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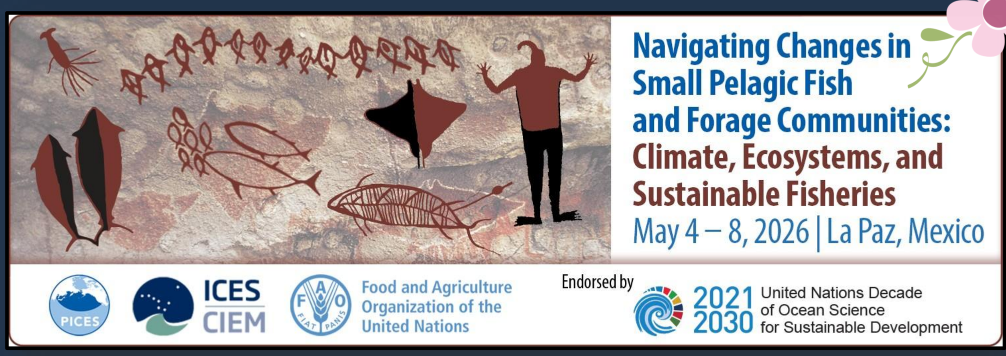


Satellite Remote Sensing and eDNA Metabarcoding for Adaptive Management of Small Pelagic Fish in the Humboldt Current : A Korea–Peru Initiative

Jun-Ho Lee*[1,2], Sung Kim[2], Won-Kyung Baek[2] and Aníbal Aliaga Rosales[1,3]

[1]Korea-Perú Joint Research Center on Ocean Science & Technology for Latin America (KOPELAR), Callao, Perú
[2]Korea Institute of Ocean Science & Technology (KIOST), Busan, South Korea
[3]Instituto del Mar del Perú (IMARPE), Callao, Perú

* Corresponding author : leejh@kiost.ac.kr

S5: Spatiotemporal Dynamics of Small Pelagic Fishes in a Changing Ocean

Abstract

Small pelagic fish (SPF), particularly anchoveta (*Engraulis ringens*), form the basis of Peru's globally significant fishery but exhibit extreme sensitivity to El Niño–Southern Oscillation (ENSO) events. Biomass reductions of up to ~70–80% have been reported during strong El Niño events, associated with weakened upwelling and reduced primary productivity. Anticipating such variability is crucial for sustainable management in the face of accelerating climate change. This study, developed through the KOPELAR (Korea–Peru Joint Research Center on Ocean Science and Technology for Latin America), proposes an integrated monitoring framework that combines satellite remote sensing of SST, Chlorophyll-*a*, and upwelling indices, as well as eDNA metabarcoding, for high-resolution biodiversity assessment. By aligning these datasets with long-term observations from the Instituto del Mar del Perú (IMARPE) and NOAA, we aim to quantify climate-driven habitat shifts and refine early-warning indicators for anchoveta distribution and resilience. Our approach enhances ecosystem-based fisheries management (EBFM) in the Humboldt Current by advancing predictive capabilities and fostering trans-Pacific scientific collaboration. The Korea–Peru framework offers a transferable model for climate-adaptive fisheries policy and long-term marine ecosystem sustainability.

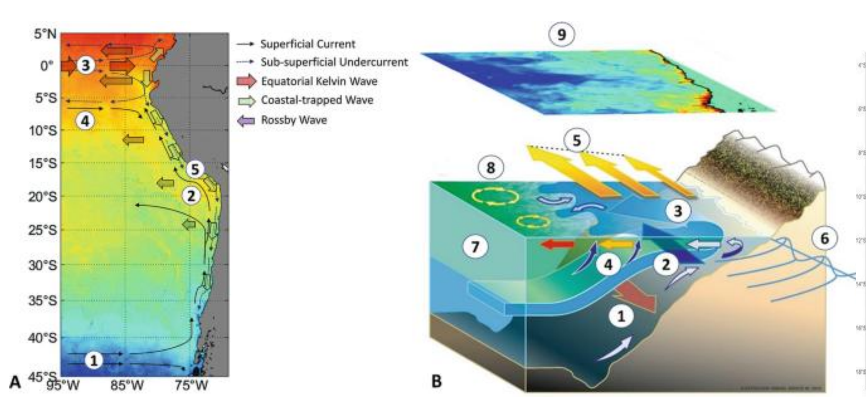
Introduction

Small pelagic fish (SPF), particularly Anchoveta (*Engraulis ringens*), the dominant SPF in Peru, supports the world's largest single-species fishery, with annual landings typically ranging between 3 and 8 million tons. These species play a critical ecological role in marine food webs and are essential for global food security and fishmeal production. The Humboldt Current System is among the most productive marine ecosystems globally, driven by strong coastal upwelling that supplies nutrient-rich waters to the surface. However, SPF populations in this region exhibit pronounced sensitivity to El Niño–Southern Oscillation (ENSO) variability. During strong El Niño events, sea surface temperature (SST) anomalies exceeding +2 °C can weaken upwelling, deepen the thermocline, and suppress primary productivity. These environmental changes have been associated with severe reductions in Anchoveta distribution and catch, with extreme cases reporting declines of 70–80% in certain regions and years. Conversely, La Niña conditions typically enhance upwelling and promote the recovery of productivity. Despite extensive research on climate–ecosystem interactions, there remains a critical need for integrated monitoring systems that link environmental variability to real-time fisheries management. The objective of this study is to develop a science-based, integrated monitoring framework that combines satellite remote sensing, environmental DNA (eDNA), and long-term observational datasets to support adaptive management of SPF under climate change.

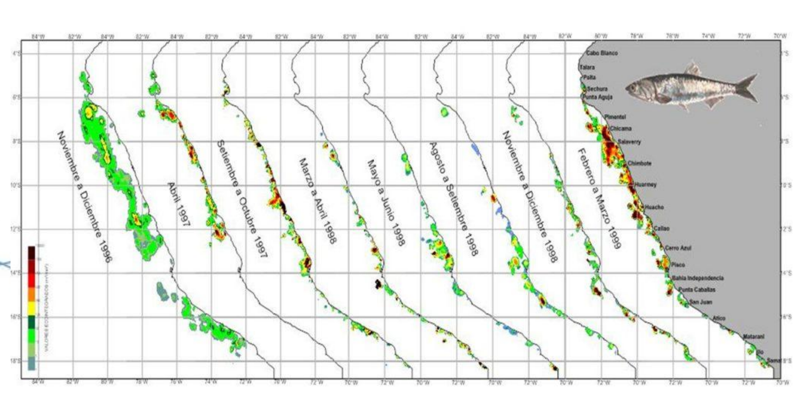
✓ **Small pelagic fish (SPF):**
Particularly, anchoveta (*Engraulis ringens*) represents the largest single-species fishery globally (~3–8 million tonnes annually). However, SPF dynamics in the Humboldt Current System are highly sensitive to El Niño–Southern Oscillation (ENSO) variability

✓ **Strong El Niño events ➔ SST anomalies +2 °C:**
Upwelling weakening, Primary productivity collapse, Result: severe reductions in anchoveta distribution and catch (reported up to ~70–80% in extreme events)

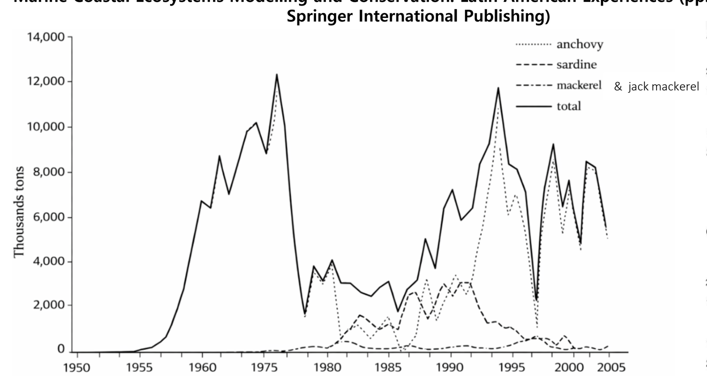
✓ **Objective:**
To develop an integrated monitoring framework combining: Satellite remote sensing, eDNA metabarcoding, and long-term observation data for adaptive SPF management under climate change



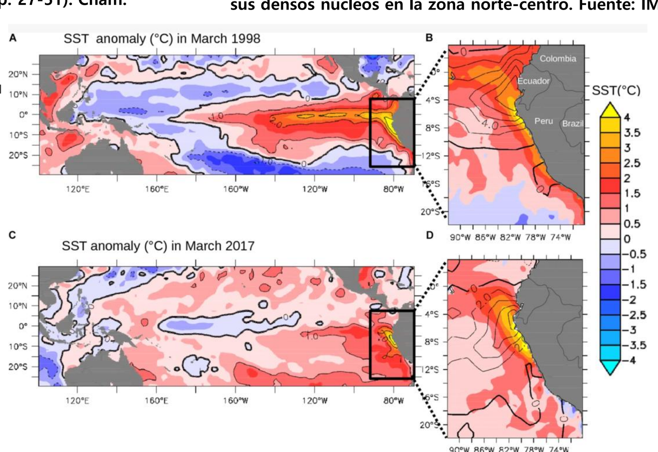
(Source: Chevallier, A., Stotz, W., Ramos, M., & Mendo, J. (2020). The Humboldt Current Large Marine Ecosystem (HCLME), a challenging scenario for modelers and their contribution for the manager. In Marine Coastal Ecosystems Modelling and Conservation: Latin American Experiences (pp. 27-51). Cham: Springer International Publishing)



(Source: Distribución y abundancia relativa de anchoveta frente a la RNSCH entre 1999-2001. Los colores representan densidades acústicamente medidas. Se destaca la distribución costera y sus densos núcleos en la zona norte-centro. Fuente: IMARPE, Gutiérrez M, 2014)



(Source: Aranda, M. (2009). Developments on fisheries management in Peru: The new individual vessel quota system for the anchoveta fishery. Fisheries Research, 96(2-3), 308-312, Landing of Peruvian pelagic fisheries 1950-2006, PRODUCE, Peru)



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(Source: https://ihma.org.pe/anchoveta/?utm_source=chatgpt.com)

(Source: (A) SST anomaly (in °C) and (B) SST anomaly (in °C, color scale) and precipitation (in mm day-1, contours) during the 1997–1998 El Niño in March 1998; (C, D) are the same as (A, B) during the 2017 coastal El Niño in March 2017. Anomalies were computed with respect to the 1981–2016 climatology)

Purpose

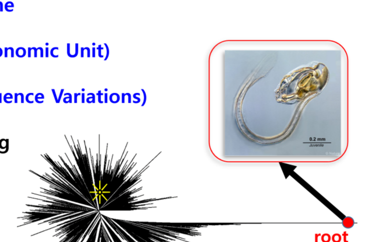
We aim to quantify climate-driven habitat shifts and refine early-warning indicators for Anchoveta distribution and resilience. Our approach enhances ecosystem-based fisheries management (EBFM) in the Humboldt Current by advancing predictive capabilities and fostering cross-regional collaboration.

Study Area & Data-1

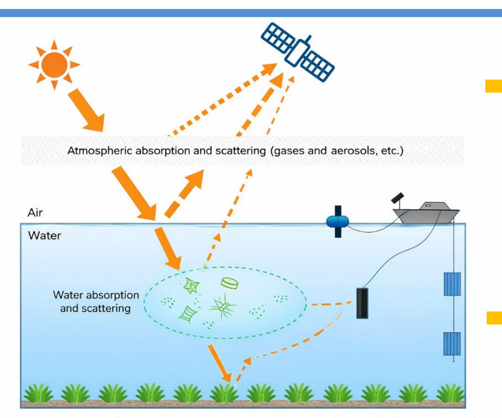
✓ **Study Area:**
- Peru coastal upwelling system (~5°–18°S)
- One of the most productive marine ecosystems globally

✓ **Data Sources:**
- Satellite Remote Sensing Data
  - Satellite SST products: NOAA OISST and ERSST
  - Ocean-climate contextual datasets: NOAA climate indices, and regional oceanographic products
  - Peruvian in situ coastal observations: IMARPE long-term monitoring Atmospheric Forcing
  - Wind stress and upwelling indices derived from ERA5 reanalysis
- In-*situ* Observations
  - Long-term coastal monitoring data from Instituto del Mar del Perú
  - NOAA climate and oceanographic datasets
- Biological Data
  - eDNA metabarcoding (12S rRNA, MiFish primers)

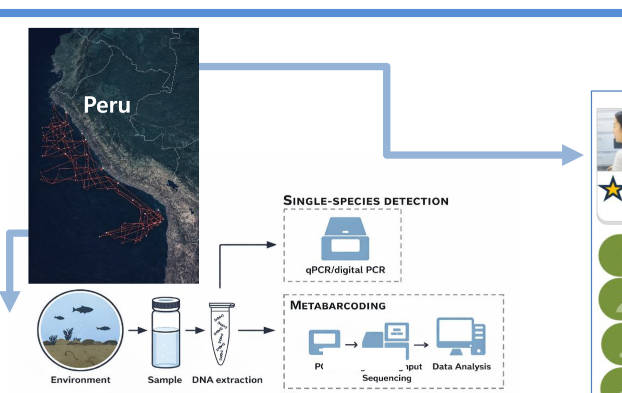
DNA barcode is an identification key like morphological traits
- Mixed eggs DNA metabarcoding pipeline
  - ✓ Mothur PhyloOTU (Operational Taxonomic Unit)
  - ✓ Qiime2 DADA2 ASV (Amplicon Sequence Variations)
- Single egg sequence (Sanger sequencing
- Phylogenetic Tree Construction for identification



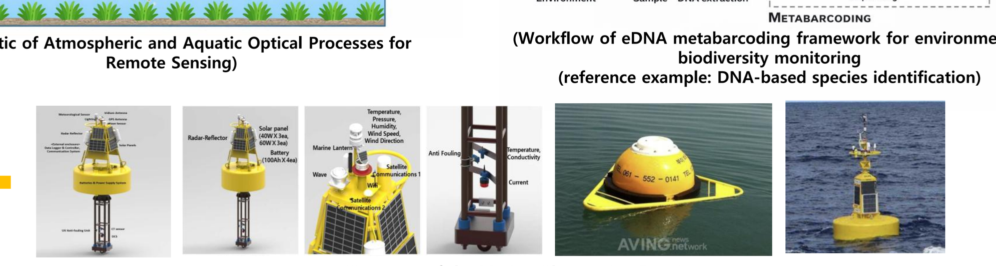
[Chordata COX1 148,253 seq. FastTree]
(Source: Dr. Sung KIM, KIOST, DNA barcode is an identification key like morphological traits)



(Schematic of Atmospheric and Aquatic Optical Processes for Remote Sensing)



(Workflow of eDNA metabarcoding framework for environmental biodiversity monitoring (reference example: DNA-based species identification)



(Structure of the Marine Observation Buoy)

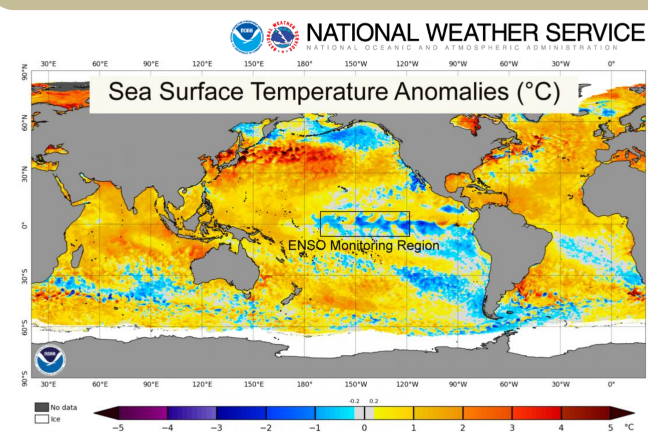
The study focuses on the Peruvian coastal region (approximately 5°–18°S), a core area of the Humboldt Current upwelling system characterized by high biological productivity and strong environmental gradients. Multiple data sources can be integrated to capture environmental variability and ecosystem responses: These datasets provide complementary perspectives on environmental conditions, biological responses, and ecosystem dynamics across multiple spatial and temporal scales.

Data-2 & Methods

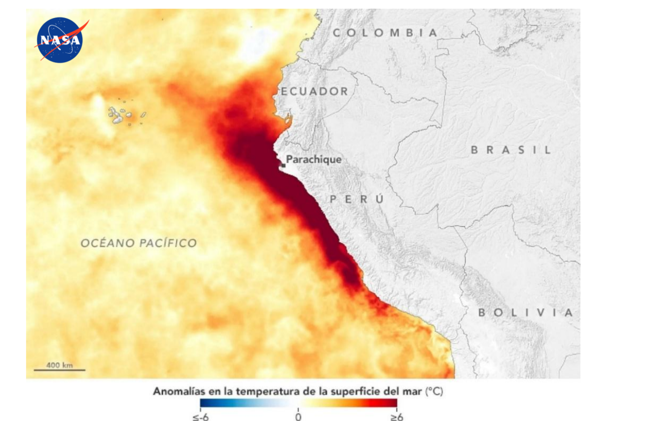
✓ **Satellite-derived chlorophyll-*a* time series showing strong interannual variability associated with ENSO events in the Peruvian upwelling system**
- **During El Niño–Southern Oscillation (ENSO) conditions:**
  El Niño ➔ decrease in Chl-*a*
  La Niña ➔ increase in Chl-*a*

  👉 IMARPE also uses Chl-*a* as a core monitoring indicator
  ➔ A long-term time series was established based on observations
- **SST Anomaly:**
  * The core variable of ENSO = Sea Surface Temperature (SST) anomaly
  * During El Niño:
  - SST increases by approximately +2 to +4 °C
  - Collapse of coastal upwelling

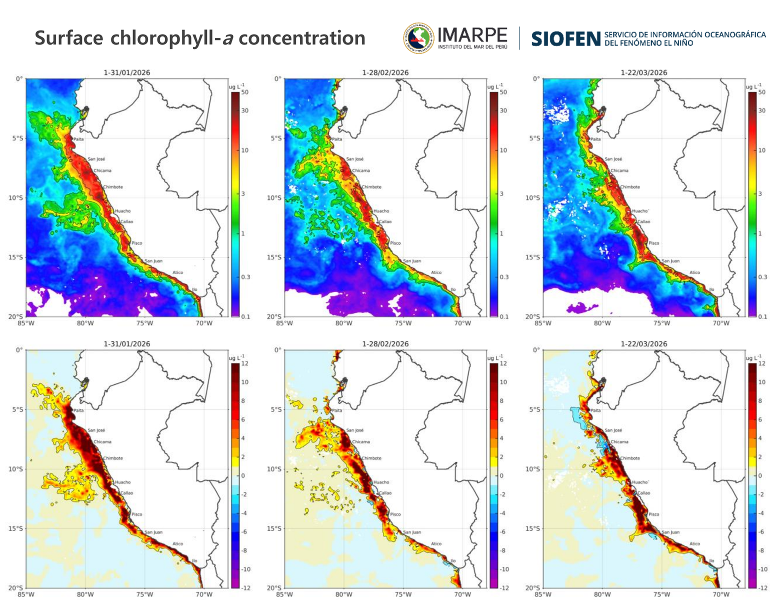
👉 Reduced primary productivity directly affects SPF habitat suitability and population dynamics



(Source: Global Sea Surface Temperature Anomalies and El Niño–Southern Oscillation (ENSO) Monitoring Region, Sea Surface Temperature Anomalies: Mid November 2025, National Ocean Service)



(Source: Sea Surface Temperature Anomalies off the Coast of Peru on April 4, 2023, Torrential Rains and Coastal Ocean Warming in Peru – NASA Earth Science https://ciencia.nasa.gov/ciencias-terrestres/calentamiento-de-aguas-y-lluvias-torrenciales-en-peru)



(Source: Monthly averages (left and center panels) and biweekly to monthly averages (right panel) of satellite-derived surface chlorophyll-*a* concentration (upper panels) and its anomaly (lower panels), obtained from the MODIS-Aqua satellite (μg/L) over the past three months Chlorophyll-a – IMARPE SIOFEN, https://siofen.imarpe.gob.pe/nivel3/clorofila-a, Source: MODIS-Aqua; Climatology: 2003–2020; Processing: AFIOF/DGIOCC/IMARPE)

Satellite-derived environmental indicators, including SST anomalies (ΔSST), chlorophyll-*a* anomalies (ΔChl-*a*), and wind-driven upwelling indices, were integrated to define Environmental Operational Indicators (EOIs) representing ecosystem productivity and habitat suitability. In parallel, eDNA metabarcoding using 12S rRNA (MiFish primers) and high-throughput sequencing is proposed as a complementary tool to detect species presence, particularly in low-density environments, complementing conventional survey limitations. All datasets, including satellite observations, IMARPE, and NOAA data, are intended to be aligned in a future operational framework, and event-based analyses are proposed under El Niño, La Niña, and marine heatwave conditions to evaluate ecosystem responses and identify predictive relationships with anchoveta distribution.

✓ **Satellite-derived Environmental Indicators**
- SST anomalies (ΔSST)
- Chlorophyll-*a* anomalies (ΔChl-a)
- Wind-driven upwelling indices

👉 Environmental Operational Indicators (EOIs)

+

✓ **eDNA Metabarcoding**
- Marker gene: 12S rRNA (MiFish primers)
- High-throughput sequencing (HTS)
- Bioinformatics-based taxonomic assignment

👉 Enables detection of low-density species and enhances spatial resolution relative to conventional surveys
👉 Complement traditional survey gaps

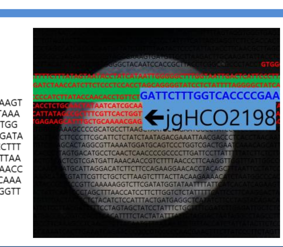
+

✓ **Data Integration and Analysis**
- Multi-source datasets are intended to be aligned to assess ecosystem responses to climate variability through event-based analyses.
- El Niño and La Niña conditions
- Marine heatwave events

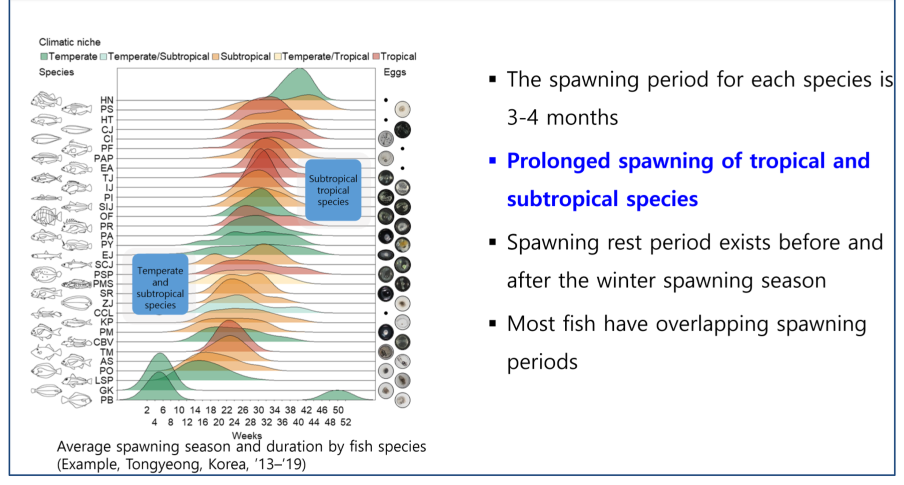
👉 Relationships between environmental indicators and Small pelagic fish (SPF) distribution were evaluated to identify early-warning signals and predictive patterns

DNA barcode (Combination of ATGC; Digital code)

Mitogenome of *Trachipterus ishikawae*



Spawning characteristics of key species



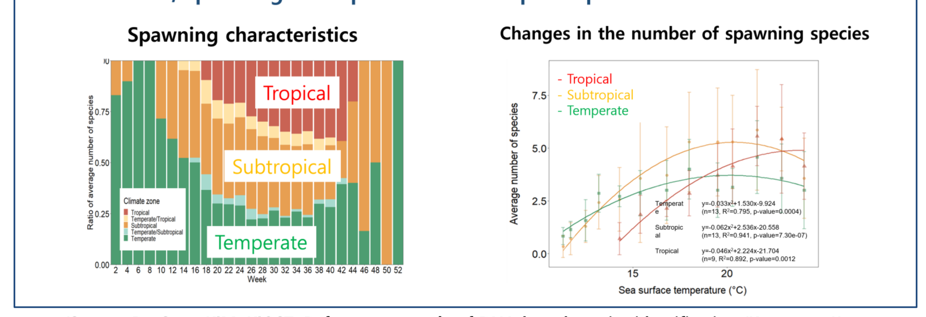
Average spawning season and duration by fish species (Example, Tongyeong, Korea, '13–'19)

- The spawning period for each species is 3-4 months
- Prolonged spawning of tropical and subtropical species
- Spawning rest period exists before and after the winter spawning season
- Most fish have overlapping spawning periods

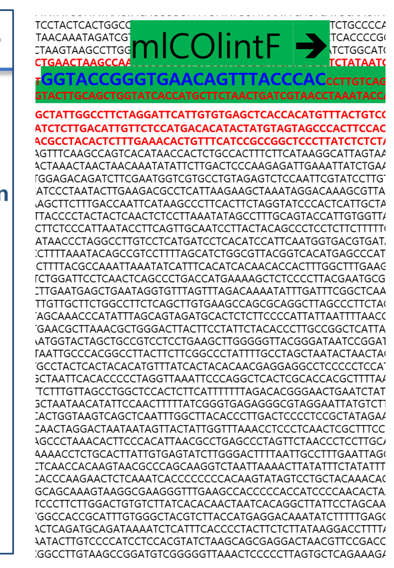
(Source: Dr. Sung KIM, KIOST, Reference example of DNA-based species identification (Korea case))

Oceanic Climate Characteristics based on spawning patterns

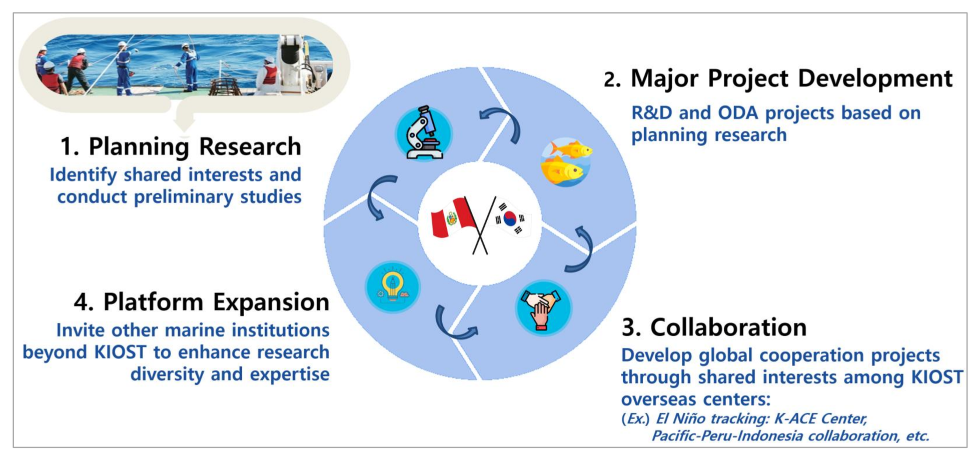
- In megacosm, the summer season is subtropical waters (Example, Korea, '13–'19)
- Changes in the number of spawning species by climate zone according to season
- In summer, spawning of tropical and subtropical species dominates



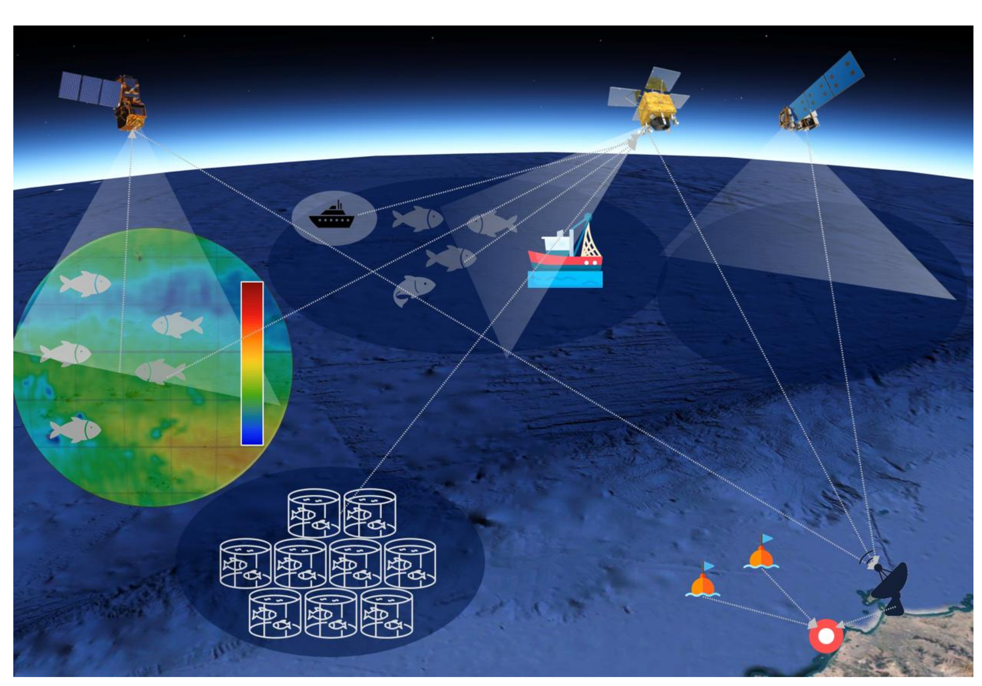
(Source: Dr. Sung KIM, KIOST, Reference example of DNA-based species identification (Korea case))



Discussion and Conclusion



(Implications for Science, Collaboration, and Fisheries Management)



(Integrated Multi-Scale Monitoring and Prediction Framework for Small Pelagic Fisheries (SPF))

✓ **Discussion:**

👉 Scientific Implications, Korea–Peru Scientific Cooperation, Management Implications

The findings indicate that small pelagic fish (SPF) variability in the Humboldt Current system is predominantly driven by environmental variability rather than fishing pressure alone. Satellite remote sensing enables basin-scale monitoring of key environmental drivers such as sea surface temperature (SST) and chlorophyll-*a* (Chl-*a*), while eDNA (DNA) provides fine-scale ecological detection of species presence and community composition. The integration of these complementary approaches enables a multiscale understanding of ecosystem dynamics, bridging physical and biological processes. The Korea–Peru Joint Research Center on Ocean Science and Technology for Latin America (KOPELAR) provides an effective platform for integrating advanced observation technologies with long-term fisheries datasets. Korea contributes expertise in satellite-based ocean monitoring, forecasting systems, and digital observation technologies, whereas Peru contributes extensive in situ observations and long-term fisheries monitoring through IMARPE. This collaboration facilitates multi-scale, interdisciplinary research by combining global-scale environmental information with locally validated ecological and fisheries data.
The proposed integrated framework supports ecosystem-based fisheries management (EBFM) by enabling climate-responsive and adaptive decision-making. Early warning indicators, such as simultaneous SST increases and Chl-*a* decreases, can signal elevated ecological risk and potential declines in SPF stocks. These insights can inform adaptive management strategies, including dynamic total allowable catch (TAC) adjustments and spatial fishing closures. Ultimately, this approach supports climate-informed fisheries governance and improves the resilience of marine resource management systems.

✓ **Conclusion:**

👉 Korea–Perú collaborative framework

This study demonstrates that small pelagic fish (SPF) systems in the Humboldt Current are highly vulnerable to climate variability, particularly ENSO-driven changes. By integrating satellite remote sensing, eDNA (DNA), and long-term observations, we propose a novel framework for adaptive, ecosystem-based fisheries management. The Korea–Peru collaboration (KOPELAR) highlights a transferable model for climate-resilient fisheries management with enhanced predictive and monitoring capabilities.

Contact Information

If you have questions, please contact me
Dr. LEE, Junho

E-mail: leejh@kiost.ac.kr
www.kiost.ac.kr

KIOST KOREA INSTITUTE OF OCEAN SCIENCE & TECHNOLOGY
KOPELAR Korea-Peru Research Center for Ocean Science and Technology for Latin America