Comité national français de l'Union géodésique et géophysique internationale

Rapport quadriennal 2011-2015

Quadriennal Report 2011-2015

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Avant-Propos

Le rapport qui est présenté ici rassemble les contributions de plusieurs sections du CNFGG. Il ne donne malheureusement qu'une vue partielle des activités de la communauté française, faute d'avoir pu obtenir des éléments de l'ensemble des disciplines concernées.

Le CNFGG se réorganise actuellement afin d'assurer à l'avenir des rapports d'activité raisonnablement complets. Nous avons l'ambition d'être un observatoire de l'activité nationale dans le domaine de la géodésie et de la géophysique, concrétisé notamment par un site web rediffusant ce genre d'informations.

En parallèle, le CNFGG s'est engagé pour mobiliser la communauté française en vue d'une participation active à l'UGGI et ses associations.

Je remercie donc toutes celles et ceux qui ont participé à la rédaction de ce rapport.

Claude Boucher
Président du CNFGG

Composition du conseil du CNFGG
http://cnfgg.eu

Le Comité National Français de Géodésie et de Géophysique (CNFGG), créé en 1919, a pour mission de représenter, sous l'autorité de l'Académie des sciences, la communauté scientifique française au sein de l'Union Géodésique et Géophysique Internationale (UGGI/IUGG) et de ses Associations disciplinaires.

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Section 1

Géodésie
Geodesy

CNFGG quadrienal report 2011-2015
Section 1 : Geodesy

Trough its members the section 1 of the CNFGG gathers French competences in terms of research a realization aspects in geodesy. They pertain to national organisms such as BDL, BRGM, CNES, CNRS, EOST, ESGT, IGN, OCA, OMP, OP, SHOM, UPF involved in different geodetic activities.
This quadriennal report of the geodesy section cannot evidently claim being exhaustive. It includes a selection of reports delivered from eigth organisms: Bureau des longitudes, Centre national d'études spatiales, Ecole supérieure des géometres et topographes, Ecole et Observatoire de Strasbourg, Institut national de l'information géographique et forestière, Observatoire de la cote d'azur, Observatoire de Paris, Service hydrographique et océanographique de la marine. It includes moreover in appendix a list of publications from these organisms.

1) Bureau des longitudes (François Barlier)

Missions

The *Bureau des longitudes*, established in 1795, devotes its activities to scientific areas which come from its history (astronomy, geodesy, geophysics, etc.), constantly adapting to developments and projects in these areas. It functions as a scientific academy, with one session per month, plus meetings of working groups on specific topics for the preparation of books, documents, or colloquiums.
The *Bureau des longitudes* has been given the mission of publication and provision of public French astronomical ephemeris (*Connaissance des temps*, *Annuaire du Bureau des longitudes*), both having an annual publication. It has the scientific responsibility of these ephemeredes, whose implementation is entrusted, since 1998, to the *Institut de mécanique céleste et de calcul des éphémérides* (IMCCE), a division of Paris Observatory. The *Bureau des longitudes* "*Commission des éphémérides*" has been in charge of defining, in coordination with IMCCE, the content and evolution of these publications, with a special care to comply with the IAU and IUGG resolutions. This was especially the case for the IAU 2006/IUGG 2007 resolutions. As a member of the Research Group of Space Geodesy (GRGS), the *Bureau des longitudes* has a representative in its Directing Board, its Executive Committee and Scientific Council and gives advice on the GRGS organization, work and projects.
As part of its mission to disseminate scientific information, the *Bureau des longitudes* organizes each year a series of monthly lectures related to its areas, as well as one scientific colloquium, each year on a specific theme. These lectures and colloquiums have brought together a wide audience during the period 2012-2015. The *Bureau des longitudes* also participates in the organization and scientific sponsorship of colloquiums at national, European or international level, especially in the field of celestial and space navigation. It gives advice and recommendations on scientific issues related to its areas, in particular as published documents, with the participation of outside experts and in cooperation with other institutions.

Organization

The *Bureau des longitudes* is composed of 13 members, ex-officio representatives and additional corresponding members as described below:
Members (as of May 2015, provided in chronological order of the year of election): J. Kovalevsky, R. Cayrel, N. Capitaine, J.-L. Le Mouël, S. Débarbat, J.-P. Poirier, F. Barlier, P. Baüer, N. Dimarcq, J. Laskar, C. Boucher, F. Mignard, A. Cazenave. B.Guinot is honorary member.
Ex-officio representatives (as of May 2015): J. Parent du Châtelet (MétéoFrance), B. Frachon (SHOM, D. Hestroffer (Paris Observatory), D. Priou (IGN), Mioara Mandéa (CNES).

Corresponding members (as of May 2015, provided in chronological order of the year of election): J. Chapront, J.-C.Duplessy, J.-E. Arlot, V. Brumberg, J.-C. Husson, J.-L. Simon, G. Balmino, M. Crépon, P. Willis, S. Ferraz-Mello, E.F. Arias, C. Turon, C. Sotin, J. Achache, Y. Desnoës, F. Rémy, C. Balkovski, V. Déhant, M. Diament, A. Souriau, A. Morbidelli, T. Quinn, P.Charlot, P. Briole, L. Blanchet, M-F Lequentrec-Lalancette, A.Fienga, G.Reverdin.
G. Amat, J-C Pecker, M. Lefebvre are honorary members.
The Bureau is elected and appointed for a 1-year period; its composition for 2012-2015, was:
for 2012 -2013 : President: Pierre Baüer, Vice-President : François Barlier, Secretary: Pascal Willis: for 2014-2015: President: François Barlier, Vice-President: Claude Boucher, Secretary: Pascal Willis for 2014, Marie-Françoise Lequentrec-Lalancette for 2015.

Meetings 2012-2015

Monthly meetings and scientific colloquiums

Besides its regular monthly meetings open to a large public (see above), the scientific colloquiums (including 4 to 5 presentations each), organized on a yearly basis at mid-June by the *Bureau des longitudes* have been as follows:
2012 : *De l'Astronomie de J.D Cassini (1625-1712) à la sonde spatiale Cassini ;* 2013: *se repérer dans l'espace et le temps ;* 2014 : *La voie lactée, notre Galaxie redécouverte par Gaia;* 2015 : *Le système international de référence terrestre - Développement, réalisations et usages.*

Scientific colloquiums with the scientific sponsorship of the Bureau des longitudes

The *Bureau des longitudes* was involved in the organization of Colloquiums on "Scientific and Fundamental Aspects of the Galileo System", organized by the European Space Agency, in Toulouse (France) from 1 to 4 October 2007, and in Padova (Italy) from 14 to 16 October 2009, in Copenhagen (Denmark) from 31 August 2011- to 2 September 2011, in Prague (Czech Republic) from 4 - to 6 december 2013, respectively. The Bureau des longitudes was also involved in a scientific day on «GNSS et Sciences » at CNES on 29 January 2015 and in an international workshop in Astronomy and Dynamics organized on the occasion of the 60th birthday of Jacques Laskar by IMCCE/Paris Observatory (April 28-30, 2015). More details as well as past scientific conferences can be found at (http://www.bureau-des-longitudes.fr/conferences.htm).

Publications 2012-2015

Besides its responsibility of yearly publications of the French astronomical ephemerides (see above), the Bureau des longitudes publishes books, written by its members or corresponding members, with the participation of outside experts and in cooperation with other institutions on selected scientific topics related to its mission. Several « Cahiers thématiques » have been Published in the «Annuaire du Bureau des longitudes/Guide des données astronomiques » :

Annuaire 2015:

Les systèmes d'observation météorologique par satellite by Jean Pailleux. Mission accomplie pour le programme exoplanètes de CoRot : une population de planètes à l'étonnante diversité by Daniel Rouan.

Annuaire 2014

Fluctuations hydro-astmosphériques de la rotation terrestre by Christian Bizouard. Les géantes rouges dévoilées par CoRoT et Kepler by Benoit Mosser. Météores et bolides by Jérémie Vaubaillon

Annuaire 2013

Le seigneur des anneaux by André Brahic.
Comètes et astréroïdes, de subtiles analogies by Anny-Chantal Levasseur-Regourd.

Le Soleil : une étoile magnétique et active, source de particules énergétiques by Nicole Vilmer.
A new book will be edited in Summer 2015 by Hermann editor on the references of « Space and Time » coordinated by C. Boucher and P. Willis.
In a coopération with the «Bibliothèque nationale de France» the «Bibilothèque de Observatoire de Paris» had put in a numerical form the « Annuaire du Bureau des longitudes » up to 1950, the «Connaissance des temps » up to 1935, the «Annales du Bureau des longitudes» (all the collection).

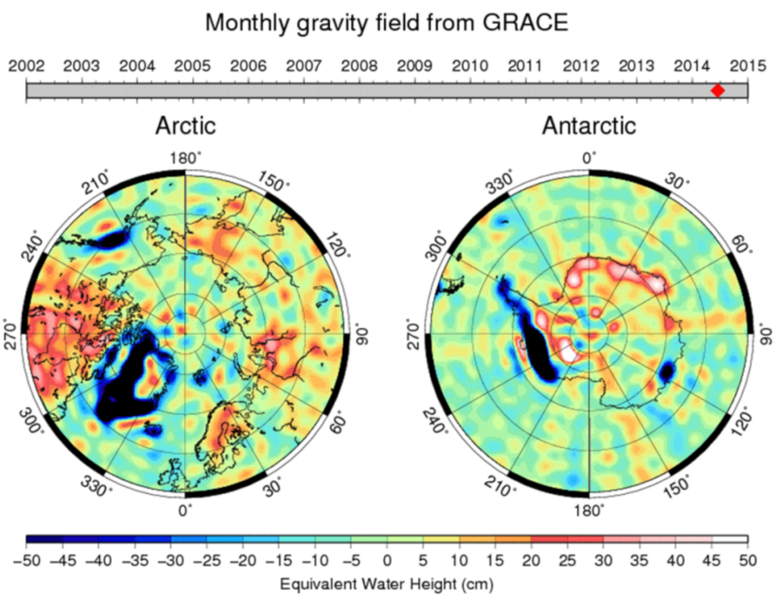
2) Centre national d'études spatiales (CNES) et Groupe de recherche en géodésie spatiale (GRGS)

R. Biancale, J.-M. Lemoine, S. Bruinsma, J. Laurent-Varin, F. Perosanz

The CNES/GRGS Space Geodesy Team has been involved in different projects and studies among others in gravity field determination or precise positioning. For instance main activities of the team have been processing the data of the GRACE and GOCE missions of space gravimetry, the determination of the gravity field of the Churyumov-Gerasimenko comet to determine the Philae lander trajectory in the framework of ESA's Rosetta mission, as well as precise positioning with GNSS and DORIS.

GRACE

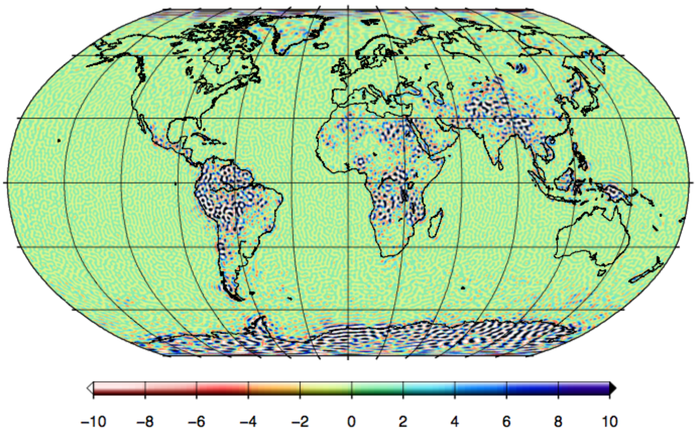
The GRACE mission (Gravity Recovery and Climate Experiment), a NASA-DLR cooperation, was launched on 17 March 2002 and is still operational, despite battery weaknesses that require powering down the accelerometers and the KBR device for a few weeks twice per year, when passing in the shadow of the Earth, in order to reduce the thermal control of the instruments.
CNES/GRGS processes the data regularly with a latency of about six months to generate monthly gravity models, which are also provided as global grids converted to equivalent water height. Moreover, a new release (GRGS-RL03) was recently produced over 12 years allowing improved interpretations of hydrological mass variations. They are publicly available through the GRGS web site. They provide valuable insights into the fields of hydrology, glaciology, ocean dynamics and solid Earth sciences.



In addition, the high-resolution model EIGEN6-C4 was produed in cooperation with GFZ-Potsdam. It was calculated by combining data from the GRACE, GOCE and LAGEOS satellites with high-resolution terrestrial data from altimetry over oceans (DTU10) and gravimetry over land (EGM2008). This model is expanded up to the spherical harmonic degree and order 2190, equivalent to a resolution of the order of around 9 km and contains as well temporal terms up to degree and order 50.

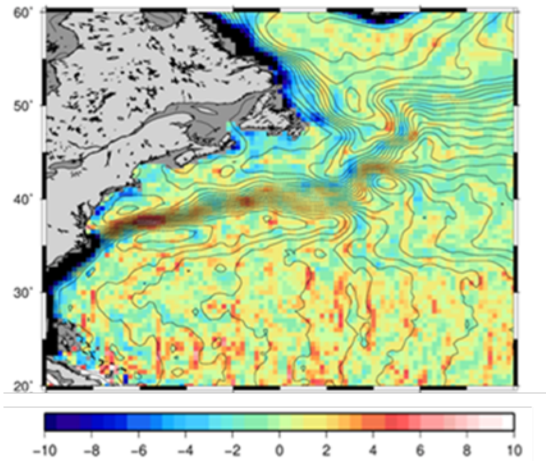
GOCE

GOCE (Gravity field and steady-state Ocean Circulation Explorer), ESA's first Earth Explorer, was launched on 17 March 2009 and re-entered the atmosphere on 11 November 2013. The mission objectives are specified at 100 km resolution: Geoid (gravity anomaly) accuracy of 1 to 2 cm (1 mGal). GOCE was equipped with a tri-axial gravity gradiometer, GPS receiver, laser retro-reflector, star sensors and an ion propulsion engine with variable thrust to reach these goals. The High-level Processing Facility (HPF) computed the GOCE level 2 products on behalf of ESA; CNES/GRGS and GFZ Potsdam produced gravity field models computed via the direct numerical approach in this framework. The latest model, DIR-R5, is constructed with LAGEOS-1/2, GRACE and GOCE data in order to reach high accuracy over the entire spectral range of the model.
The cumulated (formal) error of DIR-R5 at degree 200 in terms geoid height (gravity anomaly) is 0.8 cm (0.2 mGal). The calibration factor, estimated using GPS/leveling data over Germany, is 2. The GOCE mission objectives have been reached according to this evaluation.



The Figure to the left displays the gravity anomaly difference (mGal) to degree/order 200 between DIR-R5 and EGM2008. The large differences over the continents are improvements thanks to GOCE data over regions for which sparse or low quality data were available for EGM2008.

The relative accuracy of the geoid models was assessed through the comparison of geoid-derived and observed (drifters) mean geostrophic currents. The standard deviation (s) of the difference is then calculated. The Figure to the right illustrates this improvement for the Gulf Stream, where DIR-R5 shows better consistency with drifters than every former models. The optimal resolution of GOCE for oceanographic application is estimated to be between 100 and 125 km.



ROSETTA

On 12 November 2014, the general public with all the space centres turned their gaze to the landing of Philae from the ROSETTA probe onto the surface of the comet Churyumov-

Gerasimenko, at more than three astronomical units[1] from the Earth. In addition to the scientific outlook of this mission, this success is a singular technical feat, which required long preparation over many years. The trajectory alone – from the launch pad in French Guiana on 2 March 2004 to the landing on 12 November 2014 - lasted more than ten years. The probe had to follow a complex path through the solar system with multiple gravity assists from Earth and Mars (Earth-Mars-Earth-Earth) to reach the highly eccentric orbit of the comet targeted. During its trip, ROSETTA crossed the asteroid belt twice where it could observe Stein (5 September 2008) and Lutetia (10 July 2010) and thus obtain photos and scientific measurements of remarkable quality.

All systems did not work well, such as the anchor harpoons of Philae, the mission is considered successful and allows for scientific measurements in situ, which is a historic premiere. To accomplish this mission several space agencies, like ESA and CNES, worked coordinated. The French space agency had the responsibility of Philae as well as proposing a consensual "touchdown" site, taking the scientific objectives and operational constraints into account. Several Philae descent trajectory simulations were calculated by the flight dynamic teams, with the objective to reduce the risks.

The CNES/GRGS Space Geodesy Team was involved in modelling the gravity of the comet using knowledge of its shape and the tracking measurements at the approach of the comet. The gravity, which plays a major role in the dynamics of the descent of Philae, was to be known with the greatest possible precision. Two models were developed, in spherical harmonic expansion and as a discrete grid of the space surrounding the comet.

Philae touched down at the predicted location before bouncing twice at least.

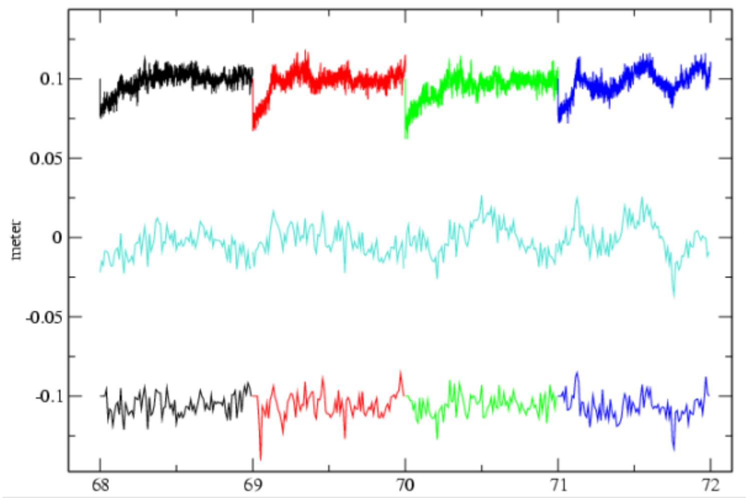
GNSS

The contribution to the International GNSS service has driven our activities in the domain of GNSS processing. Our GPS products are contributing to the combined IGS products since 2010, we became an official Analysis Center for the GLONASS constellation in 2011, and for Galileo in 2012 in the framework of the Multi-GNSS experiment. The motivation of such investment in multi-GNSS processing capability is twofold:

- Hybridizing GNSS signals from multiple constellations will improve earth kinematic observation. Future ITRF realization as well as Earth Orientation Parameters (EOPs) determination will be improved;
- The precise satellite orbit and clock products will be available for high accuracy applications that will benefit from an increased number of satellites in visibility.

Our products are based on an original zero-difference approach. Because they keep the integer property of the satellite clocks, they also include the capability to fix integer phase measurement ambiguities As a consequence, the users of our orbit and clock products are also able to do PPP positioning with fixed ambiguities. The accuracy is then significantly improved as shown in the following figure.

[1] *The astronomical unit (au), approximately the Earth-Sun distance is 149,597,870,700 meters exactly.*



The position of a fixed point is calculated every 300 seconds during 4 consecutive days in order to evaluate the level of repeatability of the solution. The upper curve represents the PPP solution from daily batches. The middle curve is derived from a single 4 days processing which improves the daily boundaries discontinuities. The down curve corresponds to daily solutions including ambiguities resolution which both guaranties the continuity and improves the repeatability of the solution.

This opened a wide area of applications and has given the opportunity to develop numerous cooperations and to contribute to various scientific projects:

- Antarctic glaciers vibration: GNSS measurements on the Metz Glacier (project CRACICE, B. Legresy, LEGOS) have been processed using the PPP technique as no reference station was available in that area. The existence of proper oscillation modes has been demonstrated by Lydie Lescarmontier in her Ph. D (Lescarmontier et al. 2012);
- Open sea level measurement: the tracking of GNSS buoys at a 5 cm level using the PPP mode has been demonstrated by Francois Fund during his Post Doc at CNES/GRGS (Fund et al. 2013);
- Space altimeter CAL/VAL on lakes: The PPP technique is a new opportunity to track boats and buoys with GNSS measurements in order to evaluate satellite altimeter biases. Several experiments on the Issikkul lake were successful (Crétaux et al. 2013).

These results have demonstrated that the PPP technique can be a powerful alternative to the classical differential GNSS positioning approach. This is the major result of our activity during the period 2011-2014.

3) Ecole supérieure des Géomètres et Topographes (ESGT)

(Stéphane Durand)

Le présent rapport ne fait état que de l'activité de recherche de l'équipe L2G dans les domaines liés aux activités de la section 1 du CNFGG, à savoir la géodésie, la gravimétrie et l'interférométrie radar différentielle (DInsar).

Le L2G utilise principalement la géodésie pour mesurer les déformations de l'écorce terrestre, à toutes les échelles, qu'elles soient d'origine naturelle ou anthropique. Différentes techniques sont maîtrisées au laboratoire :

- la topométrie de précision, qui consiste à mesurer des distances, des angles et des dénivelées entre les points d'un réseau ;
- le GNSS différentiel qui fournit des mesures ponctuelles ;

- l'interférométrie radar qui exploite les interférences obtenues entre les images radar acquises par un satellite à deux dates différentes pour mettre en évidence des déformations de surface, et que nous considérons à ce titre comme une technique géodésique ;
- La gravimétrie qui consiste à mesurer les composantes du vecteur gravité.

Cette maîtrise de différents domaines de la géodésie (GNSS, INSAR, gravimétrie, topométrie) est un point fort du laboratoire et lui permet de proposer une approche multi-technique de la mesure de déformation, déclinée en plusieurs sous thèmes :

- L'étude des surcharges et la propagation dans l'atmosphère
- Le développement d'une instrumentation de gravimétrie mobile LiMOG
- La combinaison de techniques

Surcharges et propagations

Etude des surcharges

Les effets de surcharge correspondent à des déformations de la croûte terrestre induites par les redistributions des masses atmosphériques, hydrologiques et océaniques. Ces effets sont périodiques (annuels, semi-annuels…) et les déformations qu'ils induisent peuvent atteindre plusieurs centimètres en vertical et ont en général une amplitude horizontale trois fois plus faible. Ces déformations sont aujourd'hui bien observables par les techniques de géodésie spatiale et par le GPS en particulier grâce aux progrès récents dans l'instrumentation et dans le traitement des données. En effet, ces techniques permettent d'atteindre un positionnement millimétrique de points à la surface de la Terre. Ainsi l'étude des effets de surcharge se fait principalement par l'analyse de longues séries temporelles de coordonnées de différentes stations géodésiques. Dans l'idéal plusieurs années de données sont nécessaires afin de déterminer les contributions annuelles et semi-annuelles de chacun des effets de surcharge. Ceci implique donc des temps de traitement souvent longs et coûteux en termes de ressources informatiques.

Au sein du L2G, nous étudions les effets de surcharge depuis de nombreuses années. Les deux études principales menées sont résumées ci-après.

Suite à une première étude issue d'une campagne multi technique, la thèse de François Fund (Nov. 2006 – Nov. 2009) nous a conduit à étudier le phénomène de surcharge océanique maréale dans le grand Ouest de la France. Par rapport aux précédentes études, ce travail apportait une plus forte densité de stations, une période de données plus conséquente et une optimisation du traitement tenant compte des dernières évolutions. Cette étude a été menée en collaboration avec Antoine Mocquet (directeur de thèse, Université de Nantes) et Johannes Boehm (Université de Vienne, Autriche).

En parallèle, une autre étude était centrée sur les autres effets de surcharge qui ne sont pas pris en compte dans le traitement des données de géodésie spatiale, à savoir les surcharges océaniques non maréales, atmosphériques et hydrologiques. Cette étude a permis de déterminer leurs effets sur les résultats de positionnement et en particulier les artefacts induits par ces différents effets de surcharge sur l'estimation des vitesses tectoniques issue de campagnes de mesures GPS espacées dans le temps. Pour cela les résultats GPS ont été comparés aux modèles géodynamiques de déformation. Ceci a été réalisé notamment dans le cadre des campagnes GPS RESPYR pour la mesure des déformations des Pyrénées. Ces travaux ont été menés en collaboration avec des chercheurs de l'Observatoire Midi-Pyrénées (Félix Perosanz, Pascal Gegout, Alexis Rigo, Richard Biancale) et avec Tonie van Dam (Université du Luxembourg) et Zhao Li (Université du Luxembourg) et Jean-Paul Boy (EOST) pour les aspects modélisations.

Une étude plus poussée de ces effets de surcharge a été réalisée dans le cadre de la thèse de Marcell Ferenc (2011-2014) (financement CNES – Région Pays de la Loire), soutenue le 9 décembre 2014.
Nous avons démontré la capacité du positionnement iPPP GPS pour suivre les déformations sub-diurnes induites par la tempête Xynthia (2010) en utilisant les produits REPRO2 du centre d'analyse du GRGS et le logiciel GINS-PC (CNES/GRGS). L'analyse spatiale et temporelle menée a notamment permis de mieux comprendre la réponse de l'océan à une variation brusque et intense de la pression atmosphérique. Ces travaux ont donné lieu à plusieurs communications dans des congrès internationaux et nationaux. D'autre part des outils d'analyse en composante principale des séries temporelles ont été mis en place et validés au cours d'un stage de master de Ayoub Asri. La poursuite de ces travaux à une échelle globale pour un ensemble de sites répartis dans différentes parties du globe avec différentes configurations environnementales contribuera à la validation des modèles des effets de surcharge.

Propagation troposphérique

Les techniques de géodésie spatiale sont sensibles à la propagation des ondes dans l'atmosphère terrestre. Cet effet fausse les mesures et doit être corrigé lors du traitement des données. La troposphère, couche la plus basse de l'atmosphère, est la couche qui a le plus d'impact sur les mesures. Une bonne correction de la propagation dans la troposphère permet d'atteindre une grande précision dans le positionnement (quelques millimètres), précision requise désormais pour de nombreuses études géodynamiques, et en particulier celle des effets de charge. C'est pourquoi les études des effets de propagation et de charge sont étroitement liées.
Ainsi, afin d'optimiser la précision dans l'étude des surcharges, des travaux sur la propagation des signaux GNSS dans l'atmosphère se sont également poursuivis dans l'équipe au cours de la même période.
Après le doctorat de François Fund portant sur l'évaluation des produits troposphériques issus des données météos dans le cadre du réseau européen GPS qui a donné lieu à plusieurs publications, nous avons poursuivi les travaux sur la propagation troposphérique dans le cadre du travail de fin d'études de Anne-Lise Lavaux en 2011. Le contenu en vapeur d'eau de l'atmosphère a été calculé pour un réseau de stations situé en Espagne. Nous avons étudié la sensibilité de cette estimation aux modèles, aux stratégies de traitement et aux logiciels.
En 2012, nous poursuivons dans ce champ d'investigation par une étude comparative des résultats du contenu en vapeur d'eau sur deux réseaux GPS, l'un en Corse et l'autre en région parisienne. Ces deux réseaux denses de stations permanentes GPS sont situés dans des environnements topographiques et géographiques opposés ce qui permettra d'évaluer la qualité de notre estimation.
Toutes ces études s'inscrivent dans le cadre du projet TOSCA « surcharge et propagation » dans lequel sont impliqués L.Morel (co-proposant), J. Nicolas et M. Ferenc.

Traitement de données GNSS

Dans l'objectif global du laboratoire qui concerne l'étude des déformations de la croûte terrestre à différentes échelles spatio-temporelles, nous avons poursuivi les études par géodésie spatiale et notamment les traitements de données GNSS. Ces études ont nécessité l'utilisation de la suite logicielle GINS-PC et du logiciel GIPSY sur le serveur de calcul du laboratoire.
Le calcul de la déformation des Pyrénées par GPS, projet financé par l'INSU en 2008, à partir des observations GPS de plusieurs campagnes (1995, 1997, 2008 et 2010) et d'un traitement avec les logiciels GINS-PC et GIPSY a été mené. Il a montré le niveau très faible de déformation de ce massif .
Ces résultats s'accordent au premier ordre avec les traitements réalisés par d'autres logiciels mais de futures investigations sont nécessaires pour analyser et comprendre les disparités. Collaboration avec

Alexis Rigo (Observatoire Midi Pyrénées, Toulouse), Félix Perosanz (CNES) et Philippe Vernant (Université Montpellier).
D'autres traitements comme le PPP (Precise Point Positioning) interviennent régulièrement dans le cadre de différents projets (propagation troposphérique, traitements cinématiques à hautes fréquences, trajectographie d'avion pour Lidar) et permettent également l'évolution de l'enseignement en géodésie à l'ESGT et la diffusion des nouvelles méthodes GNSS pour la topographie. De plus, la capacité récente de GINS-PC à faire du PPP avec ambiguïtés entières fixées ouvre de larges perspectives.
Ces traitements se sont poursuivis toujours dans le cadre du projet TOSCA « outils et méthode de traitement GNSS pour les Géosciences » comme par exemple l'étude de l'influence de l'incohérence des valeurs de calibration des antennes GPS (IGS05 et IGS08) avec les orbites IGS (IGS05). Ce projet TOSCA implique J. Nicolas en tant que co-proposant et L. Morel, F. Durand, M. Ferenc en tant que participants.

Interférométrie radar différentielle (DinSAR)

Contrairement aux techniques GNSS et topométrie terrestre qui ne fournissent des déformations que par dérivation d'une position ponctuelle, la technique DInSAR (interférométrie radar différentielle) fournit directement un déplacement, sous certaines conditions toutefois (notamment une grande stabilité de la surface, qui exclut l'eau et la végétation arborée). La technique classique et la technique des points stables (*permanent scatterers*) ont été implémentées à partir d'outils gratuits (compilation et écriture de scripts) : DORIS, STAMPS, et testées à partir de données ERS. Des premiers travaux en contexte urbain ont été menés à travers un stage de niveau master 2 en 2008 et un post-doctorat en 2009-2010, avec l'étude des déformations sur la ville de Nantes. Ces travaux s'inscrivaient dans le projet de télédétection urbaine de l'IRSTV.

Gravimétrie mobile

L'activité de recherche en gravimétrie est ancienne au sein du L2G. Elle est actuellement portée par 3 membres du L2G, José Cali (MCF), Jérôme Verdun (MCF) et Frédéric Durand (IGE).
L'équipe participe à **l'action de recherche en gravimétrie mobile du LAREG/IGN** qui porte sur le développement de différentes méthodes d'estimation du champ de pesanteur à partir des observations issues du capteur mobile LiMO-g. Une thèse (Li Qi) débutée en 2009 avait pour objectif de développer une méthode intégrale de résolution de l'équation différentielle de navigation. La discrétisation de la solution intégrale permettrait d'estimer par la méthode des moindres carrés implicites la perturbation de pesanteur. L'avantage de cette méthode réside dans le fait que la perturbation de pesanteur peut être considérée comme une variable spatiale ce qui permet l'utilisation de modèles empiriques de variation du champ de pesanteur issus de modèles globaux de champ plus réalistes que ceux utilisés actuellement dans la méthode d'estimation par filtrage temporel de Kalman. Malheureusement, cette thèse n'a pu aboutir.
Néanmoins les compétences acquises sur cette thématique ont permis de mettre en place **des collaborations avec l'IUEM de Brest /l'IFREMER** qui trouve dans l'équipe du L2G l'expertise qui lui manque pour développer une instrumentation similaire à embarquer à bord d'engins sous-marins (AUV, ROV) pour faire des levés conjoints de bathymétrie/gravimétrie en fond de mer.
Plusieurs projets de recherche ont été déposés pour renforcer cette collaboration :

- Actions de recherche sur projets INSU, sciences de la Terre, appel d'offre 2010 GraviMob (Gravimétrie mobile sous-marine. Le projet n'a pas été retenu en l'état mais un reliquat de financement a été octroyé.

- ANR /ASTRID 2011 : Projet GRAVIMOB : Gradiométrie et Gravimétrie Mobiles Sous-Marines. Projet non retenu.

Au début de l'année 2012, une rencontre à Toulon avec les personnes de l'IFREMER/IUEM et LAREG a eu lieu. Il a été décidé d'embarquer le capteur mobile LiMO-g dans un AUV pour effectuer des tests de faisabilité, prévus en octobre 2012.

Concernant le second point l'effort porte sur le traitement des données issues de la campagne de Sainte-Maxime. Actuellement seules des données semi-synthétiques issues de cette campagne ont été traitées par filtrage de Kalman pour valider la chaîne de traitement. Il s'agit ici de montrer à la communauté scientifique les premiers résultats d'estimation des perturbations de pesanteur le long d'un profil à partir des seules mesures réalisées par le capteur mobile LiMO-g ce qui permettrait de valider le prototype.

Dans ce but, un travail de fin d'études a été proposé, en 2012, à un étudiant de l'ESGT, Nicolas Damenet, pour développer une méthode d'estimation du champ de pesanteur par filtrage de Kalman spatialisé. Les résultats feront prochainement l'objet d'une publication.

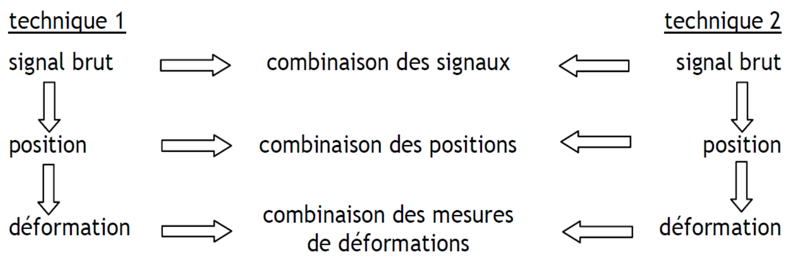
Une thèse, intitulée « modélisation à haute résolution du champ de gravité terrestre par combinaison de mesures issues de la gravimétrie satellitaire et la gravimétrie terrestre mobile : application au domaine sous-marin » a débutée en janvier 2014 (Clément Roussel), co-financée par la DGA et la Région Pays de Loire.

Combinaison de techniques

Le L2G possède des compétences théoriques et pratiques sur plusieurs techniques de mesures de déformation, notamment la topométrie terrestre, le positionnement GNSS et l'interférométrie radar (InSAR). Dès ses origines, le laboratoire a donc naturellement cherché à comparer ces différentes techniques dans ses travaux de mesure de la déformation du sol.

La combinaison des techniques géodésiques de mesures de déformation a été identifiée dans le quadriennal 2007-2010 comme un des axes de recherche du L2G, et l'évaluation de l'AERES en fin de quadriennal a confirmé l'importance de poursuivre cet axe par la suite.

La thèse de Benoit Legru (2007-2011) a permis de mieux cerner les potentialités de combinaison entre les techniques et les différents niveaux de combinaison. Comme illustré par la figure ci-après, la combinaison entre techniques peut en effet être réalisée soit au niveau des coordonnées ou des déformations calculées en utilisant chaque technique séparément, soit au niveau des observations, dans un traitement en bloc ou par cumul d'équations normales. Ainsi, bien qu'ayant limité la combinaison à deux techniques (GNSS et topométrie), cette thèse a permis d'établir un environnement conceptuel dans lequel les combinaisons d'autres techniques peuvent ensuite être envisagées.



Au cours du précédent quadriennal, le L2G a suivi deux pistes pour la combinaison des techniques géodésiques :

- la combinaison des observations issues de différentes techniques par cumul d'équations normales ;
- la modélisation de la troposphère par la technique GNSS afin de corriger les interférogrammes en INSAR.

Les deux premières techniques ayant fait l'objet d'une combinaison au sein du L2G sont le GNSS et la topométrie. Le laboratoire a, au cours du précédent quadriennal développé ses

propres outils pour le traitement combiné et la simulation des mesures GNSS et topométriques, appelé CoMeT (Compensation de Mesures Topographiques).
Au cours de la thèse de Benoit Legru, l'intérêt de la combinaison GNSS/topométrie a été montré, d'abord en simulation puis sur des données réelles. Les bénéfices attendus sont l'amélioration de la précision de mesure, mais aussi la possibilité d'accéder à une gamme plus étendue d'échelles spatiales et temporelles.
Le stage ingénieur de Paul Antoine Bacci en 2012 a été l'occasion de s'intéresser à la combinaison entre deux autres techniques : GNSS et INSAR. Il s'agissait d'utiliser des modèles troposphériques estimés par GNSS pour permettre l'amélioration du traitement INSAR. Les résultats obtenus lors de ce travail seront publiés prochainement. Il s'agit là d'une première tentative de combiner les mesures de déformation issues des techniques GNSS et INSAR, qui sont complémentaires à bien des égards :
possibilité de « caler » l'interférogramme sur quelques points GPS pour lever les ambiguïtés de l'interférométrie ; complémentarité des anisotropies de sensibilités (le GPS est plus sensible à la composante horizontale qu'à la composante verticale, et l'InSAR n'est sensible qu'à la projection du déplacement sur l'axe de visée) ; interpolation dans l'espace et dans le temps (utilisation du GPS pour densifier l'InSAR dans le temps et de l'InSAR pour densifier le GPS dans l'espace.

4) Ecole et Observatoire des Sciences de la Terre (EOST)

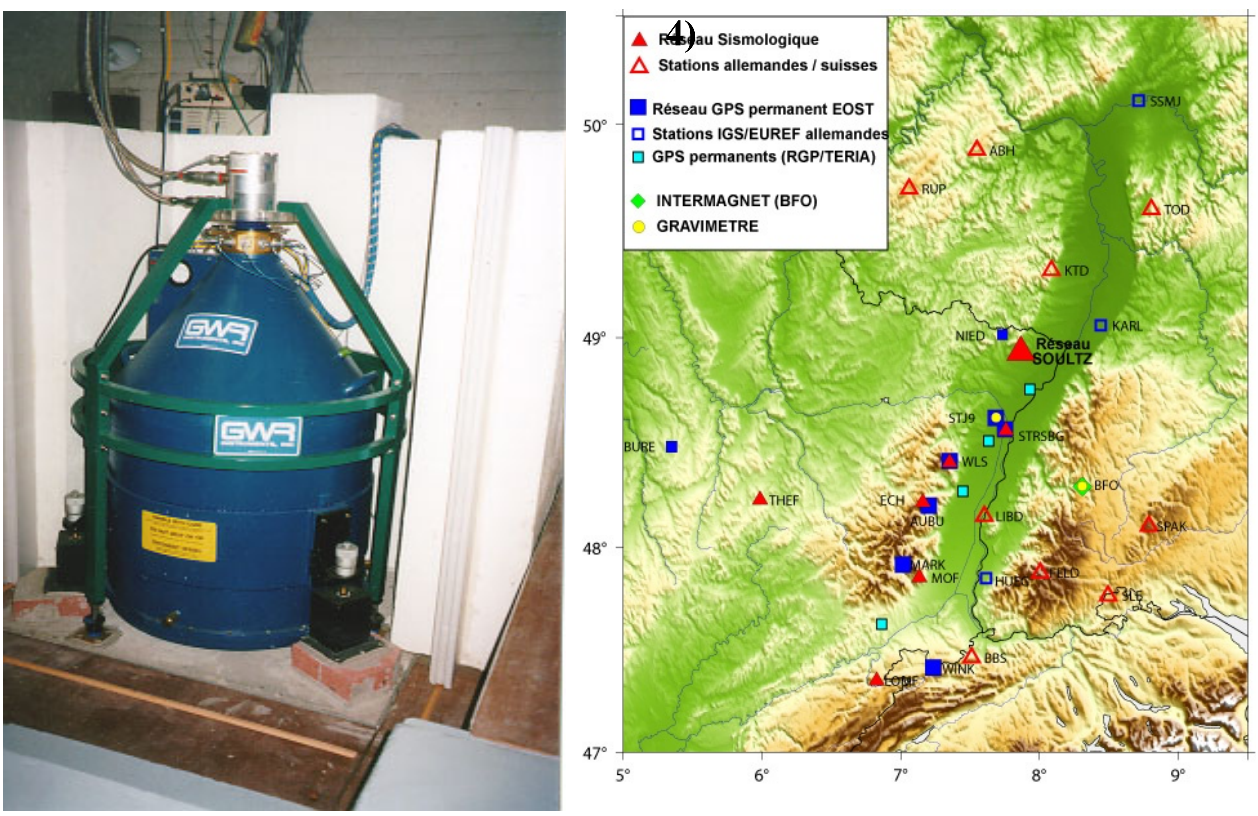
(Jean-Paul Boy, Jacques Hinderer, Séverine Rosat, Jean-Daniel Bernard, Frédéric Littel, Frédéric Masson, Patric Ulrich)

Introduction

Les activités géodésiques de l'EOST portent sur l'étude des variations temporelles de la gravité et les déformations du sol. Elles reposent entre autre sur les services nationaux d'observatoire géodésie gravimétrie labellisé par le CNRS/INSU.
L'EOST assure la responsabilité de l'Observatoire Gravimétrique de Strasbourg (OGS) comprenant les instruments installés depuis 1987 à station J9 à proximité de Strasbourg et le gravimètre supraconducteur de Djougou (Bénin) depuis juillet 2010, ainsi que d'une dizaine stations GPS permanentes du réseau national RENAG dans le Nord-Est de la France.
En complément, l'EOST a développé un service proposant des modèles des effets induits charges par les charges superficielles (atmosphère, océan et hydrologie continentale) sur les différents observables géodésiques. Ce service est désormais reconnu comme produit officiel du Global Geophysical Fluid Center de l'IERS.
L'EOST a rejoint en 2013 le Groupe de Recherche de Géodésie Spatiale (GRGS) fédérant 12 équipes appartenant à des institutions nationales ayant des activités en géodésie spatiale.

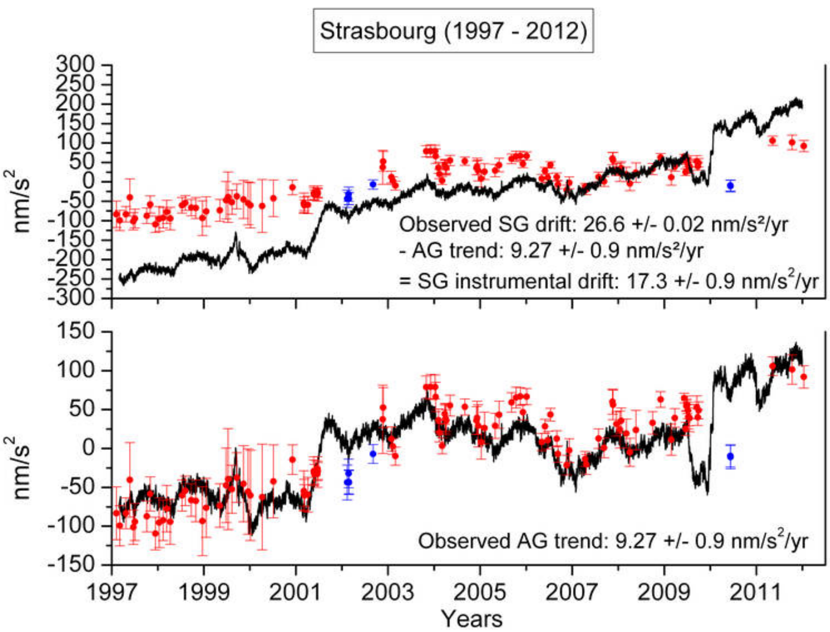
Infrastructure d'observation

Les mesures des variations temporelles de gravité, à l'aide de gravimètres supraconducteurs, ont débuté en 1987 sur le site de l'OGS (fort J9) ; ce premier instrument a été échangé par un modèle plus récent en 1996, et celui-ci sera prochainement remplacé par un modèle de dernière génération grâce à l'EQUIPEX RESIF.



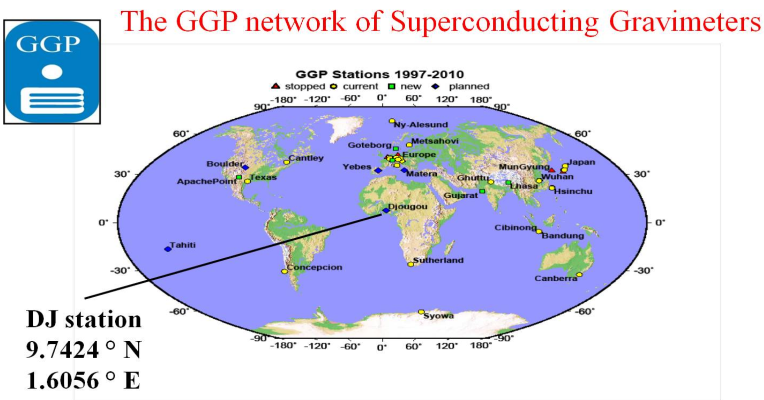
Gravimètre supraconducteur GWR CO26 en fonctionnement à l'Observatoire Gravimétrique de Strasbourg et localisation des différents réseaux permanents géophysiques dans le Nord-Est de la France (sismologie, GPS, magnétisme, etc.).

En complément, des mesures répétées à l'aide du gravimètre absolu FG5 #206 depuis 1997 sont effectuées sur le site de l'OGS, permettant d'étalonner le gravimètre supraconducteur et d'investiguer sa dérive temporelle, comme le montre la figure ci-dessous.



Variations temporelles de gravité mesurées par le gravimètre GWR CO26 (noir) et comparaison avec les mesures absolues (rouge) entre 1997 et 2012 (d'après Rosat et al., 2009).

En parallèle de nombreuses mesures environnementales complémentaires (station météorologique, sondes d'humidité du sol, etc.) ont été installées au cours des dernières années.
En juillet 2010, un autre gravimètre supraconducteur (GWR SG-060) a été installé en zone équatoriale, à proximité de Djougou au Bénin. Cet instrument permet de compléter la couverture géographique du réseau mondial GGP (Global Geodynamics Project) de gravimètres supraconducteurs, à la fois en Afrique (un autre instrument en Afrique du Sud) et dans la zone équatoriale. Malgré des conditions difficiles (climat chaud et humide, logistique), cet instrument fonctionne sans interruption depuis et se caractérise par une qualité et un bruit similaires aux autres instruments du réseau, notamment celui de Strasbourg.



Gravimètre SG-060 installé à Djougou (Bénin) et réseau mondial GGP (Global Geodynamics Project).

Perspectives

Parmi les projets en cours de l'EOST et de l'Observatoire Gravimétrique figure le développement d'un nouveau service de l'IAG regroupant les activités du Global Geodynamics Project et de l'International Centre for Earth Tides (ICET) : International Geodynamics and Earth Tide Service (IGETS), dont l'EOST sera le bureau central. Ce projet doit être validé par l'IAG lors de la prochaine assemblée générale de l'IUGG à Prague en juin/juillet prochain. Ce service reposera également sur le service des charges développé à l'EOST.
A l'échelle nationale, nous proposerons la labellisation par le CNRS/INSU de la station équatoriale de Djougou, afin de pérenniser son fonctionnement.

5) Institut national de l'information géographique et forestière (IGN) (François l'Ecu, Olivier Jamet)

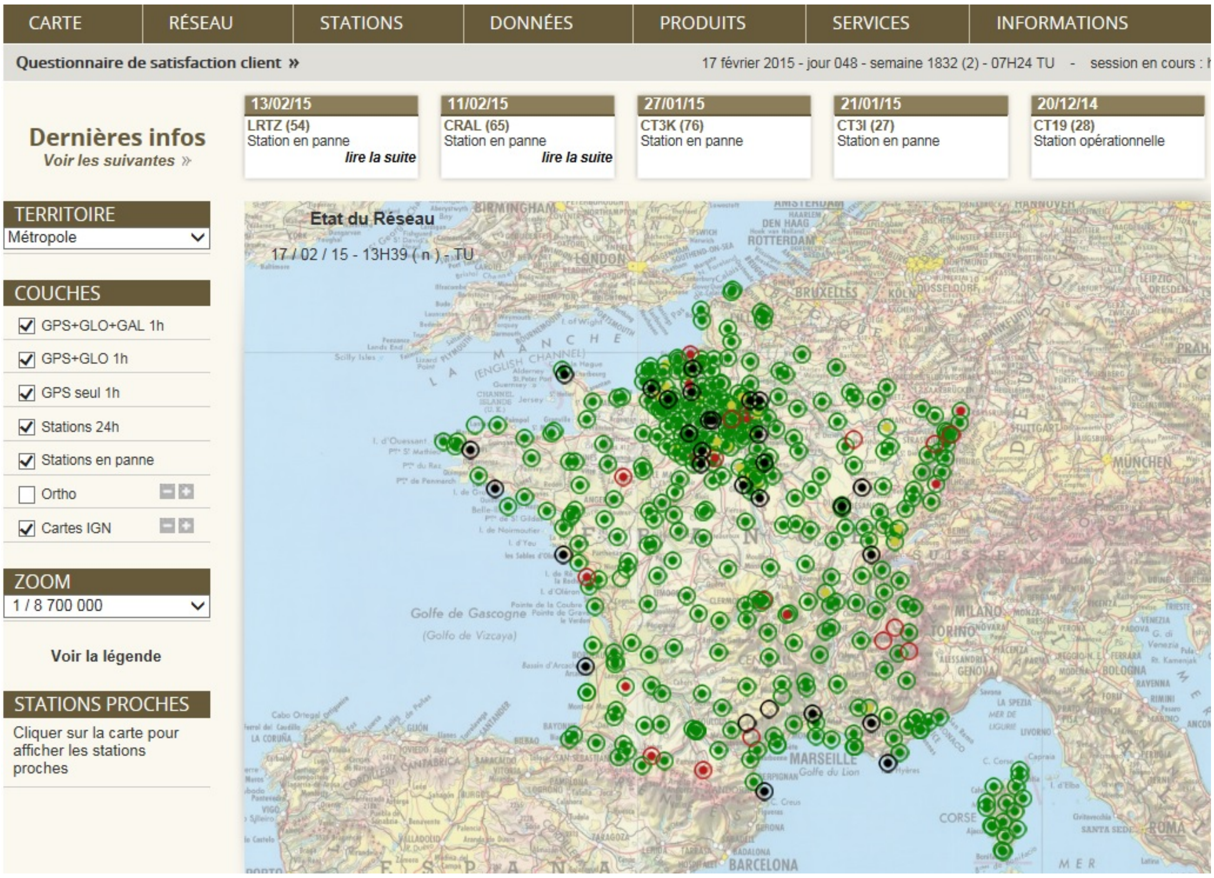
The geodetic activity of IGN is divided in two parts: operational and research, respectively managed by SGN (Service de Géodésie et Nivellement) and LAREG (LAboratoire de Recherche En Géodésie).

Operational part: SGN

The SGN is in charge of the realization and maintenance of the national geodetic, gravimetric and height references in France, has also a significant activity on international networks and services, and conducts studies and developments in all fields of geodesy.

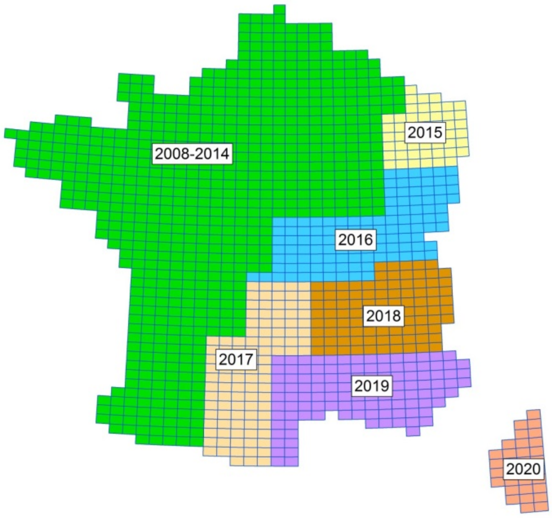
National infrastructure

The RGP is the French GNSS permanent network. The constitution of this network is based on a wide partnership between the IGN, public institutions (universities, research laboratories, urban communities, etc…) and private companies, especially RTK network managers. The great increase of the number of stations, from 203 at the beginning of 2011 to 405 at the end of 2014 is mainly due to those private partners. We have to mention, that during this time, the equipment of French overseas territories has been continued by setting up stations in Martinique and in Guadeloupe. The present repartition of stations is IGN (6 %), public institutions (26 %), private companies (68 %). Today, the network is practically full GNSS: the 25 IGN stations are all GPS-GLONASS-GALILEO; 34 % of public institutions stations are GPS-GLONASS and 30 % of them are GPS-GLONASS-GALILEO; 66 % of private societies stations are GPS-GLONASS. SGN collects data, checks data quality, delivers data on the Internet, process hourly, daily and weekly solutions and manages two operational centers. SGN contributes to E-GVAP by sending every hour tropospheric parameters (ZTD) which are introduced by Météo-France in its atmospheric prediction models.



The maintenance of RBF (Réseau de Base Français), geodetic network of about 1000 points, has been continued. Because the IGN is responsible for the national gravimetric reference since 2011, the RBF has been chosen to set up this physical component on French territory: today, each RBF point obviously has geometrical position (λ, φ, h), an altitude (H); and also at least one point per site has a gravitational value (g). From 2011 to 2014, network geometry and adjustment processes have been significantly improved, thus leading to a global network accuracy of 20 µGals, on metropolitan part, Martinique and Guadeloupe.

Concerning the French Vertical Reference (IGN69), the maintenance process based on "triplets" has been continued. A "triplet" is a group of at least three levelling benchmarks, far away one another at the most one kilometer. Anywhere in France, somebody is at less than five kilometers far from a “triplet”, thus provides an easy access to the vertical reference. Since 2008, about 1100 “triplets” are observed by year, using precise levelling to control inside stability, and GNSS to provide ellipsoidal height and check the absolute stability with respect to the RGP stations.



The first maintenance cycle of then French 13200 triplets will be achieved in 2020. Today, 64% of this step is performed, and 32% has been realized from 2011 to 2014.
The observations of the reference levelling network NIREF (NIvellement de REFérence) have been carried on. This network will be the French component to EVRS.

During the four last years, the main activity has consisted in a new levelling of the Marseille-Dunkerque line (not finished yet), in order to improve understanding of the famous IGN69 northern-southern bias.

International involvement

The implication of SGN in different international services has been continued since 2011: IGS (International GNSS Service) as data center and combination center; IDS (International DORIS Service) as data center and analysis center; and EUREF (EUropean REference Frame) as data center and analysis center.
Concerning DORIS network installation and maintenance, three new stations were set up: Le Lamentin (Martinique), Socorro (Mexico), and Owenga (New-Zealand).

During the period 2011-2014, the new REGINA GNSS network has appeared (REseau Gnss pour l’Igs et la NAvigation), managed by CNES and IGN. Today, REGINA is composed of 30 permanent stations around the world, and six additional are planned from now to the end of 2015. The objectives of REGINA are numerous. Firstly, it aims at improving ITRF: the stations are collocated on DORIS sites, thus enables accurate ties between the two technics, using GNSS and topometry. Secondly, the idea is to prepare the GALILEO arrival, more specifically by developing real-time PPP multi-constellations tools and services based on this new global network. The SGN is responsible for the ground operational part, and for the implementation of the real-time treatment center CT2R2 (Centre de Traitement Temps Réel Regina).

On another field, SGN has been strongly involved in SONEL project (Système d'Observation du Niveau des Eaux Littorales). The purpose of SONEL is to acquire, treat, store and distribute data collected from tide gauges and space geodesy technics, so as to study long-period variations of sea level. In this project, SGN is associated with LIENSs (LIttoral ENvironnement et Sociétés, CNRS/Université de La Rochelle), LEGOS (Laboratoire d'Etudes en Géophysique et Océanographique Spatiales, CNRS/Université Paul Sabatier), and SHOM (Service Hydrographique et Océanographique de la Marine), and is responsible for the geodetic ground works : GNSS stations collocation on tide gauges sites in France and abroad (GLOSS and TIGA programs), GNSS and levelling ties, and GNSS data center.

Studies and developments

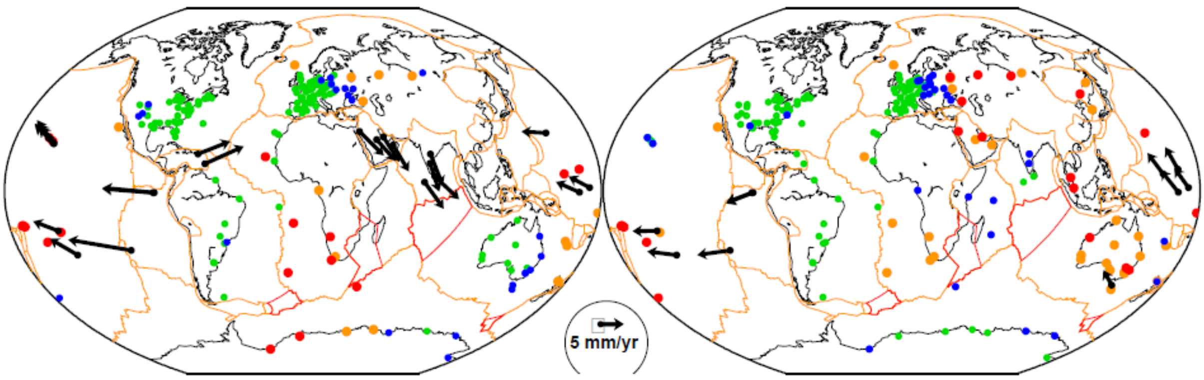
About GGSP (Galileo Geodetic Service Provider), collaboration between SGN and LAREG has been increased, the first achieving weekly solutions and combinations, rapid daily solutions; and the second computing GTRF (Galileo Terrestrial Reference Frame) and time series.

On vertical reference aspects, SGN is computing for metropolitan territory a new gravimetric quasi-geoid using RTM process (Residual Terrain Method), using high-density gravimetric data, accurate data terrain model, and EGM08 as global gravity field model. For its adaptation on vertical reference frame, about 6000 ERNIT program GNSS-levelled points will be used.

So as to be consistent with the emergence of REGINA network and GALILEO program arrival, SGN has initiated the development of multi-constellations ultra-rapid orbits and satellite clocks. Firstly, for its own present needs: hourly computations of RGP network (Météo-France partnership), RGP observations quality check. Secondly, so as to improve its role of national geodetic reference provider, by contributing in a closed future to a PPP real-time positioning service. Today, operational GPS-GLONASS rapid orbits are computed using Bernese software, and the capabilities of Napeos software are studied in order to deliver GPS-GLONASS-GALILEO products.

Research part: LAREG

The *Laboratoire de Recherche en Géodésie* (LAREG) is a research team of the Research and Training Department of IGN in charge of scientific activities in the fields of reference system theory and realization, gravity field modeling and determination, and more generally space geodesy. The team is part of the french Research Group of Space Geodesy (GRGS) and hosts the IERS International Terrestrial Reference System (ITRS) Center.
The ITRS Center is in charge of the ITRS definition, development, realization and publications of the International Terrestrial Reference Frame (ITRF) solutions.
The members of the ITRS Center, often in cooperation with other scientists, conduct research and developments activities relating to the ITRF in particular and reference frames in general. R&D activities include ITRF accuracy evaluation, mean sea level, loading effects, combination strategies, and maintenance and update of CATREF (Combination and analysis of terrestrial reference frames) software developed by IGN for the ITRF computations. The main scientific ITRF results, as well as specific data analysis and combination are published in peer-reviewed journals, but also presented at international scientific conferences.
The main highlights of the ITRS Center activities during the period 2011-2015 are reflected by the list of selected publications as summarized in the references' section. Among other highlights, we mention here the ITRF2008 publication and its corresponding plate motion model (ITRF2008-PMM). The following figure illustrates the main results of this study, showing the magnitude of the velocity differences between ITRF2008-PMM and the two known geophysical models (NNR-NUVEL-1A and NNR-MORVEL56). We observed in particular a large angular residual velocity of the order of 4 mm/yr of the Australian plate between ITRF2008-PMM and NNR-MORVEL56, as illustrated by figure 1. This bias is not observed when comparing ITRF2008-PMM to NNR-NUVEL-1A, suggesting that it is originated from the new model NNR-MORVEL56.



Velocity differences after rotational transformation between ITRF2008 and NNR-NUVEL-1A (left) and NNR-MORVEL56 (right). In mm/yr: green: less than 2; blue: between 2 and 3; orange between 3 and 4; red between 4 and 5; black larger than 5.

Besides the activities of the ITRS Center, LAREG is involved in several international activities, either in the context of scientific international services (in particular the IERS Combination at the observation level working group, the ILRS GRGS analysis center, and several IAG commision activities) or in the context of research contracts (LAREG contributed in particular to the HYMEX – hydrological cycle in the Mediterranean experiment – international project).

6) Observatoire de la Côte d'Azur (OCA) (Pierre Exertier)

Equipe « astrogeo » de l'UMR 7329 GEOAZUR

Introduction

Geodesy is directly involved in the measurements of key parameters, and questions as : what is the current speed of the rise of sea level in different regions of the globe ? How the Earth deforms it under the influence of continental drift, seismic events or melting ice caps ? These questions are asked now to scientists, but first and foremost, Fundamental Geodetic Observatories should allow to build and maintain a common reference system very accurate, which should provide the measurement of 3D displacements of about 0.1 mm / year in recent years. Fundamental Geodetic Observatories must define a primary global reference frame by maintaining the accuracy to which belong the secondary frames, regional or local, for the development of the society.

Astrogeo team, and Grasse geodetic facilities

The team "astrogeo" (Geodesy and Metrology of the Nearby Universe) works on topics first based on fundamental Astronomy (Space mechanics, geodynamics and space&time reference systems and frames, Relativity), and on topics on the edge of geophysical and geodesy. Its research activities are organized into somes major themes, as:

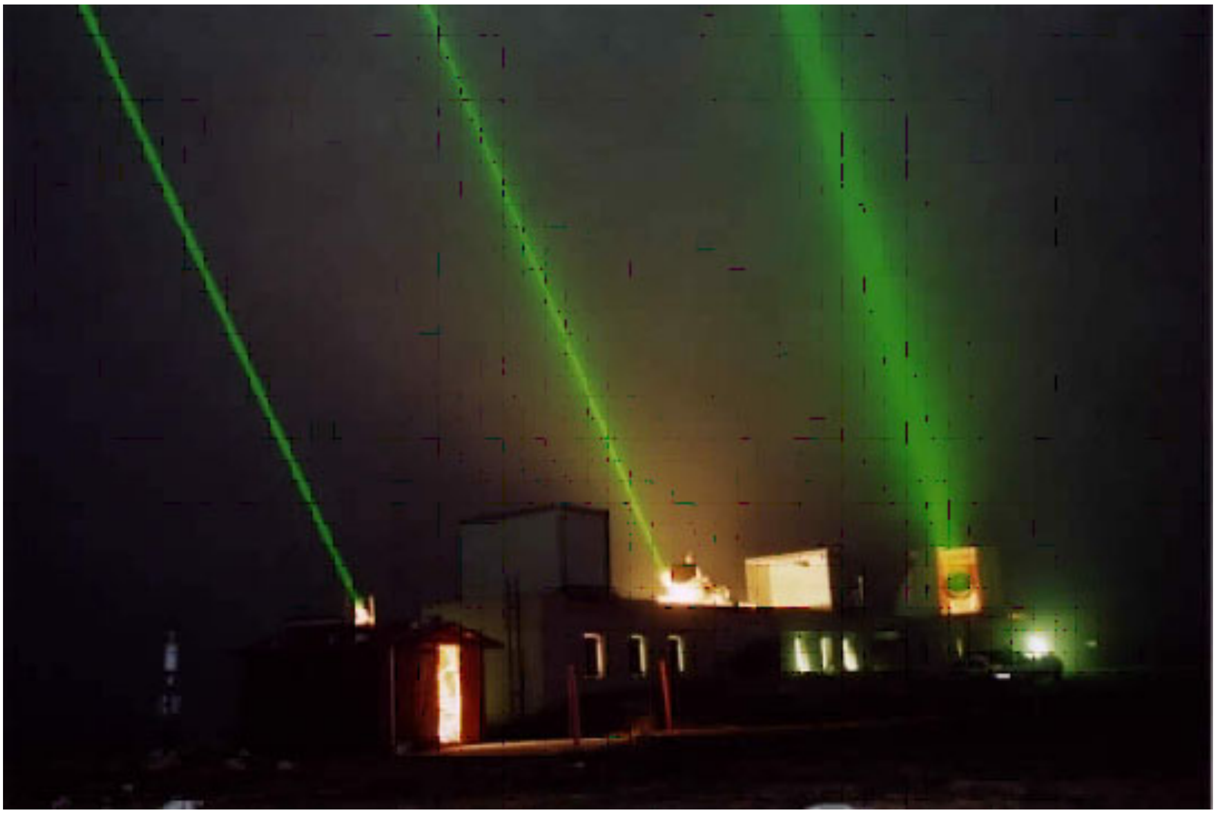
- Combined methodological approach of **gravitational systems** (trajectories of natural bodies and space vehicules), physics of the planets/satellites environment (internal structure, gravity, rotation) and **fundamental physics** (G dot, PPN parameters, dynamics and geometry),
- Equivalence Principle (EP) of Einstein theory, and the development of the future **Microscope** (CNES, ESA, for 2016) space satellite,
- Study of the constancy of the terrestrial reference by space techniques (GPS, **laser ranging**, and **radar altimetry of ocean surface**: marine geoid, with Jason missions) .
- Time transfer techniques comparison (optics based on laser and GNSS), and the exploitation/ operation of the **T2L2** space mission on **Jason-2** satellite: for time transfer by space laser studies and operations (ground/ground and ground/space) and fundamental physics.

Potential participation in the ACES/Pharao space project (on ISS), in terms of time&frequency transfer studies, and data processing with the ELT laser instrument (very close to T2L2).

In addition, « astrogeo » team is also developing the Satellite/Lunar Laser Ranging (SLR/LLR) station, MeO - CERGA, which is located on the « plateau de Calern », near Grasse, France.

The MeO telescope with its electronics and opto-mechanical parts (it is able to proceed Time Transfer, SLR and LLR techniques), was completely renewed during the 2005-2009 period. From 2010 up to now, the laser ranging operations re-started, essentially for LLR on the Moon and dedicated spacecraft like LRO, Radio-Astron, etc., and satellite missions as Jason-2, GNSS and LAGEOS.

In synergy with « Observatoire de Paris », the team is also involved in the International Laser Ranging Service (ILRS) as Analysis Center for Earth rotation and polar motion, station geocentric coordinates, and ephemeris (via the INPOP planetary solution). As an example of data acquisition on the Moon targets (Apollo and Lunakhod reflectors), the figure above shows the 5 year history of ranging Normal Points, after 2009.



Laser Ranging on the Moon (LLR) from Grasse, France.

SLR-NG for Tahiti, a future Geodetic Observatory

The team « astrogeo » was positioned in 2011 for participating in the development of a Fundamental Geodetic Observatory in Tahiti, including the 4 space techniques (GPS, DORIS, Laser and VLBI). Tahiti, which is one of the MOBLAS laser site of NASA, must be developed (with VLBI2010 antenna and New Generation Laser Ranging) for reasons of global Geodesy, satellite tracking (orbitography), etc. Above all, the objective is to establish a new form of cooperation between several French organizations, the University of French Polynesia (UPF), the authorities of the territory, and NASA.

A summary document and recommendations of the Fundamental Geodetic Observatory has been drafted and was presented to authorities in March 2012; it tooks particular objectives of GGOS. This is currently underway, with the following objectives:

- How the state of the Tahiti instruments (laser station, tracking instruments (GPS / DORIS, tide gauges, VLBI)
- Establish a budget for the new Geodetic Observatory - assessment of current support (UPF, CNES, others)
- Propose a labeling (GGOS oriented)
- Organize the administrative structure
- List the production constraints (land, access, infrastructure, tools, staff ...)
- Consolidate the funding opportunities for new instruments and infrastructure
- A schedule

An « EQUIPEX » project was prepared and submitted in September 2011, involving CNES, IGN and several laboratories led by INSU, in the sense of developing new technologies for the future geodetic observatory, essentially a New Generation Laser Ranging system. Several studies and research activities were conducted with new ingeneers, leading to a novel concept : a transportable system of 500 kg, a telescope of 45cm, and a kilo-Hertz laser. The complete budget has been estimated at 1.3 MEuros ; several companies were approached to help in defining the concept and coasts.

Time Transfer by Laser Link (T2L2) space experiment

The Time Transfer by Laser Link (T2L2) instrument is passenger of the oceanographic space mission Jason2, that was launched in June 2008 at an altitude of 1335 Km. T2L2 consists of an optical system (detection) and an electronic device for the timing. The principle of the experiment is based on the SLR technique; thanks to the laser reflector array located on the satellite in support of the precise orbitography, T2L2 benefits from the 2-way ranging, whose repeatability error and accuracy reach a few millimeters and less than 1 centimeter, respectively. At ground level, T2L2 relies on the International Laser Ranging Service (ILRS) network, whose stations are tracking the satellite for 5 to 6 times per day maximum of 10 to 15 minutes each.

The a priori potential of the T2L2 experiment is important in terms of time&frequency metrology, space geodesy and fundamental physics. The satellite altitude and the field of view of the optics of T2L2 being of ±55°, Common View (CV) passes are possible between remote ground stations at 6000 km. Great efforts have been made on the ground (OCA, Grasse geodetic site) in order to: *i*) improve the measurement of the time delays in the cables (principle, methods and hardware), *ii*) determine the best point of reference of the time and frequency laboratory (PPS and its distribution to devices: GPS, laser, etc.), *iii*) calibrate each time transfer technique, optical and microwaves.

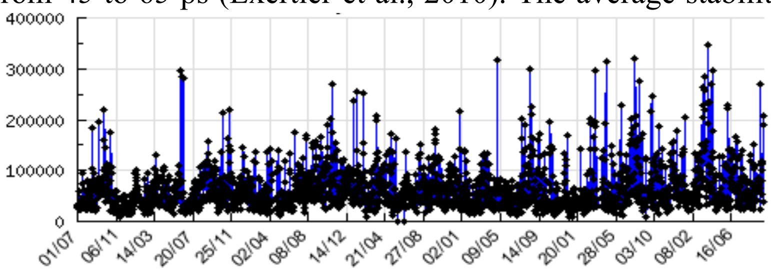
Campaigns

Several calibration time transfer campaigns have been conducted since 2009, notably in the « Observatoire de Paris », Grasse (F), Herstmonceux (UK), and Wettzell (G) with different configurations in order to: *i*) properly measure the performances of the time transfer by laser link (for short and long term stability), *ii*) progress in the measurement (method and hardware) of the ground links (delay, cables, etc.) including the time distribution of pulses between equipment such as clock, SLR system, and GPS antennas, *iii*) compare the T2L2 time transfer to existing microwave techniques such as GPS. In addition, we used the French Transportable Laser Ranging Station (FTLRS, Nicolas et al., 2000) to conduct campaigns from the Observatoire de Paris in addition to European SLR's and the Grasse geodetic observatorie (Guillemot et al., 2012; Samain et al., 2011; Exertier et al., 2014).

Analyses and performances

Given the very high reliability of T2L2 over time (7 years in space), we developed a data reduction scheme that operates on a daily basis. In parallel, we have developed an interactive website (https://t2l2.oca.eu/) to describe the data over time: ground and board data and statistics. For the web user, it's possible to compute a given ground to space time transfer (from a selected set of SLR stations) or to obtain a history over several days. Actually, the website serves primarily to calculate the ground to ground time transfer ($\Delta t_{B\text{-}S}$ - $\Delta t_{B\text{-}S'}$) between the two reference clock systems of two selected SLR stations (S) and (S').

T2L2 is able to record an average of 100,000 optical events (t_B epochs) per day, including noise and true laser shots. From 5 to 6 SLR participating stations in 2008, T2L2 implies today 22-24 stations (see Figure 2). They send their data (t_e epochs in UTC and 2-way distances dt_{2w}) regularly to the European Data Center (EDC, located in Muenchen, Germany) and to the Crustal Dynamics Data Information System (CDDIS, in the US). Given the wide variety of clock systems and laser stations, we built a data reduction scheme based on the robust estimation (mathematical and numerical meaning). Statistically, we can say that the estimated noise at 1 s ranges from 45 to 65 ps (Exertier et al., 2010). The average stability achieved in today's data processing is 4-8 ps at 75 s (average of the time standard deviation obtained from many passages of ground to space time transfer for 2 laser stations equipped with H-maser). The ground-to-ground time transfer (in CV) is computed from both time synchronization ($\Delta t_{B\text{-}S1}$ and $\Delta t_{B\text{-}S2}$) between station (S1 and S2) clocks (Exertier et al., 2014). We made the demonstration of a repeatability of 35 ps over 1 day and more, and an accuracy of 140 ps after the time calibration of the involved laser telescopes.



7) Observatoire de Paris **(Christian Bizouard)**

ACTIVITES DE RECHERCHES

Astronomie fondamentale : conceptualisation et réalisation des systèmes de référence spatiaux-temporels

L'Observatoire de Paris poursuit la longue tradition de l'Astronomie fondamentale développée depuis sa fondation en 1667. Tout en veillant à la définition conceptuelle des divers systèmes de référence spatio-temporels, nous participons à leur réalisation. Un aspect majeur est la maintenance du repère de référence céleste par VLBI [Lambert 2014, Lambert 2013] et l'étude astrométrique des quasars le constituant [Titov et Lambert 2013, Liu et al 2012, Taris et al 2011, Taris et al 2013, Moor et al 2011], ce qui permet de sonder les paramètres de l'espace-temps au sens de la relativité générale [Lambert S. et Le Poncin-Lafitte, 2011]. En parallèle nous raffinons la paramétrisation de la transformation de rotation du système de référence céleste au système de référence, c'est-à-dire la rotation terrestre elle-même. Sous l'effet des forces de marées luni-solaires, ces paramètres varient d'une façon qui est en partie prédictible et donc sujette à des modèles analytiques, que nous nous attachons à façonner. Ces activités reçoivent leur consécration dans les travaux de l'Union Astronomique Internationale au sein des groupes chargés de préparer les résolutions UAI, la terminologie scientifique, les modèles et les standards propres à cette thématique, [Capitaine 2012, Vondrak et al 2011].

Détermination des variations de la rotation terrestre par géodésie spatiale

Non seulement la vitesse de rotation de la Terre et la direction de son axe varient légèrement, mais ces variations sont en partie irrégulières. Faute de pouvoir les modéliser convenablement et donc les prédire à long terme, on doit les déterminer de façon routinière en vue de multiples applications allant de la géolocalisation à la géophysique. A cette fin, on traite les observations obtenues par les techniques de géodésie spatiale: systèmes de positionnement GNSS et DORIS, télémétrie laser sur les satellites artificiels (SLR) et sur la Lune (LLR) [Bourgoin et al, 2014, Bouquillon et al 2013] et interférométrie à très longue base sur les quasars extra-galactiques (VLBI).
Ainsi, déterminer les variations de la rotation terrestre est l'une de nos activités phares, s'effectuant en grande partie pour le compte du Service de la Rotation de la Terre, qui est l'un des membres moteurs de l'International Earth Rotation and Reference System Service (IERS). D'une part nous participons, dans le cadre de nos services (voir ci-dessous), à la réduction intra-technique des observations (Solution VLBI – OPA de Sébastien Lambert, reconnue par l'International VLBI Service), solution LLR de Sébastien Bouquillon avalisée par l'International Laser Ranging Service) ou combinons leurs résultats finaux (solution C04, Bulletin B). D'autre part nous développons une solution multi-technique fondée sur la combinaison des équations normales de l'ensemble des observations GNSS, VLBI, SLR et DORIS (projet DYNAMO effectué en partenariat avec les équipes du GRGS). Cette méthode présente deux intérêts : i) en unifiant le traitement, elle élimine les incohérences entre les techniques ii) elle donne un ajustement cohérent des paramètres de rotation de la Terre et des coordonnées des stations géodésiques les sous-tendant (le repère terrestre) iii) elle permet en principe d'augmenter la résolution temporelles des paramètres géodésiques globaux, dont les paramètres de rotation de la Terre comme la nutation et UT1, mais cet objectif n'est pas encore atteint [Biancale et al, 2013].

Effets géophysiques

Notre domaine devient de plus en plus important pour les géosciences. En effet, grâce à la précision croissante des techniques de géodésie spatiale, les variations de la rotation de la Terre dévoilent toute une gamme d'irrégularités traduisant les redistributions de masse se déroulant à la surface de la Terre (atmosphère+océans+eaux continentales ou hydro-atmosphère) ou en son sein [Bizouard 2014]. Nous les modélisons à la lumière des données concernant ces processus [Bizouard et al 2014, Sidorenkov et al 2014]. Quelques progrès substantiels ont faits dans la compréhension du terme de Chandler [Bizouard et al 2011, Zotov et Bizouard 2012, Bizouard 2014, Zotov et Bizouard 2015]. En retour, les données de rotation terrestre offrent un verdict sur la qualité des modèles de circulation globale dans l'hydro-atmosphère ou certaines hypothèses géophysiques [Zotov et al, 2015, Seaone et al 2011]; dans certains cas elles permettent même de préciser les propriétés rhéologiques de la Terre (élasticité, visco-élasticité), voire sa structure interne (aplatissement du noyau fluide par exemple). Cette jonction entre géodésie spatiale et processus géophysiques globaux est en constant renouvellement, et d'année en année offre un éclairage de plus en plus précis sur les couplages existant entre la Terre solide et ses parties fluides, qu'elles soient internes ou externes. L'objet géophysique de ces études est parfois élargi aux planètes [Karatekin et al 2011], et est appliqué à la prédiction des PRT [Gambis et al 2011], nécessaire à la mise en œuvre des techniques de géodésie spatiale.

Théorie de la rotation de la Terre

La modélisation géophysique doit s'appuyer sur une théorie solide d'un corps en rotation. La précision des observations augmentant, nous avons abordé des effets négligés communément:

Modélisation des effets asymétriques [Bizouard et Zotov, 2013]

Une recherche interdisciplinaire au sein du département.

Nos activités évoluent dans un cadre interdisciplinaire dépassant celui de l'astronomie et des géosciences, touchant à la fois aux capteurs inertiels à ondes de matière comme alternative éventuelle à la géodésie spatiale pour mesurer la rotation terrestre (projet MIGA), aux liens optiques fibrés (interféromètre Sagnac géant), à la réalisation du temps légal, et à l'histoire de l'astronomie (projet Observations, Mesures, INcertitudes).

ACTIVITES DE SERVICES

Plusieurs composantes de services internationaux, à savoir centres de produits IERS, centres

Service international de la rotation de la Terre et des systèmes de référence (IERS)

Le «Earth Orientation Parameter Product Center» (EOP-PC) est chargé de produire et de diffuser en tant que référence internationale les variations irrégulières de la rotation terrestre sous la forme des Paramètres de Rotation de la Terre (PRT) ou Earth Orientation Parameters (EOP). Les séries temporelles correspondantes résultent d'une combinaison optimale des séries issues d'une technique astro-géodésique donnée (GNSS, VLBI, SLR, DORIS. Leur utilisation travaillant dans les domaines liés à la navigation, l'astronomie, la géodésie et les sciences spatiales, la géophysique, et le temps. Une base de données sous ORACLE contient l'ensemble des informations historiques de référence concernant les variations de la rotation de la Terre.

Les principales « innovations » pour la période incriminée sont :

- la mise en place d'un service WEB permettant la diffusion de UT1-UTC par NTP
- la création et la maintenance d'une série à long terme de la durée du jour et de UT1 de 1830 jusqu'à aujourd'hui (pour les études des géophysiciens).
- la restructuration de la page WEB du service : hpiers.obspm.fr/eop-pc

Le Centre de produits des Systèmes de référence célestes (ICRS-PC).

Il a été chargé par l'UAI du suivi du Repère International de Référence Céleste (ICRF) et d'en estimer les rattachements avec d'autres repères célestes (optique, GAIA,..). Il poursuit en parallèle plusieurs thématiques de recherche associées à la géodésie spatiale et aux systèmes de référence célestes : il s'agit du suivi au sol de satellites géostationnaires, de la construction d'une base de données des quasars par le biais du catalogue LQAC et de l'astrométrie grand champ.

Le Groupe de travail sur les combinaisons au niveau des observations

Actuellement les séries de variations de la rotation terrestre sont calculées séparément des systèmes de référence terrestre et céleste. Cependant la cohérence entre les produits dérivés par chaque technique n'est pas pleinement assurée. L'approche de combinaison inter-technique globale devrait résoudre cette problématique. La tâche principale de ce groupe crée en 2009 est d'étudier les avantages de ces méthodes de combinaison par rapport aux méthodes courantes de combinaison de séries temporelles.

Centres d'analyse et de données du Service international VLBI pour la géodésie et l'astrométrie (IVS/OPAR). Les développements récents du centre d'analyse concernent la mise en place des solutions opérationnelles trimestrielles et rapides, ces dernières devant être lancées deux à trois fois par semaine. La solution trimestrielle donne des séries temporelles d'EOP et des catalogues de positions/vitesses des stations d'observation et de coordonnées de radiosources extragalactiques. Les EOP sont disséminés à l'IVS via les centres de données primaires de ce service et au centre de produits de l'IERS (IERS/EOP-PC). La solution rapide, générée dans les 48 heures après la corrélation des observations, donne uniquement les paramètres de rotation de la Terre (EOP) et les positions des stations d'observation. Les produits du centre d'analyse sont compatibles avec le format de l'Observatoire Virtuel (OV).

Centre d'analyse des données Laser Lune

POLAC est un centre d'analyse des observations LLR (Lunar Laser Ranging) au sein du réseau ILRS (International Laser Ranging Service). Il appartient au service INSU labellisé S01. Il travaille en étroite collaboration avec l'équipe de télémétrie laser de l'Observatoire de la côte d'Azur (équipe ASTROGéo) et avec les services EOP-PC et ICRS-PC de l'IERS implantés à l'Observatoire de Paris (SYRTE).
Les responsabilités du service POLAC sont les suivantes :

- La collecte, la validation, l'archivage et la mise à disposition des observations de télémétrie LLR.
- Le développement, la maintenance et l'amélioration des logiciels de réduction des observations LLR (programme CAROLL).
- La réduction des observations LLR et l'estimation des paramètres qui ont une signature sensible sur les résidus LLR (paramètres caractéristiques de la dynamique du système terre-lune, raccordement du repère céleste dynamique à d'autres repères célestes et terrestres, etc…).
- la mise à disposition de ces analyses et résultats à l'ensemble de la communauté scientifique (site web POLAC: polac.obspm.fr).
- Mise en place depuis 2012 d'un service de prédiction et de validation des observations LLR destiné aux observateurs des stations Laser Lune (web service et service mail automatique). (à noter que Lunokhod 1 a été observé pour la première fois avec MeO par Jean-Marie et Dominique Feraudy fin Mars 2013 à l'aide de nos prédictions qui sont depuis utiliser pour toutes leurs observations LLR)

Les principaux scientifiques collaborant avec le service POLAC sont Jean-Marie Torre, Dominique Feraudy et Etienne Samain (Nice, France), Hervé Manche (Paris, France), Jürgen Müller (Hannover, Allemagne), Ulrich Schreiber (Wettzell, Allemagne), James Williams (Pasadena, USA) et Randall Ricklefs (Austin, USA). Les deux télescopes qui fournissent actuellement la majorité des observations LLR sont la station laser MeO de Grasse en France, la station laser de l'observatoire d'Apache Point au Nouveau-Mexique.

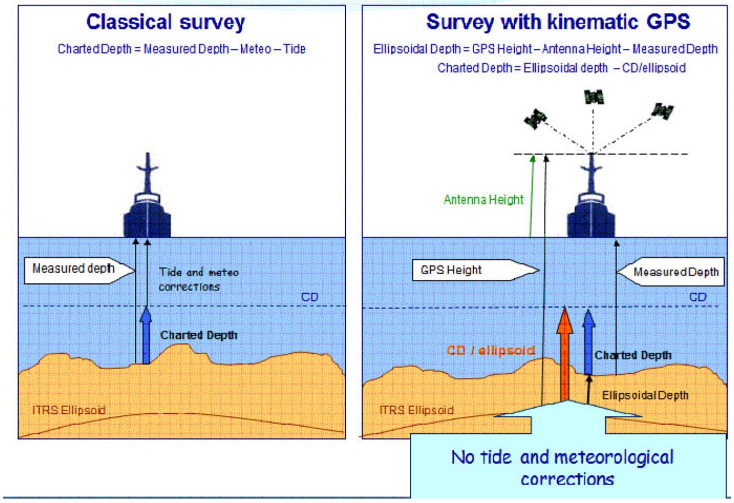
8) Service Hydrographique et Océanographique de la Marine (SHOM) Marie-Françoise Lequentrec-Lalancette

Besides the classical geodetic activity made for the benefit of hydrography, SHOM activities during these four years, have been developed on observation and modeling of marine reference surfaces and the geoid. As French referent institute for the ocean tide, SHOM is involved in the sea level observatory networks and in most of the French tides gauges (REFMAR, RONIM projects). Shipborne gravimetry continued on the sea surface (vessels : BHO Beautemps-Beaupré and N /O Pourquoi-Pas?). On the ocean bottom some experiments have been done with the Nautile submersible (DEMANE survey). The contribution of satellite gravimetric and altimetric data has not been overlooked thanks to gravimetric satellites

(CHAMP, GRACE, GOCE) and to retracking altimetric profiles (transition from 1Hz to 10Hz recording). Regarding the observation of sea surface heights, implementation of a GPS buoy was performed. SHOM has been also involved in national collaborations and projects (ANR Gremlit for example). He is involved in GRGS (Groupe de Recherche en Géodésie Spatiale), in the Solid Earth thematic cluster "Form @ Ter", in the CNES or INSU prospective meetings. As This report summarizes the key points and lists the conference presentations or publications.

BATHYELLI Project

The purpose of this project is the definition of the ocean height references to realize bathymetric surveys directly compared to a reference ellipsoid rather than to the mean sea level. In the oceans, the creation of vertical reference surfaces, related to a reference ellipsoid is a necessary step to enable the use of GPS (Global Positioning System) in bathymetric soundings. This is a recommendation of the International Hydrographic Organization which should lead in the longer term to homogenous references between countries. Now, the vertical reference on the oceans has to be referred to a Chart Datum related to the ITRS (International Terrestrial Reference System). This is to provide a stable and precise Datum in coastal and deep water oceans. Indeed the relationship between the Mean Sea level and the Chart datum are well known. The problem is then to compute the mean sea level related to the ITRS. The surface is then computed using satellite altimetry, GNSS observations and tide gauge records. This work is still in progress but already a first reference series as the limit of the lowest astronomical seas was posted on the gate of SHOM: http://data.shom.fr

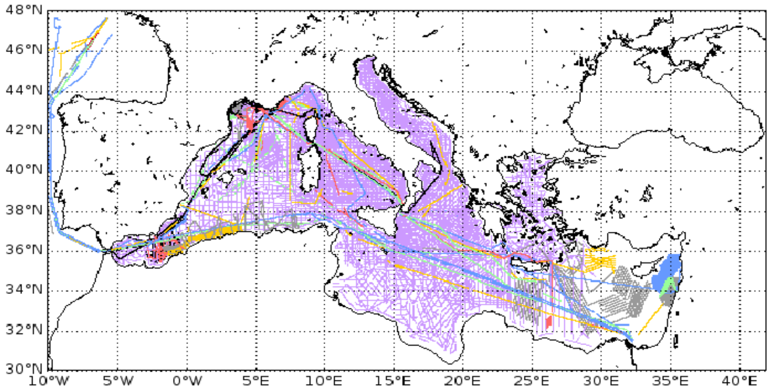


Bouée GPS SHOM — *Principe du levé sur l'éllipsoïde)*

(*From André G.et al., . XYZ, 140, 51-56)* — *(From Tanguy et al., XYZ, 140, 43-50)*

GEOMED Project

This project aims to achieve a global geoid the Mediterranean Sea. It is an international collaboration that includes the International Gravimetric Bureau, CNES, the Observatoire de Paris , SHOM, the universities of Milan, Thessaloniki, Jaén and Zagreb as well as Turkey Mapping Institute and the DTU space from Denmark.
For this project, SHOM has the responsibility for validation and processing the marine gravimetric data that represent more than two millions marine gravity measurements to analyze. Surveys extend over several decades with various accuracies in gravity measurements or in geographical positioning. The methodology and software used for SHOM processing have been applied to the Mediterranean data.



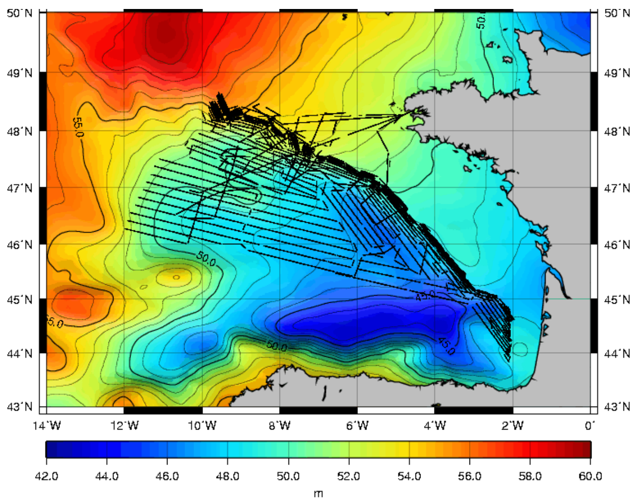
Public marine gravity data
(from MF Lequentrec-Lalancette et al., EGU General Assembly 2014, Geophysical Research Abstracts, Vol. 16, EGU2014-5961)

Swotter Project

During this four-year work SHOM supported by CNE has been estimated the contribution of the acquisition of satellite SWOT on the knowledge of the oceanic geoid and the free air anomaly. This satellite is a wide swath sensor, and represents a real technological gap in the field of the nadir altimetry. The SHOM contributes to the SWOT scientific definition team.

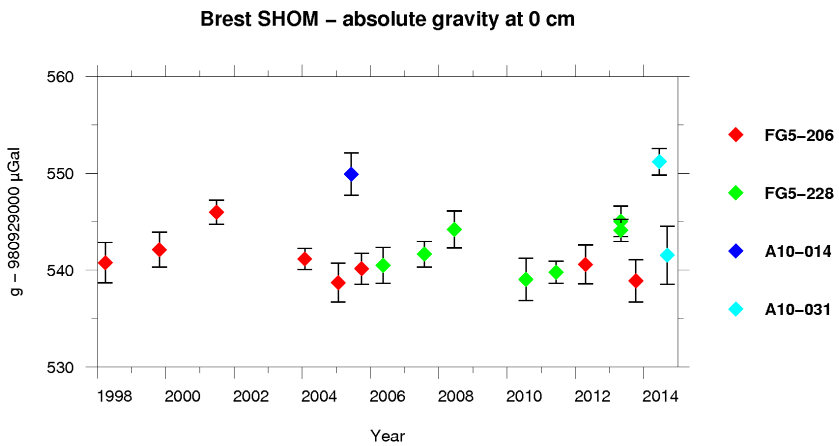
Geoid computation – absolute gravimetry – stability references

SHOM has developed computational tools to determine gravimetric quantities at sea: the free air anomaly, the geoid undulations and the vertical deviation. They are based on the objective method of collocation and the resolution by the equation Stokes and Vening Menez. Studies have been made in the Atlantic Ocean and especially in the Bay of Biscay. It has been shown that shipborne gravity data improve the knowledge of the geoid to ten centimeters compared to satellite altimetry.



Geoid improved by marine gravity data in the Bay of Biscaye
(from Lequentrec-Lalancette et al., 2011, Proceedings of ESA, Bergen)

The geodetic observations and long-term complementary gravimetric tide on outstanding issues such as Brest is recommended by GLOSS group. In this context SHOM supports absolute gravimetric campaigns. Since 1998 many measures have been acquired in order to have an independent observation of GPS of the stability of the basement near the Brest tide gauge. Annual measurements of FG5 absolute gravimeter have been conducted by the University of Montpellier and Strasbourg EOST for fifteen years. Furthermore, SHOM acquired an absolute field gravimeter A10 to allow the connection in the harbors between off shore relative gravimetric data and absolute gravity values. Between sea campaigns, the A10 will be used to supplement the FG5 measures depending on its observed accuracy. This is an ongoing work.



(From M.F. LeQuentrec-Lalancette et al., IAG, Postdam, 2013)

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Section 5

Sciences de l'atmosphère
Atmosphéric Sciences

Report of "section 5" of the CNFGG (IAMAS-France) to IUGG

by Andrea I. Flossmann, Sophie Godin-Beekmann and Nick Hall

Abstract :

Section 5 of CNFGG represents the French meteorology and atmospheric physics community at IUGG/IAMAS. Even though section 5 is the smallest section of CNFGG, the community it represents has contributed major achievements towards advancing our understanding of the functioning of the atmosphere. Some of these contributions, where initiatives originating in France have organized the international community (AMMA, MISTRALS) and where the French input to understanding climate change (modelling, satellite observation, in-situ monitoring) was particularly visible are detailed.

Introduction:

The section 5 (Meteorology and Atmospheric Physics) of the CNFGG was without activity for quite some time. Only in 2013, it reconstructed itself with a bureau that is composed of a president (A.I. Flossmann), a vice-president (S. Godin-Beekmann) and a secretary (N. Hall). Even though section 5 is assuming now its task of representing the community at IAMAS (IUGG), it is still the smallest section of the CNFGG. Furthermore, due to its long absence, it suffers from an on-going recruiting problem. Efforts have been made to increase its visibility, e.g. through a CNFGG conference on one of its themes (Colloque « Aérosol » in Orléans, 5-7 Nov 2014) and a dedicated Facebook page (https://www.facebook.com/pages/IAMAS-France/661069707243119?ref=hl). However, it remains difficult to explain to our otherwise quite active community the interest to adhere (and pay) to the CNFGG.
Despite the long absence of section 5, the atmospheric science community in France is currently quite well organized. Institutional scientific structures are provided by the French INSU (Institut national des sciences de l'Univers)/CNRS), the CNES (Centre national d'études spatiales), Météo-France (the French weather service) and IRD (Institut de recherche pour le développement) and their different committees, among others. For the contact with the larger public different associations (e.g. "Météo et Climat") and individual initiatives (e.g. "Le climat en question") complete the landscape. The scientific representation on the international level is mostly based on individual initiatives, including representation in IAMAS or other IUGG, EGU or AGU committees. French scientists have also, e.g., contributed to the elaboration of the recent IPCC and WMO/UNEP stratospheric ozone reports.
In the framework of this reporting exercise, a report of the atmospheric science in France based on section 5 alone is obviously without interest. A report of the entire achievements of the atmospheric science in France since 2012 is equally not feasible.
Thus, below some highlights have been selected. The material presented here is based on the institutional reports of INSU, CNES, Météo-France and some scientific publications. **The four subjects are chosen as they pertain to areas where France has made a unique contribution to international science through its capacity of structuring its community on crucial questions where the available competence could make a significant impact.**
The first subject is the study of the African Monsoon. France has historically numerous ties to and responsibilities in Africa and successfully applied its competences in the project AMMA ("Analyse Multidisciplinaire de la Mousson Africaine", http://www.amma-international.org/). Even though the core of the AMMA experiments were performed prior to the reporting

period, it should nevertheless appear here for two reasons: first, it was not reported in the last period as section 5 was inexistent and, thus, did not furnish a report; second: the work is still on-going and important parts of the exploitation and analysis of the data were done in the present reporting period. The two leading French scientists (JL Redelsperger and T. Lebel) were awarded the CNRS silver medal for this exceptional effort.
A second subject is centred on the study of the Mediterranean, which has been identified as a region particularly vulnerable to climate change. Here, France has contributed its competences by organizing the HYMEX (HYdrological cycle in the Mediterranean EXperiment) and CHARMEX (the Chemistry - Aerosol Mediterranean Experiment) projects as part of the MISTRALS (Mediterranean Integrated STudies at the Regional and Local Scales) initiative.
A third paragraph is dedicated to the French space initiatives in the domain of atmospheric remote sensing. Here, the role of the CNES-associated satellites PARASOL, CALIPSO, Mega-Tropiques and IASI will be highlighted.
The last subject touches the contribution of France to the improvement of our understanding of climate change, in the frame of the 5th IPCC report. It describes in particular the effort to organize the acquisition, exploitation and long-term storage of in-situ data to monitor and document the change in the composition of the atmosphere.

Understanding of the African Monsoon:

African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve the knowledge and understanding of the West African monsoon, as well as the environmental and socio-economic impacts of its variability. The following information was taken mainly from Lebel et al (2009). AMMA was launched by scientists of the French community, based on the privileged ties of France in West-Africa. AMMA relies on a field programme, which was the largest, and most extensive ever attempted in Africa. This field programme was organised in nested time-scales: The long-term monitoring programme (LOP, 2001 – 2009) was based on existing infrastructure, some of which has been active for many years (including operational networks and specific research projects) and some of which was reinforced thanks to AMMA. In 2005, a widespread intensification and co-ordination of these networks was set up for the duration of the so-called Enhanced Observing Period (EOP, 2005 – 2007), which also saw the implementation of specific land-based and sea-based instruments. At the core of the EOP, a one-year series of Special Observing Periods (SOPs) was organized in 2006, during which intensive measurements from the surface (continent-based and ocean-based) and from the air (research aircraft and balloons) took place.
Principal findings from the AMMA program related specifically to atmospheric science can be listed as the following:
- Detection of regional modes of intra-seasonal variability and their relation to other tropical disturbances,
- Advances in the theory relating to growth and initiation of African easterly waves
- Comprehensive documentation of multiple aspects of the monsoons system: from the Saharan heat low to the intertropical front, the population of different classes of convective system, the diurnal cycle, the monsoon flux and the temporal character of the monsoon onset.

For further details see Janicot et al (2011) and Lafore et al (2011).

The scientific diversity of measurements embraced oceanic, hydrological and atmospheric studies, in physical, chemical and socio-economic disciplines, from the global scale to the ‘local’ scale of specific instrument sites. Several hundred scientists, working in a difficult environment, were, and are still, involved in the AMMA programme. In spite of the difficulties, this programme has been very successful and has generated a multidisciplinary observational database, whose exploitation is still ongoing. In addition, the importance of the AMMA project for structuring and educating the scientific community in West-Africa needs to be highlighted.

The Mediterranean basin:

The climate change reports (IPCC, 2013) have identified the Mediterranean as a particularly vulnerable region in the future due to the predicted pole-ward shift of the northern end of the Hadley cell and the storm tracks. As a consequence, MISTRALS (Mediterranean Integrated STudies at Regional And Local Scales; http://www.mistrals-home.org/spip/?lang=en) has been set up. In particular due to the initiative of Météo-France and INSU, a decennial program for systematic observations and research dedicated to the understanding of the Mediterranean Basin environmental process under the planet global change was conceived.
MISTRALS aims to coordinate, across the Mediterranean Basin, interdisciplinary research on atmosphere, hydrosphere, lithosphere and paleo-climate, including environmental ecology and social sciences. The objective is to achieve a better understanding of the mechanisms shaping and influencing landscape, environment and human impact of this eco-region.
Thus, its aim is to anticipate the behaviour of this system over a century, from an interdisciplinary analysis conducted over the 2010-2020 decade. The ultimate goal of this program is to predict the evolution of habitable conditions in this large ecosystem, to meet the public policies concerning resources and environment, to anticipate evolution of the societies and to propose policies and adaptive measures that would optimize them. 7 programs coordinate the research concerning different aspects, where two of these projects interest the section 5 in particular: ChArMEx and HyMeX.
ChArMEx (Chemistry-Aerosol Mediterranean Experiment) aims to evaluate the current situation of the Mediterranean basin atmospheric environment and to anticipate its future development and its impact on regional climate, air quality, marine and continental biogeochemistry. The main issues addressed within ChArMEx are the evaluation of the regional budgets of tropospheric ozone and secondary organic aerosols, and the soluble input of key elements possibly limiting (P, N, Fe) or contaminating (e.g. Hg) the marine trophic chain.
HyMeX (Hydrological cycle in the Mediterranean Experiment; Drobinski et al, 2014) aims at a better understanding, quantification and modelling of the hydrological cycle in the Mediterranean, with emphasis on the predictability and evolution of extreme weather events, inter-annual to decadal variability of the Mediterranean coupled system, and associated trends in the context of global change. The multidisciplinary research and database developed within HyMeX aim to improve observational and modelling systems, better predict extreme events (in particular flooding events in Southern France), simulate the long-term water-cycle, and provide guidelines for adaptation measures. Launched by the French scientific community, the definition of HyMeX has started with the drafting of a White Book released in 2007 identifying the main scientific challenges for HyMeX regarding the Mediterranean water cycle, and making suggestions on how to address them. HyMeX has since extended to the international community.
Based on the example of AMMA, the MISTRALS projects were structured in LOPs, EOPs and SOPs. The special observation periods (SOPs) of MISTRALS took mainly place in 2012 and 2013, while the long-time observation is ongoing up to 2020. However, the analysis, compilation and interpretation of the findings have already started to appear in the peer-reviewed literature and numerous additional papers will be published until the end of the program.

Innovation from satellite:

Atmospheric sciences are increasingly benefitting from space observations, as they provide a unique overview of the entire globe or at least large fraction of it at almost the same time. The French national centre of space studies (CNES) is closely linked to the European and other worldwide space agencies. The following information was extracted mainly from the CNES report to COSPAR (2014) in Moscow.

CNES developed the infrared atmospheric sounding interferometer (IASI), launched by EUMETSAT on-board of the METOP satellite series. It provides essential input since 2006 to weather forecast and monitors key parameters (CO_2, CH_4, CO, dust, ..) for climate and atmospheric chemistry in quasi real time, as a contribution to the European GMES/Copernicus initiative.

CNES contributed to the A-train via the space missions PARASOL (CNES) and CALIPSO (NASA-CNES) to better understand the role of aerosol particles and clouds in climate change. PARASOL was launched in 2004 and provided global measurements with the Polder-type radiometer measuring polarised and directional reflectances from the Earth and the atmosphere. 2009 PARASOL left the A-train, but continued its observations on a lower orbit. CALIPSO was launched in 2006 and is providing global measurements of clouds and aerosol vertical profiles through its lidar. The thematic consortium ICARE is managing the production and distribution of the scientific outputs of PARASOL and CALIPSO through its Data Centre in Lille. In the case of CALIPSO, it acts as a mirror sire of NASA.

The French-Indian space mission MEGHA-TROPIQUES (CNES-ISRO) was launched in 2011 and is dedicated to the study of the water cycle, energy exchanges and the evolution of the climate in the tropics. It carries e.g. the microwave imager MADRAS (CNES-ISRO, out of service since 2013), the microwave sounder SAPHIR (CNES) and the Earth radiation budget sensor SCARAB (CNES).

The French scientific community contributed to the development of the sensors as well as their data acquisition and processing. Furthermore, it organised and performed numerous campaigns for in-situ (ground-based and air-borne) data validation. The work resulted in an important amount of peer-reviewed publications from the French as well as the international scientific community.

Improving our understanding of climate change:

France has developed two climate models, one by Météo-France and CERFACS, and the other by IPSL, which mainly differ in their atmospheric components. Numerous improvements have been made over the reporting period to all the components in these climate models: atmosphere (representation of convection, clouds, aerosols and orography), oceans (free surface formulation), sea ice (rheology) and land (land use). Model resolution, assimilation procedures of data and coupling between components have also been improved. Finally, several studies have focused on coupling these climate models with models of chemistry, aerosols, biogeochemical cycles and vegetation dynamics. Both models have contributed to the AR5 exercise (IPCC, 2013).

The model performance is tested against past-climate parameters, but also against present time observations. Here, satellite observations (see previous paragraph), as well as in-situ long-time monitoring data are used. In France, several such monitoring activities are performed that have developed into or merged with global monitoring networks, such as the PHOTON/AERONET network (http://aeronet.gsfc.nasa.gov/; measuring aerosol optical properties), the ICOS-RAMCES network (http://www.icos-infrastructure.eu/; measuring greenhouse gases), the MOZAIC-IAGOS network (http://www.iagos.fr/web/; atmospheric composition, aerosol and cloud particles on a global scale from commercial aircraft) and the Network for the Detection of Atmospheric Composition Changes (NDACC http://www.ndsc.ncep.noaa.gov/; monitoring the atmospheric composition of the free troposphere and the stratosphere). In addition multi-instrumented dedicated observation stations in the Paris Region (SIRTA ; http://sirta.ipsl.fr/), in the Massif Central (CO-PDD ; http://wwwobs.univ-bpclermont.fr/SO/mesures/instru.php) and in La Réunion Island (http://osur.univ-reunion.fr/) contribute to the monitoring of the atmosphere, and are part of the EU « Aerosols, Clouds, and Trace gases Research InfraStructure Network » ACTRIS (http://www.actris.net/).

Conclusion and outlook:

Obviously, selecting just four aspects of the French atmospheric science landscape is not doing justice to the overall rich and active French scientific community. In addition to West-Africa and the Mediterranean also other regions were studied (e.g. around the poles and in Asia or South America) and a variety of different thematic fields, also in collaboration with the other sections, were successfully treated, resulting in an enormous amount of peer reviewed international publications.

The examples presented here were mainly selected to document the benefits of an organized scientific approach to science where the harvest outweighs heavily the impact isolated individual efforts can have. This organising capacity of the French community on selected identified topics is currently endangered due to a change in French science funding philosophy. With the increasing importance of the French National Research Agency ANR which encourages individual competitiveness and the severe decrease in governmental funding of its public scientific entities, community-encompassing initiatives like AMMA or MISTRALS are not likely to occur again in the near future.

In an effort to help counteracting the occurring de-structuring of the French community, section 5 will increase its activities. Currently, it is constructing together with the French meteorological society (SMF: Météo et Climat) a web-based discussion platform, to increase the exchange of information and ideas in the French atmospheric science community. Other efforts will have to be added to increase its size and convince the community of the interest to adhere an academic society.

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Section 6

Sciences hydrologiques
Hydrological Sciences

French contribution to the IAHS Prediction in Ungauged Basins (PUB) initiative

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Abstract

This article reviews the main contributions of the French community to the field of quantitative hydrology within a perspective of prediction in ungauged basins (PUB). A decade launched by the International Association of Hydrological Sciences (IAHS) in 2003 fostered the research on PUB, resulting in a tremendous effort worldwide to improve our understanding of hydrological processes and hydrological behaviours at the regional scale. In this respect, France offers a diversified playground to develop and test methodologies and modelling tools, given its great hydroclimatic variability and the wealth of information available through relatively dense measurement networks. We detail the main outcomes on various PUB-related objectives, including the construction of large data sets, the improved use of data, the characterization of hydrological regimes and extremes, the application of hydrological models to ungauged basins, results on specific types of basins and the outcomes of investigations conducted in other countries through international collaborations. The remaining PUB challenges as well as perspectives related to the new Panta Rhei IAHS decade on change in hydrology and society are discussed.

Keywords
Hydrology; Ungauged basins; Modelling; France; Prediction; PUB decade; IAHS

1 Introduction

Hydrology is a data-based science. In all their investigations, hydrologists need observations of the complex systems they study, for process understanding, conceptualization, model parameter estimation and model validation. Such data are produced by observational networks, which measure a variety of variables such as river flow, sediment and pollutant loads, precipitation, temperature and other meteorological variables, and by geographic surveys of natural and anthropogenic features. However, the hydrological and meteorological networks are unevenly distributed in space, and measurements often unevenly made in time. One consequence is that whole geographic areas and/or periods of time are not monitored, often referred to as ungauged situations. Compared to gauged conditions, such cases raise difficult methodological aspects when addressing hydrological questions over a range of epistemic to engineering perspectives.

To address this problem, the International Association of Hydrological Sciences (IAHS) launched the Prediction in Ungauged Basins (PUB) decade (2003–2012). The main objective of this initiative was to foster collaborative research in the scientific community in order to elaborate "new, innovative methods for hydrological predictions in ungauged basins in different parts of the world, combined with significant reductions of predictive uncertainty" and "to demonstrate the value of data, as well as to provide the information needed to make predictions in ungauged basins, and assist in capacity building in the use of new technologies" (Sivapalan et al., 2003). A science work plan was designed, starting from a set of six key scientific questions:

1. What are the key gaps in our knowledge that limit our capacity to generate reliable predictions in ungauged catchments?
2. What are the information requirements to reduce predictive uncertainty in the future?
3. What experimentation is needed to underpin the new knowledge required?
4. How can we employ new observational technologies in improved predictive methods?
5. How can we improve the hydrological process descriptions that address key knowledge elements that can reduce uncertainty?
6. How can we maximize the scientific value of available data in generating improved predictions?

To answer these agenda-setting questions, various working groups were set up and many capitalization and dissemination activities (conferences, special issues in scientific journals, etc.; see www.iahs.info) were initiated. This resulted in a huge amount of scientific production and publications. Extended reviews of these studies conducted worldwide were provided by Blöschl et al. (2013), Hrachowitz et al. (2013) and Pomeroy et al. (2013). Summaries were also provided on more specific themes by He et al. (2011), Razavi and Coulibaly (2013), Parajka et al. (2013) and Salinas et al. (2013), and with national perspectives, e.g. in Japan (Ishidaira et al., 2012), Canada (Spence et al., 2013a; Spence et al., 2013b) and China (Liu et al., 2014).

The French scientific community was actively involved in the PUB decade and made original contributions related to observations, process understanding and modelling. France displays a variety of hydroclimatic conditions on a relatively limited territory (550,000 km^2): in the Köppen classification, oceanic, Mediterranean and mountainous conditions as well as continental influences exist in metropolitan France. Fortunately also, France has dense meteorological and hydrological measurement networks, which provide a wealth of information to hydrologists. This makes France a valuable playground to develop and test methods to answer the questions raised by the PUB decade. Furthermore, it is also the hub of several international projects and participates actively in international networking.

The main objective of this article is to provide an overview of the key findings and major achievements made in research on ungauged basins over the PUB decade, essentially in France, but reaching out to foreign contexts for the sake of acknowledging genericity, transposition, comparison and cooperation. We also give research perspectives within the context of the new IAHS decade, called Panta Rhei, launched in 2013 to address the issues of hydrology under change (Montanari et al., 2013).

The article is organized as follows. Section 2 provides an overview of the hydroclimatic and physical contexts where the research reviewed here was conducted. Section 3 presents the main achievements for various hydrological objectives. Section 4 discusses the main lessons from this research and presents a few of the main challenges for the future.

2 Data

The studies reviewed in this article were carried out mainly in metropolitan France but also in other parts of the world, such as central and western Africa. Many studies were based on large datasets, which have various advantages from a PUB perspective. Here we mainly detail the French context and the main data sources used for these studies, since they supported the core of the French developments.

2.1 On the need for large datasets for PUB

Designing methods applicable to ungauged basins requires working on gauged basins. Indeed, the efficiency and reliability of such methods must be tested against observations, using basins as if they were ungauged. It also requires quite large datasets, since there is a need to define *a priori* or regional information using neighbouring gauged catchments, which will be transferred to ungauged catchments.

Aside from detailed analysis of processes on case studies, a great deal of research focusing on PUB is based on the extensive use of data, with large catchment sets. One key motivation in using large datasets is to obtain general results and conclusions, as underlined by several authors (Andréassian et al., 2006; Andréassian et al., 2009; Gupta et al., 2014). In the context of PUB, another motivation is to describe a wide range of catchment characteristics, the variability between catchments being a prerequisite to find robust explanatory relationships between hydrological target variables and catchment descriptors. A large number of issues can be addressed on such datasets, e.g. mapping hydrological characteristics (Cipriani et al., 2012), flood frequency analysis (Aubert et al., 2014; Kochanek et al., 2014) and low flow frequency analysis (Folton and Lavabre, 2007; Nicolle et al., 2013).

In France, hydrologists enjoy quite dense observational networks managed by regional and national institutions as well as databases which provide long records. Hence it is possible to build sets of catchments gathering several dozen to more than 1,000 catchments with records covering several decades. Such large datasets require specific processing approaches (e.g. to automatically check data quality), selection options (Boldetti et al., 2010) and assessment methodologies (Mathevet et al., 2006).

2.2 Hydroclimatic conditions in France

Hydrologically, metropolitan France is drained by a few large basins – the Loire, Seine, Rhône, Garonne and Rhine rivers – and a large number of small coastal basins that flow into the North Sea, the English Channel, the Atlantic Ocean and the Mediterranean Sea, from north to south, or to surrounding countries. These basins are formed by a marked topography, with high mountains in the Alps and the Pyrenees, a more moderate relief in the Massif Central and the Vosges, and sedimentary basins in several parts of the country. They are subjected to various meteorological influences of neighbouring oceanic features. The range of climate conditions can be illustrated for example by the spatial variability in mean annual precipitation, which ranges from 300 to 2000 mm (amounts on mountains may be locally larger), or in mean annual temperature, which ranges from about 0 to 16°C. A wide variety of processes can be observed regionally, such as snowmelt and sediment transport processes in mountainous basins (Alps and Pyrenees); flash floods producing intense rainfall events in Mediterranean basins; long summer drought periods that can occur at regional and national scales; slow routing processes in large lowland basins; substantial exchanges between surface and groundwater in the sedimentary areas and the karstic basins; and artificialized hydrological conditions due to urbanization, irrigation and water infrastructures such as dams. There are even tropical basins subjected to heavy rainfall and cyclones in overseas departments (e.g. Réunion Island, Guadeloupe, Martinique, French Guiana). This results in various regime types, ranging from rain-fed, snow and glacial regimes to Mediterranean and groundwater-fed regimes (Sauquet, 2006; Snelder et al., 2009). This variety of conditions, processes and regimes provides many opportunities to address the PUB issues.

2.3 National observational networks and data

In terms of flow observation, there are more than 3,000 gauging stations spread over the hydrographic network for various purposes. Many of these stations were installed in the 1960s, when water agencies were created to monitor water resources and improve water quality. This means that today a large part of the corresponding flow records are several decades long, providing a wealth of data for long-term analyses. Flow data are available in the national HYDRO archive with free access (www.hydro.eaufrance.fr) (Leleu et al., 2014).

Many studies have also made substantial use of meteorological and climatic inputs. Historically, the national meteorological institute in France, Météo-France, is the main data producer and manages a dense network of stations throughout the country (Champeaux et al., 2009). Other institutions also manage their own complementary networks for specific purposes, such as the French electricity producer EDF for reservoir management (Perret et al., 2012) and the AgroClim service at the French National Institute for Agricultural Research (INRA) for agronomic applications (https://www6.paca.inra.fr/agroclim). For precipitation, which is one of the main drivers for hydrologists, the operational national network has more than 4,000 daily stations and nearly 1,000 sub-daily stations. Therefore the average density is good at a daily resolution (one station for about 140 km^2), and moderate at a sub-daily resolution (one station for about 550 km^2). Small catchments are often poorly monitored, as are the upper parts of mountainous catchments (no raingauge above 2250 m and very few between 1750 and 2250 m). This ground information is now supplemented by information provided by weather radars, which have covered most of the national territory since 2004 (Tabary, 2007). Statistical reanalyses are also more and more commonly produced. Key products include the SAFRAN reanalysis produced by Météo-France, which has provided 8×8-km gridded data since 1958 (Vidal et al., 2010), the kilometric SPAZM reanalysis produced by EDF over French mountain areas (Gottardi et al., 2012) and the COMEPHORE reanalysis combining raingauges and weather radar data (Delrieu et al., 2014; Tabary et al., 2012). Météo-France also produces various deterministic or ensemble weather forecast products that can be used as input to modelling chains for hydrological forecasting (Vincendon and Carriere, 2009). A wide range of observational data can be found on the Météo-France website (http://publitheque.meteo.fr/). In French Guiana, a climatology of this overseas department has recently been produced by adjusting the TRMM satellite product based on ground measurements (Brochart et al., 2015).

Based on these datasets, large hydroclimatic datasets were assembled, e.g. for hydrological modelling purposes (Le Moine, 2008; Lobligeois, 2014).

2.4 Research observatories

Datasets documenting long hydrological processes are highly valuable for understanding processers, hydrological modelling and trend studies. For this purpose, a number of research observatories (www.allenvi.fr/groupes-transversaux/infrastructures-de-recherche/les-soere2) have been set up in the past two decades, some covering over 50 years (Orgeval and Réal Collobrier Observatories, http://bdoh.irstea.fr). Several of these are standardized and promoted through the national network of experimental research basins (RBV; see http://rnbv.ipgp.fr) on critical zones, offering a wide range of hydrological contexts. Several observatories (e.g. ORACLE, OMERE, and AGHRYS) focus on the relationship between agriculture and hydrology/hydrochemistry. For example, the OMERE observatory (Voltz and Albergel, 2002) was founded to investigate the impact of human-made hydrological discontinuities in farmed Mediterranean catchments on runoff genesis (Chahinian, 2004; Hallema, 2011; Moussa et al., 2002), surface–subsurface interaction (Dages et al., 2009), contaminant transport (Lagacherie et al., 2006; Louchart et al., 2001) and erosion (Raclot et al., 2009). The Strengbach, Draix, Auradé and other observatories are dedicated to hydrogeochemical issues subjected to lower anthropogenic pressure. The observatory on the Cévennes-Vivarais region close to the Mediterranean (OHM-CV, www.ohmcv.fr, Boudevillain et al., 2011) is more specifically dedicated to the collection of rainfall and discharge data in a flash-flood-prone area, with field experiments dedicated to process understanding and modelling (see Braud et al., 2014). Urban and periurban observatories, especially in Lyon, Nantes and Paris (www.urbis-soere.org), have also been set up to investigate the impact of urban environments on the hydrological cycle. These observations have contributed to the advance of distributed hydrological modelling in periurban catchments (Braud et al., 2010a), as well as in farmed basins (Hallema et al., 2013; Moussa et al., 2002).

2.5 Complementary data for PUB studies

To set up hydrological models, information on elevation, geology, land use, pedology as well as urban infrastructure is needed and can be obtained from French institutes:

- digital terrain models and information on roads, buildings, etc. from the portal of the national geographic institute (IGN Geoportail, www.geoportail.gouv.fr);
- geological information from the national geological survey (BRGM, http://infoterre.brgm.fr);
- land use data from the Corine Land cover site (www.statistiques.developpement-durable.gouv.fr/donnees-ligne/li/1825.html);
- pedology from the soil conservation inventory (IGCS, www.gissol.fr/programme/igcs/igcs.php).

In top-down PUB studies, catchment descriptors are needed to evaluate explanatory relationships between hydrological variables and catchment descriptors at gauged sites. The catchment descriptors are computed on the basis of the information also used for distributed hydrological models. Given the empiricism of these relationships, these approaches require catchment sets as large and diverse (in terms of physical characteristics) as possible. Thus, a major issue in the use of these datasets from varied catchment sites is the availability/calculation of homogeneous catchment properties for several catchments. Global or European datasets are available for elevation data (SRTM database), land use (Corine Land cover) and soil (European Soil Database, Panagos et al., 2012). The subdivision of the

national territory into "hydro-eco-regions" (Wasson et al., 2002) has also been used for regionalization purposes.
The French hydrological community is also actively involved in studies outside France. Historically, the ORSTOM institute (now IRD, Institut de Recherche pour le Développement) has contributed to developing hydrological networks in many countries around the world, more specifically in Africa, since the 1950s. The collected rainfall and runoff data, mostly from central and western Africa, are stored in the SIEREM information system, developed by Boyer et al. (2006) (www.hydrosciences.fr/sierem/), which also includes gridded rainfall datasets at the continental (Mahé et al., 2012) and regional (Paturel et al., 2010b) scales (at 0.5×0.5° and monthly resolutions). Time series for hydrological modelling are available for more than 300 catchments. The database also includes soil and vegetation data. It supported a number of studies dedicated to tropical and equatorial environments, where modelling tools were tested in various inter-tropical climatic conditions.

3 Advances in PUB

The methods and models developed within a PUB perspective cover a wide spectrum of domains, objectives, conditions, etc. The following sections give an overview of the main aspects investigated by the French community during the PUB decade.

3.1 Enhanced acquisition and use of data

3.1.1 Use of meteorological data

Meteorological data are considered essential for predicting runoff, especially precipitation (rain and snow) and temperature data. They are largely responsible for the space–time variability of flows and for their random nature. Temperature partly controls snowmelt and evapotranspiration processes (Oudin et al., 2005). Therefore good knowledge of these variables is essential to explain the variability of flows, for example through hydrological modelling. The sensitivity of hydrological models to available rainfall data has been largely investigated and demonstrated by several authors (Andréassian et al., 2004a; Andréassian et al., 2004b; Arnaud et al., 2011).
When only partial knowledge of this information is available, interpolation methods are required to estimate variables in time (Oudin et al., 2010b) and space (Gottardi et al., 2012). The new climatic products presented above (statistical reanalyses and radar-raingauge merging) make it possible to better take into account the spatial variability of rainfall. These data are increasingly usable for prediction in ungauged basins over French territory (Javelle et al., 2010; Randrianasolo et al., 2014; Thirel et al., 2010). The added value of radar information was also investigated in various works on gauged and ungauged catchments for flood simulation, forecast and alert (Harader et al., 2012; Javelle et al., 2014; Lobligeois et al., 2014).

3.1.2 Use of sparse flow data

Between the well-gauged and fully ungauged situations, there are many cases where only sparse data are available (in space and/or time), thus corresponding to poorly gauged or sparsely gauged situations. In these cases, the available data are often too limited for applying classical hydrological estimation methods, but they do nonetheless provide valuable local information, compared to less detailed regional information. Several approaches have attempted to find the best way to combine local and regional sources: Rojas-Serna et al. (2006) for rainfall-runoff models (see section 3.5.3), Ribatet et al. (2007) for estimating flood quantiles and Chopart and Sauquet (2008) for estimating low-flow characteristics (Chopart and Sauquet, 2008). Ribatet et al. (2007) further developed an index flood model within a Bayesian framework for sites with a short record, incorporating regional information in the prior distribution. Chopart and Sauquet (2008) used estimates of low-flow characteristics derived from spot gauging data (Catalogne et al., 2014) and quantified their uncertainties in a kriging system of equations.

3.1.3 Use of historical flood and paleoflood data

Various sources of information can be combined to estimate extreme floods. Indeed in many cases, discharge data are available on a few years only, which can be considered as ungauged situations from a statistical point of view. Hence hydrologists have turned their attention to historical flood information and how to best incorporate documentary evidence of such historical floods into flood frequency estimation. In the past, several French authors collected historical data on floods at a large scale. Champion (1858-1864) provided a national inventory on French floods since the 6th century, Pardé (1961) did numerous studies of large floods over the world (see also https://iga-map.ujf-grenoble.fr/parde/), and Rodier and Roche (1984) produced a world catalogue of maximum observed floods. Table 1 summarizes the available French historical flood series collected during the PUB decade.

Table 1: Available French historical flood series collected during the PUB decade (2003-2012)

Basin	Stations	Systematic records	Historical period (largest floods)	References/Research project
Isère	Grenoble	1968–1998	1601–1967	Auffray et al. (2011), Coeur (2008) Historisque-Isère project (1998–1999) [(1)]
Ardèche	Vallon and St Martin	1980–2001	1644–1979	Naulet (2002), Naulet et al. (2005) Historisque-Ardèche project (1998–1999) [(2)] Sphere project (2000–2002) [(3)]
Gard	Alès Anduze Mialet St Jean	1893–1980 1892–2005 1892–2005 1892–2005	1604–1891 1741–1891 1741–1891 1841–1891	InondHis project (2005–2007) [(4)] ExtraFlo project (2009–2013) [(5)] Dezileau et al. (2014)
Hérault	Ganges Gignac	1970–2005 1989–2005	1795–1969 1812–1988	InondHis project (2005–2007) [(4)]
Aude	Orbiel Clamoux Saltz Lauquet	1968–2002 1964–1991 1968–2003 1968–1996	1788–1967 1844–1963 1820–1967 1820–1967	Payrastre (2005) InondHis project (2005–2007) [(4)] HYDRATE project (2006–2009) [(6)]

(1) http://www.risknat.org/baseprojets/resultats.php?num=10108&name
(2) http://www.risknat.org/projets/cper/projets_1994-1999/02-Historisque-Ardeche.pdf
(3) http://cordis.europa.eu/project/rcn/52072_en.html
(4) http://carteau.onema.fr/contenu/projet/inondhis_lr
(5) http://extraflo.irstea.fr
(6) http://www.hydrate.tesaf.unipd.it/

Three recent European projects covered historical and paleofloods. Benito et al. (2004) reviewed the historical and paleoflood data for flood risk estimation within the SPHERE project (2000–2003). Sheffer et al. (2003) concluded from paleoflood analysis that the 19th century floods on the Ardèche River were the largest of the millennium. Gaume et al. (2009) provided an extensive compilation of over 550 peak discharges of flash floods at ungauged sites over seven countries in Europe within the HYDRATE project (2006–2009). Last,

Kjeldsen et al. (2014) reviewed flood frequency estimation guidelines in Europe in the FLOODFREQ Cost Action (2009–2013).
A national historical database on floods in France (http://bdhi.fr/) has been available online since 2015, based on an inventory of major floods produced in 2011 within the framework of the EU Flood Directive implementation (Lang and Coeur, 2014; Lang et al., 2012). It contains a description of approximately 175 flood events on French rivers from 1770 to 2011.

3.1.4 Data collection on extreme flood events in ungauged basins

Better understanding the processes involved in recent major flood events is also one of the PUB objectives. Several studies were conducted in France, especially around the Cévennes-Vivarais observatory in southern France (see section 2.4), which is prone to massive precipitations at the end of the summer and in autumn, potentially causing disastrous floods (Braud et al., 2014). Post-event studies were initiated (Abbott et al., 1986; Bonnifait et al., 2009; Delrieu et al., 2005; Gaume et al., 2004; Manus et al., 2009) and progressively extended to all of Europe during the Floodsit, HYDRATE, and HYMEX projects. In the course of these projects, methods for conducting post-flood investigations in ungauged basins after flash floods have been significantly improved (Borga et al., 2008; Gaume and Borga, 2008; Ruin et al., 2013), including methods for the estimation of peak discharges (Lumbroso and Gaume, 2012). The database of well-documented extreme floods that have affected ungauged basins now includes the most significant events recently observed in France (Aude departement, 1999; Gard, 2002 and 2008; Var, 2010; Pyrenees, 2013; Hérault and Gard, 2014) and some of the major events which occurred in Europe (Marchi et al., 2010; Marchi et al., 2009; Ruiz-Villanueva et al., 2012; Zanon et al., 2010). The 2002 flood event in the Gard region was one of the largest observed and was extensively analysed through data collection, reanalyses and modelling (Anquetin et al., 2010; Braud et al., 2010b; Delrieu et al., 2005; Gaume and Bouvier, 2004).

3.1.5 Design and sensitivity to observational networks

Given the importance of acquiring data for hydrological applications, the issue of observational network design is of crucial importance in a PUB perspective. Indeed, hydrological estimations at ungauged locations often rely on regional information and/or neighbouring gauged sites. Therefore the configuration (density, spatial distribution) of measurement networks can have a direct impact on the reliability of these hydrological estimates. This issue has long been investigated in many places around the world (see the review by Lebecherel, 2015). Within the PUB decade, several studies attempted to provide a new perspective on this issue, using various approaches, tools and models.
Several studies investigated the sensitivity of hydrological modelling to the quality of information used to calculate inputs at the catchment scale, especially rainfall and potential evapotranspiration (Anctil et al., 2006; Andréassian et al., 2004a; Andréassian et al., 2004b; Andréassian et al., 2001; Arnaud et al., 2011; Dezetter et al., 2008; Oudin et al., 2010b; Oudin et al., 2006b; Paturel et al., 2010a; Paturel et al., 1995). Techniques were developed for testing the sensitivity of hydrological calculations to network configuration, namely the random decrease in density and the hydrological desert by removing neighbouring stations (Lebecherel et al., 2014).

3.2 Regimes and mean flow characterization

3.2.1 Catchment classification and regimes

Classification in hydrology aims at grouping basins with similar runoff characteristics and/or similar catchment behaviour. There are numerous ways to define catchment classes due to the various hydrologic metrics available to characterize flow regimes. Many classifications are based on the seasonal variations of flow, to identify the dominant drivers of runoff generation and the occurrence of high and low flows within the year, following the pioneering work of Pardé (1933).

Sauquet et al. (2008) developed an interpolation framework adapted for mapping monthly runoff patterns along the river network, and the results are presented using a classification adapted to the French hydro-climatic context. A hierarchical cluster analysis applied to the 12 Pardé coefficients from 872 gauging stations was adopted in their study. Deviations from the natural flow regime can be introduced and propagated along the river network to account for human influences at the monthly time scale. Snelder et al. (2009) developed a classification of river flow regimes for France from cluster analysis of 157 of the 171 hydrological indices suggested by Olden and Poff (2003). The hydrological characterization of each basin includes monthly flows, flood and low-flow descriptors estimated from daily data, indices related to interannual variability, etc. The characterization of flow variability can also be an indicator of catchment behaviour and can be made using the flow duration curve (FDC). Sauquet and Catalogne (2011) proposed a methodology to estimate FDC on ungauged catchments using a large set of 1080 French catchments.

In the field of rainfall-runoff modelling, catchment classification is also widely used for parameter transfer (between gauged *donor* catchments and ungauged *receiver* catchments). While comparing catchments identified as *physically* similar with catchments recognized as *hydrologically* similar, Oudin et al. (2010a) underlined that the two classifications were not equivalent: it is difficult to infer efficient hydrological classes based only on physical similarity classes. Andréassian et al. (2014) identified 27 classes of hydrological behaviour, based on the capacity of French catchments to be represented by a limited list of model parameters.

3.2.2 Mean flow estimation and mapping

The estimation of reference flows such as mean flow or variables characterizing low or high flows are essential for various water management applications. In France, mean flows and minimum monthly flows are typically used for withdrawal authorizations. Over the PUB decade, several studies at the national scale aimed at estimating these flow values. Sauquet (2006) developed a geostatistical approach to map mean flows on 900 catchments. Folton and Lavabre (2006) proposed a regionalized rainfall-runoff model to simulate monthly flow series and estimated mean flow characteristics. Lebecherel et al. (2013) regionalized the Turc-Mezentsev formula to estimate long-term water balance, using a large set of 609 French catchments. Yan et al. (2012) proposed a geostatistical method to map interannual water balance components, taking into account uncertainties and the water balance closure. The approach was extended to other streamflow characteristics by Gottschalk et al. (2013).

3.3 Hydrographic network characterization and hydrogeomorphological approaches

The channel network controls the spatial pattern of hydrological processes within a catchment. Moreover, the topology of the channel network and the geometric properties of reaches are the main factors controlling the routing function of hydrologic models.

Therefore, the classification of channel networks can be considered as a first step in the process of analysing and synthesizing catchments' morphometric properties. The identification of key hydrological features characterizing the channel network can contribute to the efforts to produce a rational classification of catchments for PUB regional hydrological studies and predictions. The morphometric properties of the channel network are derived from digital elevation models to determine geometric descriptors of the channel network (Le Moine, 2008; Moussa, 2009; Moussa and Bocquillon, 1993; Moussa and Bocquillon, 1996), the shape of subbasins (Moussa, 2003) and hypsometric properties (Gsell et al., 2015) and to identify the invariant properties of channel networks (Gsell et al., 2015; Moussa et al., 2011).

These easily accessible descriptors control the shape of the width function so they can be used to either derive the essential features of the catchment Geomorphologic Instantaneous Unit Hydrograph (GIUH) from topological analysis or directly estimate the Width Function Instantaneous Unit Hydrograph (WFIUF) from morphometric analysis (Cudennec and de Lavenne, 2015; Cudennec et al., 2004a; Moussa, 2008). Specific algorithms were developed to detect and describe the hydrographic network from various databases and in various hydrological contexts (Aouissi et al., 2013; Gironás et al., 2010; Lagacherie et al., 2010; Moussa and Bocquillon, 1994; Rapinel et al., 2015; Rodriguez et al., 2013). A geomorphology-based IUH approach was then used as a transfer function in both lumped and spatially distributed models for applications on natural basins (Cudennec et al., 2009; Cudennec et al., 2005; Moussa, 1997), urbanized basins (Gironás et al., 2009; Rodriguez et al., 2013; Rodriguez et al., 2005) and farmed basins (Hallema and Moussa, 2014). Application studies were also conducted to examine the design and impact of dams (Cudennec et al., 2004b; Nasri et al., 2004), the sensitivity of the descriptor values to spatial discretization (Gironás et al., 2010; Rodriguez et al., 2013), the role of rainfall space–time distribution (Cudennec et al., 2005) and for regionalization and transposition studies (Boudhraâ et al., 2009; de Lavenne et al., 2015; de Lavenne and Cudennec, 2014).

3.4 Prediction of extremes in ungauged basins

Predicting extreme hydrological events is highly valuable for various purposes (regulation, design, alert, etc.). Note that prediction can be understood as the statistical estimation of events in the frequency domain or their forecast in the time domain.

Extreme low-flow or high-flow estimation and forecast is necessary for design purposes, to improve risk anticipation and real-time management of water infrastructures. Extreme value assessment in hydrology is a difficult task because it is an extrapolation exercise, i.e. by definition it refers to hydrological events which are beyond the range of usual observations. Hydrological or statistical models will then be out of their domain of calibration, and the dominant hydrological processes may be very different from ordinary events.

Hereafter we distinguish low-flow and flood estimation studies and flood forecasting studies conducted in a PUB perspective (there are no reports on low-flow forecasting in ungauged basins in France to our knowledge).

3.4.1 Low-flow estimation

Catalogne (2012) developed a general framework for estimating the 5-year annual minimum monthly flow (noted QMNA5) used in water allocations in France. The framework suggests different strategies depending on data availability in the neighbourhood of the target site or at site (short records or only a few discharge measurements). Nicolle et al. (2013) had a similar objective and proposed a methodology to robustly estimate the QMNA5 when only short time series are available, applied to 527 catchments in France. Snelder et al. (2013) pointed out the difficulty of predicting intermittency due to the possible influence of small-scale processes.
Methodologies based on regionalized rainfall-runoff modelling were also developed to estimate QMNA5. A regionalized version of the GR2M model was implemented in the LOIEAU tool for application on ungauged basins (Folton and Lavabre, 2006).

3.4.2 Flood frequency estimation

As pointed out by Merz and Blöschl (2008), flood frequency analysis can be improved by expanding the information beyond a simple set of observations at the target site. Three types of information can be exploited: temporal (using past information from documentary sources or proxy data), spatial (gathering information from neighbouring sites or within a homogeneous region) and causal (using for example rainfall information and a rainfall-runoff model).
An additional level of difficulty is encountered when no data are directly available at the site of interest. Several approaches have been proposed in the past few years to handle this situation. Gaume et al. (2010) and Nguyen et al. (2014) presented a regional approach pooling estimated extreme discharges at ungauged sites. The new proposed inference procedure, based on Bayesian Monte Carlo Markov Chain algorithms, was included in the nsRFA package (R software). The added value of historical extremes at poorly gauged sites was also the focus of several studies with particular attention given to the estimation of uncertainties on extreme historical discharge (Neppel et al., 2010; Payrastre et al., 2011). Cipriani et al. (2012) compared different regionalization approaches applied to estimate the instantaneous peak discharges with a 10-year return period and a flood duration derived from a selection of hydrographs. To make advanced use of rainfall information, Organde et al. (2013) developed a regionalized version of a continuous simulation approach, SHYREG, coupling a regionalized rainfall generator (Arnaud et al., 2008) with a rainfall-runoff model to estimate flood quantiles at ungauged sites throughout France (Aubert et al., 2014). Similarly, the SCHADEX method (Paquet et al., 2013), developed at EDF for extreme flood assessment, was tested in ungauged conditions by Penot (2014), using a regionalized SCS model by grouping catchments based on the hydrological regimes.
These methods and many others classically used in France for flood estimation were compared in the Extraflo national research project (http://extraflo.irstea.fr/) (Lang et al., 2014). Kochanek et al. (2014) presented the results of this national comparison of flood frequency methods, showing that the SHYREG method provides better results at ungauged sites than a standard method based on the regionalization of the parameters of a GEV distribution. Since 2014, a national database has been available on line (http://shyreg.irstea.fr), providing an estimation of SHYREG flood quantiles for 130,000 French catchments varying in size between 5 and 5,000 km^2.

3.4.3 Flood forecasting

Flood forecasting at ungauged sites is a challenge. It requires that rainfall-runoff models be implemented at ungauged locations, with parameters estimated by regionalization approaches, and that these models can be run in real-time with adequate inputs. Outside France, examples

of such systems include the Grid-to-Grid model in the United Kingdom (Cole and Moore, 2009) and the European Flood Alert System (EFAS) running at the European scale for large catchments (Bartholmes et al., 2009; Thielen et al., 2009). Due to the difficulty of providing accurate 'absolute' forecasts, results are expressed in a 'relative' way, in comparison with thresholds (quantiles) derived from the climatology of the model. In France, Météo-France developed the SAFRAN-ISBA-MODCOU (SIM) model, which also operationally provides discharge forecasts for the whole country at a daily time step, without at-site calibration (Habets et al., 2008). Focusing on smaller spatial and temporal scales, the AIGA method, jointly developed by Météo-France and Irstea, aims at providing flash-flood alerts at ungauged catchments, using radar information and a simple regionalized gridded model running at the hourly time step (Javelle et al., 2014). The method will be used in real time covering all of France to provide alerts on ungauged basins. The PreDiflood project (2009–2012) enabled the development of a flash-flood forecasting prototype devoted to the identification of road inundation risks at the scale of the entire Gard region in France (5000 km^2), with more than 3000 road sections exposed to flooding, mostly downstream of small and ungauged basins (Naulin et al., 2013; Versini et al., 2010a).
To better quantify uncertainties associated with future precipitation, Randrianasolo et al. (2011) developed an approach for flood forecasting on ungauged sites using ensemble meteorological forecasts. Given that the assimilation of flow observations often has a strong impact on the efficiency of forecasting models, they also proposed a specific updating procedure based on observed flows from neighbouring gauged catchments.
A case study application of artificial neural networks for flood forecasting was conducted on a small catchment in southern France subject to flash floods by Artigue et al. (2012). Given the strong variability of rainfall on this catchment, it can be considered as poorly gauged by the existing network. The authors show the importance of the appropriate selection of inputs and model complexity in this case. Furthermore, Artigue (2012) demonstrated that the neural network forecast towards ungauged or proxy basins could be generalized using the area–discharge relationship. Last, the HYDRATE EU project also investigated flash-flood forecasting at ungauged locations, advising the use of distributed models and demonstrating the good skill of procedures based on combining the Flash Flood Guidance approach and a method of model-based threshold runoff computation (FFDI – Flash Flood Diagnostic Index), with tests on catchments in Italy and central France (Borga et al., 2011; Norbiato et al., 2008).

3.5 Use of hydrological models to predict runoff hydrographs in ungauged basins

When the objective is to produce whole flow series, continuous rainfall-runoff models are often used and their regionalization consists in transferring hydrological information (model parameters, hydrological signatures or relationships between model parameter and physiographic descriptors) from gauged (donor) catchments to ungauged catchments. Regionalization methods are usually grouped into four classes: regression-based methods, physical similarity (catchment grouping), spatial proximity and calibration on regionalized hydrological signatures. But alternative approaches are also being developed.

3.5.1 Performance of classical regionalization approaches in France

Regression-based methods have been implemented with limited performance for two daily lumped models (GR4J and TOPMO) (Oudin et al., 2006a; Rojas-Serna et al., 2006) and with more success for a simplified version of the GR3H (Aubert, 2012) and the GR2M (Folton and

Lavabre, 2006) models. Another opposite but complementary approach consists in using models that are more explicitly related to physical properties, as tested by Drogue et al. (2002) in the Alzette basin. Whatever the approach followed, deriving the relevant physical descriptors used in regression equations is probably the key for future progress of regression-based approaches (Boldetti, 2012).

Physical similarity has been used successfully by Garambois (2012) to transfer the parameters of the distributed MARINE model. On a larger set of catchments, physical similarity and spatial proximity approaches were compared by Oudin et al. (2008). The study showed that the best-performing methods in France are based on spatial proximity, followed by physical similarity and regression. The good performance of spatial proximity was attributed to the dense gauging network available in France (one gauging station per 100–200 km² compared with one per 1000 km² in the United States, for example). These comparative studies raised the question of the relation between hydrological similarity and the similarity as it can be assessed by physical descriptors or through spatial proximity (Oudin et al., 2010a).

Boldetti (2012) used hydrological signatures (such as flow quantiles or baseflow indices) to constrain the calibration of a hydrological model on ungauged catchments. His study showed that the success of this kind of approach depends to a large extent on the performance of hydrological signature regionalization. Overall, he was not able to surpass the proximity-based approach with the regionalized signature-based approach.

3.5.2 Alternative approaches

All the previous methods make the assumption that a single model structure can reproduce all catchment behaviours, the variability between the catchments being handled by the parameter set. A complementary approach is to develop tailor-made models, i.e. adjust the model structure to the dominant processes of the catchments. A single parameter set can then be used for catchments sharing the same dominant processes. The study by Crabit (2010) (see also Crabit et al., 2012; Vannier, 2013) used this approach. To avoid model calibration issues, an alternative approach where distributed models are used to test functioning hypotheses (Clark et al., 2011) was also implemented. Models tailored to the specificities of the catchments are built, generally using modelling platforms (Branger et al., 2010). Parameters are not calibrated but assigned based on existing databases and published values. By comparing simulations with observations, it is possible to determine which functioning hypotheses / parameter sets present the best agreement between simulation and observation. Vannier (2013) and Adamovic (2014) provide examples of such applications for Mediterranean regions and Jankowfsky et al. (2014) for periurban catchments.

To cope with calibration uncertainties, a promising path is to look for more robust parameter values. Several authors have indeed shown that a finite number of parameter sets is sufficient to accurately reproduce streamflow in various catchments types (Andréassian et al., 2014; Perrin et al., 2008). It is expected that those generic, robust parameter sets will be easier to regionalize, and that they can serve as a basis for hydrological classification.

Last, distributed or geomorphology-based models can also be useful tools to consider on ungauged basins. The simultaneous calibration of a model on a set of catchments (also called regional calibration) can be an efficient option, as shown for example by Engeland et al. (2006) with the distributed Ecomag model on the Saone basin. On a set of 23 catchments in the Cévennes region, Vannier et al. (2014) also showed that soil properties could be estimated by considering recession curves at a regional scale. Another approach consists in deconvoluting the discharge signal at a gauged outlet and using it to simulate the discharge at another ungauged outlet, based on assumptions on the similarity of the corresponding basins (possibly nested). This has been precisely developed with geomorphology-based transfer functions (Cudennec and de Lavenne, 2015; de Lavenne et al., 2015).

3.5.3 Poorly gauged catchments

In poorly gauged catchments, where only a few flow measurements or very short flow series are available, specific methodologies have been proposed for model parameter estimation, based on a combined use of regional and local information. Perrin et al. (2007) and Rojas-Serna et al. (2006) investigated the required number of streamflow measurements needed to calibrate a model. They showed that quite limited information can produce reliable parameter sets. Starting from similar ideas, combination approaches were developed by Rojas-Serna et al. (2006) and Lebecherel (2015), in which the parameter estimation is made by weighting regional information and local information. These techniques were applied by Drogue and Plasse (2014) and Plasse et al. (2014) to the French parts of the Meuse, Moselle and Rhine basins, with efficient results compared to classical regionalization approaches. Paturel et al. (2006) also applied such combination approaches on a set of catchments in Western Africa, with promising results. Also acknowledging the value of point flow measurements, Crabit et al. (2011) proposed an easily implementable method to acquire streamflow measurements. These studies stressed that a few flow measurements can be very useful to constrain model parameter estimation and that going in the field to collect these data is a viable alternative to heavy statistical methods. Post-flood event data can also provide valuable information for assessing the reliability of regional hydrological models dedicated to flash-flood simulation (Anquetin et al., 2010; Vannier, 2013).

3.5.4 Uncertainty quantification in ungauged basins

Running hydrological models on ungauged basins statistically increases the level of model error compared to the case where models can be calibrated in gauged conditions. This is clearly shown for example by Oudin et al. (2008) who compared calibration and regionalization approaches, showing the lower efficiency of the latter. The determination of model parameters is indeed a key step which introduces additional errors and uncertainty in the modelling process. Quantifying uncertainty on model simulation outputs in these conditions is, however, a difficult task, since by definition model errors cannot be quantified in ungauged catchments.

To answer this problem, Bourgin et al. (2014) proposed a two-step approach, in which the uncertainty estimated on gauged donor catchments is transferred to the target ungauged catchment, after considering the donors as ungauged themselves. The approach, applied to a large set of French catchments, provided quite sharp and reliable flow confidence intervals.

Another approach was proposed by Sellami et al. (2014), but more specifically focusing on parametric uncertainty, using ensembles of parameter sets with the SWAT model.

Another completely different avenue has also been opened: the use of indirect information on the magnitude of floods (observed damage or traffic disruptions) for the evaluation of models in ungauged basins has been tested with very promising results in the ANR PreDiflood (2009–2012) and CPER Rythmme (2008–2013) projects (Javelle et al., 2014; Naulin et al., 2013; Versini et al., 2010b).

3.6 Regional outliers and hydrological singularities in a PUB perspective

A key hypothesis in most PUB methodologies (Blöschl et al., 2013; Hrachowitz et al., 2013) is that at least a modest amount of information is transferable to the target ungauged basin (through knowledge of dominant processes, a spatial proximity with gauged basins, regional calibration, etc.). Despite the progress made in understanding which information is relevant and how to transfer it, there will always be cases where this transfer will fail inevitably, making these cases very interesting to push modelling approaches to their limits (Andréassian et al., 2010). This kind of hydrological singularity mainly occurs when the system under study and/or its forcings cannot be at all defined *a priori*, and hence even the most basic equation of mass balance closure cannot be written. This typically includes karstic catchments, urban catchments and, to a lesser extent, farmed and mountainous catchments. In these cases, the problem is more often to characterize the physiography of the catchment knowing its discharge, rather than the reverse. Here we review the work done in France over the past decade on these types of catchments.

3.6.1 Karstic basins

Karstic aquifers are characterized by complex internal organizations with heterogeneous properties and internal structures and actual extent that are frequently poorly known. Indeed, the actual area drained by a karstic river does not coincide with topographic catchment boundaries, with often a highly non-linear response (Taver, 2014). Hence the water balance is difficult to establish (Bakalowicz, 2005) and the contribution to floods is highly variable (Bailly-Comte et al., 2009; Bonacci et al., 2006). For these reasons, karstic basins can be considered poorly gauged, even when surface flow measurements exist, and hydrological methodologies must often be customized for them.

In terms of hydrological modelling, various approaches may be considered to model karst or to simulate spring hydrographs, ranging from lumped, semi-distributed conceptual models to systemic approaches including neural network models (Bailly-Comte et al., 2012; Coustau et al., 2012; Darras et al., 2015). For example, Le Moine et al. (2008) proposed a specific hydrological modelling approach of the Touvre karstic system using parsimonious conceptual models. The results showed that proper conceptualization of the system provides a satisfactory closure of the water balance of the whole system. Coustau et al. (2012) proposed an event-based parsimonious model and successfully applied it to the karst flash floods of the Lez and the Cesse rivers (Southern France) (Raynaud et al., 2015a).

In a forecasting perspective, Coustau et al. (2013) showed that a data assimilation loop, built on top of the conceptual model, can improve the discharge simulation on the Lez basin by estimating more suitable initial conditions. A graphical operational tool aimed at assisting decision-making in a context of limited data was built to roughly estimate the flood peak discharge (Borrell Estupina et al., 2014; Borrell Estupina et al., 2015). Hydrological modelling was also used to produce an abacus for flood management in the city of Nîmes located downstream of a karstic system (Fleury et al., 2013). Other approaches were proposed to better estimate flow components in karstic systems, such as the study by Kong-A-Siou et al. (2013) based on a neural network model designed to estimate the various contributions to the catchment discharge and the approach proposed by Raynaud et al. (2015b) based on hydrogeomorphological observations, chemical analyses and hydrodynamic modelling to estimate the karst contribution to surface discharge.

3.6.2 Urbanizing basins

Like karstic basins, catchments on which urbanization plays a significant role require specific attention: dedicated observatories have focused on these basins in the past few years in France (see section 2.4). In urban and periurban catchments, surface and subsurface runoff is constrained by sewer and rainwater networks. In periurban catchments, where land use is composed of a patchwork of natural and urbanized areas, analyses of long-term time series from the observatories showed contrasted behaviours, depending on the season and soil moisture, with a hydrological response mainly governed by urban areas in dry conditions and a significant contribution of rural areas during wet seasons (Braud et al., 2013; Furusho et al., 2014). In such basins, water pathways and catchment boundaries are modified by the various sewer networks (Jankowfsky et al., 2013). As in natural catchment hydrology, hydrologists dealing with urban catchments used the morphological features of these catchments to represent their hydrological response. The GIS maps that cities developed considerably helped in determining these features (Rodriguez et al., 2003). It was shown that the main descriptors used to characterize the response of ungauged urban catchments (physical descriptors, hydrographic network) can be sensitive to the type of data used and the segmentation options (Gironás et al., 2010; Rodriguez et al., 2013). The hydrological response determined using the drainage network pattern of the city of Nantes, in western France, is also sensitive to the spatial distribution of impermeable areas, which is essential to estimate urban surface runoff (Gironás et al., 2009; Rodriguez et al., 2005).

To better understand the role of the spatial variability of periurban land use, Jankowfsky (2011) and Jankowfsky et al. (2014) developed the object-oriented PUMMA model to simulate and understand water pathways and water balance components in small French periurban catchments. The approach was found to be efficient in reproducing the main components of the water cycle, in particular contrasted hydrological responses between wet and dry seasons. At larger scales, existing models were enhanced to better account for periurban catchment specificities (Furusho et al., 2013; Labbas, 2015). Both studies highlight the role of sewer networks in modifying the hydrological cycles in these catchments. Labbas (2015) also used the distributed model to compare different functioning hypotheses, highlighting the role of the soil and shallow groundwater to better simulate the whole hydrological cycle.

3.6.3 Farmed basins

Management of land and water resources of agricultural catchments has emerged in the last two decades as an environmental priority due to the effects of land use on runoff, erosion and pollutant transport. In agricultural catchments, the division of the landscape into fields and the ditch network introduce significant hydrologic discontinuities which partially control runoff. Human-made structures modify the natural pathways of storm water flow. Agricultural operations such as tillage have a significant influence on local surface runoff infiltration as well as surface storage by altering soil hydrologic properties and soil surface roughness (Chahinian, 2004). Also, the networks of ditches and embankments influence the water transfer from the fields to the catchment outlet (Hallema, 2011) and the flow exchange between the surface and groundwater (Dages et al., 2009). The MHYDAS model (Moussa et al., 2002) was specifically developed to account for the hydrological specificities of agricultural catchments. Various modelling applications were conducted in order to simulate runoff genesis at the plot scale, taking into account crusts (Chahinian et al., 2005; Chahinian et al., 2006b) and tillage (Chahinian et al., 2006a) when modelling overbank flow during extreme flood events (Moussa and Bocquillon, 2008); to couple hydrologic and erosion models (Gumiere et al., 2011); to develop specific parameterization strategies (Hallema et al., 2013) and sensitivity analysis procedures (Cheviron et al., 2010); and finally to use the model to quantify the impact of the spatial arrangement of land management practices on surface runoff (Colin et al., 2012).

3.6.4 Mountainous basins

From a PUB perspective, mountain catchments present two specificities. First, they are not only ungauged from the streamflow point of view, but they are also widely ungauged from the

precipitation point of view, yielding anomalous water balances (Valéry et al., 2010). Second, because of the seasonal presence of snow, hydrological models require an additional component (i.e. a snow accounting routine), which must also be parameterized.
In France, during the PUB decade, several parallel studies were designed to improve our spatial knowledge of precipitation over mountains: Météo-France kept improving the SAFRAN reanalysis (Quintana-Seguí et al., 2008); Gottardi (2009) developed an improved interpolation approach called SPAZM over the main mountains; and Valéry (2010) also developed a scheme for interpolating precipitation and temperature based on elevation. Several studies used streamflow as an indicator that could be inverted to yield information on precipitation at high altitudes, as well as altitudinal gradients (Gottardi, 2009; Le Moine et al., 2013; Valéry et al., 2009).
As far as snow accounting routines are concerned, the study reported by Valéry et al. (2014) has shown that although they gain in being calibrated, they could also be applied with regional default parameters in a PUB perspective. Research at Météo-France on a more physically based approach (Boone, 2000) also has led to calibration-free snow accounting routines.

4 Conclusion

4.1 Boosting effect of PUB and future challenges

The PUB IAHS scientific decade has been very successful in setting a common agenda for hydrologists worldwide (Blöschl et al., 2013; Hrachowitz et al., 2013; Pomeroy et al., 2013), including France, as shown in this review. It helped frame local issues and study cases within a generic perspective, exchanging concepts and methods in a synchronized global effort and initiating comparative hydrology and international datasets. It has also reinforced the science–practice interface. Of course, benefitting from the forces of scientific progress and being aware of the wide variability of the processes and objects studied within the hydrology discipline across the world and across geographic scales, a number of studies reviewed under the PUB umbrella have been developed independently and would have been developed without this framework. By its agenda-setting nature, the PUB initiative has on some occasions been *a priori* provocative and is occasionally *a posteriori* synthesizing. This review within the French perspective is a contribution to this combined effort.
Although we have reached the end of the PUB decade, and although much progress has been made on issues relevant to ungauged basins, many challenges still lay ahead. Extending the approaches which have mainly concerned quantitative hydrology to water quality is a first formidable challenge. Better linking the specialities, which often tend to evolve towards distinct sciences (hydrology vs hydrogeology, water quantity vs water quality), is also an open gateway.

4.2 Perspectives for Panta Rhei

The IAHS Panta Rhei initiative and science plan were shaped in 2013 (Montanari et al., 2013) after a wide e-consultation of the hydrological community. Scientific questions raised therein are the science front of the major part of the hydrological discipline, in both its theoretical and practical aspects. They are also strongly linked to major issues of human security, water

variability and complex connex issues representing a wide range of threats and uncertainties, as acknowledged in Science–United Nations dialogues (Cudennec et al., 2015).
We believe that several follow-ups and lessons from the work and achievements reviewed in this article within the PUB perspective can be explored and valued to address the following questions that fit in the Panta Rhei agenda:

- What are the extrapolation capacities of models in changing conditions? They were analysed in space within the PUB framework and should be analysed along the retrospective and prospective time horizons within the Panta Rhei framework (Vaze et al., 2015);
- How can we design reference observation networks addressing space–time variabilities? (see e.g. Giuntoli and Renard, 2009)
- How can we study the co-evolution of hydrology, climate and society, with complex causal, temporal, scaling, additive and feedback effects?
- What are the key links of hydrological knowledge with other critical links in space and time, such as land, food, energy and biodiversity, as currently being addressed by the debate on the post-2015 Sustainable Development Goals? (https://sustainabledevelopment.un.org/topics/sustainabledevelopmentgoals);
- How can we assess the hydrological features of the acceleration of Anthropocene intervention, including the question of global boundaries (Steffen et al., 2015a; Steffen et al., 2015b)?

The French community will contribute to these challenges within international efforts to help find solutions in water resources and risk management for our common future.

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Section 7

Sciences physiques de l'océan
Physical Sciences of the Oceans

Recent progresses in biogeochemical regional modelling of the Eastern Boundary Current systems of the South Hemisphere

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It is now recognized that the so-called Eastern Boundary Upwelling System (EBUS) are key regions for the climate system due to the complexity of oceanic and atmospheric processes connecting to the open ocean and the troposphere, and to the fact that they host Oxygen Minimum Zones (OMZ), vast oceanic regions responsible for the world's largest fraction of water column denitrification. Of particular interest are the EBUS from the South Hemisphere, i.e. the Humboldt (Peru/Chile) and Benguela (Angola/Namibia) systems owed to their rich ecosystems and marine resources. Here we report on recent modeling studies on these EBUS, emphasizing on challenges for regional projections of climate change.

Progresses in our understanding of the oceanic circulation in these regions have been partly limited by the persistent biases in current generation global coupled models which do not account properly for regional air-sea interactions. In particular, feedbacks involving low-level clouds remain a primary cause of uncertainty in global models' climate sensitivity (Sherwood et al., 2014) and contribute maintaining a warm bias in these regions (**Figure 1**).

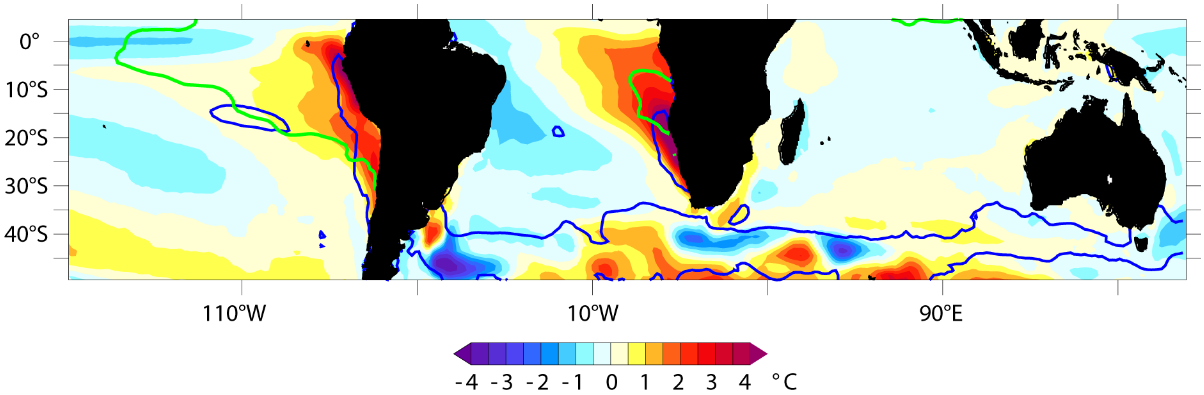

Figure 1: Difference in annual-mean SST between an ensemble of 39 CMIP5 models (historical experiment) and the observations (Reynolds data set, Reynolds et al., (2007)). The contour in thick blue line indicates the iso-contour of 0.2°C for the standard error (i.e. the dispersion among the models; inside the contour the standard error is larger than 0.2°C), whereas the green line indicates the limit of the OMZ (1mL/L iso-oxygen surface at 400m as derived from CARS data).

The primary cause of such a bias is the underestimation of the upwelled waters due to the low-resolution of the global models that prevent the formation of a well-defined upwelling cell at the coast. In recent years, regional oceanic modelling has led to a quantitative step forwards in the realism of the oceanic simulations in these regions (cf. Penven et al. (2005); Montes et al. (2010) for the Peru upwelling system and Penven et al. (2001) for the Benguela system), allowing for integrative modelling studies. As a first step towards integration of the various components of the ecosystem, biogeochemical coupled modelling has been a keystone for designing Earth modelling systems. Most focus in the community in that field has been directed towards the understanding of the OMZ dynamics. In particular, these regions have been hypothesized to respond to climate change in a way that has drawn the societal concern. A long-term trend towards expansion and deoxygenation of the OMZ has been observed in the tropical oceans (Stramma et al., 2008), which might favour coastal hypoxia, environmental conditions that can lead to the deterioration of the structure and function of ecosystems. However, climate change projections from CMIP-class models are less conclusive regarding OMZ trend (Cabré et al., 2015), calling for caution on results based from low-resolution global models.

Recent efforts have been thus directed towards tackling such issues based on regional coupled modelling, spurred by the need to provide more reliable projections of climate changes at regional scales, and the scarcity of long-term *in situ* data in these regions.

A prerequisite has been to produce atmospheric forcings suitable for regional modelling in EBUS considering strong limitations associated with the use of Reanalysis products and low-resolution global models outputs for oceanic downscaling (cf. Goubanova et al. (2011) and Cambon et al. (2013) for a discussion). Machu et al. (2015) used such an approach for their downscaling experiment of the IPSL model over the Benguela system with a regional coupled model based on the hydrodynamic ROMS model (Shchepetkin and McWilliams, 2003) and the biogeochemical model BioEBUS. BioEBUS is a nitrogen-based model derived from a $N_2P_2Z_2D_2$ model (Koné et al., 2005) in which the dissolved oxygen cycle was introduced. It was specifically designed to address the OMZ dynamics and nitrogen cycle off Namibia (see Gutknecht et al. (2013ab) for details and validation). Using this regional coupled model, Machu et al. (2015) show that among the most prominent changes brought by the regional downscaling compared to the global coupled model simulation are modifications of the structure of the lower trophic levels consisting in a shift of large offshore areas from autotrophic to heterotrophic regimes. Such a shift would have important consequences on ecosystem functioning (e.g. Duarte et al., 2013). The regional model also leads to a different distribution of phytoplankton and the nitrogen irrigation from the productive Benguela upwelling system towards the tropical/subtropical South Atlantic gyre (**Figure 2**).

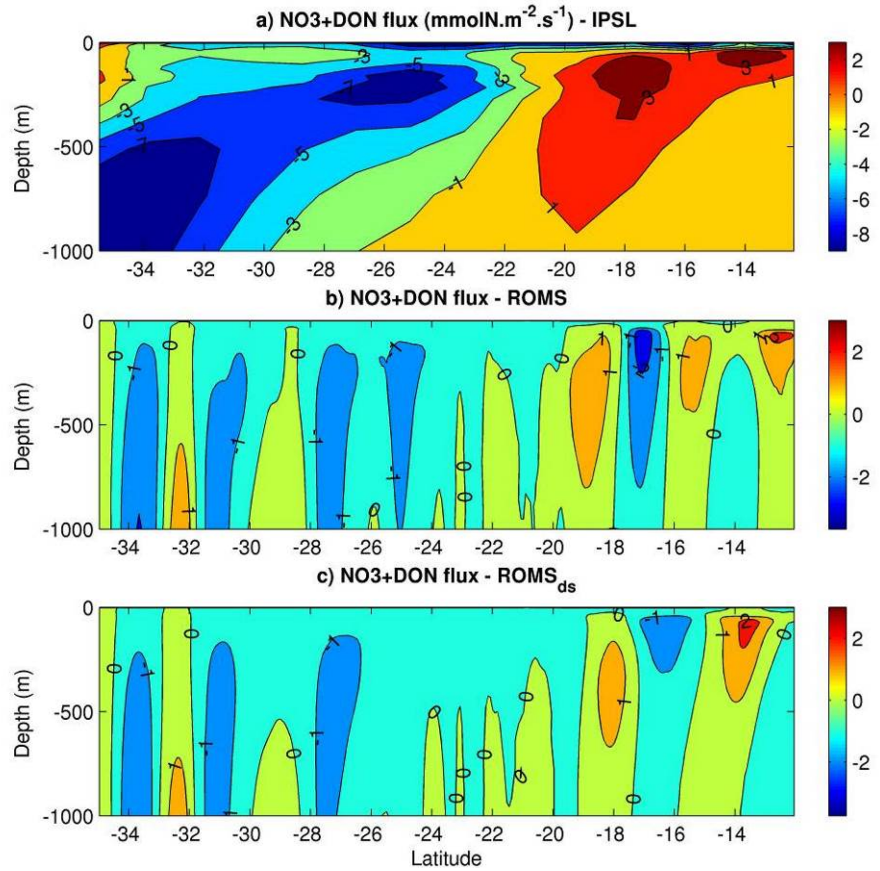

Figure 2: Section at 8°E of crosshore annual flux of nitrate plus dissolved organic nitrogen (mmol N m^{-2} s^{-1}) between 35° and 12°S for (a) the IPSL global model, (b) the regional simulation with ROMS-BioEBUS forced with IPSL atmospheric fluxes and c) the regional simulation with ROMS-BioEBUS forced with downscaled wind stress. Negative (positive) values indicate westward (eastward) flux (After Machu et al. (2015)).

This modelling approach has been also applied to the Peru/Chile upwelling system that differs from the Benguela system in that it is more strongly connected to the equatorial circulation. Montes et al. (2014) explore the sensitivity of the OMZ simulation by the same regional coupled model to the details of the equatorial circulation in the eastern Pacific. In particular, the equatorial undercurrent (EUC) connects to the Peru-Chile Undercurrent (PCUC) through a complex of pathways consisting in the extension of the EUC east of the Galapagos Island, and two branches further south, the primary and secondary Tsuchiya jets (Montes et al., 2010). Montes et al. (2014) show that a conduit by which the OMZ could vary at long timescales is through the secondary Tsuchiya jet that transports deoxygenated waters from the equatorial region to the latitude of ~10°S from which it flows eastward to connect to the PCUC. Their study also highlights the significant sensitivity of the OMZ simulation by the regional model to the characteristics of the boundary forcings (i.e. vertical and horizontal structures of currents), as well as the large non-linearity associated to biogeochemical processes (i.e. non-linear advection of O_2). Another issue arising from the societal concern in this region and that can be tackled with such a modelling approach, is how the interannual variations in the circulation in the equatorial region (e.g. El Niño) modify the OMZ at long timescales. In particular, whereas long-term trends in upwelling favourable winds are ubiquitous off Peru (K. Goubanova, pers. com), a SST cooling trend has been suggested from proxy data and the instrumental record (Gutierrez et al., 2011). It has been shown that such a cooling trend could be induced by changes in properties of the El Niño phenomenon (Dewitte et al., 2012). The similar model setting than Dewitte et al. (2012) is also able to produce a long-term deoxygenation of the upper part of the OMZ off Peru (Figure 3), indicative of likely rectified effect of O_2 variations into the mean OMZ.

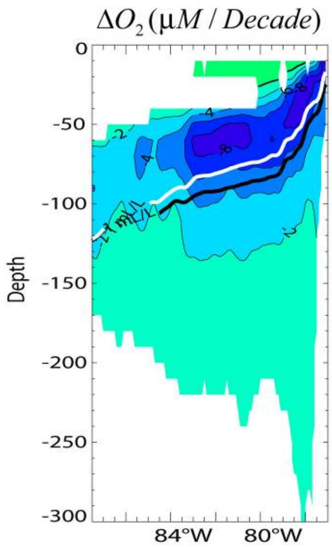

Figure 3: Long-term trend in dissolved oxygen (in microM/decade) at 12°S and over the period 1958-2008 as simulated by a regional coupled model in a configuration similar to Dewitte et al. (2012). The black thick line indicates the iso-oxygen surface at 1ml/L (i.e. oxycline depth) over the full period whereas the thick white line is for the period 2000-2008. Only the values significant at the 95% level are shown.

These modelling results demonstrate that long timescale of variability (decadal to climate change) can be addressed in EBUS through downscaling with high-resolution biogeochemical coupled models, which shall encourage further integration of the down-streamed components of the marine ecosystem. They also call for better understanding the details of processes controlling the rate of O_2 changes at different timescales and spatial scales. The interplay between O_2 eddy flux and O_2 transport by the mean current in controlling the OMZ boundaries and intensity has been a main focus in recent years within the community (cf. SOLAS program) and this on-going effort shall lead to a better understanding of the forced and internal OMZ dynamics. Besides relying on regional coupled modelling, such effort should be accompanied by dedicated observational campaigns. Off Peru, several projects have been launched in recent years, including the on-going AMOP international project (http://www.legos.obs-mip.fr/recherches/projets-en-cours/amop) that has provided invaluable *in-situ* data. Related activities will be also pursued over the Benguela system within the LMI ICEMASA (http://www.icemasa.org/), allowing for comparative studies.

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Zonal jets at 1000m in the tropics observed from ARGO floats'drifts

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Introduction: about the intermediate circulation

The upper circulation of the equatorial oceans has been extensively observed and studied. In particular, the upper circulation of the Pacific Ocean has received much attention for its relation with the El Nino phenomenon. Surface drifters and satellite altimetry gave us a pretty good picture of the mean surface circulation and of its variability. Moorings and repeated hydrographic surveys provided estimates of current velocities across the upper tropical Pacific and Atlantic Oceans, in the first 500 meters or so. In situ observations are sparse below 500 meters, and our knowledge of the oceanic currents in the intermediate and deep equatorial oceans is very limited. However some synoptic deep sections revealed interesting features. Firing (1987) and Firing et al. (1998) first showed evidence in the western Pacific of a series of near-equatorial westward and eastward jets from 3°S to 3°N at intermediate depths, characterized by a large vertical extent, alternating every 1.5°–2° in latitude, with amplitudes of about 10 cm s^{-1}, the so-called "equatorial intermediate current system". Similar alternating zonal jets have also been evidenced in the equatorial Atlantic Ocean thanks to synoptic sections (Stramma and England, 1999; Bourlès et al., 2003), and their zonal coherence along at least 25 degrees in longitude was demonstrated by Ollitrault et al (2006) using acoustic and profiling floats.

Since the advance of the Argo program, and the presence in the global ocean of thousands of autonomous floats drifting at 1000m (or deeper), we now have a new way to observe the intermediate circulation. When compiled, Argo floats' drifts are very valuable tools to determine the absolute velocity at this depth on a global scale. 15 years ago, Firing et al. (1998) noted that "one would like to have a time series of sections covering at least 6°S-6°N, and preferably 10°S-10°N (...) to show whether the pattern of meridionally alternating mean zonal flows continues poleward." He also noted that "nothing is known about what happens to them at the boundaries". Argo floats' drifts compilation from 2003 to 2013 offers a sampling density sufficient to resolve the high-resolution meridional structure and zonal extent of the equatorial intermediate current system at 1000m, and makes it possible to answer in part these questions.

Argo float subsurface drift computation, and the ANDRO dataset

Argo profiling floats are originally designed to provide vertical profiles of temperature and salinity every 10 days. They dive to the deepest depth of their profile (usually 2000m), rise to the surface, typically spend a few hours there where satellites determine their position, and dive back to their parking depth (usually 1000m) where they drift for about 9 days before diving again for their next profile. If done carefully, the positions and time of transmissions before and after each dive can be used to compute the subsurface Lagrangian velocities, averaged during the drift period.

We gathered all Argo floats that entered the 12°S-12°N region between 120°E and 70°W, from January 2003 to December 2013, and computed the Lagrangian subsurface velocity corresponding to their drift at their parking depth using their positions and times of transmission. There are several sources of uncertainties on this subsurface velocity computation; the float spends some time at the surface before its first transmission and after its last transmission, during which it drifts with the surface currents; it is also advected by the subsurface currents encountered during its ascent and descent. These errors were estimated and the median error was found to be small (less than 0.5 cm/s). The last important source of error is the parking depth: it is often erroneous in the metafile file (erroneously decoded, or constant even if the float grounded), especially for floats in the Atlantic Ocean. Each float's trajectory and the parameters of its dive were visually inspected to eliminate obvious bad values. Especially, the pressure at the parking depth was computed and inspected carefully. Most of the Argo floats have a parking depth around 1000 m. In the Tropical Pacific Ocean, there are enough floats drifting at 1500m to get a picture of the mean circulation at that depth in some areas, even if large regions remain unsampled. The subsurface velocities at 1000m and 1500m were thus mapped to produce a mean monthly climatological field on a 1° longitude 0.25° latitude grid, using an optimal objective analysis method. The details of the methods used, of the error estimations and of the gridding procedure are described in Cravatte et al. (2012).

Ollitrault and Rannou (2013) recently produced the ANDRO product, a very useful quality-controlled subsurface displacement dataset for the global ocean from all Argo floats till 31 December 2009, with validated parking pressures. We checked that this dataset was consistent with our results in the tropical Pacific.

Mean circulation at 1000m and 1500m in the tropical Pacific

The mean zonal and meridional currents in the Tropical Pacific are shown in Figures 1 and 2. The zonal velocity by far dominates the meridional velocity in most locations, except near the western boundary. Several features stand out:

a-The zonal velocity at 1000 m is dominated by alternating westward and eastward jets with a meridional scale of 1.5° and speeds about 5 cm/s. Strikingly, these jets are zonally coherent across the entire basin, confirming and extending the synoptic observations of Firing et al. (1998). Moreover, these jets are observed at least from 12°S to 12°N, a wider latitudinal range than shown by previous observations.

b-The jets are strong in the western and central parts of the basin but weaken and eventually disappear in the east (near 110°W at the equator, farther west poleward).

c-The jets are stronger in the Southern Hemisphere, where six to seven jets can be identified at 1000 m. They are weaker (except in the west) in the Northern Hemisphere, where seven to eight jets are also identified.

d- In the western Pacific, the 1000-m zonal jets appear to slant slightly poleward from east to west.

Figure 2 also shows the mean zonal and meridional velocities at 1500m. Even if some regions remain largely unsampled, it gives interesting clues about the deeper extension of the zonal jets. Alternating zonal jets are also present at 1500 m and appear, at first glance, to have a similar geographical distribution than the ones observed at 1000 m. This suggests that the jets have a large vertical extension. It is worth noting that currents at 1500 m are westward along the equator, as at 1000 m. This is surprising, because it is known that, at these depths, equatorial deep jets alternating in the vertical with a wavelength of several hundred meters are present in a narrow equatorial band (Firing et al. 1998, their Fig. 1). Thus, the similarity between 1000m and 1500m zonal currents at the equator is probably coincidental and needs to be further investigated.

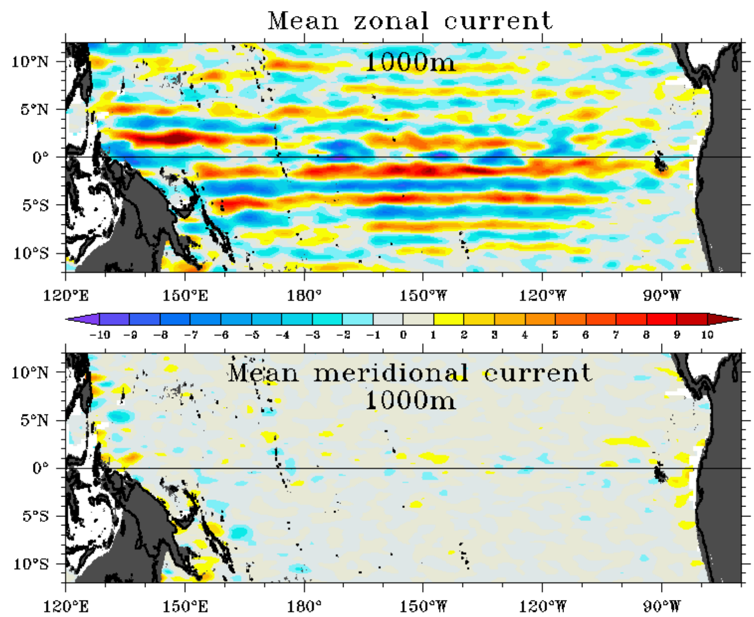

Figure 1: Mean zonal currents (upper) and mean meridional currents (lower) (cm/s) at 1000m from optimal interpolation. Topography shallower than 1000-m depth is shaded in dark gray. Updated from Cravatte et al. 2012.

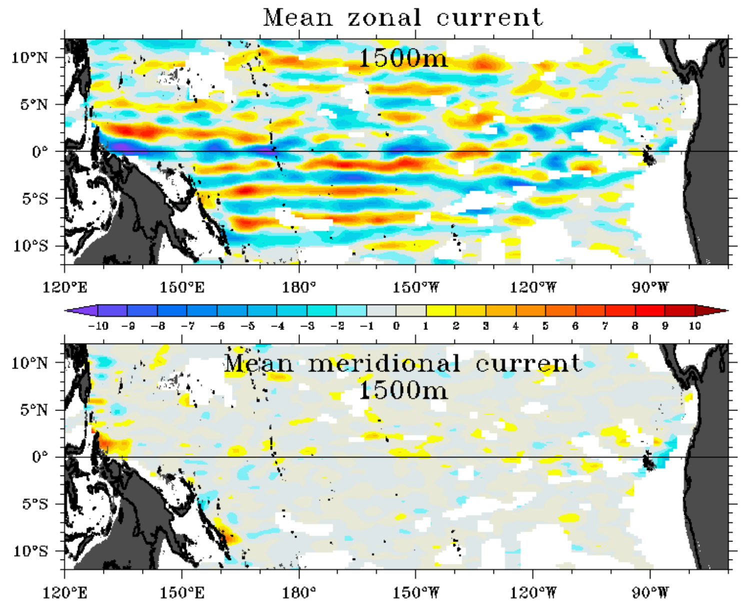

Figure 2: Mean zonal currents (upper) and mean meridional currents (lower) (cm/s) at 1500m from optimal interpolation. Topography shallower than 1000-m depth is shaded in dark gray. Updated from Cravatte et al. 2012.

What happens to them at the boundaries?

Near the western coast of the South Pacific delimited by Solomon Islands chain and Papua New Guinea, the zonal jets originate (or terminate) very close to the coast, and appear to be connected to adjacent westward or eastward jets by meridional velocities (not shown). A northward boundary current is also seen flowing along the Solomon Island chain at 1000m. In the northern Pacific, the situation is analogous, though vigorous eddies dominate the mean circulation, and these recirculations are less clear.

Seasonal variability

It is not possible to resolve the full temporal structure of the jets' variability, given the sampling and the short record spanning only a few years. However, it is possible to characterize their seasonal variability. Figure 3 shows the 1000m zonal velocity anomalies at the equator and at 4°N and 4°S. At the three latitudes, there is a very clear annual cycle of zonal velocity. Current anomalies are out of phase between the equator and 4° and propagate westward at a speed of about 0.43 m/s. This meridional structure and the phase speed correspond to the vertical propagation of the annual Rossby wave described previously based on subsurface temperature changes (e.g. Kessler and McCreary 1993). Interestingly, the zonal currents' seasonal variability exhibits a meridional scale quite different from that of the background mean jets, with a meridional wavelength of 7°–9° instead of 3°. The amplitude of the seasonal variability, which is stronger close to the equator, implies that the most equatorial jets may transiently reverse, as noticed by Gouriou et al. (2006) and explained by Marin et al. (2010). The zonal currents' annual variability is thus superimposed on the mean zonal jets, but the scale difference suggests that the seasonal dynamics are distinct from the background zonal jets' dynamics (Figure 3, middle and right panels).

In the tropical Atlantic and Indian Oceans

As in the Pacific, we analyzed the Argo float drifts at 1000m between 12°S and 12°N to characterize the mean velocity and its seasonal variability. We used the ANDRO dataset until December 2009 and updated the subsurface velocities until December 2013. Ubiquitous zonal jets are shown to extend across the tropical Atlantic, in agreement with the findings of Ollitrault et al. (2006) and Ollitrault and Colin de Verdière (2014), but they are weaker than in the Pacific, with larger amplitude in the northern hemisphere. Their meridional scale is about 400km, slightly larger than in the Pacific. They are also weak in the east, and slant poleward in the west. In the Indian Ocean, there are no coherent zonal features emerging from the mean circulation pattern, although the seasonal variability (mainly semiannual) seems to be well resolved (not shown). The mean zonal currents may be hidden by a stronger variability. Understanding the dynamical origin of these differences will be the goal of future studies.

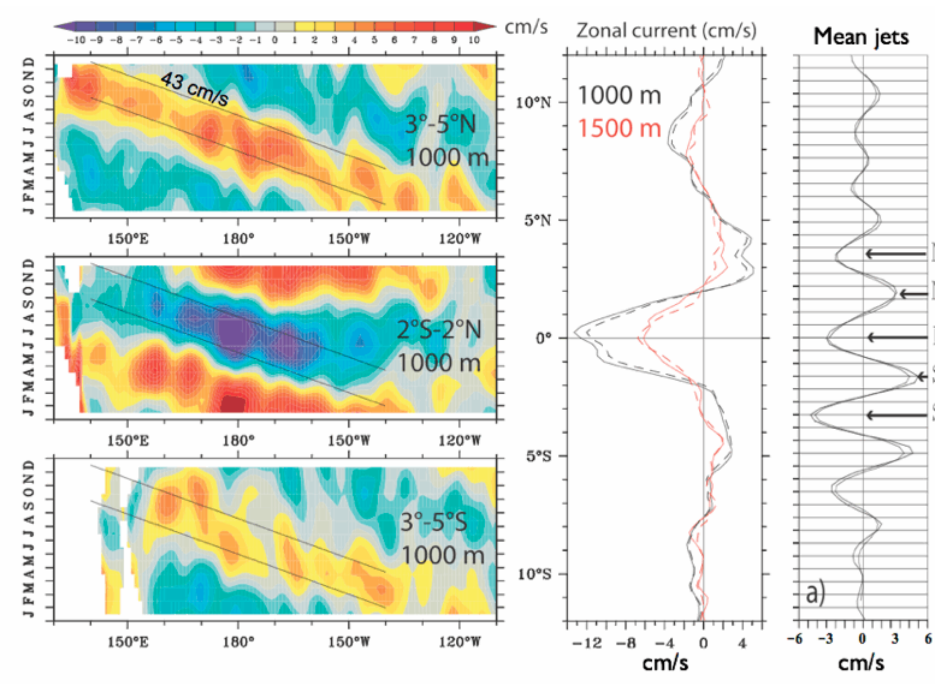

Figure 3: (left) Seasonal anomalies (mean removed) of 1000-m zonal currents (cm/s) averaged between (top) 3°– 5°N, (middle) 2°S–2°N, and (bottom) 3°–5°S. (Middle) Zonal velocity anomalies averaged along the paths shown in the left panels (in black lines), between 160°E and 160°W, for 1000-m current anomalies (thin black) and their first annual harmonic (dashed black). The same calculations have been made for zonal current anomalies at 1500-m currents, and 1500-m zonal currents anomalies and their first annual harmonic have been averaged along similar Rossby paths, shifted one month in advance (red thin and dashed lines). (Right) Mean zonal current u at 1000 m in cm/s, zonally averaged in the 160°E–120°W band in the Southern Hemisphere and in the 120°E–120°W band in the Northern Hemisphere. Adapted from Cravatte et al., 2012.

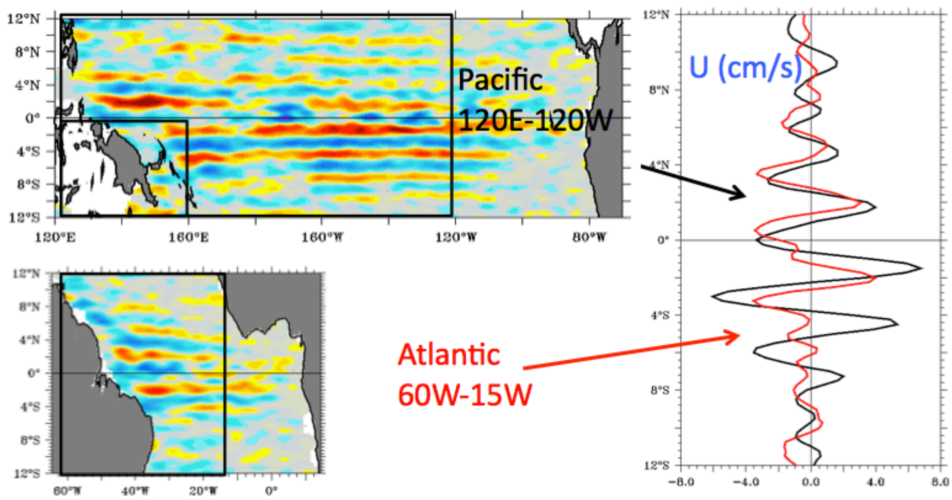

Figure 4: Left: Mean zonal currents from Argo floats drifts (cm/s) at 1000m in the Pacific (upper) and Atlantic Ocean (lower) (cm/s). Right: Mean zonal current at 1000 m in cm/s, zonally averaged in the 160°E–120°W band in the Southern Hemisphere and in the 120°E–120°W band in the Northern Hemisphere in the Pacific, and in the 60°W-15°W band in the Atlantic Ocean.

Conclusion

The analysis of ARGO floats drifts at 1000 m depth indicates that the mean intermediate circulation in the tropical Pacific is dominated by the presence of alternating zonal jets, that had previously only been sporadically observed from synoptic hydrographic cruises at specific longitudes. These jets are coherent over the whole basin width, from Solomon islands to about 2000 km of the American continent, and they are present from 12°S to 12°N. These extra-equatorial jets flow zonally either from West to East, or from East to West, at a speed of about 5-10 cm/s, alternating regularly every 1.5° in latitude. Their hydrological and biogeochemical properties are largely unknown, along with the physical processes responsible for their existence. They are also present in the Atlantic Ocean, but could not be evidenced in the Indian Ocean. Their representation in oceanic models, even at high resolution, is very poor.

The aim of the ZEBRE project funded by LEFE/IMAGO and LEFE/GMMC (PI, S. Cravatte, 2013-2015) is to better document, and understand, the dynamics of these deep extra-equatorial jets in the Pacific ocean and in the other tropical oceans, and to identify their possible link with the deep alternating jets that are observed in the midlatitudes, from the combined analyses of in situ observations (ADCP currents, three-dimensional products of geostrophic velocities, ARGO float drifts) and of numerical simulations. In the context of this project, the CASSIOPEE cruise (2015, PI F. Marin) will acquire a unique set of synoptic in situ observations of the ocean circulation from the surface to the ocean bottom in the Southwest Equatorial Pacific Ocean. The objectives of this cruise are to describe the fine scale meridional and vertical structure of these deep extra-equatorial jets, the hydrological and biogeochemical properties of the water masses they advect, and their possible interaction with the western boundary circulation.

Acknowledgements

This study strongly relies on Argo data subsurface drifts. Argo float data were collected and made freely available by the International Argo Program and the national programs that contribute to it. The Argo Program is part of the Global Ocean Observing System. We would like to thank Michel Ollitrault for his comments and for providing the ANDRO dataset.

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SPICE SOUTHWEST PACIFIC OCEAN CIRCULATION

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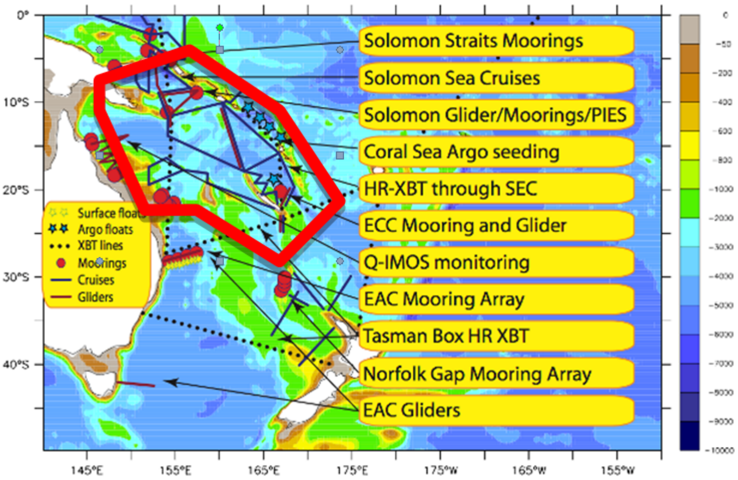
Mission

Objectifs :

Pour étudier la circulation océanique du Pacifique sud-ouest et les alimentations des eaux équatoriales dans un contexte climatique, le programme international SPICE a été lancé en 2008. La contribution française se concentre sur l'étude de la Mer de Corail et de la Mer des Salomon, point d'étranglement où les courants de bord sont intenses. Les objectifs sont les suivants:

- Décrire la circulation interne de ces mers, compliquée par les effets d'île, courants de bord et détroits
- Mesurer et modéliser les transports depuis la Mer de Corail vers l'équateur via la mer des Salomon et leurs variations aux échelles saisonnières et interannuelles ;
- Evaluer le mélange entre les masses d'eau dans cette région et son rôle dans la variabilité climatique

Le transport et les caractéristiques des eaux issues du gyre du Pacifique Sud et entrant en Mer de Corail, puis en Mer des Salomon avant d'atteindre l'équateur sont des éléments importants du système climatique, notamment liés à la dynamique du phénomène El Niño. Une description et analyse correctes du transport de ces eaux et de l'évolution de leurs propriétés sont importantes pour pouvoir améliorer les prévisions océaniques et à terme climatiques. Les forts courants de bord combinés avec une topographie compliquée et des détroits étroits entre les îles rendent la modélisation difficile pour les échelles à considérer. SPICE est un programme international collaboratif entériné par CLIVAR et animé par le LEGOS. Le LEGOS a apporté, et apporte une contribution majeure au programme, avec des travaux sur les mers de Corail, des Salomon ainsi que sur les cheminements grande échelle entre l'entrée Mer de Corail et l'équateur. Cette contribution se décline sous la forme d'un important programme de mesures in situ, de modélisation numérique (collaboration LGGE) et d'analyses de données altimétriques. Ce dispositif expérimental vise à appréhender la variabilité intrasaisonnière, saisonnière et interannuelle des transports et des propriétés des masses d'eau à l'entrée et aux sorties des mers de Corail et des Salomon.



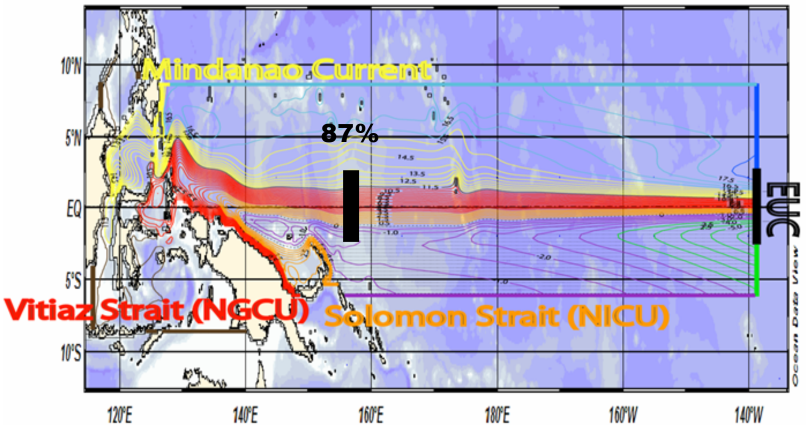
Topographie du Pacifique sud-ouest et dispositif expérimental SPICE. La zone rouge délimite les mesures, ou contributions réalisées par OLVAC.

Stratégie

L'étude est basée sur une approche modèle-observation. Un important programme de mesures in situ a été mené.

En Mer de Corail, 10 campagnes en mer et trois déploiements de mouillages ont permis de documenter les courants et les masses d'eaux et sont analysées en combinaison avec les données historiques (e.g. S-ADCP retraités). Un glider a effectué 4 transects depuis la Nouvelle-Calédonie. Un monitoring expérimental du transport du Courant Equatorial Sud par des déploiements de flotteurs Argo et de sondes XBT/XCTD à partir d'un navire commercial a aussi été mis en place (voir la fiche « Mer de Corail »).

En Mer des Salomon, qui était jusqu'alors quasi-inexplorée par les océanographes, nous avons accomplis un important effort de mesure à travers des campagnes, l'installation de mouillages dans les détroits, et de modélisation haute résolution au 1/12° et 1/36° de résolution, notamment pour mesurer la variabilité des flux vers l'équateur et les transformations de masses d'eau lors de leur transit.



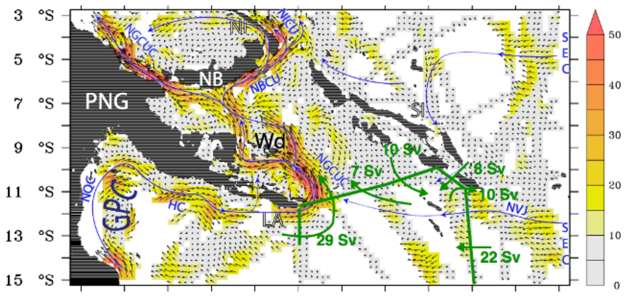
Deux résultats majeurs & prospectives

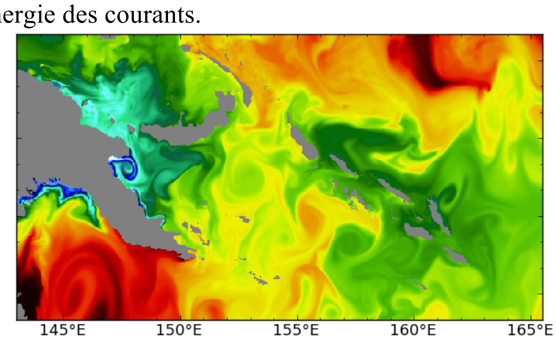
Grande échelle : connexion à l'équateur.

Pour quantifier les provenances des eaux du sous-courant équatorial (EUC), une simulation océanique (¼°) a été analysée à l'aide d'un outil Lagrangien. Les eaux des courants de bord ouest représentent 87% du transport de l'EUC, avec une contribution du New Guinea Coastal Undercurrent (NGCU) qui atteint 50%.

Trajectoires Lagrangiennes des eaux nourrissant l'EUC. Les différentes couleurs indiquent les provenances des eaux, en particulier celles passant par les deux détroits des Salomon, Vitiaz et Solomon. Grenier et al. (2011)

Petite échelle : Jets, courants de bord et sous méso-échelle. Dans cette région très dynamique, le courant équatorial sud se divise à la rencontre des îles, puis suit les côtes sous forme d'un courant de bord (ici le Gulf of Papua Current, GPC) qui, en Mer des Salomon, se renforce et se divise pour rejoindre l'équateur par différentes routes. En parallèle avec l'examen de données historiques, nous avons mis en place des simulations numériques très haute résolution donnant accès aux fines échelles générées par la forte énergie des courants.





(haut) : Courants moyens en Mer des Salomon issus des données courantométriques (ADCP) des instruments de bord des navires de recherche transitant par la région (Cravatte et al. 2011). Les transports issus de la campagne Flusec 2007 sont indiqués en vert (Gasparin et al. 2012).

(gauche) : Instantané de la salinité de surface dans une simulation numérique à très haute résolution (1/36°) réalisée en Mer des Salomon (Djath et al. 2014a,b)

Futur: Au cours des dix dernières années, des efforts considérables ont été consacrés à améliorer la compréhension de cette région, par des observations in situ, la modélisation, ainsi que la télédétection et des analyses des données historiques. De nombreux aspects ont été abordés par le LEGOS: transports de masse, de chaleur et variabilité; propriétés et dynamique des courants de bord et des jets et transformations des masses d'eau. Les projets futurs incluent l'approfondissement de certains aspects (thèses en cours), ainsi que l'exploration du mélange, de la dynamique turbulente de sous-mésoéchelle et des courants en lien avec les changements climatiques.

Website: http://spice.legos.obs-mip.fr

Partenariat et financements

SPICE est un programme international impliquant la France, les Etats-Unis, l'Australie, le Japon et les iles du Pacifique. SPICE ne dispose pas de financement propre. Les partenariats et financements spécifiques sont mentionnés dans les fiches "Solwara" et "Mer de Corail".

SOLWARA Solomon Sea circulation and geochemistry

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Objectives :

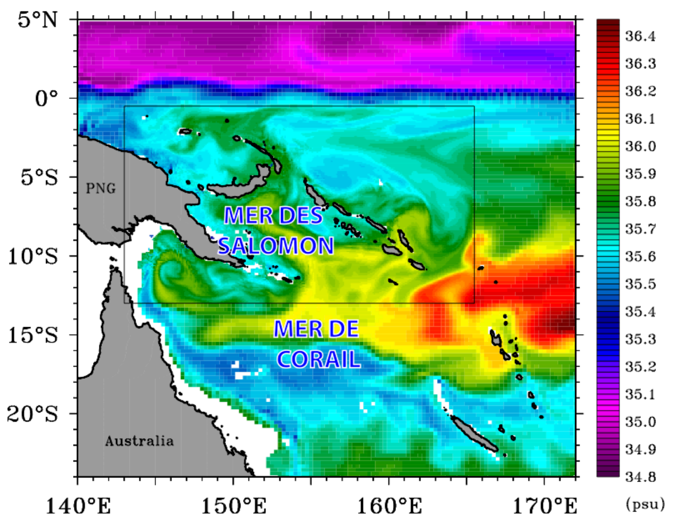
The Solwara project aims at better understanding the inflow, the outflow and the circulation within the Solomon Sea, as well as geochemical sources and water mass transformations along this pathway to the equator. The objectives are:

- To measure, model and understand the total transport from the Coral Sea to the equator and the partitioning in the transport between the different Solomon Straits on seasonal to interannual time scales;
- To evaluate the partition between the western boundary current and the direct flow from the SEC to the east Solomon Sea;
- To describe in details the inside Solomon Sea circulation and flows between trenches and islands;
- To evaluate water mass transformation and mixing through the Solomon Sea, with a special focus on the geochemical sources from the Solomon and PNG margins.
- To estimate the intensity and time scales of element exchanges along the Solomon Sea margins.
- To estimate the geographic origins, pathways and transit times of these water masses, between the Coral Sea and the equatorial region.

Main tasks

The oceanic circulation in the South Pacific redistributes waters from the large subtropical gyre toward the equator through a subtle journey, as suggested by model results and meridional gradients of trace elements. These waters are first transported from the central South Pacific, westward, in the South Equatorial Current and eventually join the equator after transiting in the western boundary current system of the Coral and Solomon Seas. This circulation is also associated with the equatorward supply of trace elements that controls biological activity in the equatorial area. The Solwara project aims at improving our physical and geochemical knowledge of the oceanic features of the Solomon Sea, as well as the development of numerical modeling tools and optimal monitoring systems to adequately sample the time-variability. Improving the realism of the oceanic circulation in this region in climate models may improve the realism of decadal variability, and thus permit a better understanding of its mechanisms. The "Solwara" project will be an important contribution to SPICE (spiceclivar.org ; fiche-SPICE) and GEOGRACES (geotraces.org) international programs.

Strategy

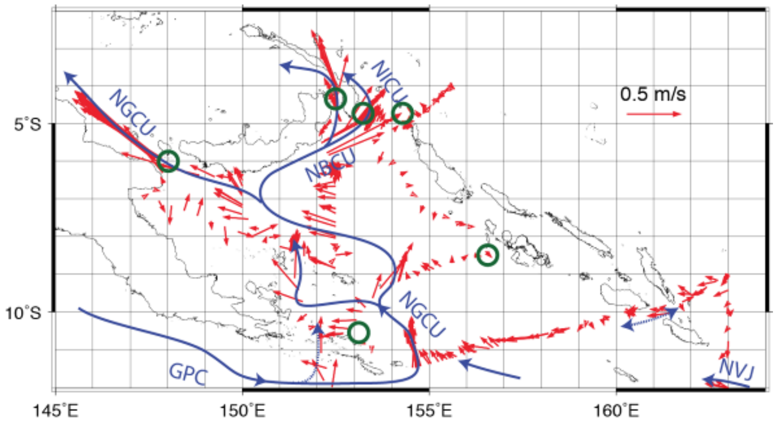


Intrusion of the South Pacific High salinity as simulated by a 1/12° résolution model embedded in a global ¼°. Melet et al. (2010a).

We base our approach on a combination of very high resolution modeling (1/12° to 1/36°) and observations. Models needed to be examined and improved over this region because of the complicated flows due to boundary currents, narrow straits and sharp shelves, which generate large uncertainties. At the same time, historical current-meter (ADCP) data were compiled to provide the first basic description of the observed circulation; and an important collaborative in situ observation program was carried out, including LEGOS cruises / moorings (below) and gliders (Scripps). Besides, altimetric data, including specific along-track products, were used to provide an adequate description of the mesoscale variability. Tracer supplies from continental margins/ocean exchange, as well as their pathways were explored using Lagrangian modeling tools associated with in situ geochemical observations.

Two major results & prospective

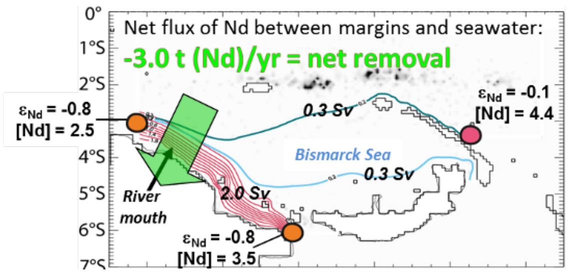
Pandora A multidisciplinary cruise (Pandora, 40 days on l'Atalante) was done in July 2012 through a France-USA collaboration. It completed a 2007 survey (Flusec, Alis) along the south boundary of the Solomon Sea, and was followed by a 30 day cruise in 2014 (RV Thompson) to renew the moorings and repeat measurements on a different season.

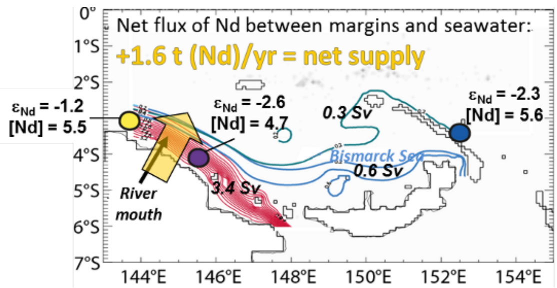


Pandora cruise trajectory (2012) as indicated by measured currents from the ship current meter (ADCP). The main currents are indicated in blue; mooring locations by the green circles. Eldin et al. (2013)

Pandora provided a quasi-synoptic description of surface and subsurface circulation and strait transports and allowed to deploy 11 moorings to measure the transport temporal variability. The data will document water mass transformations and mixing, ocean-margins exchanges on a wide range of space and time scales through the combined analysis of physical and geochemical data. Four LEGOS moorings were re-deployed in the three northern straits in 2014. These cruises provide an unprecedented "snapshot" description of the circulation, the few previous surveys being either low resolution or low coverage.

Trace Element Isotopes and Lagrangian Pathways
An original approach coupling real geochemical tracer data –measured in the framework of EUCFe and Solwara projects- with a modelled Lagrangian circulation allowed a very fine description of the dynamical tracer transports and a precise quantification of the external sources of micro-nutrients that are enriching the water masses. We demonstrated that the *lower* thermocline only is naturally fertilized by these inputs as it flows along the Papua New Guinea coast.





Circulation and Nd parameter evolution in the Bismarck Sea: (upper) Upper thermocline; (lower) Lower thermocline. Modelled pathways and transports (coloured lines and associated Sv) coupled to discrete measurements of Nd parameters (ε and concentrations; coloured points). This figure does not illustrate the whole outflow of the straits but only the fraction that finally flows along the Papua New Guinea coast, around 3°S, 144°E. Large coloured arrows represent the net exchange flux of Nd between the continental margin and the seawater, in tons of Nd per year. Adapted from Grenier et al. 2013.

Future: The tremendous data set and numerical simulation generated by the recent cruises and models will be a large research focus on the next 3 years, with at least three LEGOS theses. Substantial efforts are required to accomplish the basic analysis (geochemical lab measurements and CTD/Nutrient treatments). Future developments will include understanding the role of the Solomon Sea transports in the tropical climate system.

Website: http://solomonseaoceanography.org. (Numerical model simulations http://thredds.sedoo.fr/solwara/).

Partnership and funding

Partners: Scripps Institute of Oceanography (SIO); Pacific Marine Environmental Laboratory (NOAA/PMEL); University of the South Pacific (USP, Fiji); University of Papua New Guinea (UPNG); LGGE, Grenoble, GET, Toulouse, LOCEAN, Paris, MIO, Marseille, CSIRO, Australia.
Funding : INSU/LEFE, INSU/DT, IRD, ANR

Vertical stratification of the upper ocean: documenting the specific role of the salinity in the Tropics.

Christophe Maes

Laboratoire de Physique des Océans (LPO), CNRS, Ifremer, IRD, UBO, Plouzané, France

Observational studies in the western Pacific Ocean since the mid-1980s have suggested that the barrier layer resulting from the salinity stratification within the mixed layer could influence significantly ocean-atmosphere interactions, and consequently the variability of the El Nino/Southern Oscillation (ENSO) phenomenon. In addition, despite considerable progress in the representation of the tropical mean state and climate variability by coupled ocean-atmosphere general circulation models, several studies have concluded that it is not yet possible to say whether ENSO activity will be enhanced or damped by global warming. In the Pacific Ocean, a stringent test for models is a correct representation of the mean zonal gradient of sea surface temperature (SST) along the equator and also a correct position of the salinity front separating the Western Pacific Warm Pool (WPWP) from the central cold waters. Analyzing 19 models from the World Climate Research Program Coupled Model Intercomparison Project Phase 5 (CMIP5), Brown et al. (2014) have demonstrated that it remains difficult for these coupled models to simulate the mean longitude, the interannual excursions, and the zonal convergence of ocean currents associated with the WPWP. It remains also difficult in some cases to discriminate the physical mechanisms, as for example, the warm pool displacements result from a net heating or cooling rather than a zonal advection of warm water, and to relate them to the intrinsic interannual variability simulated by the model itself. One major ingredient that needs some improvements is the simulation and the generation of the salinity barrier layer that is a key element of the whole Pacific ocean-atmosphere coupled system (Maes and Belamari 2011).

While the sea surface salinity (SSS) and barrier layer variabilities in the equatorial Pacific have been investigated in previous studies, using oceanographic cruise data, reconstructed salinity profiles, and Voluntary Observing Ship thermosalinograph measurements, it has been possible only recently to combine the SSS measurements from satellite missions with the vertical structure at depth as observed by the Argo floats, in order to monitor salinity variations with accuracy within the Pacific basin (Qu et al. 2014). The availability of these unique data sets also raises some new questions about the conceptual view of the ocean vertical structure that is based on a definition of several layers within which the water properties exhibit different degrees of vertical uniformity. Maes and O'Kane (2014a) propose a new perspective for describing the impact of the salinity on the static stratification of the oceanic upper layers, using a methodology keyed to the Brunt-Vaisala frequency, N^2. This perspective recognizes that the stabilizing effect of the salinity operates near the bottom of the mixed layer but that its effect could be expanded downward to the main pycnocline and to regions where both the salinity and temperature are mixed over the same depth. Significant seasonal variations in N^2 profiles are found to be limited to the upper 300 m depth, and in several regions of the tropics, the salinity part contributes 40–50% to N^2, approximately equal to the thermal stratification contribution (see the **figure 1**). The study that achieved these results was undoubtedly made possible by the expansion of the ocean observing system through the Argo float network, which offers concomitant temperature and salinity profiles at depth and at the global scale. When the same diagnostics are applied to the pre-Argo period, differences as large as 30% in terms of amplitude are observed in the seasonal variability of the salinity signature in the Tropical areas (Maes and O'Kane, 2014b). These results newly emphasize the challenge of investigating and exploring the role of the salinity stratification in seasonal prediction systems and long-term climate variability.

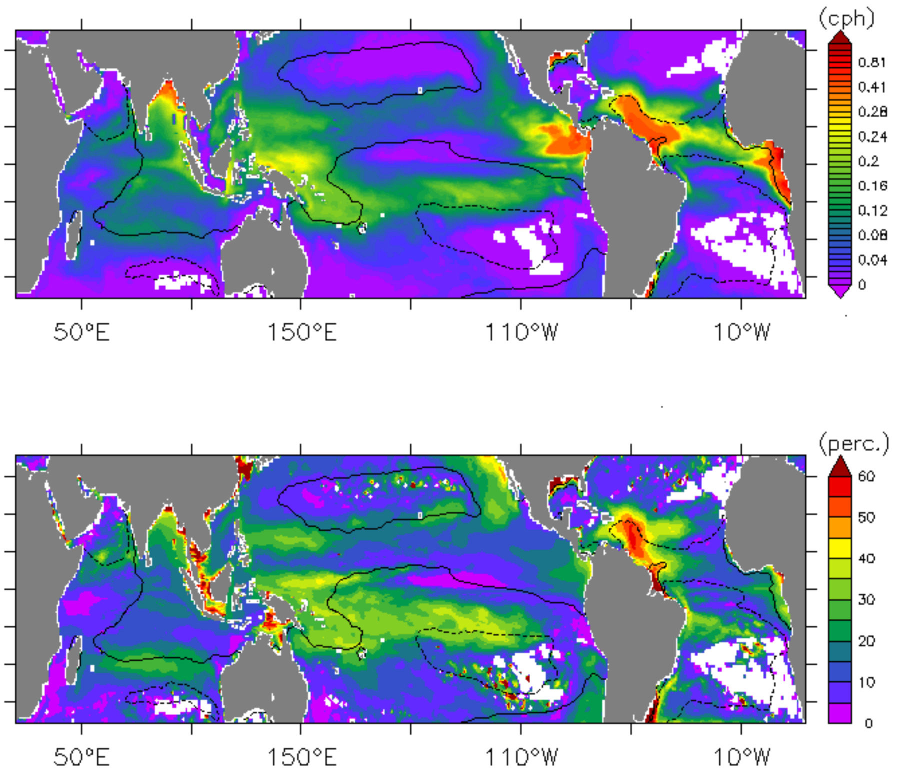


Figure 1: Annual mean of (top) the OSS (Ocean Salinity Stratification) defined as the stabilizing effect (positive) due to the haline part of N^2 (in cph) and of (bottom) the ratio (in %) of $N^2(S)$ to $N^2(T, S)$. The contour lines represent the 34.8 (continuous) and 35.8 (dash) of SSS. The mean fields are based on the seasonal climatology described by Maes and O'Kane (2014a).

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Sea Surface Salinity from SMOS satellite mission: a synthesis of the main 2010-2015 oceanic results in France

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Ocean salinity is an important driver of ocean circulation and represents a key indicator of changes in the global water cycle. Recent advances in observing sea surface salinity (SSS) from space have provided an unprecedented capability to study the influence of salinity on ocean circulation and its relations to climate variability and the water cycle (Reul et al. 2014a). The Soil Moisture and Ocean Salinity (SMOS) satellite mission has been launched in 2009 under the auspices of the European Spatial Agency (ESA). It is the first satellite mission that provided a global monitoring of sea surface salinity (SSS) from space. Since 2010, SMOS provides a quasi-synoptic monitoring of the global ocean every 3 to 5 days. In tropical and subtropical areas, the precision of monthly SSS anomalies at 50 to 100km resolution has been determined to be close to 0.2 psu. Several French teams have been strongly involved in the physics of measurements of the L-band radiometry, in the calibration and validation of the SMOS salinity measurements and in their use for studying ocean processes. Here we review the scientific results achieved by the french teams thanks to these novel measurements.

Large scale interannual SSS anomalies in the Indian Ocean, linked to the Indian Ocean Dipole (Durand et al. 2013), and in the western tropical Pacific, linked to the 2010-11 La Niña (Hasson et al. 2014), have been detected by SMOS with a spatio-temporal resolution very complementary to Argo and ships of opportunity. These anomalies are related to freshwater fluxes as well as to ocean advection anomalies. In addition, tropical instability waves in the equatorial Pacific Ocean were observed to vary interannually (Yin et al. 2014). Combining SMOS SSS with ship SSS and an ocean model, Hasson et al. (2013) identified decadal trend of the longitudinal displacement of the salinity maximum in the South-Eastern tropical Pacific Ocean. Along the equator, SMOS measurements reveal the signature of the equatorial upwelling with fine spatial scales associated with the thermohaline signature of the dense waters (Maes et al. 2014). Another great advance with the SMOS data set has been to conduct unprecedented studies on the small scales of SSS at typical 50 to 100 km. Reul et al (2014b) show for instance that the eddies resulting from the meandering of the Gulf Stream region could be followed by SSS during the summer when the warming of the mixed-layer is blurring the SST signature of eddies and meanders. In the same context, Maes et al. (2013) revealed the importance of the eddies stirring in the Coral Sea and Kolodziejczyk et al. (2015) focused on the seasonal variability of the surface horizontal thermohaline structure in the subtropical Atlantic Ocean. Near-coastal studies, especially dedicated to the main riverine inputs in the ocean were also conducted (Hopkins et al. 2013; Reul et al. 2014a, 2014c; Fournier et al. 2015). The peculiar seasonal dynamics of SSS off Panama, in the so-called eastern Pacific fresh pool, was carefully analyzed with complementary and sporadic in situ data, and with SMOS, which provided the unprecedented large scale context (Alory et al. 2012). Feedbacks of barrier-layers and salt-driven stratification in freshwater pools on local air-sea interactions, such as the favored intensification of hurricanes as they cross the Amazon river plume as been identified and demonstrated (Grodsky et al. 2014; Reul et al. 2014c). It is important to note that most of these studies have explored new possibilities of monitoring these signals and would represent the roots for further analyses in the context of climate change.

In the tropical convergence zones, spatio-temporal variability of SMOS SSS was demonstrated to be strongly related to rain events (Boutin et al. 2013, 2014). Given that satellite radiometry senses the salinity in the top centimeter of the ocean while most in situ systems measure it at a few meter depths, this pleads for an improved description and understanding of the penetration of the fresh water in the upper ocean. Last, using SSS as a tracer of water masses, SMOS SSS brought new insights on the processes driving variability of biogeochemical parameters. Fournier et al. (2015) revisited the relationships between SSS and upper water column optical properties in the Amazon plume, and Land et al. (2015) discussed the general possibility of better monitoring the short-term, small-spatial scales of the carbonate variability in the ocean thanks to the synergistic use of satellite SSS, SST and ocean color. Brown et al. (2015) highlighted the dominant roles of the upwelling and freshwater fluxes in driving the air-sea CO2 flux variability in the northeastern tropical Pacific Ocean.

A new era of SSS observing system from Space has started with the launch of SMOS. It was followed by the launch of Aquarius in 2011. Both missions provide complementary observations, SMOS (~50km, 3-5days) providing a better spatial resolution and revisit time than Aquarius (~150km, 7days), but with large regions blurred by radio frequency interferences and experiencing larger systematic biases. The recently launched Soil Moisture Active Passive (SMAP) mission is expected to consolidate and complement these new data sets, likely by providing high resolution SSS monitoring in contrasted areas.

Acknowledgements: We acknowledge major contributions of Gael Alory, Séverine Fournier, Audrey Hasson, Nicolas Kolodziejczyk and Xiaobin Yin. Most of these studies have been supported through CNES/TOSCA and ESA grants.

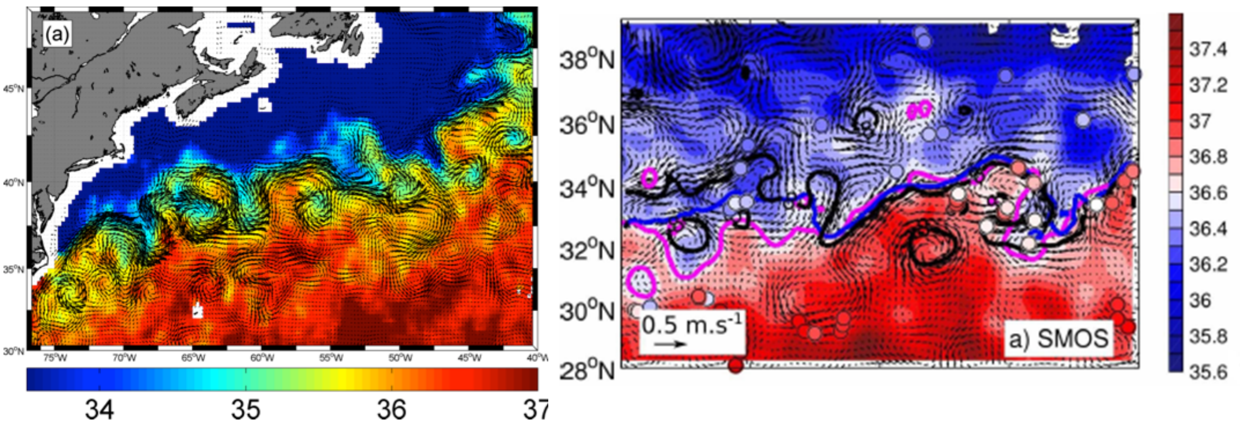

Figure 1: Small scale (~50km) SSS variability monitored by SMOS in the Gulf Stream region (left; Reul et al. 2014b) and in the Azores front region (right; Kolodziejczyk et al. 2014) and their relationship to mesoscale surface currents.

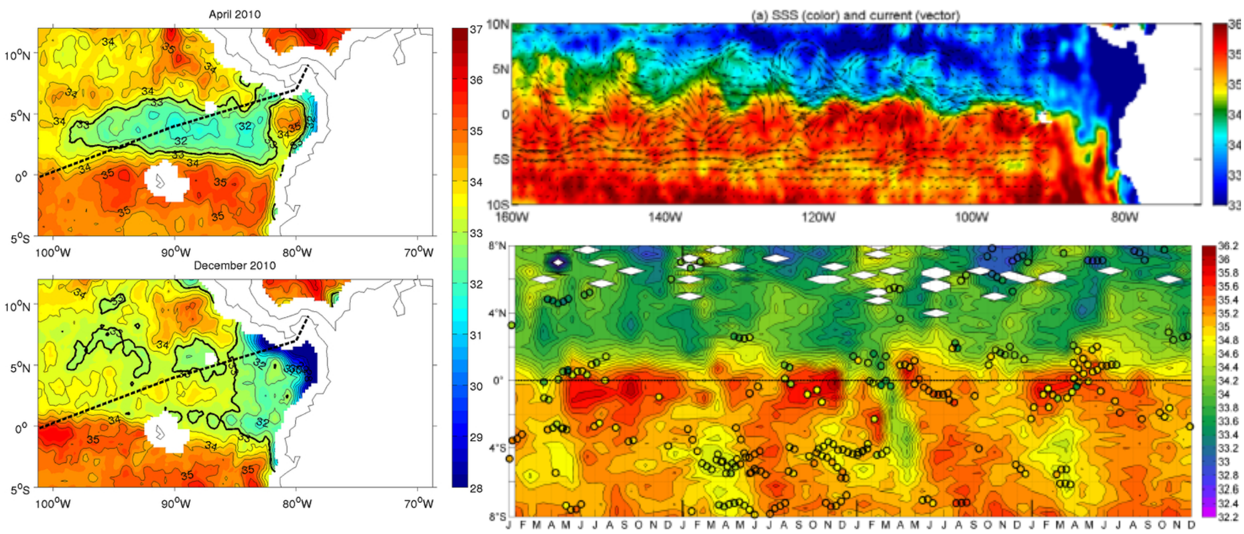

Figure 2: SMOS SSS in the tropical Pacific Ocean: on left, Seasonal dynamics of SSS off Panama, in the far Eastern Pacific Fresh Pool (Alory et al. 2012); on right, (top) signature of tropical instability waves (Yin et al. 2014), and (bottom) temporal variability at 110W between 8°N and 8°S (Maes et al. 2014).

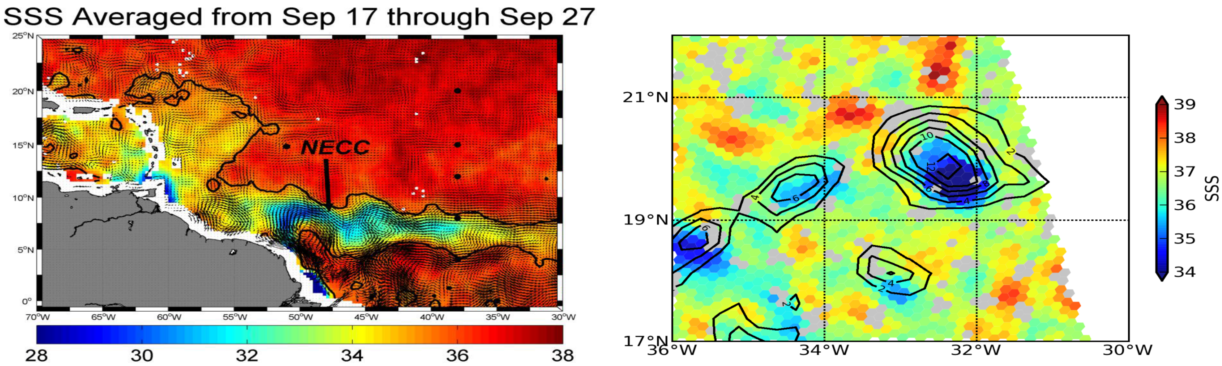

Figure 3: SSS variability related to freshwater fluxes: (left) in the Amazone plume in Sept. 2010 (see further details in Reul et al. 2014a and Fournier et al. 2015) and (right) under rainfall (Boutin et al. 2014)

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Ocean waves in Earth system sciences : towards a broad-band understanding

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Several branches of geosciences have led to a more complete understanding of ocean wave dynamics and their connection with the atmosphere and ocean. Waves are particularly important for air-sea interactions, remote sensing, seismology, and coastal oceanography including natural hazards with coastal flooding or extreme waves. This synergy of efforts was the main topic of the IOWAGA projet. (http://wwz.ifremer.fr/iowaga/)

Numerical modelling and ocean wave forecasting

The most widely used form of numerical wave models uses a phase-averaged spectral representation of the wave action evolution in space and time. This approach leads to a set of coupled transport equation with source terms, one for each spectral component, i.e. of the order of 1000. The main difficulties and sources of errors of this approach are the definition of parametrizations used in the source terms (e.g. Leckler et al. 2013), the quality of the forcing fields (winds, currents, sea ice … which can be modified by wave feedback in coupled models), and the numerical method to integrate the wave action equation (WAE). Two main approaches have been used for solving the WAE, either a splitting technique, akin to the barotropic / baroclining splitting of most ocean circulation models primitive equation models (e.g. WAMDI 1988), or an implicit integration of the WAE (e.g. Booij et al. 1999). A review of these techniques and compromises particular to coastal applications is given by Roland and Ardhuin (2014), together with an update on parameterization relevant for coastal areas, in particular bottom friction. These developments have led to a major improvement in forecast accuracy, with the implementation of parameterization based on Ardhuin et al. (2010) in operational forecasting systems at Meteo-France in 2012 and NOAA/NCEP in 2013. Investigations on the impact of these parameterizations in a coupled wave-atmosphere context are under way, in order to make a smooth operation possible also at ECMWF. Improvements in coastal wave forecasts required the use of several “new” ingredients. In particular it was shown that the forcing by tidal currents could have several important effects (e.g. figure 1), and taking into account the nature of bottom sediments was important to define the bottom roughness.

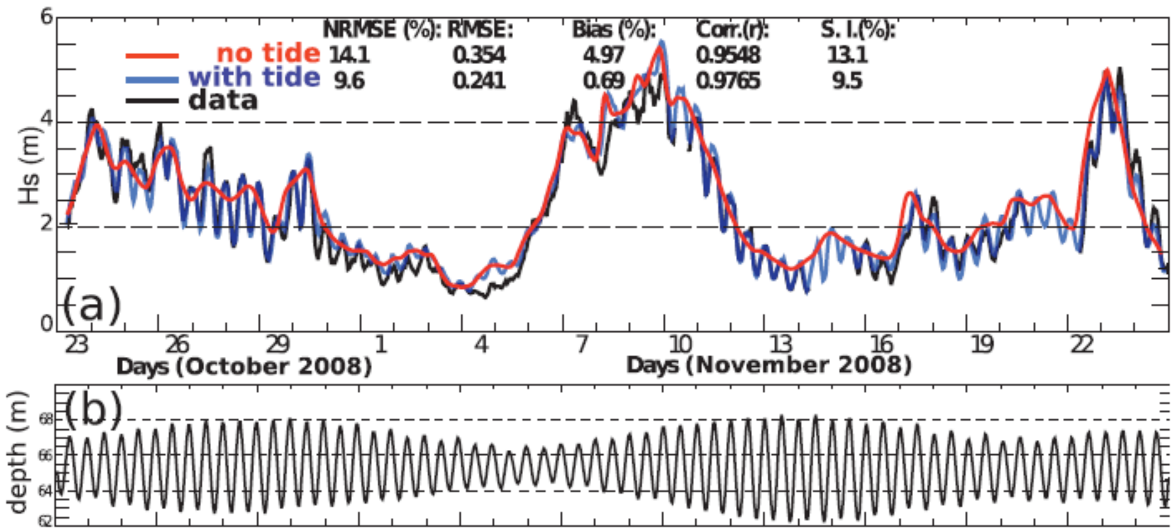

Figure 1: (a) Typical time series of wave heights at the buoy 62069 (also known as « Pierres Noires » located 20 km west of the entrance to the Bay of Brest, in 50 m depth. The observed values are represented by the black solid line. Two model results are shown, one including forcing by tidal currents (semitransparent blue), and the other without currents (red). (b) Modeled water level at the buoy, indicating the phase of the tide. Taken from Ardhuin et al. (2012).

Coupled circulation and waves in three dimensions

Following the theoretical foundation laid in the previous decade (McWilliams et al. 2004, Ardhuin et al. 2008), the investigation of wave-induced currents in three dimensions has entered the age of practical and even operational applications. This effort has been driven by needs for predicting pollutant transport either in deep water, where the near-surface shear is dominated by the Stokes drift, all the way to the beach with water quality issues related to fecal bacteria or harmful algae. Particular difficulties remain for the formulation of a mixing scheme for phase-averaged waves and currents (e.g. Teles et al. 2013). Still, coupled 3D models have been successfully applied to coastal areas (Michaud et al. 2012) and a semi-closed stratified bays (Delpey et al. 2014). In that latter case, it was found that wave-induced momentum and mas fluxes had a strong influence on the flushing time of the 1-km diameter bay of Saint-Jean de Luz, with very different responses of the freshwater budget in 2D and 3D.

Infra-gravity waves

Although the details of the generation processes of infragravity waves at the shore at strongly debated, the investigation of water levels at small scale and the puzzle of the seismic hum sources have led Ardhuin et al. (2014) to propose a robust parameterization for free wave generation at the shoreline. Using this, the model WAVEWATCH III (Tolman et al. 2014) was extend to low frequencies and was used to demonstrate that infragravity wave bursts off the coast of Japan originate on the U.S. West coast (Rawat et al. 2014). The same model was also used to show that the propagation of infragravity waves over a sloping bottom can explain the measured low frequency seismic noise known as hum (Ardhuin et al. 2014). This is illustrated in figure 2.

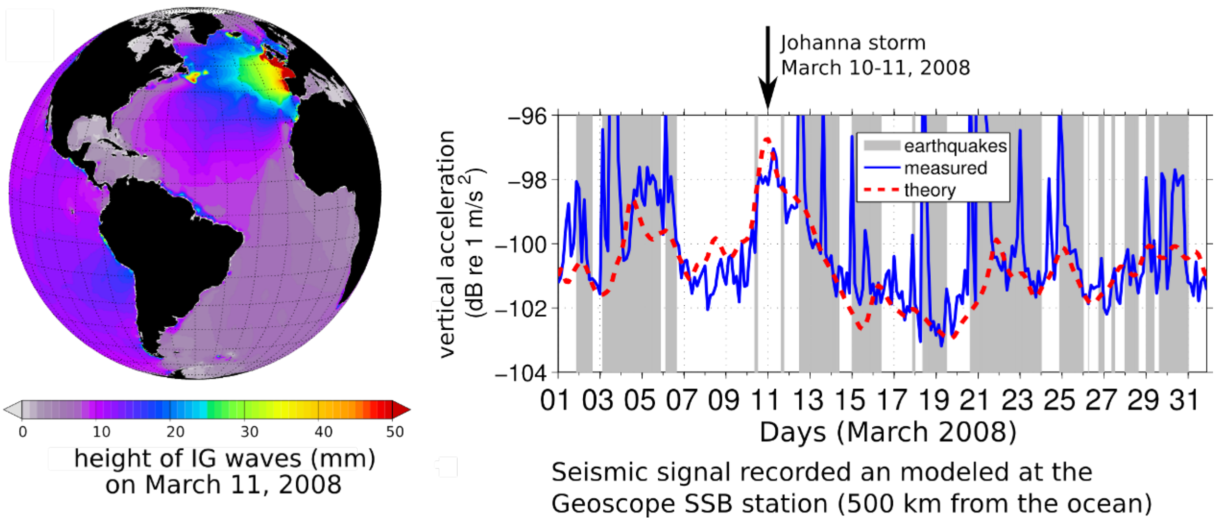

Figure 2: the March 11 event is the second most energetic infragravity wave envent for 2008 in the North Atlantic. The (short) wave heights at the coast exceeded 11 m with peak periods up to 25 s. This event occurred during an "earthquake-free" window and is thus clearly identified in seismic records throughout western Europe.

Short wave properties and remote sensing

One of the difficult problems in the solutions of the WAE is to arrive at a proper balance in the short wave region (around 1 m wavelength) both in terms of energy and also in terms of its directional distribution. Parameterizations available today either assume the energy level, say proportional to the inverse fifth power of the frequency, or make assumptions on the dissipation processes. These generally fail to produce a proper energy level, and generally produce a too narrow spectral distribution. Since these short waves carry most of the wind stress, a better reproduction of the short wave spectrum is necessary to arrive at a consistent definition of the air-sea momentum flux. Also, these short waves respond most strongly to current gradients, both divergence and shear (e.g. Kudryavtsev et al. 2005, Rascle et al. 2014), and they produce patterns in images of the sun glitter or in radar backscatter images. Understanding these responses thus offers a unique method to measure surface currents at near-kilometer resolution. A series of in situ experiments in strong current shears is under way to test the shear-to-wave-gradient transfer function. A first deployment was performed in September 2014.

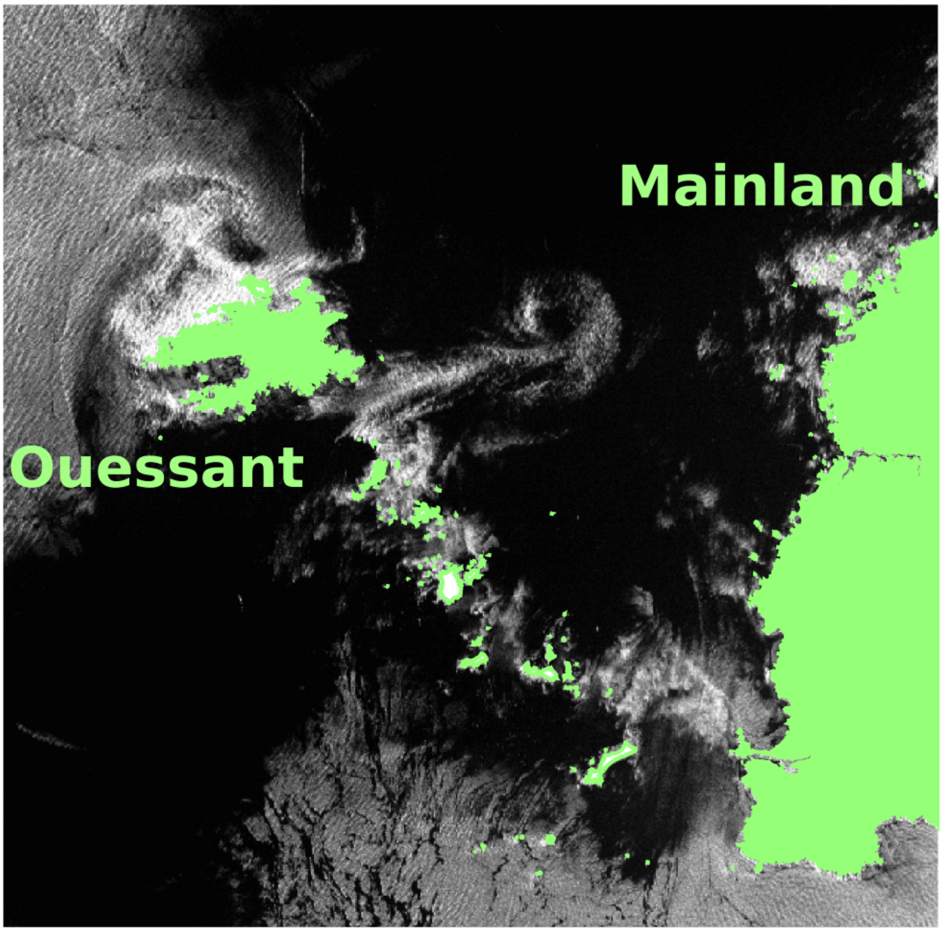

Figure 3: Piece of a SAR image acquired by Sentinel-1A on September 1st, 2014. White regions correspond to stronger backscatter (higher roughness). Regions with no wind at all or with slicks appear in black. The strong tidal currents around the island of Ouessant produce various patterns in surface roughness: roughness fronts to the west of the island, and a nice “roughness mushroom” in the region of strong currents the east of the island.

Wave-ice interactions

Another area of intense research is the interaction of waves with sea ice, which defines the marginal ice zone, with specific ice rheology properties that can shelter the pack ice from the wave-induced breaking of the ice. Until recently, the quantitative analysis of wave properties in the ice required expensive and difficult in situ missions (e.g. Kohout et al. 2014). The analysis of SAR data from ESA's latest Sentinel 1A satellite has shown that it was possible to measure wave heights in the ice from space, with a very high sensitivity (Ardhuin et al. 2015). The combination of this technique with planned in situ experiments will certainly provide a wealth of data to better understand the dissipation and scattering of waves in the ice, allowing a more accurate modelling of the marginal ice zones.

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EPIGRAM, understanding the ocean dynamics along the french coasts

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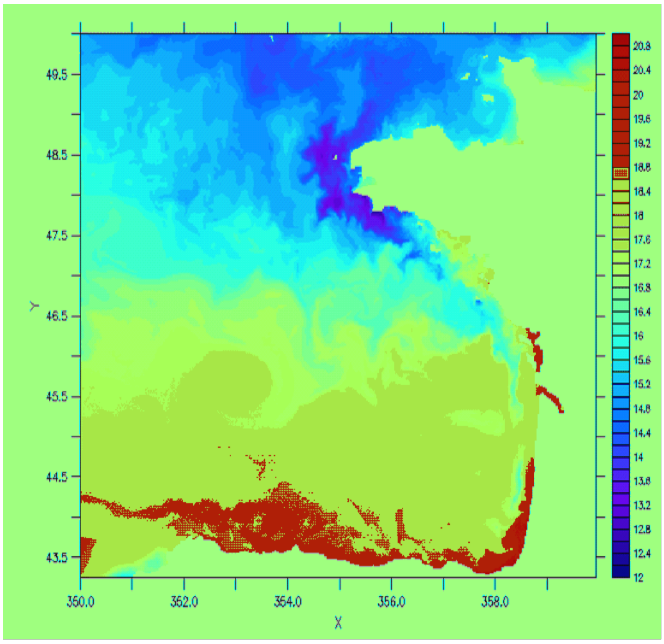
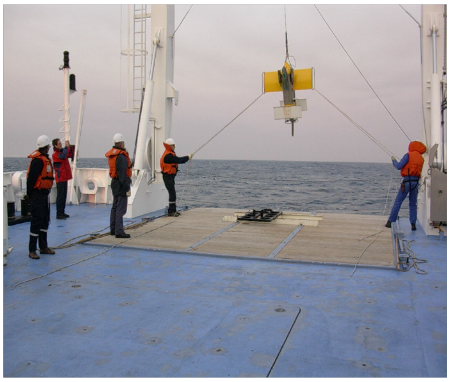
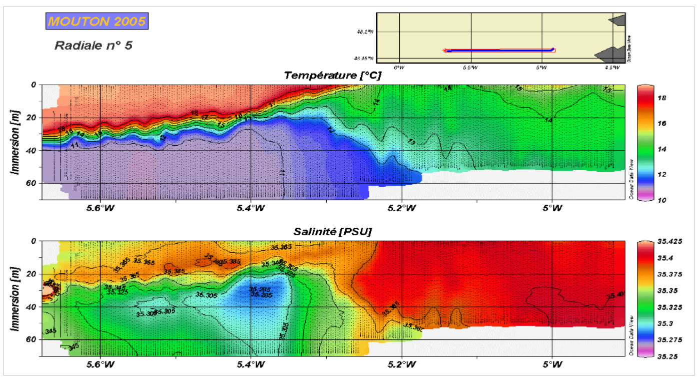


Sea surface temperature in june (result from a realistic numerical model).



Operation (SEASOAR) on board the Beautemps-Beaupré oceanographic vessel.



vertical section of temperature and salinity accross the Ushant front (MOUTON/FROMVAR campaigns).

Scientific objectives and society challenges

The scientific objectives of the EPIGRAM project are :

- the realisation of campaigns at sea and the collection of data in the bay of Biscay and the Manche (english Channel);
- the scientific analysis of the collected data (furniture of diagnostics for selected processes).
- the validation of realistic numerical models of the area ;
- improving our understanding of the major physical processes of the area.

The results obtained during the project are of major importance for the scientific community: the project allowed to gather observations at sea over an area where the evolution is driven by many different physical mechanisms. Previous campaigns of such importance over the region date back to 20 years ago. In addition, EPIGRAM permitted to develop, validate and improve realistic numerical model used for operational applications, such as :

- the drift of objects, oil spills or other pollutions;
- search and rescue operations at sea;
- the production of energy from marine origin (tide, waves, currents, thermal, …);
- the coupling of the physics with biogeochemistry for the survey of marine ecosystems, and the development of data assimilation techniques to improve the realism of the systems.

General organisation

The project is organized in 5 major scientific themes, linked with the major physical mechanisms driving the dynamics of the bay of Biscay and the Manche. About 30 specific studies have been identified and carried out concerning :

- the effect of tides ;
- internal tides ;
- seasonnal processes for the dynamics at large scale and the exchanges of water masses between the coastal and the open ocean ;
- influence of the atmospheric forcings and of river plumes on the shelf dynamics ;
- influence of waves on the coastal circulation.

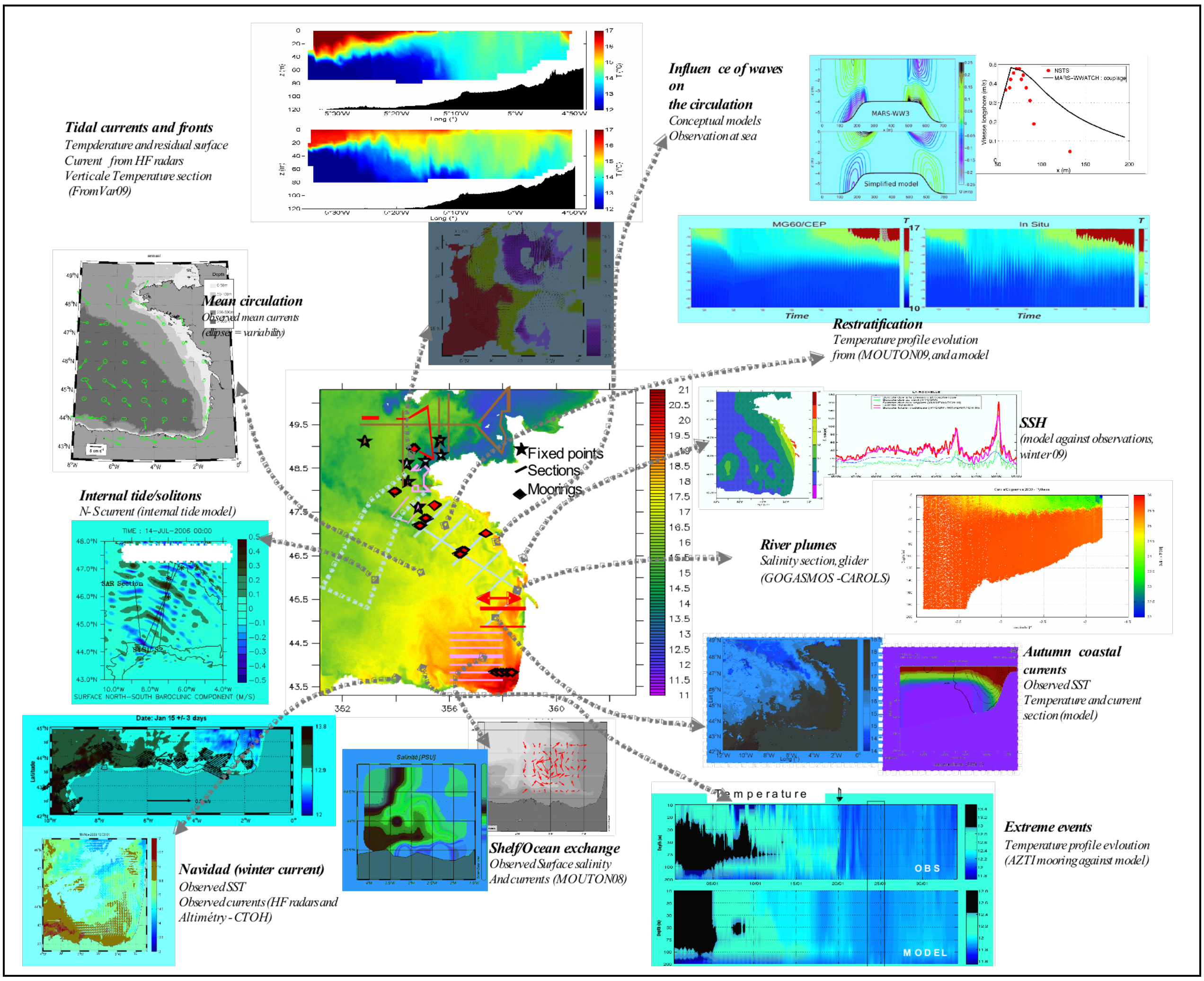
Scientific results and applications

The project was carried out between january 2009 and december 2013. It yielded :

six major campaigns at sea, some of which resumed for several years, cumulating more than 100 days at sea for data collecting and technological studies ;

all identified physical processes have been observed and studied with an imporved general understanding of the dynamics in the area ;

- the organization of the scientific community around a common objective ;
- realistic models, with pre-operationnal tests and applications (PREVIMER, MyOcean, french Navy operational system, immersion alert system), ready to be exploited ;
- 40 scientific publications in international scientific journals and 7 PhD thesis.



Participation and funding

EPIGRAM is a fundamental research project which allowed a better understanding of the dynamics in the bay of Biscay and the Manche. It gathered 13 public laboratories publics depending on 5 institutions (CNRS, Ifremer, MétéoFrance, SHOM, Universities). The project was funded by ANR and received 490.000,00€. The total amount of the project is evaluated around 7.000.000,00€.

Spontaneous emergence of low-frequency variability in the GLOBAL EDDYING Ocean

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Abstract

Oceanographers are studying the ability of the global turbulent ocean to generate chaotic variability at climate scales (1-90 years) spontaneously, i.e. without atmospheric variability beyond the annual timescale. Building on previous idealized studies, high-resolution global ocean/sea-ice simulations reveal in a realistic context the intensity and complex structure of this phenomenon, raising the question of its origin, its possible impact on climate, and the actual constraint exerted by the atmosphere on the oceanic variability.

Introduction

So-called mesoscale eddies are ubiquitous in the ocean, and are well-known examples of small-scale (from a few tens or hundreds of kilometers, from weeks to months) intrinsic ocean variability: they emerge from the instability of the main currents without any atmospheric variability. This mesoscale variability is highly chaotic: just as their atmospheric counterparts, oceanic cyclones and anticyclones are turbulent, which makes their evolution difficult to predict. Idealized ocean simulations have also shown that under certain conditions, the non-eddying general ocean circulation may develop intrinsic variability at much larger scales (up tu multiple decades, at basin-scale), under constant or purely seasonal atmospheric forcing (e.g. Dijkstra & Ghil, 2005; Sushama et al, 2007; Shimokawa & Matsuura, 2010). Ongoing research making use of state-of-the-art eddying ocean general circulation models shows that the low-frequency variability of the ocean circulation (at timescales of years to decades) also has a partially chaotic (i.e. stochastic) character, at spatial scales reaching thousands of kilometers.

Low-Frequency Intrinsic Variability (LFIV)

A numerical model of the global ocean and sea-ice, developed by the DRAKKAR consortium, was used in 2008 to simulate the 3-dimensional evolution of the general circulation and mesoscale during 327 years at high resolution (¼ ° horizontal mesh, i.e. 10-25 kilometers). This simulation was forced climatologically: it was driven every year by exactly the same atmospheric mean annual cycle (solar radiation, wind, air temperature and humidity, etc). Despite the absence of any atmospheric fluctuation slower that one year, this virtual ocean spontaneously produced a strong variability of currents and water masses, with timescales reaching several decades. The imprint on sea-surface height of this oceanic Low-Frequency Intrinsic Variability (LFIV) was described in the global realistic setup by Penduff et al (2011), focusing on interannual timescales and on comparisons with altimeter observations. Various features of this phenomenon were consistent with previous idealized studies.

Figure 1 summarizes a few results from subsequent studies (Sérazin et al, 2015; Grégorio et al, 2015) conducted within the CHAOCEAN project supported by CNES and NASA; the estimated percentage of low-frequency oceanic variance due to LFIV is shown for 4 variables. When mesoscale turbulence is simulated (horizontal resolutions of ¼° or 1/12°), this percentage locally reaches 80-100% for sea-surface height and temperature (50-80% for large scales), in particular around Antarctica and mid-latitudes western boundary currents. The low-frequency variability of the Atlantic Meridional Overturning Circulation (AMOC) intensity and of the associated heat transport is also substantially impacted by LFIV around 30°S (around 50% and 25% of their variance, respectively). This AMOC LFIV has scales reaching several decades and the size of the whole Atlantic basin. These results are consistent with idealized simulations and provide new information about the LFIV's actual intensity and structure in a realistic context. In regions where this percentage exceeds 50%, the nonlinear oceanic processes resolved in ¼° and 1/12° simulations thus account more than the atmospheric low-frequency fluctuations in the production of low-frequency variability. The processes at work are currently being studied in collaboration with dynamicists (e.g. Huck et al, 2015 ; Arbic et al, 2014).

The possible "climatic" relevance of these results may be summarized in two points. The LFIV is virtually nonexistent when mesoscale is not resolved, such as in 2°-resolution laminar ocean models (see the red line corresponding to the AMOC, Figure 1) that were largely used in recent climate projections. Moreover, the strong LFIV emerging in eddying ocean models with climatological forcing has an irregular and intermittent behavior; this low-frequency oceanic "noise" has an imprint on large-scale surface temperatures (Figure 1) in regions where air-sea fluxes are strongest in Nature, and may therefore influence the atmophere and climate in future coupled climate projections (which will use ¼° ocean models). This potential impact remains to be assessed, but the presence of oceanic LFIV will likely increase the complexity and richness of future projections.

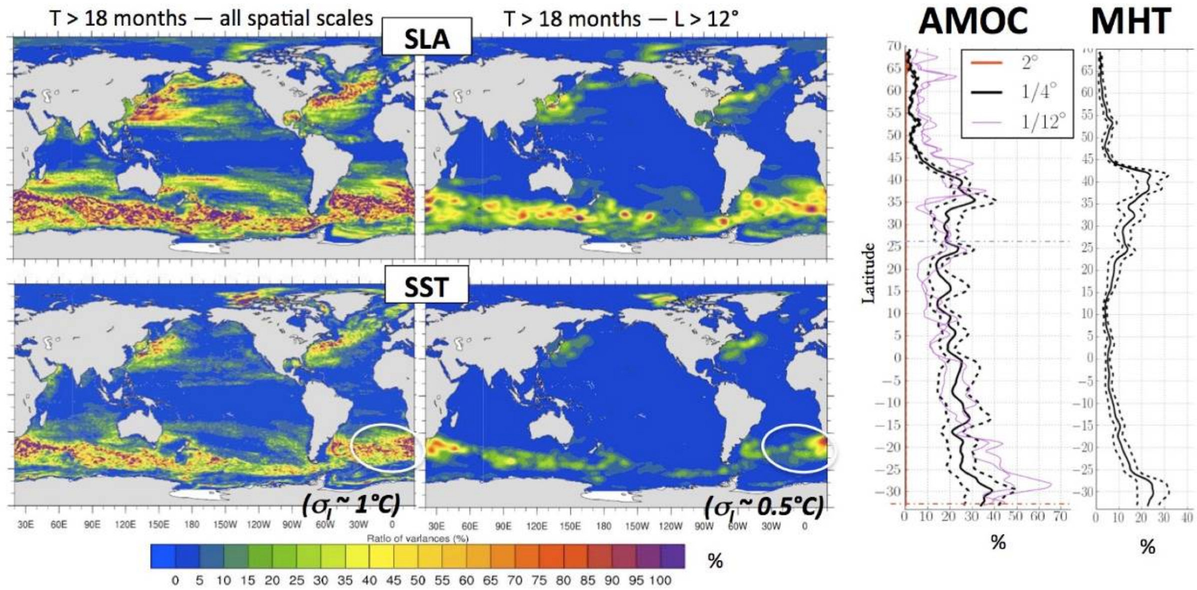

Figure 1: Percentage of interannual variance (1 to 11 year timescales) due to intrinsic processes. Maps are derived from ¼° simulations and correspond to sea-level (SLA, top) and sea-surface temperature (SST, bottom), considering all resolved spatial scales (left) and scales larger than 1000 km (right). Right panels show the same percentage in the Atlantic for the overturning circulation intensity (AMOC) and the associated heat transport (MHT) ; AMOC results are given for 2°, ¼° and 1/12° global simulations (Sérazin et al, 2015 ; Grégorio et al 2015)

Ensemble simulations

These results raise oceanographic questions as well: is the emergence of LFIV in the turbulent regime able to make the low-frequency oceanic variability less deterministic than we thought? May small perturbations or uncertainties in initial oceanic conditions grow, evolve and organize themselves over yearly or decadal timescales? What then are the respective imprints of chaotic LFIV and atmospheric variability on the ocean variability measured by satellites and in-situ instruments? To address these questions and anticipate the analysis of future coupled simulations, oceanographers and climatologists from LGGE and CERFACS are preparing a turbulent ocean/sea-ice ensemble simulation, the first of its kind. In 2015, fifty ¼° global ocean/sea-ice simulations will be performed in parallel over the period 1958 to 2014, after a slight perturbation of their initial states. The main objectives of this ANR project (OCCIPUT) supported by a PRACE computational allocation, is to examine in detail the structure and evolution of the ensemble mean (deterministic) and ensemble dispersion (chaotic) of key quantities, and to identify the variables and regions where the LFIV dominates that forced by the atmosphere.

A prototype of this global 57-year simulation, consisting of 10 members integrated between 1993 and 2012 in the North Atlantic, has recently provided original results. Figure 2 shows the sea-surface temperature (SST) interannual variability (1993-2000) forced by the atmosphere (left), generated by intrinsic variability in 2000 (middle), and the ratio of these two fields (right). Like Figure 1, this third panel shows that along the Gulf Stream extension, near Newfoundland and Norway, chaotic intrinsic processes generate more interannual SST variability than the atmospheric interannual variability does. Ongoing analyzes indicate that these contributions depend on depth, on the variable considered, and fluctuate temporally. The 50-member ensemble simulation planned in 2015 is presented in more detail in Penduff et al (2014): it will allow us to quantify more precisely the impact of this chaotic phenomenon in the global ocean, up to decadal scales, and its modulation by the low-frequency forcing.

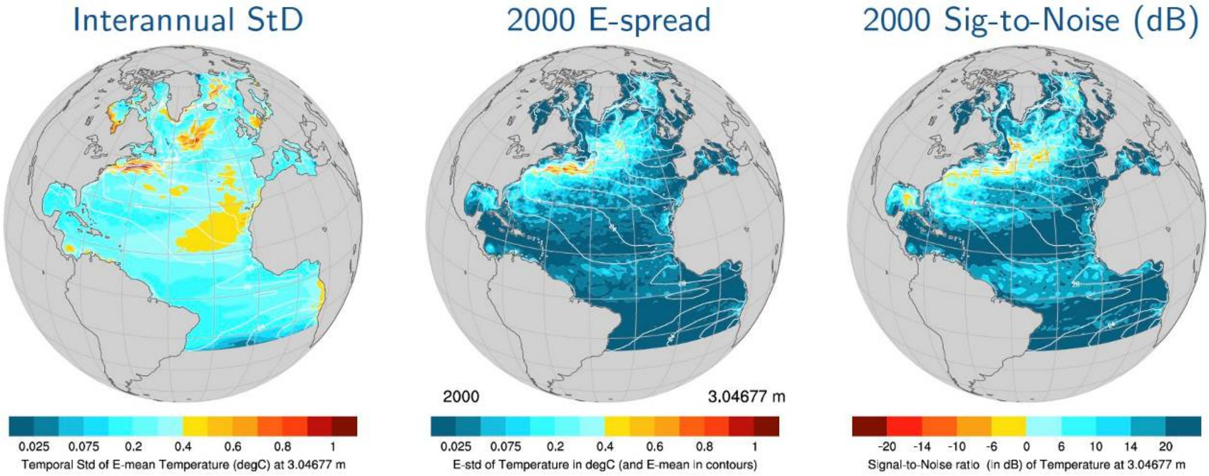

Figure 2: Atmospherically-forced and intrinsic interannual variability of sea-surface temperature (SST) from the OCCIPUT regional prototype (10 ensemble members). Colors show the interannual standard deviation of the SST ensemble mean over 1993-2000 (variability forced by the atmosphere or "signal", left); the ensemble standard deviation computed from the 10 SST fields averaged in 2000 (LFIV in the middle); the signal-to-noise ratio in decibels (right; the interannual variability is mostly intrinsic in yellow and red areas). Contours: SST ensemble mean averaged over 1993-2000 (left panel) and in 2000 (middle and right panels).

Acknowledgements

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Dansgaard-Oeschger cycles

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Measurements of oxygen isotope ratio in air bubbles trapped in Greenland ice cores have revealed the presence of large climate shifts, known as Dansgaard-Oeschger events (DO hereafter), that are ubiquitous during the past 8 glacial cycles (Loulergue et al. 2008). These dramatic events are associated with strong (8-16°C) and rapid (decadal) warming of the high latitudes climate of the North Atlantic (Fig. 1). The sequence of the events starts with an abrupt warming followed by a plateau phase (interstadial) which lasts several centuries, and an abrupt decline back to cold (stadial) conditions. Then the climate slowly warms until a new abrupt warming event occurs to complete a cycle in a period of about 1,500 years. Interglacial periods by contrast are more stable and do not exhibit such abrupt climate shifts. Of course, observations remains too sparse both in time and space to provide a quantitative understanding of the physical mechanisms at play. Nevertheless, the relatively long time scales involved in these climate variations suggest a potential role of the deep ocean circulation: if we divide the volume $V=4\times10^{17}$ m^3 of the Atlantic basin by the strength Ψ=15 Sv of the Atlantic Meridional Overturning Circulation (AMOC), an advective timescale of about 1000 years emerges. However a number of physical mechanisms allowing quasi-periodic transitions between different modes of operation of the AMOC have been proposed. Among them one must distinguish between those where abrupt millennial climate shifts result from changes in external forcing (e.g freshwater cycle, solar cycle) from those where either internal instabilities of the large-scale ocean circulation or nonlinear sea ice – ocean - ice sheet interactions play a fundamental role.

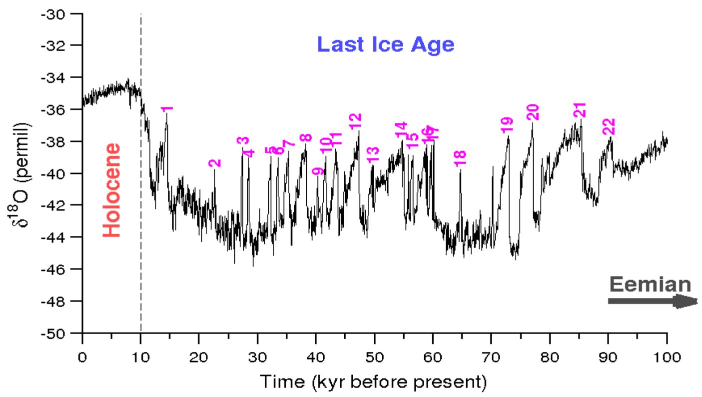

Fig. 1 Time-evolution of GRIP ice core $\delta^{18}O$. The peaks represent DO events. Warmer climates are associated with higher $\delta^{18}O$.

External causes mostly point to calving due ice-sheet instabilities that can deliver massive amounts of meltwater to the North Atlantic ocean, and therefore strongly perturb the ocean circulation and ultimately the northward heat transport that contributes to the maintenance of the climate. It is however not clear whether these massive icebergs discharges are a cause or a consequence of changes in the AMOC. Following this idea, abrupt transitions between warm interstadials and cold stadials have first been obtained in ocean climate models in response to imposed periodic fluctuations in freshwater forcing, but only when the magnitude of the forcing is large enough (Ganopolski and Rahmstorf, 2001). The origin of the 1,500 yr periodicity was left unspecified but it was suggested that it might be related to solar forcing as suggested by Braun et al. (2005) for instance. Muscheler and Beer (2006) did not however find any convincing persistent solar influence on DO cycles. An alternative mechanism called stochastic resonance, a process that results from the combination of a small periodic forcing and noise, was proposed to explain the origin of DO cycles (see Monahan et al. (2008) for a critical review of this theory). On different grounds, Timmermann et al. (2003) argued that the absence of abrupt millennial oscillations during interglacial periods is intimately linked to the absence of the Laurentide ice-sheet during those periods. They suggested that DO events are the joint result of stochastic forcing and Heinrich events through the coherence resonance mechanism, and offered thus a dynamical basis to explain the observation that Heinrich events are followed by a series of DO cycles. Interactions between the large-scale atmospheric circulation and ice-sheet topography has also been proposed as a candidate for DO events (Wunsch 2006).

By contrast, a number of studies conducted with models varying in complexity from conceptual to intermediate have revealed internal instabilities of the AMOC on millennial timescales without the need for either time-varying external forcing, atmospheric noise or ice sheet-ocean interaction. It is thus on this specific ground that A. Colin de Verdière, O. Arzel and co-authors have developed a new theory, published in a series of 6 papers between 2006 and 2013, that has contributed to elucidate the question as to why the AMOC during cold glacial periods is less stable than during warm interglacials. In this context, the authors propose that the origin of DO cycles is intimately linked to the coolness of the climate which ultimately reduces the oceanic heat transport through the temperature stratification. In what follows, a brief history of the mechanisms upon which this idea has been developed is presented.

Winton (1993) was the first to obtain abrupt millennial variability using an idealized ocean model. The "deep-decoupling" oscillations thus simulated feature the sawtooth shape profile reminiscent of DO cycles and are characterized by a deep-coupled (advective) phase with strong meridional circulation and heat transport, and a deep-decoupled (diffusive) phase with reduced meridional circulation and heat transport. In this scenario, the heat accumulated for centuries in the deep ocean during the weak phase of the oscillation is released on a short time period to the atmosphere through a convective instability of the polar water column. In such a mechanism, which requires both advective and convective processes, the circulation oscillates between two *unstable* states. This is very different from oscillations resulting from periodic changes in freshwater forcing (e.g. Ganopolski and Rahmstorf, 2001) that require only advective processes, and can as such be easily reproduced in the Stommel (1961) box model where only advective processes are present and the circulation oscillates between two *stable* states. When convection is added to the Stommel box model, DO type oscillations emerge naturally and Colin de Verdière (2006, 2007) was able to extract and rationalize the bifurcation sequence of these deep-decoupling oscillations with the freshwater forcing as the main control parameter. If the freshwater forcing is strong enough and polar precipitation low enough, the circulation experiences abrupt climate shifts on millennial timescales. Since climate reconstructions suggest weaker hydrological cycles during glacial periods, in agreement with what is expected from the Clausius-Clapeyron equation, this theory implies that the stability of glacial climates would be higher than that of interglacials. However glacial climates are punctuated by major

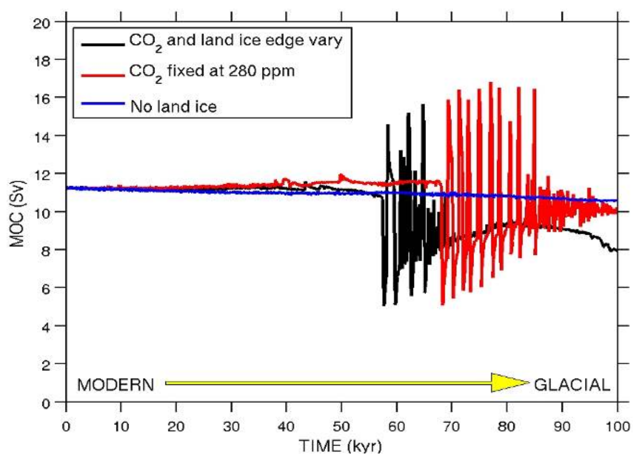

Fig. 2 Time series of the maximum strength of the MOC simulated by the UVic model (idealized geometry) when both the atmospheric CO2 concentration and the land ice edge in the Northern Hemisphere (black line) slowly evolve, over a 100,000-yr years period, from warm (CO2=280 ppm; no land ice) to cold climate conditions (CO2=200 ppm; land ice edge at 50°N). The red line shows the MOC response when the atmospheric CO2 concentration is fixed to its modern value, while the land ice edge slowly moves southward from the northern domain boundary (i.e., 84°N) to 50°N. The blue line shows the AMOC response when land ice is absent and when the atmospheric CO2 concentration slowly decreases from its modern to its glacial value. From Arzel et al. (2010).

reorganizations on millennial timescales while warmer interglacials, such as the actual Holocene, are characterized by a remarkable placidity. Therefore if deep-decoupling oscillations are to be the key to observed DO oscillations, another source of instability than the freshwater forcing per se must necessarily be at play. A first possibility emerged when Winton (1997) showed that cold climates are indeed less stable than warm climates. The nonlinearity of the seawater equation of state was shown to be the source of the instability: a weaker thermal expansion coefficient at lower temperatures implies a stronger sensitivity of polar waters to freshwater forcing. By contrast, using a linear equation of state, Loving and Vallis (2005) reproduced DO type oscillations in an idealized ocean-atmosphere-sea ice model for sufficiently cold background conditions. Here the control parameter was atmospheric infrared emissivity rather than freshwater forcing.

The origin of the oscillations obtained by Loving and Vallis (2005) was unraveled by Colin de Verdière and te Raa (2010) with a help of a simple 2D model. It was shown that it is the weakening of the oceanic heat transport, which is the major regulator of the circulation, under cold background conditions that is the key to the existence of such instabilities. A weaker northward heat transport is achieved because of the weaker temperature stratification induced by surface cooling, the temperature of the deep ocean remaining close to that of polar surface waters lying at proximity of the sea ice edge. Imagine that the circulation weakens, then the sea surface temperature gradient increases to bring the circulation back on track. The ability of the circulation to resume therefore depends on the ability of the AMOC to transports heat northwards. Climates with weaker Atlantic northward heat transport tends therefore to be associated with less stable AMOC, and are therefore prone to abrupt millennial variability. This is particularly obvious when the climate slowly cools from warm to cold background conditions (Fig. 2). This experiment, conducted with the UVic coupled (ocean-atmosphere-sea ice) model set-up in an idealized Atlantic geometry, further indicates that the existence of millennial oscillations primarily depends on the land ice extent (ice-sheet), with the CO2 levels playing a secondary role (Arzel et al. 2010). Climbing a step further up in the model hierarchy, Arzel et al. (2012) reach the same conclusions using a realistic geometry of the UVic coupled model (Fig. 3). The comparison of the bifurcation structure of the AMOC between climates using different background conditions clearly indicate that the existence of DO-type oscillations (Fig. 4) in the model is intimately related to the strength of the northward oceanic heat transport in the Atlantic basin (Fig. 5). More recently, Arzel and England (2013) showed that wind-stress feedback is an efficient amplifier of abrupt millennial variability, through ocean-atmosphere-sea ice interactions. Of course, which physical mechanism lies at the heart of the existence of glacial variability is unknown. Much modeling effort will be needed to determine if any of the mechanisms discussed here could present any relevance for glacial climate variability. Testing the robustness of the newly developed theory in climate models of increasing complexity would certainly be very informative.

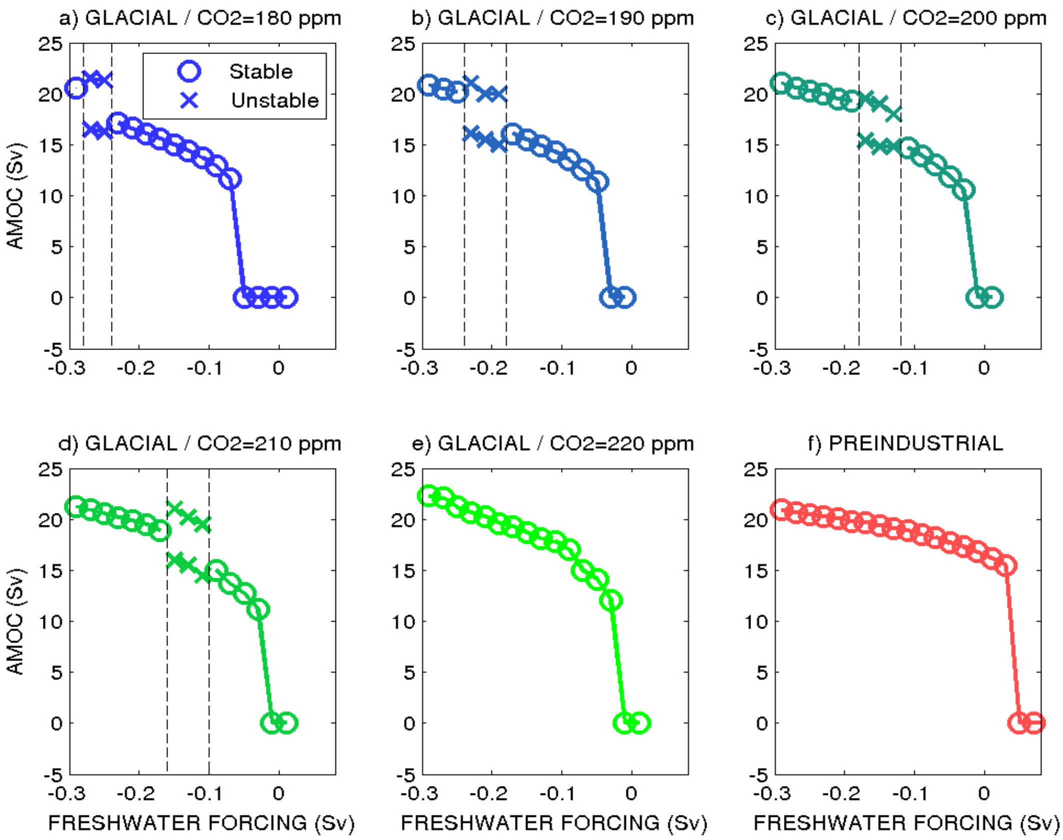

Fig. 3 Range of background climate states for which abrupt millennial-scale climate transitions between two *unstable* states (indicated by crosses) of the AMOC. Glacial climates used ice-sheet topography at 19 kyr BP. The stability of the circulation is assessed in terms of CO2 levels and strength of the surface freshwater forcing (a globally-compensated freshwater anomaly is superimposed to the simulated freshwater forcing in the 20-50°N latitude band over the Atlantic ocean). Both the preindustrial and the warmest glacial climates are stable, while the other ones exhibit DO-type oscillations in a range of freshwater forcing. From Arzel et al. (2012).

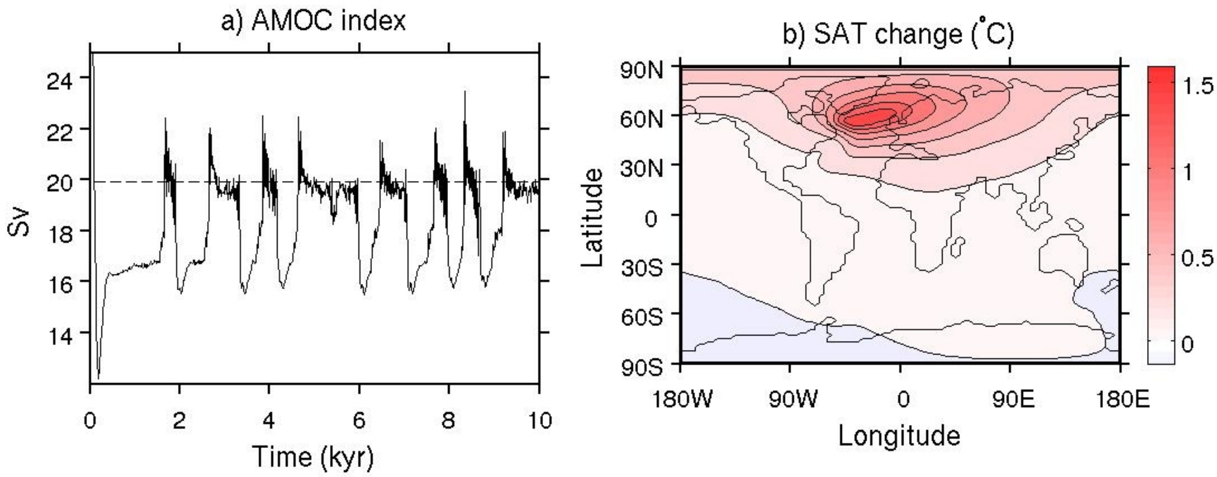

Fig. 4 Timeseries of the strength of the AMOC (Sv) in a numerical simulation of the UVic model showing abrupt millennial oscillations (left) and surface air temperature change during an abrupt event (right). The relatively weak changes in sea ice extent during a stadial-interstadial transition could explain the relatively weak SAT change compared to those observed. This could be (at least partly) due to the absence of change in surface wind-stress in the model. This aspect has been explored by Arzel et al. (2013). From Arzel et al. (2012).

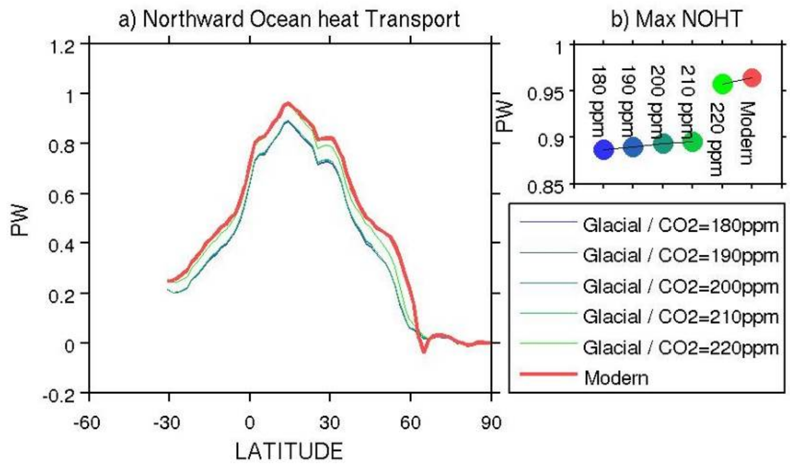

Fig. 5 Comparison of Atlantic northward heat transports between different climates (the same freshwater forcing is used, i.e. -0.29 Sv, see Fig. 3). The upper right panel highlights an abrupt transition in the maximum heat transport. This transition marks the limit between climate states exhibiting DO-type oscillations and those that are stable (see Fig. 3). From Arzel et al. (2012).

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On the Reference Level Problem in Oceanography

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As is well known, the determination of the large scale geostrophic circulation from hydrology (temperature-salinity distribution) is incomplete and requires the knowledge of the velocity field or geopotential at one level, the so called level of reference. Lacking this at ocean basin scales, a number of assumptions have been used in the past to provide inverse solutions such as minimum kinetic energy at the reference level, quasi-adiabatic flows, Sverdrup balance, conservation of large scale potential vorticity to name just a few (see Wunsch, 1996). Nowadays adjoint methods allow to integrate data from very different nature into fluid mechanics model equations producing time dependent three dimensional large scale oceanic flows (see .e.g. Mazloff et al., 2010 with results from the ECCO MIT model).

However with the increasing space-time coverage of Argo float displacements, new direct methods are now possible. Indeed a high quality data base of float displacements, named ANDRO has been generated by Ollitrault and Rannou, 2013 from which it is possible to infer the time mean circulation of the World Ocean on 1^o x 1^o squares around 1000 dbar with unprecedented details (see Ollitrault and Colin de Verdière, 2014 for an extended description). Now to use that information to provide a reference level and obtain the full three dimensional circulation with the help of the temperature-salinity distribution has required a novel approach. The question is to find out how to obtain the geopotential from the time mean velocity fields. Away from the tropics, both are linked by the geostrophic relation:

$$\begin{aligned} -\mathrm{fv} &= -\frac{1}{\mathrm{a}\cos\theta}\frac{\partial\Phi}{\partial\lambda} \quad \text{(a)} \\ +\mathrm{fu} &= -\frac{1}{\mathrm{a}}\frac{\partial\Phi}{\partial\theta} \quad \text{(b)} \end{aligned} \tag{1}$$

where Φ is the geopotential of the relevant pressure surface (here typically 1000 db), λ is longitude, θ is latitude, a is the earth radius assumed constant (a = 6370 km) and $f = 2\ \Omega\ \sin\theta$ is the Coriolis parameter. In this isobaric formulation the derivatives on the right are carried out at constant pressure. Taking the curl of (1) gives:

$$\frac{\partial(\mathrm{fu})}{\partial\lambda} + \frac{\partial(\mathrm{fv}\cos\theta)}{\partial\theta} = 0 \qquad \text{or} \qquad \nabla_H \cdot (f \cdot \mathbf{u}) = 0 \tag{2}$$

with the horizontal divergence in spherical coordinates given by:

$$\nabla_H \cdot (...) = \frac{1}{\mathrm{a}\cos\theta}\left[\frac{\partial}{\partial\lambda}(...) + \frac{\partial}{\partial\theta}(\cos\theta ...)\right]$$

The naïve use of equation (1a) to get Φ by integrating zonally the v velocity introduces a constant of integration function of θ. To get that function of θ, equation (1b) is used in turn but for this method to work, a compatibility condition is required which is precisely that (2) be satisfied, but unfortunately it is not… Why? Although individual float displacement which represent ten days nominal average of the velocities are geostrophic to a good approximation, there is little hope that the time mean velocities satisfy this consequence of geostrophy represented by equation (2). There are two reasons for this: first (2) is a vorticity equation which has an accuracy inferior to the Rossby number accuracy of (1) and second the number of float days in each square box to compute the time averages is inhomogeneous as it varies from a few months to several years. Because of this underlying inhomogeneity, the divergence of the ANDRO mean velocity fields is O(U/Δx) while the divergence from (2) is smaller of O(U/earth radius) only. It is therefore not possible to use the equations (1) as they stand to get Φ.

To obtain the geopotential ϕ from the velocity fields, the solution developed by Ollitrault and Colin de Verdière, 2014 has been to take the divergence of equations (1). By differentiating (1a) × cos θ with respect to λ and (1b) with respect to θ, one obtains:

$$\frac{\partial^2\Phi}{\partial\lambda^2}+\frac{\partial^2\Phi}{\partial\theta^2}=a\left[\frac{\partial(fv\cos\theta)}{\partial\lambda}-\frac{\partial(fu)}{\partial\theta}\right] \tag{3}$$

This equation is nothing but a special form of the divergence of the horizontal momentum equation which is at the heart of quasi-geostrophic inversions from vorticity to stream function. An important difference with quasi-geostrophy, however, is that here the geopotential is not a streamfunction since the flow is horizontally divergent [see (2)]. Equation (3) is the equation of balance for planetary geostrophic dynamics. It has been mentioned first by Charney, 1955 in the context of numerical weather prediction. The regimes of validity of this equation have been discussed by Gent and McWilliams (1983) who show that it conserves the Rossby number accuracy of the momentum equations. This Poisson equation requires boundary conditions at the edges of the domain under consideration. Near solid boundaries, the geostrophic relation becomes a poor approximation for the velocity component *normal* to the coast. Since it goes to zero at the coast, there is no Coriolis force left to balance the along shore pressure gradients and non linear terms must be considered. On the other hand the velocity along the coast can still be assumed geostrophic to a good approximation. Indeed the Florida and Gulf Stream transports have been estimated early using cross-shore hydrographic sections (Wüst 1924 e.g.). Thus if **n** is the outward unit normal at the edge of the domain and **s** the tangential vector such that **s** = **k** × **n**, (with **k** the upward unit vector), the appropriate geostrophic boundary condition to be used in conjunction with (3) reads:

$$\tilde{\nabla}\Phi\cdot\mathbf{n}=\mathbf{u}^*\cdot\mathbf{s} \tag{4}$$

with $a\cdot\tilde{\nabla}=(\frac{\partial}{\partial\lambda},\frac{\partial}{\partial\theta})$ and $\mathbf{u}^*$ = (fu, fv cos θ).

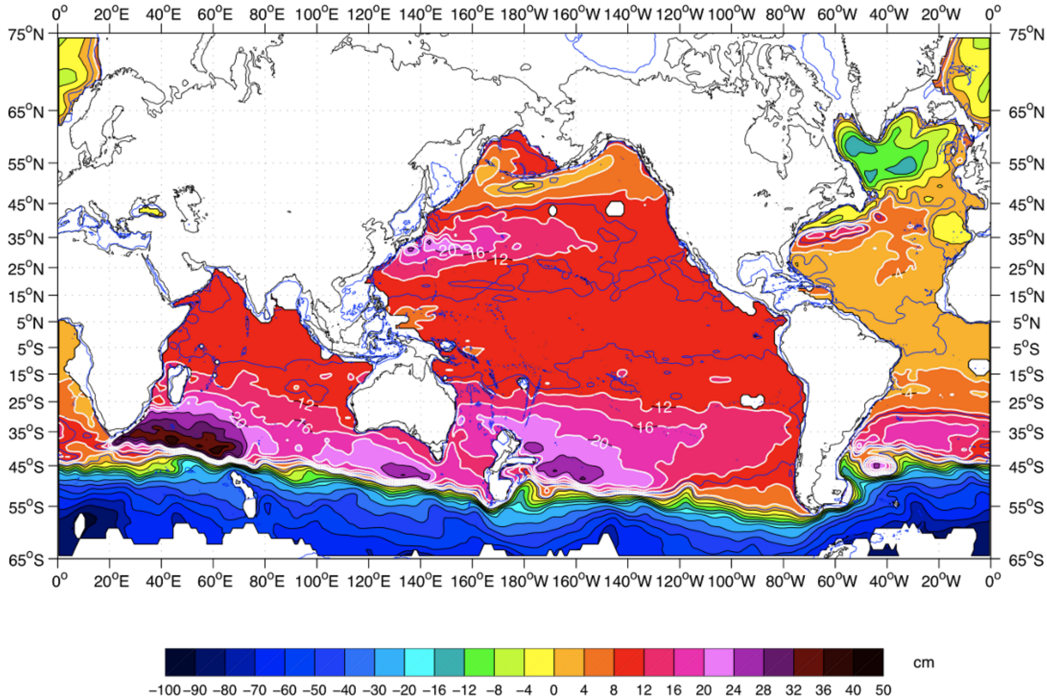
The condition (5) is a Neumann type boundary condition for the elliptic Poisson problem (3). Observed along coast velocities are used to find the normal pressure gradient that is imposed to the interior. Imposing instead a Dirichlet condition, that is a constant geopotential would assume that geostrophy remains valid for velocities normal to the coast, which is generally not true. The solution is defined up to an arbitrary constant provided a consistency relation exists between the forcing of (3) and the boundary condition (4). This consistency relationship is obtained by integrating (3) over the domain *D*. In the two dimensional (λ,θ) Cartesian space (3) can be rewritten as:

$$\tilde{\nabla}^2\Phi=\mathbf{k}\cdot\tilde{\nabla}\times\mathbf{u}^* \tag{5}$$

Using the divergence theorem on the left hand side and Green's theorem on the right hand side, the domain integral $\iint_D$ **(5)** dλdθ becomes:

$$\int_{\partial D}\tilde{\nabla}\Phi\cdot\mathbf{n}ds=\int_{\partial D}\mathbf{u}^*\cdot\mathbf{s}ds \tag{6}$$

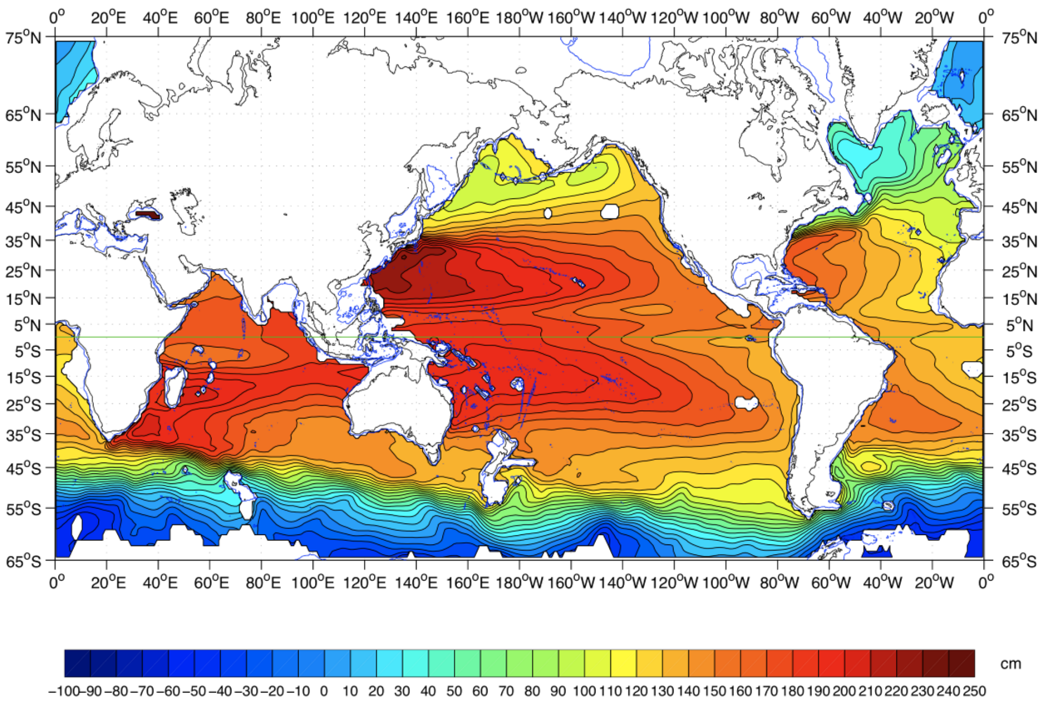
Use of the boundary condition (4) therefore guarantees that the compatibility condition (6) is satisfied. In practice the interior of the domain *D* will be defined by those points where the Cartesian vorticity $\tilde{\nabla}\times\mathbf{u}^*$ has been estimated, which are adjacent either to a solid boundary or to a data hole. Note that the problem has no singularity at the equator and can therefore be solved directly for the World Ocean. Of course as the equator is approached, the Coriolis acceleration vanishes and so does the pressure gradient. The geopotential Φ ($m^2\ s^{-2}$) so estimated on the mean 1000 dbar surface is given below as δz = 100 Φ/g_c i.e. in cm height (with g_c = 9.80665 m s^{-2}).



Note the strong inertial recirculations of the subtropical gyres, with the Agulhas gyre being the strongest, the powerful Antarctic circumpolar current with its western boundary current type meridional excursions downstream of New Zealand and Drake Passage and finally the strong anticyclonic Zapiola gyre in the Argentinian basin. There is also a weak cyclonic cell in the region of the Mediterrannean water plume. Note finally that the velocity data alone is able to show that the Pacific (and Indian) ocean is higher than the Atlantic.

Once the geopotential is found, geostrophic velocities are found from (1) and now these velocities satisfy the vorticity equation (2). The whole operation amounts to project the velocity data on the geostrophic mode thereby filtering out the unwanted divergent motions. It is now possible to obtain the geopotential and the geostrophic velocities at all pressures using hydrostatics $\partial\Phi/\partial p = -1/\rho$ where ρ is obtained from a temperature-salinity climatology. The absolute mean topography of the ocean surface shown below has been obtained with the help of the World Ocean Atlas 2009 (Locarnini et al. 2010).

Mean absolute geopotential height (cm) at 0 m



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An international initiative:
South Atlantic Meridional Overturning Circulation (SAMOC)
Years 2011– 2014

Sabrina Speich LPO-IUEM (1011-2013) & LMD-IPSL (since 2014); Silvia Garzoli (NOAA, AOML, USA); Alberto Piola (Nat. Hydrog. Institute, Argentina); Edmo Campos (Brazil)

Participating Laboratories : LPO, France; LMI ICEMASA (France South Africa), Univ. of Cape Town, South Africa; CSIR, Cape Town, South Africa; NOAA, USA; Univ. of San Paolo, Brazil; AWI, Germany; Hydrographic Institut, Buenos Aires, Argentina.

Contribution to *CLIVAR, SAMOC, ARGO International, SOCCO (South Africa), SOCLIM (BNP-ParisBas)*

Funding sources: ANR, Ifremer, INSU (France), FAPESP (Brazil), NOAA (USA), SANAP & DEA (South Africa), National Hydrographic Institute, Argentina.

Objectives*:*

Earth's climate, responding to the different thermo- dynamic properties of the land and ocean surfaces, is sensitive to the continental configuration. Indeed, because of the ocean– land configuration, each ocean basin is exposed to different atmospheric forcing, taking on correspondingly distinct property and circulation characteristics. These in turn provide feedback to the climate system through their effect on Sea Surface Temperature (SST) distribution, heat and freshwater fluxes and ocean overturning. Similarity between oceans is inhibited by their varied degrees of isolation from one another, and thus the coupled ocean–atmosphere system is influenced by the efficiency of interocean exchanges that link the ocean basins. The Southern Ocean and the South Atlantic are critical nexus for the global ocean circulation and climate. They connect efficiently North Atlantic and Arctic water masses with the rest of the world ocean. Limited observations suggest that the Southern Ocean and South Atlantic are changing. They are warming more rapidly than the global ocean average. However, the short and incomplete nature of existing data means that the causes and consequences of observed changes are difficult to assess. Sustained observations are required to detect, interpret and respond to changes. Within the South Atlantic Meridional Overturning Circulation (SAMOC) international initiative we have initiate a monitoring array experiment devoted to assess the capability of deep moored arrays together with Argo profiling floats and remote sensed data to 1) estimate the Meridional Overturning Circulation in the South Atlantic; 3) infer regional water masses transformation, pathways and variability 2) apprehend dynamical processes driving water masses exchanges and transformations. The profiling Argo floats obtained under the LEFE GMMC-Coriolis programme have been deployed within SAMOC to achieve such objectives. In addition, because of the knowledge on regional dynamics and water masses acquired since the Clivar GoodHope programme, we were able to start implement new method for Argo data validation and calibration.

Main results

Variations in the Meridional Overturning Circulation (MOC) are known to have global implications to the climate system, however until recently most MOC observing programs have been focused in the North Atlantic. Recent model and data analyses have suggested that critical water mass changes to the upper and lower limbs of the MOC occur in the South Atlantic, and only limited latitudinal coherence has been found to date between the MOC observations made by the North Atlantic observing systems at different latitudes. As a result, a priority for a the ocean science community involved in field experiments has been the establishment of a MOC observing system in the South Atlantic, and recently the International CLIVAR panel endorsed a South Atlantic MOC ("SAMOC") Initiative to both strengthen existing programs seeking to study the MOC in the South Atlantic and to encourage further expansion of the MOC observing system in the region. The MOC is a primary mechanism for the transport and storage of heat, freshwater and carbon by the ocean and therefore has a large impact on climate variability and change. The MOC is a three-dimensional circulation pattern that links each of the basins and spans the full-depth of the global oceans. Given the complex, multibasin nature of the MOC, achieving a more complete understanding of its behaviour and changes requires a more comprehensive observing system, one that extends across neighbouring ocean basins as the one we are developing for the South Atlantic within the CLIVAR SAMOC initiative.

Within the MOC, the South Atlantic Ocean plays a key role as a nexus for water masses formed elsewhere and en-route to remote regions of the global ocean. Because of this important interbasin exchanges, the South Atlantic Ocean is the only major ocean basin that transports heat from the pole towards the equator. However, the South Atlantic is not merely a passive conduit for remotely formed water masses. Indeed, within this basin water masses are significantly altered by local air-sea interactions and diapycnal/isopycnal fluxes, particularly in regions of intense mesoscale activity and steep topography. These contributions have been shown to have a crucial role in the strength of the MOC in paleoceanographic and modelling studies.

Here we will briefly summarize some of the results we obtained during these years. We will introduce first the preliminary results on estimates of the daily MOC strength and depth at 35°S during a ~20 month long pilot array of mooring as well as Argo data and model outputs. Then, we will summarize studies that focalized on water masses exchanges and transformation and related processes within the region as well as new developments in the use of the Argo data set and in the validation-calibration processing of Argo data. Last, we used the Argo data float to calibrate and characterize the 200 stations undertaken by TaraOceans during its journey across the world ocean basins.

<u>35°S Meridional Overturning Circulation strength and variability (Meinen et al. 2013)</u>

We obtained preliminary estimates of the daily MOC strength at 34.5°S during a ~20 month long pilot array of mooring. Data from two boundary arrays deployed along 34.5°S and from Argo are combined to produce the first continuous in situ time series observations of the basin-wide MOC in the South Atlantic.

The MOC variability show to be as large as that at 26N, with both eastern and western boundary flows contributing equally to the variance. Data Daily estimates of the MOC between March 2009 and December 2010 range between 3 Sv and 39 Sv (1 Sv = 10^6 m^3 s^{-1}) after a 10-day low-pass filter is applied. Much of the variability in this ~20 month record occurs at periods shorter than 100 days. Approximately two-thirds of the MOC variability is due to changes in the geostrophic (baroclinic plus barotropic) volume transport, with the remainder associated with the direct wind-forced Ekman transport. When low-pass filtered to match previously published analyses in the North Atlantic, the observed temporal standard deviation at 34.5°S matches or somewhat exceeds that observed by time series observations at 16°N, 26.5°N and 41°N. The higher standard deviation may be due to opposite-signed variability unobserved by the array inshore of the 1000 m isobath (e.g. partially observed eddies). For periods shorter than 20 days the basin-wide MOC variations are most strongly influenced by Ekman flows, while at periods between 20 and 90 days the geostrophic flows tend to exert slightly more control over the total transport variability of the MOC. The geostrophic shear variations are roughly equally controlled by density variations on the western and eastern boundaries at all time scales captured in the record. The observed time-mean MOC vertical structure and temporal variability agree well with the limited independent observations available for confirmation (Meinen et al., 2013)

<u>Three-dimensional fields from the Argo Array (work in progress in collaboration with E. Rusciano and B. Blanke; Blanke et al. 2014; Rusciano et al. 2015 in prep)</u>

We developed a procedure to obtain three-dimensional climatological fields of T, S and absolute geostrophic velocities from Argo data available in the South Atlantic from 2004 to 2013. The 3-D velocity field extends from the surface to 2000 dbar with a vertical resolution of 10 dbar. These fields are derived by combining on a 1° by 1° spatial grid a total of more than 600 000 individual profiles of temperature and salinity located in the South Atlantic Ocean. By deriving the dynamic height from floats and combining the derived relative geostrophic velocity with the ANDRO world atlas (Argo New Displacements Rannou and Ollitrault) of deep displacements (Ollitrault and Rannou, 2013), we computed the absolute geostrophic velocity and transports down to 2000 m. We are now using this field to achieve various studies. The first one concerns the description o Intermediate Waters properties and circulation in the region. The second one try to apply Lagrangian estimates to the 3D climatological field we derived to investigate on the path and along path transformations of the upper 2000 m water column in the South Atlantic. While the firs study is ready for submission, the latter is under development.

Intermediate water properties and circulation in the South Atlantic (Rusciano et al. 2012; Rusciano et al. 2015)

We combined the Argo measured variables and the ANDRO velocity data set to infer the absolute geostrophic velocities and to estimate the evolution of the dynamical properties of South Atlantic intermediate waters within the isoneutral layer ($27.1 < \gamma_n < 27.6$). We found four different regional types of Intermediate Waters converging in the area south of 15°S: Three Antarctic Intermediate Water (AAIW) varieties (the Atlantic, A-AAIW, characterized by $S \leq 34.2$; the Indian, I-AAIW, $34.3 \leq S \leq 34.4$; and the recently identified Indo-Atlantic, IA-AAIW, $34.2 < S < 34.3$), and a saltier Tropical South Atlantic Intermediate Water (TSA-IW, $34.4 < S \leq 34.6$).

Across 17°S two veins of intermediate waters flows northward. One along the western boundary carrying 2.3 Sv of modified Indian AAIW (I-AAIW). The other along the eastern boundary carrying 4.5 Sv of tropical intermediate waters (TSA-IW). South, between the Subantarctic Front and 27°N, intermediate waters circulate around the South Atlantic subtropical gyre. The saltiest AAIW circulate at the northern edge of the gyre while the core is made of AAIW derived from a mixing of Indian and Atlantic AAIW. This mixing happens essentially at depth in the Cape Basin (Southeastern Atlantic) where the complex dynamics of the Agulhas Retroflection and Agulhas ring injections, the strong interaction with steep topography and the coming across of waters of remote origins (South African slope and the South Atlantic Current) enhance water masses stirring and therefore impact heat and salt exchanges. No fresh A-AAIW is observed to penetrates north of 30°S.

The thermohaline variability of the Southeast Atlantic sector of the Southern Ocean between 1992-2012 using an altimetry-based Gravest Empirical Mode (Master thesis of L. Hutchinson; Hutchinson et al. 2015 in prep)

By taking advantage of the numerous repeat hydrographic CTD sections along the GoodHope line, the large number of Argo floats deployed in the area, and the available satellite altimetry data, an Altimetry Gravest Empirical Mode (AGEM) is developed for the ACC south of Africa. The AGEM has improved precision to comparable proxies and offers an ideal technique to investigate the thermohaline variability of the upper 2000dbar of the water column over the past two decades. In order to assess and attribute changes in ocean dynamics and water masses, we separate the diabatic and adiabatic components of the reconstructed trends. Integrated over the whole top 2000dbar of the ACC south of Africa, results show adiabatic changes of 0.016 ± 0.010°C.yr^{-1} and $3.86\text{x}10^{-4} \pm 1.30\text{x}10^{-3}$ yr^{-1}, and diabatic trends of $8.29\text{x}10^{-4} \pm 9.20\text{x}10^{-3}$ °C.yr-1 and $-5.72\text{x}10^{-4} \pm 1.0\text{x}10^{-3}$ yr-1 for temperature and salinity respectively. By combining the original AGEM fields with the diabatic differences, a new AGEM (AD-AGEM) is created rendering mean property changes of 0.012 ± 0.011 °C.yr^{-1} and $-5.47\text{x}10^{-4} \pm 1.60\text{x}10^{-3}$ yr^{-1}. The study focuses on the temporal evolution of the Antarctic Intermediate Water (AAIW), finding mean trends of -0.015 ± 0.096 °C.yr-1 and $-2.8\text{ x}10^{-3} \pm 1.33\text{ x}10^{-2}$ yr^{-1} for the layer within the Subantarctic zone, and 0.029 ± 0.12 °C.yr^{-1} and $7.17\text{x}10^{-4} \pm 5.90\text{x}10^{-3}$ yr^{-1} for the Polar Frontal Zone. The results expose the uniqueness of the ACC south of Africa in its response to climate change.

Evolution of properties of Agulhas rings in the South Atlantic (Master2 thesis of Rémi Laxenaire; Laxenaire et al. 2015 in prep)

The Indo-Atlantic exchange achieved by mesoscale eddies formed in the region of the Agulhas Current Retroflection is investigated by combining daily satellite altimetry data, profiling floats. The eddy tracking algorithm developed by Alexis Chaigneau and Cori Pegliasco (Chaigneau and Pegliasco 2013 -not yet published-) is used and further developed in our study. This algorithm takes into account eddy shapes, merging and, thanks to this study, splitting events. The method is validated in a region characterized by a particularly high eddy activity, and where eddy formation, strong eddy-eddy interactions and influence of the bottom topography are observed.

The collocation of identified eddies and Argo profiles allows us to study isolated records of the internal structure of eddies in the water column.

The thermal contents anomalies associated with the eddies, and computed with the Argo profiles, are mapped over the area of study. The anticyclones (cyclones) show positive (negative) anomalies that vary from $+10^{10}$ J/m^2 (-10^{10} J/m^2) south of Africa to $+4.10^9$ J/m2 (-4.10^9 J/m^2) in the western part of the domain, in the South Atlantic. A continuous gradient exists between these two extremes. These Eulerian mappings highlight the importance of both the cyclones and anticyclones for heat content.

One Agulhas ring is sampled on the vertical by 19 Argo profiles between the Cape Basin and the western part of the domain in the South Atlantic. We show the presence of a homogeneous surface layer down to 300 m that subducts when the Walvis Ridge is crossed. A reminiscence of this layer is found in the region of the Mid-Atlantic Ridge, but it is no more detectable west of it. An eddy with a similar behaviour was detected in the simulation. This comparative Lagrangian study highlights that Agulhas Rings can present a warm and salty layer up to the sea surface during more than 1 year, during which exchanges with atmosphere can occur, before the anticyclones subduct. Moreover, we show that the anticyclones can advect Indian water masses to the western part of the South Atlantic.

Delayed mode analysis of Argo floats: improvements of the method in the Southern Ocean (in collaboration with C. Cabanes and J. Lepesquer; Cabanes et al. 2014)

Argo floats conductivity sensors can be subject to drift and offset due to bio-fouling or other technical problems. Several approaches have been proposed to correct the float salinity measurements in delayed time. The method developed by Owens and Wong 2009 (OW, 2009) is now widely used by the Argo community. However, our experience has shown that it is sometimes difficult to detect a float salinity drift or offset in the the Southern Ocean around southern Africa only on the basis of the results from OW method and it can be necessary to use complementary approaches. In our study we have shown that some modifications of the standard OW method are necessary to gain confidence in the results proposed by the method and to make it easier for the PI of the float the decide whether a salinity correction is necessary. We have followed Cabanes et al. (2014) and slightly modified the OW method in order to better take into account the large variability of the salinity field, which is assumed to be constant in the standard method. Indeed, this high variability is caused, in the Southern Ocean, by a complex ocean dynamics characterized by intense mesoscale features and various water masses varying at the same scale.

To take into account these complex variations, additional modifications have been implemented to better take into account the presence of fronts and large eddy variability. Particularly, in this area, we implemented a new methodology that takes into account in the comparison with historical data water-masses properties such as variable theta-related depths and the dynamic height of the Argo profile. The work is still in progress, however we hope to finalise this improvements to the Argo data delayed mode analyses this year.

Future of the project :

The SAMOC international initiative is continuing. In particular, SAMOC has received much attention lately from the European Commission, USA and Canada within the Galway Agreement on Atlantic observing implementation. The participation of SAMOC community in the H2020 EU AtlantOS project will foster collaborations with Northern Hemisphere countries and the capability of the observing system will evaluated and possibly enhanced. Due to the new appointment of the French PI, Sabrina Speich, to the "Laboratoire de Meteorologie Dynamique" (LMD) of the "Institute Pierre-Simon Laplace" (IPSL) in Paris, has broke off momentarily the activity of SAMOC in terms of Coriolis Argo floats deployment.

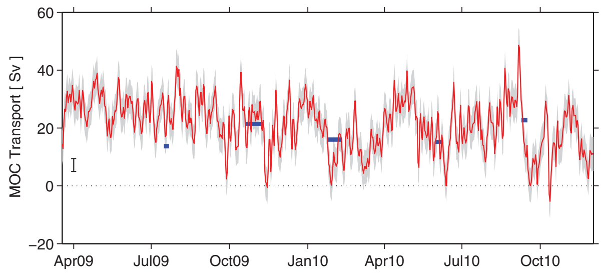

Figure 1 : Transport time series of the MOC at 34.5□S (red line) with estimated daily error bars (gray shading) as derived in Meinen et al. 2013. Black vertical error bar at left illustrates the estimated bias accuracy. Also shown are five MOC estimates determined from trans-basin XBT sections where the horizontal length of the bar illustrates the start and end times of each trans-basin cruise.

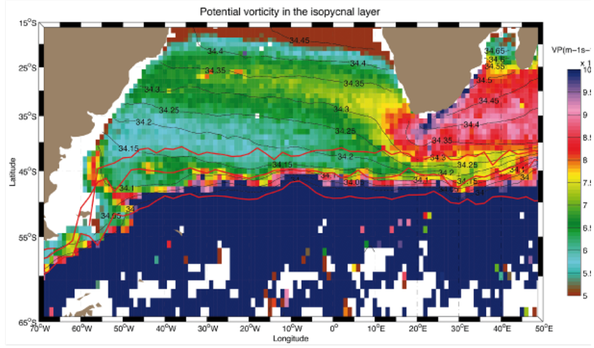

Figure 2 : Isopycnic potential vorticity (10^{-11} m-1s^{-1}) computed in the neutral density isopycnal layer (27.1 < γ_n < 27.6).

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The ACC at Drake Passage: volume transport and meridional heat flux

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Many observational studies have sought to establish how the transport of the ACC varies with time and space. Most of these have focused on the flow through Drake Passage (DP), since all the transport through that section contributes to the circumpolar transport, and complications with additional flows are safely avoided. The landmark International Southern Ocean Studies (ISOS) program with intensive field experiments in DP (i.e. the Drake 79 mooring array) provided fundamental insights into the spatial and temporal structure of the flow and led to the canonical value of total ACC transport of 134 Sv with a standard deviation of 11 Sv for a year-long record.

The satellite altimetry opened new perspectives to the monitoring of the ACC circulation and its transport (i.e Barré et al., 2011). To monitor transport using altimetry, hydrographic data and current meter time series were collected during three years (2006-2009) along the ground track 104 of Jason altimetry satellite as part of the DRAKE project (Provost et al., 2011) (Figure 1).

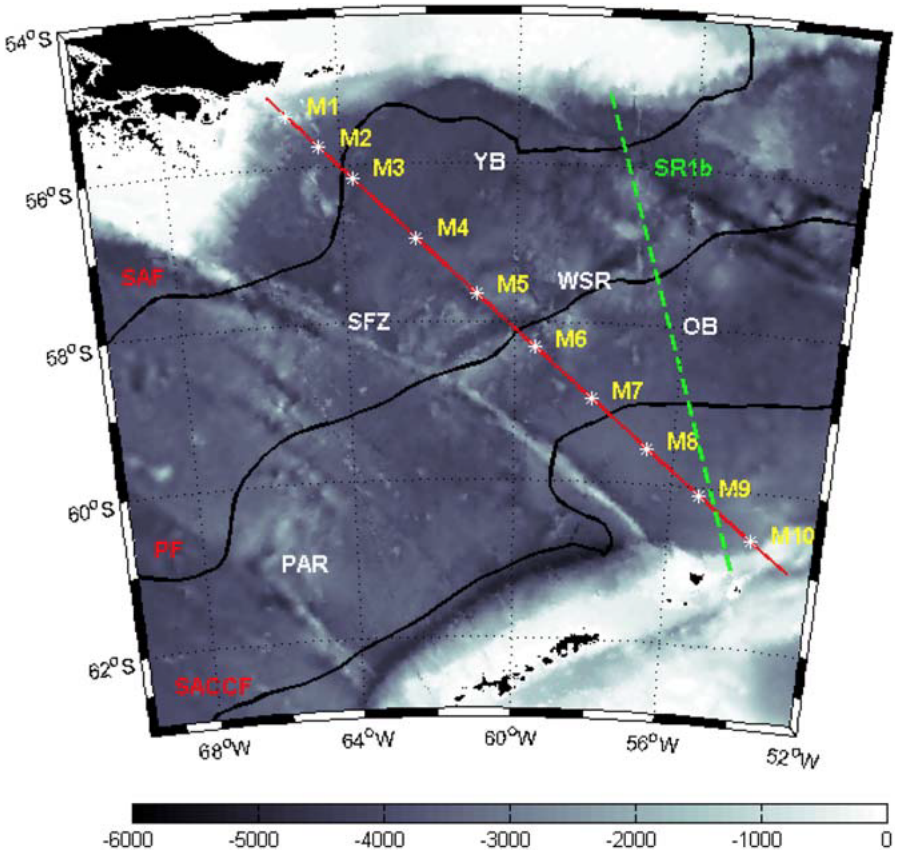

Figure 1. Bathymetry in the Drake Passage in meters. In red, Jason satellite ground track 104 where an asterisk indicates a mooring location (M1 through M10). In green, the SR1b annually repeated hydrography line. OB, Ona Basin; YB, Yaghan Basin; SFZ, Shackleton Fracture Zone; WSR, West Scotia Ridge; PAR, Phoenix Atlantic Ridge. The black lines represent the mean location of the fronts : SAF, Subantarctic Front; PF, Polar Front; SACCF, Southern ACC Front.

The Drake *in situ* data were used to evaluate the altimetry products. Both hydrographic data and velocity time series showed that altimetric data, and in particular the multi-satellite gridded products provided accurate information on surface geostrophic velocity variations (Barré et al., 2011; Renault et al., 2011; Ferrari et al., 2012; Ferrari et al., 2013). A 21-year (1992-2013) ACC transport time series with a 7-day resolution was produced from the combination of information from 3 years of *in situ* velocity data and satellite altimetry observations along the Jason ground track 104 (Koenig et al., 2014). Time- and space-varying transfer functions relating altimetry-derived surface currents and velocity profiles in the water column derived from the current meter mooring data were constructed. The transport time series was then extended over the altimetric era with a time resolution of 7 days. This time series was decomposed into three transport components: total transport (TT), baroclinic transport (BC, calculated relative to the zero bottom velocity), and the barotropic transport (BT, calculated by integrating the bottom velocity over the entire water column) (Fig. 2). The internal consistency and the robustness of the method were carefully assessed and comparisons with independent data spanning the 20 years (such as SR1b annually repeadted hydrography line) demonstrated that the accuracy of the method and periods larger than 30 days are reliable (Koenig et al., 2014).

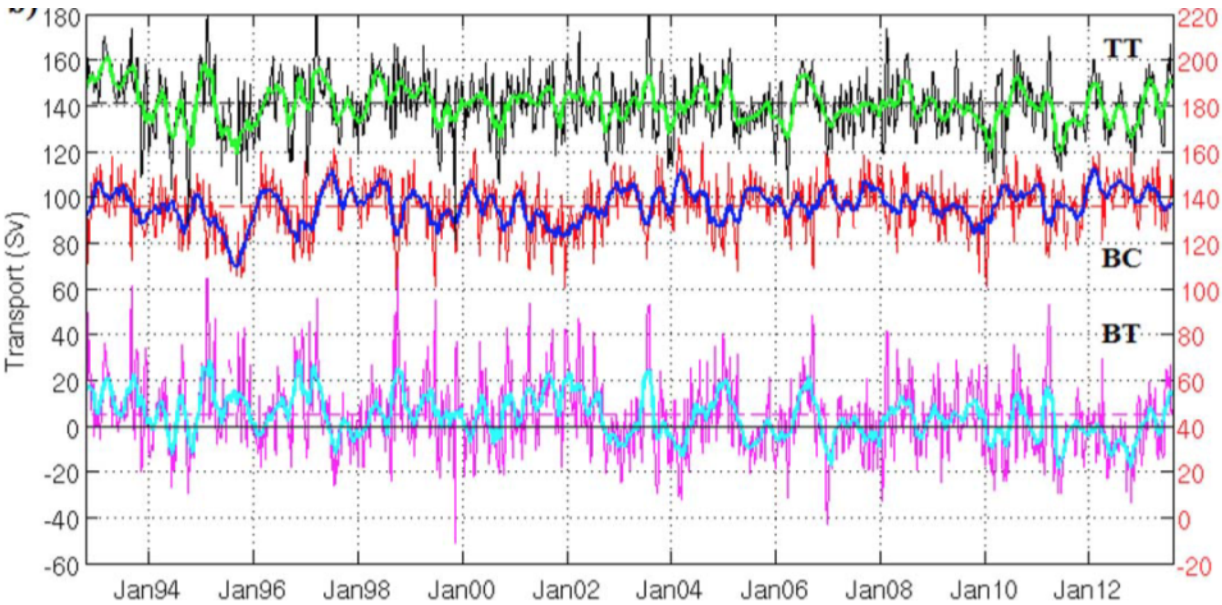

Figure 2: Time series of the total (in black), baroclinic (in red), and barotropic (in magenta) transport from 0 to bottom, with their smoothed time series (respectively green, blue, and light blue) obtained with a 1 month running mean. Total mean: 141 Sv, std: 13 Sv. Barotropic mean: 5 Sv, std: 16 Sv. Baroclinic mean: 136 Sv; std: 11 Sv. Note that the red right axis to the right refers to the baroclinic transport only.

While the time-mean whole-track TT (141 Sv) is largely determined by the BC component (136 Sv), with a minor contribution from the BT component (5 Sv), its temporal variability shows the opposite tendency. In fact, the strongest transport variability is associated with BT (16 Sv std) and the least variability with BC (11 Sv std), with the TT variability (13 Sv std) lying in between the two, indicating that the BC variability is partly compensating the BT variability, consistent with a significant anti-correlation (r = -0.6) between the BT and BC.

In terms of the frequency content, the intraseasonal variability of periods of 1 to 5 months constitutes the majority of the variability for all three transport components. Common to both BT and TT are two energy-containing frequency bands, one for periods of 1-2 months and the other for 3-5 months. These contain significant peaks centered at 28, 36 and 50 days in the 1-2 month band and distinctive (though not significant at the 95% level) peaks at 99 and 142 days in the 3-5 month band. Among these, the 50-day peak constitutes the most energetic signal. The spectral energy decreases sharply with increasing periods with significant low-frequency signals only at annual and biannual timescales.

The lagged SLA regressions onto the three transport components reveal different projections in space and time according to each component. The SLA patterns significantly correlated with BT are confined entirely within the Yaghan Basin, with a representative intraseasonal timescale of about 2 months. In contrast, the BC-regressed SLA patterns project much more extensively in the upstream area from DP as slowly propagating wave-trains annually recurrent at the entrance to DP on one hand,

and on the other hand, along the whole continental slope of South America as quickly propagating coastal trapped waves-like features.

The intraseasonal BT variability in the Yaghan Basin is not generated and advected from the exterior but is developed within the Yaghan Basin where it eventually dissipates without propagating outside of the basin. It is a basin mode (Koenig et al., 2015). More work is needed to get a deeper insight of the generating mechanism of the 50-day BT signal.

Aside from moderate annual to biannual signals, the interannual transport variability at DP is completely overwhelmed by the prevalent intraseasonal variability, at least during the last two decades examined here. We did not find any systematic relationship between climatic indices such as SAM or ENSO and the DP transport variability, but their co-variability depends on a particular epoch and periodicity in question. The relatively short data length (20 years) prevents documenting any decadal-scale variability of the DP transport and its response to concomitant atmospheric forcing. Much longer transport data are needed to address these questions.

Meridional heat flux across the ACC: mean flow and eddy contributions

Point measurements from current meter moorings provide only unit-dependent mean temperature flux estimates and not meaningful estimates of the heat flux due to the mean flow because the zero on the temperature scale is arbitrary. For a proper estimate of heat flux due to the mean flow, the individual mean temperature fluxes need to be summed over a mass-balanced region. To handle this major constraint of integrating estimates over a mass-balanced region, we use both mooring data and outputs of a high-resolution three-dimensional numerical model of the ocean circulation with realistic topography (Fig. 3).

Thus, the contributions of the eddy flow and mean flow to the across-stream heat fluxes in DP were calculated using two in situ mooring data sets in DP and MERCATOR model outputs. The two in situ mooring data sets, the year-long historical DRAKE 1979 data and the 3 year-long DRAKE 2006–2009 data, span the entire DP from north to south and are located in each side of a major submarine ridge, the SFZ (Fig.3).

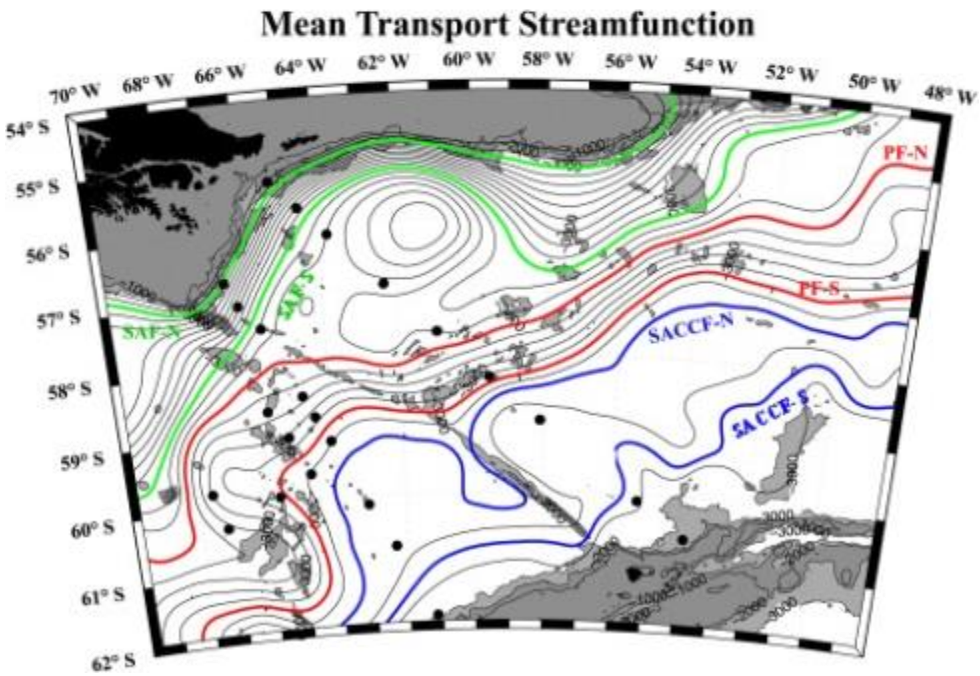

Figure 3: 3 year (2006-2009) mean transport streamfunction from Mercator model outputs. Streamlines between -85 and +40 m^4s^{-1} are plotted in black solid lines with a $5m^4s^{-1}$ step. Major branches of the SAF, PF and SACCF are identified with a green, red, and blue solid line, respectively. Black dots east of the SFZ correspond to the Drake 79 moorings, those west of SFZ to Drake 2006-2009. Note the mean cyclonic recirculation between the SAF and PF.

Model eddy heat fluxes compared satisfactorily with estimates from in situ moorings, both in amplitude and direction. They were mostly poleward except for the central Yaghan Basin, in the cyclonic recirculation region. Model eddy heat fluxes are of the same sign and larger in the upper layer than below 500m. The model vertically integrated eddy heat fluxes exhibit scales compatible with the size of mesoscale eddy activity. The model provides reasonable eddy heat fluxes at the mooring locations, showing a maximum between the SAF and PF and then decreasing southward. To make a large-scale budget, we relied on the model estimates. The order of magnitude of the poleward eddy heat flux in DP at 60°W is in the order of 2% of the heat loss to the atmosphere south of 60°S, whereas DP (between 48°Wand 64°W) covers about 4% of the circumpolar longitudes and is a region of the ACC with a large EKE.

Cross-stream temperature fluxes due to the mean flow show both positive and negative significant values at the mooring sites. Downstream of the SFZ, all the significant fluxes are positive, i.e., equatorward, in agreement with the general downwelling observed in the Yaghan and Ona Basins [Ferrari et al.., 2012, 2013]. However, in the area upstream of the SFZ, the distribution of equatorward and poleward fluxes is more complex. Model-derived temperature fluxes are of the same order of magnitude and when significant have the same sign as estimates from in situ observations with an 86% agreement. Model-derived depth-integrated temperature fluxes by the mean flow have values between +300 and -300 kW m^{-2} and exhibit small spatial scales with alternating signs. These small-scale patterns are similar to those of bottom vertical velocity estimates having opposite signs. The rotation of the mean velocity vectors with depth is mainly due to non-zero currents over sloping topography. The rough hilly topography in DP leads to the small-scale vertical velocities and temperature fluxes. In contrast to the eddy heat flux, the contribution of the upper layer (0–500 m) is not significant for the heat flux due to the mean flow.

The integrated values along the mass-balanced regions delimited by different fronts in DP are all found to be poleward, with a maximum in the region between the SAF and PF for both eddy and mean flow contributions to the meridional heat flux. The contribution of the mean flow is larger than the eddy contribution for any of the mass-balanced regions, the ratio between the two varying between 8.6 (in the SAF region) and 2.3 (in the SACCF-PF region). The model-estimated poleward heat flux across the SACCF in DP (covering about 4% of the circumpolar longitudes between 48°W and 64°W) is 20.055 PW (eddy contribution: 20.01, mean flow contribution 20.045 PW), i.e., in the order of 10% of the heat lost to the atmosphere south of 60°S. In other words, the across-stream heat flux in DP has a contribution from the mean flow of about 80% and the eddy flow for the remaining 20%. It plays a significant role for the circumpolar poleward heat flux despite its limited longitudinal extent.

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Direct observations of the ACC transport across the Kerguelen Plateau

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The Kerguelen Plateau is a major topographic obstacle to the eastward flowing Antarctic Circumpolar Current (ACC). Whilst approximately two thirds of the ACC transport is diverted to the north of the Kerguelen Islands, most of the remaining flow engulfs in the Fawn Trough, the only deep passage across the plateau. As part of the TRACK (TRansport ACross the Kerguelen plateau) project, three mooring lines of current meters were deployed in the Fawn Trough for one year in February 2009 and recovered in January 2010, underneath ground-track 94 of the Jason-2 satellite altimeter. Full depth CTD-LADCP casts across and in the vicinity of the trough were carried out during the deployment and recovery cruises (Fig. 1b).

The TRACK constituted the first direct observations of the ACC transport crossing the Kerguelen Plateau (Park et al., 2009). The 2009 TRACK1 cruise data showed that the net eastward transport to the south of the Heard/McDonald Islands is 56 Sv (1 Sv = 10^6 m^3 s^{-1}), most of which (43 Sv) being tightly channeled into the Fawn Trough, which appears as a predominant cross-plateau gateway of circumpolar flow associated with the Southern ACC Front (SACCF), as shown by a schematic of the major branches of the ACC transport transiting through the Kerguelen Plateau region (Fig. 1a). There are also two secondary passages, with 6 Sv being attached to the nearshore slope just south of the Heard/McDonald Islands and 7 Sv passing through the northern Princess Elizabeth Trough. With an additional 2 Sv inferred just south of the Kerguelen Islands, the transport across the entire plateau amounts to 58 Sv, accounting for about 40% of the total ACC transport (147-152 Sv) passing across the Kerguelen longitudes. Here, the dominant branch of ACC (~90 Sv) flows along the Subantarctic Front (SAF) north of the Kerguelen Islands.

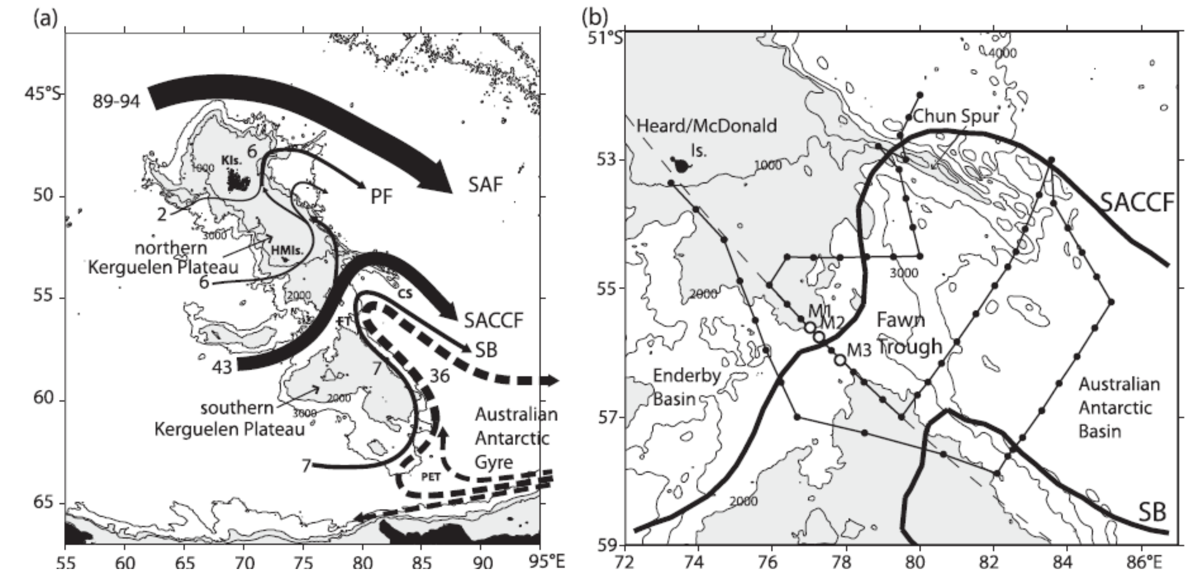

Figure 1. (a) Schematic of major pathways and transports (in Sv) of the ACC system (bold solid lines) and the deep western boundary current of the Australian-Antarctic Gyre (bold dashed lines). (b) The 2009 TRACK cruise plan, with three moorings (M1, M2, M3) in the Fawn Trough and an array of CTD stations (black dots). Adapted from Park et al. (2009).

Based on the one-year-long current meter mooring data, a time series of the transport in the Fawn Trough has been estimated (Vivier et al., 2014), featuring a mean eastward transport of 34 Sv (possibly biased low by at most 5 Sv) and a root mean squared variability of 6 Sv, consistent with

LADCP estimates (43 Sv in February 2009 and 38 Sv in January 2010). In addition, we have analyzed to what extent the transport can be directly monitored from along-track satellite altimeter data, which would enable study of the variability of the Fawn Trough Current centered at the SACCF from a now 20-year long archive. While a canonical method to derive transport from altimetry gives here unsatisfactory comparisons with in situ estimates, an ad-hoc approach using only the two northernmost mooring lines yields an estimate well correlated (r = ~0.8) with in situ transport at subseasonal time scales during the one year period of observations. At interannual time scales, however, both methods provide significantly correlated (r = 0.7) transport estimates, suggesting that long-term transport fluctuations across the Kerguelen Plateau can be confidently estimated from altimetry (Fig. 2). These consistently indicate a measurable impact of the outstanding 1997-98 El Niño-Southern Oscillation (ENSO) event, yielding an increase of the annual mean transport of ~3 Sv, possibly with a one year lag. The transport estimate based on the ad-hoc approach is significantly correlated (r = 0.6) with the Southern Annular Mode (SAM) index at interannual time scales, suggesting that an intensification of the circumpolar winds drives an increase in the transport across the Kerguelen Plateau.

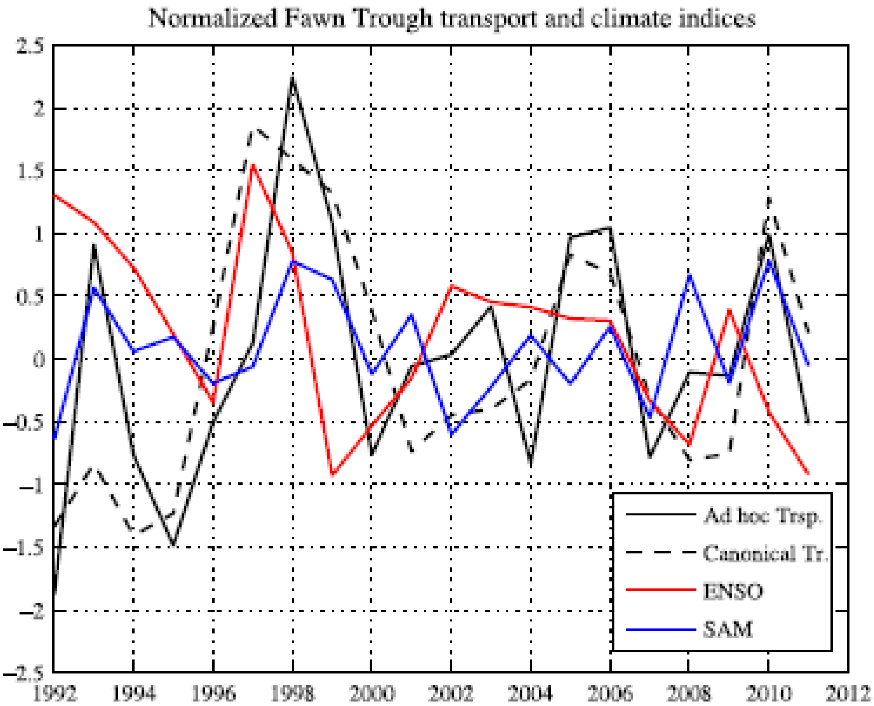

Figure 2. Normalized yearly averaged volume transport time series at Fawn Trough estimated from two different methods based on altimetry: canonical approach using all three moorings (black solid) vs ad hoc approach using the two northernmost moorings (back dashed). Also superimposed are the ENSO index (red) and SAM index (blue). From Vivier et al. (2014).

Finally, the major mechanisms of the oceanic poleward heat flux in the Southern Ocean are still in debate. The long-standing belief stipulates that the poleward heat flux across the ACC is mainly due to mesoscale transient eddies and the cross-stream heat flux by time-mean flow is insignificant. This long standing paradigm has been challenged by the TRACK observations. In fact, the moored current meter data in the Fawn Trough permitted us to estimate the cross-stream heat flux caused not only by transient eddies but also, for the first time, by the time-mean flow (Sekma et al., 2013). It has been shown that the poleward eddy heat flux in this southern part of the ACC is negligible, while that from the mean flow is overwhelming by two orders of magnitude (Table 1). This is related to the existence of the nonequivalent barotropic structure of the mean flow, which arises from the unusual anticlockwise turning of currents with decreasing depth. The latter feature is associated with significant bottom upwelling engendered by strong bottom currents flowing over the sloping topography of the Fawn Trough. The circumpolar implications of these local observations are discussed in terms of the depth-integrated linear vorticity budget from the FRAM model, which suggests that the six topographic features along the southern flank of the ACC equivalent to the Fawn Trough case would yield sufficient poleward heat flux to balance the oceanic heat loss in the subpolar region. As eddy activity on the southern flank of the ACC is too weak to transport sufficient heat poleward, the nonequivalent barotropic structure of the mean flow in several topographically constricted passages should accomplish the required task.

Table 1. Estimates of heat flux (kW m^{-2}) on the three moorings in the Fawn Trough. Significant estimates at the 95% confidence level are shown boldfaced. Error bars for the mean heat flux are given as ± the standard error. From Sekma et al. (2013).

	Pressure	Eddy Heat Flux			Mean Heat Flux
	(db)	Geographic	90d-LP	Shear	Shear
M1	281	0.10	0.21	0.24	**−84.8 ±24.7**
	981	−0.23	−0.25	**1.61**	**−489.0 ±18.5**
	1454	−0.35	**−0.39**	−0.71	**164.9 ±31.4**
	1950	−0.22	−0.20		
M2	362	**−2.35**	**−2.38**	1.42	−248.4 ±138.5
	1026	1.03	0.82	−3.50	−211.4 ±178.9
	1510	0.41	0.38	0.32	**−611.7 ±12.2**
	2311	−0.68	−0.69		
M3	532	−0.58	−0.65	**−2.40**	**−368.7 ±27.1**
	1228	−1.80	−1.81	2.28	**−141.6 ±56.9**
	1732	1.52	1.55	**−3.72**	**−260.1 ±15.9**
	2372	**1.33**	**1.31**		
Depth mean		−0.09	−0.12	−0.52	**−218.6 ±22.8**

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