Blueprint for large-scale, operational, Earth Observation-based systems for Harmful Algal Blooms monitoring

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Introduction

The objective of this Breakout Workshop (BW) was to propose recommendations leading to an agreed blueprint for large-scale, effective, operational Earth Observation (EO)–based systems for monitoring Harmful Algal Blooms (HABs). The workshop aimed to reach consensus on a clear definition of HABs applicable in the EO context, to clarify the scope of these systems and support the choice of proper methods and their harmonization. The BW aimed also at identifying a strategy to reconcile the diverse methods and to supersede the regional/empirical character of HAB-related approaches and relate them to a more formal framework based on first principles.

Session Summary

The session included three presentations followed by a discussion moderated by the co-chairs:

- 'CyanoTRACKER: Solving CyanoHABs Monitoring Challenges using Sensing Integrated Cyber-Physical Systems Approach', by Deepak Mishra (University of Georgia, Athens).
- 'The National Oceans and Coastal Information Management System Fisheries and Aquaculture Decision Support Tool', by Marie Smith (CSIR, Cape Town).
- 'HABs and gaps: constructing climate data records to assess lake functioning over decadal timescales', by Stefan Simis (PML, Plymouth).

CyanoTRACKER is an early-warning system for phytoplankton algal blooms and cyanobacterial HABs monitoring worldwide, available since 2016. It employs a multi-cloud framework for early detection, integrating social media and community observations and remote sensing measurements from in situ, UAS, and satellite sensors. During CyanoTRACKER presentations, a few needs/gaps were identified:

i. The need for cross-calibration among different data sources to be integrated in the system
ii. Limited capability for monitoring small water bodies using satellite sensors

Latest developments of CyanoTRACKER project include the use of physics-informed Machine Learning techniques to map phycocyanin, the development of new costeffective in situ sensors (Cyanosense 2.0), the use of OCI-PACE data products for species-based classification, and the use of geostationary satellite sensors (e.g., GOCI) to assess diurnal variation of blooms in large lakes.

The Fisheries and Aquaculture Decision Support Tool is part of **OCIMS** (National Oceans and Coastal Information Management System), providing support to Fisheries and Aquaculture activities in the South Africa Exclusive Economic Zones, to improve preparedness and mitigate negative impacts. The system, based on Sentinel-3 OLCI derived data, provides maps of daily chlorophyll-a concentration (chl-a) and Phytoplankton type classification. Key success factors (relevant for other systems) are:

i. Strong stakeholder engagement, enabling user-driven system and product design
ii. Regional tailoring through a dedicated chl-a algorithm
iii. Near-Real Time (NRT) products for daily decision making preferred to highest quality products
iv. Comprehensive bloom characterization using additional products (i.e., spectral features)
v. Risk indication rather than toxic species identification, pending further measurements

Multivariate time-series analyses are fundamental for direct management, particularly for defining baselines, identifying trends, and detecting anomalies. **ESA Lakes Climate Change Initiative (CCI)** supports these analyses by providing stable long time series of EO-derived data on lake water level, extent, volume change, surface temperature, ice cover and thickness, water reflectance, and derived bio-optical quantities. The latter are obtained from MERIS, MODIS, and Sentinel-3 OLCI sensors through the CALIMNOS processing chain, which includes atmospheric correction, a pre-classification of optical water type (13 classes), and a weighted blending of class-optimized algorithms validated against global in situ data. Uncertainty values are also provided. Within this framework, the presentation focused also on the gaps that may still hinder our ability to fully understand and characterize blooms, along with a set of recommendations to address them.

i. There is a spectral capability gap before MERIS (<2002) and between MERIS and OLCI missions (2012-2016). Robust methods for trend fitting or lake-specific bias corrections may bridge observations gaps
ii. MSI revisit time is too long; additionally, MSI dedicated algorithms are less sensitive due to lack of key spectral bands
iii. Insufficient data for small lakes limit EO usefulness for lake management
iv. Focus should be put on the development of hybrid observation-model approaches and multivariate analyses to support different blooms type and conditions, through the characterization of the lake and its catchment. This may also help resolve ongoing confusion over surface accumulations as ecological blooms

v. Reconstructing multi-year time series through autoregression models supports chl-a and turbidity changes prediction 5-10 days ahead.

Finally, to overcome inconsistency and limitations of current HAB identification methods (usually based on biomass and pigment concentration estimates), a novel cyanobacteria identification method by Lomeo et al. (2025)[1] was also presented. The method identifies per-pixel cyanobacteria occurrences based on multispectral classification and class membership weighting, with dedicated extended classification library.

Review of Existing IOCS Recommendations

A list of recommendations from previous IOCS meetings and extracted from the IOCCG report n. 20 (*Observation of Harmful Algal Blooms with Ocean Colour Radiometry*), is summarized and reviewed below.

- ➔ <u>user needs</u> (actioned: some of the recently launched applications (e.g., EPA CyAN) and initiatives (e.g. EC-JRC ECOSTAT) have aided in enhancing dialogue with end-users)
  - User requirements and user driven products should be defined, distinguishing between operational and research products.
  - The needs of the management community should be better understood
  - The level of uncertainty that can be accepted by users needs to be defined
- ➔ <u>sensors</u> (actioned: Sentinel Next Generation missions, PACE, and commercial missions may address these requirements)
  - Future sensors such as the Landsat and Sentinel-2 series should incorporate additional narrow spectral channels
  - Access to spectral information in the red and NIR, around 590 nm, 520—570 nm should be provided
  - For NRT operational applications, low latency ideally should be less than 6 hours
  - Constellations of small, low-earth orbiting satellites may present opportunities to achieve shorter-term but high imaging frequency requirements for regional HAB monitoring

[1] Lomeo, D., et al. (2025). A novel cyanobacteria occurrence index derived from optical water types in a tropical lake. *ISPRS J. Photogramm. Remote Sens.* 223, 58–77. doi: https://doi.org/10.1016/j.isprsjprs.2025.03.006

➔ <u>algorithms</u>

- Atmospheric corrections for optically complex (including HAB) waters needs improvements (actioned: more performant atmospheric correction now available. In situ data availability is however the bottleneck for further development)
- Algorithms need to be optimised for certain water types
- There is a need for moving away from empirical relationships towards a mechanistic understanding of the causal in-water constituent interactions which result in the bulk satellite-observed optical signals (actioned through hyperspectral sensors development)
- Efforts should concentrate on the development of better global suites of high biomass algorithms

➔ <u>validation</u>

- In situ data should be made available to the HAB community towards improved geographic applicability of algorithms and products
- Transparency in algorithm performance is encouraged (reporting detection limits, error margins, confidence intervals).

New IOCS Recommendations

A set of recommendations were suggested and discussed, covering the following topics.

➔ Bloom definition: between observable discoloration of the water surface and a population-dynamics informed distinction of bloom, there is persistent confusion on how a bloom is to be defined. The harmful nature of a bloom is usually not discernable and rather follows from expert insight. The frequent inclusion of cyanobacteria as algae may further confuse practitioners.

Assigned to community and agencies:

- Bloom definition and thresholds should be identified together with users, considering regulatory policy instruments and applying an ecoregion-specific approach.

➔ Chl-a concentration alone is not enough for HAB monitoring systems.

Assigned to community and agencies:

- Additional information (based on spectral features, pigment absorption, PFT ...) should support bloom monitoring

- Thresholds and anomaly identification criteria depend on the type of application and should be defined through long time series analyses
- Vertical mixing conditions should be taken into account when informing on the severity of blooms, particularly in regard to cyanobacteria
- The recommendations of Water-ForCE[2] for multivariate, multi-mission service development should be implemented.

➔ Temporal, spectral and spatial gaps still limit the applicability of EO data for management purposes.

Assigned to agencies:

- Observation frequency and observation capabilities for inland waters, particularly for small lakes, should be increased
- Constellations of multiple twin sensors may support increasing temporal coverage and NRT services.

Assigned to community:

- Observation gaps should be addressed though robust methods for trend fitting or lake-specific bias corrections to be developed
- The use of multivariate datasets and hybrid observation-model approaches are encouraged to support the identification and characterization of different bloom types and conditions.

➔ In situ data collection and sharing are key to success for algorithm calibration and system validation

Assigned to agencies and IOCCG:

- Fundings and a coordinated system for data curation are essential to support continued in situ data collection, harmonization, quality control and sharing
- A coordinated, curated effort should be made to integrate existing datasets, map the measured parameters, highlight gaps in data availability, and assess spatial coverage to guide future data collection
- The recommendations of Water-ForCE for data collection, sharing, and new in situ measurements should be implemented

Assigned to community:

- In situ data should be combined with EO data to confirm bloom characteristics (e.g., toxicity)

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[2] https://waterforce.eu/

- In situ data should be collected also outside bloom conditions, in high non-toxic biomass conditions and in clear lakes.