ESA-SOLAS
EARTH OBSERVATION AND SEA-AIR INTERACTIONS SCIENCE PRIORITIES

ESRIN, Frascati, Italy
28th – 31st October, 2014

ESRIN, Frascati, Italy
13th-15th June, 2016

Editors:

Emilie Breviere, GEOMAR Helmholtz Centre for Ocean Research, Germany
Craig Donlon, ESA
Diego Fernández-Prieto, ESA
Christoph Garbe, University of Heidelberg, Germany
Veronique Garçon, LEGOS/CNRS, Toulouse, France
Stefan Kontradowitz, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
Simon Pinnock, ESA
Roberto Sabia, Telespazio-Vega UK for ESA

REF: EOP-SA/0362/DFP-dfp

Table of Contents

Scientific Committee and Contributors

Paulo Artaxo, Instituto de Física, Brazil
Vittorio Brando, Institute of Atmospheric Sciences and Climate, Italy
Tom Bell, Plymouth Marine Laboratory, Plymouth, UK
Jerome Benveniste, European Space Agency (ESA-ESRIN), Frascati, Italy
Emmanuel Boss , University of Maine, USA
Jacqueline Boutin, LOCEAN, Paris, France
Astrid Bracher, IUP, University of Bremen, Bremen, Germany
Pierre Brasseur, LGGE/CNRS, Grenoble, France
Emilie Breviere, GEOMAR Helmholtz Centre for Ocean Research, Germany
John P. Burrows, IUP/IFE, University of Bremen, Bremen, Germany
Bertrand Chapron, IFREMER, Plouzané, France
Jacek Chowdhary, NASA, USA
Craig Donlon, ESA
Oleg Dubovik, French National Centre for Scientific Research, France
Gerrit de Leeuw, Finnish Meteorological Institute, Helsinki, Finland
Anja Engel, GEOMAR, Kiel, Germany
Maria Cristina Facchini, Institute of Atmospheric Sciences and Climate (ISAC), National Research Council (CNR), Italy
Chris Fairall, NOAA/ESRL, University of Colorado, Boulder, CO, USA
Diego Fernández-Prieto, ESA
Jordi Font, Institut de Ciències del Mar, CSIC, Barcelona, Spain
Huiwang Gao, Ocean University of China, Qingdao, China
Christoph Garbe, University of Heidelberg, Germany
Veronique Garçon, LEGOS/CNRS, Toulouse, France
Michelle Graco, IMARPE, Callao, Peru
Cécile Guieu, LOV, Villefranche-sur-mer, France
Tristan Harmel, Pierre and Marie Curie University, France
Christoph Heinze, University of Bergen, Bergen, Norway
Chris Hostetler, NASA, USA
Cedric Jamet, Laboratoire d'Océanologie et de Géosciences, France
Kirk Knobelspiesse, NASA, USA
Stefan Kontradowitz, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
Ilan Koren, Weizmann Institute of Science, Rehovot, Israel
Yoav Lehahn, Weizmann Institute of Science, Israel
Maurice Levasseur, Université Laval, Canada
Peter Liss, University of East Anglia, Norwich, UK
Pavel Litvinov, L'Université de Lille, France
Christa Marandino, GEOMAR, Kiel, Germany
Lisa Miller, Institute of Ocean Sciences, Fisheries and Oceans, Canada
Peter Minnett, Rosenstiel School of Marine and Atmospheric Science, Miami, FL, USA

Amit Mishra, DST INSPIRE FACULTY at Radio and Atmospheric Science Division, National Physical Laboratory, New Delhi, India
Kiyak Nazliolgun, Istanbul Teknik Üniversitesi, Turkey
Griet Neukermans, Université Laval Québec, Canada
Colin O'Dowd, National University of Ireland Galway, Galway, Ireland
Ananda Pascual, IMEDEA(CSIC-UIB), Esporles - Islas Baleares, Spain
Simon Pinnock, ESA
Marcos Portabella, Institut de Ciències del Mar, CSIC, Barcelona, Spain
Trish Quinn, NOAA PMEL, Seattle, WA, US
Eric Saltzman, National Science Foundation, USA
Sarma, V.V.S.S., CSIR - National Institut of Oceanography, India Peter Regner, Andrew Sayer, NASA, USA Parvadha Suntharalingam, UEA, UK
Yeala Shaked, Hebrew University of Jerusalem, Israel
Knut Stamnes, Stevens Institute of Technology, USA
Erik Swietlicki, Lund University, Sweden
Nicolas Reul, IFREMER, La Seyne-sur-Mer, France
Ian Robinson, National Oceanography Centre, Southampton, UK
Natalia Rudorff, National Institute for Space Research Brazil, Brazil
Roberto Sabia, Telespazio-Vega UK for ESA
Alfonso Saiz-Lopez, Instituto de Química Física Rocasolano, CSIC, Madrid, Spain
Eric Saltzman, University of California, Irvine, CA, USA
Jamie Shutler, Plymouth Marine Laboratory, Plymouth, UK
Rafel Simo, Institut de Ciències del Mar, CSIC, Barcelona, Spain
Parvadha Suntharalingam, UEA, UK
Brian Ward, National University of Ireland Galway, Galway, Ireland
Andrew Watson, University of Exeter, Exeter, UK
David Woolf, Heriot-Watt University, Edinburgh, Scotland
Mingxi Yang, Plymouth Marine Laboratory, Plymouth, UK
Christopher Zappa, LDEO, Columbia University, Palisades, NY, USA

List of Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
AOD	Aerosol Optical Depth
ASCAT	Advanced SCATterometer
AVHRR	Advanced Very High Resolution Radiometer
BUFR	Binary Universal Form for the Representation of meteorological data
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CCN	Cloud Condensation Nuclei
DMS	DiMethylSulfide
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño–Southern Oscillation
GCOS	Global Climate Observing System
GHG	GreenHouse Gas
GOME-2	Global Ozone Monitoring Experiment–2
GOTM	General Ocean Turbulence Model
HOAPS	Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data
IASI	Infrared Atmospheric Sounding Interferometer
ITCZ	InterTropical Convergence Zone
J-OFURO	Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations
LHF	Latent Heat Flux
MAN	Maritime Aerosol Network
MISR	Multi-angle Imaging SpectroRadiometer
MIZ	Marginal Ice Zone
MODIS	Moderate Resolution Imaging Spectroradiometer
NCEP	National Centers for Environmental Prediction
NWP	Numerical Weather Prediction
OA	Ocean Acidification
OAFlux	Objectively Analyzed air-sea Fluxes
OI SSS	Optimal Interpolation Sea Surface Salinity
OM	Organic Matter
OMI	Ozone Monitoring Instrument
OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis
PBL	Planetary Boundary Layer
RMSD	Root-Mean-Square Deviation
SAR	Synthetic Aperture Radar
SEVIRI	Spinning Enhanced Visible and InfraRed Imager

SHF	Sensible Heat Flux
SMOS	Soil Moisture and Ocean Salinity
SOCAT	Surface Ocean CO2 Atlas
SPCZ	South Pacific Convergence Zone
SPURS-2	Salinity Processes in the Upper Ocean Regional Study 2
SSA	Sea-Spray Aerosol
SSH	Sea-Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TAO	Tropical Atmosphere Ocean
TROPOMI	TROPOspheric Monitoring Instrument
VOS	Voluntary Observing Ship
WRF	Weather Research & Forecasting

Meeting abstracts book and presentations

A link to all meeting presentations and abstract book can be found here:

http://www.eo4oceanatmosphere2014.info

Acknowledgements

Special thanks are given to SOLAS, the SOLAS Scientific Steering Committee and all scientists whose studies and recommendations contributed to this paper as well as to all participants worldwide that made these workshops possible.

1. Objectives of this document

This paper summarizes the main results and conclusions of the “Earth Observation for Ocean-Atmosphere Interactions Science 2014” conference, organized jointly by the European Space Agency (ESA), the Surface Ocean and Lower Atmosphere Study (SOLAS) and the European Geosciences Union (EGU). The meeting, hosted at the ESRIN facilities of ESA in October 2014, involved more than 120 scientists over 25 countries and addressed the latest advances and scientific developments in the use of Earth Observation technology to observe, monitor and predict the different components and processes governing the ocean-atmosphere interactions, reviewing the related applications. This paper gives a broad overview of the conference talks, summarizes the main results of the discussions and provides guidance and recommendations for future research and the development of activities in this scientific area.

The report was subsequently updated and enriched with the results of the workshop “Harnessing Remote Sensing to Address Critical Science Questions in the Ocean-Atmosphere Interface” organised by SOLAS in June 2016 and hosted in ESA-ESRIN.

The outcome of the meetings and its conclusions will contribute to guide scientific activities on ocean-atmosphere interactions research, supporting the scientific community and SOLAS strategic objectives.

This document, together with additional inputs, will contribute to establish a strong science component on ocean-atmosphere interactions in the upcoming programmatic elements of ESA (for the 2017-2021 timeframe).

The current document elaborates on the meetings discussions as well as on the different information exchanges with the participants and other experts during and after the meetings.

It is worth mentioning that the workshops did not cover all areas of research and science in the context of ocean-atmosphere interactions research, and that this document only provides a partial outlook, addressing some of the main Earth Observation contributions to sea-air interactions science priorities.

The meetings and this document focus mainly on scientific aspects and research needs. Needs for the services and operational aspects were not discussed in detail at the meeting and are only mentioned in this document when pertinent but are not described at length.

Although services are only hinted at in this document, the scientific advances and research developments discussed below (in terms of novel missions, new methods and algorithms, innovative products, and enhanced knowledge of Earth system processes) represent some of the main areas to be further developed for the next generation of EO applications and information services for oceanography and climate, among others.

2. Introduction

Physical and biochemical interactions between oceans and atmosphere involve several key processes governing the Earth system dynamics and its climate. Momentum, heat/freshwater fluxes, aerosol and gas exchange between the ocean surface and the atmosphere boundary layer influence key components of the Earth system such as ocean circulation, Earth radiation budget, global carbon cycle and biodiversity, among others. In this context, the measurement, quantification and long-term monitoring of the different ocean and atmospheric variables involved in these key processes is of major importance to better understand, characterise and predict their behavior and their influence on climate and human activities.

The International Surface Ocean - Lower Atmosphere Study (SOLAS) project is an international research initiative aiming to "achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere, and how this coupled system affects and is affected by climate and environmental change." Achieving this challenging objective not only calls for interdisciplinary research (involving biogeochemistry, physics, mathematical modelling, etc.), but also requires marine and atmospheric scientists to work closely together with Earth Observation (EO) scientists and modelers. SOLAS has just marked its 10^{th} anniversary, and in order to define the next SOLAS scientific challenges for the future, the SOLAS community has defined eight research themes that form part of a Science Plan for the next phase of SOLAS. The SOLAS research themes are:

- Greenhouse gases and the oceans;
- The air-sea interface and fluxes of mass, energy;
- Atmospheric nutrient and particles supply to the surface ocean;
- Interconnections between aerosols, clouds and ecosystems;
- Ocean emissions and tropospheric oxidizing capacity;
- Interconnections between ocean biogeochemistry and stratospheric chemistry;
- Multiple stressors and ocean ecosystems;
- High Sensitivity Systems.

Recent advances in EO technology allowed improved global observations of several key parameters governing the ocean-atmosphere interactions. In the coming years, an increasing number of EO missions (Sentinels series, Earth Explorers, Third-Party Missions) will provide an unprecedented capacity to observe the sea-surface and the atmosphere, opening a new era in EO for ocean-atmosphere interactions science. The full exploitation of this capacity by scientific and institutional users, in particular to better understand the role of ocean-atmosphere interactions in climate change, requires coordination. Transparent research efforts must develop robust global geo-information products and facilitate their integration into suitable coupled biochemical/physical models describing and predicting ocean-atmosphere processes. In this context, the exploitation of data from existing and planned satellite missions and the identification of "missing" remote sensing observations from space, will be instrumental to further pursue the SOLAS science objectives.

ESA, SOLAS and EGU organized the "Earth Observation and Ocean-Atmosphere Interactions Science 2014" Conference, which took place on the 28-31 October 2014 at ESA/ESRIN, Italy, to advance our knowledge of the potential offered by EO technology to answer some of the major open questions in both domains. The specific objectives of this topical conference were:

- To increase the scientific understanding of the main processes governing ocean-atmosphere interactions and their impacts on the Earth system and climate with special attention to the 8 SOLAS strategic science themes;
- To review the current advances in EO technology and its capacity to contribute to the SOLAS next decade science challenges;
- To discuss the challenges and opportunities offered by the new generation of EO satellites, as well as the major observational gaps for the coming years.
- To accelerate the development of novel and reliable multi-mission data products capable of exploiting the synergies of the increasing number of complementary EO missions to better address the major scientific gaps in ocean-atmosphere interactions;
- To foster the integration of EO data into advanced coupled models describing and forecasting main ocean-atmosphere processes;
- To consolidate a scientific roadmap outlining priorities, challenges and scientific requirements to further advance in the development and exploitation of global observations and consistent data records capable of supporting the international scientific efforts of the SOLAS community.

The conference brought together the EO, SOLAS and EGU communities, as well as scientific institutions and space agencies involved in the observation, characterization and forecasting of ocean-atmosphere interactions and their impacts. The event represented a significant opportunity to facilitate communication and scientific exchange among these different communities and enhance the coordination of scientific efforts leading to a common view of major scientific needs and priority areas for the future.

Latter, the 13-15 June 2016, ESA hosted in ESRIN the SOLAS workshop, "Harnessing Remote Sensing to Address Critical Science Questions in the Ocean-Atmosphere Interface". The meeting was dedicated to highlight key challenges in the Surface Ocean - Lower Atmosphere Study (SOLAS) science, and how remote sensing measurements and approaches can help address them. To do so the workshop brought remote sensing, SOLAS, and related sciences experts together to brainstorm on the issue, and to produce an example of key SOLAS problems that could be approached by newer/improved remote sensing methodologies. Three of the main SOLAS themes were selected for discussion;

1. Ocean biogeochemical control on atmospheric chemistry;
2. Air sea interface and fluxes of mass and energy;
3. Interconnections between aerosols, clouds and marine ecosystems.

This report summarizes major insights of the conference and workshop talks, gathers the main conclusions and recommendations from the different discussion and presents a basis for further activities in support of the ocean-atmosphere scientific community.

3. Novel EO missions

The session addressed a number of EO mission concepts under development, mainly focused on the sea state and dynamics, one of the most important aspects of the ocean-atmosphere interactions.

For instance, the Wavemill/Ocean Surface Current Mission (OSCM) concept could deliver new high-resolution observations of Total Surface Current Velocities (TSCV) at a few kilometers resolution. Alternative concepts addressing similar objectives, but based on Along Track Interferometry (e.g., at Ku-band), were also discussed. This information is relevant to research on air-sea interactions, ocean/atmosphere coupling, upper ocean dynamics, vertical transports, large-scale ocean circulation, with implications for long-term climate forecasting. The concept is based on an active microwave sensor at Ku-band (~2.0 cm), which allows single-pass along-track interferometry between two SAR images. TSCV are estimated by measuring phase differences via Along Track Interferometry, where the same area of ocean is illuminated with a radar swath at two different times; being constant all the other parameters, the phase difference between the two received signals will be due to ocean currents.

The China-France Oceanographic Satellite (CFOSAT) aimed at measuring ocean surface wind and waves was also described at the meeting. These parameters represent a key input for atmospheric, oceanic and wave forecast systems, improving knowledge and parameterization of processes affecting surface waves and the characterization and modelling of air/sea exchanges and coupled effects. The mission, expected to be operational in 2018, is based on two different Ku-band scatterometers for waves and winds, respectively. The simultaneous measurements of wind and long waves, as well as a "proxy" for moment flux (mean square slope of the surface) will contribute to the study of the impact of waves through wave-breaking and whitecap coverage with mass, heat and gas exchanges (e.g. CO_2, sea spray production).

Finally, the development status and the potential and limitations over oceans of the Earth Explores (EE8) candidate missions Flex (for estimation of the land fluorescence) and Carbonsat (for CO_2 atmospheric total column) were introduced.

The discussion addressed several aspects of the scientific needs, requirements and observational gaps for the ocean-atmosphere interactions community in the coming decade. Four main gaps in observations have been identified and potential concepts proposed:

- A polarimetric multi-frequency microwave radiometer would be useful to provide high-resolution brightness temperatures (5 km sampling at 10 km resolution) for

detecting SST, SSS over river plume regions, high-wind regimes, rainfall information and integrated atmospheric water vapour.
- A sub-mesoscale "surface vorticity mapper" using quad-pol Doppler active microwave instruments may provide a means to decompose wind/wave and total surface current information.
- A dedicated ocean current mission to detect wind, wave and currents, based on a Doppler instrument would be extremely valuable.
- A novel dedicated mission addressing the needs of the ocean acidification issue is a high priority, aiming at measuring biogeochemical parameters from space characterising different biochemical components of the carbonate system (e.g., total alkalinity).

In addition, more general recommendations of the way forward were made for maximising the scientific exploitation of existing missions and to prepare for the development of novel concepts for the future:

- It is mandatory to fully explore all frequency domains, from L-band to mm-wavelengths. The exploration and exploitation of multi-frequency synergies may open the door to novel and robust observation products. In this context, it is mandatory to pursue consistency in algorithms and exploit interactions among satellites and sensors (e.g. winds, SST, SSS). Further low-level work on the interaction of electromagnetic waves with the sea surface is required.
- In this context, the opportunities offered by SMOS and Aquarius L-band and in future SMAP missions are very interesting as their measurements carry information on the dielectric constant. Developing a continuum of dielectric properties at different frequencies, which are related to several ocean phenomena, may open the door to new perspectives in the way of estimating several parameters. Further low-level work on the interaction of electromagnetic waves with the sea surface is required.

- The complementarity with in-situ measurements needs to be reinforced; especially over dedicated collaborative ocean areas (ocean test facilities). In this context:
  - The utility of community-based online tools, such as the "OceanFlux-engine" (cloud-based computing technology) to test/share results and crowd-source experiments should be further exploited.
  - An easy access for in-situ scientists to all available EO data coincident with their in-situ data is a high priority requirement. One way to approach this is to promote the idea of specific super-sites, focusing on in-situ and EO data collection/collation on particular areas. As an example, the ESA Felyx project can already help to extract all EO data coincident with available in-situ measurements.

- In order to address most of the mesoscale processes, the spatial resolution desired for future mission would be on the order of 5-15km, preferably at the low-frequency end of the microwave band.

- The need for higher resolution to detect phenomena at (sub)-mesoscale (<20 km) is also an important requirement. At these scales temporal aggregation of data is not valid and the challenge is to work with "snapshots" of ocean dynamics as manifest in the complex 2D structures imaged at the sea surface. Further work on the application of snapshot and conventional medium-resolution (>40 km) daily average data is required.

- It would be highly beneficial to better sample high latitudes (the enhanced revisit time provided by polar satellites is already an asset depending on swath width of a specific instrument), where optical sensors have limitations due to cloud cover and cloud/ice discrimination. The reason for that is associated to the different ocean-atmosphere processes and the dynamics taking place in the polar areas. As an example, the Arctic ocean spin-up process is becoming a major issue for the future that needs urgent and focused attention. The loss of sea-ice cover is changing the air-sea interaction over the Arctic Ocean impacting sea ice and the fluxes of heat, gas and momentum. Further research is required in the Arctic Ocean to fully understand the consequence of this changing environment.

- Passive microwave imaging sensors represent a promising tool for studying air-sea interaction (having the potential capability to measure SST, SSS and surface wind and sea-state). Today such a capability is missing in the Copernicus space segment.

- In this context, convoy and constellation concepts, as discussed in the ESA-NASA Convoy workshop, are extremely attractive. Novel dedicated satellites, flying in formation with operational long-term firmly planned missions (e.g., the Sentinel series) is one possible solution to collect near coincident data from complementary passive and active sensors. This concept should be further explored and other potential concepts could be investigated (e.g., MetOp led/followed by a multi-frequency passive microwave sensor, gathering SSS information together with SST, whilst Ocean Colour is measured by S3 for ocean acidification). Wider exploitation of geostationary data should also be pursued.

- The potential offered by Lidar instruments also needs further investigation in the ocean context. For instance, to evaluate the vertical water column densities to certain depths (an opportunity for this experiment could be provided by the forthcoming launch of the ESA Earth Explorer-5 ADM Aeolus).

- The ocean carbon cycle and its changes over large temporal scales is a major priority for investigation. Air-sea gas flux estimation needs to be tackled by satellite missions in synergy with in situ and other supporting data. Some potential ideas have been mentioned to address this complex issue (e.g., study the ocean by a satellite-in-situ combined mission, linking acoustic measurements performed at the ocean with dedicated satellite observations).

- Sentinel-1 SLC Wave Mode needs to be systematically disseminated to ensure continuity and heritage with the previous Envisat mission. The additional knowledge from S1 together with the whole 20 years archive of ERS- and ENVISAT SAR measurements could shed new light into ocean phenomenology (e.g., slicks, crossing seas, wave-current coupling), atmosphere phenomenology (e.g., rain cells, wind streak alignments and occurrences), and interactions (wind/swell/atmosphere), as well as to provide global range velocity on monthly scales.

4. Greenhouse gases fluxes

The quantification and prediction of CO_2 fluxes between the atmosphere and ocean represents a major science question for the ocean-atmosphere interactions community. Human-induced carbon fluxes addition to a large natural system, which was in steady state in pre-industrial time, is a topical issue. The ocean represents a major sink of the total CO_2 emissions (approximately 26% of the total emissions) amounting to 9.4±1.8 Gt CO_2/yr being the North Atlantic the most intense sink. Today's computation of the total carbon budget is mainly based on the combination of different techniques, observations and modelling approaches, (with well-constrained estimates for the emissions, the atmospheric increase is derived from observations, the ocean sink is derived mainly from modelling approaches and the vegetation uptake is computed as the difference). In this context, ocean fluxes derived from models may not capture properly the variability of the real ocean. At the same time regional uptakes can be substantially wrong. Therefore, there is a major need to develop the capability to estimate ocean uptake more directly from observations.

In this context, the SOCAT initiative, presented by Bakker et al., (2014) represents one of the most valuable international efforts of the ocean observing community. SOCAT, involving more than 100 contributors, is a powerful data synthesis product of in-situ observations documenting the ocean carbon cycle. It generated a quality controlled, fully documented and freely-available dataset of ocean pCO_2 (fugacity) from 1968 to the present with more than 10 million data points. This dataset represent today a major reference for ocean CO_2 studies and a unique complement to satellite observations to further advance in the computation of CO_2 fluxes at global scales.

However, in-situ observations do not provide a complete temporal and spatial coverage globally, with poor sampling in certain ocean regions and gaps in space and time that imply a number of limitations and constraints in the use of this type of data for global and regional studies. Direct estimation of the CO_2 fluxes from satellite data alone, based on the bulk formula equation, is not possible yet with sufficient quality. While different parameterisations of the gas transfer velocity and solubility may be derived from satellite observations such as SST, winds, ocean colour and SSS, the computation of the pCO_2 gradient between the ocean and the atmosphere requires in-situ observations as those provided by the SOCAT dataset.

Current satellite technologies cannot measure the partial pressure of in water CO_2 and therefore there is a critical need to ensure that such in-situ measurements are expanded in terms of coverage and sustained. While satellite technology may significantly contribute to better estimates of ocean uptake of CO_2 and acidification, without the complementary in-situ ocean data it would be significantly constrained. New satellite technologies, fully exploiting the dielectric constant of seawater may provide a way forward (e.g. how could we measure the carbonate system from space?). However, in this context a much better understanding of electromagnetic waves interaction with the sea surface is required.

Several research efforts are dedicated to explore the potential of satellite data to overcome the coverage limitation of in-situ datasets for the estimation of pCO2. As an example, a neural network approach was presented by Parard et al., (2015) to estimate pCO2 variability and the CO2 flux in the Baltic Sea with satellite data (e.g., SST, Ocean Colour, winds), where in-situ data were only available over a rather restricted area.

Another example, presented by Brown et al., (2015) demonstrated the potential of using SMOS data, OSTIA SST and ASCAT data in the Eastern Pacific Ocean to estimate high resolution surface ocean pCO2 data. The method was based on a statistical model linking the SOCAT data to the satellite observations which revealed the impact of different atmospheric forcing (e.g., rain, winds) in the pCO2 variability in different areas of the study region.

An alternative method was proposed by Yahia et al., (Hernandez-Carrasco et al., 2015) as part of the ESA project OceanFlux-Upwelling, where a novel methodology to derive high-resolution estimates of Ocean pCO2 at 4Km resolution was presented. The method, an inversion scheme based on singularity exponents and optimal wavelets, uses the information cascade at different resolutions between SST and Ocean color satellite data and CarbonTracker CO2 fluxes data at low resolution (~110 km) to derive pCO2 of the oceans at high-resolution.

On a global perspective and looking at the CO2 fluxes, the ESA project OceanFlux-GHG presented the first EO-driven global climatology of air-sea CO_2 gas fluxes. The project presented by Shutler et al., also addressed a number of related issues such as the development of calibrated and validated algorithms for estimating gas transfer velocity from space, the study of the CO_2 sink in Arctic waters, the results of modelling the carbonate system in European shelf seas, and methods for quantifying uncertainties in EO-derived air-sea gas fluxes. As a major achievement of the project, a community open-source gas flux processing tool, FluxEngine (Shutler et al., 2015), was presented and tested through a crowdsourcing exercise during the Conference. This tool is now available for the scientific community, allowing an online user-driven (via scientific crowd-sourcing approaches) computation of CO2 global climatologies based on EO data and in-situ observations.

It is also worth noting the great importance of the application of suitable techniques, instruments and quality control in the in-situ data collection. These data are critical to further advance our basic knowledge on the dynamic processes governing the gas transfer velocity. An example of this, was presented by Yang et al., (2014) where the impact of different aspects (e.g., waves, winds, surfactants) in in-situ measurements (eddy-covariance) of air/sea DMS, acetone and methanol transfer velocity and turbulent fluxes were studied, especially under strong wind conditions.

The potential of EO technology to provide information on other relevant variables and parameters were also discussed. Grieco et al. (2015) presented the potential offered by IASI to provide GHG measurements over the Mediterranean area. Also, the potential of SAR images to identify surfactants (supporting the study of its related bacteria in the laboratory) in the ocean surface was discussed by Hamilton et. al., (2015).
In this context:

- Further efforts are required in order to advance in the synergistic use of EO and in-situ datasets to better quantify ocean CO2 fluxes and contribute to reliable observations-based estimates of the global carbon budget. In fact, the current global CO2 uptake of 2.6 Pg C yr-1 (2013 estimation) is not readily obtained from sea-air CO2 flux estimates. There is an urgent need to consolidate reliable methods and techniques that may address this need.

- In the short-term, the recent or upcoming availability of missions such as Sentinel 1, Sentinel 3, SMOS, Aquarius and MetOp, together with in-situ observations will open the door to the development of global CO2 flux estimates as a stand-alone product purely based on observations.

- A major source of uncertainty when computing fluxes over large areas come from the limited coverage of in-situ observations (e.g., pCO2). In this context, further efforts are needed to optimize the observing networks and maintain and expand existing dedicated international efforts such as SOCAT. In addition, further research needs to be dedicated to the development of robust methodologies that may exploit the spatial and temporal coverage of satellite data to overcome the sampling limitations of in-situ observations.

- An effort should be made to maintain current and establish new air-sea flux fiducial reference networks, and to increase the number of ships making high quality routine flux measurements. Flux measurements should be established on ships of opportunity (VOS) and bulk flux parameters evaluated. Direct covariance flux measurements (particularly in extreme locations or conditions) should also be established. New technologies for flux measurements, particularly high-resolution gas analysers, should be developed.

- Flux parameterisations will have to be continuously improved, together with recommending additions/improvements for model and reanalysis outputs for direct evaluation against available flux datasets. The documentation of methods used for model-produced fluxes and the corresponding dissemination of results will have to be improved, as well.

- Special attention is required to improve computation uncertainties. Today, uncertainty estimates are not available in many data sets, are not always propagated consistently and the magnitude of uncertainty does not include all terms.

- More efforts should be dedicated to explore and exploit the capabilities provided by multiple sensors (e.g., SSS, SST, Ocean Colour, Winds, sea state) in synergy. Not only to enhance our capacity to estimate CO2 fluxes but also to gain a deeper knowledge inside the processes and interactions governing the gas exchange under various conditions and in different ocean regions.

- This implies the need for high-resolution remote sensing information to better estimate and study sub-grid scale processes and associated uncertainties.

- This research should not only be focused on CO2 but should be also extended to cover multiple gases and their associated processes and impacts in the Earth system.

- Generation of the OceanFlux climatology represents a significant way forward to jointly exploit EO data and in-situ observations. Advancing in this process requires a rigorous methodological approach and a transparent process on choices and assumptions. Also, open questions still need to be addressed by the community, such as the adoption of a "reference year", which may lead to several compromises and ambiguities. In this context, calculations for individual months may mostly be a better solution.

- Finally, there is clearly a need to facilitate open access to data and tools for the scientific community. The availability of FluxEngine, as a community platform, is a positive way forward to be further developed and expanded.

5. Ocean/Atmosphere Interactions at High Latitudes

Ocean at high latitudes is experiencing unprecedented changes under the double pressure of climate change and human activities. In the Arctic, for instance, rapid economic, social and political development coincides with further environmental transformations (i.e. sea-ice extent, ice thickness and drifts, and/or the evolving sea-state climate). In this context, the Arctic Ocean interactions with sea ice, atmosphere and land (through, for instance, rivers outflows) represent a major area of research where EO technology may contribute.

The rapid loss of summer sea-ice cover is changing the way sea ice, ocean and atmosphere interact at different levels. Increasing our understanding on the ocean-atmosphere-sea-ice interactions and the different processes involved represents a major research need. The availability of long-term SAR, altimeter, optical and passive microwave information, together with the availability of new data from recent missions (CryoSat, SMOS, Sentinels) represents a major opportunity for further advancements in this important area.

In the session, several aspects of the ocean-sea ice–atmosphere interactions have been addressed.

Zappa et al., (2014) discussed the different processes taking place at the marginal ice zone. In particular, the study based on different types of satellite, in situ observations and laboratory analysis, identified and characterized different mechanisms taking place (e.g., link of SST, sea ice presence and mixing processes, gas transfer variability with ice floe concentration) in the MIZ that confirm the complex interactions between sea ice concentration, ocean temperature, mixing processes below floes and gas transfer with the atmosphere.

Yackel (Fuller et al., 2014) demonstrated the use of time series of C-band SAR to characterize the snow, sea ice and ocean interfaces and their dynamics and contribute to estimate surface-atmosphere physical and biogeochemical fluxes through the ocean-sea ice-atmosphere interface. Snow thickness on sea ice was identified as a critical parameter in this context.

Land and Shutler (Shutler et al., 2013) addressed the potential offered by EO to estimate the effects of calcifying plankton (coccolithophores) on CO_2 fluxes in the north Atlantic and the Arctic. This study is intimately related to the atmosphere-ocean flux of greenhouse gases, which is a critical part of the climate system and a major factor in the development of the oceans. The Arctic Ocean contributes only ~1% to the global ocean volume but it is thought to account for 5-14% of the total oceanic sink for anthropogenic carbon dioxide (CO_2), a process which begins via air-sea gas exchange. Despite CO_2

receiving most of the attention, other greenhouse gas fluxes that are inter-linked with the carbon cycle include methane (CH_4) and nitrous oxide (N_2O): thus studying these fluxes can aid our understanding of the ocean carbon cycle. Equally, understanding and characterizing DMS - dimethyl-sulphide (considered to be cloud condensation nuclei (CCN)) and oxygen gas fluxes (which can be used to estimate ocean primary production) is also important to help our understanding of the changing Arctic. For example, increased CCN could lead to increased cloud generation leading to further warming in the Arctic and increased loss of sea ice. The inhospitable and heterogeneous nature of high latitudes makes it difficult and expensive to rely solely on in-situ observations for monitoring and understanding this changing environment. Synergistic use of satellites, in-situ data and models, provides a solution to obtaining more spatially complete observations. These data can be used for driving innovative process studies, climate model evaluation and data assimilation, and developing monitoring methodologies.

Cold water can absorb more CO_2 than warmer water, so polar oceans are uptaking CO_2 at a faster rate than elsewhere on the planet. One of the additional issues with the Arctic Ocean is the potential for enhanced ocean acidification in the future as a result of the increased input of freshwater, as sea ice retreats and the planet warms up. It is thought that the addition of freshwater into the Arctic will dilute the ocean's ability to cope with higher acidity (total alkalinity), but this is yet to be tested and verified by observations.

Baseline data is required to understand the current carbonate chemistry and biology in the Arctic, and the processes that could potentially enhance the rate of ocean acidification. Without this knowledge, it is difficult to make predictions about how ecosystems will respond to ocean acidification in the future, and this impedes our ability to mitigate change, as well as to manage the environment.

In this context, research efforts shall be dedicated to:

- developing novel methods for monitoring alkalinity and air-sea CO_2 flux and studying their monthly to inter-annual variations;
- characterizing seasonal dynamics at the lower latitude Arctic gateways to link primary production observations (and food webs) with other factors including ice cover, carbonate chemistry and air-sea gas exchange;
- developing upwelling indices that can identify when and where upwelled events occur along coasts (lower temperature water upwelled with lower pH) and ice edges (warmer water upwelling with higher pH) and to characterize which coasts and regions are most at risk from this phenomenon and;
- further improvements and advances in estimating ice cover, ice thickness, snow depth and sea ice densities (e.g., reliable snow depth and sea ice densities will improve estimates of ice thickness). The study of these parameters in the marginal ice zones is especially important, as this is where gas exchanges are likely to occur.

6. Heat and Freshwater Fluxes

Despite the majority of the presentations in this session focused on the estimation, accuracy and errors characterization of the SST and SSS signals, as major tracers of the heat and freshwaters fluxes, the session encompassed also additional topics of wider relevance, including ocean deep convection, water masses and hurricane intensification forecasting. Whist satellite measurements (form both geostationary and polar platforms) were indeed predominant, a distinctive focus on models and in-situ measurements was present, as well.

Minnett et al. (Emery et al., 2014) reported on ship-based measurements of the air-sea temperature difference. The air-sea temperature difference (ΔT) is important in controlling the stability of the lower atmosphere and the efficiency of heat, moisture and gases transfers from ocean to atmosphere. Infrared spectroradiometers can measure the skin SST and the air-temperature with a single instrument with real-time internal calibration. The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) is used at this scope, measuring the spectra of atmospheric and sea-surface emission. Histograms of air-sea ΔT show very similar form irrespective of region, season and SST. Very few cases of $\Delta T>0$ were measured, which were limited to areas downwind of coasts, and associated with atmospheric and SST fronts. Some aspects of air-sea ΔT histograms are reasonably well represented in models (ECMWF, WRF), but air-sea ΔT appear to be poorly represented in conditions of high SST variability. Infrared hyperspectral measurements have the potential to “recalibrate” the quantitative understanding of air-sea ΔT and the exchanges that depend on them, with implications for remote sensing of air-sea fluxes.

Following on measurements suitable for validating satellite data, Wick and colleagues showed the added-value of drop-sondes as a valuable validation source for satellite-derived flux data. Several products of turbulent air-sea heat flux exist (OAFlux, HOAPS, J-OFURO), but validation, typically from ship and buoy data, is still limited and performance in extreme environments is largely unknown. The study goal therefore was to validate flux inputs/products in more extreme environments and improve the uncertainty estimates. In turbulent flux calculation the greatest variable uncertainty is in near-surface air temperature (Ta) and specific humidity (Qa). Both parameters are retrieved by different multi-channel microwave imager and sounder data (e.g., SSM/I and AMSU). NASA Global Hawk Unmanned Aircraft has been used to drop sondes in several measurements campaigns, especially close and under storms and hurricanes. Agreement in T_a/Q_a outside of hurricane environment is encouraging, whilst satellite Ta and Qa variations in tropical storm environment agree well with drop-sonde observations. Drop-sondes represent a valuable validation source for satellite-derived flux data, providing significant new data in extreme environments.

Harris and colleagues (Koner et al., 2015) presented a high-resolution SST analysis with geostationary data corrected for diurnal variability. A 5-km blended SST analysis is produced daily from 24 hours of AVHRR & Geo-SST (without using buoy data). The objective was to include diurnal warming correction in SST analysis. Sample model profiles of warming with depth and model forcing fields for the Diurnal Warming correction have been shown. NCEP heat fluxes assume fixed SST, but in the presence of diurnal warming, the heat fluxes will change. A flux feedback adjustment has been implemented by scaling accordingly the bulk formulae. As per the product accuracy, median bias (analysis–buoy) is of -0.02 K, while Robust Standard Deviation is 0.29 K. The new code is currently being made operational. It is possible to run a full turbulence scheme in a timely manner for operations, despite uncertainty in forcing fluxes are likely to be a significant issue.

On the same topic, Karagali and colleagues (Karagali et al., 2009) showed some modelling efforts in predicting the vertical extent of the SST Diurnal Variability (DV). First, regional extent of Diurnal Warming (DW) has been characterized by comparing SEVIRI and AATSR satellite measurements. DW has an impact on air-sea fluxes and atmospheric stability, and it represents an issue for multi-sensor SST estimation. For instance, SEVIRI day-time SST can exceed the night-time foundation value by 1° or more. A General Ocean Turbulence Model (GOTM) performances and sensitivity have been analyzed in comparison with SEVIRI and buoys data in 3 test areas (North and sub-tropical Atlantic and Baltic sea). The GOTM reproduces temperature values as observed from buoys at 1 m, 2 m and SEVIRI data. Vertical temperature structure down to 140 m is reasonably resolved within 0.5°. Different parameterizations will have a different impact in the SST estimation. As a further effort, GOTM will be compared with SEVIRI and model-derived DV from a recent study from the same authors.

Marullo and colleagues (Marullo et al., 2014) provided estimates of the SST diurnal cycle and heat budget over the Mediterranean Sea. The proposed method aimed at reconstructing the SST diurnal cycle combining geostationary satellite observations and operational model analysis, and evaluate the impact of this reconstructed hourly SST field on the basin annual heat budget. Errors are evaluated using drifters. This methodology is able to correctly reconstruct the diurnal SST cycle including sub-diurnal components and Diurnal Warming (DW) events. Data analysis confirms that the Mediterranean Sea is one of the world ocean region in which DW events are more frequent. The diurnally varying SST has an important impact on the Mediterranean heat budget.

Clayson et al. (2014) addressed the topic of air-sea flux distributions across the global oceans from satellite data and models, with the objective of studying the variability and extremes in air-sea fluxes of heat and moisture in the water/energy cycle context, and how fluxes distribution varies with time, location, differing weather and climate states. Extremes and their changes for Latent Heat Flux (LHF), wind speed and (Qs-Qa) have been analyzed. Surface fluxes are decomposed by weather states, which result in distributions of fluxes with different mean and extreme characteristics, providing an improved understanding of surface energy flux variability. Both the weather state and the Mixed-Layer state affect the resulting impacts on SST.

Again on SST, Soloviev and colleagues (Soloviev et al., 2013) have explored the effect of stable atmospheric stratification and surfactants on SST under low wind speed conditions. Simulations of diurnal cycle have been studied with a Computational Fluid Dynamic (CFD) model, through which both velocity and temperature fields under stable and unstable atmosphere and solar insolation have been analyzed. Surfactant effects, which are less important under stable compared to unstable atmospheric conditions. suppress coherent streaks and turbulence in the near-surface layer of the ocean. The CFD model results suggest that rapid increase of SST can take place during stable atmospheric conditions and solar insolation, in low wind speed regimes, and SST equilibrates with the air temperature within minutes. Areas with the stable marine boundary layer (upwelling, hurricane, cold wakes and currents etc.) may have increased diurnal SST amplitudes and equilibrate SST in composite satellite IR imagery.

Boutin (Boutin et al., 2013) showed first results on Sea Surface Salinity by analyzing SSS under rain cells, through the use of SMOS satellite and in-situ Argo and drifters observations. In rainy regions (such as the ITCZ, SPCZ), SMOS SSS is fresher than Argo OI SSS maps, with a rain-induced signature on SSS of at least -0.14 pss/mm/hr at moderate wind speed. Despite validating satellite SSS in rainy regions is difficult due to lack of systematic collocation of in-situ and satellite measurements (salinity, rain rate, wind speed) at relevant time/space scales, large variability of SMOS SSS is also in reasonable agreement with drifters salinity measurements at 45cm depth (rain signature on SSS of -0.21 pss/mm/hr at moderate wind speed). Monthly difference between SMOS and Argo OI SSS cannot however be fully explained; applying a -0.2 pss/mm/hr correction on SMOS SSS leads anyway to a smaller than observed averaged difference, calling for a need to look in more details into Argo OI smoothing/relaxation to climatology and SMOS artefacts (e.g., RFIs). The upcoming SPURS-2 experiment should help constraining the horizontal and vertical salinity variability within a satellite pixel in rainy areas, providing an in-situ reference for satellite SSS.

Diurnal Variations in Near-Surface Salinity have been studied by Drushka et al., (2014), aiming at sorting out the day/night bias in satellite salinity. Contributions driving the average diurnal salinity (evaporation, precipitation, entrainment) have been estimated, with the latter two consistently dominating. Sensitivity tests have been carried out with a 1-dimensional Generalized Ocean Turbulence Model (GOTM), validated against the TAO array, where the rain and wind variations have been studied. This 1-d turbulence model shows that wind and rain strength significantly affects lens formation and salinity anomaly, whereas the strongest salinity anomalies are obtained when rain coincides with weak winds and surface mixed layer is thin.

DeMott and colleagues (DeMott et al., 2013) showed an assessment of the impact of air-sea interactions on tropical convection at intra-seasonal timescales. Intra-seasonal variability of the Madden Julian Oscillation (MJO) and its interaction with the ocean has been studied. The MJO has an impact on several systems at different latitudes (monsoon, tropical cyclogenesis, ENSO onset, polar oscillation etc), but many state-of-the-art models struggle with MJO simulation. Ocean coupling can affect, even remarkably, MJO simulation, and its relative impact depends upon SST and air humidity variability. The way the MJO interacts with the ocean (atmosphere forcing of the ocean) has been discussed. The MJO senses SST anomalies via surface fluxes and how can SST-modulated surface fluxes impact the MJO has been discussed. In particular, surface fluxes do not directly impact MJO propagation, while they influence convective intensity.

Herrmann and colleagues (Herrmann et al., 2009) discussed about monitoring ocean deep convection from space through a multi-sensor approach. Oceanic deep convection is at the origin of ocean deep waters, and it occurs in a few regions of the world (Labrador, Greenland, Weddell), among which the NW Mediterranean. It has strong inter-annual variability and a relevant impact on ecosystems. The objective is to provide a method to monitor dense water formation (τ_{DW}) using satellite data. Ocean color data are used since deep convection generates strong vertical mixing and therefore very low Chlorophyll surface values. SSH from satellite altimetry data are used since the densification of water that triggers the deep convection determines an acceleration of cyclonic circulation (dynamic effect) and consequent lowering of sea surface. A method to establish a linear relationships between surface Chl and SSH and yearly τ_{DW} in a hydrodynamic-biogeochemical coupled simulation is devised, and then applied on real satellite data to produce long-term time-series of τ_{DW}. Two independent yearly time series of τ_{DW} are reasonably consistent with available estimations. Estimates of errors and uncertainties related to model, measurements and the linear relationship hypothesis are being tested.

Satellite-based estimation of water mass formation was discussed by Klockmann et al., (2014, Sabia et al., 2014) starting on the derivation of surface Temperature-Salinity (T-S) diagrams out of satellite SSS and SST measurements. This framework has been extended by exploiting these T-S diagrams as a diagnostic tool to derive water masses (a water body with physical properties distinct from the surrounding water) formation rates and areas. The formation of water masses as a function of SMOS SSS and OSTIA SST was derived by calculating first the surface density flux (as a function of heat and freshwater fluxes). and then taking the derivative of the total density flux with respect to density. Yearly, seasonal and monthly water mass formation rates for different SST and SSS ranges were presented. The formation peaks were remapped geographically, to analyze the extent of the formation areas. Water mass formations derived from SMOS and OSTIA compared reasonably well with the results obtained from in-situ data.

Known water masses could then be identified and traced. To obtain observations of water mass formation is of great interest, since they serve as indirect observations of the thermo-haline circulation.

Reul and colleagues (Reul et al., 2012) reported on a recent capability of SMOS L-Band data to monitor the evolution of surface winds and sea surface properties beneath hurricanes and severe storms. Detailed information on surface winds under Tropical Cyclones (TC) is crucial to better forecast storms evolution, but their measurements from space with traditional instruments (radars, high-frequency radiometers) is challenging due to rain contamination or loss of sensitivity at very high winds. Low-frequency microwave radiometers offer new capabilities for ocean surface remote sensing in extreme conditions. Distinctive SMOS brightness temperature (Tb) signal could be associated with the passage of TCs, and correlations between L-band Tb increase with TC intensity from Cat-1 to Cat-5 was demonstrated. L-band observations provide a first atmosphere-uncorrupted view of the ocean surface in extreme conditions, retrieving wind speed with a ~5m/s accuracy. A complete storm database has been generated for the SMOS mission archive including TCs & ETCs since 2010 till now. SMOS wind speed data assimilation experiments into operational forecast models will be performed to investigate the data impact on storm track and intensity forecasts skills.

7. Momentum Fluxes

Measuring and studying ocean surface waves and associated near-surface processes is important to understand ocean-atmosphere interactions, which are especially complex given that the energy originally provided by the Sun, in one form or another, crosses the air-sea interface at least three times before becoming kinetic energy of oceanic waves and currents.

Measurements of meteo-marine processes can be made at increasingly small scales and regular time intervals from spaceborne Synthetic Aperture Radar. XWAVE is a robust algorithm for sea state retrieval on small regional scales using TerraSAR-X. Also, Sentinel-1 WV will provide an improved global view of the atmosphere variability at scales smaller than 20km, as well as systematic and global observations of usually unresolved processes, including, amongst others, wind streaks and convection cells. In preparation for Sentinel-1 a synthetic swell field database has been generated using the full ENVISAT ASAR WM archive.

Scatterometer-derived sea surface wind measurements also contribute to enhanced understanding of meteo-marine processes. Scatterometer measurements of sea surface wind variability associated with convective systems represent a valuable source of air-sea interaction information. Various scatterometer rain effects can be identified: rain splash induced roughness/damping dominates at low winds and extreme rain; deep convective precipitating cells cause cooling of elevated air and wind downbursts, these generate gust fronts extending over a few hundred km; and wind downbursts substantially modify air-sea interaction in rainy areas (including evaporation, atmospheric dynamics, ocean mixing, etc.). In this context, it has been found that the MLE (Maximum-Likelihood Estimator) and SE (Singularity Exponent) are well correlated with sub-WVC (Wind Vector Cell) wind variability. Also, MLE and SE are complementary and their combination provides an effective QC relative to both buoy and ECMWF reference (notably an approach based on MUlti-Dimensional Histogram (MUDH)). It was also determined that increased sub-WVC variability dominates the ASCAT quality degradation. Further investigation is required concerning a remaining 1 m/s bias in ASCAT rejected winds. Temporal buoy wind information is useful to address representativeness errors; however, it is not directly comparable to 2-D area-mean scatterometer winds. Preliminary triple collocation shows that ASCAT wind quality for QC'ed WVCs is comparable to that of mean buoy winds at scatterometer scales, and the QC may therefore be relevant for applications like data assimilation for, e.g., nowcasting, oceanography and climate studies.

Wind climate data records will be created from several scatterometer missions spanning more than 20 years in total. Focus will be on a proper inter-calibration of the various data records. The latest versions of wind processing software will be used to get state of the art wind products. Information will be provided to estimate sampling errors. Wind and ice map data will also be provided by various archives both in BUFR and user-friendly NetCDF-CF formats.

The ESA eSurge-Venice project demonstrates how satellite data can improve the storm surge forecasting in the Gulf of Venice. ECMWF model data in general underestimate the wind speed with respect to satellite winds in the North Adriatic sea (largely due to incomplete orography and the relatively large scale of grid cells used by the model). The differences between models and satellite data are variable in space and time. In this context three reanalysis experiments were conducted on ~ 20 storm surge events. For modified wind forcing, the RMSD passed from 14.9 cm to 9.7 cm. For direct altimeter data assimilation, the RMSD passed from 14.9 cm to 13.8 cm. For modified wind forcing + altimeter assimilation, the RMSD passed from 14.9 cm to 9.3 cm. Open issues include determining whether there is an optimal form of the factor (now it is: $1+\Delta ws$) to modify the NWP wind speed. Future directions include extending the assimilation of altimeter into SSMs to the Mediterranean Sea.

To better understand sea surface dynamics and air-sea interactions, measurements were made in the Gulf of Tehuantepec (INTOA experiment) on the influence of swell on wind stress, and laboratory studies were conducted on wave growth and surface drift at accelerated wind conditions. The lower wave growth rate was determined to be 2 orders of magnitude smaller than previously reported. The measurements of wind drift and velocity profiles revealed an important shear in the upper 2 cm. Important questions still to answer include: How linear or exponential is the drift profile? Is there any potential role of surface drift on wave development? The next field campaign in the Gulf of Tehuantepec will include CO_2 fluxes.

Some analysis was made on the importance of the differences between NWP models and EO derived winds. NWP winds improve in time, but still today turbulence, PBL and convection processes show systematic biases. These biases are the result of a careful tuning process and are not easy to correct. PBL and mesoscale processes determine local dynamical conditions and local climate change sensitivity. Excellent EO data exists on surface winds and stresses. These depict processes important to improve understanding of Weather and Climate models. Time and space collocated NWP and EO sources need to be compared closely to analyse differences. Also, satellite-sampled climatologies need to be compared with uniformly sampled climatologies to obtain satellite sampling errors.

Satellite measurements of SST, and studies of the SST-winds relationship is another important factor in ocean surface fluxes. The wind-SST coupling is the pathway to transport moisture and diabatic heat from the Marine Atmospheric Boundary Layer (MABL) into the free atmosphere (Minobe et al. 2008; WCRP Grand Challenge). Atmospheric feedback can impact local oceanic currents, transport, temperature structure, eddy structure, and eddy kinetic energy (Chelton et al. 2007; Jin et al. 2009). Moreover, the wind-SST coupling impacts the large-scale (i.e., basin scale) ocean circulation (Hogg et al. 2009; WCRP Grand Challenge).

It has been determined that differences in surface turbulent fluxes exhibit a seasonal cycle with a peak in winter (DJF), a transitional period in spring (MAM) and fall (SON), and a minimum in summer (JJA). Winter averages for SHF (4 W/m^2), LHF (6 W/m^2), and Tau (0.03 N/m^2) are non-negligible for many applications. Differences are important, even in summer, for very long time scale applications such as the upper ocean energy budget (Levitus et al. 2005). The local daily variations are much larger, and are presumed to be important for cyclogenesis and ocean circulation and certainly for ocean mixing. Models require finer resolution and better boundary-layer parameterizations to capture these processes, and great care must be taken when assimilating point data from ships and buoys, particularly to tune L3 and L4 gridded products. GCOS will consider adding missing surface fluxes to the list of Essential Climate Variables in 2015.

The surface heat budget over the North Sea in coupled climate simulations has been analysed, including various scenarios of the atmosphere-ice-ocean model, RCA4-NEMO. This is the first ensemble with coupled RCM (Regional Climate Model) for the North Sea and Baltic Sea. The RCA4-NEMO hindcast compared fairly well with observations, and the spatial variability of uncertainties offered an insight into model sensitivity. It was determined that the heat exchange over the North Sea shifts under warmer conditions.

Various key points to consider, and some future developments, include:

- Models of ocean surface fluxes require finer resolution and better boundary-layer parameterizations to capture local daily variations (which can be important for cyclogenesis, ocean circulation and ocean mixing). Also, great care must be taken when assimilating point data from ships and buoys, particularly to tune level 3 and level 4 gridded products.

- S1 wave-mode and corresponding Single Look Complex (SLC) data will provide an improved global view of the atmosphere variability at a scale smaller than 20km. It will provide systematic and global observations of processes that are usually unresoloved (such as wind streaks and convection cells).

- Scatterometer-derived sea surface wind variability associated with convective systems represents a valuable source of air-sea interaction information. In this context, a wind variability product and ASCAT coastal winds would be very valuable.
- Sea State (and wind) climate data records will be created from several scatterometer missions spanning more than 20 years in total. Focus will be on a proper inter-

calibration of the various data records. The latest versions of processing software will be used to get state of the art products. Information will be provided to estimate sampling errors. Wind and ice map data will also be provided. Enhanced resources are needed for international collaboration/standards.

- The full spectrum of waves (from capillaries through ultra-gravity) should be explored. Wave breaking needs to be considered as a conduit for energy and momentum transfer driving Langmuir circulation. Polarimetry information can give phase-resolved waves.

8. Aerosol

The session was introduced by the presentation of Gerrit de Leeuw on the use of satellites in aerosol and cloud studies over ocean (Ovadnevaite, 2014). The main message was that an enormous data set is available from satellite data, going back over three decades and 10-20 years of comprehensive data which have hardly been explored. Much research is based on long-term measurements, in particular at Mace Head. Can satellite data, with many years of data covering a wide variety of conditions, be used as a surrogate for certain aspects, to answer specific question for which satellites may provide the relevant data, and thus be explored at different locations and for different conditions? Open research questions include, e.g.:

- The source function and the contribution of organic matter, which changes the hygroscopic properties (observed for instance in aerosol scattering at Mace Head).
- How do different OM containing SSA properties affect AOD and cloud properties: is this visible in satellites?
- The effect of SST on SSA production and on cloud properties, with a different behaviour for SST smaller or higher than about 7^{o}C: contradicting results from laboratory experiments and ocean observations.
- The high AOD band over the Southern Ocean is observed from some satellites and shows also in model results, but other satellites (CALIOP, SeaWiFS) and MAN do not show this.
- Wind speed dependence of AOD from different data sets (Smirnov et a., 2011): why does that occur?

During the round table discussion the effect of surfactants on aerosol production, measured in the Miami wave tank, was brought up as a mechanism which could provide some explanation coupling the biology to the aerosol production. Cooperation between sea surface and aerosol production communities could benefit from better cooperation. It was mentioned that the discrepancy in temperature dependence of the aerosol source function could be due to different conditions in a laboratory tank, in particular the presence of surfactants may play a role. It is important to first determine which questions we want to answer from laboratory measurements for global application.

As regards the application of satellites, the uncertainties need to be taken into account. Over ocean we have the most accurate data sets, but still there are discrepancies between AOD data from different instruments/algorithms (e.g. MODIS vs MISR; the three AATSR algorithms). This may be due to imperfect cloud masking (20% discrepancy between aerosol and cloud communities), and surface corrections for, e.g. whitecaps, OC, sub surface reflectances. Lidar should not be influenced by this, and there is discrepancy between CALIOP and other instruments and in particular with AERONET/MAN which is commonly used as 'ground truth'.

Issues with cloud retrieval exist as well. The cloud droplet number concentrations should provide information on aerosols. However a large difference between aerosols and clouds are the time scales: cloud properties change in minutes, whereas the aerosol properties may show diurnal variations.

The presentations during the session were mainly on process studies, for future programs we should prioritize: production, uncertainties, direct / indirect effects on climate.

9. Physical and biogeochemical processes

The session addressed a variety of topics affecting differently physical and biogeochemical processes at the ocean-atmosphere interface (ranging from ocean color estimates to phytoplankton communities studies, and from ocean light availability to ocean acidification). Whist satellite measurements were indeed predominant, a distinctive focus on in-situ measurements was present, as well.

The session started with a presentation by Zibordi et al. (2016) on QC and uncertainties of the AERONET-OC in-situ network, in view of its use with satellite OC data. This operational network consists of modified sun-photometers to support ocean color validation activities with highly consistent time-series of $L_{WN}(\lambda)$ and $\tau_a(\lambda)$ (normalized water-leaving radiance and aerosol optical thickness), in coastal and occasionally at open sea sites. The JRC has the scientific responsibility of the processing algorithms and performs the quality assurance of data products. Example of validation of MODIS-A products were shown. Major application is the validation of satellite ocean color primary data products. However, it also offers the capability of supporting climatological studies on atmospheric and marine processes related to primary or derived quantities.

Satellite OC has been used to study the role of photoacclimation (PA, the adaptation of the phytoplankton cells to light and nutrients, which can increase/reduce the production of Chlorophyll) on phytoplankton seasonal cycle in the Mediterranean Sea, as reported by Bellacicco et al. (2014) Satellite Chl:C ratio high values in winter/spring and low values in summer show that PA can dominate the phytoplankton seasonal cycle. To study phytoplankton and its space-time variability, satellite Chl describing intra-cellular processes needs to be complemented with Phytoplankton Carbon, which defines algal biomass variability and community dynamics.

Phytoplankton photophysiology (fundamental phytoplankton bio-optical properties at the heart of methods for estimating primary production from space) estimates were at the core of the talk by Jackson et al., (2013) within the context of the MAPPS (MArine primary Production: model Parameters from Space) project. The MAPPS project strives to improve the ability to estimate phytoplankton photophysiological parameters at the global scale, exploring satellite based methods for estimating P-I (Photosynthesis-Irradiance) parameters. Initial results of algorithms comparison have been shown. Accurate estimation of photophysiological parameters is an essential part of modelling phytoplankton primary production.

On a related topic, the determination of the light availability in ocean water using Vibrational Raman Scattering (VRS) has been explored in the talk by Dinter et al. (2015) Light availability or Depth Integrated Scalar Irradiance (DISI) can be directly correlated to the strength of VRS. VRS is an inelastic scattering effect, where incoming light exciting water molecules to vibrations generate a reemission in another wavelength. The strength of VRS signal has a nearly linear relationship to DISI. This new method has the potential to determine PAR directly (without former determination of a, b, and PAR(0+)). It is applicable to other hyperspectral sensors like GOME-2, OMI, or the upcoming TROPOMI with different overpass times.

Two presentations were focusing on the topical issue of Ocean Acidification (OA). Land and colleagues (Land et al., 2015) highlighted the major objectives of the ESA Pathfinders-OA project, a feasibility study whose objective is to quantify the value added of remotely-sensed parameters for OA research. To date, the majority of the scientific studies into the potential impacts of OA have focused on the use of models and in situ studies. Space observations from satellite Earth Observation have yet to be fully exploited and could provide quasi-synoptic and calibrated measurements for investigating OA processes on global scales. The project is evaluating algorithms for the Arctic seas, the Bay of Bengal, The Caribbean and Amazon Plume and globally. In each region it is foreseen to develop novel carbonate system algorithms and evaluate these and in-situ derived algorithms from the literature.

Within the same project, Sabia (Land et al., 2015) showed the methodology to be applied and the identified processing chain. Specifically, this will be performed by exploiting the information content of Ocean Colour (OC) data, SST, Wind Speed (WS) and Sea Surface Salinity (SSS) parameters (with an emphasis on the latter). A proper merging of these different satellites datasets will allow to compute at least two independent proxies among the seawater carbon dioxide system parameters: namely, the partial pressure of CO2 in surface seawater (pCO2); the total Dissolved Inorganic Carbon (DIC) and the total alkalinity (AT). Through the knowledge of these parameters, the final objective is to come up with the best educated guess of the surface ocean pH and aragonite saturation state.

10. Earth Observation and SOLAS Science Priorities

As per SOLAS Science Plan, the SOLAS science mission is organized around five core themes. In addition, the study of these five core themes are integrated in efforts to understand key environments, such as upwelling systems, the polar oceans, and coastal waters, as well as to evaluate the environmental efficacy and impacts of geoengineering proposals and other policy decisions and societal developments. In the following, Earth Observation and SOLAS Science Priorities are organized around these five core themes and the crosscutting themes.

10.1. Theme 1: Greenhouse gases and the oceans

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most significant long-lived greenhouse gases (GHGs) after water vapor. Physical and biogeochemical processes in the surface ocean play an important role in controlling GHG fluxes to the atmosphere. Understanding sensitivities of these processes to climate and environmental change is of direct importance for the mitigation of climate change.

Fundamental questions are:

- *Which surface ocean processes are controlling GHG cycling at regional to global scales?*
- *What are the feedback mechanisms between climate change and oceanic GHG emission?*
- *How can we assess future oceanic fluxes of GHGs in a changing ocean and atmosphere?*

In order to assess variations in GHG fluxes within the ocean and across the air-sea interface, a dense observing system is needed. Earth observers close a gap in making long term observations feasible with both, a high temporal and a high spatial resolution. Remote sensing is the only tool that provides consistent global coverage. However, such observations of oceanic and atmospheric processes need to be linked to oceanic measurements in a more systematic way. Development of new tools and a wide spread adoption of existing ones by a growing community is an utmost necessity. Cloud and aerosols parameters as well as upper ocean ecosystem parameters are regularly obtained with remote-sensing tools. Following the steps of SCIAMACHY and GOSAT, a constellation of satellites such as CarbonSat will advance our knowledge on the natural and man-made sources and sinks of the anthropogenic greenhouse gases carbon dioxide (CO_2) and methane (CH_4). As of now, a suite of recent data syntheses and collections on marine carbon and nitrogen cycles has emerged (GLODAP, CARINA, PACIFICA, SOCAT, MEMENTO, SeaWiFS, MODIS, GOSAT, etc.). In spite of these advances, several oceanic areas remain under-sampled in space and time.

The following key actions could be undertaken by an ESA-SOLAS collaboration:

- Measure natural and man-made sources and sinks of the anthropogenic greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous-oxide (N_2O).
- Link cloud and aerosols parameters, upper ocean ecosystem parameters, surface ocean lower atmosphere transport parameters and sources and sinks of GHG.
- Develop novel processing techniques and identify additional parameters required to constrain the system. The measurement of these parameters by Earth Observations should be the goal for future satellites or constellation of satellites.
- Establish systematic linkage between earth observations and oceanic measurements.
- Sample under-represented oceanic areas, linking both ocean-going measurements and earth observations.

10.2. Theme 2: Air sea interface and fluxes of mass and energy

Ocean-atmosphere fluxes play a critical role in the regulation of climate. We therefore need to develop a mechanistic understanding of physical, chemical and biological processes affecting exchange of gas, mass and energy across the air-sea interface from nano to global scales.

Central questions in this area are:

- *What are the biogeochemical mechanisms that influence fluxes of gas, mass and energy at the surface ocean boundary layer and what is their sensitivity to changes in climate/environmental controls?*
- *How can turbulence be incorporated into parameterization schemes describing the air-sea fluxes of mass and energy?*
- *What are the feedbacks between processes governing air-sea fluxes and climate?*

This theme is concerned with processes responsible for air-sea exchange of mass, momentum, and energy. These processes act upon the air-sea interface and regulate the fluxes of mass and energy between the ocean and the lower atmosphere. A central component of this theme is to develop a physically-based air-sea exchange parameterization which accurately assesses the fluxes over a wide range of natural conditions. This explicitly includes spatially complex regions such as the coastal zones and the marginal ice zones.
Scatterometer on satellites provide estimates of winds through which turbulence and gas transfer coefficients are estimated. Their foot print is relatively large (~25km x

25km). Novel methods using polarimetry of glint show promise to provide winds on significantly smaller scales (O(4km)). High-resolution lidars can provide estimates over large parts of the ocean of the upper-ocean's mixed layer, a critical length scale for upper ocean turbulence and biogeochemical processes.

In a continued ESA-SOLAS collaboration, the following key aspects could be addressed:

- Link biogeochemical mechanisms to fluxes of gases, mass and energy through integrated modeling and EO of relevant parameters.
- Develop novel parameterizations by linking consistent global, long-term earth observations and in-situ campaigns.
- Identify urgently needed new products and/or lead the required development of future missions to develop these new products, through new satellites or a constellation of satellites.
- Identifying optical signatures of organic matter at the air-sea interface that can be linked to exchange processes.
- Determining accumulation of surface active agents at the air-sea interface.

10.3. Theme 3: Atmospheric deposition and ocean biogeochemistry

Atmospheric depositions play a fundamental role in marine ecosystems with consequences on local, regional and global biogeochemical cycles, as well as on the climate system.

Research questions in this theme are:

- *What are the large-scale impacts of atmospheric deposition to the ocean on global elemental cycles (e.g., C and N) and climate change feedbacks in major marine biomes?*
- *How biogeochemical and ecological processes interact in response to natural or anthropogenic material input from the atmosphere across contrasted regions?*
- *How global warming and other anthropogenic stressors synergistically alter the uptake of atmospheric nutrients and metals by marine biota in different oceanic regions?*
- *How atmospheric deposition of elements (eg. N and Fe) would change biodiversity of ocean through change in nutrient ratios?*
- *How atmospheric deposition change global acidification and its impacts on ecosystem?*

New or improved tools are rapidly expanding our capacity to effectively study the impacts of atmospheric deposition on ocean biogeochemistry. Central to improving our understanding of the complex processes at the ocean surface-lower atmosphere boundary are systematic measurements of atmospheric deposition and nutrients in the surface mixed layer. Particularly in regions where atmospheric supply plays an important role, earth observations can play a key in filling gaps in our knowledge. Such areas are predominantly nitrate- and iron-limited regions. Targeted analyses integrating results from atmospheric chemistry and ocean biogeochemistry models are increasingly being used to address the impacts of atmospheric deposition of nutrients on ocean ecosystems and to assess potential feedbacks to climate. Efforts should be focused on using results of in-situ and EO measurements to improve nutrient deposition parameterizations and the representation of ocean biogeochemical responses to atmospheric nutrient input in the relevant models. New remote sensing tools such as lidar, polarimeters and hyper spectral images should complement those approaches. New lidars can simultaneously probe the atmosphere and the ocean beneath at O(1m) resolution providing a novel way to simultaneously study both system and the interaction between them. This will close the gap between earth observations and in-situ measurements.

The following key actions could be undertaken by the ESA-SOLAS collaboration:

- Identification of composition of wet and dry deposition from space and aircraft with high spatial and temporal sampling.
- Systematic linkage of earth observations and oceanic measurements.
- Establish long term observations in nitrate- and iron-limited regions.
- Measure all relevant parameters to quantify complex systems and their interactions.
- Improved parameterizations of atmospheric nutrient deposition and ocean biogeochemistry response in models of atmospheric chemistry and ocean biogeochemistry, using both in-situ and EO measurements to enable quantification of deposition impacts in an earth-system context.

10.4. Theme 4: Interconnections between aerosols, clouds and marine ecosystems

Interconnections between aerosols, clouds, and marine ecosystems are one of the largest sources of uncertainty in future climate projections.

Relevant research questions are:

- *How are primary and secondary aerosol load and properties linked to the marine ecosystem?*
- *How do aerosols affect marine clouds?*
- *What are the feedbacks between clouds and the marine ecosystem?*

- *How does seawater pollution (particularly microplastics) affect the ocean-aerosols-clouds system?*

First and foremost, dominant processes linking ocean physic/biogeochemistry and clouds properties need to be quantified, such as fluxes of local primary and secondary aerosols, the mass and number concentration of long-range transported aerosols, and their links with cloud properties. In the ocean, sources of primary and secondary aerosols must be studied in the context of phytoplankton blooms composition and dynamics. The strength of these sources will then be related to the formation of cloud condensation nuclei and finally to cloud properties (ex. albedo and longevity). The basis for such advances in the field is the underlying quality-controlled data, obtained both from the field, as well as through remote sensing. These data will be used to develop much-needed, empirically constrained parameterizations of the local emission flux and production rates of ocean-derived sea spray aerosol (SSA), including SSA-organics, and gaseous precursors of secondary aerosol (SA), as well as the entrainment flux of long-range transported aerosol and impacts on cloud properties. In particular, remote sensing should address the critical demise phase of phytoplankton blooms, which is the most relevant for the SSA-mediated organic matter transfer to the atmosphere. Novel products are needed to describe the life stage of phytoplankton blooms and the byproducts consequent to the demise phase. Improved empirical parameterizations will require coordinated ocean and atmospheric sampling of the key variables in different ocean provinces and bloom conditions, and the development of new methodologies for better resolving the size distribution, chemical and optical properties of MBL aerosols (marine and long range transport). Such information will provide the initial conditions of CCN and radiative properties for cloud resolving models (CRMs), chemical transport models (CTMs), and global climate models (GCMs) to better estimate the impacts of ocean-derived and long-range transported aerosols on clouds and radiation budgets and to understand feedbacks of aerosols on marine ecosystems.
Interaction of seawater pollutants with the marine organic matter pool and its consequences on aerosol properties should be investigated as a novel and potentially out-breaking topic. Combined earth observations and field experiments are needed in order to understand the relevance of these interactions at regional and global level. Particularly, satellite observations should provide information on the abundance and spatial distribution of microplastics, the finest of which (< 20 μm) may have a role in SSA formation and interaction with the climate system.

Topics for continued ESA-SOLAS collaboration should be:

- Develop empirical models relating ocean variables obtained from remote sensing and sources of primary and secondary aerosols.
- In situ and high-resolution satellite observations of aerosols, winds and cloud properties to improve process understanding and develop parameterizations of marine-cloud interactions.

- Simultaneous observation of ocean and atmosphere from remote sensors and on research vessel show great promise to study both fluxes of material from atmosphere into the ocean (e.g. dust deposition) and the sources of contribution of the ocean of primary and secondary aerosols.
- Improve the current marine ecosystem description capabilities from remote sensing, prioritizing phytoplankton bloom life stage indicators, in order to improve current SSA-organics emission and flux parametrizations.
- Participation by the marine aerosol community in the development of new remote sensing platforms and sensors, ensuring their relevance to ocean-aerosol-clouds feedbacks and informing the overall community of the potential of remote sensing tools.
- Derive high quality long-term data sets of the aforementioned quantities from remote sensing.
- Deriving remote sensing tools to help elucidating the global distribution of microplastics and their role in the aerosol-cloud system after transport in SSA.

10.5. Theme 5: Ocean biogeochemical control on atmospheric chemistry

Ocean emissions of reactive gases and aerosols influence atmospheric photochemistry, air quality, and stratospheric ozone.

Key questions in this theme are

- *What are the marine biogeochemical controls on the release of photochemically reactive gases into the atmosphere?*
- *How will future changes in ocean biogeochemistry and anthropogenic emissions (NOx, VOCs) interact to influence tropospheric photochemistry and stratospheric ozone?*

The atmosphere's photochemical system is influenced by a wide range of natural ocean emissions of reactive gases and aerosols. These emissions can influence the ability of the atmosphere to process and remove anthropogenic pollutants and the levels of stratospheric ozone. Oceanic emissions also interact with pollutants in coastal regions, altering chemical reactions and influencing air quality. It is increasingly clear that biogeochemical cycles in the ocean are also affected by anthropogenic emissions and the deposition of nutrients and pollutants to surface waters. Despite the significant progress made in recent decades, the biogeochemical controls on ocean-atmosphere exchange of reactive gases and aerosols are still poorly understood. The goal of this theme is to assess how air-sea interactions impact atmospheric chemistry and how future changes in oceanic ecosystems will influence the oxidation capacity of the troposphere and future trends in stratospheric ozone.

Progress in this area requires linked earth observations and field studies combining atmospheric and oceanic measurements to characterize 1) the chemical composition and spatial/temporal variability of sea surface emissions of organohalogen compounds, volatile organic carbon and volatile oxygenated organic carbon compounds; 2) the generation of reactive volatile species at the sea surface; and 3) the biogeochemistry of oceanic emissions. These will involve survey-type missions and process-oriented intensive campaigns to study surface ocean cycling, air-sea exchange rates, and atmospheric photochemistry. Combined earth observations and modeling studies are needed in order to understand the rates and pathways of atmospheric cycling of reactive emissions and how they interact with both the natural marine atmosphere and with anthropogenic pollutants in continental outflow regions.

Joint ESA-SOLAS projects should be in the following areas:

- New approaches for deriving earth observations of chemical composition and spatial/temporal variability of sea surface emissions of organohalogen, volatile organic carbon and volatile oxygenated organic carbon compounds.
- Development of capabilities for space-based high spatial resolution measurements of climate active marine gases emitted from coastal locations
- Development of data-driven models for quantifying the biogeochemistry of oceanic emissions and the generation of reactive volatile species at the sea surface.
- Development of novel simultaneous ocean-atmosphere retrieval allowing the quantification of processes such as dust deposition effects on ocean and phytoplankton phonological control of aerosol production.

10.6. Crosscutting Themes

In the complex, non-linear system of the surface ocean and lower atmosphere, the five SOLAS themes interact and influence each other. Understanding the processes involved and making predictions will not be possible by studying these themes independently. The SOLAS community has identified upwelling systems, the polar oceans, and coastal waters as oceanic systems where integrated studies are particularly urgent, needing to be either initiated or expanded. These are broad topics that overlap, which is intentional, and this list is not exclusive. Quite to the contrary, it is expected that SOLAS scientists will continue to identify additional regional, high-sensitivity, and high-priority systems for integrated studies. Other integrated topics that have been proposed or are in development include the Indian Ocean, coral reefs, pollutant transport, oligotrophic gyres, and impacts of catastrophic and extreme events, as well as many others.

Relevant to these topics are the challenges and quantities of interest proposed in the previous five themes. Here, additional challenges arise due to the regional focus. For Earth observations, these are:

- Application to upwelling areas and the high resolution necessary for resolving the dominant processes.
- For upwelling systems, characterized by highly variable dynamic, satellite-based predictions of pCO_2 in coastal waters would be very powerful. Such retrieval needs to be validate with observational data. Such observations could also be used to predict alkalinity and be linked to the organism distribution.
- Measurements of sea ice at sub-km scale resolution, assessing conditions of the ice and quantifying its influence on the earth observations und underlying exchange processes.
- Quality control and accuracy in coastal waters. Dealing with clouds in the coastal marine boundary layer.
- Advance in the diagnosis of the phytoplankton functional groups from satellite data (taxonomic composition and size-structure of the surface phytoplankton community- satellite-estimated phytoplankton absorption efficiency) and the relation with aerosol loading, some specific gases as DMS that is relevant for the climate change and also the CO_2 fluxes.
- Red tides, biogeochemistry and the control of the atmospheric chemistry. Red tides are an increasing problem in marine waters that determine changes in the biogeochemistry of the surface waters and also in the atmosphere, as source of the aerolized toxins atmospheric deposition, etc.

Productivity in the upwelling regions is controlled by two main factors. First, equatorward winds along the Eastern Boundary Upwelling Systems are linked to atmospheric high-pressure systems and force Ekman transport and pumping. This drives upwelling of deep nutrient-rich water into the euphotic zone, where favorable light conditions sustain phytoplankton growth. Locally, the mesoscale low-level atmospheric circulation can also be affected by air-sea-land interactions, which impacts the upwelling and productivity. Second, remote forcing can modulate upwelling at timescales from intraseasonal (*e.g.* Kelvin waves) to interdecadal (*e.g.* gyre circulation) and longer. This variability is often associated with tropical modes (ENSO in the Pacific; the Benguela Niño and the Atlantic Equatorial mode in the Atlantic) and the low-frequency climate modes such as the Pacific Decadal Oscillation (PDO), the North Pacific Gyre Oscillation (NPGO), the Atlantic Multidecadal Oscillation (AMO) or the Northern Annular Mode (NAM). New emerging retrieval techniques for characterization of the ocean and atmosphere should help deconvolving the intricacy of processes within these regions.

REFERENCES

Bakker, D. C. E., Pfeil, B., Smith, K., Hankin, S., Olsen, A., Alin, S. R., Cosca, C., Harasawa, S., Kozyr, A., Nojiri, Y., O'Brien, K. M., Schuster, U., Telszewski, M., Tilbrook, B., Wada, C., Akl, J., Barbero, L., Bates, N. R., Boutin, J., Bozec, Y., Cai, W.-J., Castle, R. D., Chavez, F. P., Chen, L., Chierici, M., Currie, K., De Baar, H. J. W., Evans, W., Feely, R. A., Fransson, A., Gao, Z., Hales, B., Hardman-Mountford, N. J., Hoppema, M., Huang, W.-J., Hunt, C. W., Huss, B., Ichikawa, T., Johannessen, T., Jones, E. M., Jones, S., Jutterstrom, S., Kitidis, V., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Manke, A. B., Mathis, J. T., Merlivat, L., Metzl, N., Murata, A., Newberger, T., Omar, A. M., Ono, T., Park, G.-H., Paterson, K., Pierrot, D., Ríos, A. F., Sabine, C. L., Saito, S., Salisbury, J., Sarma, V. V. S. S., Schlitzer, R., Sieger, R., Skjelvan, I., Steinhoff, T., Sullivan, K. F., Sun, H., Sutton, A. J., Suzuki, T., Sweeney, C., Takahashi, T., Tjiputra, J., Tsurushima, N., Van Heuven, S. M. A. C., Vandemark, D., Vlahos, P., Wallace, D. W. R., Wanninkhof, R., Watson, A. J. (2014) An update to the Surface Ocean CO2 Atlas (SOCAT version 2). Earth System Science Data 6: 69-90. doi:10.5194/essd-6-69-2014

Bellacicco, Marco, et al. "The Role Of Photoacclimation On The Phytoplankton Seasonal Cycle In The Mediterranean Sea Through Satellite Ocean Color Data." EGU General Assembly Conference Abstracts. Vol. 16. 2014.

Boutin, Jacqueline, et al. "Sea surface freshening inferred from SMOS and ARGO salinity: Impact of rain." Ocean Sci 9.1 (2013): 183-192.

Brown W., C., J. Boutin, and L. Merlivat. "New insights into fCO 2 variability in the tropical eastern Pacific Ocean using SMOS SSS." Biogeosciences 12.23 (2015): 7315-7329.

Chelton, Dudley B., et al. "Global observations of large oceanic eddies." Geophysical Research Letters 34.15 (2007).

Clayson, C. A. "Air-Sea interactions: Observations and models." AGU Fall Meeting Abstracts. Vol. 1. 2014.

DeMott, C. A., et al. "Tropical Air-Sea Interactions and Tropospheric Moistening at Intraseasonal Timescales." AGU Fall Meeting Abstracts. Vol. 1. 2013.

Dinter, T., et al. "Retrieving the availability of light in the ocean utilising spectral signatures of Vibrational Raman Scattering in hyper-spectral satellite measurements." Ocean Science 11.3 (2015): 373-389.

Drushka, Kyla, Sarah T. Gille, and Janet Sprintall. "The diurnal salinity cycle in the tropics." Journal of Geophysical Research: Oceans 119.9 (2014): 5874-5890.

Emery, W.J., Good, W.S., Tandy Jr., W., Izaguirre, M.A., Minnett, P.J. A microbolometer airborne calibrated infrared radiometer: The ball experimental sea surface temperature (BESST) radiometer, IEEE Transactions on Geoscience and Remote Sensing, 52 (12), art. no. 6822518, pp. 7775-7781. (2014)

MC Fuller, T Geldsetzer, JPS Gill, JJ Yackel, C Derksen, C-band backscatter from a complexly-layered snow cover on first-year sea ice, Hydrological Processes 28 (16), 4614-4625, 2014.

Grieco, Giuseppe, Guido Masiello, and Carmine Serio. "Operational Monitoring of Trace Gases over the Mediterranean Sea." Advances in Meteorology 2015 (2015).

Hamilton, Bryan, et al. "Surfactant associated bacteria in the sea surface microlayer: Case studies in the Straits of Florida and the Gulf of Mexico." Canadian Journal of Remote Sensing 41.2 (2015): 135-143.

Hernández-Carrasco, I., et al. "Reconstruction of super-resolution ocean pCO 2 and air–sea fluxes of CO 2 from satellite imagery in the southeastern Atlantic." Biogeosciences 12.17 (2015): 5229-5245.

Herrmann, Marine, Jérôme Bouffard, and Karine Béranger. "Monitoring open-ocean deep convection from space." Geophysical Research Letters 36.3 (2009).

Hogg, Andrew Mc C., et al. "The effects of mesoscale ocean-atmosphere coupling on the large-scale ocean circulation." Journal of Climate 22.15 (2009): 4066-4082.

Jackson, Thomas. Phytoplankton community structure, photophysiology and primary production in the Atlantic Arctic. Diss. University of Oxford, 2013.

Jin, Xin, et al. "SST-wind interaction in coastal upwelling: Oceanic simulation with empirical coupling." Journal of Physical Oceanography 39.11 (2009): 2957-2970.

Karagali, Ioanna, Jacob Høyer, and Charlotte Hasager. "SST diurnal variability in the North Sea and the Baltic Sea." Remote Sensing of Environment 121 (2012): 159-170.

Klockmann, Marlene, et al. "Towards an estimation of water masses formation areas from SMOS-based TS diagrams." EGU general assembly (2014).

Koner, P.K., Harris, A., Maturi, E., A Physical Deterministic Inverse Method for Operational Satellite Remote Sensing: An Application for Sea Surface Temperature

Retrievals, IEEE Transactions on Geoscience and Remote Sensing, 53 (11), art. no. 7130591, pp. 5872-5888, 2015.

Land, P. E., et al. "Exploiting satellite earth observation to quantify current global oceanic DMS flux and its future climate sensitivity." Journal of Geophysical Research: Oceans 119.11 (2014): 7725-7740.

Land, Peter E., et al. "Salinity from space unlocks satellite-based assessment of ocean acidification." Environmental science & technology 49.4 (2015): 1987-1994.

Levitus, Sydney, J. Antonov, and T. Boyer. "Warming of the world ocean, 1955–2003." Geophysical Research Letters 32.2 (2005).

Marullo, S., et al. "Combining model and geostationary satellite data to reconstruct hourly SST field over the Mediterranean Sea." Remote sensing of environment 146 (2014): 11-23.

Minobe, Shoshiro, et al. "Influence of the Gulf Stream on the troposphere." Nature 452.7184 (2008): 206-209.

Ovadnevaite, J., et al. "A sea spray aerosol flux parameterization encapsulating wave state." Atmos. Chem. Phys 14.4 (2014): 1837-1852.

Parard, Gaëlle, Anastase Alexandre Charantonis, and Anna Rutgerson. "Remote sensing the sea surface CO 2 of the Baltic Sea using the SOMLO methodology." Biogeosciences 12.11 (2015): 3369-3384.

Reul, Nicolas, et al. "SMOS satellite L-band radiometer: A new capability for ocean surface remote sensing in hurricanes." Journal of Geophysical Research: Oceans 117.C2 (2012).

Sabia, Roberto, et al. "Remote sensing of surface ocean PH exploiting sea surface salinity satellite observations." Geoscience and Remote Sensing Symposium (IGARSS), 2015 IEEE International. IEEE, 2015.

Shutler, J. D., et al. "Coccolithophore surface distributions in the North Atlantic and their modulation of the air-sea flux of CO 2 from 10 years of satellite Earth observation data." Biogeosciences 10.4 (2013): 2699-2709.

Shutler, Jamie D., et al. "FluxEngine: A flexible processing system for calculating atmosphere-ocean carbon dioxide gas fluxes and climatologies." Journal of Atmospheric and Oceanic Technology 2015 (2015).

Smirnov, A., Carlos M. Duarte, and T. L. Diehl. "Maritime Aerosol Network as a component of AERONET-first results and comparison with global aerosol models and satellite retrievals." (2011).

Soloviev, Alexander, and Roger Lukas. The near-surface layer of the ocean: structure, dynamics and applications. Vol. 48. Springer Science & Business Media, 2013.

Yang, Mingxi, Byron W. Blomquist, and Philip D. Nightingale. "Air-sea exchange of methanol and acetone during HiWinGS: Estimation of air phase, water phase gas transfer velocities." Journal of Geophysical Research: Oceans 119.10 (2014): 7308-7323.

Zappa, Christopher, et al. "Local effects of ice floes and leads on skin sea surface temperature, mixing and gas transfer in the marginal ice zone." EGU General Assembly Conference Abstracts. Vol. 16. 2014.

Zibordi, Giuseppe. "Experimental evaluation of theoretical sea surface reflectance factors relevant to above-water radiometry." Optics Express 24.6 (2016): A446-A459.