

Developing an Observing Air–Sea Interactions Strategy (OASIS) for the global ocean

M. F. Cronin ^{1,*}, S. Swart ^{2,3}, C. A. Marandino ⁴, C. Anderson ⁵, P. Browne ^{6,†}, S. Chen ^{7,†}, W. R. Joubert ^{8,†}, U. Schuster ⁹, R. Venkatesan ^{10,11}, C. I. Addey ^{12,13,†}, O. Alves ¹⁴, F. Arduin ¹⁵, S. Battle ^{1,16}, M. A. Bourassa ¹⁷, Z. Chen ¹⁸, M. Chory ^{19,†}, C. Clayson ²⁰, R. B. de Souza ²¹, M. du Plessis ^{2,†}, M. Edmondson ^{19,†}, J. B. Edson ²⁰, S. T. Gille ⁵, J. Hermes ²², V. Hormann ⁵, S. A. Josey ²³, M. Kurz ^{24,†}, T. Lee ²⁵, F. Maicu ^{26,†}, E. H. Moustahfid ^{27,28}, S.-A. Nicholson ^{29,†}, E. S. Nyadjro ^{30,31}, J. Palter ³², R. G. Patterson ^{33,†}, S. G. Penny ^{34,35}, L. P. Pezzi ³⁶, N. Pinardi ²⁶, J. E. J. Reeves Eyre ^{37,38,†}, N. Rome ¹⁹, A. C. Subramanian ^{39,†}, C. Stienberger ^{40,†}, T. Steinhoff ^{4,41}, A. J. Sutton ¹, H. Tomita ⁴², S. M. Wills ^{43,†}, C. Wilson ^{19,†} and L. Yu ²⁰

¹Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, 7600 Sandpoint Way NE, Seattle, WA 98115, USA

²Department of Marine Sciences, University of Gothenburg, 40530 Gothenburg, Sweden

³Department of Oceanography, University of Cape Town, Rondebosch, Cape Town 7700, South Africa

⁴GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsterbrookweg 20, 24105 Kiel, Germany

⁵Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, USA

⁶European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK

⁷State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou 310012, China

⁸South African Weather Service, Private Bag X097, Pretoria 0001, South Africa

⁹Department of Geography, University of Exeter, Exeter EX4 4RJ, UK

¹⁰National Centre for Coastal Research, Ministry of Earth Sciences, Chennai 600100, India

¹¹University of Massachusetts Dartmouth, Dartmouth, MA, USA

¹²State Key Laboratory of Marine Environmental Science, College of Ocean and Earth Sciences, Xiamen University, Xiamen, Fujian 361102, China

¹³Department of Oceanography, University of Hawaii at Manoa, Honolulu, HI 96822, USA

¹⁴Bureau of Meteorology, Docklands, Melbourne, VIC 3008, Australia

¹⁵Laboratoire d'Océanographie Physique et Spatiale, CNRS, Ifremer, IRD, Université de Bretagne Occidentale, Brest 29238, France

¹⁶Innovim LLC, Greenbelt, MD 20770, USA

¹⁷Department of Earth, Ocean and Atmospheric Science and Center for Ocean-Atmospheric Prediction Studies, Florida State University, Tallahassee, FL 32310, USA

¹⁸Physical Oceanography Laboratory, Ocean University of China, Qingdao, Shandong 266005, China

¹⁹Consortium for Ocean Leadership, Washington, DC 20005, USA

²⁰Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

²¹Earth System Numerical Modeling Division, National Institute for Space Research, Cachoeira Paulista, Sao Paulo 12630-000, Brazil

²²South African Environmental Observation Network, Foreshore, 8001, Cape Town, South Africa

²³National Oceanography Centre, Southampton SO14 3ZH, UK

²⁴Office of Oceanic and Atmospheric Research, National Oceanic and Atmospheric Administration, Silver Spring, MD 20910, USA

²⁵Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

²⁶Department of Physics and Astronomy, University of Bologna, 40129 Bologna, Italy

²⁷Global Ocean Monitoring and Observing Program, Office of Oceanic and Atmospheric Research, National Oceanic and Atmospheric Administration, Silver Spring, MD 20910, USA

²⁸U.S. Integrated Ocean Observing System, National Oceanic and Atmospheric Administration, Silver Spring, MD 20910, USA

²⁹Southern Ocean Carbon-Climate Observatory, Council for Scientific and Industrial Research, Rosebank, Cape Town 7700, South Africa

³⁰Northern Gulf Institute, Mississippi State University, Stennis Space Center, MS 39529, USA

³¹National Centers for Environmental Information, National Oceanic and Atmospheric Administration, Stennis Space Center, MS 39529, USA

³²Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882, USA

³³Charles Darwin University, Casuarina, Darwin, NT 0810, Australia

³⁴Sofar Ocean Technologies, San Francisco, CA 94105, USA

³⁵Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309, USA

Received: March 31, 2022. Revised: July 21, 2022. Accepted: July 22, 2022

© The Author(s) 2022. Published by Oxford University Press on behalf of International Council for the Exploration of the Sea. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

³⁶Laboratory of Ocean and Atmosphere Studies (LOA), Earth Observation and Geoinformatics Division, National Institute for Space Research (OBT/INPE), São José dos Campos, SP 12227-010, Brazil

³⁷ERT Inc., Laurel, MD 20707, USA

³⁸NOAA/NWS/NCEP Climate Prediction Center, College Park, MD 20740, USA

³⁹Dept. of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, CO 80309, USA

⁴⁰University Corporation for Atmospheric Research of Colorado Boulder, University of Colorado, Boulder, CO 80309, USA

⁴¹NORCE Norwegian Research Centre, Jahnebakken 5, 5007 Bergen, Norway

⁴²Graduate School of Environmental Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan

⁴³Cooperative Institute for Climate Ocean, and Ecosystem Studies, University of Washington, Seattle, WA 98105, USA

* Corresponding author: tel: +1(206)526-6449; e-mail: meghan.f.cronin@noaa.gov

† Early Career Ocean Professionals.

The Observing Air–Sea Interactions Strategy (OASIS) is a new United Nations Decade of Ocean Science for Sustainable Development programme working to develop a practical, integrated approach for observing air–sea interactions globally for improved Earth system (including ecosystem) forecasts, CO₂ uptake assessments called for by the Paris Agreement, and invaluable surface ocean information for decision makers. Our “Theory of Change” relies upon leveraged multi-disciplinary activities, partnerships, and capacity strengthening. Recommendations from >40 OceanObs’19 community papers and a series of workshops have been consolidated into three interlinked Grand Ideas for creating #1: a globally distributed network of mobile air–sea observing platforms built around an expanded array of long-term time-series stations; #2: a satellite network, with high spatial and temporal resolution, optimized for measuring air–sea fluxes; and #3: improved representation of air–sea coupling in a hierarchy of Earth system models. OASIS activities are organized across five Theme Teams: (1) Observing Network Design & Model Improvement; (2) Partnership & Capacity Strengthening; (3) UN Decade OASIS Actions; (4) Best Practices & Interoperability Experiments; and (5) Findable–Accessible–Interoperable–Reusable (FAIR) models, data, and OASIS products. Stakeholders, including researchers, are actively recruited to participate in Theme Teams to help promote a predicted, safe, clean, healthy, resilient, and productive ocean.

Keywords: air-sea flux, carbon dioxide uptake, climate, global, multi-stressor, Observing Air-Sea Interactions Strategy (OASIS), observation, satellite, UN Decade of Ocean Sciences for Sustainable Development, weather.

Introduction

The sea surface supports maritime commerce and is the portion of the ocean viewed from space. The sea surface, and the interacting layers of ocean and atmosphere, has a profound influence on human and marine life. The ocean modulates the Earth’s weather and climate through exchanges of heat, moisture, momentum, greenhouse gasses, and aerosols at the air–sea interface. These air–sea fluxes act as forces on the ocean’s physical and living environment, without which the ocean would essentially be static, dark, and dead. Observations of air–sea interactions are used in forecasts of floods, droughts, marine heatwaves, severe storms, sea state, coastal inundation, climate variability, and other hazards with significant implications for regional and global economies and populations, especially those of coastal regions and Small Island Developing States (SIDS). Over the next decade, as nations meet or fail to meet the reductions of greenhouse gas emissions called for by the Paris Agreement, it will be ever more critical to monitor ocean CO₂ absorption and resulting impacts on the ocean carbonate system and marine life.

Co-designing the OASIS

The Observing Air–Sea Interactions Strategy (OASIS) has its roots in *OceanObs’19* (<https://www.oceanobs19.net>), a once-per-decade conference to build a community vision for transforming ocean observations and ocean information over the next decade. Of the 140 published community perspective papers from OceanObs’19, >40 were related to observing air–sea interactions. Three interlinked “Grand Ideas” emerged (Figure 1) for creating Grand Idea #1: a globally distributed network of mobile air–sea interaction observing platforms built around an expanded array of fixed stations that provide long-term time-series in key regions. At some point, these stations should each be enhanced with process studies and/or supersites, which would fully resolve interactions and feedbacks. These observations would then help to construct and validate satellite retrievals, develop new artificial intelligence

modelling tools, and support “Grand Idea” #2: creating a satellite network, with high spatial and temporal resolution, optimized for measuring air–sea fluxes. Finally, “Grand Idea” #3, which depends on the first two, calls for improved understanding and process representation of the air–sea coupling in a hierarchy of Earth system models. Together, these expanded observing capabilities and improved representations of air–sea interaction will lead to more reliable weather, climate, and ecosystem forecasts and reanalyses.

The individual recommendations defining these transformational actions are now being harmonized by cross discipline Theme Teams (TT), and anchored to societal issues through a series of virtual workshops with stakeholder partners following the principles of co-design laid out by IOC-UNESCO (2021). These UN Ocean Decade Laboratories satellite events have included virtual workshops on air–sea observations for a Predicted Ocean (Cronin *et al.*, 2021), a Clean Ocean (Marandino *et al.*, 2022), a Safe Ocean (Venkatesan *et al.*, 2022), an Accessible Ocean, and Offshore Wind Energy. More information on past and planned workshops can be found on airseaobs.org.

Theory of change

It is clear that to realize these Grand Ideas, we must work together. A “Theory of Change” was proposed (Figure 2), which turns one of the most challenging aspects of measuring air–sea fluxes, the need to measure multiple co-located Essential Ocean Variables (EOVs), into a transformative opportunity to co-design an ideal and fit-for-purpose observing system. Multifunctional platforms are not only more economical than multiple single-function platforms, they also encourage collaborations across disciplines and areas of expertise. New sensors must be carefully tested and integrated into platforms to ensure interoperability and maximize utility. By developing best practices and technical readiness procedures, and fostering a culture of mentorship and partnership, the capacity of the observing system could be significantly expanded

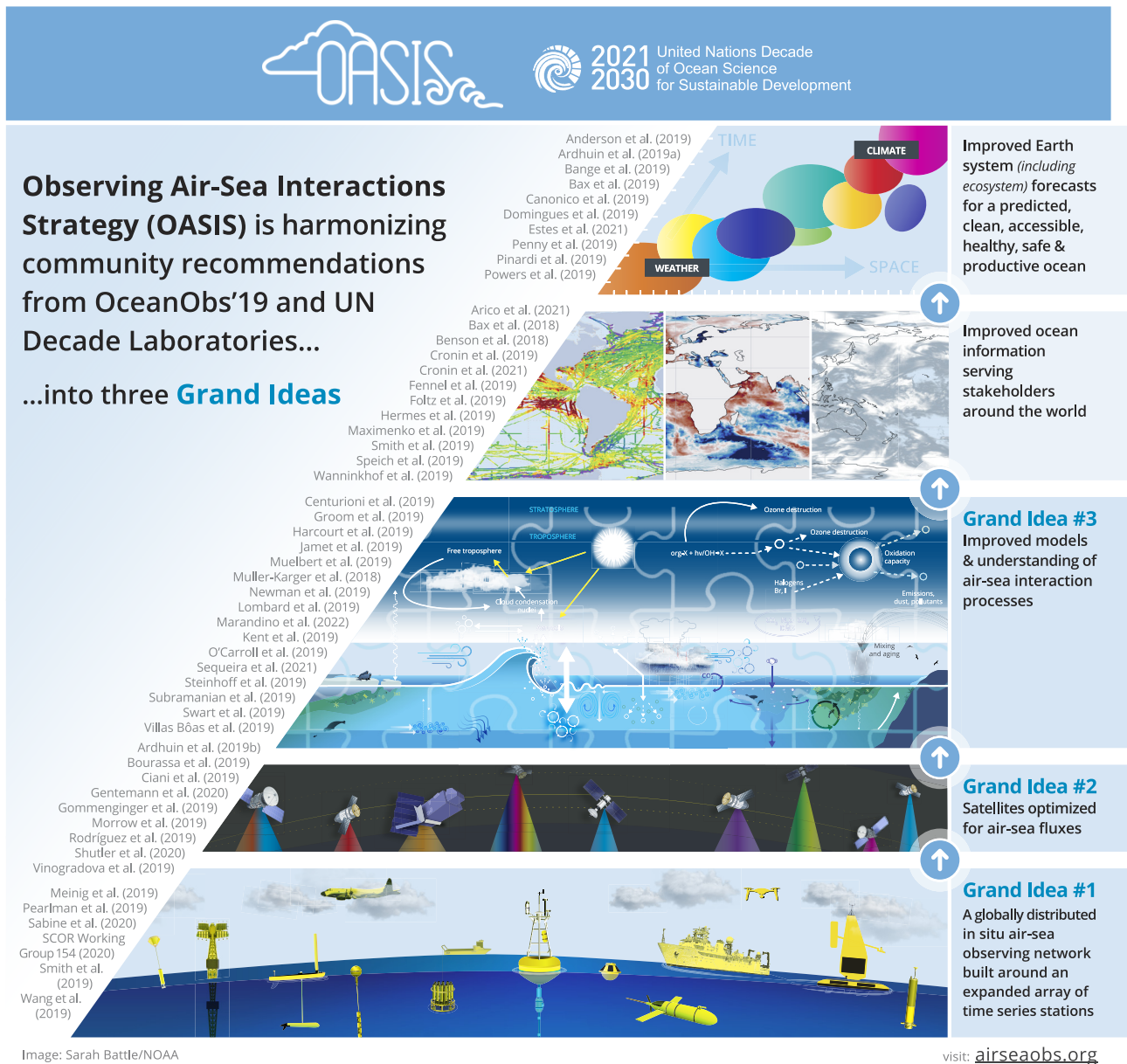


Figure 1. Three interlinked “Grand Ideas” of the OASIS and their relation to an end-to-end ocean information delivery for improved Earth system forecasts, including for ecosystems. Community strategy paper citations calling for the OASIS recommendations are shown here and in the reference list. Mapped fields in the second from the top layer, include (left) surface $p\text{CO}_2$ from the Surface Ocean CO_2 Atlas (Bakker *et al.*, 2016), (middle) daily average net downward heat flux on 3 September 2010 from prototype ORAS6 reanalysis, and (right) total cloud cover from ECMWF Reanalysis-5 (ERA5) reanalysis (Hersbach *et al.*, 2020) at 3 September 2010 T -12:00.

while providing opportunities for engagement by Early Career Ocean Professionals (ECOPs) and scientists from under-resourced nations and institutions. In addition, the collocation of multiple EOVS, including Essential Biodiversity Variables (EBVs), will revolutionize our ability to interrogate impacts from multiple stressors on ecosystems, from changes in biogeochemistry to components of the food web, and build robust state-of-the-art ecological forecasts.

OASIS SCOR working group #162 and TTs

Membership of the OASIS Scientific Committee for Ocean Research (SCOR) Working Group (WG) #162 covers multiple disciplines and methodologies, and spans data cre-

ators to information users (i.e. “end-to-end”). OASIS includes representatives from all Global Ocean Observing System (GOOS) panels (physics and climate, biogeochemistry, and biology/ecosystem). The WG spans the globe and is diverse in terms of gender and career level. Nearly all members were involved in OceanObs'19 either as lead or contributing authors with significant ties to user communities in their respective nations and regions.

One of the WG’s first activities was to get OASIS endorsed as a UN Decade of Ocean Science for Sustainable Development Programme. OASIS will work with community members across five TT (Figure 3):

The “Observing Network Design & Model Development” TT will harmonize OceanObs'19 and other community rec-

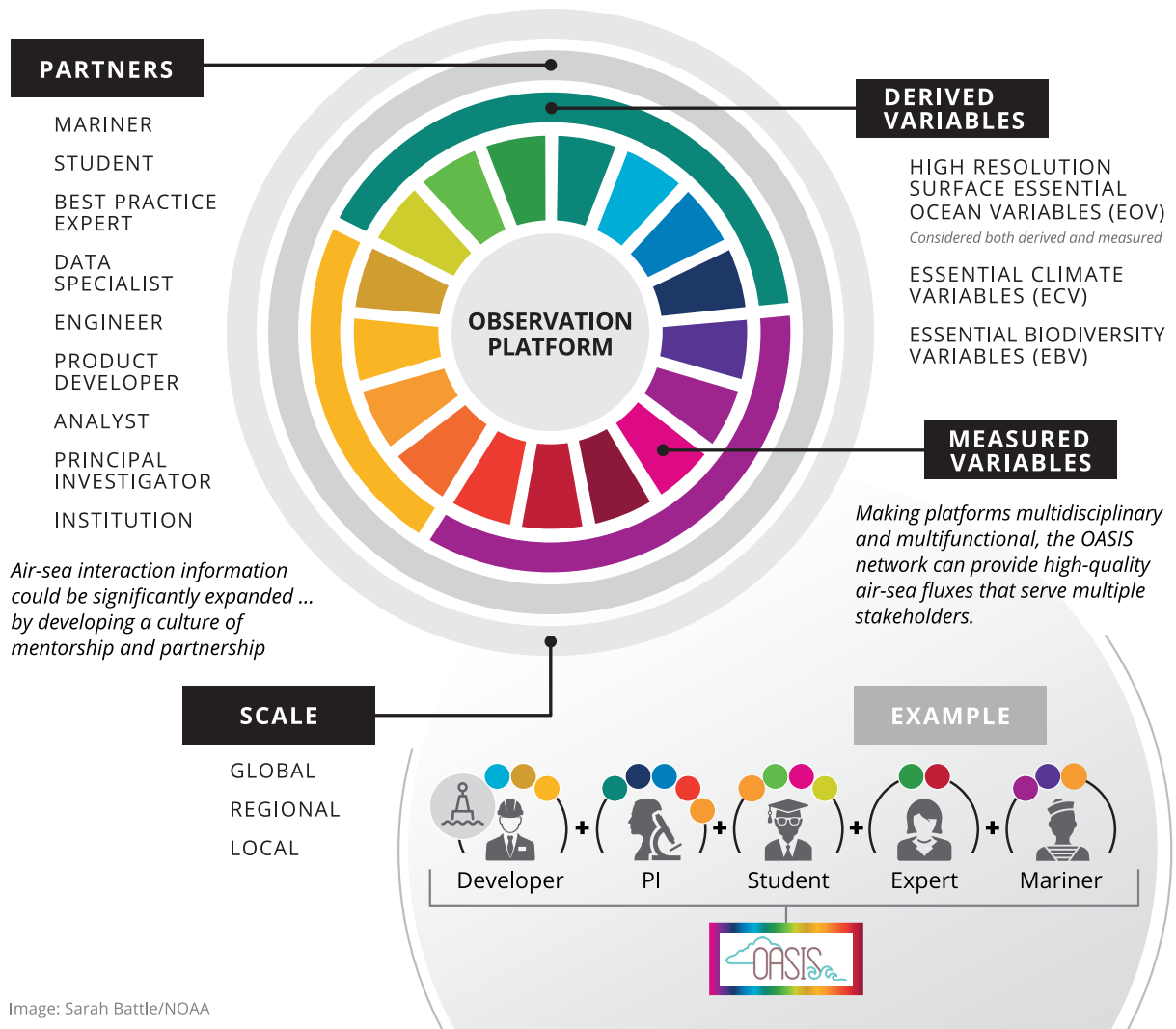


Figure 2. OASIS Theory of Change.

ommendations into a coherent strategy and will define process studies and transformational actions needed to reach our 2030 goals of a predicted, healthy, resilient, productive, clean, and safe ocean.

The “Partnership & Capacity Strengthening” TT will work with the other teams to offer curricula for a range of learners, from children to graduate students to mariners. Additionally, workshops, short courses, and mentoring programs will be initiated around the world.

The “UN Decade OASIS Actions” TT will work to implement OASIS projects by leveraging opportunities provided through the UN Ocean Decade and Ocean Decade National Committees.

The “Best Practices & Interoperability Experiments” TT will develop, document, and share best practices for collecting observations while simultaneously performing experiments to ensure that the air–sea interaction variables are interoperable across platforms.

The “Findable–Accessible–Interoperable–Reusable (FAIR) Data, Models & OASIS Products” TT will guide the development and accessibility of air–sea flux software toolboxes and gridded flux products, and work to make air–sea interaction information open and FAIR.

To get involved in any of these TTs, and/or sign up to receive the OASIS newsletter, go to: <https://airseaobs.org/get-involved>.

Looking forward to 2030, and back to 1972

OASIS hopes to make a major change in the observing and understanding of air–sea interactions through transformational actions, including an expanded *in situ* observing network, improved observations from space, improved understanding and representation in coupled models, and a significant increase in the capacity to make observations globally and have them used globally.

The famous photo of Earth (Figure 4) taken by the Apollo 17 astronauts en route to the Moon in 1972 changed our perspective of our place in the Universe. Fifty years later, anthropogenic global warming is undeniable, and our adverse impact on Earth must change.

OASIS can help build an observing network that would track the ocean’s uptake of heat and carbon dioxide, and constrain numerical models for improved weather, climate, water, and ecosystem forecasts and reanalyses. Through OASIS, we hope that the world gains a better understanding of the deli-

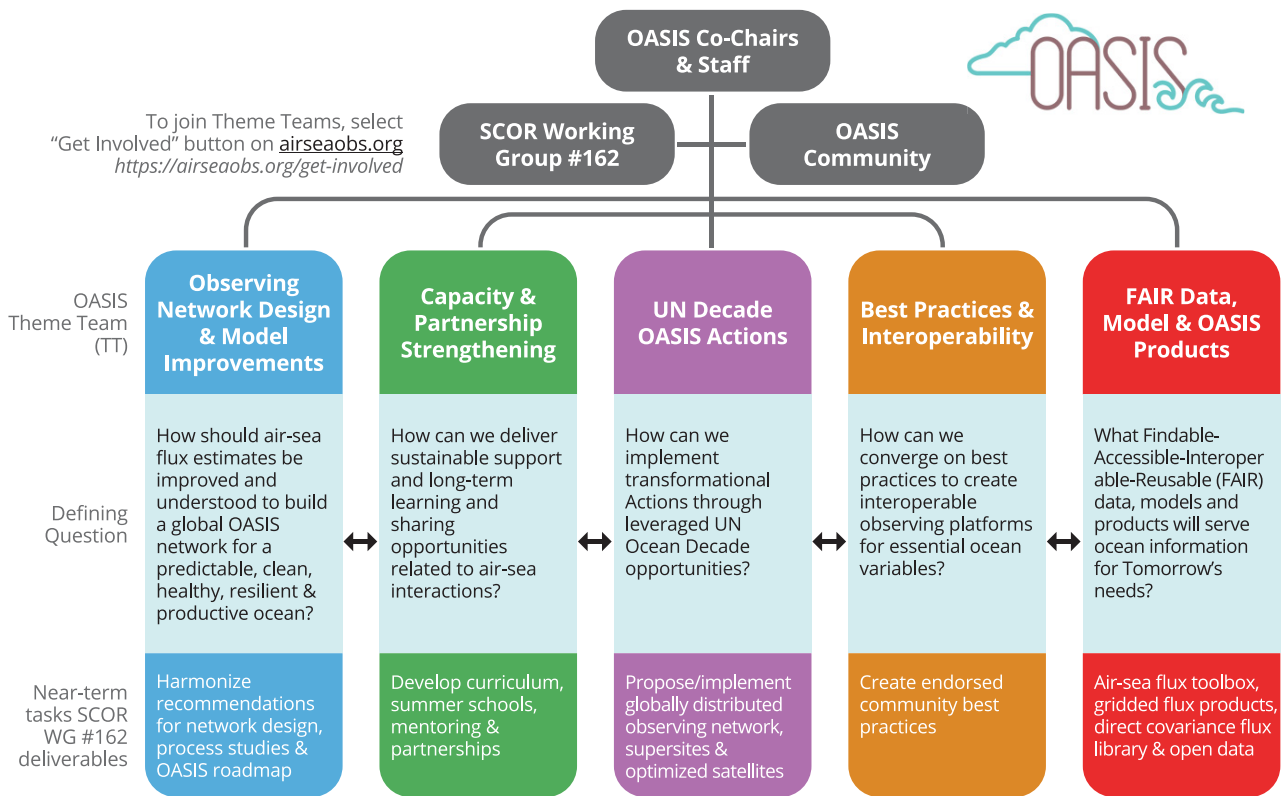


Figure 3. OASIS organization chart depicting the five community-based TTs.



Figure 4. The "Blue Marble" photograph of the Earth was taken by the crew of Apollo 17 en route to the Moon on 7 December 1972. Image courtesy: NASA (see: https://www.nasa.gov/topics/earth/features/astronauts_eyes.html).

cate balances that govern weather, climate, water, the carbon cycle, and the ocean environment, and a better understanding of how to maintain these balances for the benefit of all.

Funding

We acknowledge funding provided by national committees of the Scientific Committee on Oceanic Research (SCOR) and from a grant to SCOR from the U.S. National Science Foundation (OCE-1840868) to support SCOR Working Group #162 (OASIS) activities.

Data availability

No new data were generated or analysed in support of this research.

Authors' contribution

OASIS was conceived by the SCOR WG #162 and lead authors of OceanObs19 papers included here as co-authors. MFC drafted the manuscript and finalized edits; all authors discussed ideas and contributed edits. SB created Figures 1–3. The manuscript is submitted with the approval of all the authors.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgements

This is PMEL Paper #5361.

References

Anderson, C. R., Berdalet, E., Kudela, R. M., Cusack, C. K., Silke, J., O'Rourke, E., Dugan, D., *et al.* 2019. Scaling up from regional case studies to a global harmful algal bloom observing system. *Frontiers in Marine Science*, 6:250. doi:10.3389/fmars.2019.00250.

- Ardhuin, F., Brandt, P., Gaultier, L., Donlon, C., Battaglia, A., Boy, F., Casal, T., *et al.* 2019b. SKIM, a candidate satellite mission exploring global ocean currents and waves. *Frontiers in Marine Science*, 6:209. doi:10.3389/fmars.2019.00124.
- Ardhuin, F., Stopa, J. E., Chapron, B., Collard, F., Husson, R., Jensen, R. E., Johannessen, J., *et al.* 2019a. Observing sea states. *Frontiers in Marine Science*, 6:124. doi: 10.3389/fmars.2019.00209.
- Aricò, S., Arrieta, J. M., Bakker, D. C. E., Boyd, P. W., Cotrim da Cunha, L., Chai, F., Dai, M., *et al.* 2021. Integrated ocean carbon research: a summary of ocean carbon research, and vision of coordinated ocean carbon research and observations for the next decade. In (IOC Technical Series, 158.)Ed. by R. Wanninkhof, C. Sabine, and S. Aricò. UNESCO, Paris. 46. doi:10.25607/h0gj-pq41.
- Bakker, D. C. E., Pfeil, B., Landa, C. S., Metz, N., O'Brien, K. M., Olsen, A., Smith, K., *et al.* 2016. A multi-decade record of high-quality $f\text{CO}_2$ data in version 3 of the Surface Ocean CO₂ Atlas (SOCAT). *Earth System Science Data*, 8:383–413. doi.org/10.5194/essd-8-383-2016.
- Bange, H. W., Arévalo-Martínez, D. L., de la Paz, M., Farías, L., Kaiser, J., Kock, A., Law, C. S., *et al.* 2019. A harmonized nitrous oxide (N₂O) ocean observation network for the 21st century. *Frontiers in Marine Science*, 6:157. doi:10.3389/fmars.2019.00157.
- Bax, N. J., Appeltans, W., Brainard, R., Duffy, J. E., Dunstan, P., Hanich, Q., Harden Davies, H., *et al.* 2018. Linking capacity development to GOOS monitoring networks to achieve sustained ocean observation. *Frontiers in Marine Science*, 5:346. doi:10.3389/fmars.2018.00346.
- Bax, N. J., Miloslavich, P., Muller-Karger, F. E., Allain, V., Appeltans, W., Batten, S. D., Benedetti-Cecchi, L., *et al.* 2019. A response to scientific and societal needs for marine biological observations. *Frontiers in Marine Science*, 6:395. doi:10.3389/fmars.2019.00395.
- Benson, A., Brooks, C. M., Canonico, G., Duffy, E., Muller-Karger, F., Sosik, H. M., Miloslavich, P., *et al.* 2018. Integrated observations and informatics improve understanding of changing marine ecosystems. *Frontiers in Marine Science*, 5:428. doi:10.3389/fmars.2018.00428.
- Bourassa, M. A., Meissner, T., Cerovecki, I., Chang, P. S., Dong, X., De Chiara, G., Donlon, C., *et al.* 2019. Remotely sensed winds and wind stresses for marine forecasting and ocean modeling. *Frontiers in Marine Science*, 6:443. doi:10.3389/fmars.2019.00443.
- Canonico, G., Buttigieg, P. L., Montes, E., Muller-Karger, F. E., Stepien, C., Wright, D., Benson, A., *et al.* 2019. Global observational needs and resources for marine biodiversity. *Frontiers in Marine Science*, 6:367. doi:10.3389/fmars.2019.00367.
- Centurioni, L. R., Turton, J., Lumpkin, R., Braasch, L., Brassington, G., Chao, Y., Charpentier, E., *et al.* 2019. Global *in situ* observations of essential climate and ocean variables at the air–sea interface. *Frontiers in Marine Science*, 6:419. doi:10.3389/fmars.2019.00419.
- Cronin, M. F., Gentemann, C. L., Edson, J., Ueki, I., Bourassa, M., Brown, S., Clayson, C. A., *et al.* 2019. Air–sea fluxes with a focus on heat and momentum. *Frontiers in Marine Science*, 6:430. doi:10.3389/fmars.2019.00430.
- M.F. Cronin, C.A. Marandino, S. Schwartz, M. Chory, P. Browne, A. Subramanian, W. Joubert, *et al.* eds. 2021. Workshop Report for the Observing Air-Sea Interactions Strategy (OASIS) for a Predicted Ocean, a Satellite Event for the UN Decade of Ocean Science for Sustainable Development—Predicted Ocean Laboratory. SCOR Working Group #162 for developing an Observing Air-Sea Interactions Strategy (OASIS), Newark, NJ. 19pp. doi:10.3289/SCOR_WG_162_2021.
- Domingues, R., Kuwano-Yoshida, A., Chardon-Maldonado, P., Todd, R. E., Halliwell, G., Kim, H.-S., Lin, I.-I., *et al.* 2019. Ocean observations in support of studies and forecasts of tropical and extratropical cyclones. *Frontiers in Marine Science*, 6:446. doi:10.3389/fmars.2019.00446.
- Estes, M., Anderson, C., Appeltans, W., Bax, N., Bednaršek, N., Canonico, G., *et al.* 2021. Enhanced monitoring of life in the sea is a critical component of conservation management and sustainable economic growth. *Marine Policy*, 132, 104699. doi.org/10.1016/j.marpol.2021.104699.
- Fennel, K., Alin, S., Barbero, L., Evans, W., Bourgeois, T., Cooley, S., Dunne, J., *et al.* 2019. Carbon cycling in the North American coastal ocean: a synthesis. *Biogeosciences*, 16: 1281–1304. <https://doi.org/10.5194/bg-16-1281-2019>.
- Foltz, G. R., Brandt, P., Richter, I., Rodríguez-Fonseca, B., Hernandez, F., Dengler, M., Rodrigues, R. R., *et al.* 2019. The tropical atlantic observing system. *Frontiers in Marine Science*, 6:206. doi:10.3389/fmars.2019.00206.
- Gentemann, C. L., Clayson, C. A., Brown, S., Lee, T., Parfitt, R., Farrar, J. T., Bourassa, M., *et al.* 2020. FluxSat: measuring the ocean–atmosphere turbulent exchange of heat and moisture from space. *Remote Sensing*, 12:1796. <https://doi.org/10.3390/rs12111796>.
- Gommenginger, C., Chapron, B., Hogg, A., Buckingham, C., Fox-Kemper, B., Eriksson, L., Soulat, F., *et al.* 2019. SEASTAR: a mission to study ocean submesoscale dynamics and small-scale atmosphere–ocean processes in coastal, shelf and polar seas. *Frontiers in Marine Science*, 6:457. doi:10.3389/fmars.2019.00457.
- Groom, S., Sathyendranath, S., Ban, Y., Bernard, S., Brewin, R., Brotas, V., Brockmann, C., *et al.* 2019. Satellite ocean colour: current status and future perspective. *Frontiers in Marine Science*, 6:485. doi:10.3389/fmars.2019.00485.
- Harcourt, R., Sequeira, A. M. M., Zhang, X., Roquet, F., Komatsu, K., Heupel, M., McMahon, C., *et al.* 2019. Animal-Borne telemetry: an integral component of the ocean observing toolkit. *Frontiers in Marine Science*, 6:326. doi:10.3389/fmars.2019.00326.
- Hermes, J. C., Masumoto, Y., Beal, L. M., Roxy, M. K., Vialard, J., Andres, M., Annamalai, H., *et al.* 2019. A sustained ocean observing system in the indian ocean for climate related scientific knowledge and societal needs. *Frontiers in Marine Science*, 6:355. doi:10.3389/fmars.2019.00355.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., *et al.* 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146:1999–2049. <https://doi.org/10.1002/qj.3803>.
- IOC-UNESCO 2021. Co-designing the science we need for the ocean we want: guidance and recommendations for collaborative approaches to designing & implementing decade actions. In: (The Ocean Decade Series, 29). UNESCO, Paris.
- Jamet, C., Ibrahim, A., Ahmad, Z., Angelini, F., Babin, M., Behrenfeld, M. J., Boss, E., *et al.* 2019. Going beyond standard ocean color observations: lidar and polarimetry. *Frontiers in Marine Science*, 6:251. doi: 10.3389/fmars.2019.00251.
- Kent, E. C., Rayner, N. A., Berry, D. I., Eastman, R., Grigorjeva, V. G., Huang, B., Kennedy, J. J., *et al.* 2019. Observing requirements for long-term climate records at the ocean surface. *Frontiers in Marine Science*, 6:441. doi: 10.3389/fmars.2019.00441.
- Lombard, F., Boss, E., Waite, A. M., Vogt, M., Uitz, J., Stemann, L., Sosik, H. M., *et al.* 2019. Globally consistent quantitative observations of planktonic ecosystems. *Frontiers in Marine Science*, 6:196. doi:10.3389/fmars.2019.00196.
- Marandino, C., Cronin, M. F., Chory, M., Maximenko, N., Anderson, C., Ballesteros, M. A., Booge, D., *et al.* 2022. Workshop Report for the Observing Air-Sea Interactions Strategy (OASIS) for a Clean Ocean, a satellite event for the UN Decade of Ocean Science for Sustainable Development—Clean Ocean Laboratory, held virtually on November 18–19, 2021. SCOR Working Group #162 for developing an Observing Air-Sea Interactions Strategy (OASIS). doi:10.3289/SCOR_WG_162_2022_1.
- Maximenko, N., Corradi, P., Law, K. L., Van Sebille, E., Garaba, S. P., Lampitt, R. S., Galgani, F., *et al.* 2019. Toward the integrated marine debris observing system. *Frontiers in Marine Science*, 6:447. doi:10.3389/fmars.2019.00447.
- Meinig, C., Burger, E. F., Cohen, N., Cokelet, E. D., Cronin, M. F., Cross, J. N., de Halleux, S., *et al.* 2019. Public–private partnerships to advance regional ocean-observing capabilities: a saildrone and NOAA-PMEL case study and future considerations to expand to global scale observing. *Frontiers in Marine Science*, 6:448. doi:10.3389/fmars.2019.00448.

- Morrow, R., Fu, L. - L., Arduin, F., Benkiran, M., Chapron, B., Cosme, E., d'Ovidio, F., *et al.* 2019. Global observations of fine-scale ocean surface topography with the surface water and ocean topography (SWOT) mission. *Frontiers in Marine Science*, 6:232. doi:10.3389/fmars.2019.00232.
- Muelbert, J. H., Nidzicko, N. J., Acosta, A. T. R., Beaulieu, S. E., Bernardino, A. F., Boikova, E., Bornman, T. G., *et al.* 2019. ILTER—the International Long-Term Ecological Research network as a platform for global coastal and ocean observation. *Frontiers in Marine Science*, 6:527. doi:10.3389/fmars.2019.00527.
- Muller-Karger, F. E., Miloslavich, P., Bax, N. J., Simmons, S., Costello, M. J., Sousa Pinto, I., Canonico, G., *et al.* 2018. Advancing marine biological observations and data requirements of the complementary essential ocean variables (EOVs) and essential biodiversity variables (EBVs) frameworks. *Frontiers in Marine Science*, 5:211. doi:10.3389/fmars.2018.00211.
- Newman, L., Heil, P., Trebilco, R., Katsumata, K., Constable, A., van Wijk, E., Assmann, K., *et al.* 2019. Delivering sustained, coordinated, and integrated observations of the southern ocean for global impact. *Frontiers in Marine Science*, 6:433. doi:10.3389/fmars.2019.00433.
- O'Carroll, A. G., Armstrong, E. M., Beggs, H. M., Bouali, M., Casey, K. S., Corlett, G. K., Dash, P., *et al.* 2019. Observational needs of sea surface temperature. *Frontiers in Marine Science*, 6:420. doi:10.3389/fmars.2019.00420.
- Pearlman, J., Bushnell, M., Coppola, L., Karstensen, J., Buttigieg, P. L., Pearlman, F., Simpson, P., *et al.* 2019. Evolving and sustaining ocean best practices and standards for the next decade. *Frontiers in Marine Science*, 6:277. doi:10.3389/fmars.2019.00277.
- Penny, S. G., Akella, S., Balmaseda, M. A., Browne, P., Carton, J. A., Chevallier, M., Counillon, F., *et al.* 2019. Observational needs for improving ocean and coupled reanalysis, S2S prediction, and decadal prediction. *Frontiers in Marine Science*, 6:391. doi:10.3389/fmars.2019.00391.
- Pinardi, N., Stander, J., Legler, D. M., O'Brien, K., Boyer, T., Cuff, T., Bahrel, P., *et al.* 2019. The joint IOC (of UNESCO) and WMO collaborative effort for met-ocean services. *Frontiers in Marine Science*, 6:410. doi:10.3389/fmars.2019.00410.
- Powers, M., Begg, Z., Smith, G., and Miles, E. 2019. Lessons from the Pacific Ocean Portal: building Pacific island capacity to interpret, apply, and communicate ocean information. *Frontiers in Marine Science*, 6:476. doi:10.3389/fmars.2019.00476.
- Rodríguez, E., Bourassa, M., Chelton, D., Farrar, J. T., Long, D., Perkovic-Martin, D., and Samelson, R. 2019. The winds and currents mission concept. *Frontiers in Marine Science*, 6:438. doi:10.3389/fmars.2019.00438.
- Sabine, C., Sutton, A., McCabe, K., Lawrence-Slavas, N., Alin, S., Feely, R., Jenkins, R., *et al.* 2020. Evaluation of a new carbon dioxide system for autonomous surface vehicles. *Journal of Atmospheric and Oceanic Technology*, 37: 1305–1317. <https://doi.org/10.1175/JTECH-D-20-0010.1>.
- SCOR Working Group 154. 2020. Recommendations for plankton measurements on the GO-SHIP program with relevance to other sea-going expeditions. SCOR Working Group 154 GO-SHIP Report. Scientific Committee on Oceanic Research, Oostende, Belgium. 70 pp. <http://dx.doi.org/10.25607/OBP-718>.
- Sequeira, A. M. M., O'Toole, M., Keates, T. R., *et al.* 2021. A standardisation framework for bio-logging data to advance ecological research and conservation. *Methods in Ecology and Evolution*, 12:996–1007. <https://doi.org/10.1111/2041-210X.13593>.
- Shutler, J. D., Wanninkhof, R., Nightingale, P. D., Woolf, D. K., Bakker, D. C. E., Watson, A., Ashton, I., *et al.* 2020. Satellites will address critical science priorities for quantifying ocean carbon. *Frontiers in Ecology and the Environment*, 18:27–35. doi: 10.1002/fee.2129.
- Smith, S. R., Alory, G., Andersson, A., Asher, W., Baker, A., Berry, D. I., Drushka, K., *et al.* 2019. Ship-Based contributions to global ocean, weather, and climate observing systems. *Frontiers in Marine Science*, 6:434. doi:10.3389/fmars.2019.00434.
- Smith, N., Kessler, W. S., Cravatte, S., Sprintall, J., Wijffels, S., Cronin, M. F., Sutton, A., *et al.* 2019. Tropical Pacific observing system. *Frontiers in Marine Science*, 6:31. doi:10.3389/fmars.2019.00031.
- Speich, S., Lee, T., Muller-Karger, F., Lorenzoni, L., Pascual, A., Jin, D., Delory, E., *et al.* 2019. Editorial: oceanobs'19: an ocean of opportunity. *Frontiers in Marine Science*, 6:570. doi:10.3389/fmars.2019.00570.
- Steinhoff, T., Gkritzalis, T., Lauvset, S. K., Jones, S., Schuster, U., Olsen, A., Becker, M., *et al.* 2019. Constraining the oceanic uptake and fluxes of greenhouse gases by building an ocean network of certified stations: the ocean component of the integrated carbon observation system, ICOS-oceans. *Frontiers in Marine Science*, 6:544. doi:10.3389/fmars.2019.00544.
- Subramanian, A. C., Balmaseda, M. A., Centurioni, L., Chattopadhyay, R., Cornuelle, B. D., DeMott, C., Flatau, M., *et al.* 2019. Ocean observations to improve our understanding, modeling, and forecasting of subseasonal-to-seasonal variability. *Frontiers in Marine Science*, 6:427. doi:10.3389/fmars.2019.00427.
- Swart, S., Gille, S. T., Delille, B., Josey, S., Mazloff, M., Newman, L., Thompson, A. F., *et al.* 2019. Constraining southern ocean air-sea-ice fluxes through enhanced observations. *Frontiers in Marine Science*, 6:421. doi:10.3389/fmars.2019.00421.
- Trowbridge, J., Weller, R., Kelly, D., Plueddemann, A., Barth, J. A., and Kawka, O. 2019. The ocean observatories initiative. *Frontiers in Marine Science*, 6:74. doi:10.3389/fmars.2019.00074.
- Venkatesan, R., Cronin, M. F., Anderson, C., Aucan, J., Aydelett, M. L., Boulay, S. O. C., Chardón-Maldonado, P. *et al.* 2022. Workshop Report for the Air-Sea Observations for a Safe Ocean, a satellite event for the UN Decade of Ocean Science for Sustainable Development - Safe Ocean Laboratory, held virtually on April 7, 2022. doi:10.3389/fmars.2019.00425.
- Villas Bôas, A. B., Arduin, F., Ayet, A., Bourassa, M. A., Brandt, P., Chapron, B., Cornuelle, B. D., *et al.* 2019. Integrated observations of global surface winds, currents, and waves: requirements and challenges for the next decade. *Frontiers in Marine Science*, 6:425. doi:10.3389/fmars.2019.00425.
- Vinogradova, N., Lee, T., Boutin, J., Drushka, K., Fournier, S., Sabia, R., Stammer, D., *et al.* 2019. Satellite salinity observing system: recent discoveries and the way forward. *Frontiers in Marine Science*, 6:243. doi:10.3389/fmars.2019.00243.
- Wang, Z. A., Moustahfid, H., Mueller, A. V., Michel, A. P. M., Mowlem, M., Glazer, B. T., Mooney, T. A., *et al.* 2019. Advancing observation of ocean biogeochemistry, biology, and ecosystems with cost-effective *in situ* sensing technologies. *Frontiers in Marine Science*, 6:519. doi:10.3389/fmars.2019.00519.
- Wanninkhof, R., Pickers, P. A., Omar, A. M., Sutton, A., Murata, A., Olsen, A., Stephens, B. B., *et al.* 2019. A surface ocean CO₂ reference network, SOCONET and associated marine boundary layer CO₂ measurements. *Frontiers in Marine Science*, 6:400. doi:10.3389/fmars.2019.00400.