SANGOMA: Stochastic Assimilation for the Next Generation Ocean Model Applications EU FP7 SPACE-2011-1 project 283580

Deliverable 5.1: List of remote sensed variables

Due date: 31/10/2012

Delivery date: 18/04/2014 and 31/10/2015

Delivery type: Report , PU

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Chapter 1

Introduction

This report is an updated version of the deliverable 5.1 of the SANGOMA project, is aimed at presenting new data types very promising for use in future data assimilation setups in oceanography. For large-scale ocean model applications, remotely sensed parameters, such as sea surface salinity (SSS) and sea surface temperature (SST), but also ice thickness chemical fluxes and various other parameters will be considered and their error characteristics assessed. Coastal applications and regional models will mostly examine *high-frequency radars* and *gliders*. Both families of instruments, *i.e* destined to research or to real-time forecasting are taken into account. The presentation of the data types is organized as follow:

- Parameters : the type of data.
- Resolution : spatial resolution of the instrument.
- Coverage and specifications : the extend of the scanned zone. Mostly global for polar-orbital satellites. Additional infos like satellite inclination, altitude and mission dates.
- Observation operator : a proposed observation operator for this type of data assimilation.
- Observation errors : typical instrumental error/accuracy, or manipulated data from instrumental source errors.
- Data access : link to a web resource where to access and/or ask for the data. For most ESA satellites, data is available from the ESA Earthnet Online portal `https://earth.esa.int/web/guest/home`. The access is public via a previous registration. Likewise, for most NASA oceanographic data products, the Jet Propulsion Laboratory of California (JET) provides a free and public access via registration via the portal PO.DAAC (Physical Oceanography, Distributed Active Archive Center) `http://podaac.jpl.nasa.gov/`.
- Used in assimilation : a selection of papers (a few) about research already done for this type of data assimilation.
- More info : links to additional infos about mission/instrument design.

Note that the data sources presented here are only a little subset of what exists an of what is planned to be launched by spatial agencies. Also, the observation operator is mostly given as spatial interpolation, as it is often the case. But maybe for some of those data, a more complex design of the operator will be interesting, or even necessary.

Chapter 2

Data types description

2.1 Data types

Coastal applications		
High-frequency radars	Parameters	Radial currents and wave by back-scattering of Bragg-waves.
	Coverage and specifications	Horizontal coverage is of the order of 60 km offshore, and up to 200 km when using lower frequencies ($\sim$ MHz). Coverage depends on salinity (low conductivity of the ocean surface attenuates the Bragg-waves) and wave regime. Obstacles, such as small islands, can also reduce the range.
	Resolution	Horizontal resolution depends on the frequency of radar. Radial currents are measured on a polar grid. Angular resolution is about 6° and the radial resolution is of the order of kilometers. The radial currents represent essentially an average over the first meters of the ocean. The temporal resolution can be of the order of minutes for HF radar system using beam-forming (WERA system) and of the order of hours for system using direction finding (CODAR). Every radar system measures only radial currents relative to the position of the antennas locations. Total currents (*i.e.* cartesian horizontal vectors) can be derived where the two (or more) systems overlap.

Observation operator	Ones needs to perform a weighted vertical average of modeled ocean currents, project the currents vectors to the radial direction for each site, remove and filter spatial scales not resolved on the polar grid of the observation. This method greatly simplifies the construction of the observation operator, which would need otherwise to contain all of the above calculations.
Observational errors	They are usually provided based on the estimated noise during the integration period. Observational error increases typically with distance from the system location and usually varies in time.
Data access	In general, the data are not publicly available. • http://hfradar.ndbc.noaa.gov/ • http://www.ioos.gov/hfradar/welcome.html • LSEET (Laboratoire de Sondages ElectromagnÃ©tiques de l'Environnement Terrestre), MIO (Mediterranean Institute of Oceanography). • ACTIMAR, Brest. Data format : binary files.
Used in assimilation	• Barth, A., Alvera-Azcárate, A., & Weisberg, R. H. (2008). Assimilation of high-frequency radar currents in a nested model of the West Florida Shelf. Journal of geophysical research, 113(C8), C08033. • Barth, A., Alvera-Azcárate, A., Beckers, J., & Staneva, J. (2010). Correcting surface winds by assimilating high-frequency radar surface currents in the German Bight. Ocean Dynamics, 1-29. • Lewis, J. K., Shulman, I., & Blumberg, A. F. (1998). Assimilation of Doppler radar current data into numerical ocean models. Continental Shelf Research, 18(5), 541-559.

	More info	• Pandian, P. K., Emmanuel, O., Ruscoe, J., Side, J., Harris, R., Kerr, S., & Bullen, C. (2010). An overview of recent technologies on wave and current measurement in coastal and marine applications. Journal of Oceanography and Marine Science, 1(1), 001-010. • Shay, L. K., Graber, H. C., Ross, D. B., & Chapman, R. D. (1995). Mesoscale ocean surface current structure detected by high-frequency radar. Journal of Atmospheric and Oceanic Technology, 12(4), 881-900. • Wyatt, L. (2005). HF radar for coastal monitoring-a comparison of methods and measurements. Oceans 2005-Europe, 1, 314-318 Vol. 1.
Gliders	Parameters	Gliders can board several sensors to measure various parameters, such as a temperature, conductivity and thus salinity, optical sensors such as fluorescence and thus chlorophyll-A concentration, backscatter but also multispectral radiometers and hyperspectral absorption meters.
	Coverage and specifications	• For standard coastal mission, distances are of the order of several hundreds of km to several thousands of kilometers, travelling around 24 km per day. Vertical extent can also vary from 200 m to 1000 m for Slocum models, and more for other models. • The tracks are dead-reckoned, using a heading, a sonic altimeter and a depth sensor. When surfacing, a contact is established with the GPS antenna, allowing to correct trajectories.
	Resolution	Gliders travel at a horizontal speed of about 20-30 cm/s. The finesse (ratio of horizontal speed to vertical speed) is about 2 to 4. Sampling frequency can be chosen from seconds to days.
	Observation operator	The observation operator will be a classical one, performing spatial interpolation.
	Observational errors	The observation errors are those of the sensors, i.e. typical CTD accuracy • Temperature : 0.002°C • Salinity : 0.005 psu • Position error

	Data access	• Data for the Ligurian Sea can be viewed at the Villefranche-sur-mer observatory portal : http://www.oao.obs-vlfr.fr/robots-a-sensorssm/gliderssm • Coriolis Everyone's Gliding Observatories Data http://www.ego-network.org/dokuwiki/doku.php?id=public:dataaccess. Data format : netcdf.
	Used in assimilation	• Dobricic, S., Pinardi, N., Testor, P., & Send, U. (2010). Impact of data assimilation of glider observations in the Ionian Sea (Eastern Mediterranean). Dynamics of Atmospheres and Oceans, 50(1), 78-92. • Melet, A., Verron, J., & Brankart, J. M. (2011). Potential outcomes of glider data assimilation in the Solomon Sea: Control of the water mass properties and parameter estimation. Journal of Marine Systems, 94(C), 232-246. • Shulman, I., Rowley, C., Anderson, S., DeRada, S., Kindle, J., Martin, P., Doyle, J., et al. (2009). Impact of glider data assimilation on the Monterey Bay model. Deep Sea Research Part II: Topical Studies in Oceanography, 56(3-5), 188-198.
	More info	• Bachmayer, R., Leonard, N. E., Graver, J., Fiorelli, E., Bhatta, P., & Paley, D. (2004). Underwater gliders: recent developments and future applications. • Graver, J. G. (2005). Underwater gliders: Dynamics, control and design. • Rudnick, D. L., Davis, R. E., Eriksen, C. C., Fratantoni, D. M., & Perry, M. J. (2004). Underwater gliders for ocean research. Marine Technology Society Journal, 38(2), 73-84. • Schofield, O., Kohut, J., Aragon, D., Creed, L., Graver, J., Haldeman, C., Kerfoot, J., et al. (2007). Slocum Gliders: Robust and ready. Journal of Field Robotics, 24(6), 473-485.
Global applications - remotely sensed data		
Wide-swath altimetry	Parameters	Sea-surface height, or its anomaly. Ka-band Radar Interferometry at 0.85 cm wavelength.

	Coverage and specifications	Global. More precisely, the SWOT mission will use a 120 km wide swath between 78°N and 78°S, *i.e.* two ground swath of 60 km separated by a 20 km gap. Orbit altitude : 970 km.
	Resolution	The intrinsic pixel resolution vary from 60 m to 10 m and at best 2 m along-track resolution. This is to be compared with tracks of classical altimeters separated by a $\sim$ 200 km distance. Furthermore, the waveforms of those altimeters are greatly contaminated by land and their spatial and temporal resolution are inappropriate for coastal applications. Time resolution : the maximum repeat orbit is 22 days. The orbit is at 970 km height and 78°inclination.
	Observation operator	Horizontal interpolation of sea surface height.
	Observational errors	Accuracy : 1cm when averaged over areas of 1 km^2
	Data access	SWOT : Future mission (expected to be launched in 2018 - 2020)
	Used in assimilation	• Biancamaria, S., Durand, M., & Andreadis, K. M. (2011). Assimilation of virtual wide swath altimetry to improve Arctic river modeling. *Remote Sensing of Environment.* • Le Hénaff, M., De Mey, P., Mourre, B., & Le Traon, P.-Y. (2008). Contribution of a Wide-Swath Altimeter in a Shelf Seas Assimilation System: Impact of the Satellite Roll Errors. *Journal of Atmospheric and Oceanic Technology*, 25(11), 2133-2144.
	More info	http://www.sciencedirect.com/science/article/pii/S0034425710002816
Ice thickness	Parameter	CryoSAT-2/ICESat: Sea ice freeboard thickness (related to ice thickness). Measured by laser altimetry at 1064 and 532 nm. SMOSIce: Thickness of thin ice.
	Resolution	• CryoSat-2: 250m in the along track direction in SAR mode. • GLAS/ICESat: The laser footprints on the ground are 60 m wide and separated by 170 m. 250 m in the along-track direction in SAR mode. • SMOSIce: 35 km.

Coverage and specifications	• CryoSat-2: global between 86°N and 86°S. Polar orbit at 717 km with 92 inclination degrees. Launched on 8 April 2010 for a mission duration of minimum 3 years. Repeat cycles : 369 days with 30 days sub-cycle. • GLAS/ICESat : Global between 86°N and 86°S. Launched on 13 January 2002 until August 14, 2010. Note : a second generation mission, ICESat-2, is scheduled for launch in early 2016. Repeat cycle : 81 and 9 days. The 81 days orbit is 11 times denser than 8 days. • SMOSIce: daily coverage until 86°N in the Arctic.
Observational operator	CryoSAT/ICESat: Horizontal interpolation of ice freeboard using ice thickness, snow depths and ice density. SMOSIce: Horizontal interpolation of ice thickness.
Observational errors	• Cryosat-2: the altimeter accuracy is centimetric. • ICESat: Intrinsic precision better than 10 cm for a 60 m wide laser sport, providing the capability to measure subdecadal changes in ice sheet thickness of only a few tens of centimeters. • SMOSIce: 10cm for ice thickness lower than 50cm. Infinite over that threshold.
Data access	• CryoSat-2 : `https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat/content?p_r_p_564233524_assetIdentifier=how-to-access-cryosat-data-6842`. Public access with registration. • ICESat: `http://nsidc.org/data/icesat/order.html` `http://nsidc.org/data/docs/daac/glas_icesat_l1_l2_global_altimetry.gd.html#3` Public access. Data format: scaled-integer binary format with a big-endian (Unix) byte order. • SMOSIce: Restricted. Contact Lars Kaleschke at Uni. Hamburg.

	Used in assimilation	• CryoSat-2: Lisæter, K. A., G. Evensen, and S. Laxon (2007), Assimilating synthetic CryoSat sea ice thickness in a coupled ice-ocean model, J. Geophys. Res., 112, C07023 • ICESat: Padman, L., Erofeeva, S. Y., & Fricker, H. A. (2008). Improving Antarctic tide models by assimilation of ICESat laser altimetry over ice shelves. Geophysical Research Letters. • ICESat: Mathiot, P., König Beatty, C., Fichefet, T., Goosse, H., Massonnet, F., and Vancoppenolle, M. (2012), Better constraints on the sea-ice state using global sea-ice data assimilation, Geosci. Model Dev., 5, 1501-1515, doi:10.5194/gmd-5-1501-2012. • SMOSIce: Not yet.
	More info	• Cryosat : https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat • ICESat : – http://icesat.gsfc.nasa.gov/icesat/index.php – http://icesat.gsfc.nasa.gov/icesat/publications/GRL/schutz-1.pdf • SMOSIce: https://wiki.zmaw.de/ifm/SMOSIce
Sea Sufrace Salinity (SSS)	Parameters	The sea surface salinity is measured at the L-band (1.4 GHz), transparent to the atmosphere and sensible to microwave emissivity fluctuations of water surface. Also soil moisture.
	Resolution	• SMOS resolution is 35-50 km, resampled on a 15km grid, but the resolution is often degraded to reduce noise (e.g. 1°every 10 days). • Aquarius : Global Coverage and the spatial resolution is 100-300 km.
	Coverage and specifications	• SMOS : Global. Altitude : 758 km. Inclination : 98°. Launched on 2 November 2009 until november 2012. Repeat cycle: 23 days. • Aquarius : Altitude : 657 km. Specifications of 7 days is repeated 4 times per month.

Observation operator	Generally a simple interpolation and possibly a spatial filter.
Observation errors	• SMOS : Salinity : 0.5-1.5 psu, and 0.1 psu for 10-30 days averaged data for an area of 200 km x 200 km. Soil moisture accuracy : 4%. • Aquarius : Salinity : 0.2 psu
Data access	• SMOS : https://earth.esa.int/web/guest/data-access/browse-data-products/-/asset_publisher/y8Qb/content/level-2-ocean-salinity-6895?p_r_p_564233524_assetIdentifier=level-2-ocean-salinity-6895&redirect=%2Fc%2Fportal%2Flayout%3Fp_l_id%3D65465. Public access • Aquarius : http://podaac.jpl.nasa.gov/SeaSurfaceSalinity/Aquarius. Public access via previous registration. L2 and L3 products available via FTP. Data format : binary file (HDF).
Used in assimilation	SMOS & Aquarius • Tranchant, B., Testut, C., Renault, L., Ferry, N., Birol, F., & Brasseur, P. (2008). Expected impact of the future SMOS and Aquarius Ocean surface salinity missions in the Mercator Ocean operational systems: New perspectives to monitor ocean circulation. Remote Sensing of Environment, 112(4), 1476-1487. • Brassington, Divakaran. (2008). The theoretical impact of remotely sensed sea surface salinity observations in a multi-variate assimilation system. Ocean Modelling, 27(1-2), 12-12.
More info	• SMOS https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/smos • Aquarius http://www.tos.org/oceanography/issues/issue_archive/issue_pdfs/21_1/21.1_lagerloef.pdf

Sentinel	Parameters	Family of satellites that are to replace ENVISAT and to be launched the next decade. Sentinel 1A,1B,1C,2A,2B,2C,3A,3B,3C,4A ought to measure various parameters like sea surface topography, soil moisture, snow cover, sea ice cover, ocean surface winds, ocean color, cloud types, profiles and top temperature, vegetation, albedo, radiation budget and more.
	Coverage and specifications	Global. Altitude : 693 km for Sentinel-1, 786 km for Sentinel-2 and 814 km for Sentinel-3. Repeat cycles : 12, 10 and 27 days respectively for family 1, 2 and 3. Inclinations around 98 °. Mission durations are about 8 years. Swath width : $\sim$ 250-290 km for Sentinel-1 and 2. 1270 km for Sentinel-3.
	Resolution	• Sentinel-1: SAR: ground resolution of 20 m. 9m for strip mode. • Sentinel-2 : Optical sensors : $\sim$ 20 m (10-60 m depending on the band). • Sentinel-3 : SLTSR (Sea and Land Surface Temperature Radiometer): spatial resolution in the visible and shortwave infrared channels of 500 m and 1 km in the thermal infrared channels. OLCI (Ocean and Land Color Instrument): 300 m over all surfaces. SRAL (Synthetic Aperture Radar Altimeter): 300 m.
	Observation operator	To be determined.
	Observation errors	• Sentinel-1 : C-band SAR. Radiometric accuracy 1 dB (3 sigma). • Sentinel-2 : MSI Multi-Spectral Instrument. Absolute radiometric accuracy for Level 1C data: 3 - 5% • Sentinel-3 : SLTSR Sea and Land Surface Temperature Radiometer : Temperature : 0.3 K. OLCI : 2% absolute accuracy, 0.1% relative.
	Data access	Sentinel 1 and 2 launched in April 2014 and June 2015. Will be distributed by GMES `http://gmesdata.esa.int/web/gsc/home` and `https://sentinel.esa.int/web/sentinel/home`
	Used in assimilation	

	More info	• http://www.esa.int/esaLP/SEM097EH1TF_LPgmes_0.html • http://database.eohandbook.com/database/missiontable.aspx • https://sentinel.esa.int/web/sentinel/home
Sentinel 1	Parameters	Ocean Wind Field (OWI) Component, Ocean Swell Spectra (OSW) Component, Surface Radial Velocity (RVL). https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/product-types-processing-levels/level-2
	Coverage and specifications	Global. Altitude : 693 km for Sentinel-1 Repeat cycles : 12 days. Inclinations around 98 °. Mission durations are about 8 years. Swath width : $\sim$ 250-290 km
	Resolution	• Sentinel-1: OSW: 20km; OWI and RVL: 1km.
	Observation operator	To be determined.
	Observation errors	• RVL: 0.29-0.34m/s; OWI: 2m/s, 30°OSW: see https://sentinel.esa.int/web/sentinel/sentinel-1-sar-wiki/-/wiki/Sentinel+One/Ocean+Swell+Spectra+%28OSW%29%20Component SWH: 0.5;
	Data access	Sentinel 1 and 2 launched in April 2014 and June 2015. Will be distributed by GMES http://gmesdata.esa.int/web/gsc/home and https://sentinel.esa.int/web/sentinel/home
	Used in assimilation	
	More info	• http://www.esa.int/esaLP/SEM097EH1TF_LPgmes_0.html • http://database.eohandbook.com/database/missiontable.aspx • https://sentinel.esa.int/web/sentinel/sentinel-1-sar-wiki

Sentinel 2	Parameters	Mostly land oriented products but Bottom-of-atmosphere reflectance also usefull for ocean color in Mediterranean Sea, closed seas and coastal waters (20km distance). https://sentinel.esa.int/web/sentinel/user-guides/sentinel-2-msi/product-types/level-2a
	Coverage and specifications	Global. Altitude : 786 km for Sentinel-2.. Repeat cycles : 10 days. Inclinations around 98 °. Mission durations are about 8 years. Swath width : $\sim$ 250-290 km
	Resolution	• Band depending (10m to 60m)
	Observation operator	To be determined.
	Observation errors	•
	Data access	Sentinel 1 and 2 launched in April 2014 and June 2015. Will be distributed by GMES http://gmesdata.esa.int/web/gsc/home and https://sentinel.esa.int/web/sentinel/home
	Used in assimilation	
	More info	• http://www.esa.int/esaLP/SEM097EH1TF_LPgmes_0.html • http://database.eohandbook.com/database/missiontable.aspx • https://sentinel.esa.int/web/sentinel/sentinel-2-sar-wiki
Sentinel 3	Parameters	OLCI: Ocean and Land Colour Instrument, Sea and Land Surface Temperature Radiometer (SLSTR), Synthetic Aperture Radar Altimeter (SRAL) and Microwave Radiometer (MWR)
	Coverage and specifications	Global. Altitude : 840 km for Sentinel-1. Repeat cycles : 27 days. Inclinations around 98 °. Mission durations are about 8 years. Swath width : $\sim$ 1270 km
	Resolution	• Color: 300m, SST: 1km, SRAL: 300m

	Observation operator	To be determined.
	Observation errors	•
	Data access	
	Used in assimilation	
	More info	• http://www.esa.int/esaLP/SEM097EH1TF_LPgmes_0.html • http://database.eohandbook.com/database/missiontable.aspx • https://sentinel.esa.int/web/sentinel/sentinel-3-sar-wiki
Carbon fluxes - CarbonSat	Parameters	Concentration and distribution of carbon dioxide and methane.
	Coverage and specifications	Global within 1-6 days. Swath width from 160 to 500 km. Expected launch in 2019 for a 3-5 lifetime mission.
	Resolution	Better than 2x2 km.
	Observation operator	To be determined.
	Observation errors	CO2 concentration : 1 ppm. CH4 concentration : 9 ppb.
	Data access	Not yet launched.
	Used in assimilation	
	More info	• Mission overview http://www.iup.uni-bremen.de/carbonsat/CarbonSat_FactSheet.pdf
Gravity field - GOCE	Parameters	Gravity-field anomalies are used to retrieve the mean dynamic topography (MDT).
	Coverage and specifications	Inclination : 96.7 °. Altitude: 254.9 km.. Launched on March,17 2009 until end 2012. Will be prolonged and lowered to 235 km.
	Resolution	Better than 100km.
	Observation operator	To be determined.

Observational error	The accuracy of the gravity-field anomalies measurement is 1 mGal (where 1mGal = 10^{-5} ms^{-2}). The accuracy of the geoid measure is 1-2cm.
Data access	https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/goce/content?p_r_p_564233524_assetIdentifier=goce-data-access-7219 Public access. Data format : XML for Level-2 products.
Used in assimilation	• Haines, K., Johannessen, J. A., Knudsen, P., Lea, D., Rio, M. H., Bertino, L., et al. (2011). An ocean modelling and assimilation guide to using GOCE geoid products. Ocean Science, 7(1), 151-164. • Haines, K., Johannesson, J., Knudsen, P., Lea, D., & Rio, M. H. (2010). Using the goce mdt in ocean data assimilation. Ocean Science Discussions, 7, 1849-1887.
More info	https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/goce

2.2 Other links

- CEOS Earth Observation Database, ESA : http://database.eohandbook.com/. This database allows the user to browse and search for any kind of instrument and sensor type, providing all the information above and much more.
- How to access EO data (ESA) : https://earth.esa.int/web/guest/data-access/how-to-access-eo-data/earth-observation-data-distributed-by-esa
- Sentinel: https://sentinel.esa.int/web/sentinel/home