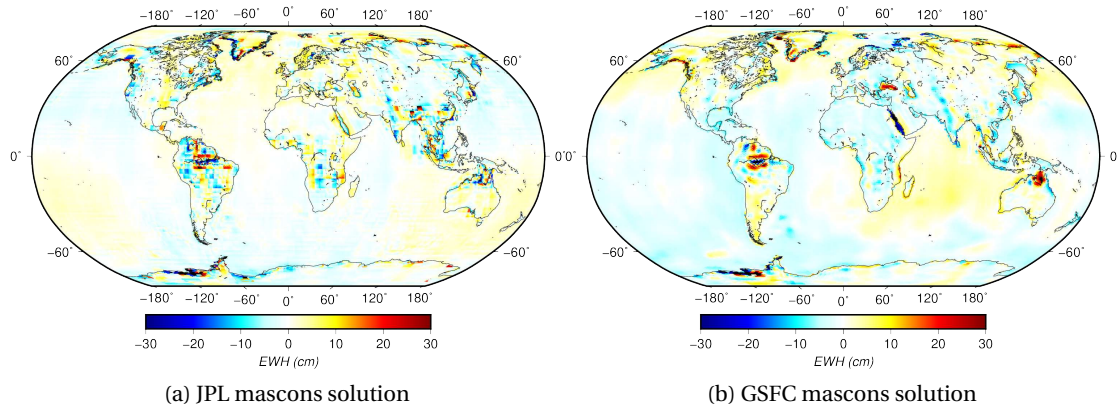


Figure 3.7 – Mascons surface mass density anomalies differences for January 2006 relative to July 2005, expressed in equivalent water height (in cm) between the mascons solution from CSR and another mascons solution.

3.2 Regional comparisons with other GRACE solutions

3.2.1 Hydrological signals in the Caspian and Aral Seas regions

The massive water losses from the Caspian and Aral Seas are a major issue in terms of the region's natural resources, and they have been studied using independent ground-based and satellite data (Swenson and Wahr, 2007, Chen et al., 2017). The Caspian Sea is losing water fast and it can thus provide information about regional and global climate change, as well as about the coastal response pattern to water loss (Chen et al., 2017, Kaplin and Selivanov, 1995).

The spectacular shrinking of the Aral Sea since the 1960s is also an active research topic, as the original decline is due to the diversion of water from the major rivers that feed it into the surrounding cotton fields. This process has induced significant changes of regional climate, leading to great losses of fishery resources and wildlife, along with the development of salt and dust plumes that affect the life of millions of people. There is, therefore, a need to accurately quantify the current water balance of the Aral Basin to evaluate the success of the restoration projects, cf. Crétaux et al. (2005), Gaybullaeve et al. (2012), Micklin (2007), Opp et al. (2017) and Shi and Wang (2015).

The above-cited studies were based on either in situ measurements, altimetry data or satellite

Chapter 3. Comparison of the M-SSA GRACE solution to other solutions

imagery. In situ measurements, like lake gauges or altimetric data — including the Topex/-Poseidon, Jason-1 and Jason-2 missions — require the poorly known water temperature and salinity to correct the raw measurements for the steric effect in computing mass variations (Chen et al., 2017). Finally, satellite imagery data, for example from the MODIS-Aqua mission, need atmospheric corrections and are affected by the salt and dust plumes frequent in the Aral basin (Shi and Wang, 2015). Moreover, altimetric and satellite imagery data only provide information on surface water, and thus require multi-sensor studies to separate the various inputs to the region's water balance (Swenson and Wahr, 2007). Hence the use of gravimetric data can provide highly useful complementary information for the study of the latter.

Figure 3.8(a–e) shows the EWH mass rates from January 2003 to December 2014 around the Caspian Sea for the standard SH GRACE solution, the M-SSA GRACE solution, and the CSR, JPL and GSFC mascons ones. The standard SH solution shows a significant mass loss around the Caspian Sea, highlighted by rectangle A in Figure 3.8a; this mass loss is slightly more concentrated within the actual area of the sea itself in the mascon CSR solution, cf. Figure 3.8c. However, while a mass loss is also observed around the Aral Sea (rectangle B in Figure 3.8a) in the standard SH solution, it almost disappears in all the mascons solution of panel (c–e).

The GRACE M-SSA solution in Figure 3.8b, though, does capture this signal, with contours in both the Caspian and Aral Seas that are more sharply focused than in the other solutions. The localized signal is consistent with other studies based, for example, from Moderate-Resolution Imaging Spectroradiometer (Moradi et al., 2014) or by Advanced Very High Resolution Radiometer and Topex/Poseidon–Jason-1–Jason-2 data (Shi et al., 2014) that show a decrease of the volume — and slightly of the surface — of the Caspian between 2002 and 2013 and a diminution of almost 50% in the water coverage of the South Aral Sea during the same time interval. Unfortunately, there is a lack of temperature and salinity data to account for the steric effect; therefore, we can't access the true signal to evaluate more precisely the different solutions.

3.2. Regional comparisons with other GRACE solutions

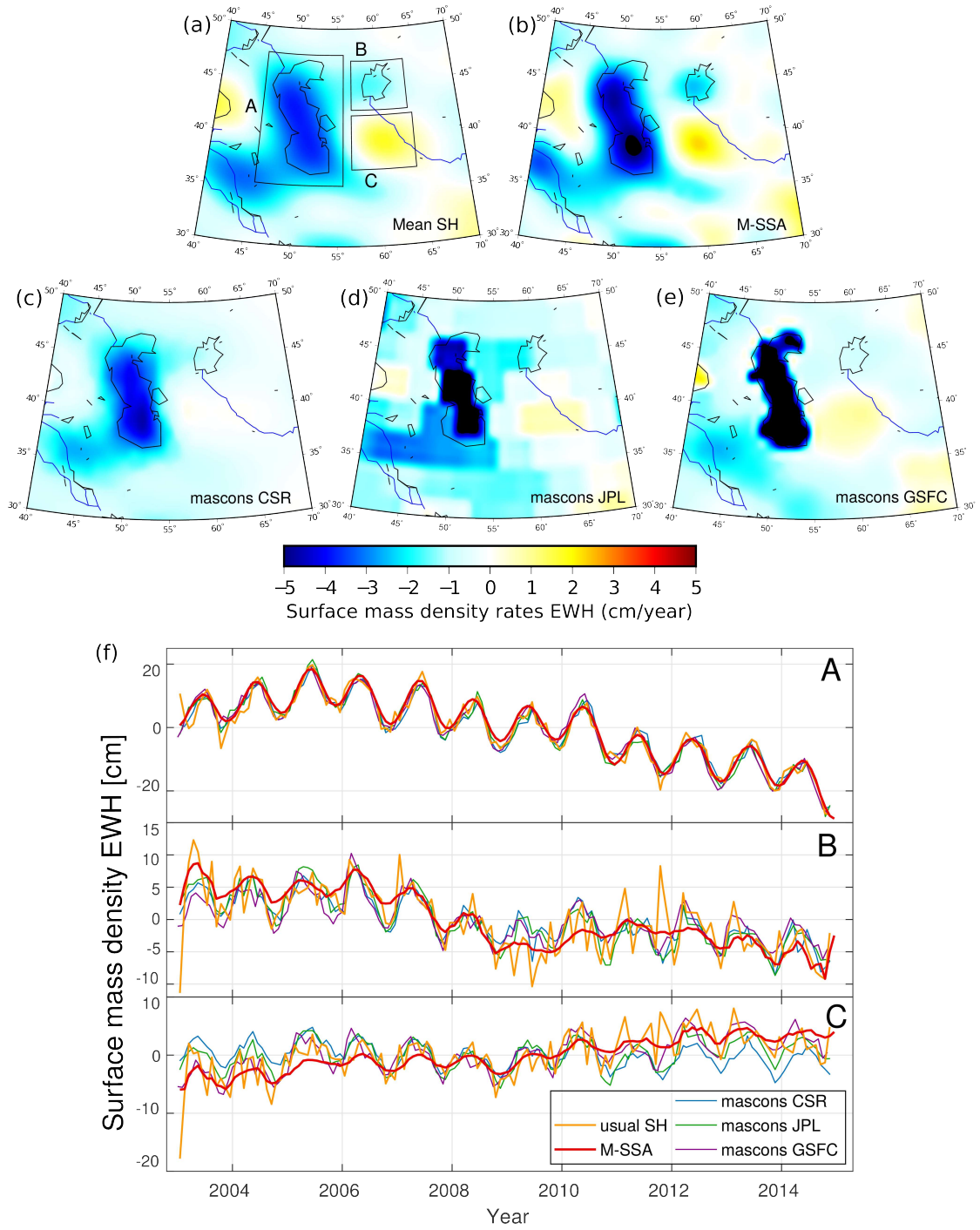


Figure 3.8 – (a-e) Surface mass density rates from January 2003 to December 2014 expressed in EWH (cm/year) for the Aral Sea and surrounding regions: (a) The standard SH solution, i.e., the mean of the DDK5-filtered JPL, GFZ and CSR solutions; (b) the M-SSA final solution; (c) the CSR mascon solution; (d) the JPL mascon solution; and (e) the GSFC mascon solution. (f) Time series of the mass anomalies averaged over each of the 3 areas for each solution. (A) Caspian Sea, (B) Aral Sea, and (C) North Turkmenistan; colors shown in the panel's legend.

In addition, a positive mass rate is observed in northern Turkmenistan, south of the Aral Sea, in the M-SSA solution, as well as in the standard SH one and slightly in the JPL and GSFC mascon ones, but not in the CSR mascon solutions (rectangle C in Figure 3.8a). This mass increase is consistent with independent studies (e.g., [Saiko and Zonn, 2000](#)), showing that the construction of irrigation dams on the Amu Darya river, which feeds the Aral Sea, is responsible for a significant increase in water storage within this highly cultivated area. Note that between 2003 and 2007, $10km^3$ of water diverted from the Amu Darya river have been added to the Sarykamish lake (<http://hydroweb.theia-land.fr>). Since 2009, it is the Karakum lake with an expected volume of $130km^3$ which gets filled with the residual water diverted from the Amu Darya river ([Kostianoy et al., 2011](#)). This example of the Caspian Sea shows that the GRACE M-SSA solution is able to preserve the shape of a regional hydrological signal as well as — and perhaps better than — other commonly used GRACE solutions, while the example of the Aral Sea and of nearby areas shows that the magnitude of the signal is better preserved in the GRACE M-SSA solution.

3.2.2 Continental mass balance

In order to further quantify the variability of continental water mass balance estimates from various GRACE solutions, we focused on four areas that exhibit a large hydrological or glacial signal and for which the M-SSA solution presents differences in trend. The time series for these four areas from several GRACE analysis centers are presented in Figure 3.9. The seasonal variations are similar for all the analysis centers but we can see a difference in trend between the solutions based on SHs and the ones based on mascons.

We calculated the percentage of difference $\% \Delta$ in the trends tr_{sol} , from January 2003 to December 2014, between 4 published solutions and the M-SSA one, for these 7 areas using:

$$\% \Delta = \frac{tr_{sol} - tr_{MSSA}}{tr_{MSSA}} * 100. \quad (3.1)$$

These percentages are presented in Table 3.1. In most of the cases, EWH absolute value of the trends in the M-SSA solution are larger than those from the mascon ones, with the largest difference observed for the CSR-mascon solution. We also note that these differences are

3.2. Regional comparisons with other GRACE solutions

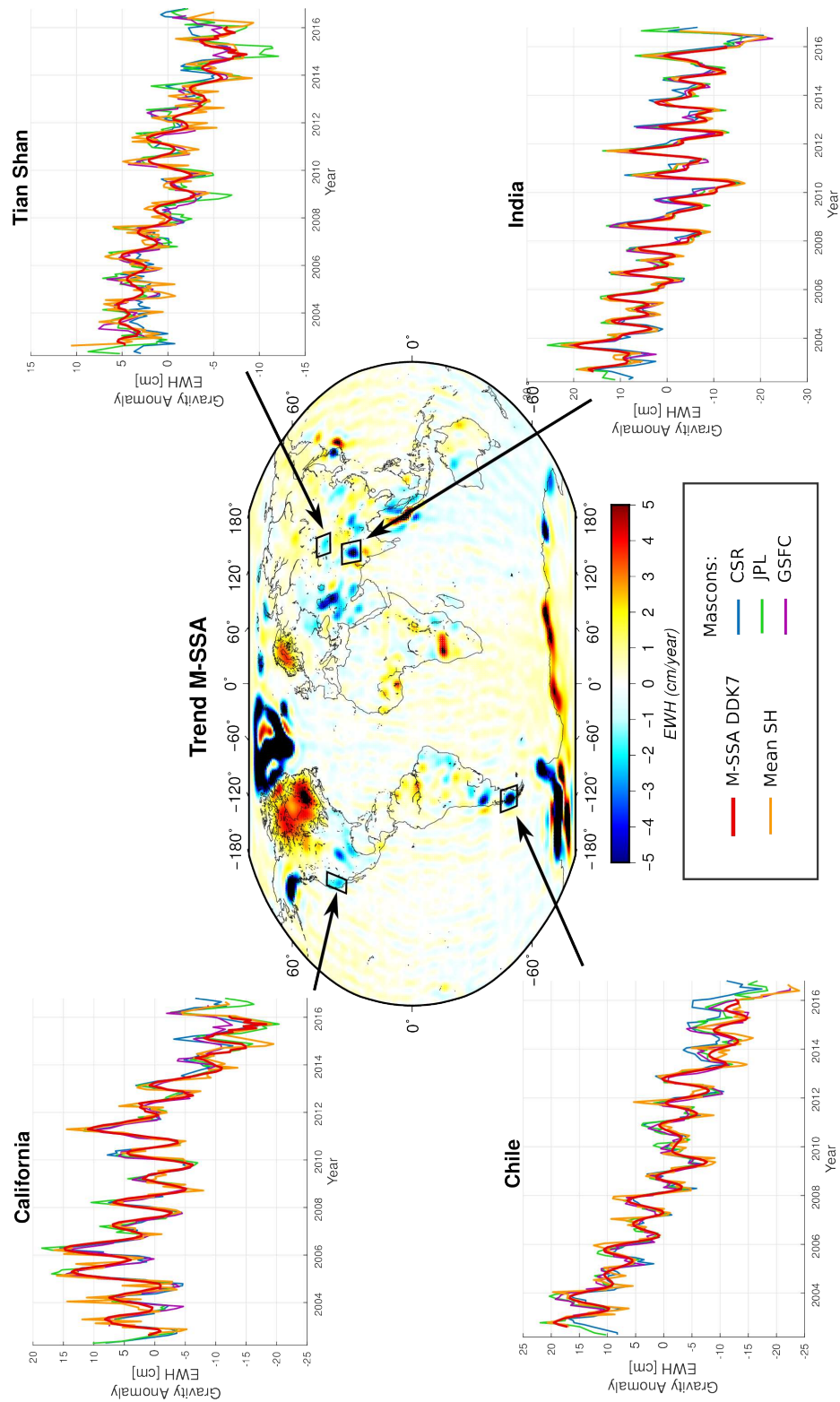


Figure 3.9 – Surface mass density rates from 2003 to 2015 expressed in equivalent water height (EWH) per year (in cm/year) of the M-SSA solution and surface mass density anomalies in EWH time series at four places on Earth represented by the boxes on the map.

Chapter 3. Comparison of the M-SSA GRACE solution to other solutions

Solution	Aral Sea	California	Caspian Sea	Chile	India	Tian Shan	North Turkmenistan
mean SH	-13%	2%	-3%	4%	7%	6%	-29%
mascons CSR	-34%	-22%	-7%	-20%	-29%	-38%	-114%
mascons JPL	-7%	-1%	3%	4%	11%	14%	-94%
mascons GSFC	-41%	-18%	-1%	7%	-11%	2%	-43%

Table 3.1 – Percentage of difference $\% \Delta$ between the EWH trend, from January 2003 to December 2014, based on the M-SSA solution and on four published ones for 7 inland areas; see Figure 3.8 and Figure 3.9.

larger in areas where a large part of the signal is due to human activity, such as northern India or northern Turkmenistan, where the loss of mass is due to agriculture (Rodell et al., 2009, Saiko and Zonn, 2000) and therefore not shown in most hydrological models. As the true values of these trends are not available, it is difficult to conclude on which solution is the best. However, there are large discrepancies between solutions and some can be due to the regularization used for the mascons solutions.

3.2.3 Co- and post-seismic gravity oceanic signals

An application of GRACE data has been the quantification of co- and post-seismic gravity signals. This information complements displacement data from GNSS or InSAR measurements, for instance (e.g., Panet et al., 2007, Chen et al., 2007c, Han et al., 2010).

Here we compare the M-SSA solution with others, before and after six recent major earthquakes: (1) the Mw 8.0, 2009, Samoa outer-rise earthquake; (2) the Mw 8.8, 2010, Maule subduction earthquake off the Chilean coast; (3-4) the Mw 8.3, 2006, and Mw 8.1, 2007, Kuril Island subduction earthquakes; and (5-6) the Mw 9, 2004, Sumatra and Mw 8.4, 2007, Bengkulu subduction earthquakes off the Sumatra shore; see Figure 3.10.

The co- and post-seismic signals caused by these large events concern both the continental and oceanic areas that surround their epicenter. As mascons solutions, due to the employment of regularization strategies, tend to hamper the signal over the oceans (Figure 3.3a), one does not expect them to be particularly reliable for the study of such events, for which they were not

3.2. Regional comparisons with other GRACE solutions

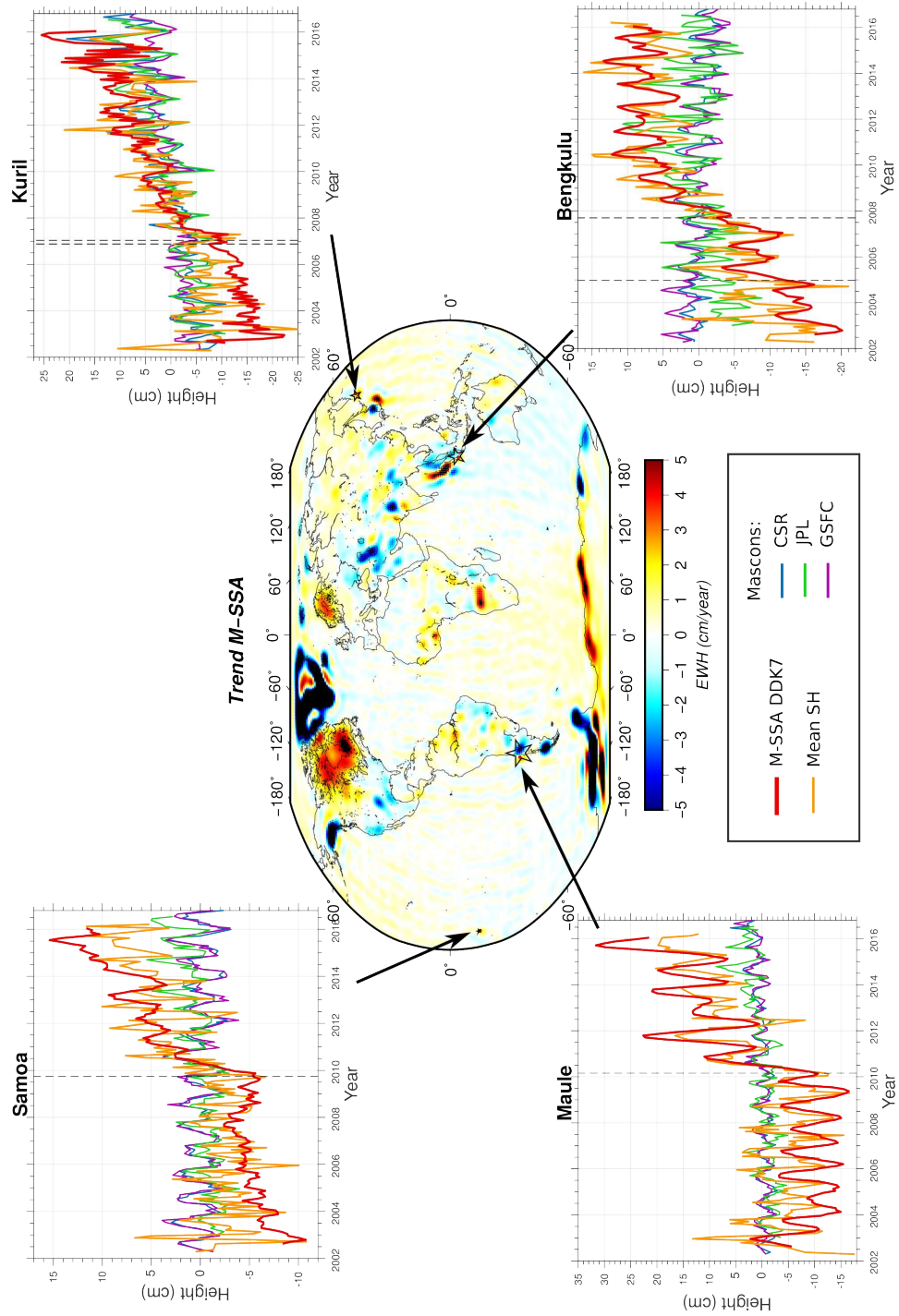


Figure 3.10 – Surface mass density anomalies time series, expressed as EWH in cm, for the M-SSA, mean SH-DDK5, CSR, JPL and GSFC mascons GRACE solutions at the location of six recent major earthquakes. Their epicenters are indicated by open stars on the center map, which also shows the January 2003 – December 2014 EWH trend from the M-SSA solution (in cm/year). Note that the co-seismic signals manifest themselves as a jump seen as positive and negative rates in the trend map.

designed. Indeed, the mascons solutions in Figure 3.10 show no significant co- or post-seismic signal in any of the 4 regions, while the SH-based GRACE solutions show a clear co-seismic offset, followed by an accelerated gravity change that is associated, in all likelihood, with the post-seismic deformation observed by GNSS.

The weakly prefiltered, DDK7-based M-SSA solution also captures larger co- and post-seismic signals than the standard mean of the more strongly prefiltered, DDK5-based SH solutions. This difference is most likely due to the degree of the DDK filter used. We conclude that the M-SSA solution preserves the co- and post-seismic signals in oceanic regions surrounding large subduction-related earthquakes as the the official mean DDK5 solution does. Because of the lighter, DDK7 filtering allowed by the M-SSA methodology described above, it is likely that the M-SSA solution better preserves the actual co- and post-seismic signals.

3.3 Global comparison with other geodetic products: loading deformation

Strong seasonal signals are observed in Global Navigation Satellite System (GNSS) station positions time series ([Blewitt et al., 2001](#)), both for horizontal and vertical components. These displacements are primarily due to surface mass redistribution: non-tidal oceanic loading, continental hydrology ([van Dam et al., 2001](#), [Dong et al., 2002](#)), ice and snow ([Grapenthin et al., 2006](#), [Matsuo and Heki, 2010](#), [Jiang et al., 2010](#)), and atmospheric pressure ([Kaniuth and Vetter, 2006](#)). As a result, GRACE has been largely used over the past decade to model the horizontal and vertical displacements induced by surface loading ([Davis et al., 2004](#), [Bettinelli et al., 2008](#), [Fu and Freymueller, 2012](#), [Fu et al., 2012, 2013](#), [Nahmani et al., 2012](#), [Chanard et al., 2018b](#)).

Vertical displacements are well predicted at the global scale when using a realistic elastic spherical and layered Earth model and any GRACE data. Similarly, providing that a particular attention is given to the spherical harmonic degree-1 contribution, horizontal displacements, particularly in the North-South direction, can be fairly well predicted as well using GRACE ([Chanard et al., 2018b](#)). Noise with a North-South spatial structure, e.g. the well established

3.3. Global comparison with other geodetic products: loading deformation

spurious North-South stripes, in the GRACE data may limit the ability to predict loading deformation for the East-West component.

Here, we model surface displacement induced by the GRACE mass redistribution and compare predictions with observations at a set of permanent GNSS stations. We use different GRACE solutions to assess the performance of different filtering methods.

3.3.1 Data

GRACE data

We use the monthly GRACE solutions presented in chapter 2 (see 2.3.2 and Table 2.2 for details). Note that the atmospheric and non-tidal oceanic loads are added back to enable the comparison with GNSS position time series. We used the detrended equivalent water height (EWH) time series from August 2002 to December 2014. As we use the Love numbers theory, the EWH time series are then expanded into spherical harmonics from degree 2 to 80.

GNSS time series

We use the daily GNSS position time series from the International GNSS Service second reprocessing campaign ([Reischung et al., 2016](#), IGS repro2). The discontinuities due to earthquakes, change in equipment or other causes are identified and corrected and the post-seismic deformations are modeled and removed as in the ITRF2014 computation ([Altamimi et al., 2016](#)). Out of the 1220 available stations, we selected 606 of them based on their formal error (see [Chanard et al., 2018b](#), for more details).

3.3.2 Loading model

We use a numerical model based on a spherical harmonics decomposition of the loads and the Love numbers theory to compute the Earth's surface deformation induced by surface load variations derived from GRACE.

Chapter 3. Comparison of the M-SSA GRACE solution to other solutions

The surface load grids $\sigma(t, \phi, \lambda)$, varying with time (t), longitude (ϕ) and latitude (λ), are decomposed into a sum of spherical harmonic coefficients ($\sigma_{lm}^C, \sigma_{lm}^S$) of degree and order (l, m) for each time t as:

$$\sigma(t, \phi, \lambda) = \sum_{l=1}^{\infty} \sum_{m=0}^l \sum_{\psi \in S, C} \sigma_{lm}^{\psi}(t) Y_{lm}^{\psi}(\phi, \lambda) \quad (3.2)$$

(Y_{lm}^C, Y_{lm}^S) are defined in terms of Legendre polynomials P_{lm} as:

$$\begin{pmatrix} Y_{lm}^C(\phi, \lambda) \\ Y_{lm}^S(\phi, \lambda) \end{pmatrix} = \sqrt{\frac{(2l+1)(l-m)!}{4\pi(l+m)!}} P_{lm}(\sin \phi) \begin{pmatrix} \cos(m\lambda) \\ \sin(m\lambda) \end{pmatrix} \quad (3.3)$$

Surface displacements at a point of coordinates (ϕ, λ) induced by the load at a given time t are obtained by solving a system of equations for the deformation of a self-gravitational spheroidal body, similarly to [Farrell \(1972\)](#). The surface displacements are expressed as:

$$\begin{aligned} dE(t, \phi, \lambda) &= \frac{4\pi R_E^3}{M_E} \sum_{l=0}^{\infty} \sum_{m=0}^l \sum_{\psi \in S, C} \frac{\ell_1}{2l+1} \frac{1}{\cos \phi} \sigma_{lm}^{\psi}(t) \frac{\partial Y_{lm}^{\psi}}{\partial \lambda}(\phi, \lambda) \\ dN(t, \phi, \lambda) &= \frac{4\pi R_E^3}{M_E} \sum_{l=0}^{\infty} \sum_{m=0}^l \sum_{\psi \in S, C} \frac{\ell_1}{2l+1} \sigma_{lm}^{\psi}(t) \frac{\partial Y_{lm}^{\psi}}{\partial \phi}(\phi, \lambda) \\ dU(t, \phi, \lambda) &= \frac{4\pi R_E^3}{M_E} \sum_{l=0}^{\infty} \sum_{m=0}^l \sum_{\psi \in S, C} \frac{\ell_1}{2l+1} \sigma_{lm}^{\psi}(t) Y_{lm}^{\psi}(\phi, \lambda) \end{aligned} \quad (3.4)$$

where (ℓ_1, ℓ_1) are the tangential and radial load Love numbers, and (ℓ_1, ℓ_1) depend on the reference frame considered. M_E and R_E are the Earth's mass and radius respectively. In this study, we use a purely elastic Earth structure based on the Preliminary Reference Earth Model (PREM: [Dziewonski and Anderson, 1981](#)), where the top 40 km are replaced by the CRUST 2.0 1D average continental crust up to 40 km depth ([Bassin et al., 2000](#)).

Similarly as [Chanard et al. \(2018b\)](#), we re-estimate the degree-1 deformation field from a global comparison between the displacements derived from GRACE, with no degree-1 loads, and the GNSS observations.

3.3.3 Comparison with GNSS time series

3.3.4 Comparison with GNSS time series

Using the previous equations, we calculate the horizontal and vertical displacements at the position of 606 GNSS stations.

To quantify how well the model explains the GNSS observations, we compute the weighted root mean square (WRMS) at each station i , for all three component j with N_i observations, between the GNSS observations d with error σ and the model displacements m :

$$WRMS_{i,j}^{d-m} = \sqrt{\frac{\sum_{k=1}^{N_i} (\frac{d_{i,j,k} - m_{i,j,k}}{\sigma_{i,j,k}})^2}{\sum_{k=1}^{N_i} \frac{1}{\sigma_{i,j,k}^2}}} \quad (3.5)$$

We compute the WRMS reduction (WRMSr), which compares the WRMS with the model m with the null model:

$$WRMSr_{i,j} = \frac{WRMSr_{i,j}^{d-0} - WRMSr_{i,j}^{d-m}}{WRMSr_{i,j}^{d-0}} \quad (3.6)$$

We compare the annual WRMSr, for which we fit a sine function to both the GNSS and GRACE-derived time series.

Table 3.2 shows that the MSSA-GRACE v2 solution considerably improves the predictions of seasonal east deformation observed by GNSS, most likely because of the efficiently removed NS striping effect. The fit between model and observation on other components is slightly improved and remains coherent with results obtained using other GRACE solutions. This is confirmed by Figures 3.11, 3.12 and 3.13 showing maps of WRMSr for East, North and Vertical components, at all stations considered in this study. While North and Vertical WRMSr obtained using the M-SSA v2 GRACE solution remain consistent with the mean of DDK5-filtered CSR, JPL and GFZ solutions, the East predictions are considerably improved and the M-SSA v2 GRACE solution reconciles the model-observations fit on both horizontal components. We also plotted the amplitude of M-SSA v2 model versus observations for our monthly data at all 606 stations and estimated a linear regression between both (Figure 3.14). All three compo-

Chapter 3. Comparison of the M-SSA GRACE solution to other solutions

Annual WRMSr	East		North		Vertical	
Monthly solutions	Stations	Mean	Stations	Mean	Stations	Mean
GRGS RL04	75.4	17.1	85.1	35.5	90.8	55.8
CSR RL06	78.1	18.5	84.2	35.1	91.7	56.5
GFZ RL06	78.5	17.9	84.5	35.6	91.5	56.8
JPL RL06	73.2	17.6	84.1	35.4	89.6	54.7
TU-GRAZ 2018	78.9	18.9	85.3	36.8	92.9	57.1
MSSA-GRACE v2	82.1	29.2	88.1	39.9	94.0	58.4

Table 3.2 – Annual weighted root mean square reduction (WRMSr)

nents show, using the M-SSA v2 GRACE solution, a slope close to 1 (≈ 1.1) and a relatively good agreement between observations and model, with some scattering that may be due to other seasonal sources of deformation (thermoelastic or poroelastic deformation for instance), or local hydrological effects that may not be captured by GRACE due to its large spatial resolution.

To conclude, preliminary comparisons of M-SSA v2 GRACE solution predictions of GNSS seasonal deformation show promising results, particularly on the East component compared to other GRACE spherical harmonics solutions due to the efficient removal of north-south striping effects. In the future, we will compare performances of our final solution with mascons solutions as well.

The M-SSA-GRACE v2 solution presents less North-South spurious stripes and better preserves the geophysical signal than the other published solutions. To investigate one other possible use of GRACE data, we now look at the ice-related signal around South Georgia island.

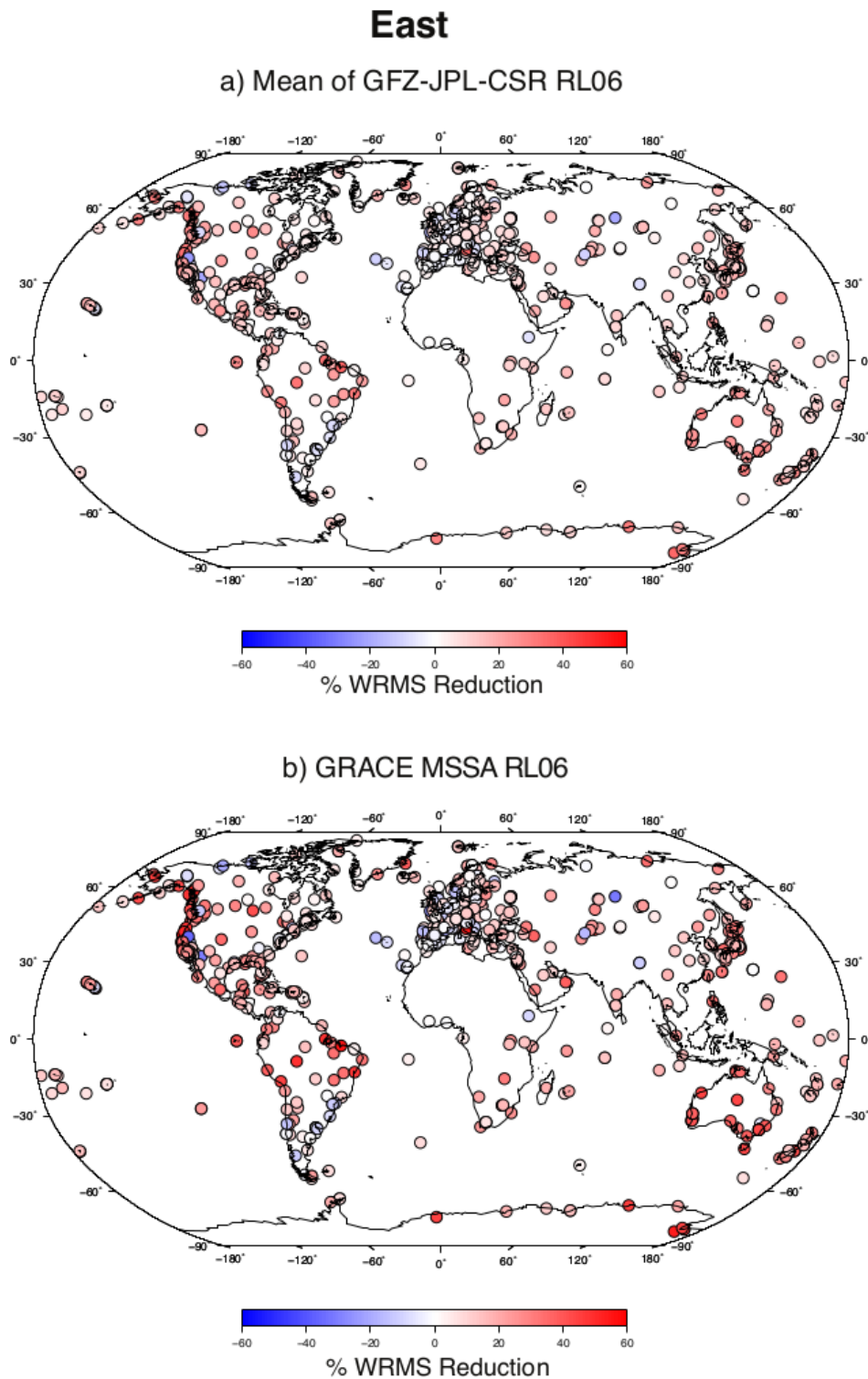


Figure 3.11 – East WRMS reductions (equation 3.6) obtained for the East, North and vertical components of 606 globally distributed continuous GNSS stations using GRACE-derived displacements, using (a) the mean of GRACE solutions provided by the DDK5-filtered CSR, JPL and GFZ and (b) using the M-SSA v2 GRACE solution.

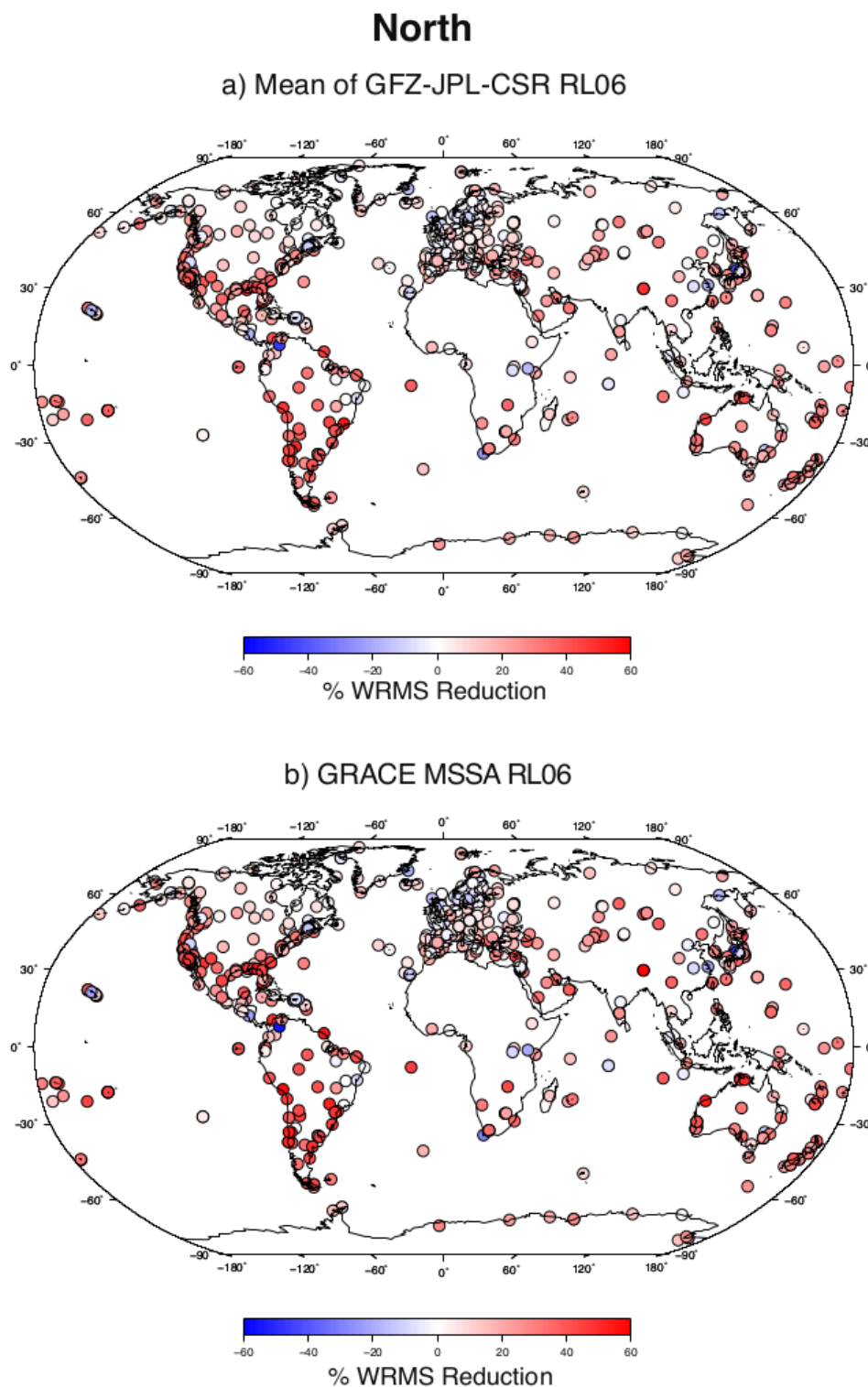


Figure 3.12 – North WRMS reductions (equation 3.6) obtained for the East, North and vertical components of 606 globally distributed continuous GNSS stations using GRACE-derived displacements, using (a) the mean of GRACE solutions provided by the DDK5-filtered CSR, JPL and GFZ and (b) using the M-SSA v2 GRACE solution.

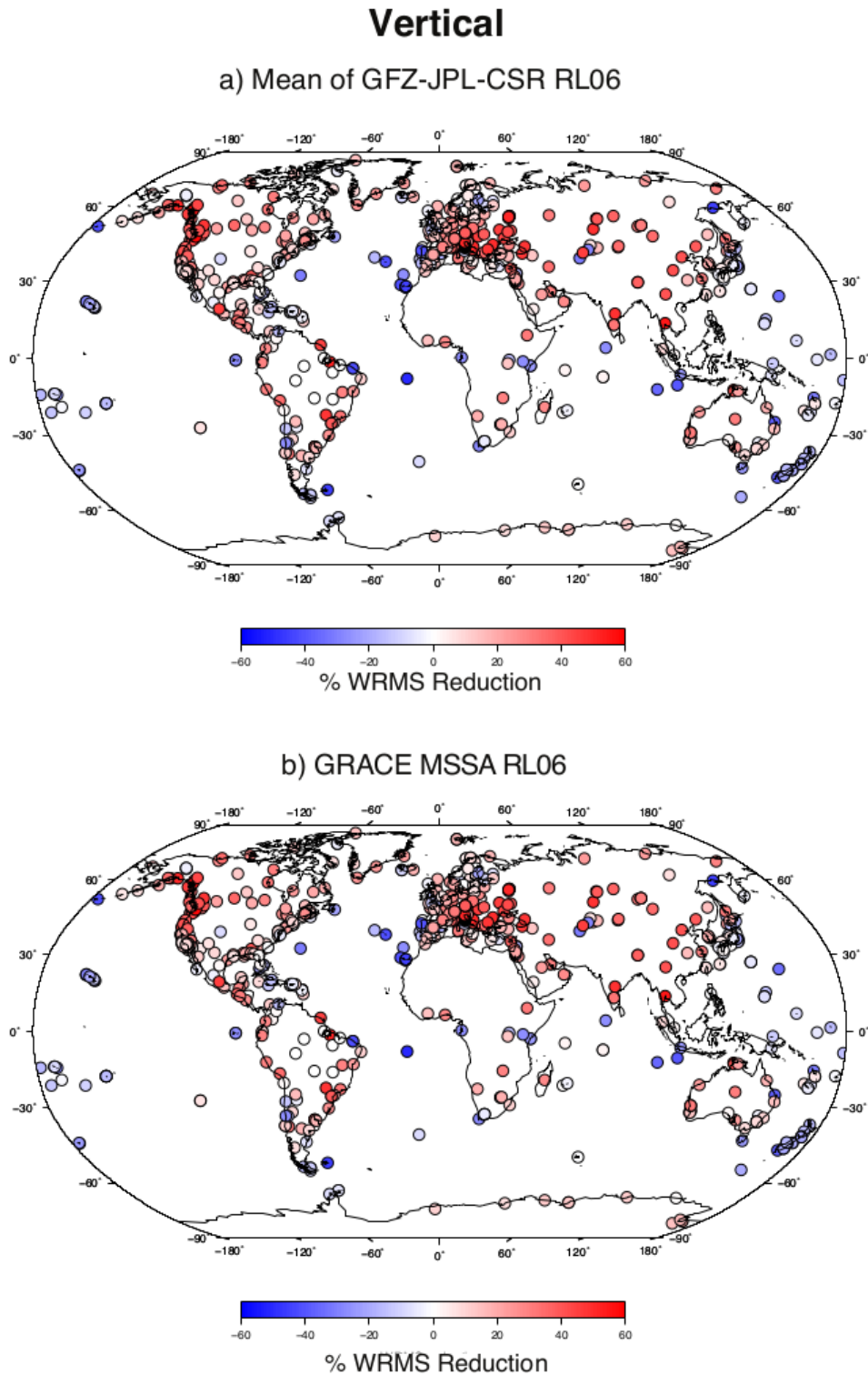


Figure 3.13 – Vertical WRMS reductions (equation 3.6) obtained for the East, North and vertical components of 606 globally distributed continuous GNSS stations using GRACE-derived displacements, using (a) the mean of GRACE solutions provided by the DDK5-filtered CSR, JPL and GFZ and (b) using the M-SSA v2 GRACE solution.

Chapter 3. Comparison of the M-SSA GRACE solution to other solutions

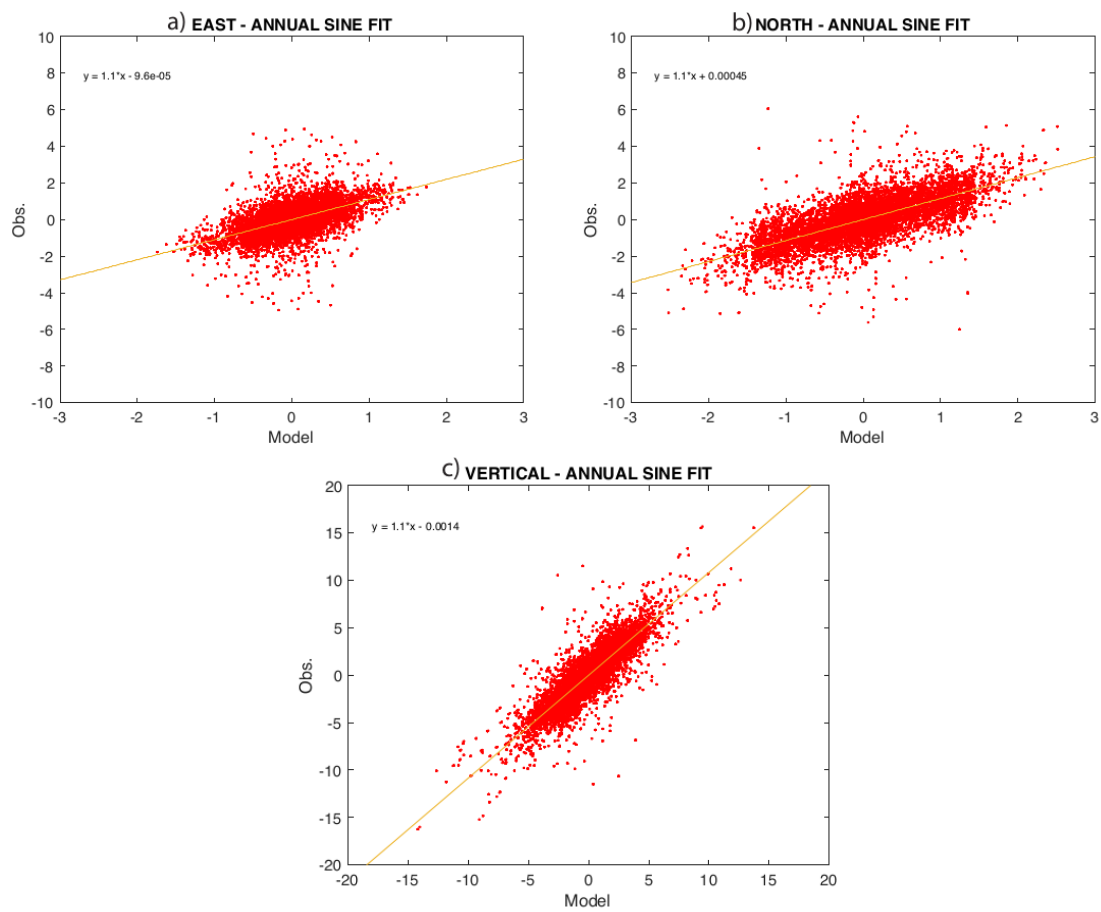


Figure 3.14 – Amplitude of monthly averaged GNSS observations from 606 IGS stations versus monthly M-SSA v2 GRACE derived model for (a) East, (b) North and (c) Vertical components.

GRACE GRAVITY TREND AROUND SOUTH GEORGIA ISLAND

One of the main purposes of the GRACE mission is to quantify the evolution of ice mass, presently melting either on the rim of major ice-sheets (Antarctica, Greenland) or over smaller glaciers. One major difficulty to access the recent ice melting signal in the gravity data is its separation from post-glacial rebound signals induced by the melt of past ice sheets. Here we use our refined GRACE solution to analyze gravity signals around the South-Georgia island and propose, on this example, a discussion concerning the potential impact of post-glacial rebound on the estimate of present-day melting using GRACE gravity data..

4.1 Study area

South Georgia is one of the largest sub-Antarctic island. It is an isolated island 170 km long and up to 40 km wide, located around 37° W and 55° S (see Figure 4.1). The island presents

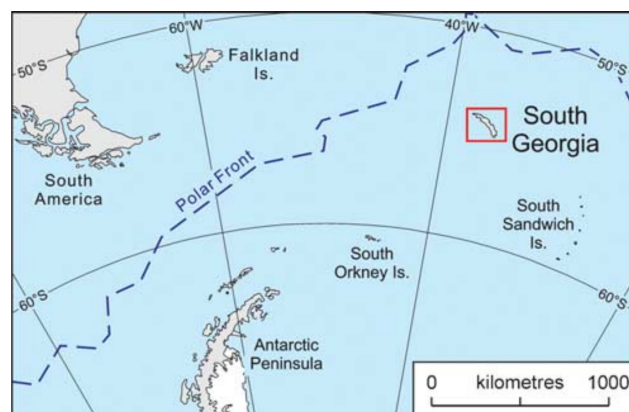


Figure 4.1 – Figure from [Cook et al. \(2010\)](#). South Gerogia location map.

Chapter 4. GRACE gravity trend around South Georgia Island

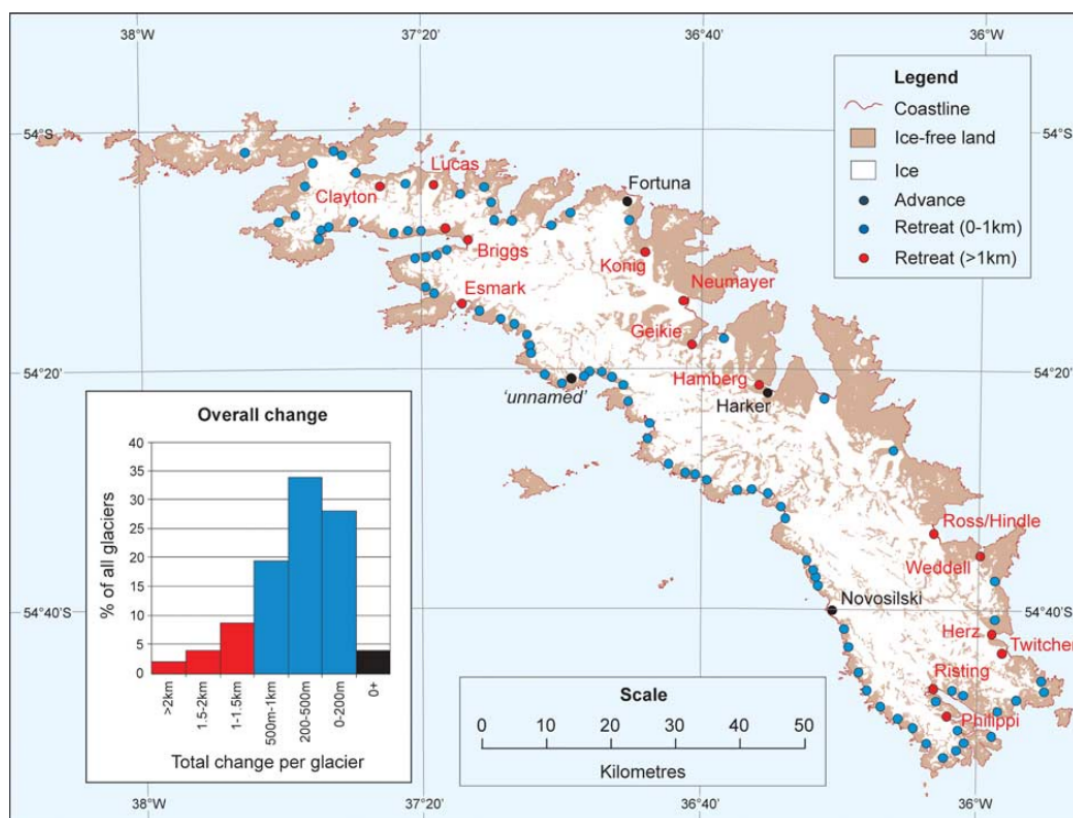


Figure 4.2 – Figure from [Cook et al. \(2010\)](#). Change in glacier length since earliest records (typically 1950s). NB names refer to glaciers of significance: those that have advanced, or those that have retreated over 1 km.

a mountain range, with several peaks higher than 2000 m and up to 2960 m. As shown by Figure 4.2, the vast majority of the island is covered by glaciers, ice and snow.

Due to its location and landscape, South Georgia is really sensitive to regional climate and is therefore a good indicator of potential climate changes. For example, the climate of South Georgia is influenced by several oceanic currents that can influence the global climate trend. Because the fluctuation of the glaciers of the island is an important indicator of climate change, the evolution of South Georgia's glaciers has been investigated over the last century. These studies used several sources of data including oblique, aerial and satellite photographs, historical sources and geomorphological records. They conclude that since the 1950's, more than 90% of the glaciers have retreated with an acceleration since the beginning of the 21st century ([Cook](#)

et al., 2010, Gordon et al., 2008). The inset of Figure 4.2 shows that most of the glaciers retreat by less than 1 km and that the largest retreats are observed on the North coast of South Georgia.

Here, we will try to evaluate the quantity of present-day ice melting using GRACE data and analyze how the various methods used to retrieve the gravity data affect the observed signal around South Georgia and hence the interpretation in terms of present-day ice-melting.

4.2 Today's gravity anomalies as seen by GRACE

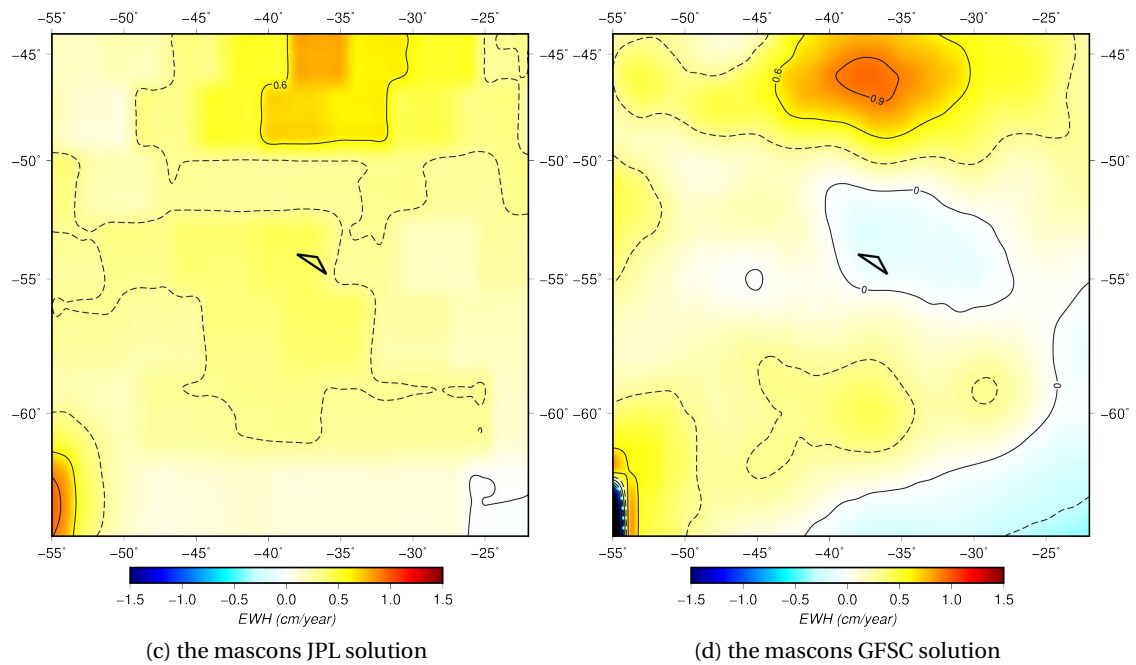
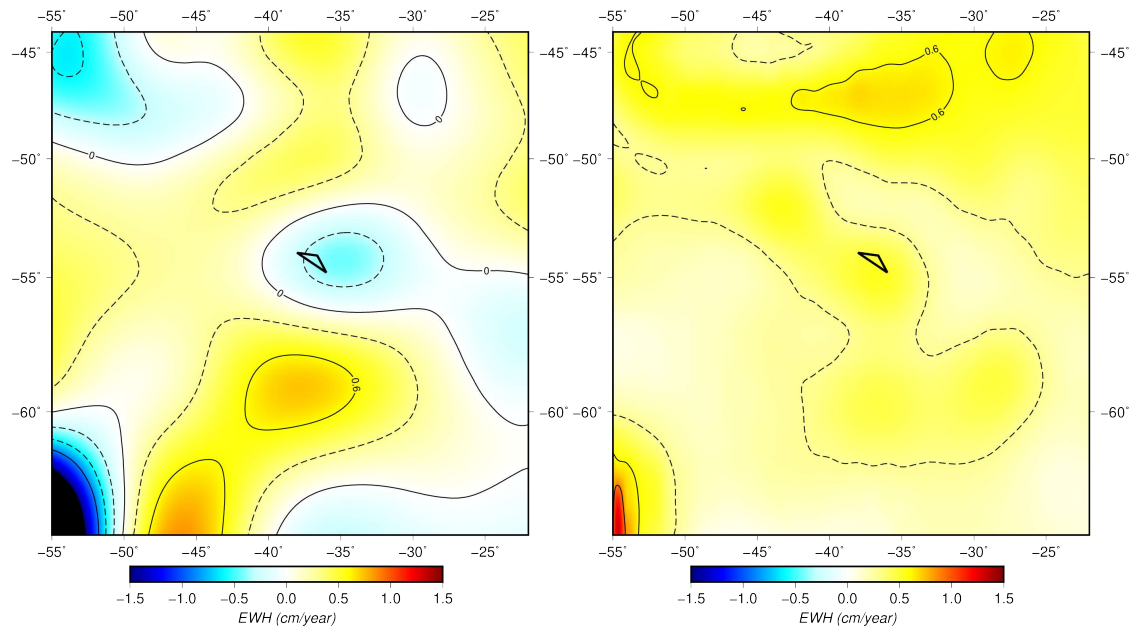
The spatio-temporal variations of gravity measured by GRACE give new insights on the ice melting signals. However, the actual spatial resolution of GRACE solutions (and their post-processing) does not allow for univocal interpretation of the long term trend around such a small and isolated island.

Figure 4.3 shows the mass density rates around South Georgia from May 2003 to December 2013 for several GRACE solutions. The usual spherical harmonics solution — mean of the three official solutions (CSR, GFZ, JPL) filtered with the DDK5 decorrelation filter — in Figure 4.3a exhibits a light negative trend close to South Georgia, but the signal is of the same size and amplitude as the noise around and can hardly be used for further studies.

The mascons solutions from the CSR and the JPL, Figure 4.3b and c, present an almost homogeneous positive trend in the whole area, and the one from GSFC, Figure 4.3d, shows a rather small negative signal close to South Georgia island.

Our first M-SSA solution (v1: 2.3.1) is shown in Figure 4.3e. We can observe a negative trend well localized around South Georgia island and patterns of positive trend around it. In our most refine M-SSA v2 solution (2.3.2) — shown in Figure 4.3f — we can still observe the negative trend over South Georgia but also a well defined circular positive trend around it.

Chapter 4. GRACE gravity trend around South Georgia Island



4.3. Tentative of interpretation of the signal in terms of present-day ice melting

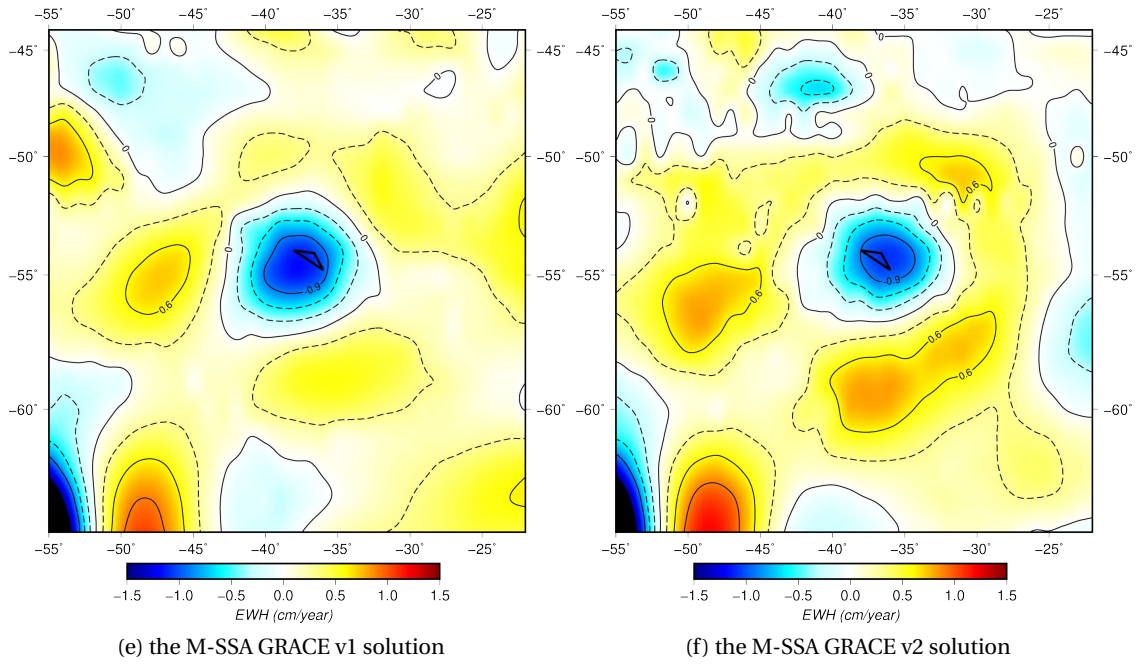


Figure 4.3 – Surface mass density rates from January 2003 to December 2013 expressed in EWH (cm/year) around South Georgia from four GRACE solutions.

4.3 Tentative of interpretation of the signal in terms of present-day ice melting

First, we tried to see if this signal could be interpreted as present-day ice melting, as the positive signal around the island could be attributed to Gibbs effect resulting from the suppression of small wavelengths inherent to the GRACE post-treatment.

To test this hypothesis, we create a grid presenting a negative mass over South Georgia. We then transform this grid into spherical harmonics, filter it with the DDK7 decorrelation filter — as the GRACE data used to produce our M-SSA v2 solution —, and transform it back into an EWH grid. The result is presented in Figure 4.4.

The Gibbs effect created by a mass of approximately the same size and amplitude as the one observed in South Georgia is more than 4 times smaller than the positive signal observed

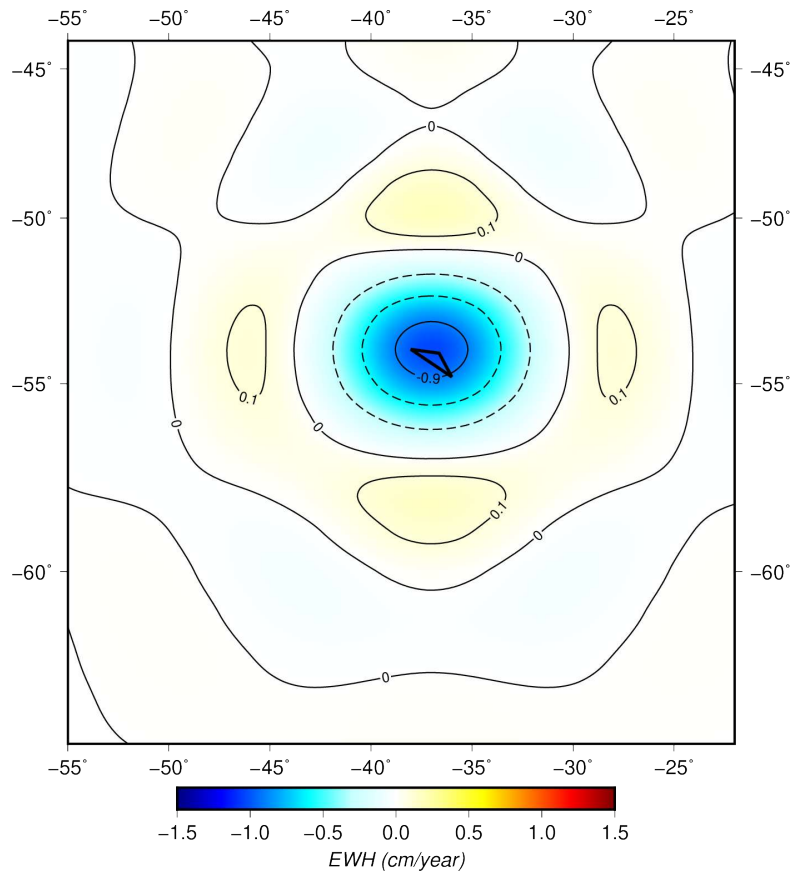


Figure 4.4 – Surface mass density rate obtained around South Georgia with a recent mass loss of 21.7 cm/year EWH filtered with DDK7 decorrelation filter.

around the island in Figure 4.3f and about 2 times smaller than in Figure 4.3e. Therefore this signal is clearly not a mere Gibbs effect. It could of course correspond to random noise which, by chance, would gather around the South-Georgia island. In the next section, we consider this last hypothesis but also explore whether this positive signal could not rather have a geophysical origin.

4.4 Gravity signal linked to ice melting since the LGM?

4.4.1 Data suggesting the presence of a larger ice-sheet during LGM

The South Georgia island is surrounded by a broad plateau with a shallow bathymetry. This plateau is carved with deep valleys (see Figures 4.5 and 4.6), which are the relics of fjords

4.4. Gravity signal linked to ice melting since the LGM?

extending to the rim of the plateau, clearly indicating that once, the whole plateau was covered of ice (Graham et al., 2008).

If the presence of ice sheet in South Georgia during the LGM is undeniable (Clapperton, 1990, Bentley et al., 2007), the extent and thickness of the ice as well as the date of deglaciation are still discussed.

There are two types of models for the extent of the ice sheet at the Last Glacial Maximum (LGM): the ones restricting the ice sheet to inner fjords of the island (Bentley et al., 2007, Hodgson et al., 2014), and the others considering an ice sheet extending to the edge of the continental shelf around South Georgia (Barlow et al., 2016, Graham et al., 2017).

The model with the minimum extent of ice sheet from Bentley et al. (2007) is based on dated inland geomorphological evidences such as the pattern of moraines that are just beyond the fjords mouths. Hodgson et al. (2014) also proposed a minimally extended ice caps for the LGM using the results from Bentley et al. (2007) and bathymetric survey. However, they suggested the interest of dating the sediments in the submarine moraine with offshore work.

Graham et al. (2008) mapped with an unprecedented precision the geomorphology of the continental shelf (Figure 4.5). This gave new insights into glacial dynamics. For example, the level of details allows to explain the troughs imaged on Figure 4.6 as features formed by glacial erosion. This study concludes that an ice sheet, at least once, was extending to the edge of the continental shelf. In a more recent study, Graham et al. (2017) date marine sediment cores and use the previous geomorphological maps to concludes that the ice sheet during the LGM extended onto the continental shelf. The newly mapped moraines are shown on Figure 4.7.

The age of the deglaciation after the LGM (19 – 26 ka BP) is also under discussion. Some studies propose a deglaciation around 18.6 ka BP (Van der Putten and Verbruggen, 2005), others around 10.8 ka to 10.2 ka BP (Smith, 1981) when some propose a warming around 18 ka

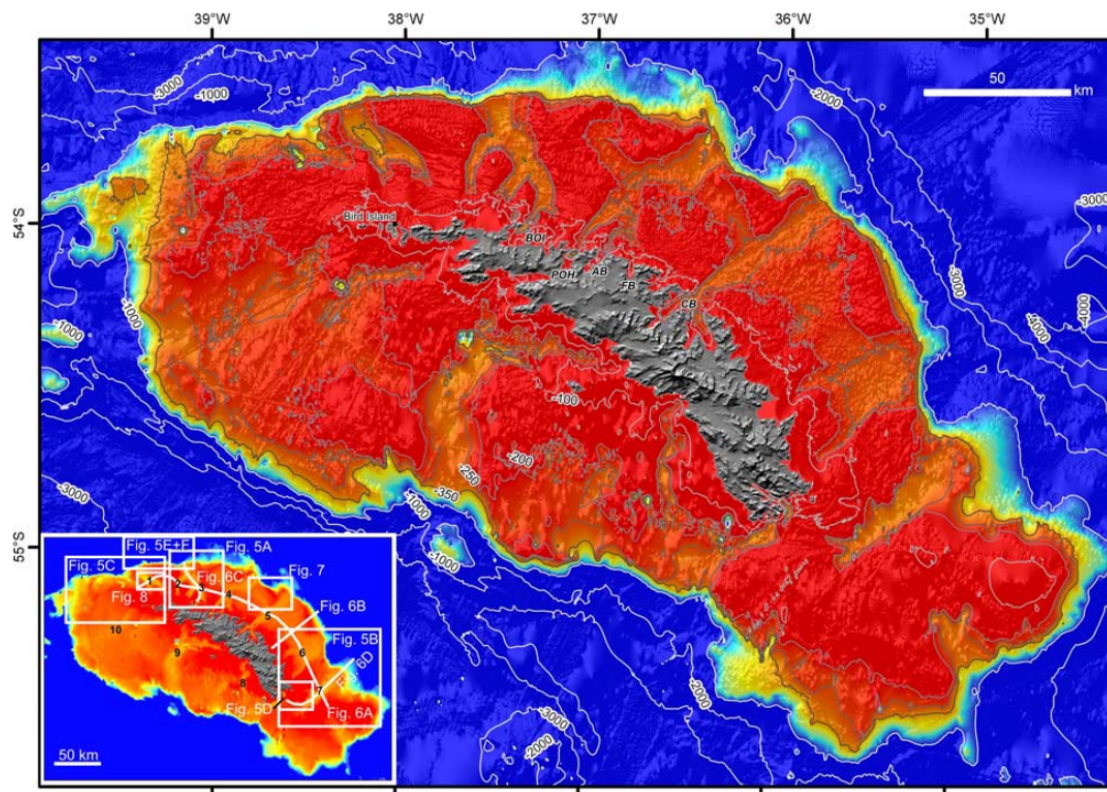


Figure 4.5 – Figure 3 from [Graham et al. \(2008\)](#). Newly compiled bathymetric map of the South Georgia continental shelf (223 m cell size grid, UTM Zone 24S projection). Note the aligned trough systems widening from fjordal areas toward the outer shelf, converging tributaries, banked shelf edge features, well-defined shape of the continental margin, and distribution of troughs north and south of the island. Contours on the shelf are at 350, 200, and 100 m. Color bar is skewed toward these water depths on the shelf. Hillshade of DEM of South Georgia from P. Fretwell. Locations of Figures 5 (here Figure 4.6) shown inset. BOI, Bay of Isles; POH, Prince Olav Harbour; AB, Antarctica Bay; FB, Fortuna Bay; CB, Cumberland Bay.

4.4. Gravity signal linked to ice melting since the LGM?

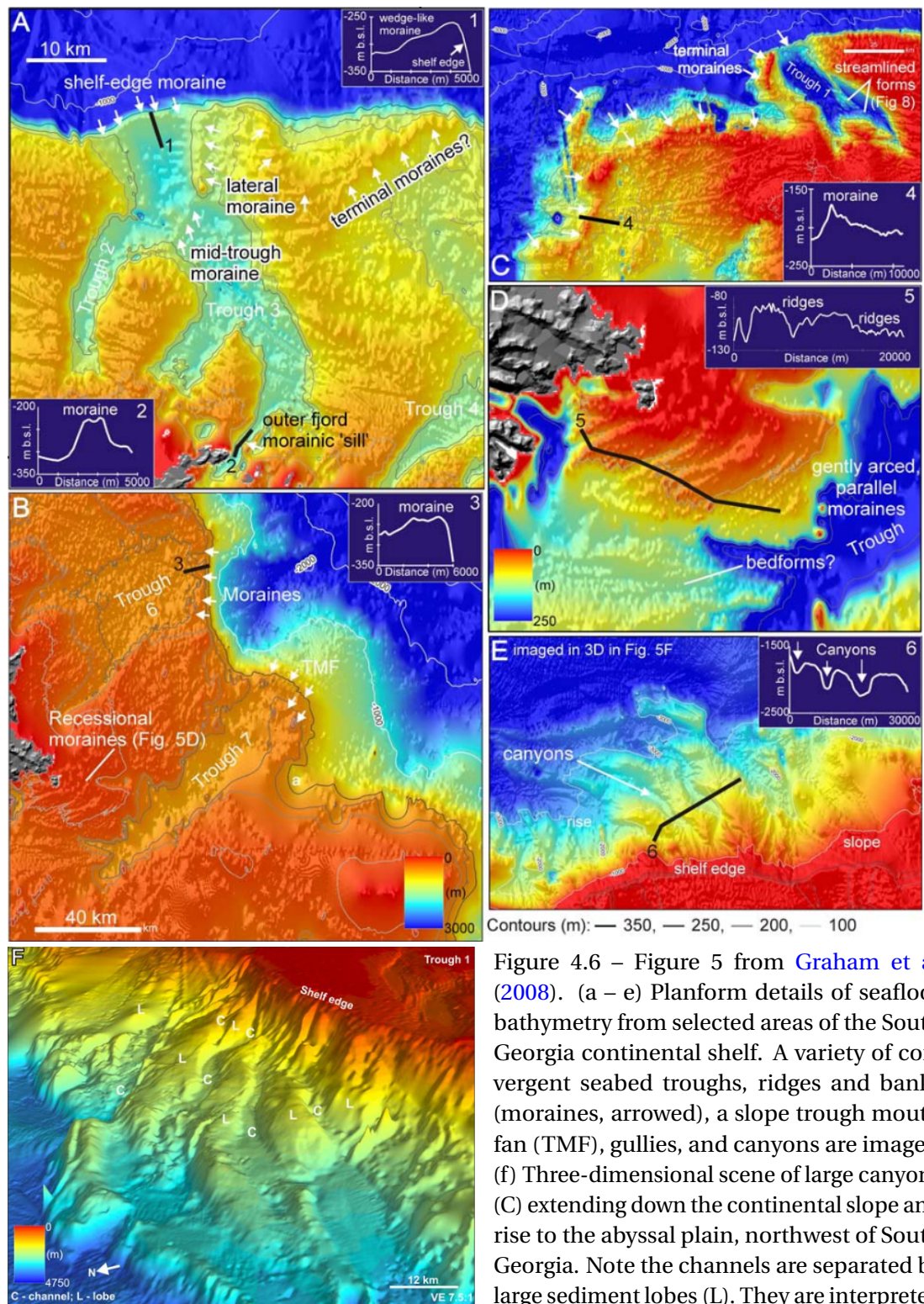


Figure 4.6 – Figure 5 from [Graham et al. \(2008\)](#). (a – e) Planform details of seafloor bathymetry from selected areas of the South Georgia continental shelf. A variety of convergent seabed troughs, ridges and banks (moraines, arrowed), a slope trough mouth fan (TMF), gullies, and canyons are imaged. (f) Three-dimensional scene of large canyons (C) extending down the continental slope and rise to the abyssal plain, northwest of South Georgia. Note the channels are separated by large sediment lobes (L). They are interpreted as contourite or debris flow features, interspersed with small sediment drifts. See Figure 4.5 inset for locations.

Chapter 4. GRACE gravity trend around South Georgia Island

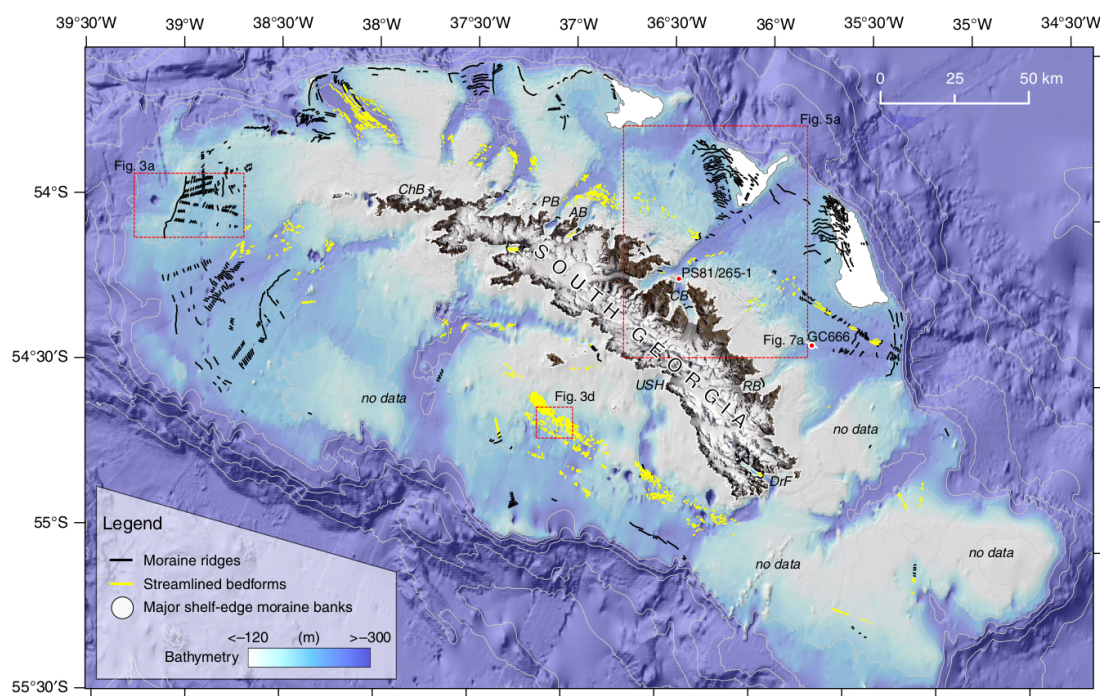


Figure 4.7 – Figure 2 from [Graham et al. \(2017\)](#). Bathymetry of the South Georgia continental block ([Graham et al., 2008](#)), with newly mapped moraine ridges (black), streamlined bedforms (yellow) and moraine banks (light grey) depicting the imprint of an entire sub-polar palaeo-ice cap. Locations of subsequent figures shown by red boxes. ChB: Church Bay, PB: Possession Bay, AB: Antarctic Bay, CB: Cumberland Bay, RB: Royal Bay, DrF: Drygalski Fjord, USH: Undine South Harbour.

BP and then a cooling between 14.5 ka and 12.7 ka BP ([Putnam et al., 2010](#)).

[Barlow et al. \(2016\)](#) present another evidence of a sizable LGM glaciation extending to the rim of the submarine plateau. They gathered data on the marine limit and relative sea-level (RSL) over the island (Figures 4.8 and 4.9). In particular, they show that the RSL has decreased during the last 5 ka at a rate of about 1.5 mm/year. The regional sea-level in this area did not vary during the last 5 ka. This suggests an uplift of the island of about 1.5 mm/year during the last 5 ka. [Barlow et al. \(2016\)](#) show that this is not compatible with the hypothesis of an LGM ice-sheet restricted to the inner fjords. They propose a deglaciation age around 15 ka BP, with a thick (> 1000 m) ice sheet extending to the edge of the ice shelf.

4.4. Gravity signal linked to ice melting since the LGM?

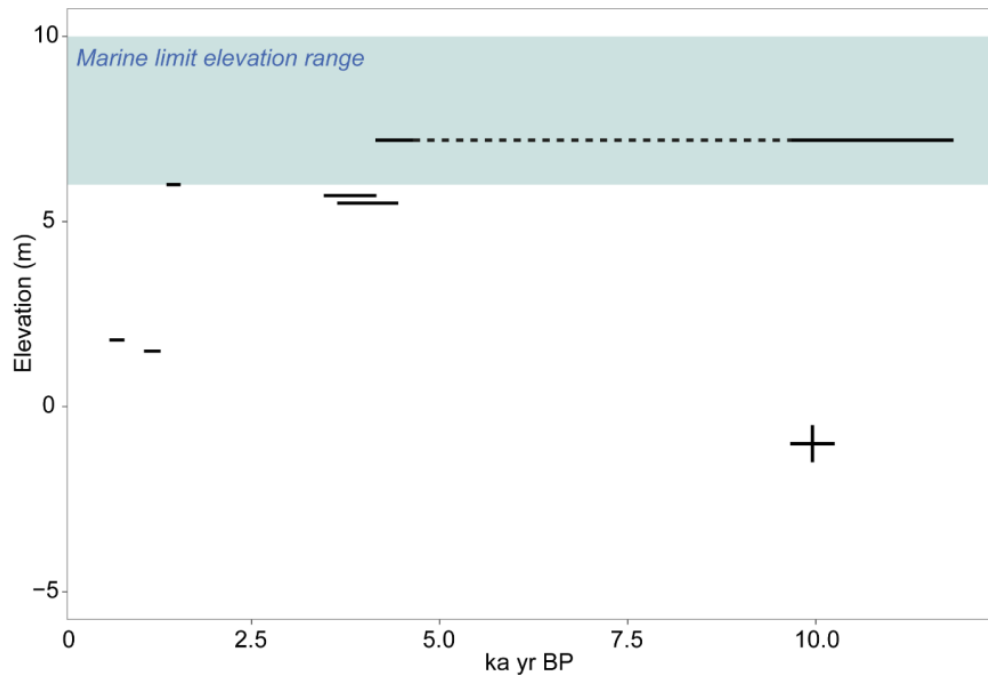


Figure 4.8 – Figure 3 from Barlow et al. (2016). Relative sea-level data for South Georgia. Blue band gives 6-10 m typical range of highest raised beaches mapped on the island. Dotted line joins the maximum and minimum ages of the formation of the raised beach at St Andrews Bay.

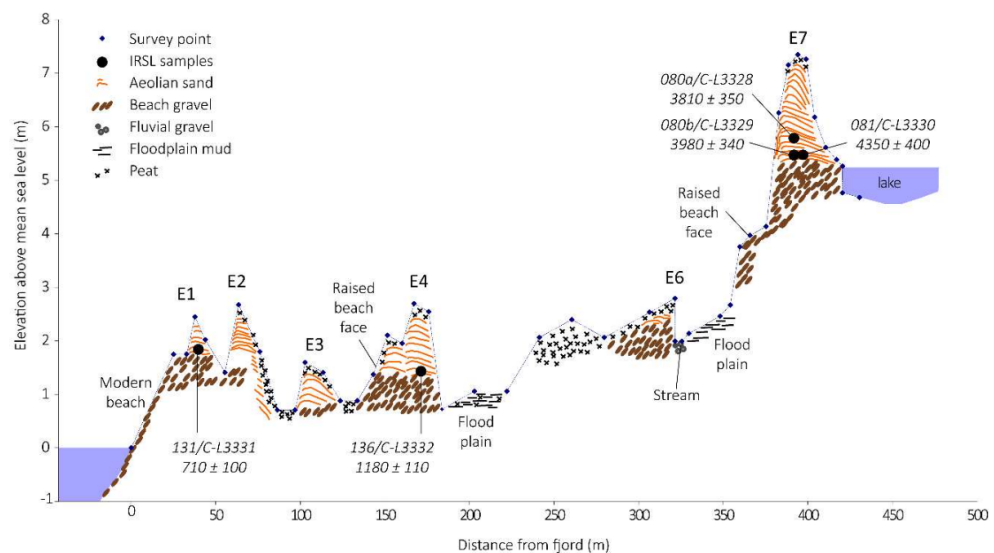


Figure 4.9 – Figure 4 from Barlow et al. (2016). Topographic and geologic cross section through the centre of Enten Valley from Cumberland Fjord (left) 400 m west to a small beach-dammed lake (right). Luminescence ages are shown with field/lab codes, while major beach ridges are labeled E1-7, though E5 is not well expressed on this transect and not marked.

4.4.2 GIA modeling

Because the region of ice melting and the gravity anomaly that we want to study here are of rather limited spatial extent, we have opted for a cartesian approach to the GIA problem. This approach is however based on the same time-frequency method as spherical codes used in our team for studying the GIA globally ([Craig et al., 2016](#), [Caron et al., 2017](#)).

This method assumes periodic ice loading, with a period equivalent to one glacial cycle (around 100 kyr). We use a load as presented in Figure 4.10, with a maximum ice thickness between 20 ka and 18 ka BP, a first deglaciation until 16 ka BP, then a small glaciation until 14 ka BP and finally a deglaciation ending around 10 ka BP ; and ice covering the whole plateau around South Georgia. In the examples shown in section 4.4.3, the maximum ice thickness has been taken equal to 1200 m. We then decompose that load in frequencies.

First, for spatial wavelength λ from 100 km to 4000 km and for each frequencies, we calculate the vertical velocity created at all depths and at the surface. For that, we use the elastic propagator matrix given for the cartesian case by ([Cathles, 1975](#), p 77–78). However, to go from a purely elastic case to a viscoelastic case, we must replace the real elastic shear and bulk moduli by the complex viscoelastic shear and bulk moduli function of the frequency. We get then a complex number which, for a given mantle rheology provides either the surface vertical velocity or the surface gravity induced by a load of given spatial wavelength and given time frequency.

To compute the induced gravity anomaly, we must integrate the effect of the deflection of the surface and the effect of the density variations at depth:

$$-w \frac{d(\rho)}{dz} - \rho \nabla \tilde{u} \quad (4.1)$$

where ρ is the density that we deduce from the PREM model, w the vertical displacement and $\tilde{u}$ the displacement vector.

4.4. Gravity signal linked to ice melting since the LGM?

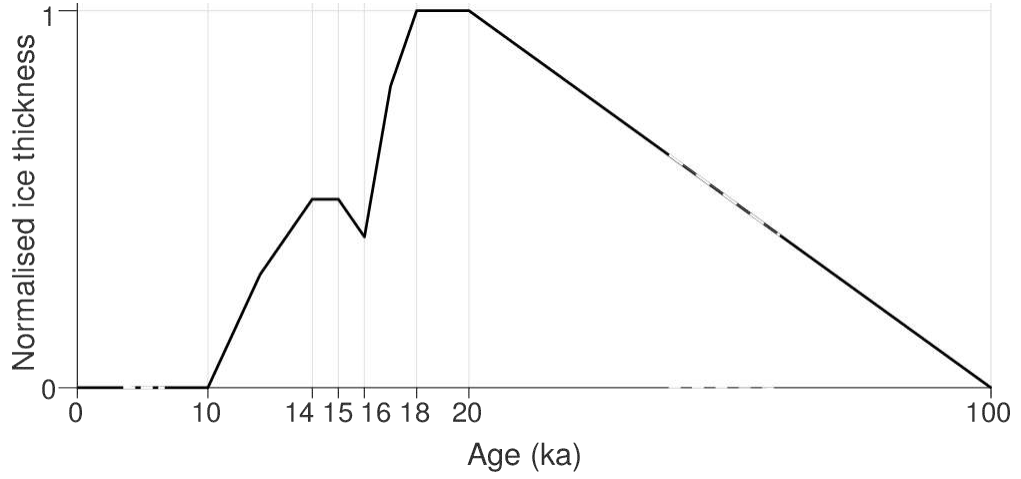


Figure 4.10 – Ice history over South Georgia continental shelf in our model.

From that, we compute the gravity anomaly at the surface. This response for each spatial wavelength, with the load history of Figure 4.10, will be referred to as $gravity_response(\lambda)$.

Second, we calculate how our GRACE processing filters spatially the signal. To do so, we use the amplitude ratio of the spherical harmonics, presented in Figure 2.8b. These ratios correspond to the filtering effect of our methodology for all spherical harmonics. For each degree, we take the mean of the ratios for orders under 15 and compute the filtering factor — $filtering(\lambda)$ — for each spatial wavelength from 100 km to 4000 km.

We take the 2D Fourier transform — $mass(k_x, k_y)$ — of a mass located over the whole continental shelf of South Georgia. We compute the surface response — $response(k_x, k_y)$ — to a mass of this shape and with an history as presented in Figure 4.10 as:

$$response(k_x, k_y) = mass(k_x, k_y) \times gravity_response(\lambda) \times filtering(\lambda) \quad (4.2)$$

where $\lambda = \frac{2\pi}{\sqrt{k_x^2 + k_y^2}}$.

Finally, we take the inverse 2D Fourier transform of this response to obtain the actual modeled signal induced by this mass.

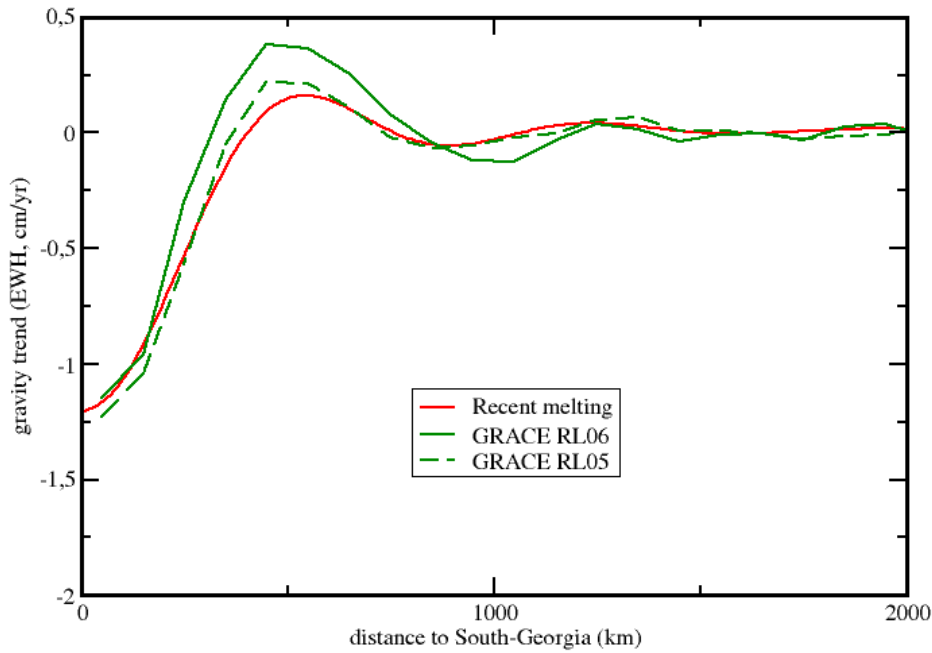


Figure 4.11 – Radially represented gravity tendency signal from South Georgia: in green the observed trend in the M-SSA GRACE v1 (dashed) and v2 solutions, and in red the recent ice melting signal rescaled so that the minimum fits the observed one.

4.4.3 Global fit of the gravity signal

Figure 4.11 shows in green the radially averaged trend around South Georgia from our M-SSA GRACE v1 and v2 solutions. The red line represents the gravity signal associated with recent ice melting scaled so that the minimum fits the observed one.

Figure 4.12 illustrates an other interpretation of the South Georgia gravity signal when the potential signal induced by GIA is taken into account. In green, we can see again the mass anomaly rate observed in the M-SSA GRACE v1 (dashed line) and v2 solutions radially averaged around the island. The result of the GIA calculation from 4.4.2 is shown in blue. The black line represents recent ice melting rescaled so that the minimum of the sum of recent ice melting and GIA fits the observed one. This requires a present-day ice-melting 1.4 times bigger than in Figure 4.11. The GIA signal is here computed for the case of a 110 km thick lithosphere over an asthenosphere with a viscosity of 3×10^{20} Pa.s down to 250 km depth, the rest of the upper mantle with a viscosity of 1.5×10^{21} Pa.s and 10^{22} Pa.s lower mantle.

4.4. Gravity signal linked to ice melting since the LGM?

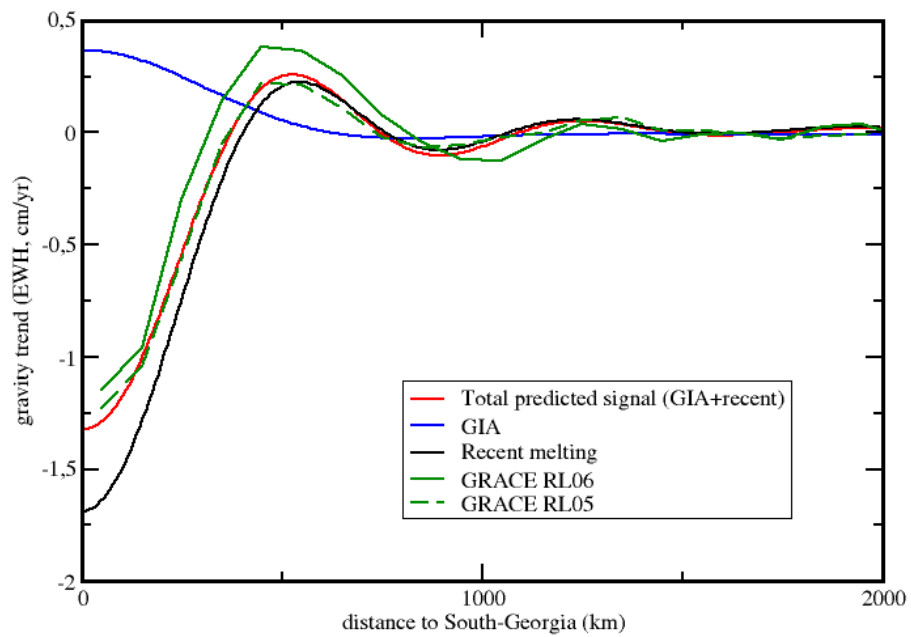


Figure 4.12 – Radially represented gravity trend signal from South Georgia: in green the observed trend in the M-SSA GRACE v1 (dashed) and v2 solutions, in black the recent ice melting signal, in blue the calculated glacial isostatic adjustment (GIA), and in red the sum of the recent ice melting and GIA signals.

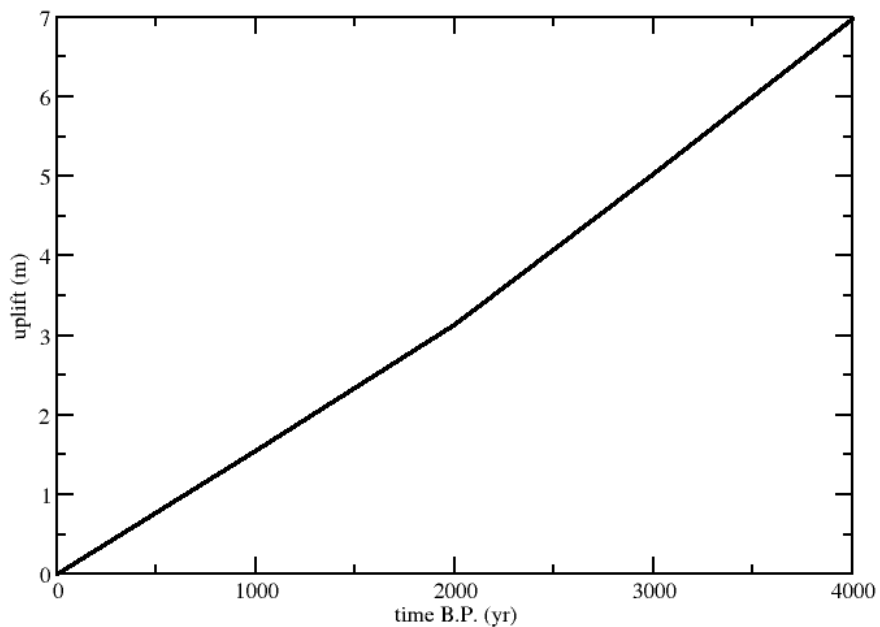


Figure 4.13 – Uplift (in m) induced by our GIA model in the last 4000 year at the center of South Georgia.

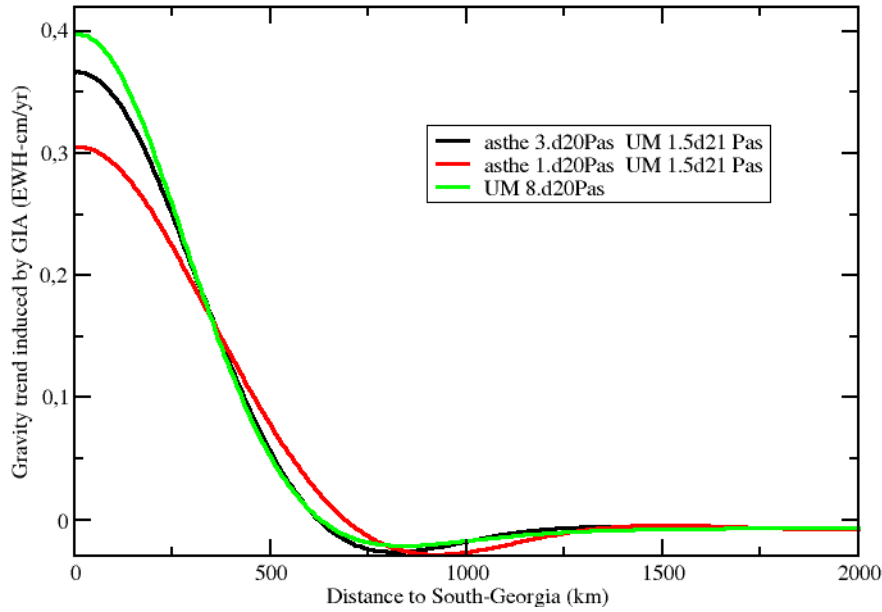


Figure 4.14 – Radially represented gravity trend signal induced by GIA for different mantle viscosity models: in black a viscosity of 3×10^{20} Pa.s in the astenosphere and of 1.5×10^{21} Pa.s for the upper mantle ; in red a viscosity of 1×10^{20} Pa.s in the astenosphere and of 1.5×10^{21} Pa.s for the upper mantle ; and in green a viscosity of 8×10^{20} Pa.s for the whole upper mantle without specific astenospheric layer. The viscosity of the lower mantle has been set to 10^{22} Pa.s for all models.

The red line is the sum of the recent ice melting (black) and the GIA signal (blue). This line is really close to the one showing the observed signal for the v1, although the positive ring of the v1 solution is not perfectly fitted. We favour this interpretation where of the gravity trend in our GRACE solution is likely due to both recent ice melting and GIA. Moreover, the uplift induced by our GIA model in the last 4000 year at the center of South Georgia (Figure 4.13) is coherent with the RSL data of [Barlow et al. \(2016\)](#) (Figure 4.8).

Further investigation would be needed to constrain more precisely the range of parameters causing such GIA signal. For example, Figure 4.14 illustrates the different gravity trend signal induced by GIA using three different viscosity profiles but the same ice history.

4.5 Discussion

The gravity signal observed in the South Georgia region shows a large variability depending on the GRACE solution used: mascons, usual DDK-filtered spherical harmonics or M-SSA solutions. The M-SSA solutions presents a large central depression with positive trends around so that the global average in the region is close to zero. The depression over the island can be explained by present day glacier melting, but the amplitude of positive rim around the depression appears to be too large to be a mere Gibbs effect.

An uplift of the bedrock induced by GIA related to the melting of a possible large ice-sheet covering the south Georgia plateau at LGM can help explaining the shape of the gravity anomaly. We show that the gravity signal is best compatible with a thick LGM ice-sheet covering the whole continental plateau which would have molten before 11 ka BP. In that case, the inferred quantity of present-day ice melting compatible with the gravity signal is multiplied by 1.4.

Although rather impressive when related to the volume of the present-day remaining ice, present-day melting in South Georgia does not represent a large contribution to global sea-level rise. However, this is of course one more example of accelerating ice melting in response to climate change.

The most important message in this chapter comes from the fact that superimposing GIA and present-day ice melting, helps explaining the amplitude of the depression over the island and of the positive signal around it. What counts is not only the average value over the region, but the relative distribution of the signal. Indeed, the volume of present-day ice-melting is affected by the superposition of a GIA signal.

We believe that almost all areas losing ice at present-day have in the past been covered by larger ice-sheets. This is poorly quantified because such small areas contribute only little to the local sea-level rise during the last 20 kyr and the geological data are often insufficient to

Chapter 4. GRACE gravity trend around South Georgia Island

constrain the ice volumes since the LGM. GPS data and local gravity measurement, when available, do however provide useful constraints in the uplift GIA signal ([Khan et al., 2016](#), [van Dam et al., 2017](#)).

Trying to retrieve the small wavelengths signal provided by GRACE (and GRACE-FO) missions without a priori on the origin and spatial distribution of the mass variations generating this signal is essential for constraining better the present day melting of glaciers and ice-sheets. In particular, scrutinizing the gravity anomalies over the oceans, close to melting ice-sheets may provide a wealth of information.

CONCLUSIONS

The GRACE satellite mission has brought unprecedented insights on the variations of the Earth gravity field. With over a decade of monthly solutions available, GRACE data has been used in a large number of geophysical studies. However, because the gravity field is sampled using the variations in the long-track distance between the two satellites, which circle the Earth in a near polar orbit and because correction models for known phenomena may induce errors, the observations bear a high sensitivity in the North-South direction. This results in stripes along the North-South direction. Several methods have been developed to reduce the effect of this noise in the GRACE data which include spatial and frequency based smoothing methods. These methods reduce the noise but unfortunately damp and/or reduce the spatial resolution of the geophysical signals thereby hindering a direct quantitative interpretation from GRACE observations. In addition, they require large assumptions on the spatial structure of either the noise or the signal and may bias the final GRACE data products.

In this manuscript, we first presented a new filtering method to remove efficiently North-South stripes from the GRACE data with minimum constraints on the a priori spatial and temporal evolution of the gravity signal. The method is based on the Multichannel Singular Spectrum Analysis (M-SSA), which we used at two levels. Firstly, we combine the GRACE solutions in spherical harmonics (SH) from several processing centers so that their common modes of variability are preserved, while their differences are filtered out. This allows to start with GRACE solutions filtered to a minimum using a filter that retains more small wavelengths compared to common solutions. Secondly, we take advantage of the spatial and temporal correlations of variations in the gravity field to design a simple M-SSA-based data-adaptive filter that efficiently removes the residual North-South stripes while preserving the shape

Conclusions

and amplitude of the signal. We produced two new GRACE Level-3 solutions by applying this methodology to RL05 and then RL06 Level-2 data.

We then compared our solutions to other published solutions. Using M-SSA as a data-adaptive filter allows us to use the less filtered DDK7 product as a starting point for the analysis, which better preserves the shape and amplitude of the actual geophysical signals as compared with the smoother, commonly used, DDK5 product. We studied examples of large continental hydrological signals in and near the Caspian and Aral Seas to show that the SH-based M-SSA method recovers EWH changes as well as, or better than, the standard — filtering and averaging — SH-based or more recent mascon-based solutions. In this region of large recent EWH changes, the M-SSA solution shows signals that are more localized and of larger amplitude than other solutions. For example, the M-SSA solution identifies an area of irrigation-related water mass increase in northern Turkmenistan that was probably buried in the noise of the standard SH solution and not parameterized in the mascon solution's regularization. We also show that the oceanic gravity signal due to large subduction-related earthquakes is well preserved by the M-SSA solution. In particular, we recover a signal linked to magnitude 8 earthquakes which is absent from the mascon solutions. The M-SSA solution described here still requires spectrally filtered products from the analysis centers, but removes North–South residual stripes more effectively than the standard mean of SH-based, DDK5-filtered solutions. We then studied the surface loading induced-displacement predicted by GRACE data and showed that reducing the spurious North–South stripes allows for a significantly better determination of the horizontal East–West displacements at GNSS stations and a slight improvement for the N-S and vertical displacements.

Finally, we investigated one other possible use of GRACE data and looked at the ice melting signal over South Georgia island. We saw that the signal observed over such a small area really differs depending on the GRACE data used. In our most refined M-SSA GRACE solutions, we observed a depression over the island and a positive signal around it. We concluded by showing that superimposing GIA and present-day ice melting can explain the gravity signal seen in our solution and that the short wavelength relative distribution of the gravity sig-

nal matters in GIA/present-day ice-melting problems. Considering only the mean value of the gravity signal over a region may leads to errors in the quantification of present-day melting.

The scientific content of Chapters 2 and 3 was summarize in a paper currently in the process of revision in *Geophysical Journal International*: Prevost, Paoline, Kristel Chanard, Luce Fleitout, Eric Calais, Damian Walwer, Tonie van Dam, and Michael Ghil. "Data-adaptive spatio-temporal filtering of grace data. *Geophysical Journal International*, in moderate revisions".

PERSPECTIVES

The launch of GRACE in 2002 signaled the start of a new era in satellite geodesy. Although satellite laser ranging has long been providing time-variable gravity results for a small handful of global-scale spherical harmonic components, it is the much higher spatial resolution provided by GRACE that has allowed for the wide variety of applications mentioned in this thesis. Changes in continental water storage, in ice sheet mass, in ocean bottom pressure, mega-earthquakes signatures, recent ice melting, post-glacial rebound or any other contribution anywhere on the globe, that involves significant redistribution of mass at scales of a few hundred kilometers and greater were potential targets for GRACE. The filtering method proposed in this thesis, used to better recover mass variability from GRACE fields, is straightforward, easy to implement and performing.

While GRACE has been decommissioned in 2017, a follow-on mission was launched in 2018: GRACE-FO. This mission is similar to GRACE, presents several spacecraft and instrumentation upgrades, but has a similar orbit and design and uses the same K-Band Ranging (KBR) technology to measure the inter-satellites distance. In addition, GRACE-FO also uses a laser-ranging interferometry (LRI) to measure this inter-satellites distance. While this new technology should reduce the measurement noise in the data, persistent North-South striping effects should remain a problem to solve ([Flechtner et al., 2016](#)). The M-SSA methodology developed here could easily be applied in operational routine to the future GRACE-FO data sets.

The work presented in Chapter 3 attempted to show that the M-SSA solution we developed performs better than the mascon inversions in oceanic context or when the signal is linked to human activities. Indeed as mascon solutions use a priori information on the signal to compute their regularization matrix, they may miss unexpected signals. A new approach

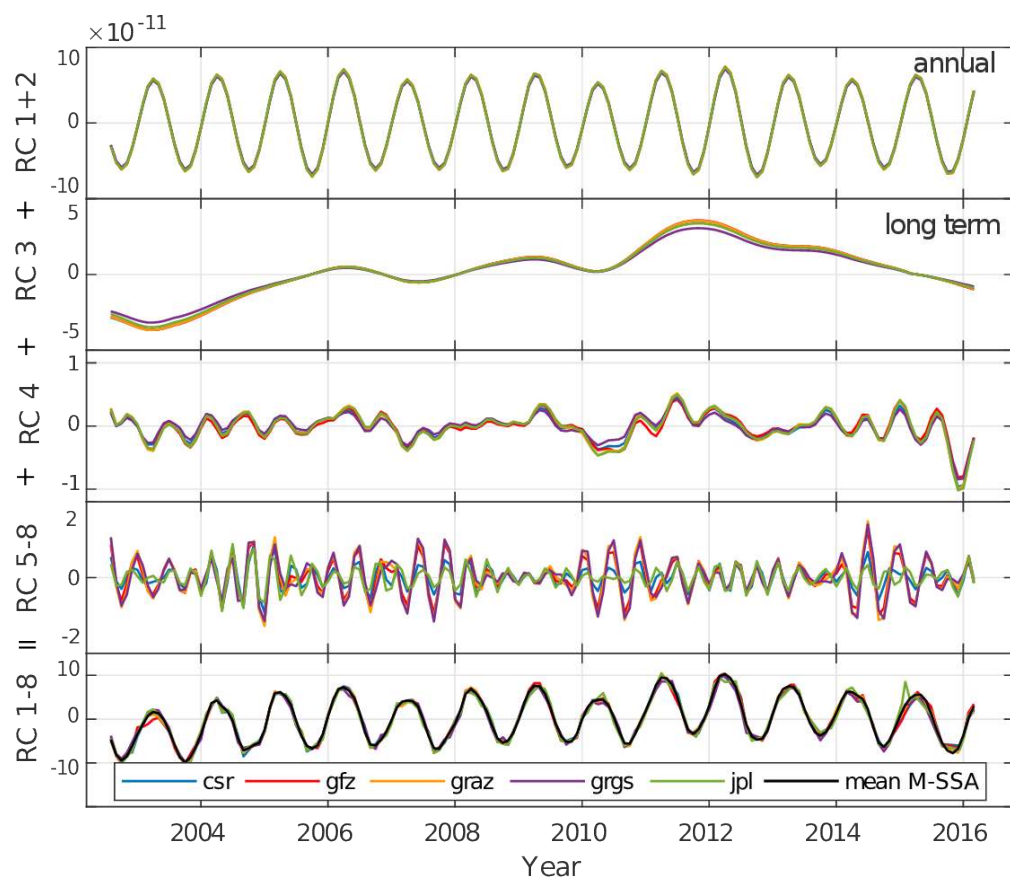
could consist in using the M-SSA solution as an a priori information to build the mascons solutions (Save et al., 2016).

Post-seismic deformations following mega-earthquakes can be interpreted in term of the viscoelastic relaxation of the mantle and are often studied with GNSS data (Trubienko et al., 2014, Klein et al., 2016). However, part of these post-seismic signals are in oceanic context and cannot be studied by GNSS. Therefore, GRACE data bring new insights on this process (Panet et al., 2010). We showed that the MSSA-GRACE solution, less filtered than the usually used GRACE solutions, preserves a fair co- and post-seismic signals in oceanic and continental regions and not only for the three largest earthquakes (Sumatra-Andaman, Maule and Tohoku-Oki). Thus, it could be used to revisit the co- and post-seismic signatures of a larger set of earthquakes. In particular, studying the response to earthquakes with strongly different magnitude, so inducing in the asthenosphere deviatoric stresses differing by one order of magnitude, might be interesting for testing the relevance of power-law rheology in the asthenosphere.

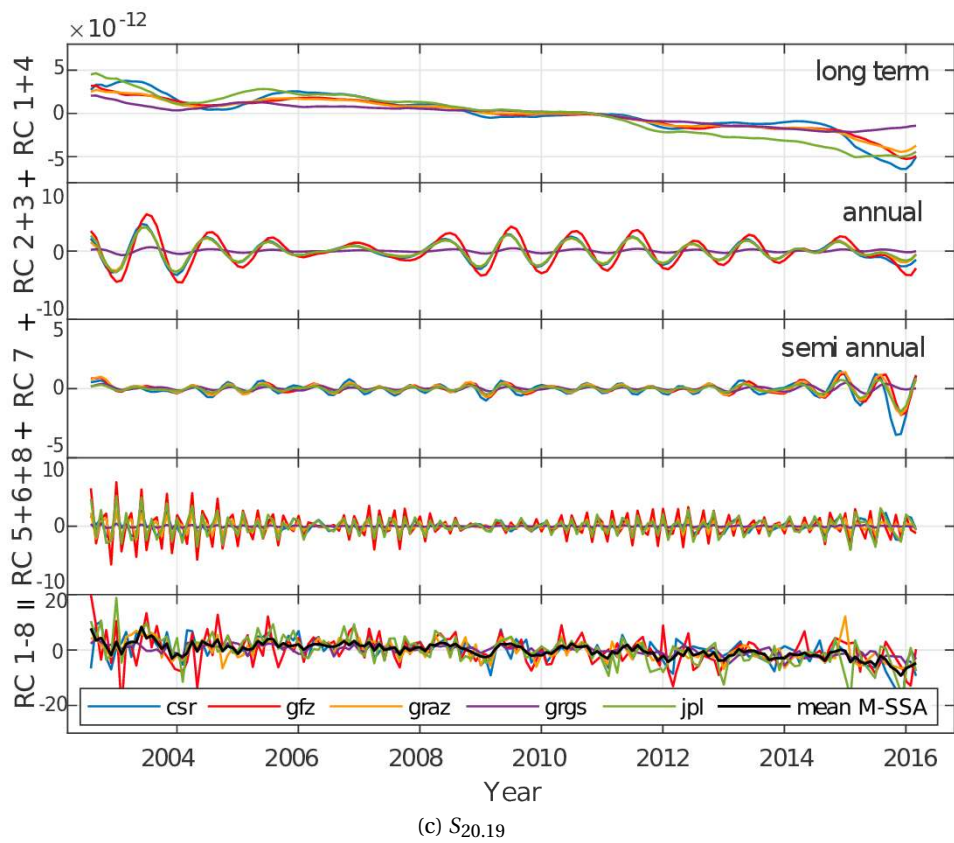
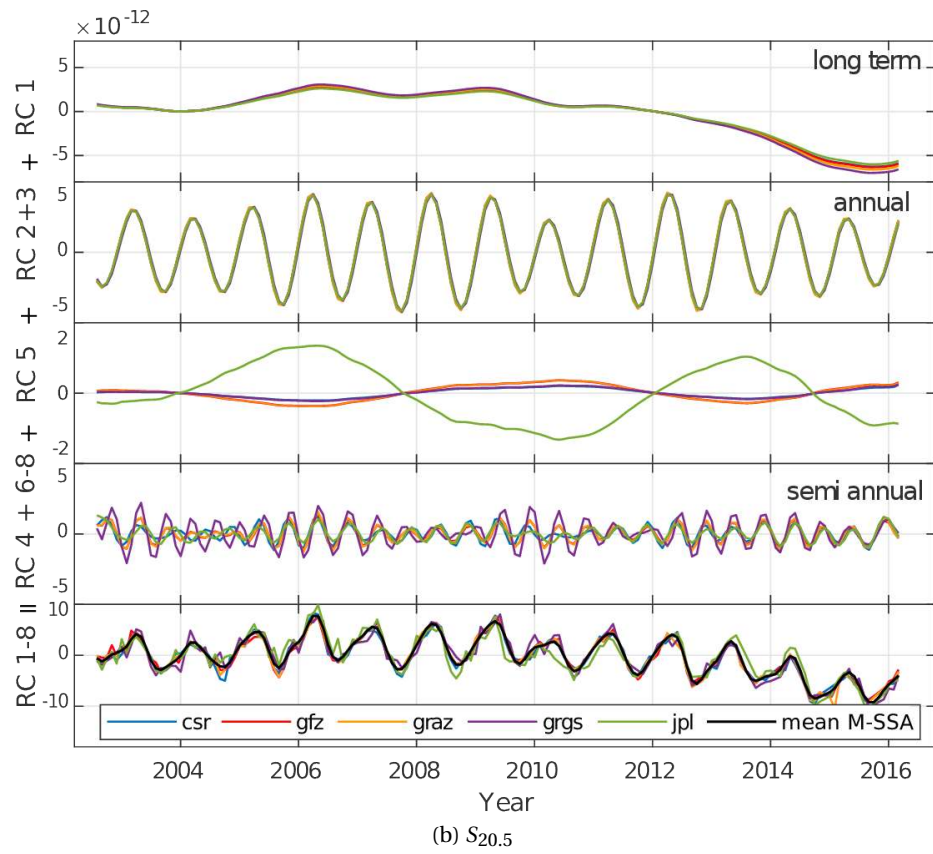
Moreover, as discussed in Chapter 4, a more refined GRACE solution can lead to a better separation of present ice-melting signal from glacial isostatic adjustment (GIA) signal. The case of South Georgia island should be further explored to bring constraints on the rheology of the area and on the ice history in sub-Antarctic areas. As the relative contribution of recent ice melting versus GIA is a key parameter to climatic issues such as sea level rise estimates, an improved GRACE solution can only be a step forward towards better understanding these still debated questions in all polar regions. In particular, in areas of recent ice melting, the most common practice has been to subtract from GRACE data a poorly constrained GIA signal and interpret the spatially averaged remaining signal as a direct consequence of present-day ice melting. In our view, the shortest wavelengths detectable with GRACE may contain very valuable information on the relative local contributions of GIA and present-day melting to the gravity variations. The signal in the oceans, close to the continental margins covered by ice-sheets, should in particular be analysed with care.

Finally, an improved GRACE solution where North-South striping has been efficiently removed could be useful to refine global hydrological mass balance estimates, providing that spherical harmonic degree-one mass, not measured by GRACE, are replaced by other geodetic estimates like by using a combination method with ocean bottom pressure model ([Sun et al., 2017](#)). In turn, this could help constraining hydrological signals of interest for global climate change studies.

GRACE gravity, through its continuous mapping of gravity variation, has largely improved our understanding on Earth's surface processes and interactions between hydrosphere, lithosphere, cryosphere and biosphere and the impact of climate change to an extent where new requirements have emerged to define the GRACE-FO mission in order to enhance the gravity signals for objective discourses. We showed that inherent noise and data resolution are important issues to exploit GRACE data to its maximum capacity. The M-SSA method developed in this thesis allows for refined geophysical applications. As similar noise sources will likely remain an issue in the GRACE-FO data exploitation, the M-SSA method may be adapted to the new mission in order to maximize the potential geophysical applications of the new spatio-temporal gravity field measurements.

(a) $S_{4.2}$

Appendix A. M-SSA decompositions



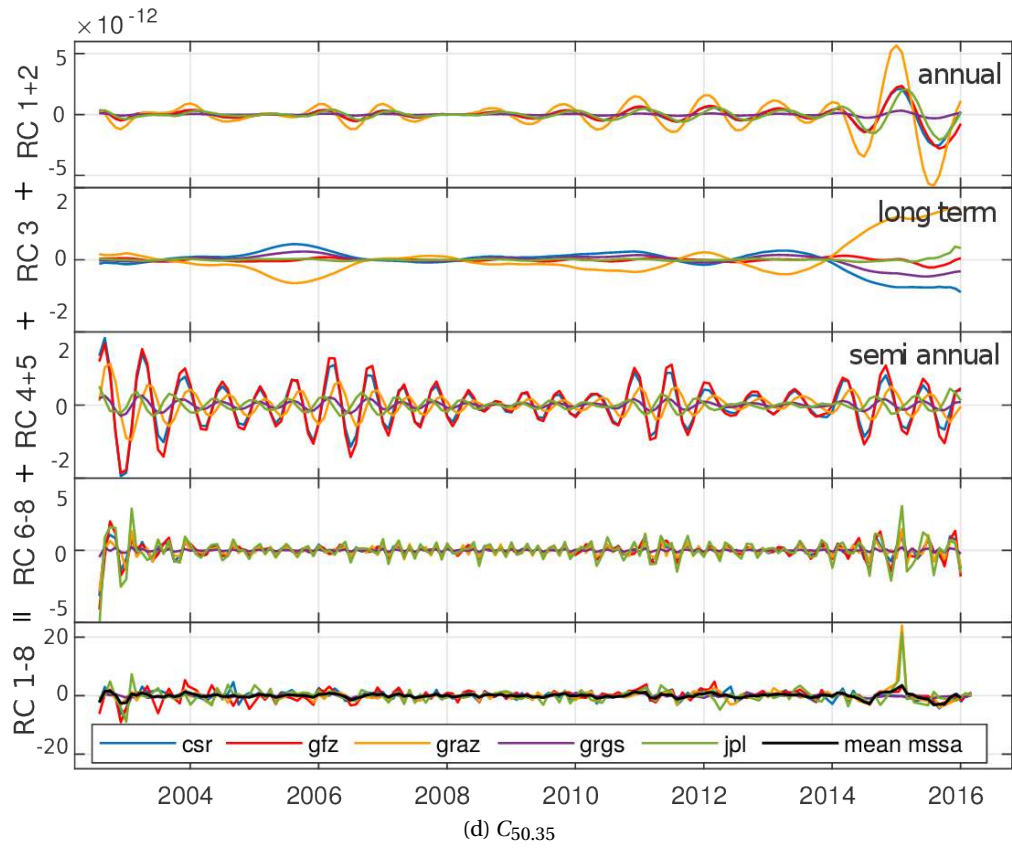
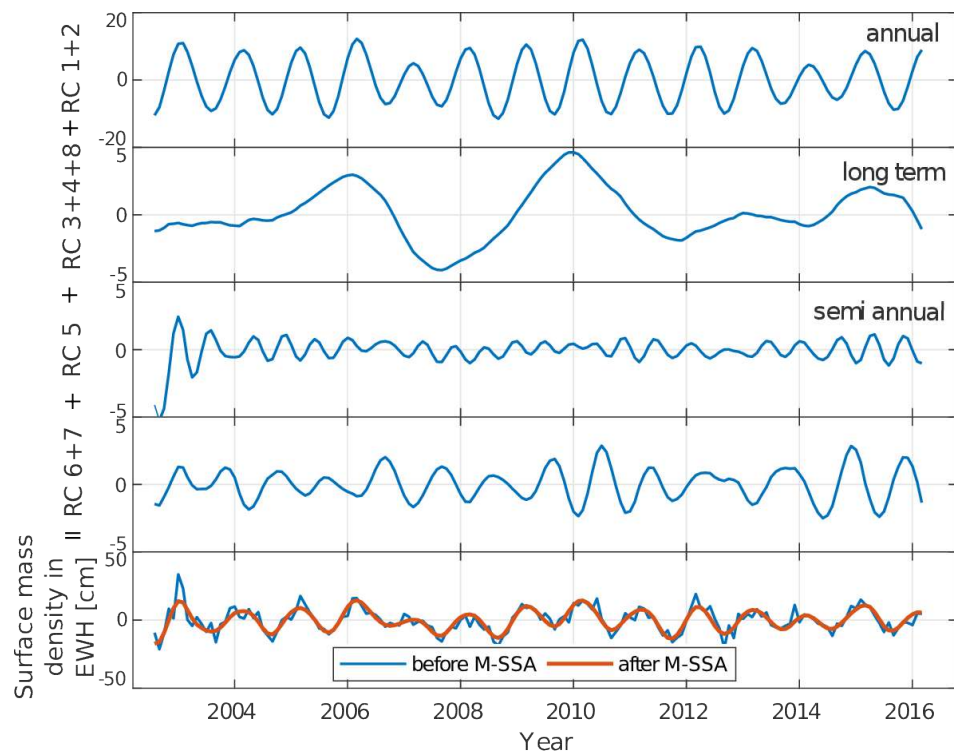
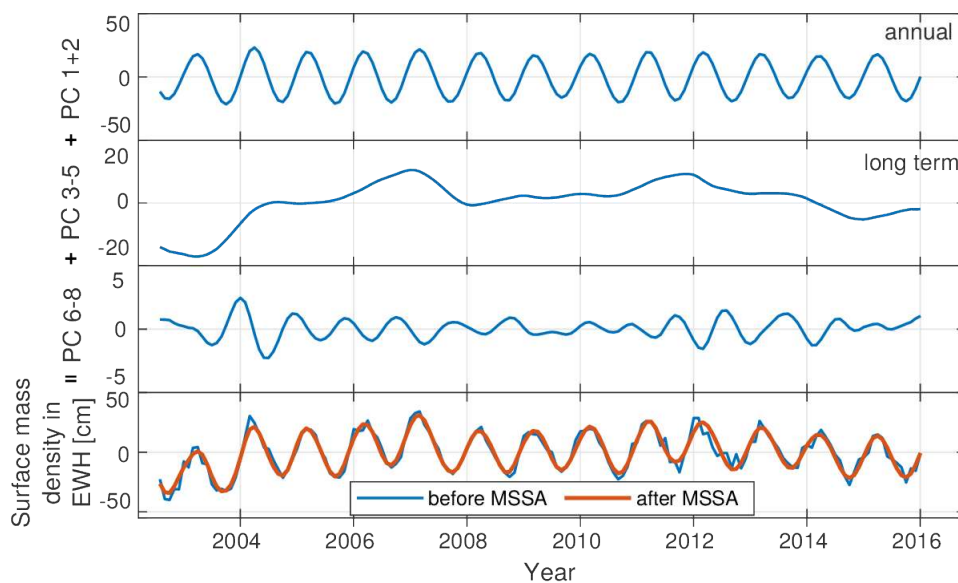


Figure A.1 – Multichannel Singular Spectrum Analysis (M-SSA) step 1 decomposition of GRACE spherical harmonics. The first 4 panels show one or a visually made combination of partial reconstructions (RCs) of similar nature for each processing center: CSR (blue), GFZ (red), yellow (GRAZ), CNES/GRGS (purple) and JPL (green). The bottom panel shows the signal reconstructions using the first 8 RCs for each of the 5 GRACE solutions and the mean of the reconstructions (black).

Appendix A. M-SSA decompositions

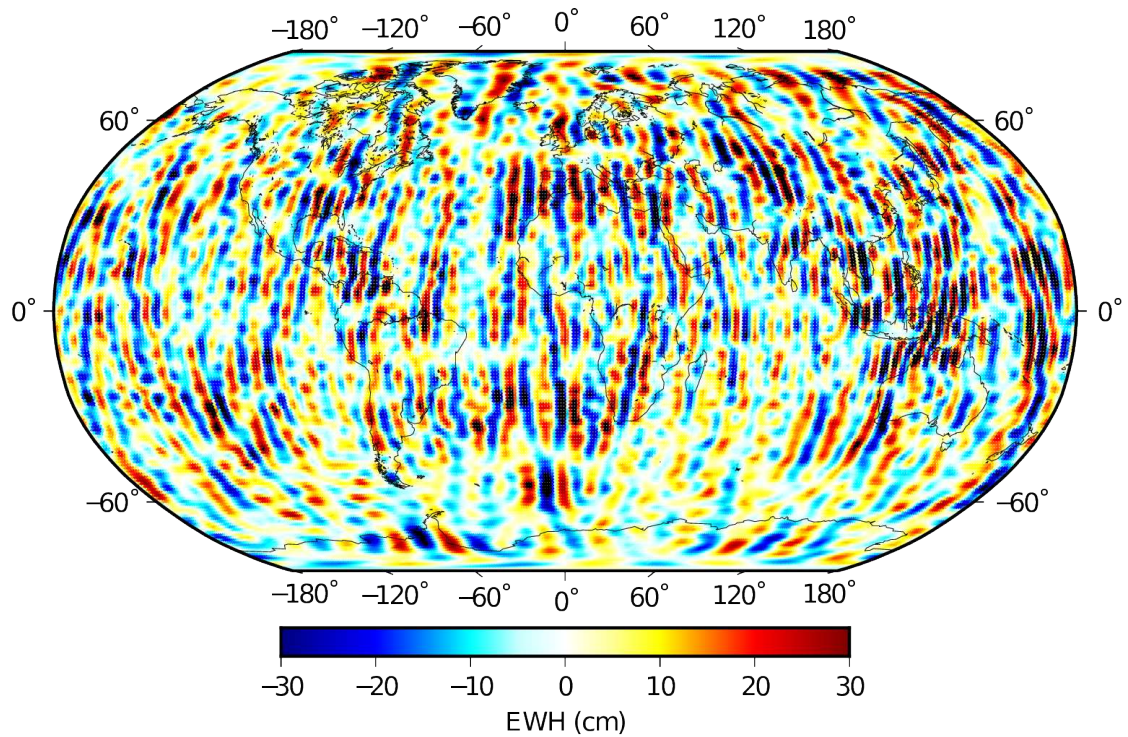


(a) Latitude 40° N and longitude 20° E



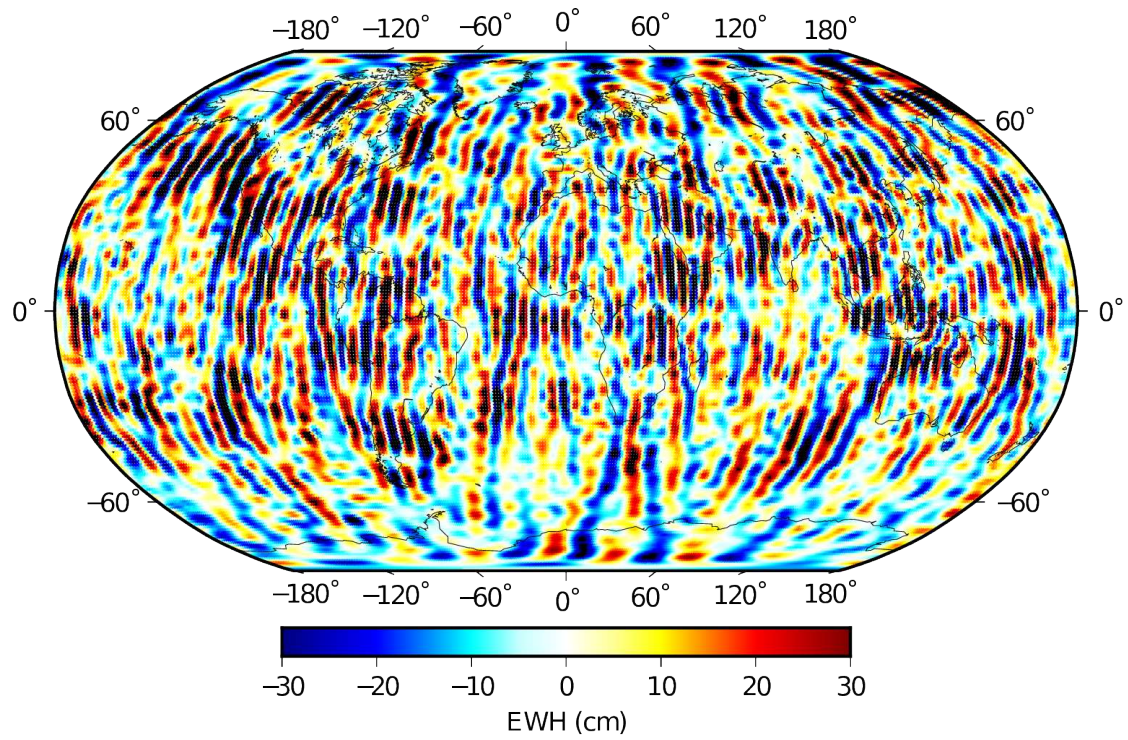
(b) Latitude 16° S and longitude 48° W

Figure A.2 – Multichannel Singular Spectrum Analysis (M-SSA) step 2 decomposition of surface mass density anomalies time series derived from GRACE. The first 3 or 4 panels show one or a visually made combinations of partial reconstructions (RCs) of similar nature. The bottom panel shows the time series prior to the final M-SSA (blue) and the signal reconstructed using the first 8 RCs (red).

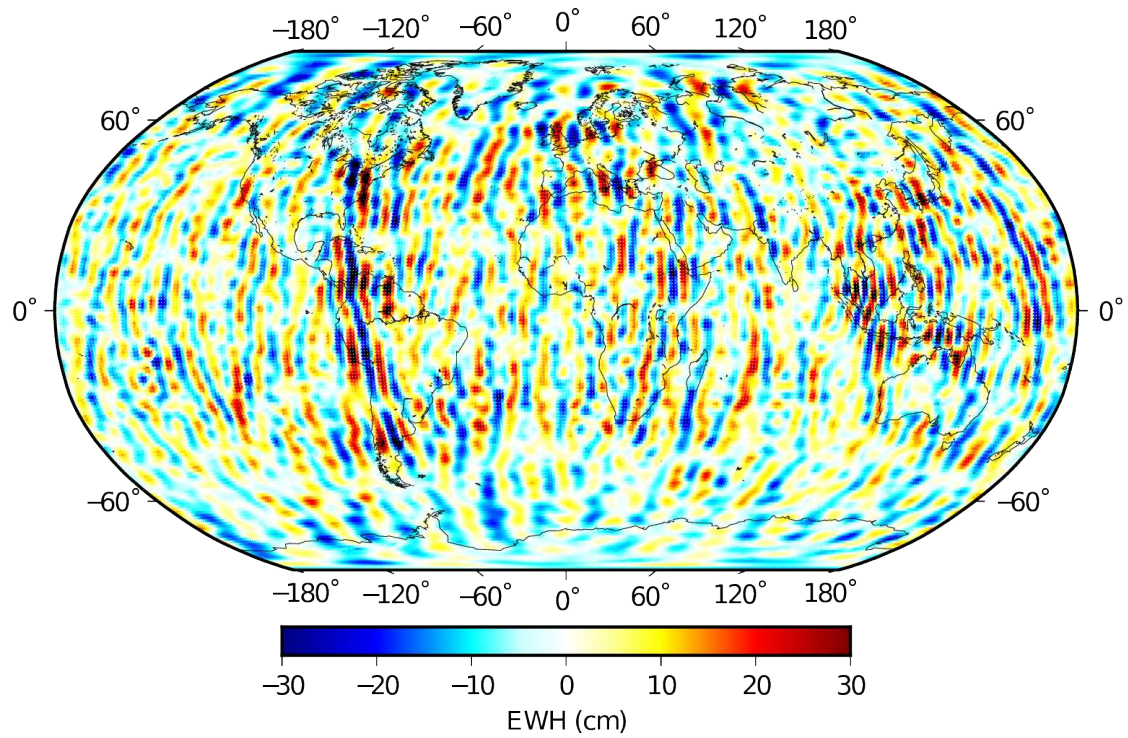


(a) solution from CSR

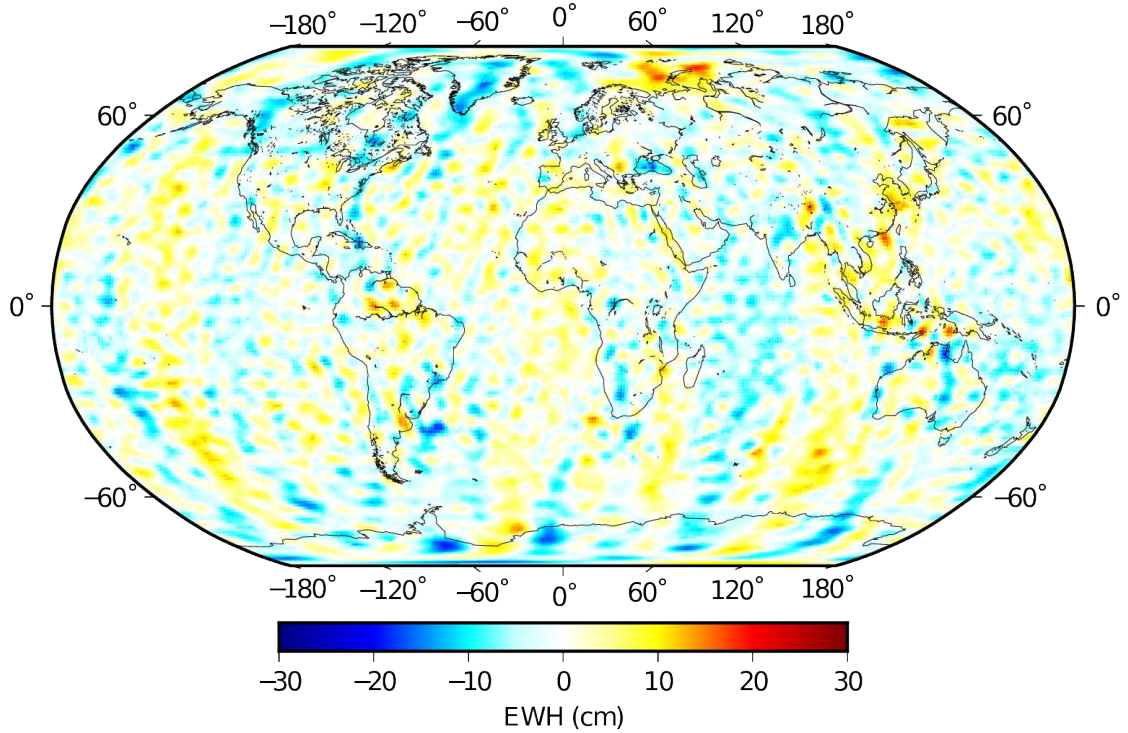
Appendix B. GRACE solutions differences



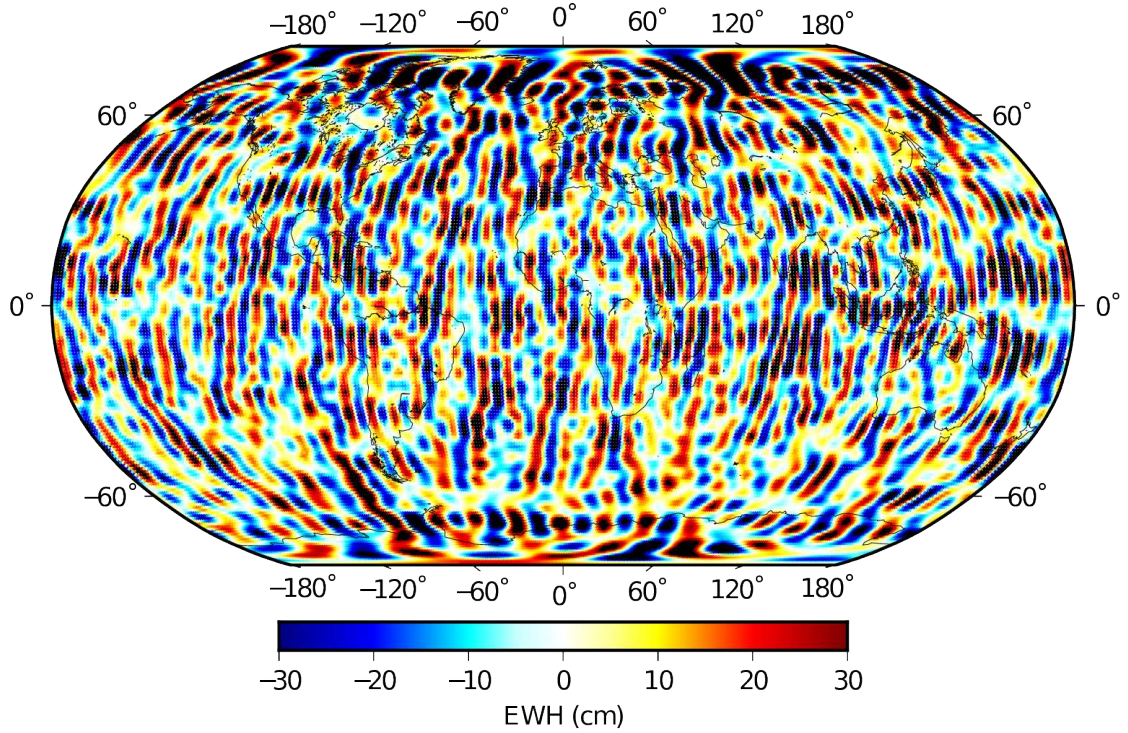
(a) solution from GFZ



(b) solution from GRAZ



(a) solution from GRGS



(b) solution from JPL

Figure B.3 – Surface mass density anomalies difference for January 2006 relative to July 2005 expressed in equivalent water height (in cm), between one of the used common solutions filtered with the decorrelation filter DDK7 and the M-SSA solution.

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RÉSUMÉ

L'estimation des variations spatio-temporelles du champ de gravité terrestre à partir des mesures de la mission satellitaire Gravity Recovery and Climate Experiment (GRACE) ont permis de mieux comprendre les redistributions de masse à des échelles de temps mensuelle, saisonnière ou décennale. Les solutions GRACE produites par différents centres, adoptant des stratégies de traitement différentes, conduisent à des résultats cohérents. Cependant, ces solutions présentent aussi des erreurs aléatoires et systématiques, celles-ci pouvant avoir une structure spatio-temporelle spécifique.

Afin de réduire le bruit et améliorer la qualité des signaux géophysiques présents dans les données GRACE, plusieurs méthodes ont été proposées mais nécessitent en général des informations a priori sur la structure spatio-temporelle du bruit pourtant mal connue. Malgré les efforts considérables effectués pour améliorer la qualité des données GRACE pour des applications géophysiques de plus en plus fines, le filtrage du bruit reste une question problématique comme exposé dans le Chapitre 1.

Dans cette thèse, nous proposons une approche différente, utilisant une technique de filtrage spatio-temporel, la Multichannel Singular Spectrum Analysis (M-SSA) décrite dans le Chapitre 2. La M-SSA est une méthode s'adaptant aux données, à variables multiples et non-paramétrique, qui exploite simultanément les corrélations spatiales et temporelles d'un champ géophysique. Nous utilisons la M-SSA sur 13 ans de données GRACE en harmoniques sphériques distribuées par cinq centres de calculs. Nous montrons que cette méthode permet d'extraire les modes de variabilité communs aux différentes solutions, et de réduire significativement les erreurs spatio-temporelles spécifiques à chaque solution et liées aux différentes stratégies de calculs. En particulier, cette méthode filtre efficacement les stries Nord-Sud dues, entre autres, aux imperfections des modèles de corrections des phénomènes connus.

Dans le Chapitre 3, nous comparons notre solution GRACE à d'autres solutions en harmoniques sphériques et à des solutions basées sur des blocs de concentration de masse (mascons) utilisant des a priori sur la structure spatio-temporelle du signal géophysique. Nous comparons également les performances de notre solution M-SSA GRACE par rapport à d'autres solutions en calculant la déformation de surface induite par les variations de masse déduites des mesures GRACE et en la comparant avec des mesures indépendantes de déplacement provenant des stations du Global Navigation Satellite System (GNSS).

Enfin, nous discutons dans le Chapitre 4 d'une application possible d'une solution GRACE améliorée pour répondre à des questions encore débattues liées au rebond post-glaciaire. Plus précisément, nous nous intéressons à la séparation du signal du rebond post-glaciaire, lié à la fonte ancienne, du signal de fonte récente des glaces dans la région de la Géorgie du Sud.

MOTS CLÉS

GRACE – gravité – M-SSA

ABSTRACT

Measurements of the spatio-temporal variations of Earth's gravity field recovered from the Gravity Recovery and Climate Experiment (GRACE) mission have led to unprecedented insights into large spatial mass redistribution at secular, seasonal, and sub-seasonal time scales. GRACE solutions from various processing centers, while adopting different processing strategies, result in rather coherent estimates. However, these solutions also exhibit random as well as systematic errors, with specific spatial and temporal patterns in the latter.

In order to dampen the noise and enhance the geophysical signals in the GRACE data, several methods have been proposed. Among these, methods based on filtering techniques require a priori assumptions regarding the spatio-temporal structure of the errors. Despite the large effort to improve the quality of GRACE data for always finer geophysical applications, removing noise remains a problematic question as discussed in Chapter 1.

In this thesis, we explore an alternative approach, using a spatio-temporal filter, namely the Multichannel Singular Spectrum Analysis (M-SSA) described in Chapter 2. M-SSA is a data-adaptive, multivariate, and non-parametric method that simultaneously exploits the spatial and temporal correlations of geophysical fields to extract common modes of variability. We perform an M-SSA simultaneously on 13 years of GRACE spherical harmonics solutions from five different processing centers. We show that the method allows for the extraction of common modes of variability between solutions, and removal of the solution-specific spatio-temporal errors arising from each processing strategies. In particular, the method filters out efficiently the spurious North-South stripes, most likely caused by aliasing of the imperfect geophysical correction models of known phenomena.

In Chapter 3, we compare our GRACE solution to other spherical harmonics solutions and to mass concentration (mascon) solutions which use a priori information on the spatio-temporal pattern of geophysical signals. We also compare performance of our M-SSA GRACE solution with respect to others by predicting surface displacements induced by GRACE-derived mass loading and comparing results with independent displacement data from stations of the Global Navigation Satellite System (GNSS).

Finally, in Chapter 4 we discuss the possible application of a refined GRACE solution to answer debated post-glacial rebound questions. More precisely, we focus on separating the post-glacial rebound signal related to past ice melting and the present ice melting in the region of South Georgia.

KEYWORDS

GRACE – gravity – M-SSA