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solas event report

Report 09 I May 2018

Workshop on:

“Remote Sensing for Studying the Ocean Atmosphere Interface”

13 - 15 March, 2018
Potomac, Maryland, USA

An international remote sensing workshop was held at the Bolger Center, Potomac, MD, USA, on 13 - 15 March, 2018, which brought together 43 experts and students from eight countries to discuss novel and new remote sensing techniques to study the ocean atmosphere interface (Figure 1). The workshop was sponsored by the European Space Agency (ESA), through Future Earth, the US National Aeronautics and Space Administration (NASA), the Scientific Committee for Ocean Research (SCOR), and the Surface Ocean - Lower Atmosphere Study (SOLAS). The objective of the workshop was to facilitate the exchange of ideas and information about developments in remote sensing that can provide new information and insights about the ocean-atmosphere interface, and will help forge collaborations among workshop participants and with the wider community.

The SOLAS community is in a very fortunate position in having both multi-decadal time series of relevant variables such as sea-surface temperature, surface winds and ocean colour, derived from measurements on earth observation satellites, and recently launched, new satellite sensors with improved capabilities such as better

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Figure 1: Participants of the Workshop.
Front row left to right: Gary A. Wick, Ajoy Kumar, Johnson Zachariah, Alexander Gilerson, Kirk Knobelspiesse, Jack Kaye, Paula Bontempi, Prabhat K. Koner, Chris Ruf, Baijun Tian, Magdalena D. Anguelova, Diego Fernández Prieto, J. Vanderlei Martins, Rachel Pinker, Abderrahim Bentamy.
Middle row left to right: Malgorzata Szczodrak, Isaiah Lonie, Chelle L. Gentemann, Kyle Ehmann, Peter Cornillon, Robert Foster, Alexander Smirnov, Ivan Savelyev.
Back row left to right: Xiujun Wendy Wang, Lorraine Remer, James Carton, Diego Loyola, Peter Minnett, Lisa A. Miller, Brent A. McBride, Amir Ibrahim, Hiroyuki Tomita, Oliver Wurl, Phil Hwang, Hongbin Yu, Xuepeng Zhao, Eric C. Hackert, Santha Akella.
Missing: Santiago Gassó, Abhishek Chatterjee, Stéphane Saux Picart, Leonid Yurganov.
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spectral resolution, spatial and temporal sampling. There are also many new missions under development for future launch. Many of these data sets support the major research themes of SOLAS, and these themes were presented during the opening session of the workshop in an overview presentation by Dr Lisa Miller, the Chair of the SOLAS Scientific Steering Committee.

To set the stage for the workshop, two invited presentations were given to describe current and planned missions of NASA and ESA. Dr Jack Kaye, Associate Director for Research, Earth Science Division of NASA's Science Mission Directorate described the current and planned missions that provide information relevant to the SOLAS objectives, and introduced new missions recommended by the recently completed Decadal Survey from the US National Academies. Of particular relevance to SOLAS are the two MODerate-resolution Imaging Spectroradiometers (MODIS) on the NASA satellites Terra and Aqua, the Visible Infrared Imaging Radiometer Suite (VIIRS) on S-NPP (and a second version was recently launched on the NOAA-20 satellite), and the Soil Moisture Active Passive microwave radiometer (SMAP) that also measures ocean surface salinity. The overview of ESA's missions relevant to SOLAS objectives was given by Dr Diego Fernández-Prieto of the European Space Research Institute (ESRIN) in Frascati, Italy. The Sentinel satellites of the European Copernicus Programme are major contributors to the study of the ocean-atmosphere. Of special note are Sentinel-3A, launched on February 16, 2016, and its twin, Sentinel-3B, which was launched shortly after the workshop on April 25, 2018. Both Sentinel-3s have satellite oceanography as their prime focus, but all of the six Sentinel satellite types have the potential to contribute to SOLAS objectives, as have many of ESA's Earth Observation satellites, such as CryoSAT and SMOS (Soil Moisture Ocean Salinity).

Continuing to set the scene for discussions at the workshop, there were a series of oral presentations and many posters. The oral presentations were grouped into new and future sensors and missions, remote sensing of challenging properties and processes, remote sensing of air-sea fluxes, and remote sensing in challenging conditions. Posters on these topics were available throughout the second day of the workshop, with a dedicated evening session.

The new sensors and missions included NASA's planned PACE (Phytoplankton, Aerosols, Clouds and ocean Ecosystems) mission, a hyperspectral imaging radiometer intended to extend key climate data records based on current and heritage sensors, and to address new and emerging science questions using advanced capabilities. Also presented was NASA's Cyclone Global Navigation Satellite System (CYGNSS), which consists of eight microsatellites, each with a four-channel GPS bi-static radar receiver to measure the sea-surface roughness, and hence wind speed, by using microwave illumination of the sea surface from the constellation of GPS satellites. An additional microsatellite of relevance to SOLAS is the Hyperangular Imaging Polarimeter (HARP) to measure aerosols, clouds and ocean surface properties in the visible range. HARP is expected to be launched from the International Space Station late 2018. European hyperspectral sensors, both on orbit (e.g. TropOMI) and planned (e.g. Sentinel 5) with primary applications for measuring atmospheric trace gasses and air sea interactions, were described along with innovative analysis techniques for extracting information from the "big data" they produce. Finally, a new, robotic Sea Surface Scanner (S3) was introduced as a device for sampling surface films that influence remotely-sensed signals.

To open the session on "Challenging properties and processes" Dr Kirk Knobelspiesse of NASA Goddard Space Flight Center gave an invited presentation entitled "Aerosol Remote Sensing: why is it so difficult?" which led into a series of presentations on satellite measurements of aerosols and their impacts on the ocean atmosphere system. Other SOLAS-relevant challenges are those of measuring gasses, such as methane and carbon dioxide, and air temperature very close to the sea surface; new techniques for such measurements were presented. Of particular note is the response of the carbon cycle to El Niño using data from the Orbiting Carbon Observatory-2. Additional remote sensing challenges discussed are assessing and correcting the effects of skylight reflected at the sea surface on measurements of ocean colour, determining the vertical temperature gradient within the sea-surface thermal skin layer, and measuring subsurface turbulence.

The session on "Air-Sea Fluxes" was opened by Dr Abderrahim Bentamy from IFREMER in France with an overview presentation on "Remotely Sensed Data Requirements for Turbulent Heat Flux Determination". This was followed by presentations on improved measurements of near-surface humidity and latent heat fluxes, and the effects of sea-spray on remote sensing of the ocean surface, including the CYGNSS approach of using reflected GPS signals. Also in this session there was a presentation on a novel method to improve estimates of surface heat and moisture fluxes and the upper ocean heat budget with a case study of the Indian Ocean.

The final session focussed on "Challenging Conditions" and the two presentations were directed at the Arctic Ocean Marginal Ice Zone. Dr Phil Hwang, of the University of Huddersfield in the UK gave an invited presentation on "Observation of Arctic Sea Ice Breakup and Floe Size during the Winter-to-Summer Transition" and Dr. Chelle Gentemann of Earth and Space Research introduced a new collaborative study on improving remote sensing of surface temperatures and air-sea ice interactions in the marginal ice zone.

Additional background and discussion points on these topics were presented in the poster session.

The second part of the workshop comprised a series of break-out sessions involving subgroups of participants (Figure 2). The objectives of the breakout sessions were:

Figure 2: Breakout session on the “Low Hanging Fruit”. © Jessica Gier

- Discuss what has been presented here, and what has not
- Identify pressing research topics and who can collaborate
- Recommend next priorities for research and space agencies
- Recommend topics for future workshops and sessions at the SOLAS Open Science Conference 2019, Sapporo, Japan

These breakout sessions were focussed on the remote sensing of aerosols, remote sensing in the Marginal Ice Zone, and “Low Hanging Fruit”.

The problems associated with deriving aerosol properties at high latitudes were also discussed by the aerosol and Marginal Ice Zone breakout sessions. The merging of high resolution radar images of sea ice with optical measurements of reflected solar radiation and thermal emission was suggested, as was making better use of measurements at 1.6 µm that already exist and which will be in the PACE data stream. The objective is to better characterise the reflection of solar radiation by bright surfaces in the retrieval of aerosol properties using spectral measurements of aerosol-scattered sunlight.

The aerosol breakout group also recommended incorporating measurements from space-based lidars (e.g. the CALIOP lidar on CALIPSO) that provide information on the vertical distribution of aerosols. At high southern latitudes, there needs to be a better focus on deriving aerosol proprieties over the Southern Ocean and at terrigenous dust source regions, such as Patagonia. Moving away from high-latitudes, the measurement from the new generation of geostationary visible and infrared imagers, the Himawari Baseline Imager (HBI) on the Japanese Himawari-8 satellite and the Advanced Baseline Imager (ABI) on the US GOES-16, provide much better spatial and spectral resolution as well as more rapid sampling than their predecessors and offer the potential of much improved retrievals of aerosol properties, including better assessment of photochemical process, better understanding of aerosol-cloud interactions and aerosol removal processes (wet and dry deposition over the oceans). On longer time scales, satellite data could be used to support studies on the response of aerosol generation and deposition to the changing conditions brought on by ENSO events, for example.

The Marginal Ice Zone (MIZ) breakout-group focused on questions related to improving estimates of air-sea fluxes in the MIZ, and discussions fell into eight topics: major observations needed in the MIZ; timing of observations; clouds in the Arctic; missing observations; instrumentation; platforms; Arctic feedbacks; and emerging remote sensing needs. Measurements in the MIZ necessary to characterise air-sea exchanges include gas fluxes, aerosols, and short- and long-wave radiative fluxes. The challenges to making these measurements are great, not only because of the harsh environment but also of the small scales on which they occur which renders merging in situ measurements with remotely-sensed data very difficult. Furthermore, the processes and effects involved in the freeze-up and melting periods are not symmetric, unlike the major forcing: solar radiation. Some parameters needed to determine better vertical fluxes can only be measured using in situ devices; such parameters include pCO_2 in the water, under-ice fluxes including short-wave radiation, air temperature, and air-sea temperature differences for on-ice and off-ice winds. Other important features, such as melt ponds are more accessible to remote sensing through high resolution radar and optical sensors, but to help provide data to interpret and enhance the scientific value of the remotely-sensed data, in situ measurements are also needed such as pond salinity, depth of the ponds, and thickness of snow on the floes.

In terms of emerging remote sensing needs in the MIZ those related to biogeochemical fluxes and ecosystems were discussed. Ice edge plankton blooms occur early in the melt season but are difficult to characterise in satellite ocean colour data as the solar illumination levels are low. Accurate determination of the bloom properties is important for assessing the flow of carbon through the Arctic system and the de-oxygenation that can follow when the blooms decay, thereby stressing the ecosystem; accurate measurements are challenging using current remote sensing techniques. Remote sensing of methane is now feasible, and this opens up the prospect of studying the release of methane from gas hydrates that will result from increasing water and substrate temperatures, and this is a worrisome development as methane is a potent greenhouse gas linked to positive feedbacks for climate change in the Arctic. As also identified by the aerosol breakout, the remote sensing of clouds and aerosols in the MIZ is a formidable challenge, but nevertheless these are critical factors in understanding better the feedbacks in the Arctic. The improved quantification of feedbacks, both negative and positive, in the Arctic is a challenge to the SOLAS and remote sensing communities.

In all cases, there is a pressing need to improve the accuracy and number of variables measured in situ to not only complement the remote sensing retrievals, but also to be used in validating the satellite data and in algorithm enhancement. Many new sensors have been developed for use on autonomous platforms, including drifters, gliders, Argo profilers, saildrones and wave-gliders, and aerial drones. Also, novel approaches to taking measurements in difficult conditions have been demonstrated, such as attaching instrument packages to sea mammals and large birds.

A suggested topic for a future SOLAS workshop was made by the aerosol break-out group to be “How to encourage and support linkage of field studies and regional models to large scales via remote sensing?” An additional suggestion was to hold this, or another, SOLAS workshop in Asia to encourage involvement of more scientists from Asian countries.

An issue of great disquiet voiced by the aerosol group but which is if concern for the SOLAS community as a whole, is the likelihood of gaps in long time series of measurements when critical sensors fail. In the worst case, if there were no replacement sensor foreseen, this would lead to termination of the time series.

In his final remarks, Dr Fernández-Prieto stressed that SOLAS does wield influence in ESA in helping set the priorities for future earth observation missions and guide the specification and selection of future satellite instruments. Members of the SOLAS community should take advantage of opportunities to have a positive impact on relevant ESA missions.

Peter Minnett, University of Miami, Miami, USA
(main organiser, pminnett@miami.edu)

Organising Committee

Peter Minnett
pminnett@miami.edu
University of Miami, Miami, FL, USA

Emmanuel Boss
emmanuel.boss@maine.edu
University of Maine, Orono, ME, USA

Ilan Koren
ilan.koren@weizmann.ac.il
Weizmann Institute of Science, Rehovot, Israel

Lisa Miller
Lisa.Miller@dfo-mpo.gc.ca
Institute of Ocean Sciences, Victoria, BC, Canada

Anna Rutgersson
Anna.Rutgersson@met.uu.se
Uppsala University, Uppsala, Sweden

Brian Ward
bward@nuigalway.ie
National University of Ireland, Galway, Ireland

Link to the event website:
http://www.solas-int.org/workshop-on-remote-sensing.html

The outcomes of this workshop contribute to advance our knowledge of the Core Theme 2 (Air-sea interface and fluxes of mass and energy) of the SOLAS 2015-2025: Science Plan and Organisation.

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Magdalena D. Anguelova studied engineering physics in Bulgaria. She received her PhD in oceanography from the University of Delaware, USA, and joined the Naval Research Laboratory in 2002 as a National Research Council postdoctoral fellow. Her interests include satellite-based studies of air-sea fluxes involving breaking waves, whitecaps, bubbles, and sea spray.

Radiometric measurements of whitecaps and air-sea fluxes

Magdalena D. Anguelova

U.S. Naval Research laboratory, Washington, DC, USA

maggie.anguelova@nrl.navy.mil

Surface fluxes quantify air-sea transfers of momentum (Thorpe, 1992), heat (Andreas *et al*., 2015), gases (Wanninkhof *et al*., 2009), and particles (Veron, 2015). Breaking waves in the ocean entrain air into the water and create bubble plumes and sea spray, which enhance all air-sea fluxes. Oceanic whitecaps are the most direct manifestation of wave breaking with air entrainment. Whitecap fraction *W* -defined as the fraction of the ocean surface covered by whitecaps (sea foam)- quantifies the spatial extent of whitecaps. Therefore, *W* is a suitable forcing variable for parameterising the enhancement of the surface fluxes by breaking waves.

Different radiative properties of the whitecaps allow their detection with different measuring techniques. The high reflectance of the whitecaps in the visible portion of the electromagnetic (EM) spectrum affords measuring the whitecaps from photographs (Monahan, 1971). The high emissivity of the whitecaps in the microwave portion of the EM spectrum affords detection of whitecaps as changes of the ocean surface brightness temperature T_B (Bobak *et al*., 2011). Both reflectivity and emissivity of whitecaps are detectable in the infrared portion of the EM, which allows separation of the initial and decaying phases in the evo-

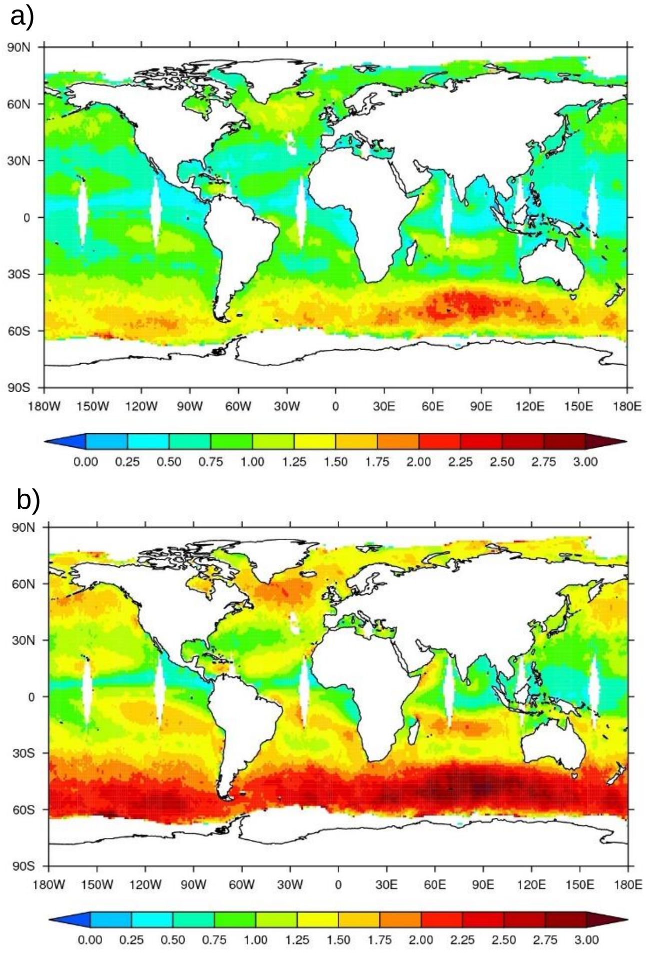

Figure 3: Mean whitecap fraction *W* for June-July-August 2014 from WindSat observations at frequency of: a) 10 GHz; b) 37 GHz.

lution of whitecaps (Potter *et al.,* 2015).

Within the framework of WindSat mission (Gaiser *et al*., 2004), we developed a method of estimating *W* from satellite-based T_B data. The algorithm uses the changes of the ocean surface emissivity at microwave frequencies from 6 to 37 GHz caused by the presence of sea foam on a rough sea surface. Satellite-based estimates of *W* (Figure 3) are useful for characterising and parameterising the geographical and seasonal variability of whitecap fraction (Salisbury *et al*., 2014). This, in turn, yields global estimates of sea spray production (Albert *et al*., 2016) and CO_2 transfer velocity (Anguelova, 2016).

We also work on expanding the utility of microwave radiometry to other frequencies. Observations at lower frequencies (below 1.5 GHz) combined with Global Positioning System (GPS) signals are useful for hurricane studies. Millimetre-wave frequencies (40-200 GHz) have the potential to measure *W* at high spatial resolution in coastal and polar waters.

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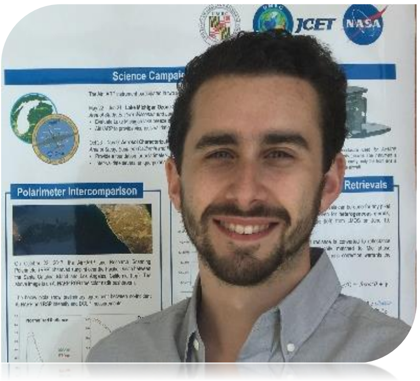

Brent McBride began his PhD at the University of Maryland, Baltimore County (UMBC) in 2015, investigating cloud microphysical properties with hyper-angular imaging polarimeter measurements. He leads optical characterisation, data analysis, and aircraft deployments of the Hyper-Angular Rainbow Polarimeter (HARP) in his role as an instrument scientist at the UMBC Earth and Space Institute.

Hyper-angular imaging polarimetry for microphysical retrieval of aerosol and cloud properties

McBride, B. A.[1], Martins, J. V. [1], Borda, R. F. [2], Barbosa, H. M. J.[3], Remer, L. [2]

[1] University of Maryland, Baltimore County, Baltimore
[2] Joint Center for Earth Systems Technology, Baltimore
[3] Universidade de Sao Paulo, Sao Paulo, Brazil

mcbride1@umbc.edu

Aerosol-cloud interaction continues to puzzle climate scientists. It is among the most significant contributors to our climate but least understood: aerosol-cloud processes are poorly represented in climate models and efforts at measurement require high accuracy, narrow resolution, and cooperation between different instruments. Much of the issue stems from light scattering: while clouds are bright, aerosols reflect little to the top of the atmosphere. Molecular scattering, ice and desert cover, and land surface reflectance all complicate the retrieval of less reflective aerosol. Aerosol are well-known cloud condensation and/or ice nuclei, and their presence in a moist environment can drastically impact the extent of cloud or ice crystal growth, compared to a clean, unpolluted scene.

Radiometric satellites, with global coverage, wide spectral range, and long lifetime in space, greatly advance the way we attack this complexity. Fantastic strides made in the past three decades in data interpretation produced elegant microphysical retrievals by comparing signal from two wave lengths (for example Nakajima and King 1990a). Co-located multi-angle sampling helps constrain aerosol microphysical properties over land and ocean (Garay *et al*., 2017). The introduction of polarised remote sensing in 1999 deepened the connection between scattered light and the cloud or aerosol size distribution (Breon *et al*., 2005) and extended assumption-limited microphysical retrievals from radiometric satellites (Reidi *et al*., 2010). Several studies converge on the idea that a multi-angle imaging polarimeter, capable of high polarimetric accuracy and narrow spatial and angular resolution, is the strongest candidate to characterise cloud and aerosol properties at the level required for climate study (Polarimetry in the Plankton-Aerosol-Cloud-ocean Ecosystem (PACE) Mission, Science Team Consensus Document).

The Hyper-Angular Rainbow Polarimeter (HARP, Figure 4), is a wide field-of-view imaging polarimeter instrument designed and developed to fill this role. Built and operated by the Laboratory for Aerosol and Cloud Optics (LACO) at the University of Maryland, Baltimore County (UMBC) in Baltimore, Maryland, USA, HARP capitalises on well-resolved atmospheric measurements done from a compact, CubeSat platform; this advancement maximises science output at a fraction of the cost of current space satellites. HARP images the same scene on the ground from up to 60 unique viewing angles at 670nm, specifically for cloud targeting, and 20 angles at 440, 550, and 870nm for aerosol retrieval. The three polarised channels of HARP simultaneously image orthogonal states of linear polarisation, and linear combinations of these channels produce the first three Stokes parameters, I, Q, and U, and the degree of linear polarization (DOLP). The flagship instrument, the HARP CubeSat, is slated to fly as a stand-alone payload in the International Space Station (ISS) orbit for a mission lifetime of one year, beginning in 2018. To prepare our data algorithms and sampling strategy, the LACO group successfully deployed an airborne version, AirHARP, to the field twice in 2017: on-board the NASA Langley B200 during the Lake Michigan Ozone Study (LMOS) from May to June and the NASA Armstrong ER-2 during the Aerosol Characterization from Polarimeter and Lidar (ACEPOL) in October and November. The LACO group is also supporting early development of HARP-2, a modified HARP CubeSat instrument that will fly as part of the PACE mission in the 2020s.

Because the HARP instruments image the angular signature of light scattering, the HARP datasets will be used to (1) infer surface and ocean properties, (2) retrieve cloud and aerosol microphysics (effective radius, variance, refractive index, cloud thermodynamic phase, AOD, and size distributions), (3) validate and extend retrievals from radiometers and vertically-resolved lidar/radar instruments. The versatility of the HARP instrument, in both science output and physical size, provides an attractive platform for answering the toughest questions about how clouds and aerosols interact and their impact on climate evolution.

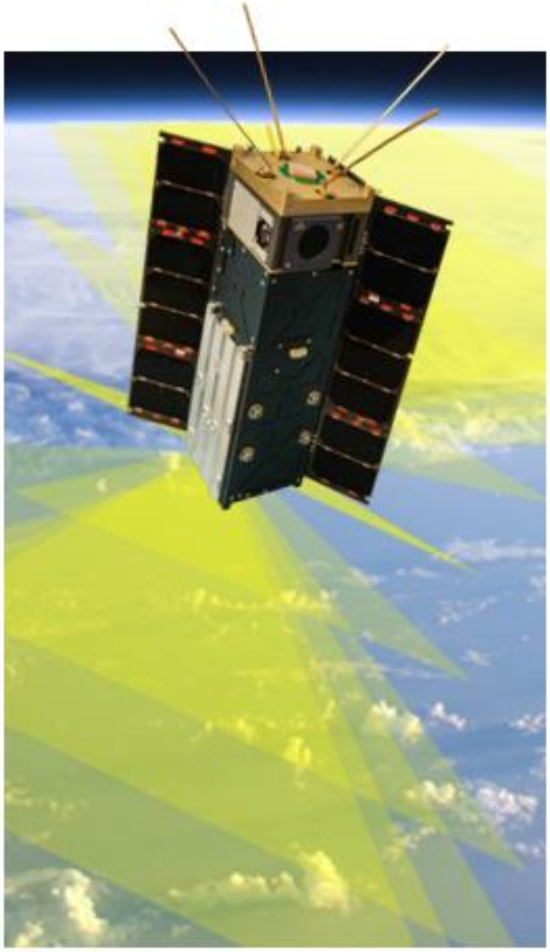

Figure 4: The HARP CubeSat spacecraft with solar panels fully deployed. Photo credit: Vanderlei Martins (UMBC/JCET)

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Hiroyuki Tomita is an assistant professor at Nagoya University. He holds a PhD from Tokai University and did a postdoc at the Japan Agency for Marine Earth Science and Technology (JAMSTEC). In 2012, he moved to Nagoya University and began research on global air-sea flux. He also serves as a project leader for the Japanese Ocean Flux Data Set with Use of Remote-Sensing Observations (J-OFURO) and a principal investigator for the Japan Aerospace Exploration Agency (JAXA) Global Change Observation Mission-Water Advanced microwave scanning radiometer 2 (GCOM-W/AMSR2).

J-OFURO3: A third-generation Japanese satellite-derived air-sea flux data set

Hiroyuki Tomita

Institute for Space-Earth Environmental Research (ISEE), Nagoya University, Nagoya, Japan

tomita@isee.nagoya-u.ac.jp

The air-sea fluxes of heat, momentum, and freshwater are essential physical quantities for understanding our climate system, so highly accurate quantitative global estimations are desirable. One possible answer to this challenge is the estimation of air-sea fluxes using multi-satellite remote sensing techniques.

A Japanese research project on satellite-derived air-sea flux, Japanese Ocean Flux Data Set with Use of Remote-Sensing Observations (J-OFURO), was established in the year 2000. Its initial public data set, J-OFURO1 (Kubota *et al*., 2002), was followed by a second-generation data set, J-OFURO2 (Tomita *et al*., 2010) in 2008, which featured improvements stemming from a pilot study's use of multi-satellite data. Following subsequent research and development, a third-generation data set, J-OFURO3, was released with significant further improvements (Tomita *et al*., 2018).

The use of multi-satellite observation is a distinct characteristic of J-OFURO3. As the number of available satellites increases, earth observations have commonly used multiple sensor platforms in recent years. As a result, current surface flux data have a higher spatial resolution with 0.25° grid size, significantly better than previous 1° grid data. This contributes to a better representation of complex flux variations related to oceanic fronts and mesoscale eddies.

Figure 5 shows spatial distribution of net heat flux over the Kuroshio extension region obtained from monthly mean of J-OFURO3 in January, 2013. This region is characterised by oceanic front and mesoscale eddies. J-OFURO3 can capture the fine-scale flux variations associated with these oceanic features.

Furthermore, in the course of development, we have improved a satellite algorithm to estimate near-surface humidity which is a key point to accurate estimation of surface heat flux. Recent research on the relationship between surface humidity, its vertical profile, and microwave satellite observations of brightness temperature allowed us to develop an algorithm for multi-satellite microwave radiometer instruments (Tomita *et al*., 2018b). The accuracy of the new satellite-derived humidity data is greatly improved, lead-

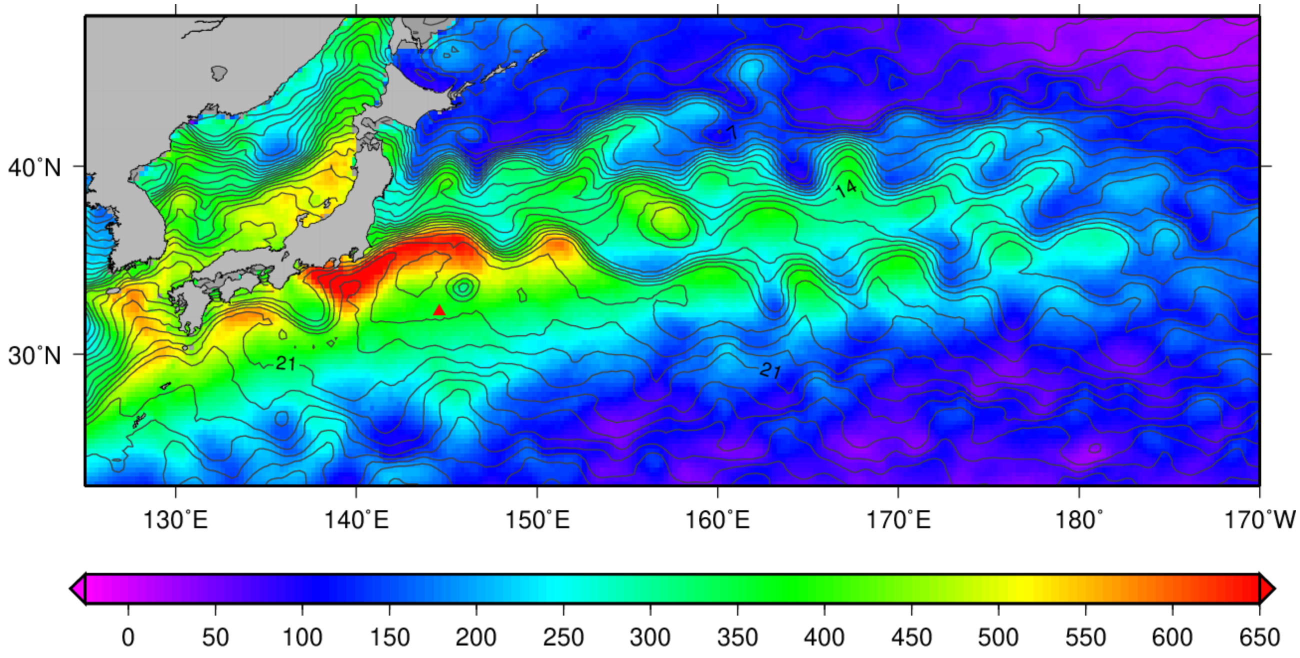

Figure 5: Spatial distribution of net heat flux [Wm-2] over the Kuroshio extension region obtained from monthly mean J-OFURO3 data for January, 2005. Positive values indicate upward flux. Contours are sea surface temperature at 0.7° K intervals. Red triangle marks the KEO buoy (32.3°N, 144.6°E) used for in situ comparison.

ing to better estimations of surface heat flux.

Comparisons with in situ observations at the KEO buoy (32.3°N, 144.6°E) confirmed that J-OFURO3's estimates are accurate, with a bias of +4.2 watt per square meter (Wm^{-2}) and root mean square (RMS) error of 45.3 Wm^{-2} in the net surface heat flux. These statistics are smaller than those obtained from previous products such as J-OFURO2 (biases of +13.5 to +68.9 Wm^{-2} and RMS errors of 60.5 to 106.8 Wm^{-2}).

J-OFURO3 offers data sets for surface heat, momentum, freshwater fluxes, and related parameters (including surface wind, humidity, and sea surface temperature) over the global oceans, excluding sea ice regions, from 1988–2013. Full data sets and documents can be accessed at https://j-ofuro.scc.u-tokai.ac.jp along with a newly designed logo symbolizing our project and data set (Figure 6).

Figure 6: The new J-OFURO logo. Top and bottom portions represent the atmosphere and the ocean, respectively, while the circles and arrows represent air-sea interactions. The symbol at top right represents both a satellite sensor and “扇子 Sensu” in Japanese, meaning the increasing success of a project.

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近海海洋环境科学国家重点实验室（厦门大学）

State Key Laboratory of Marine Environmental Science (Xiamen University)

Contact

SOLAS International Project Office

GEOMAR Helmholtz Center for Ocean Research Kiel, Germany
State Key Laboratory of Marine Environmental Science, Xiamen University, China
solas@geomar.de

Editors:
Jessica Gier
Li Li