BAMS
Meeting Summary

First International Summer School on Marine Heatwaves

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KEYWORDS:
Extreme events;
Ocean;
Climate Change

ICTP-CLIVAR Summer School on Marine Heatwaves: Global Phenomena with Regional Impacts

What: Graduate students and other early career scientists from 13 countries came together at a summer school to learn about detection, mechanisms, attribution, future projections and societal impacts of marine heat waves.

When: 24–29 July 2023

Where: Trieste, Italy

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As of writing (August 2023), persistent extremely warm ocean temperatures, known as marine heatwaves (MHWs), extended across 48% of the surface of the global oceans—the most widespread occurrence of MHWs since the beginning of the satellite era over 30 years ago (https://psl.noaa.gov/marine-heatwaves/). With the expansive growth in the development of the warm El Niño in the Pacific Ocean expected in late 2023, along with the long-term increase in ocean heat storage due to human-induced climate change, it is predicted that the global MHW coverage will remain near 50% through to February 2024—an unprecedented longevity. Indeed, the global annual number of MHW days has risen by 54% over the past century (Oliver et al. 2018), with 8 of the 10 most extreme MHWs ever recorded occurring since 2010 (Smith et al. 2021), a trend that is expected to continue in a warming climate.

MHWs can have devastating impacts on marine habitats and ecosystems and influence regional weather systems such as the monsoons and extreme weather events like tropical cyclones. MHWs lead to major economic losses through declines in fish catch, they can cause substantive mortality of sea birds and marine mammals, and they can force relocation of species because of inhospitable conditions. Reported economic costs of individual MHW events exceed US$800 million in direct losses related to fisheries and habitat closures and >US$3.1 billion in indirect losses of ecosystem services over multiple subsequent years (Smith et al. 2021). Clearly given their significant ecosystem and economic impacts, there has been a heightened interest by governments and society concerning the climate community's ability to detect and, importantly, to forecast MHWs in a timely fashion.

Climate change is clearly responsible for increasing the frequency of MHWs, but open questions remain about the internal variability that drives these extreme events above the slowly evolving background warming. Only recently have we begun to understand some of the climate drivers influencing the intensity and persistence of these extreme events. The large-scale and local processes driving MHWs, as well as the full extent of their impacts in different regions, are just emerging. In situ and in-depth observations of MHWs are also challenging but gradually evolving to improve our understanding.

Within this background of an increased awareness of MHWs, their impacts, and predictions, a Summer School on Marine Heatwaves: Global Phenomena with Regional Impacts was jointly organized by the international Climate Variability and Predictability (CLIVAR) program and the International Centre for Theoretical Physics (ICTP), Italy, with additional support from the World Climate Research Programme (WCRP), U.S.-CLIVAR, and the U.S. agencies NASA, NOAA, and NSF. The primary goal of the summer school was to share current understanding of the mechanisms, predictability, and impacts of MHWs, as well as to provide hands-on experiences and tools to enhance the capacity of early career scientists (ECSs) from underresourced countries for detecting and predicting MHWs.

The Summer School invited 42 students and ECSs from 13 countries to attend in person at the ICTP campus in Trieste, Italy (Fig. 1), while another 27 applicants were selected to

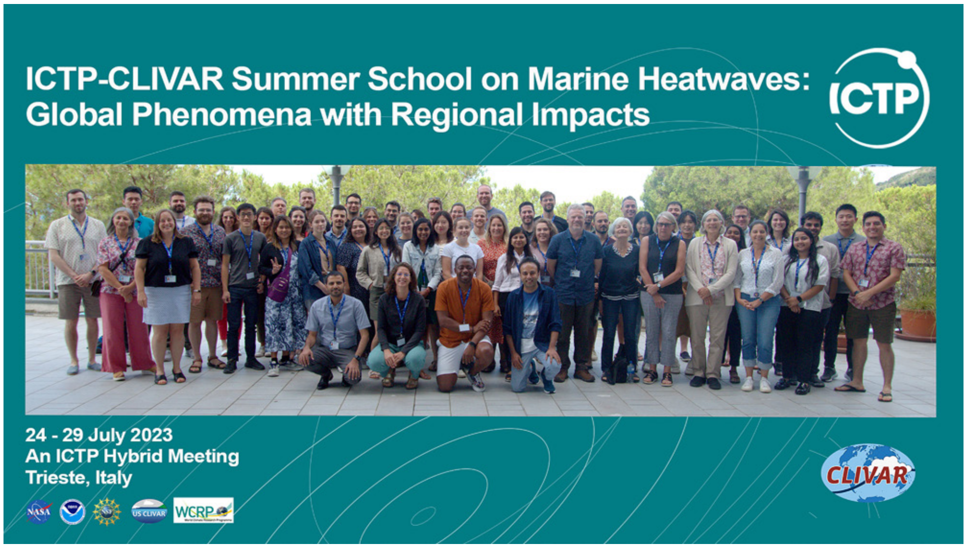

Fig. 1. Participants at the Summer School on Marine Heatwaves: Global Phenomena with Regional Impacts held in Trieste, Italy, 24–29 July 2023.

participate online. Nearly 50% of all these successful applicants were from developing countries, with parity also achieved in terms of gender of summer school participants. The 12 lecturers were equally a gender, career stage, and geographically diverse group with expertise including atmospheric science and oceanography, observationalists (in situ and satellite), data assimilation, and modelers that embraced the main themes of the summer school. All lecturers were also members of a new CLIVAR Research Focus Marine Heatwaves in the Global Ocean (https://www.clivar.org/research-foci/marine-heatwaves). An important part of the summer school was the implementation of an innovative approach known as SDA2 (Skill Development, Awareness and Application) that provided a framework to help the ECSs build long lasting and fruitful collaborations both among themselves and with their mentors.

This meeting summary gives a short description of the themes covered during the summer school and an overview of the SDA2 approach, as well as the benefits and perspectives gained by the summer school participants.

Summer school structure

To focus on all aspects of MHWs, the School was divided into four main themes: detection, drivers, impacts, and future projections of MHWs. Each theme was allocated a day including lectures, hands-on activities, and student talks. The remaining two days of the summer school were dedicated to a synthesis and recap of each theme, and student project presentations that stemmed from their pre-summer school SDA2 activities as well as hands-on sessions at the school.

For detection, topics included definitions of MHW, categorization of events, and their identification using readily available online data sources and global forecast models. Although a well-established definition of MHWs exists (Hobday et al. 2016), the choices required for its implementation can vary depending on the region and the data available. Based on Hobday et al. (2016), an MHW is identified as an event with anomalies relative to the seasonally varying local climatology and which exceeds the 90th percentile temperature threshold for at least 5 days. However, alternative intensity and duration thresholds have also been used depending on the application or the region. Another open question with the definition is the choice of reference climatology. Given the underlying warming trend, if the anomalies are computed relative to a fixed historical baseline, MHWs become more frequent, intense, and longer-lasting as a result of climate change, obscuring the internal processes leading to short-term extremes. The detection session covered the implementation of different statistical methodologies, challenges in their implementation, and exceptions to implementation. Because methodologies can differ, the decisions that need to be made on various parameters and, importantly, how these decisions might affect uncertainties, were also covered. Finally, MHWs have typically focused on prolonged warm extremes in sea surface temperature, yet recent studies that have included analysis of their vertical structure suggest that MHWs can extend to great depth or exist at depth but have no apparent surface expression (Schaeffer and Roughan 2017; Elzahaby and Schaeffer 2019). This relatively new area of research interest was another focus of the detection theme.

For mechanisms, lectures discussed our current state of understanding of the formation of MHWs starting with a global overview of local processes (e.g., heat fluxes from the atmosphere to the ocean, or advection of heat by ocean currents), large-scale remote drivers, and teleconnections (Holbrook et al. 2019). Remote drivers are associated with modes of variability that can modulate the local causal processes and so provide some degree of predictability for MHWs. El Niño–Southern Oscillation (ENSO) is a key example of a globally important mode of variability that influences the occurrence of MHWs across many regions of the world. The question with such a strong driver then is how to separate the role of ENSO from other drivers on MHWs. Lectures also examined mechanisms of MHW development in specific regions that have experienced very intense and long-lasting events, including the northeast Pacific and the Mediterranean Sea. The development of MHWs in the northeast Pacific is favored by a decadal mode of variability that is also conducive to the initiation of El Niño conditions in the central equatorial Pacific, which, in turn, contributes to an increased MHW duration (Capotondi et al. 2022). The Mediterranean Sea has experienced very intense and long-lasting warm conditions in recent decades. These events appear to be sustained by persistent atmospheric conditions, although the exact mechanisms are still under investigation. Another important aspect discussed was the simultaneous occurrence of MHWs with other extremes over land, such as droughts and heatwaves, and in the ocean, such as high ocean acidity and low ocean productivity events. An example of these so-called compound events was discussed for the South Atlantic, where droughts on land and MHWs tend to occur simultaneously and, most importantly, have the same drivers (Rodrigues et al. 2019). Consequently, advances in understanding and predicting land extremes could be applied to MHWs. As yet, little is understood about these compound events, so this topic generated much discussion by lecturers and participants alike.

For impacts, lectures covered how MHWs impact ecosystems and climate, and additionally discussed what observing systems could be put in place—especially in developing countries—to fill the gaps in global marine observational networks and improve advanced warning by prediction and potential mitigation options. The most direct impact of MHWs is on the ocean biology. Many marine species are vulnerable to MHW exposure, not just to the warm temperatures during MHWs but also to longer durations of such MHWs, which may lead to collapse of some species (Smith et al. 2023). Characteristics of ocean ecology and biogeochemistry may also change. In view of this, ocean carbonate chemistry was discussed to understand how such large increases in temperature could alter complex biogeochemical feedbacks and result in long-lasting influence on various characteristics, such as ocean acidity. Ocean biogeochemical variables such as oxygen, nutrients, carbon, and silica are frequently part of chemical reactions whose rates may change with the increase in temperature experienced during MHWs. MHW influence on the ocean–atmosphere system through increased tropical cyclone activity and intensity as well as feedback to the tropical monsoon systems were also covered. Finally, an interactive dynamic discussion on the socio-economic impacts of MHWs as well as adaptation strategies were held.

For future projections, global climate models were examined to understand how MHWs will change in a warming world, due to climate change trend as well as internal variability. With increasing temperatures, a change in the mean state of the climate is projected and so the baselines and thresholds of MHWs now and in the past may not necessarily be the same baselines and thresholds for MHWs in future. Future changes in the intensity and duration of MHWs due to changes in variability versus changes in the mean state were gained by insights from coupled model initial-condition large ensembles. Finally, a discussion of single-event attribution and future projections of MHWs and compound extremes rounded out the future projections theme.

SDA2 framework implementation: An innovative approach to build ECS collaboration

An innovative approach to help the ECSs build long-term collaborations was incorporated in the Summer School under the SDA2 framework. This framework was developed by the lead author of this article, Dr. Shikha Singh, and the MHW Summer School was the first testbed for its implementation.

The framework essentially consists of three components for a systematic development of ECSs. The "skill development" component includes exercises to build the necessary skills in the ECSs, including those skills which are upcoming or state-of-the-art in the field. This helps them to include more efficient and the latest, best practices in their research, which can lead to improvement in the effectiveness of the research. In the case of the Summer School, a variety of pre-school activities were implemented. The participants of the school were diverse in their career stages, ranging from Master's students to graduate students and postdocs, so these activities were designed to create a more common understanding and were essential to improve the productivity of the Summer School. Dr. Iury T. Simoes-Sousa, an ECS at Woods Hole Oceanographic Institution (United States), delivered a pre-summer-school webinar to all participants on "The Use of Git and GitHub for Science Coding" as a skill development activity to emphasize the usefulness and workability of version control as a tool for improving the proficiency of collaboration and individual research work. An example of a hands-on usage for research was demonstrated, and in a post-school survey, 63% of responders found the pre-workshop webinar "useful to very useful." Additionally, as part of the skill development component of SDA2, a set of papers related to each theme was circulated to the participants to be read in preparation for the Summer School. These papers were aimed at bringing a better awareness of the topics to be covered and also to pique the participants' curiosity about the themes for the School. This proved to be a very useful exercise, as the papers led to interesting questions, identifying knowledge gap areas, along with new techniques and methodologies that were brainstormed by the participants and mentors and targeted for future research and exploration that enhanced the discussion sessions. Finally, interactive sessions in which the participants had a chance to showcase themselves were held during the Summer School itself. The ECS participants were free to be creative with their presentations that showcased either their own research, or that of their research group or institution. A few participants went the creative route to perform, for example, a rap or enacted an original play concerned with MHWs, while others took the more conventional approach of presenting their research through a short talk. The broad spectrum of approaches was very engaging and inspired many spirited questions while giving the participants a chance to be creative.

The "awareness" component of SDA2 consists of the Summer School itself, wherein the experts and mentor's presentations and discussion sessions were facilitated.

Last, the "application" part of SDA2 was designed to continue the skills learned before and during the Summer School by having participants work together on timelined community research papers as quantifiable outputs/deliverables for the entire exercise. The lecturers proposed short-term projects in which they would mentor the ECS participants. Typically, each group consisted of 1–2 mentors and 6–8 ECS participants who were allocated to each group in a manner to ensure diversity in terms of geography, gender, and career stage. Each group met with its mentors before the Summer School, wherein they discussed and worked on completing some tasks. This activity also served as an ice breaker for the participants. During the Summer School, the groups worked among themselves and with the mentors on their projects. These group meetings took the form of conventional formal get-togethers, as well as more spontaneous group discussions at lunch along with half-day hiking trips up in the Karst Mountains behind Trieste. This forged deeper connections among the participants and worked to actively engage all group members. A follow-up of these projects will be carried out 3 months after the Summer School to motivate the individual groups to continue working and produce either a community paper, a journal article, or a data package. All in all, the groups were highly enthusiastic about this SDA2 activity, and tangible deliverables are expected from at least a few of the groups.

Key takeaways: Feedback and perspectives

Undoubtedly, the core outcome of the Summer School was the significant value and success of the training to the international ECS participants. The lectures and SDA2 hands-on experience provided tools and methodological research skills for a wide spectrum of participants, particularly those from underresourced countries and large ocean states, wanting to better track MHWs and understand their societal and economic impacts.

Shortly after the completion of the Summer School, participants were provided the opportunity to complete an anonymous survey evaluating different aspects of the School. The survey was optional and 34 submissions from the participants were received. The feedback was overwhelmingly positive, with fully 100% of survey respondents giving an overall opinion of the School as being "very useful and I learned a lot." Ninety-seven percent of respondents agreed that the Summer School lectures were taught at the right level of understanding. The most common constructive feedback concerned the hands-on activities at the Summer School, which could have been made more engaging and better organized. This response to hands-on activities is not an uncommon assessment stemming from many Summer Schools where participants come from a broad spectrum of backgrounds and levels of understanding of the topic area, and so it can be difficult to attain the best and most palatable pitch for "tutorial" activities. Of those who participated in the SDA2 activities, 89% strongly agreed that they received sufficient guidance from their mentors and that they were engaged and able to contribute to the group project. Indeed, in a limited choice survey question, one-third of the respondents agreed that the most useful aspect of the Summer School for participants was the potential establishment of long-term mentor–mentee relationships. Several comments from survey responders stated they were looking forward to reconnecting with their SDA2 groups and completing their project fulfilling their delivery product (i.e., journal article, code, etc).

Another selection in a limited choice survey question had 27% of respondents state that the availability of recordings and slides online would be the most useful resource of the Summer School. To this end, the Summer School organizers worked closely with the WCRP Academy Lighthouse Activity (https://www.wcrp-climate.org/academy), which forms the research training advisory and coordination arm of the WCRP. Their mission is to "equip future climate scientists with the knowledge, skills and attributes required to tackle the world's most pressing and challenging climate research questions," with a specific goal to connect the people who need climate science training with people and institutions that can provide that training. Engagement with the WCRP Academy ensures that the courses will be well archived and permanently available so as to improve global access of all ECSs from the climate research community to the workshop materials.

Apart from its educational value, the Summer School provided an invaluable opportunity for the CLIVAR MHW Research Focus to assess the current state of knowledge on this topic, and to identify areas in need of further investigation. For example, current approaches to detect MHWs that rely on a fixed historical climatology may need to be revisited to account for the increasing influence of climate change on the frequency, intensity, and durations of MHWs, and to mechanistically separate the role of the anthropogenic and internal variability components. While a significant body of research has documented the surface characteristics of MHWs, their subsurface expressions and underlying dynamics are much less known. In addition, a deeper understanding of the influence of large-scale modes of variability on the development of MHWs in different regions is needed to better assess MHW predictability as well as their likelihood of co-occurrence with other extreme conditions (e.g., droughts over the adjacent land), leading to "compound" threats to coastal communities. Similarly, the co-occurrence of MHWs and biogeochemical extremes, like ocean acidity or hypoxic conditions, remains a largely unexplored topic. All of these scientific issues, together with observational and modeling needs, will be actively pursued by the MHW Research Focus in the upcoming years, while promoting dialogue across the broader MHW community and in coordination with other related international initiatives to advance MHW science.

MHWs are a critically important topic given the increase in anthropogenic forcing. Understanding the causes and implications of MHWs to marine ecosystems and society is likely to grow in significance over the coming decades. The Summer School provided useful resources to the community interested in MHWs and acted as a platform to discuss open questions about MHW events, their drivers, impacts, and future projections. The networking and collaboration opportunity through the implementation of the SDA2 framework at the School ensured the continuance of effective mentor–mentee relationships that were forged, and will remain in place long after the closure of the Summer School.

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References

Capotondi, A., M. Newman, T. Xu, and E. Di Lorenzo, 2022: An optimal precursor of northeast Pacific marine heatwaves and central Pacific El Niño events. *Geophys. Res. Lett.*, **49**, e2021GL097350, https://doi.org/10.1029/2021GL097350.

Elzahaby, Y., and A. Schaeffer, 2019: Observational insight into the subsurface anomalies of marine heat waves. *Front. Mar. Sci.*, **6**, 745, https://doi.org/10.3389/fmars.2019.00745.

Hobday, A. J., and Coauthors, 2016: A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.*, **141**, 227–238, https://doi.org/10.1016/j.pocean.2015.12.014.

Holbrook, N. J., and Coauthors, 2019: A global assessment of marine heatwaves and their drivers. *Nat. Commun.*, **10**, 2624, https://doi.org/10.1038/s41467-019-10206-z.

Oliver, E. C. J., and Coauthors, 2018: Longer and more frequent marine heatwaves over the past century. *Nat. Commun.*, **9**, 1324, https://doi.org/10.1038/s41467-018-03732-9.

Rodrigues, R. R., A. S. Taschetto, A. S. Gupta, and G. R. Foltz, 2019: Common cause for severe droughts in South America and marine heatwaves in the South Atlantic. *Nat. Geosci.*, **12**, 620–626, https://doi.org/10.1038/s41561-019-0393-8.

Schaeffer, A., and M. Roughan, 2017: Subsurface intensification of marine heatwaves off southeastern Australia: The role of stratification and local winds. *Geophys. Res. Lett.*, **44**, 5025–5033, https://doi.org/10.1002/2017GL073714.

Smith, K. E., M. T. Burrows, A. J. Hobday, A. S. Gupta, P. J. Moore, M. Thomsen, T. Wernberg, and D. A. Smale, 2021: Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science*, **374**, eabj3593, https://doi.org/10.1126/science.abj3593.

——, and Coauthors, 2023: Biological impacts of marine heatwaves. *Annu. Rev. Mar. Sci.*, **15**, 119–145, https://doi.org/10.1146/annurev-marine-032122-121437.