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Review paper

Progress in the observation of the El Niño-Southern Oscillation phenomenon

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Abstract

The El Niño-Southern Oscillation (ENSO) is a critical climate phenomenon influencing global weather patterns, marine ecosystems, and socio-economic conditions. Recent advancements in observational techniques, including satellite remote sensing, ocean buoys, and advanced climate modeling, have significantly enhanced our understanding of ENSO dynamics. This study reviews the latest progress in monitoring ENSO events, focusing on improved predictive capabilities and real-time data collection. Enhanced satellite observations have provided high-resolution sea surface temperature and atmospheric pressure data, while buoy networks have facilitated continuous monitoring of oceanic conditions. Additionally, machine learning algorithms are increasingly employed to analyze complex datasets for better forecasting accuracy. These advancements not only improve our ability to predict the onset and intensity of El Niño and La Niña events but also aid in assessing their impacts on global weather systems. Continued interdisciplinary collaboration is essential for further refining ENSO observation techniques and mitigating its socio-economic impacts.

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1. Introduction

The El Niño-Southern Oscillation (ENSO) phenomenon refers to the alternation between the climatic phase of El Niño in the tropical Pacific Ocean and its opposite phase, La Niña. The Southern Oscillation index captures the east-west surface atmospheric pressure differences associated with these changes. ENSO is accompanied by variations in ocean temperature and a dislocation of atmospheric circulation; it is possible to predict some of these aspects, which means that for certain observations of the climatic state, in particular of the tropical Pacific Ocean, and using models that synthesize our understanding of climatic variability, ENSO conditions can be predicted with some skill and offer projections of temperature and precipitation in other regions (Wang *et al.*, 2017) (Figure 1).

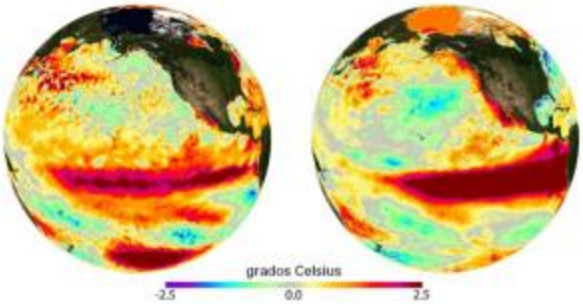


Figure 1. Anomaly during an El Niño episode between the eastern and central Pacific (SSTA by MODIS in left and by AVHRR in right, in December 2009 and December1997, respectively)

ENSO consists of three phases (Fasullo *et al.*, 2018):

1) El Niño: Characterized by warmer-than-average sea surface temperatures in the central Pacific, leading to altered weather patterns globally, such as increased rainfall in the eastern Pacific and droughts in the western Pacific.
2) La Niña: Marked by cooler-than-average sea surface temperatures, often resulting in opposite effects to El Niño, such as increased rainfall in the western Pacific and drier conditions in the eastern regions.
3) Neutral: A phase where neither El Niño nor La Niña conditions prevail, with sea surface temperatures near long-term averages.

1.1. ENSO: a problem to be solved

Understanding and predicting the onset and duration of ENSO phases has provided a basis for routine delivery of seasonal climate projections, and related information and services, to ENSO-affected regions. While there is strong scientific support for the predictability of

ENSO, predicting its global impacts is significantly more challenging as these typically occur at regional scales and may be influenced by regional and/or local effects.

In January 2014, the National Oceanic and Atmospheric Administration (NOAA) of the United States of America and the Japan Marine Science and Technology Center (JAMSTEC), in collaboration with the Ocean Observations Physics and Climate (OOPC) panel, agreed to revise the Tropical Pacific Observing System (TPOS) through workshops and associated white papers. The panel of experts on OOPC is a group of experts of the global observing system (Speich and Yu, 2021)

From these discussions emerged urgent measures to address the deterioration of the observing system, as well as what would be needed to create a more robust and sustainable system. The foundations for the objectives of the TPOS 2020 Project were thus formed.

Ocean conditions in 2015 bear some similarities to the powerful 1997 El Niño. According to the Figure 2., NASA visualization represents side-by-side comparisons of Pacific Ocean sea surface height anomalies measured by satellites in 1997 and 2015. Red part shows where the ocean is above the normal sea level. Blue shades indicate areas of lower sea levels. Sea surface height is an indicator of the temperature of the water below which above normal levels indicate warmer temperatures, and below normal colder temperatures. El Niño is characterized by a volume of warm water drifting from Southeast Asia toward South America (Eakin *et al*., 2019).

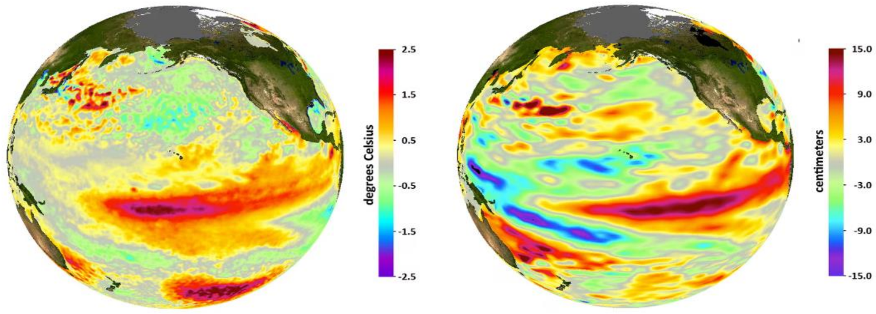


Figure 2. Deviations from normal sea surface temperatures (left) and sea surface heights (right) at the peak of the 2009-2010 central Pacific El Niño, as measured by NOAA polar orbiting satellites and Nasa’s Jason-1 spacecraft, respectively. The warmest temperatures and highest sea levels were located in the central equatorial Pacific. (Eakin *et al*., 2019)

In fact, weather and climate forecasters are tracking El Niño closely, because it could help steer beneficial rains to parts of drought-stricken California and the American West. ENSO remains a problem worth solving, because there are hardly any natural semi-regular climate signals whose prediction has such broad impact. The diversity of ENSO episodes is surprising. The regular oscillations of the 1960s and 1970s shaped the initial understanding of this phenomenon. The 1980s and 1990s were dominated by El Niño phases, including the extended events of 1982/1983 and 1997/1998. The latter period has been characterized by changes in mean conditions, reduced variability, and the so-called “Modoki” El Niño.

1.2. Origin of the TPOS 2020 Project

The deterioration of some core elements of the Tropical Oceans and Global Atmosphere (TOGA) program in recent years – and with it, the associated international collaboration – highlights the risks to a system that underpins global seasonal prediction competition, requiring a renewed international effort to assess and redesign the system. This effort must take into account, first, the sound scientific support behind TPOS and its implications for a new examination of needs, observing techniques and data production. Second, a new international agreement should be forged, not only by redesigning the system, but also by developing the governance structures required to ensure an efficient and sustainable observing network for the next decade and beyond (Figure 3).

The 15 members of the TPOS 2020 Steering Committee met for the first time in October 2014 to reaffirm these objectives and to plan the stages of the Project. It was agreed to create working groups to support the necessary activities, including:

- Assessing the observing network backbone and the large-scale aspects of TOPS
- Developing the scientific need and feasibility for observing planetary boundary layers, including atmosphere-sea fluxes, near-surface processes, and diurnal variability
- Evaluating different approaches to observing the eastern and western boundary regions
- Developing a rationale and need, as well as a strategy, for conducting biogeochemical observations
- Considering proposals for advancing modelling and data assimilation and synthesis so that observations can achieve the greatest impact

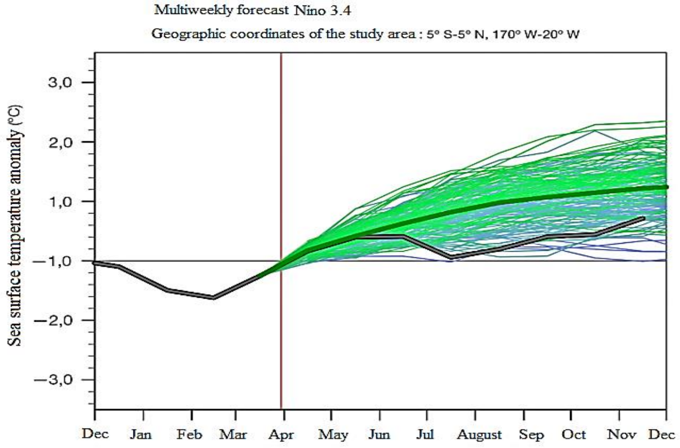


Figure 3. Ensemble predictions of ENSO (green) and actual temperature anomaly (black) in March 2014 (source: Predictive Ocean-Atmosphere Model of Australia (POAMA), Australian Bureau of Meteorology, http://poama.bom.gov.au/).

The TPOS 2020 sustained data collection network forms the backbone of the system. This term is used to emphasize that the backbone supports and underpins the other parts of the observing system, some of which can only be implemented for a limited time. The backbone will be designed to maintain consistency and intelligibility when collecting data at rates and scales that allow for the detection of climate variability and trends.

Since much of the use and benefit of data output will be achieved through model assimilation and synthesis, both the model and data assimilation development community and operational modeling centers will need to be considered key partners. Those efforts, including integrated process studies, will be designed to address phenomena related to systematic errors in models or for situations where detailed observations are needed to guide model design. The first Steering Committee meeting highlighted proposals for increased involvement of modeling centers in developing process studies that better address these questions. Possible studies will include those focused on better understanding the relationship between ocean surface conditions and convective rainfall in the tropics, and the mechanisms that communicate surface currents with the subsurface ocean.

1.3. Observation and prediction of ENSO

From 1985 to 1994, a major international project, the TOGA program, developed an observing system. Its primary purpose was to enable the prediction of large-scale interannual climate fluctuations, particularly El Niño and its global effects. The Pacific Ocean component of the TOGA observing systems, completed in 1994, is TPOS and continues to support routine forecasting systems and research. In the tropical areas of the Atlantic and Indian Oceans, corresponding networks were developed during and after TOGA, facilitating seasonal predictions and contributing to improved knowledge of climate variability in these regions. Over the 20 years since TOGA, new in-situ and satellite observing technologies have been added to TPOS, and a profound evolution has taken place in the sophistication of analysis, models and prediction systems. Furthermore, understanding of the variability and predictability of the tropical Pacific has reached a point where observational needs and system design must be re-articulated (Sarachik and Cane, 2010).

Uncertainty about ENSO events, such as 2014, occurs in the context of substantial changes across the Pacific Ocean and the entire Northern Hemisphere. In March 2014, some operational centers predicted an El Niño similar to the 1982/1983 and 1997/1998 events, based on a set of prediction models that had so far proven accurate. By mid-year, it was already clear that a widespread event would not occur. Instead, the tropical Pacific sea surface temperature anomaly followed a much cooler, but still positive, trajectory. At the same time, significant sea surface warming occurred over a wide area of the North Pacific, accompanied by large anomalies in the Northern Hemisphere circulation, although perhaps only occasionally. Do these hemispheric and oceanic patterns fit together? And how do they affect ENSO? Confused by apparent flaws in ENSO predictions in 2012 and again in 2014, several researchers are questioning whether the fluctuations in the phenomenon reflect larger trends or changes in the global climate system.

Several models continue to suggest the possibility of a small to moderate warm event after May-roughly 50 to 60 percent of the magnitude of the February 2015 event. It remains unclear whether the weaknesses of current forecast systems stem from intrinsic deficiencies in the models or from a lack of observations of key ocean variables. It is also possible that the forecast systems simply had bad luck, with most forecast models containing components that were close to the observed trajectory.

2. Advances in ENSO observation

In current decade, significant advancements were made in the observation and understanding of the El Niño-Southern Oscillation (ENSO) phenomenon. Enhanced satellite technology, including improved remote sensing capabilities, allowed for more precise monitoring of sea surface temperatures and atmospheric conditions across the Pacific Ocean. The integration of machine learning algorithms with traditional climate models facilitated better predictions of ENSO events, leading to more accurate forecasts of their impacts on global weather patterns. Collaborative international research initiatives, such as the Climate Variability and Predictability (CLIVAR) project, fostered data sharing and interdisciplinary studies.

Additionally, increased focus on the socio-economic impacts of ENSO events spurred research into adaptive strategies for vulnerable regions. The period also saw a rise in public awareness regarding climate variability's influence on extreme weather events, emphasizing the importance of ongoing observation and research in mitigating risks associated with ENSO phenomena. Moreover, El Niño and La Niña have weaker impacts during Northern Hemisphere summer than they do in winter. Summer impacts include warm conditions in northeastern Australia and cooler than average conditions across India and Southeast Asia (Hagen and Azevedo, 2024) (Figure 4).

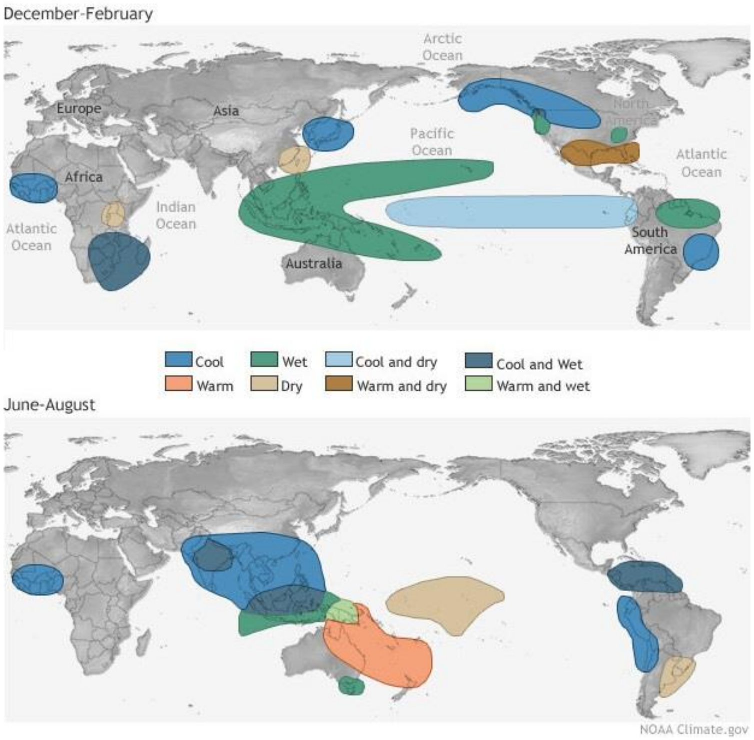
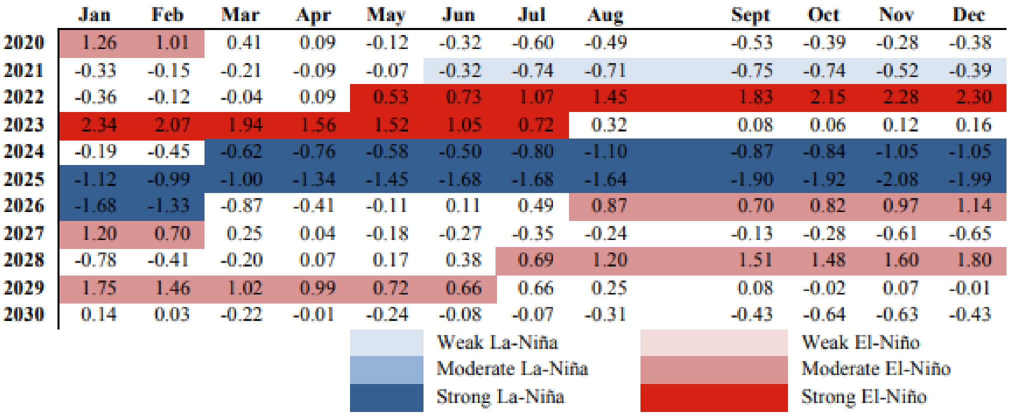


Figure 4. Enso impacts in summer and winter (https://www.climate.gov/enso, 2024)

ENSO predictions rely on various models that analyze oceanic and atmospheric data, including:

- Ocean Temperature Monitoring: Buoys and satellites measure sea surface temperatures.
- Atmospheric Pressure Patterns: The Southern Oscillation Index (SOI) tracks pressure differences between Tahiti and Darwin, Australia.
- Climate Models: Statistical and dynamical models simulate future conditions based on current data.

Table 1. Predicted frequency of ENSO events in 2020-2030 (Latief *et al*., 2018).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2020	1.26	1.01	0.41	0.09	-0.12	-0.32	-0.60	-0.49	-0.53	-0.39	-0.28	-0.38
2021	-0.33	-0.15	-0.21	-0.09	-0.07	-0.32	-0.74	-0.71	-0.75	-0.74	-0.52	-0.39
2022	-0.36	-0.12	-0.04	0.09	0.53	0.73	1.07	1.45	1.83	2.15	2.28	2.30
2023	2.34	2.07	1.94	1.56	1.52	1.05	0.72	0.32	0.08	0.06	0.12	0.16
2024	-0.19	-0.45	-0.62	-0.76	-0.58	-0.50	-0.80	-1.10	-0.87	-0.84	-1.05	-1.05
2025	-1.12	-0.99	-1.00	-1.34	-1.45	-1.68	-1.68	-1.64	-1.90	-1.92	-2.08	-1.99
2026	-1.68	-1.33	-0.87	-0.41	-0.11	0.11	0.49	0.87	0.70	0.82	0.97	1.14
2027	1.20	0.70	0.25	0.04	-0.18	-0.27	-0.35	-0.24	-0.13	-0.28	-0.61	-0.65
2028	-0.78	-0.41	-0.20	0.07	0.17	0.38	0.69	1.20	1.51	1.48	1.60	1.80
2029	1.75	1.46	1.02	0.99	0.72	0.66	0.66	0.25	0.08	-0.02	0.07	-0.01
2030	0.14	0.03	-0.22	-0.01	-0.24	-0.08	-0.07	-0.31	-0.43	-0.64	-0.63	-0.43

🟦	Weak La-Niña	🟥	Weak El-Niño
🟦	Moderate La-Niña	🟥	Moderate El-Niño
🟦	Strong La-Niña	🟥	Strong El-Niño

As of late 2023, predictions indicate a potential transition towards either an El Niño or neutral phase for the upcoming months. Continuous monitoring of oceanic conditions and atmospheric indicators will refine these forecasts. The accuracy of predictions typically improves closer to the event due to evolving data inputs. Furthermore, prediction of ENSO index from 2020 to 2030 is used in threat prediction developments (Table 1), while for hazard prediction of 2031-2040 follows ENSO incident period of 1989-2000.

According to the above studies, following affections can be obtained:

1) Increased Frequency of Extreme Events: Climate change may lead to more frequent and intense El Niño and La Niña events.
2) Shifts in Patterns: The impacts of ENSO on global weather patterns may shift, affecting rainfall, droughts, and storms.
3) Long-term Trends: Some models suggest a trend towards more extreme El Niño events due to warming oceans.
4) Weather Variability: Changes in ENSO can significantly affect global weather patterns, agriculture, and water resources.
5) Climate Adaptation: Regions affected by ENSO will need to adapt their strategies for managing climate-related risks.

The Initial Assessment and the in-depth discussions that followed at the TPOS 2020 meeting resulted in several recommendations that will define the project's six-year approach and will include, in addition to the issues already explained above, the following concerns are also considered:

- Consideration of the observing system as an integrated whole, including satellites, modelling, data management and modern in-situ technologies; the project will thus articulate the strengths of a multi-platform approach appropriate to the multi-scale variability of the tropical Pacific;
- Explicit assessment of the risks of the observing system, taking into account requirements such as necessary redundancy, sensor diversity, etc.;
- Identification and maintenance of long-term climate records;
- urgent consideration of strategies to minimize the impact of the reduction in the contribution of TRITON (Triangle Transoceanic Buoy Array) to the fixed buoy network (about 70 moorings in the tropical Pacific Ocean, the main source of upper ocean observational data in this area for the past 25 years);
- Initiating discussions with interested agencies to expand TPOS engagement in terms of ship support, participation in joint process studies, model development and data assimilation systems;
- Exploiting opportunities for observations from ships engaged in mooring maintenance, and using the core network as infrastructure to enable short-duration

process studies and to test and improve observing technology; and ensuring appropriate levels of investment in data processing and product delivery.

2.1. *The warmest year ever recorded in 2014*

The global average air temperature over land and sea surface in 2014 was 0.57 °C above the average of 14.00 °C for the 1961–1990 reference period. By comparison, temperatures were 0.55 °C above the average in 2010 and 0.54 °C above the average in 2005, as calculated by WMO. The estimated uncertainty range was 0.10 °C. WMO Secretary-General Michel Jarraud said that the trend in global warming is more important than the ranking of any particular year, and that analysis of data sets indicates that 2014 was nominally the warmest year on record, although there is very little difference between the three warmest years. The secretary-general also noted that 14 of 15 warmest years occurred in this century. As it is obvious in Figure 5, global warming will continue as rising levels of greenhouse gases in the atmosphere and increasing ocean heat content lead us to a warmer future. The WMO said the temperature difference between the warmest years is only a few hundredths of a degree, or less than the uncertainty margin (Sarachik and Cane, 2010).

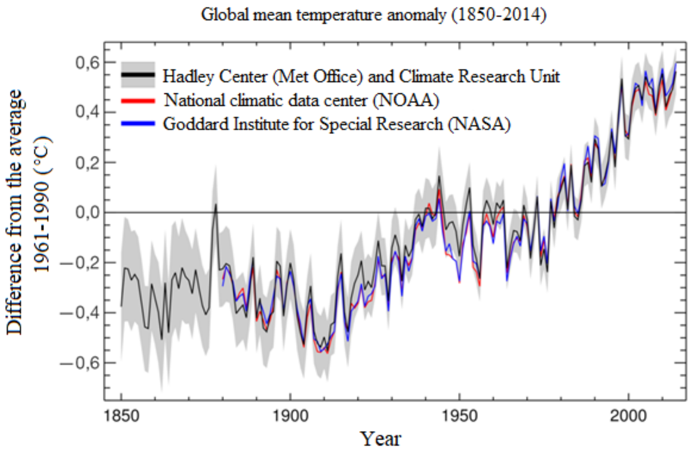


Figure 5. WMO classification 2014 as the warmest year on record by comparing major international data sets

About 93% of the excess energy trapped in the atmosphere by greenhouse gases from fossil fuels and other human activities ends up in the oceans. The heat content of the oceans is therefore critical to understanding the climate system. Global sea surface temperatures reached record levels in 2014. However, it is noteworthy that the high temperatures of 2014 occurred in the absence of a fully developed El Niño, which has an impact on global climate warming. In 2014, record heat combined with torrential rains and floods in many countries and droughts in others are consistent with what it is expected from a changing climate (Wilhite and Pulwarty, 2014). The WMO analysis is based on, among others, three complementary data sets maintained by the Hadley Centre (Met Office) and the Climate

Research Unit of the University of East Anglia, United Kingdom of Great Britain and Northern Ireland (combined); by the National Climatic Data Center of NOAA; and by the Goddard Institute for Space Research, run by the National Aeronautics and Space Administration (NASA).

2.2. Departments and management

TPOS 2020 is to be managed and implemented in the context of existing and planned ocean observing activities, in particular the Global Ocean Observing System and the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM), which coordinate the implementation of many of the existing networks in the oceanographic community.

TPOS 2020 is a project for change. It will operate independently and negotiate with its sponsors how to ensure that all departments and links are properly managed. Project management therefore includes four main elements:

- a TPOS 2020 Steering Committee responsible for oversight and coordination;
- a resource forum designed by sponsors and other resource coordinators;
- an executive made up of those responsible for the above; and
- a project office focused on coordinating activities, supported and funded by the sponsors.

It is through these partnerships and management structures that TPOS 2020 will design a modern and sustained tropical Pacific observing system that meets the scientific and societal needs of the future.

Conclusion

Recent advancements in the observation of the ENSO phenomenon have significantly enhanced our understanding of its dynamics and impacts. Improved satellite technology and ocean buoys have provided high-resolution data on sea surface temperatures, atmospheric conditions, and ocean currents. These developments enable more accurate predictions of ENSO events, facilitating better preparedness for their socio-economic effects globally. Furthermore, integrating machine learning techniques with traditional climate models has shown promise in refining forecasts. Continued interdisciplinary research is essential to unravel the complexities of ENSO and its interactions with climate change, ultimately aiding in mitigating its adverse effects on vulnerable regions.

ENSO observation and prediction are at a crucial stage. For GFCS and WMO to meet the growing demand for more sophisticated climate services, accurate and reliable observations and climate prediction models are necessity. Technology has much to offer, the next decade promises exciting advances in this field, autonomy and platforms that the observing and forecasting community could benefit from. Scientists, experts and engineers need to seize the opportunity to improve and make observations and models more efficient, and to propose new approaches to address the challenges of ENSO observation.

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