# Prediction Systems and Services

## where they are now and where they are headed

Byoung-Ju Choi (Chonnam Univ.) and Gregg Jacobs (NRL)

May 8, 2019
Halifax, Nova Scotia, Canada

# Outline

**1. Overview and background**

**2. Current status of national prediction systems** and **services**

Configuration (introduction of systems) and operation

Products, capabilities

Who are demanding and potential users

Example: KOOS and KOOFS

3. Any **challenges** or current **issues**

**4. Future directions:** where they are headed

**5. Collaboration and International recognition**

**Summary**

# 1. Overview

Objectives are to provide an idea of

1. Where prediction systems are now in terms of their capabilities?

2. Where they are headed?

and to stimulate discussion on challenges and future directions for the ocean prediction community.

# 1. Overview

Present
R&D for sustainable ocean

Future
Provide (socialize) information for sustainable ocean

(Pierre Bahurel)

# 1. Personal Overview

## Where prediction systems are now?

**National/Regional Systems**

HYCOM
MFS
Mercator Ocean
Bluelink
MRI.com
FOAM
TOPAZ
CONCEPTS
RTOFS
China, REMO, India, Korea, NZ, Denmark

*More Prediction Systems* { Global, Basin, Regional, Coastal }

**Observation Systems (global, regional)**

- SST
- ship
- Argo float
- Satellite Altimeter
- Ocean buoy
- Drifters
- HF radar

**Data Assimilation**

OI
EnKF
EnOI
3DVAR
4DVAR

Hybrid

**Numerical Models**

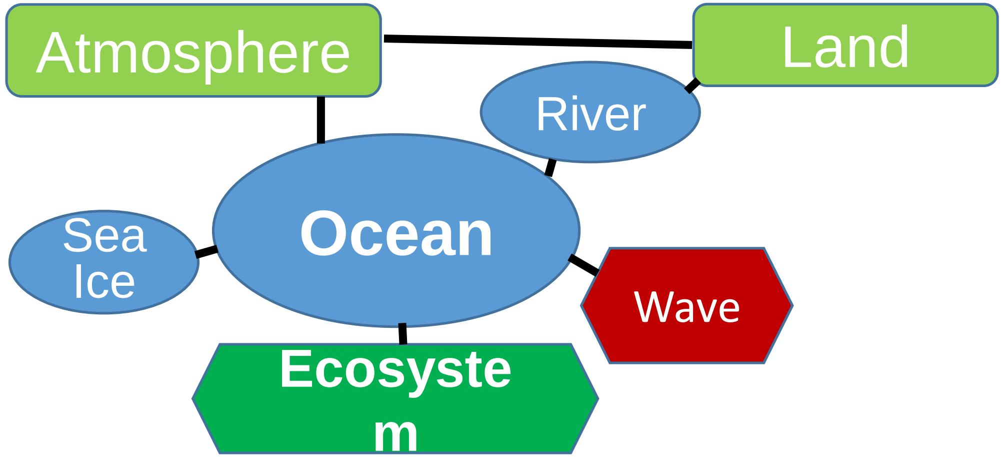
POM
LOM
MICOM
POP
MOHID
HYCOM
NEMO
ROMS
MRI
MOM
Storm Surge
Ecosystem, Sea Ice

# 1. Personal Overview

Applications with evaluation metric (with respect to end user specification)
Inundation (sea level, wave, surge), SAR (Coastguard), Defense (Navy)
Red tide, Oil Spill, Oil platform, Shipping, drift, Tsunami Warning "**Information**"

HPC(High Performance Computing)
Calibration/Validation and Evaluation
Role in Inter-governmental organizations

**High resolution (1/4° → 1/12° → 1/25°)**
Two-way nesting, improved physics and mixing
Ensemble prediction
**Coupled (integrated) systems**




National/Regional Systems { Global, Basin, Regional, Coastal }

| Observation Systems | Data Assimilation | Numerical Models |
|---|---|---|

# 1. Overview

**Where prediction systems are now?** **System reports from 2010 on the web.**


**Background**

1. Input data
2. Data serving
3. Models
4. Assimilation method
5. Assimilation products and dissemination
6. Systems
7. Links to Observations
8. Internal metrics and intercomparison plans
9. Targeted Users and envisioned external metrics
10. Reanalysis activities
11. Computing resources
12. Consolidation phase and transition to operational system (activities)
13. GODAE OceanView related achievements and measures of success

**System Information overview**

# 2. KOOFS and KOOS

Korea Operational Oceanographic System (**KOOS**)

Korea Institute of Ocean Science and Technology (KIOST)

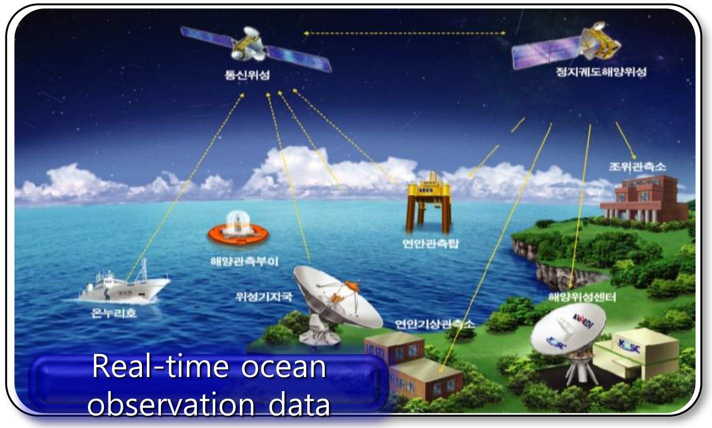
Chonnam National University

Korea Ocean **Observing** and **Forecasting** System (KOOFS)

Korea Hydrographic and Oceanographic Agency (KHOA)

Public Services

# 2.1 Korea Ocean Observing and Forecasting System (KOOFS)



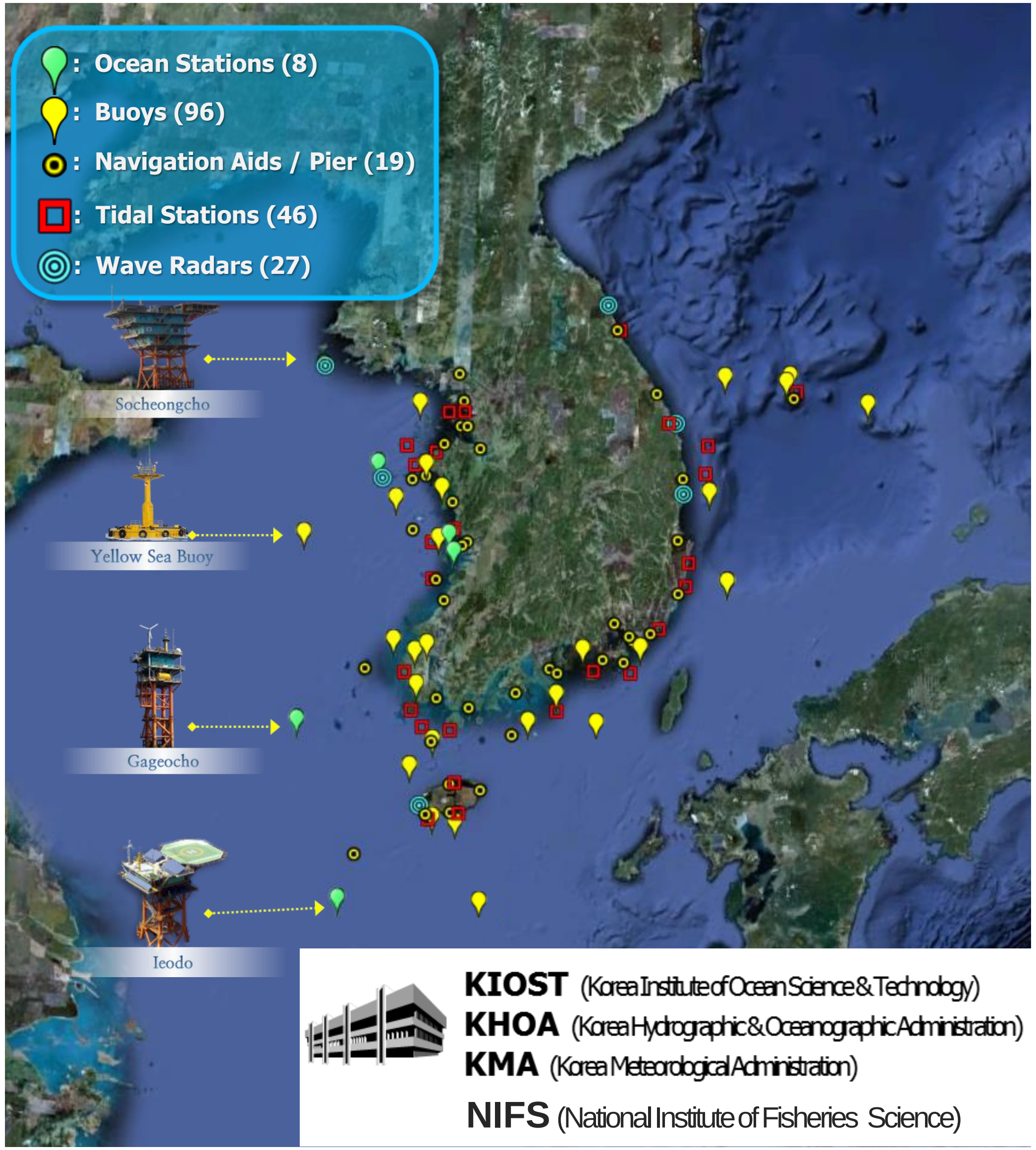

## Real-time ocean observing stations

- **Including Ocean stations, buoys, tidal stations, pier, navigations aids, and wave radar, etc.**

  **(about 190 stations, 2018 at present)**

## Observation

- **Ocean wind & wave, tide, current, sea temperature & salinity, etc**
- **Input & validation data for forecasting models**



# 2.1 Korea Ocean Observing and Forecasting System (KOOFS)

**OCEAN STATION**
**(8 STATIONS)**

Korea Hydrographic and
Oceanographic Agency

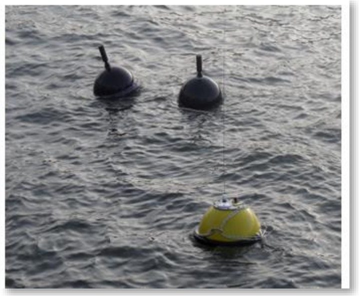
# 2.1 Korea Ocean Observing and Forecasting System (KOOFS)

## Real-time Ocean/Coastal Observations

### ❑ Buoy (96 station)


**Observation Network**

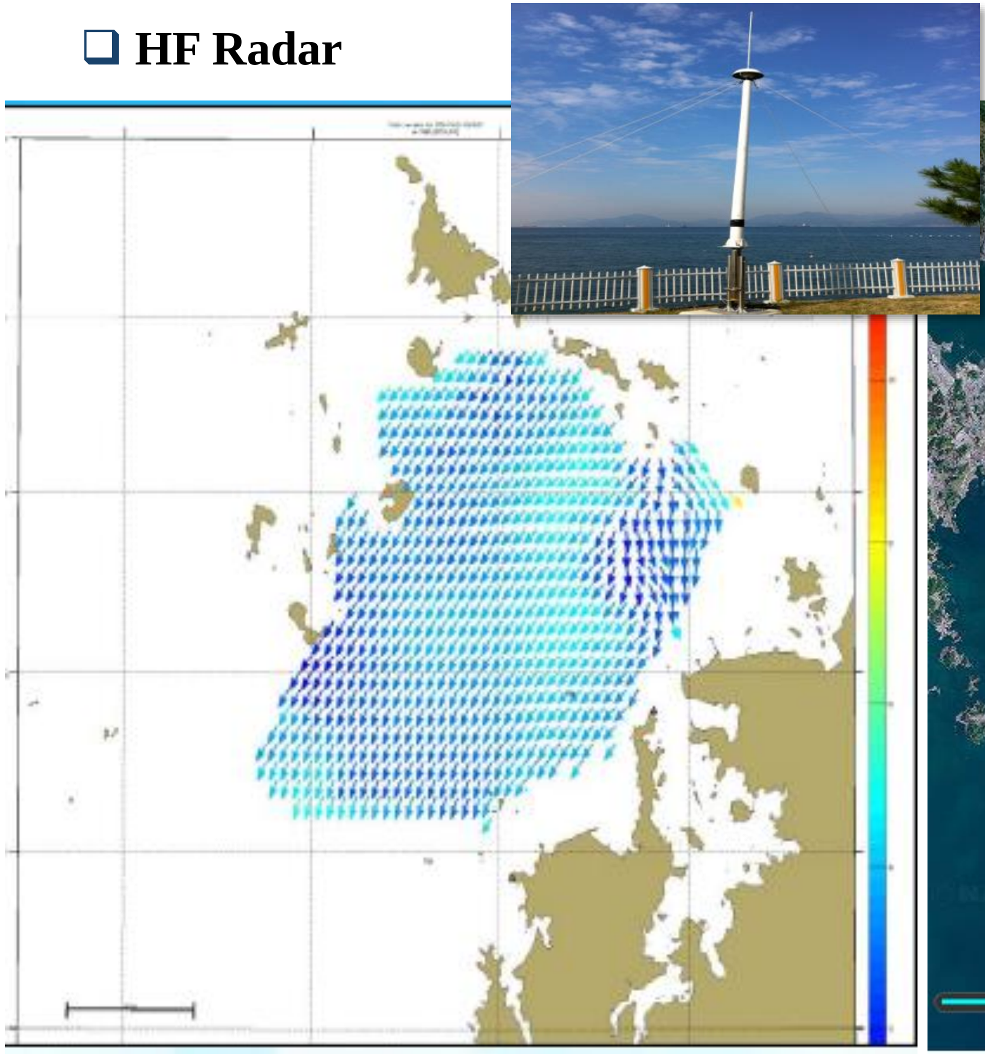
**Ocean Data Buoys : 17**
**Coastal Wave Buoys : 48**
**Long Wave Monitoring : 18**
**Wave Radars : 6**
**Ports Weather Station : 2**
**Lighthouse AWS : 9**
**Vessel AWS : 10**
**Marine Obs. Station : 1**

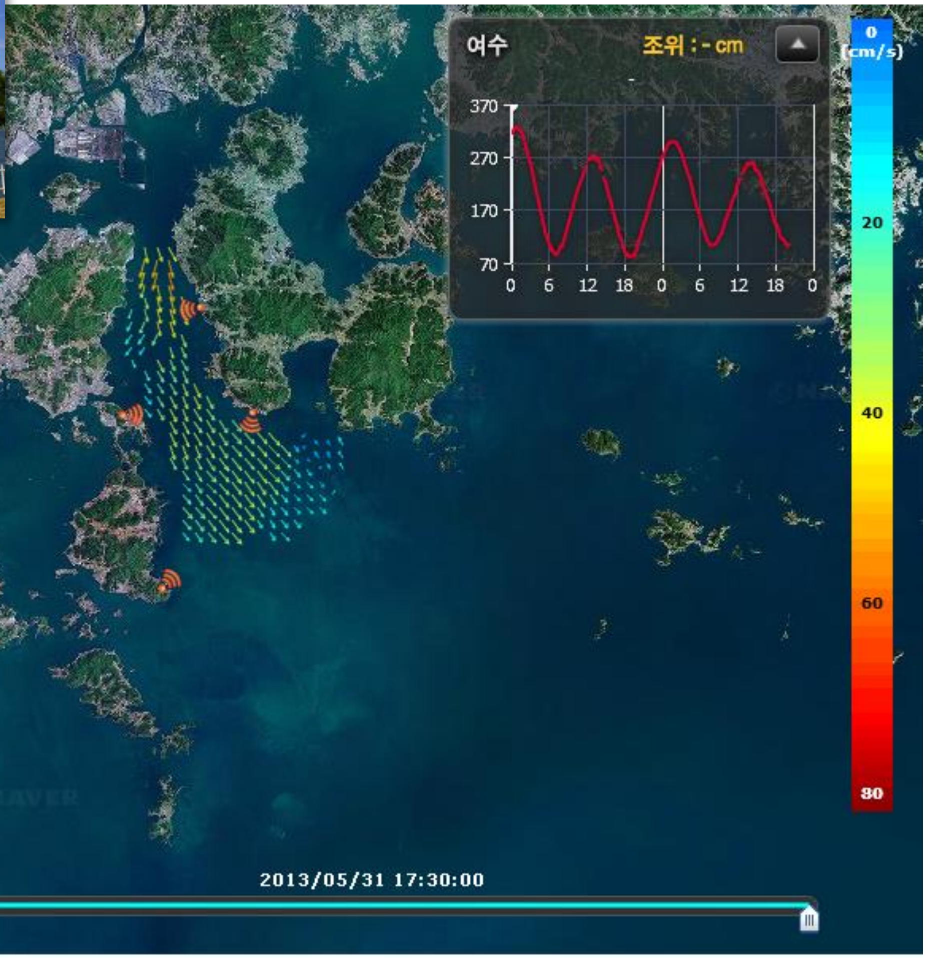


# 2.1 Korea Ocean Observing and Forecasting System (KOOFS)

## HF RADAR (5 STATIONS)

- ❑ **HF Radar**

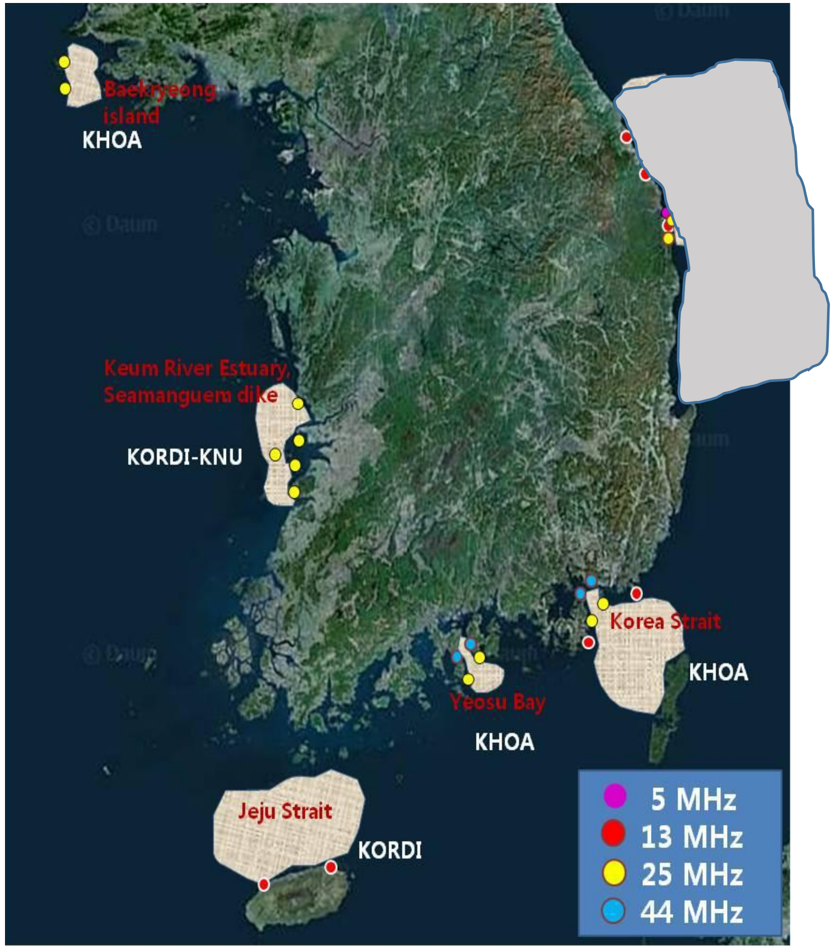




# 2.1 Korea Ocean Observing and Forecasting System (KOOFS)

Establishing new surface current observation network
 Standard HF radar data

**Long-range HF radar data (> 60 km)**

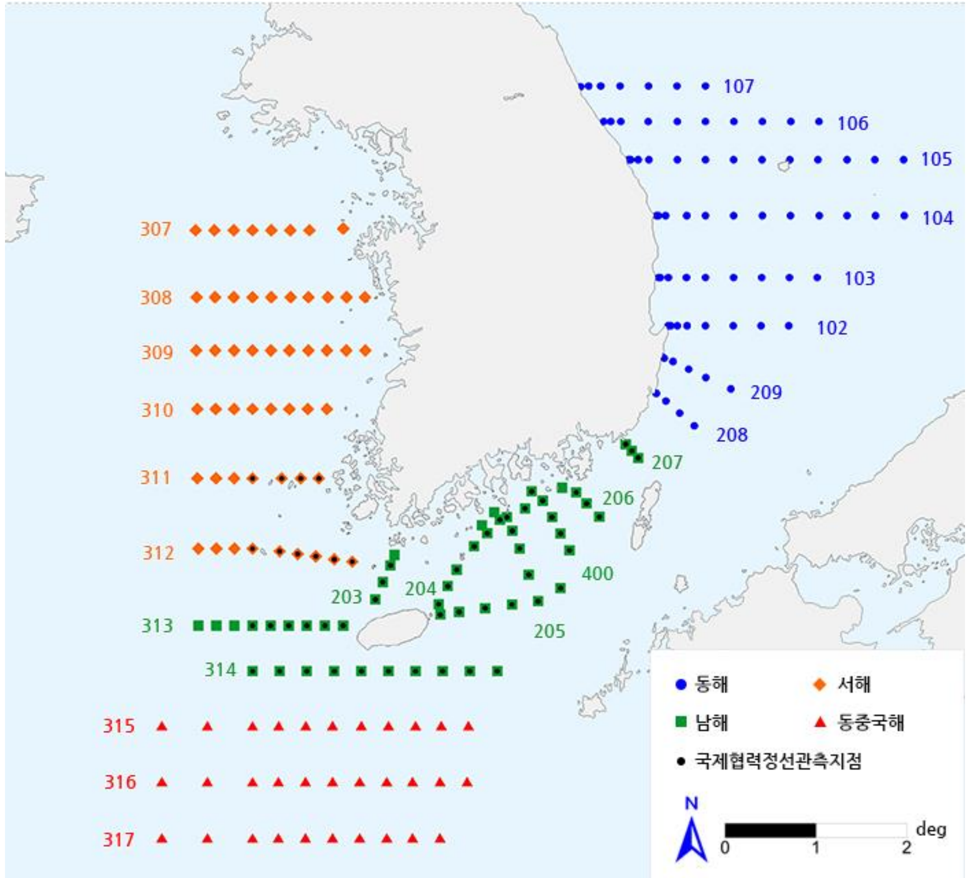



Korea Hydrographic and Oceanographic Agency

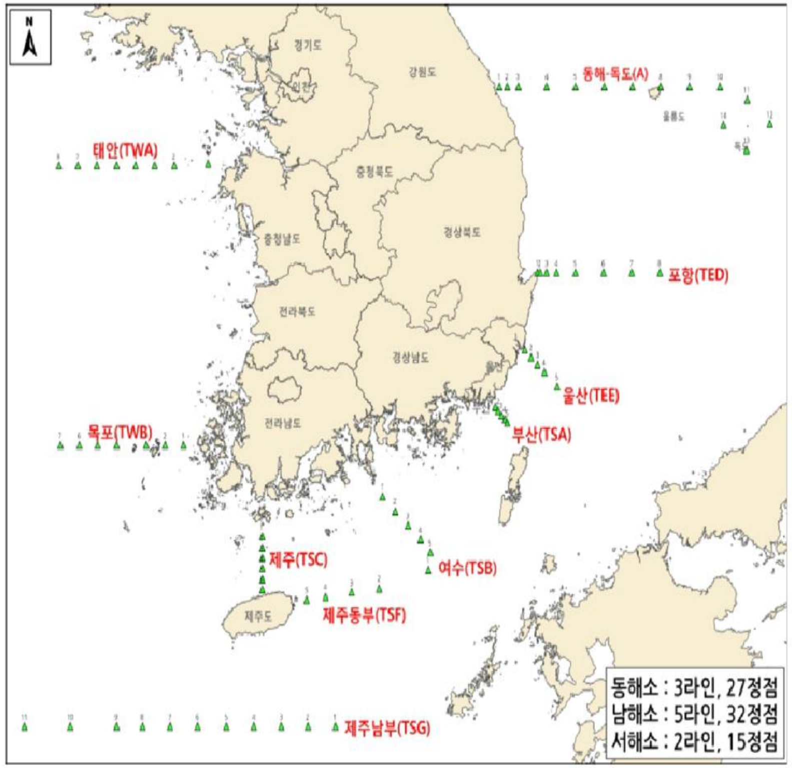
# 2.1 Korea Ocean Observing and Forecasting System (KOOFS)

Getting real-time data from **NIFS bi-monthly CTD profiles**
**KHOA bi-monthly CTD profiles**

NIFS (2, 4, 6, 8, 10, 12)

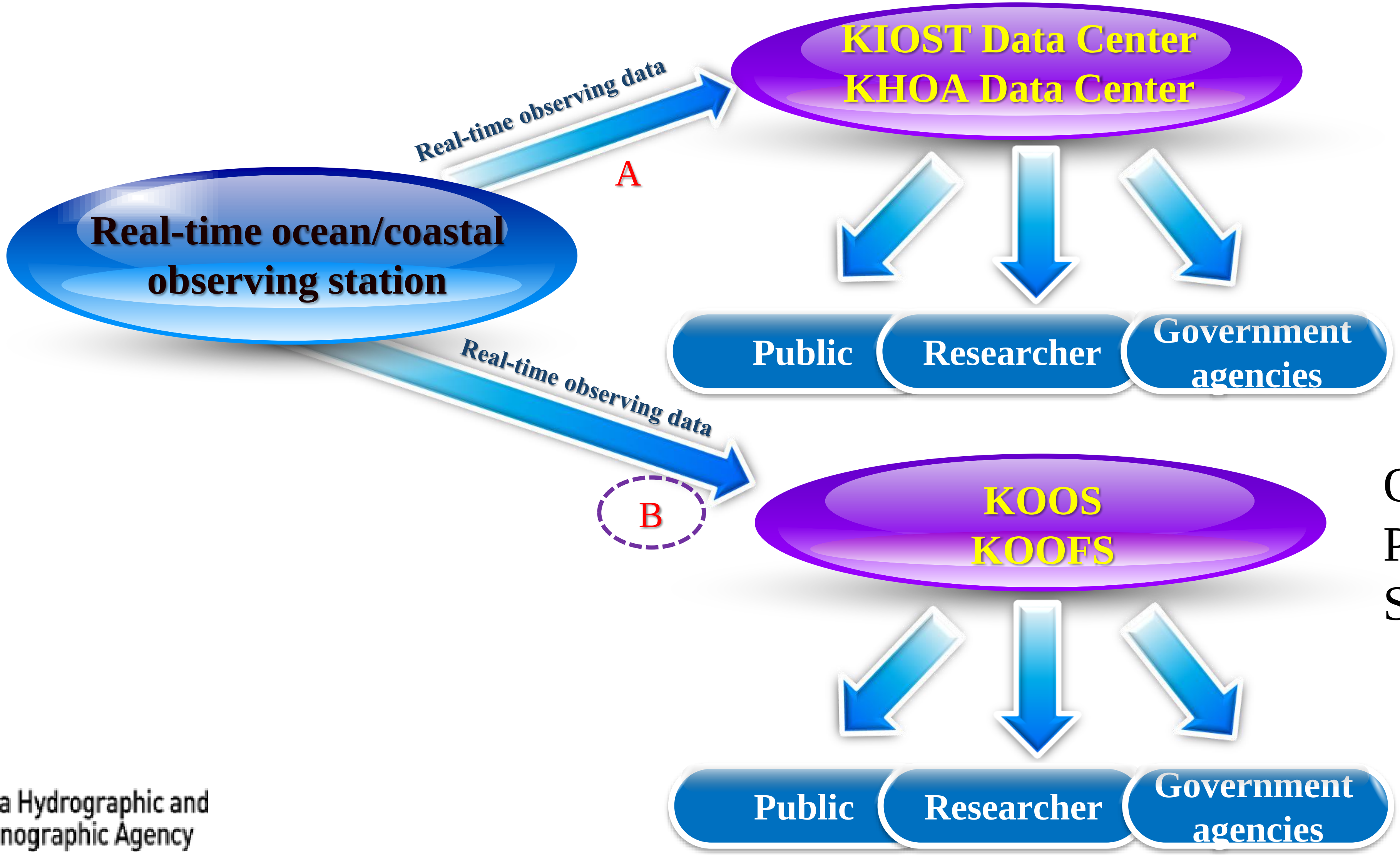



KHOA (3, 5, 7, 11)



# 2.1 Korea Ocean Observing and Forecasting System (KOOFS)

## Real-time observing data transmittance

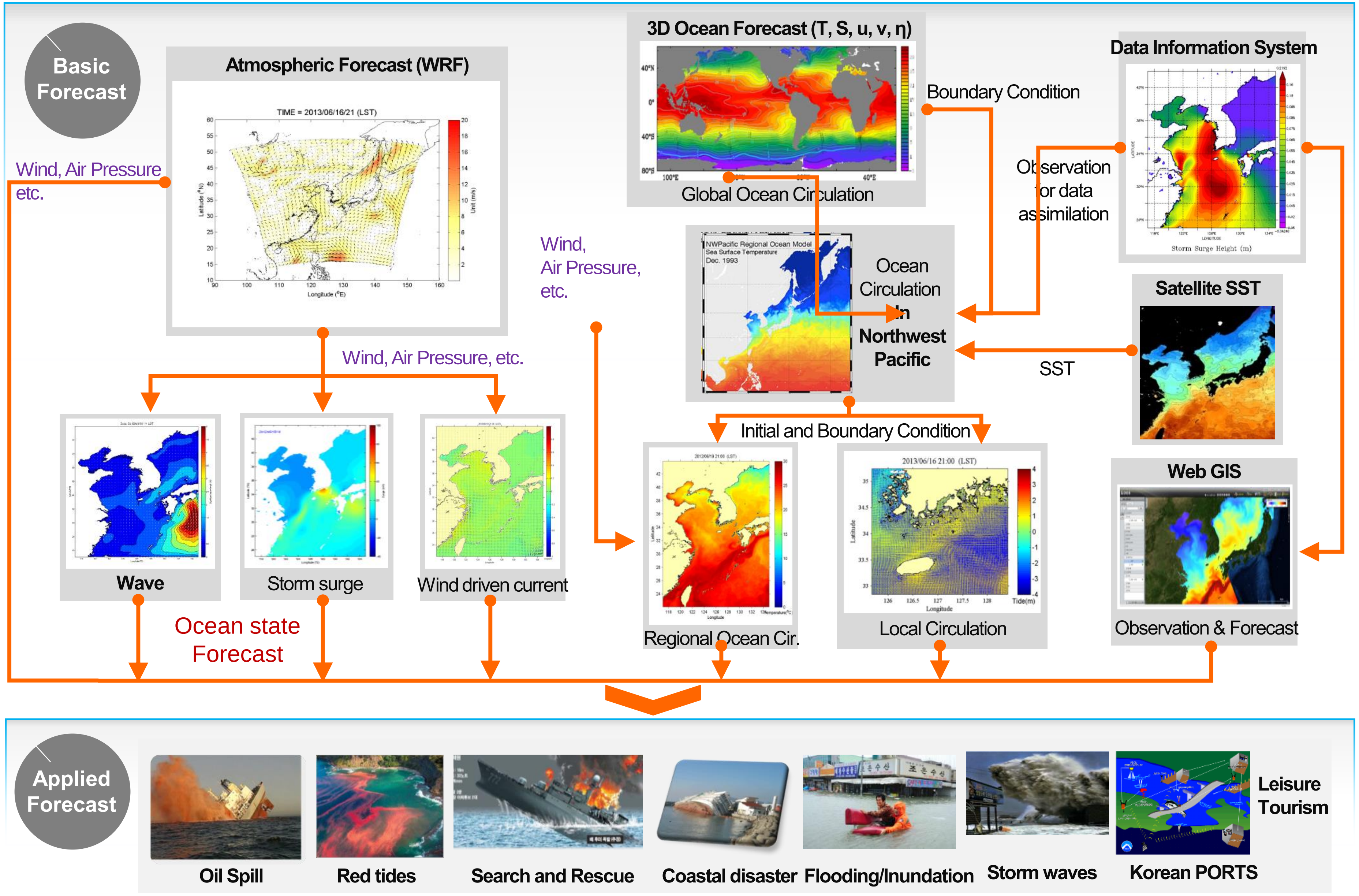



Operational Prediction Systems

Korea Hydrographic and Oceanographic Agency

OceanPredict '19

# 2.2 KOOS1 OVERVIEW (2009 - 2018)



# 2.2 KOOS1 Overview (2009 - 2018)

## Operational Weather Forecasting System

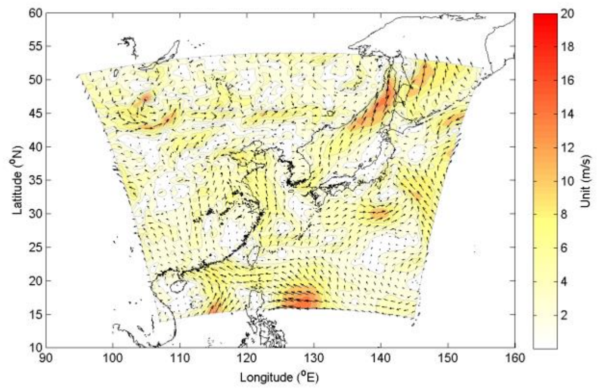
### 1st Step

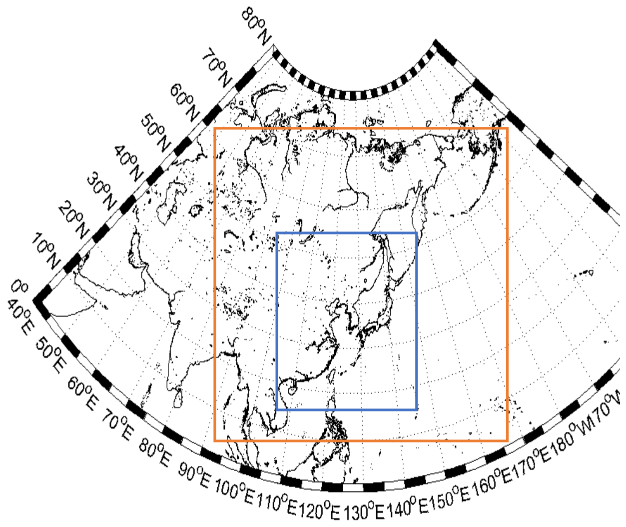
NCEP GFS data

WRF (20km→4km)

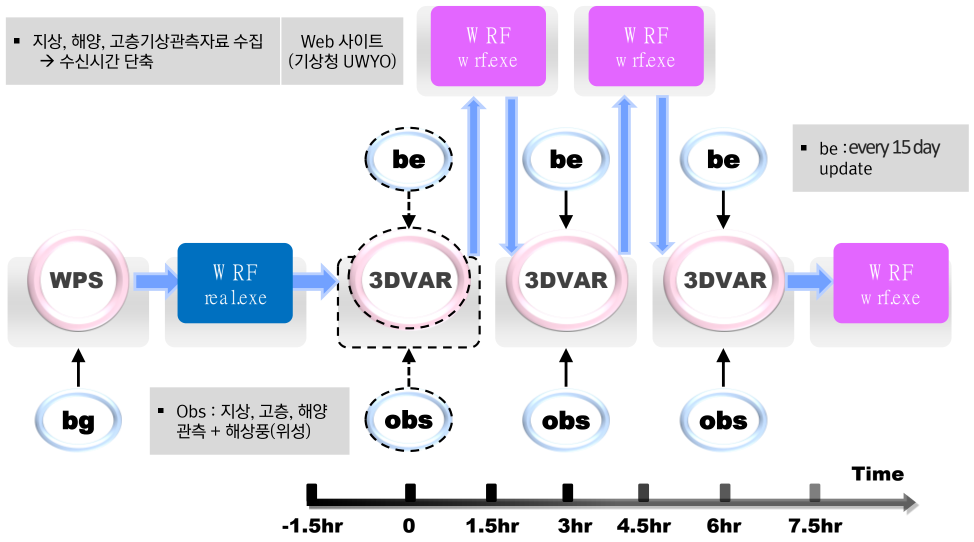
Pressure, Wind, … 20 variables (72h,2day)

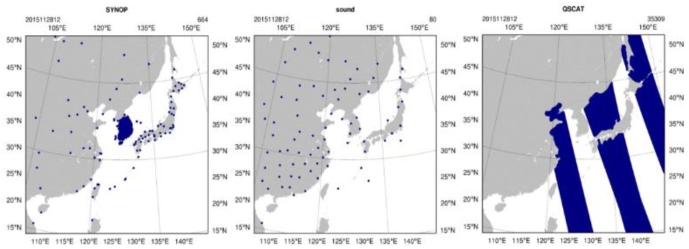
Ocean Model



Data Assimilation

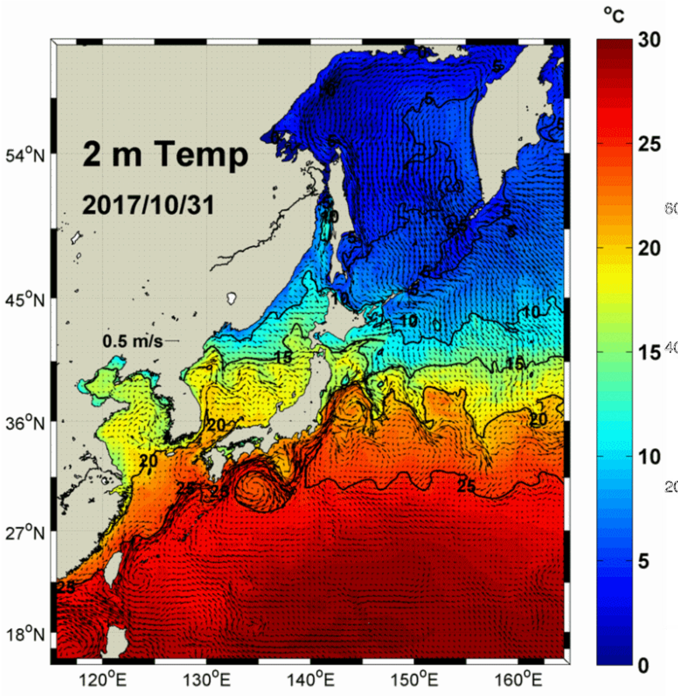


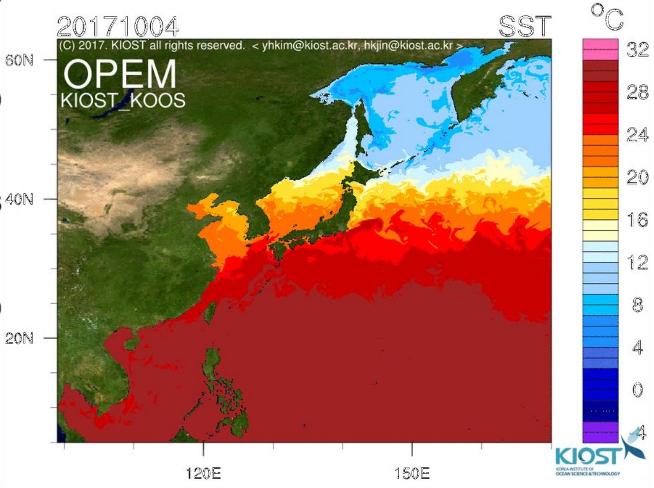

(Ground 700, Upper layer 80, Satellite Sea Surface Wind 35,000 points)

# 2.2 KOOS1 OVERVIEW (2009 - 2018)

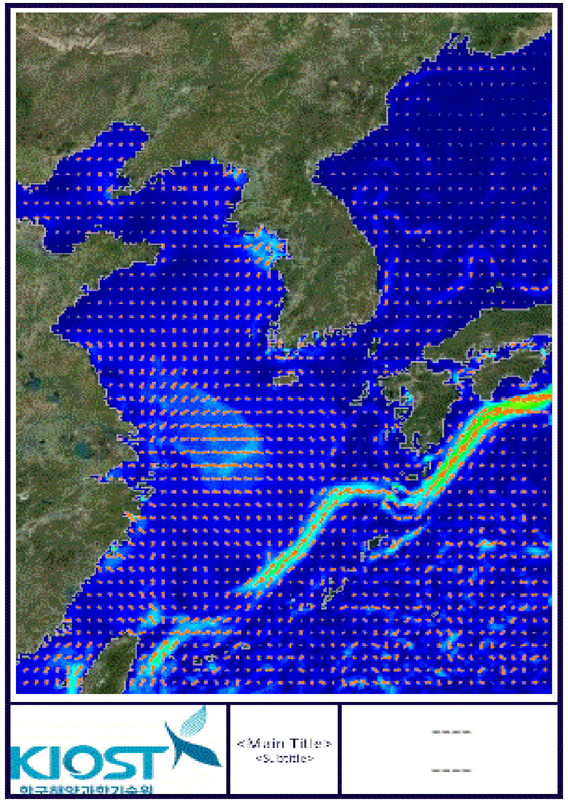
## OPERATIONAL REGIONAL OCEAN CIRCULATION FORECASTING SYSTEMS




ROMS (10 km), EnKF



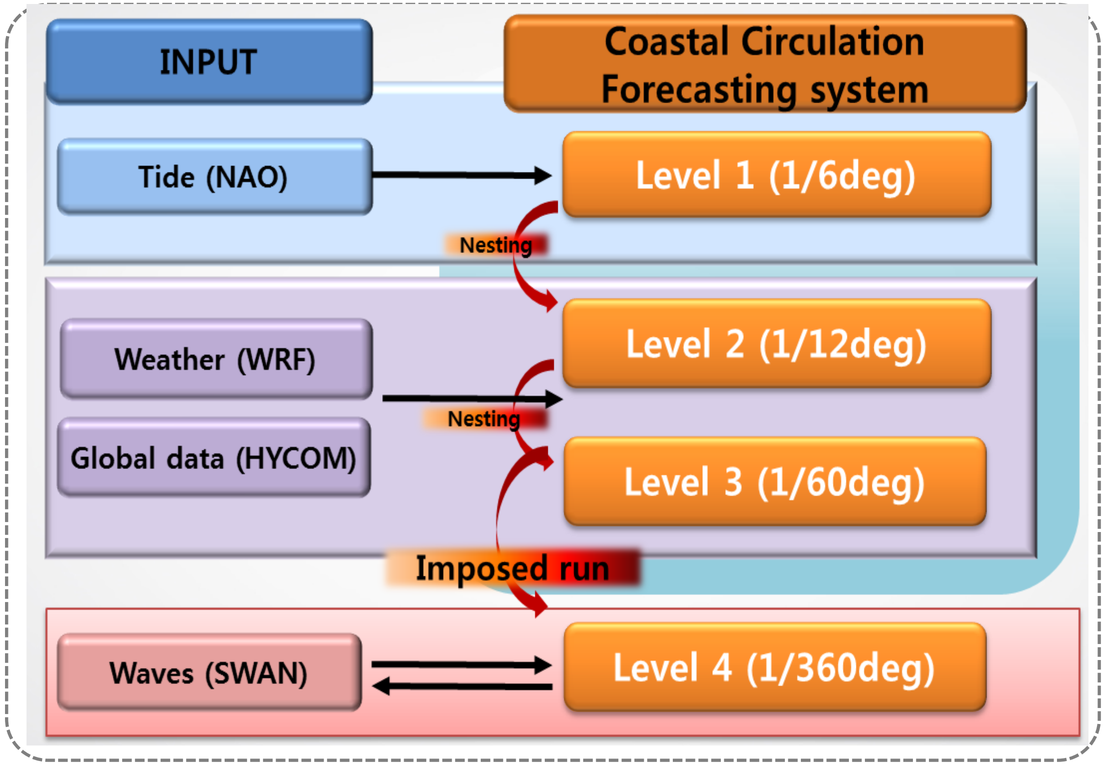

MOM (3 km), EnOI

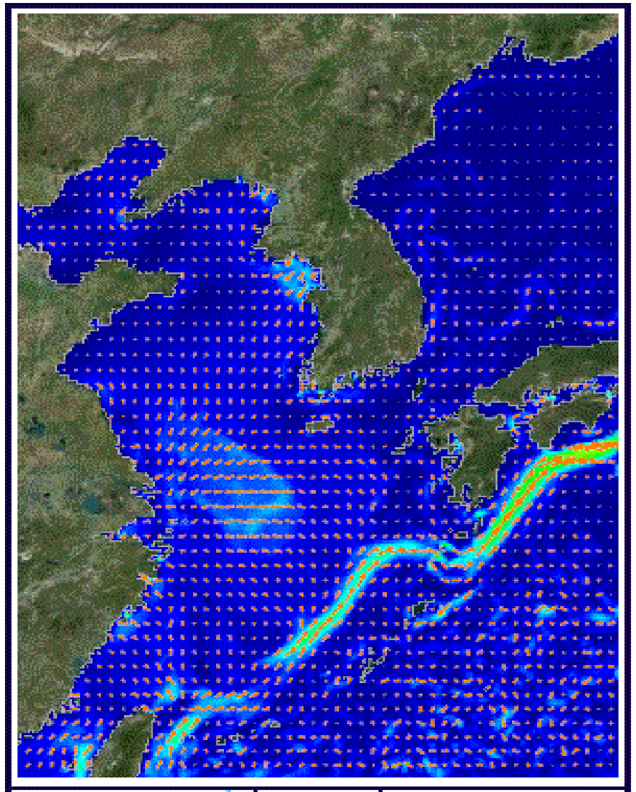


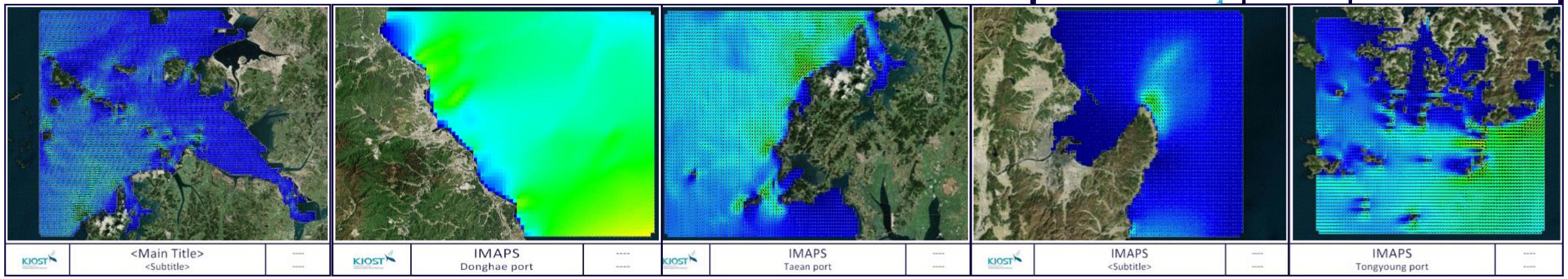

MOHID (9 km), OI

# 2.2 KOOS1 Overview (2009 - 2018)

## Operational Coastal Ocean Circulation Forecasting Systems





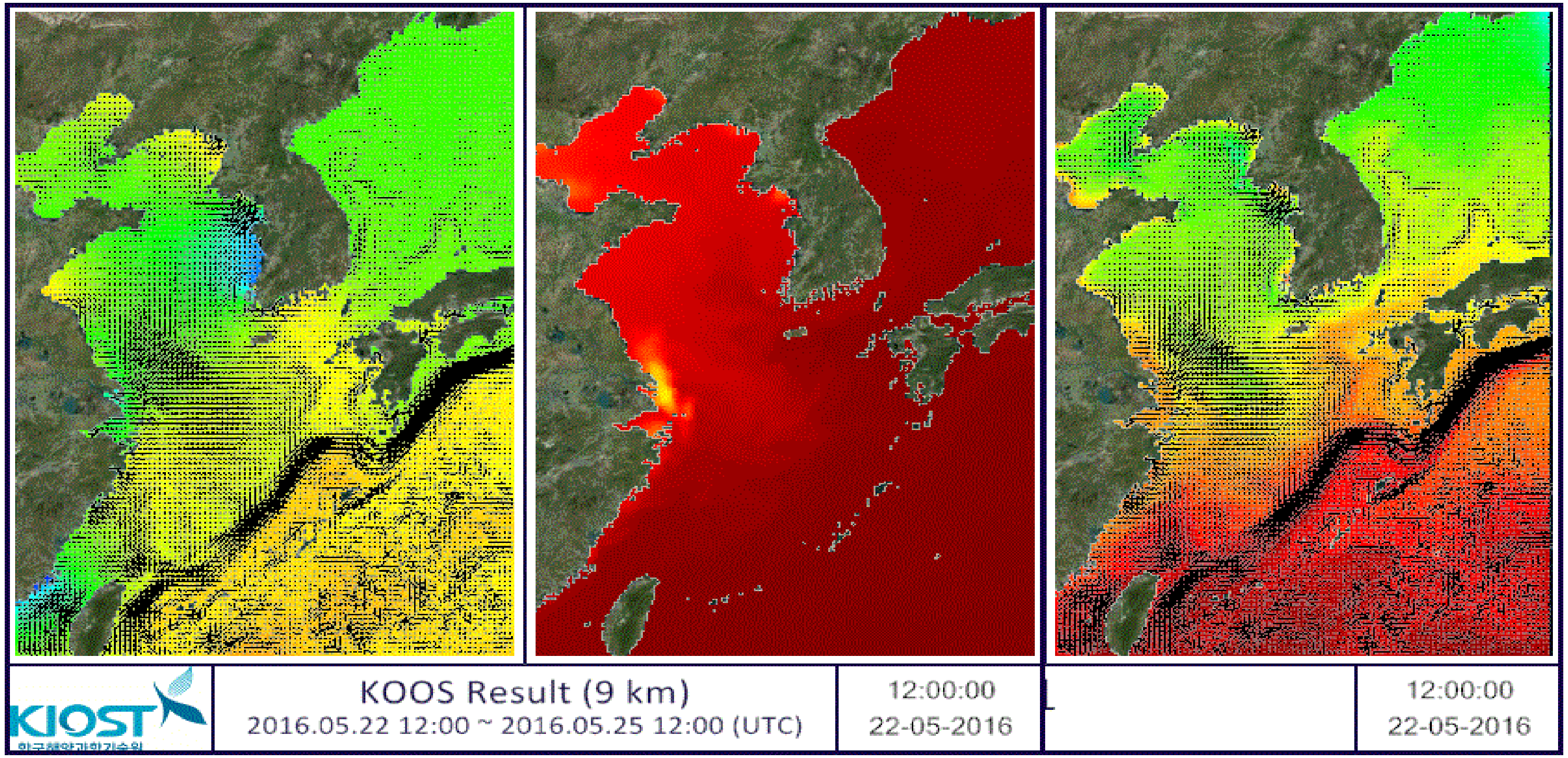
# 2.2 KOOS1 OVERVIEW (2009 - 2018)

## OPERATIONAL COASTAL OCEAN CIRCULATION FORECASTING SYSTEMS

**Regional Sea Circulation**

**L2 (9km)**

Sea Level, Current | Salinity | Temperature, Current



OceanPredict '19

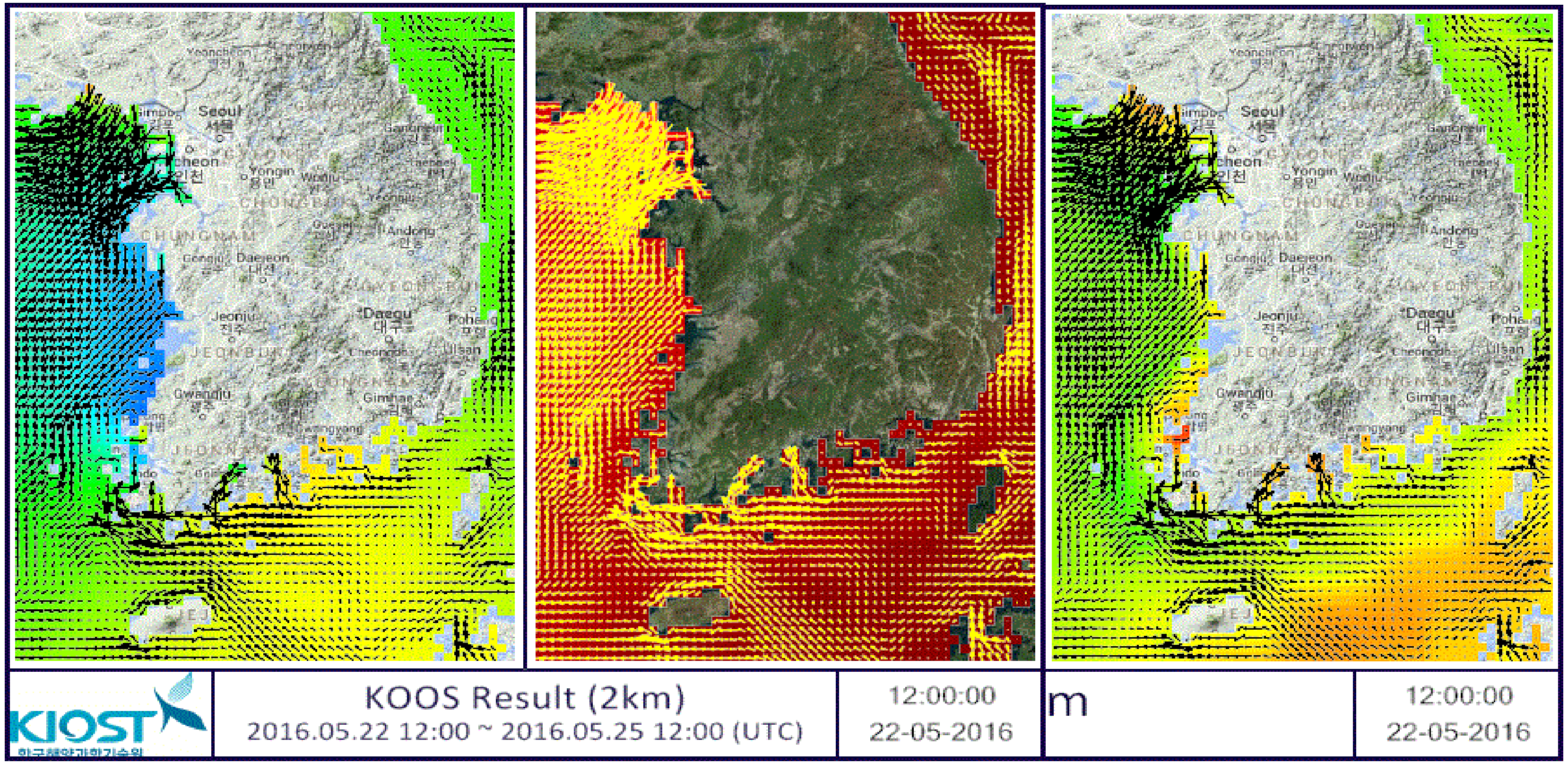
# 2.2 KOOS1 Overview (2009 - 2018)

## Operational Coastal Ocean Circulation Forecasting Systems

**Regional Sea Circulation**

**L3 (2km)**

**Sea Level, Current** | **Salinity, Current** | **Temperature, Current**



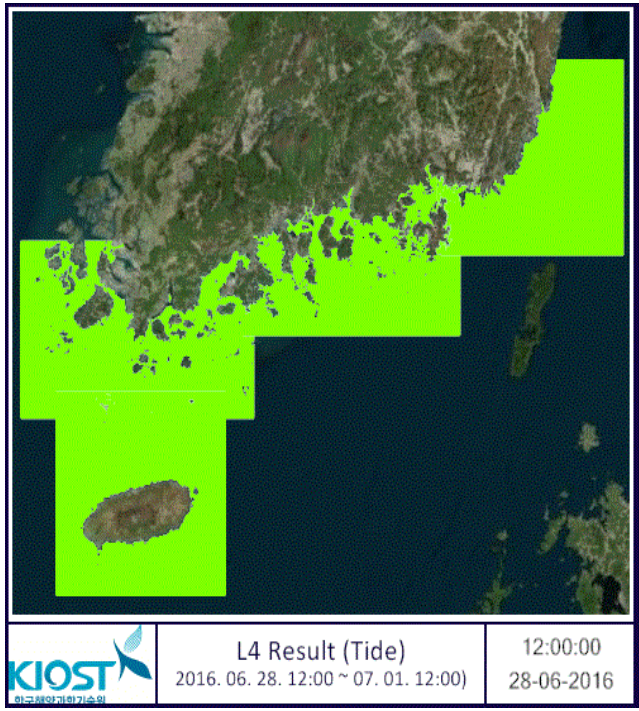
# 2.2 KOOS1 Overview (2009 - 2018)

## Operational Coastal Ocean Circulation Forecasting Systems

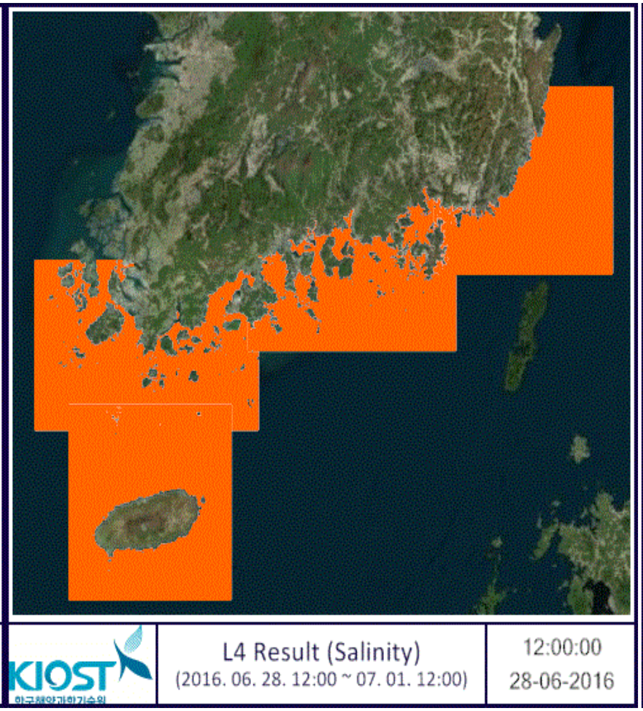
**Regional Sea Circulation**

**L4 (300m)**

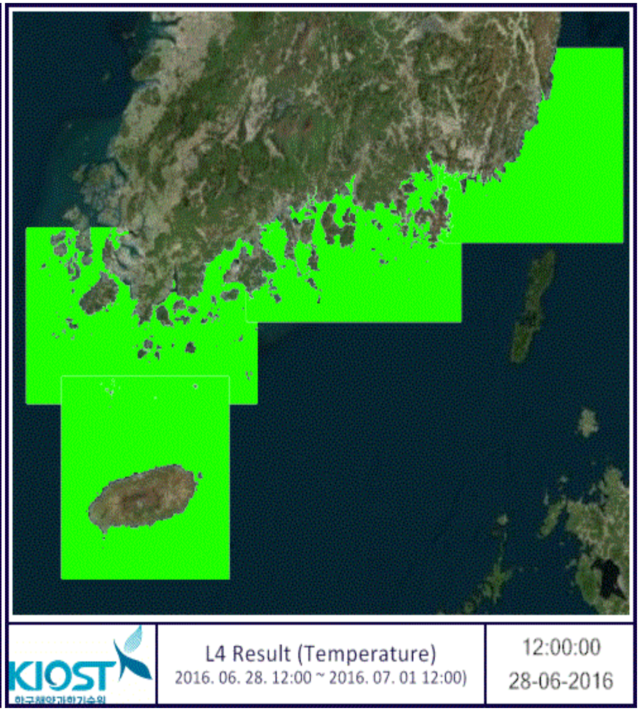
Tide & Currents




Salinity & Currents



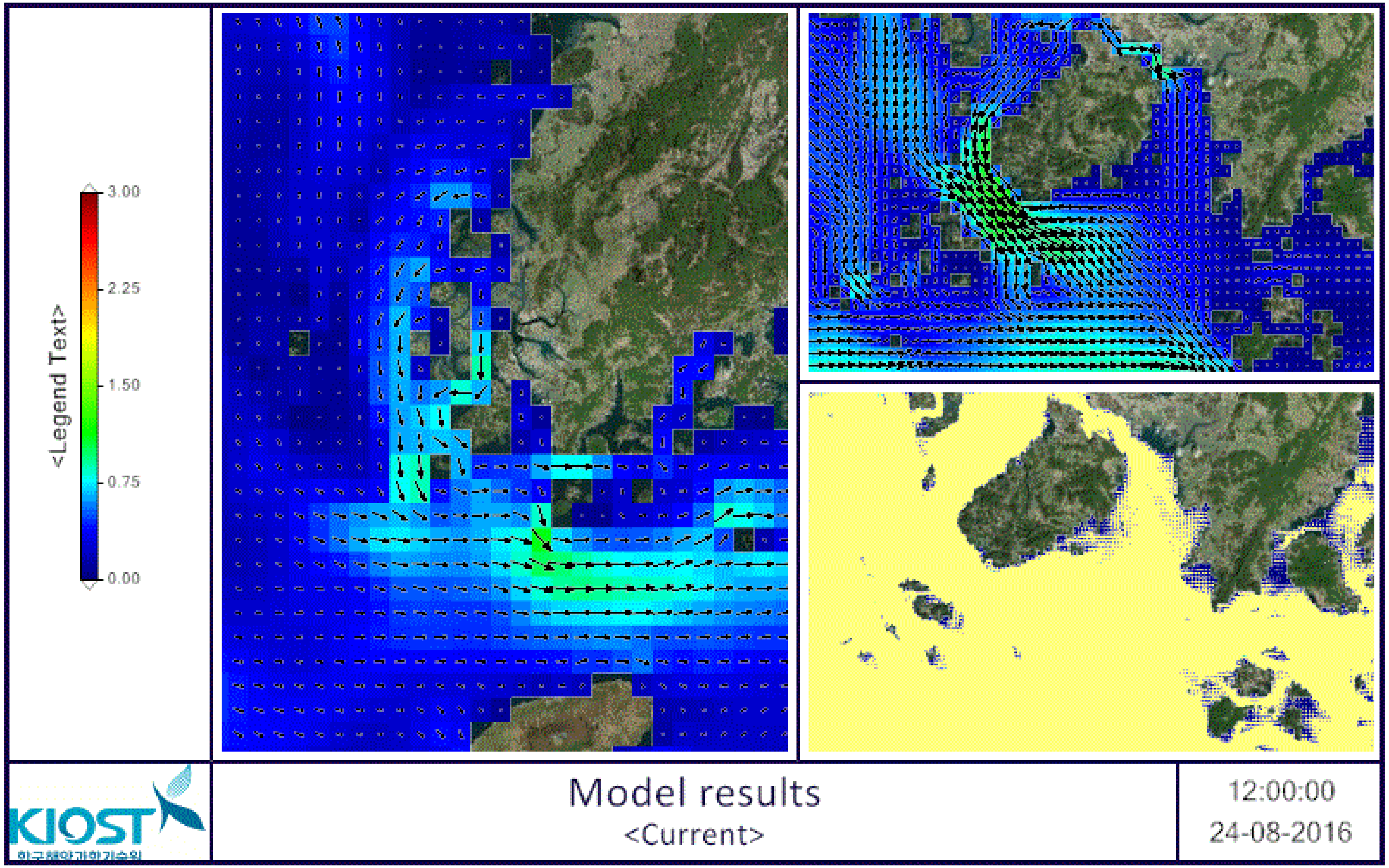

Temperature & Currents



# 2.2 KOOS1 Overview (2009 - 2018)

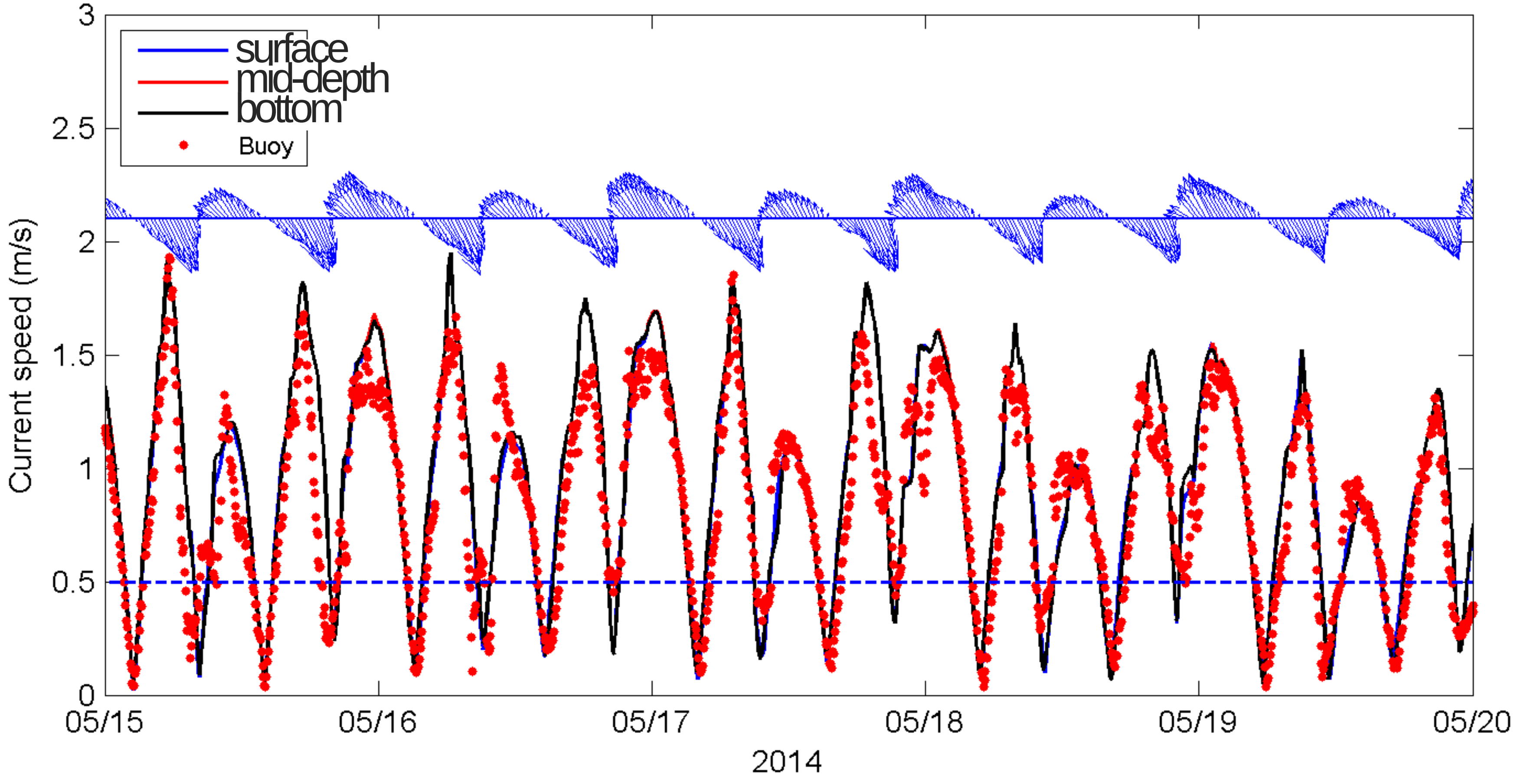
## Operational Coastal Ocean Circulation Forecasting Systems

- Comparison of models between 9 km, 2 km, 300 m resolution



# 2.2 KOOS1 Overview (2009 - 2018)

## High Resolution Coastal Circulation Forecasting System



# 2.2 KOOS 2 Overview (2018 - 2022)

KIOST

| Global | Regional | Coastal | Applications |
|---|---|---|---|
| MPAS (Global Atm.) | HWRF (typhoon)<br>WRF | MOHID<br>FVCOM<br>TELEMAC | Visualization<br>Support Decision-Making<br>SAR/ Oil Spill |
| DASK (MOM6) 1/12º | MOM5<br>ROMS<br>(NWP) | | |
| | Coupled Systems | Ensemble | |

**Data / Info system / Skill assessment**

# 2.2 KOOS 2 OVERVIEW (2018 - 2022)

Development of Global Prediction System from 2018 to 2020.

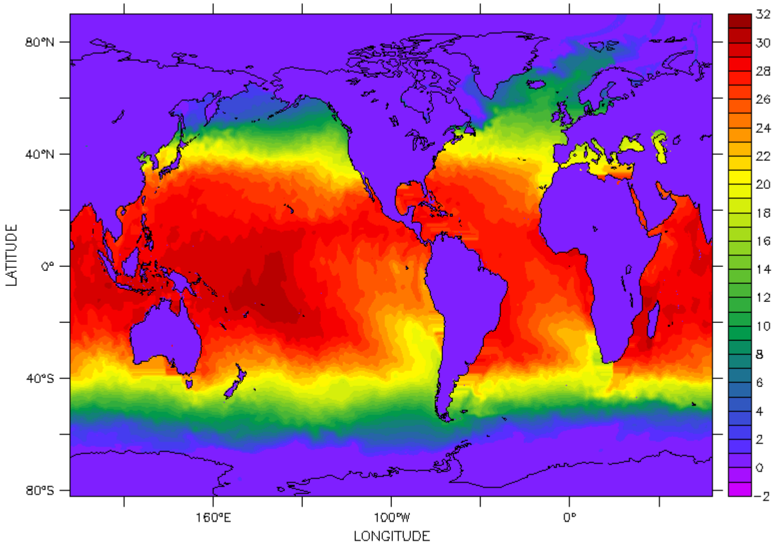
DASK (Data Assimilation System of KIOST) (Kim et al., 2015)

EnOI (Ensemble Optimal Interpolation):

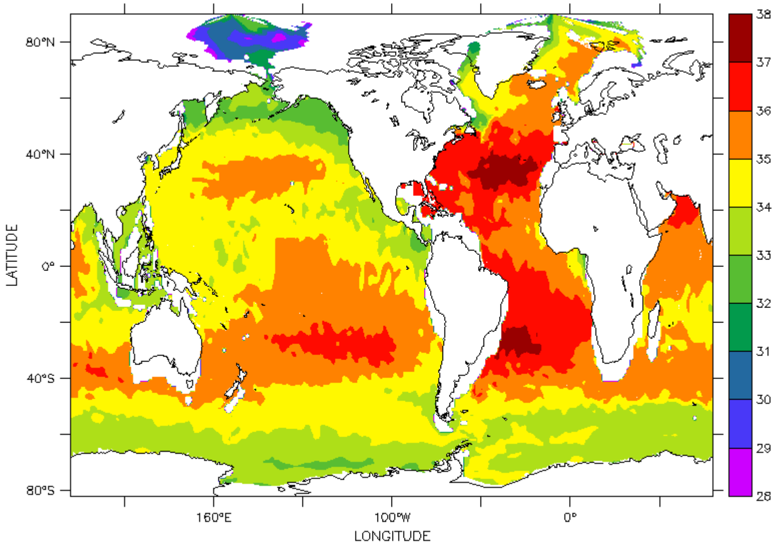
OSTIA SST , GTSPP real-time data, ARGO profile, KODC data, SSH

| | Grid spacing | Grid system |
|---|---|---|
| **Horizontal** | 1/12° | Tripolar grid |
| **Vertical** | 51 level (0-5500m) | z* coordinate |

**Global 1/12° (MOM6)**




Potential Temperature (degC)

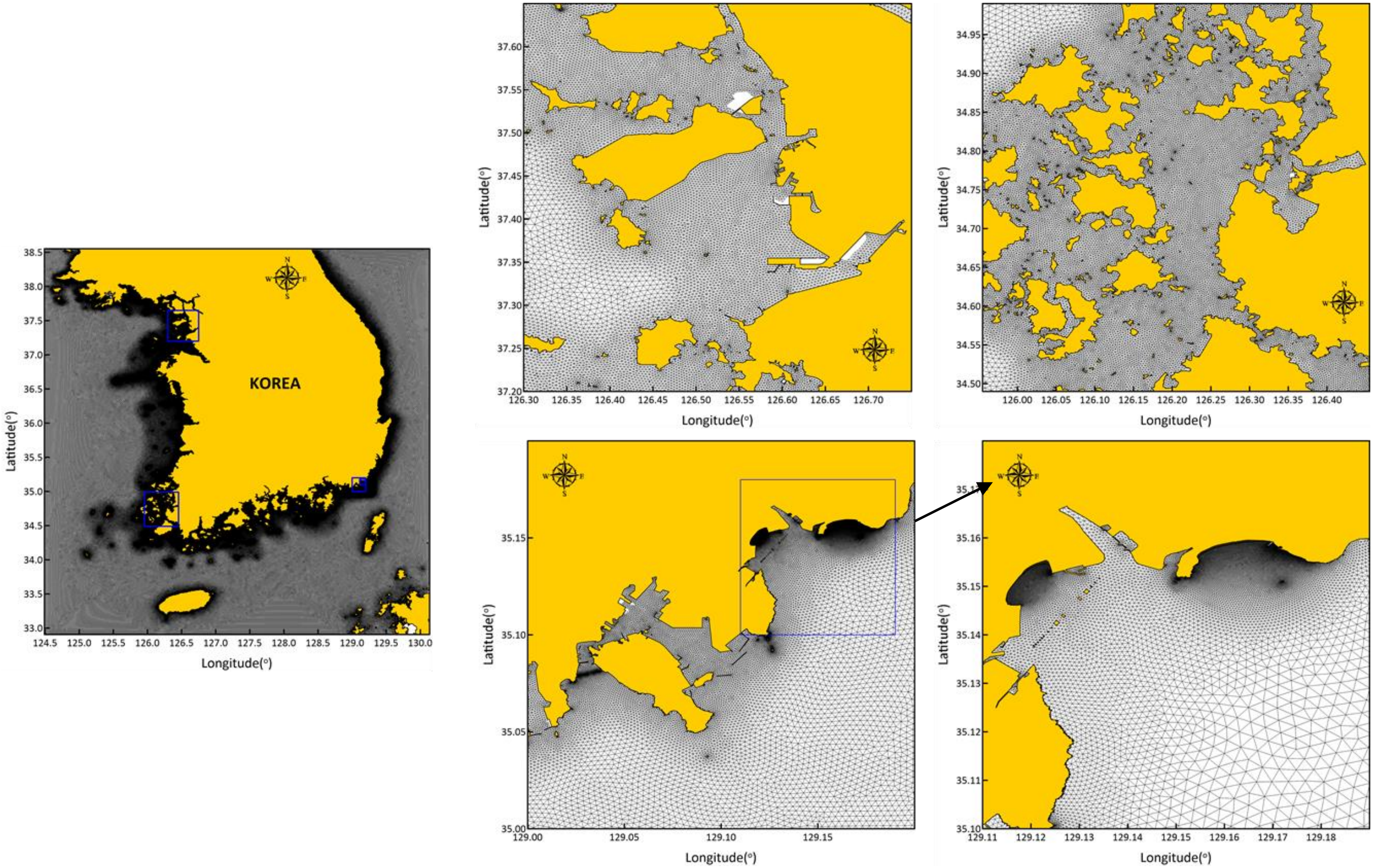



Salinity (PPT)

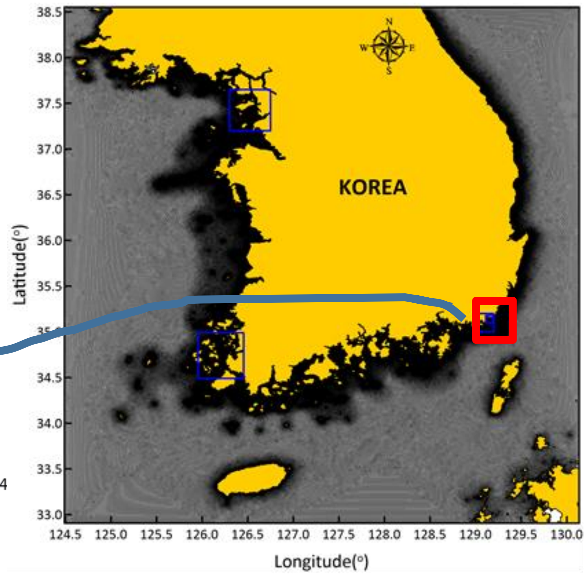
# 2.2 KOOS 2 OVERVIEW (2018 - 2022)

## TELEMAC (unstructured grid model)

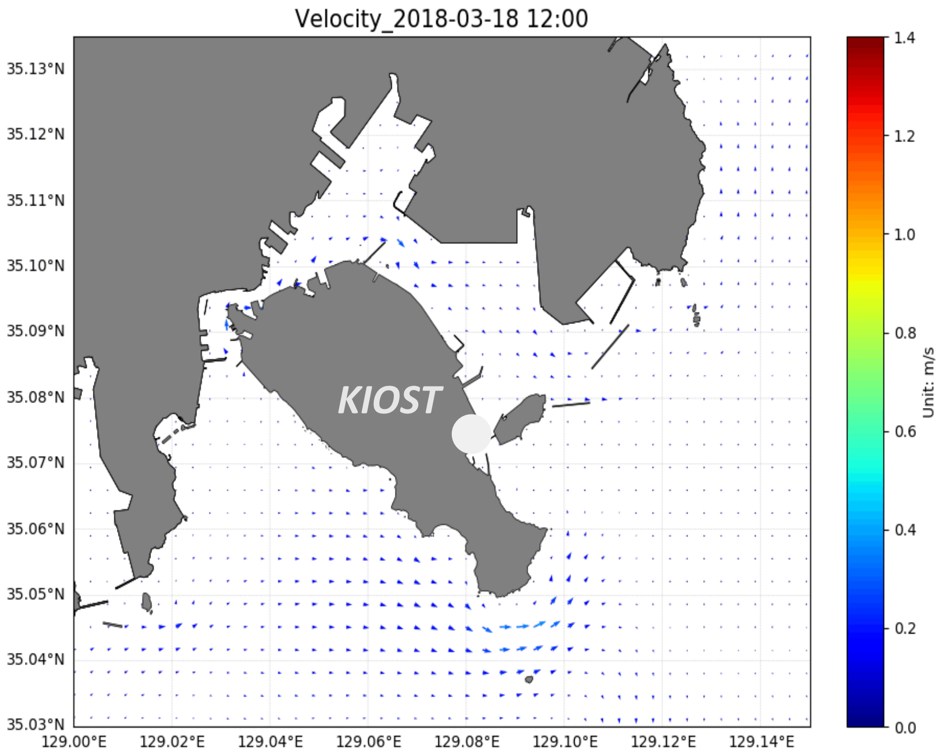
| | Model | | Domain | Horiz. Resol. (No.) | Vertical layer | DA | | I.C./B.C. | Bathymetry | Production freq. | Products | Pred. Time (interval) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Scheme | Data | | | | | |
| Ocean Circulation | TELEMAC (Coastal) | L3 | 124.12~130.33°E 32.50~38.67°N | 4 km ~ 300 m (> 10 M node) | 40 (Modified sigma) | - | - | WRF, MOHID L3 results | GEBCO + KHOA bathy+ Korbathy (1/120°) + etc | 1 / day | temp., sal., current, elevation, etc | 72H(1H) |
| | | L4 | 124.50~130.13°E 32.92~38.54°N | 500 m ~ 10 m (> 10 M node) | | | | WRF, HYCOM/MOM5, FES2014 | | | | |



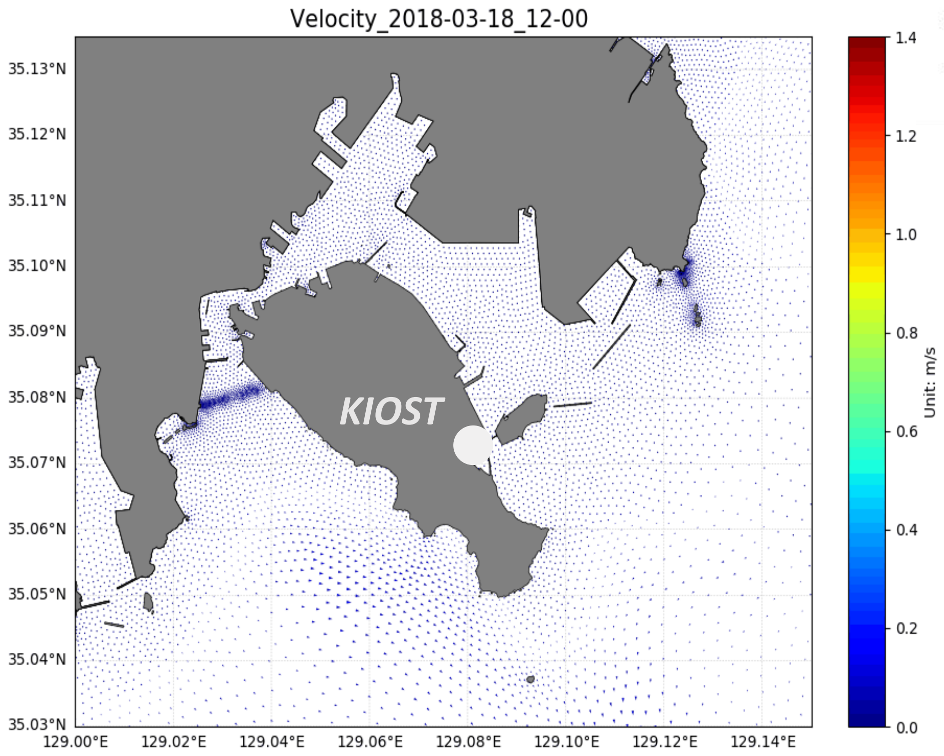
# 2.2 KOOS 2 Overview (2018 - 2022)




**Coastal KOOS (MOHID)**




**Unstructured KOOS (TELEMAC)**



# 2.3 Korea Ocean Observing and Forecasting System

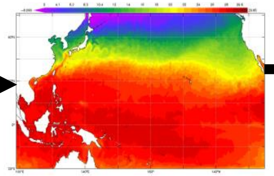
Input Data → Ocean Circulation Models → Forecast Data Services

**External Input data**

- Local UM
  - Korea Meteorological Administration
- NCEP GFS
- HYCOM
  - Consortium for Data Assimilative Modeling

**Regional Model(1)** → **Subregional Model (5)** → **Coastal Model (9)**

Regional Model:
- N. Pacific (28km)

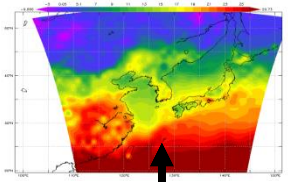


Subregional Model:
- East Sea (3km)
- YES1 (9km)
- YES2 (3km)
- South Sea (1.5km)
- West Sea (1km)
- W.S. Sea (1km)

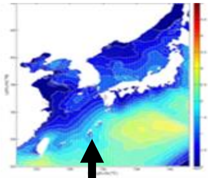
Coastal Model:
- Busan(500m)
- Ulsan(300m)
- Yeosu(300m)
- Busan Newport(100m)
- Incheon(200m)
- Daesan,Pangtak (200m)
- Gunsan(250m)
- Pohang(300m)
- Mokpo(250m)

**Weather Forecast Model (2)** → **Wave Model(1)**

- WRF (20, 4km)



- WW3 (9km)



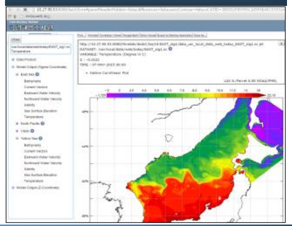
**SAR Model(1)**

- MOHID(9 km)

**Forecast Data Services**

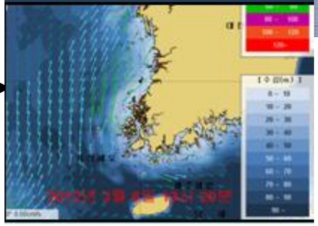
Intranet Data Services


Intranet Data Display



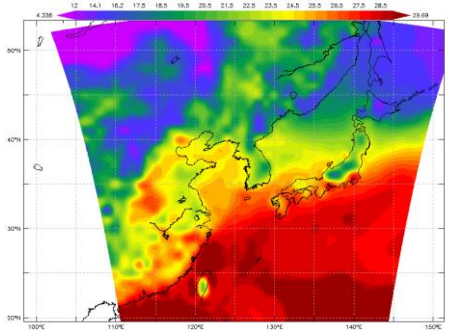
Internet Services

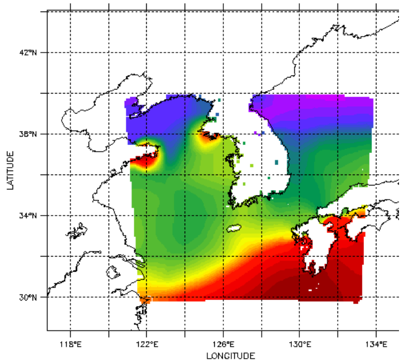
KHOA's Display Software



# 2.3 Korea Ocean Observing and Forecasting System

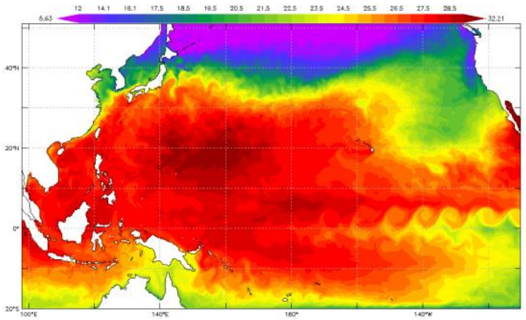
## Weather Forecast Model

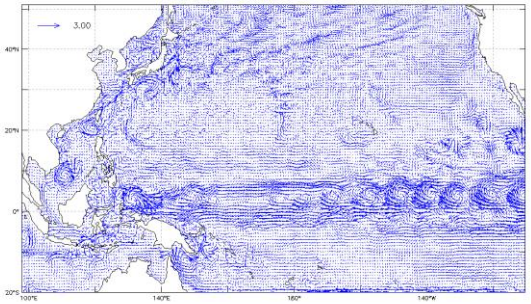




- WRF
- Horizontal resolution: 20 km, 4 km
- Vertical layer: 29

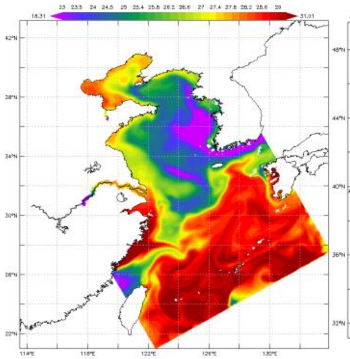
## Regional Model

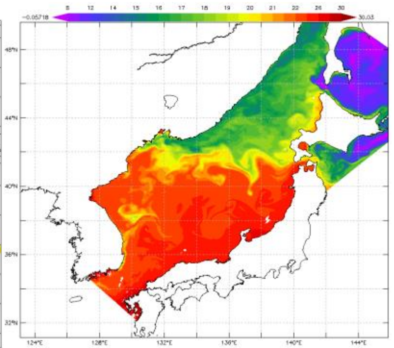


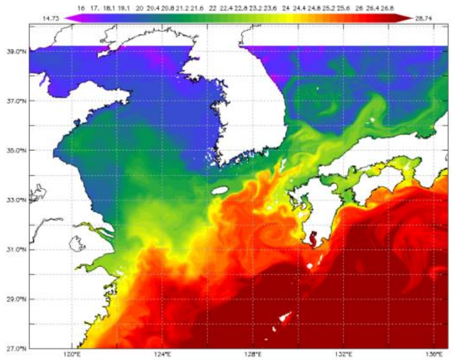


- ROMS, 4DVAR and EnOI
- Horizontal resolution: 1/4°
- Vertical layer: 30

## Subregional Model







- ROMS, EnKF and EnOI
- Horizontal: 1/12°;  1/32°
- Vertical layer: 30; 41

Korea Hydrographic and Oceanographic Agency

# 2. Users of KOOFS and KOOS

❖ Who are demanding and potential users in KOOFS and KOOS

- **Coast Guard**, Navy (defense)
- Governmental agencies (KHOA, KMA, KOEM, NIFS, etc.) Federal + Local
- Shipping (management) industry, **Port authorities**
- Marine leisure activities (marina, surfing, fishing, yacht, etc.)
- Information related Marine industries
- Universities and research institutes

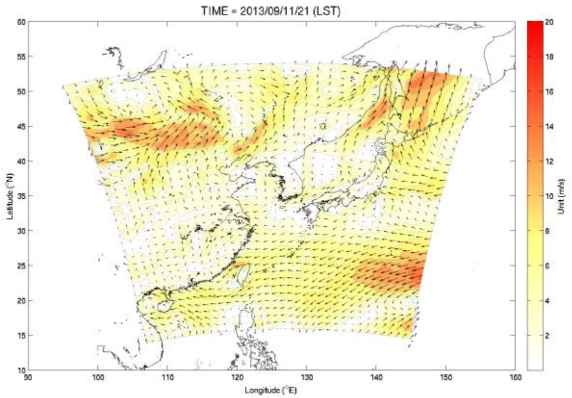
❖ Product (priority) in KOOFS and KOOS

- **Inundation (sea level, wave, storm surge)**
- Search And Rescue (Coast guard)
- Defense (Navy)
- Red tide
- Oil Spill

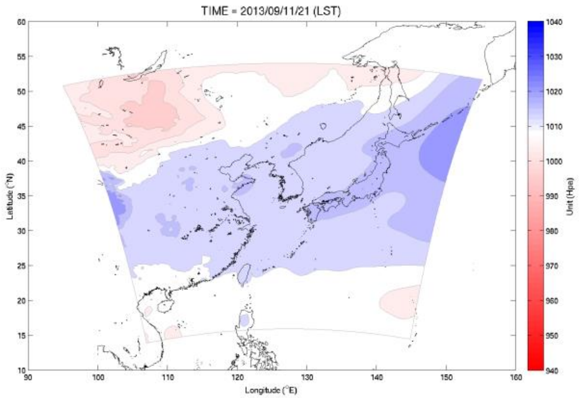
# Storm surge inundation, flood gate management

## Storm surge

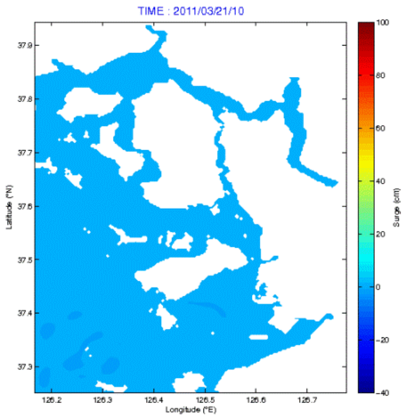
**Wind**



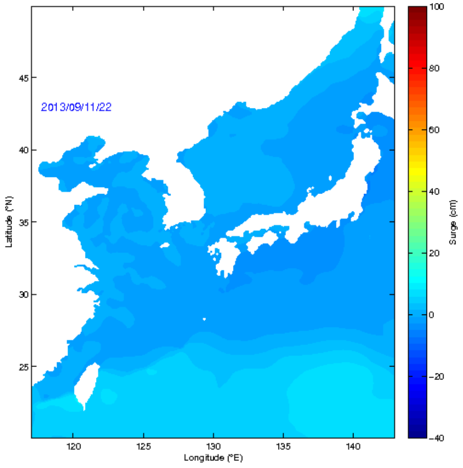

**Pressure**



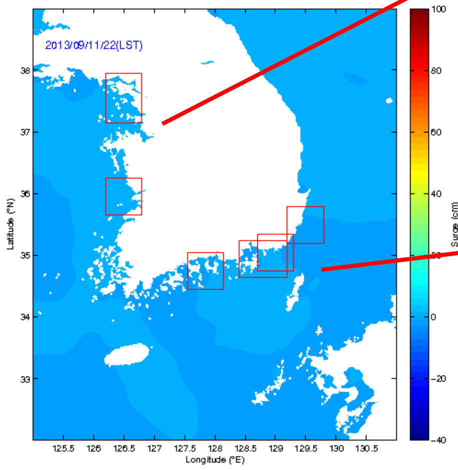

**Incheon**



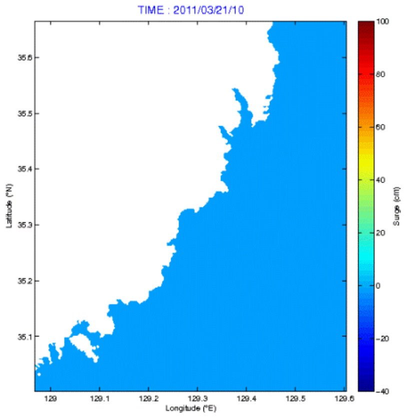

**Storm surge (wide area – 9Km)**




**Storm surge (local area – 2Km)**

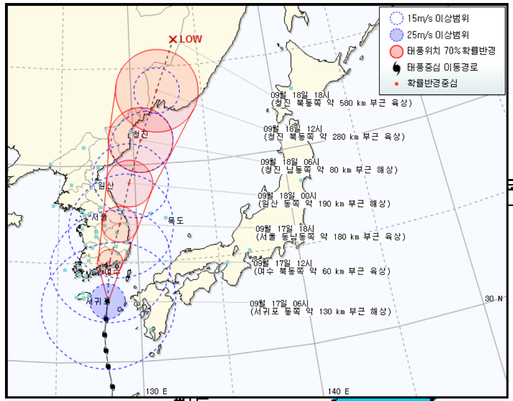


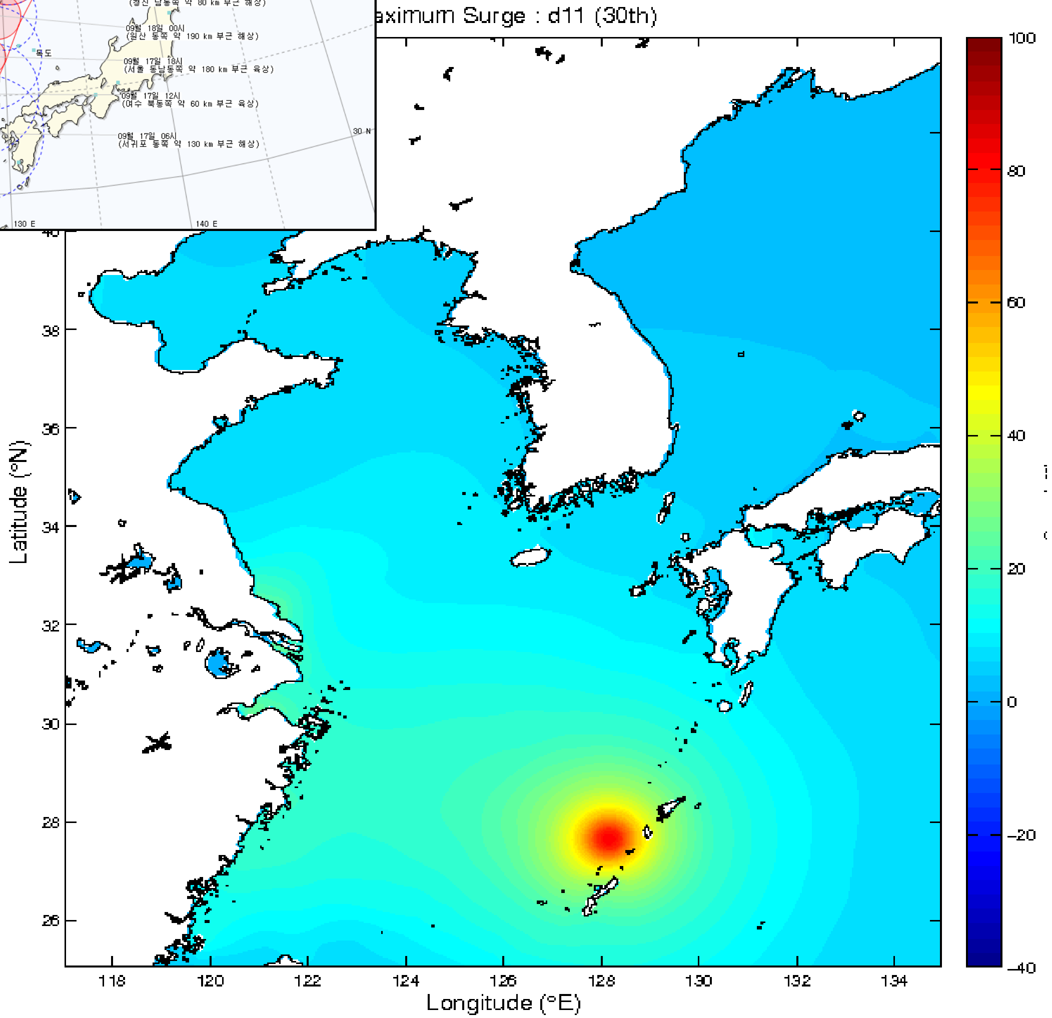

**Busan**

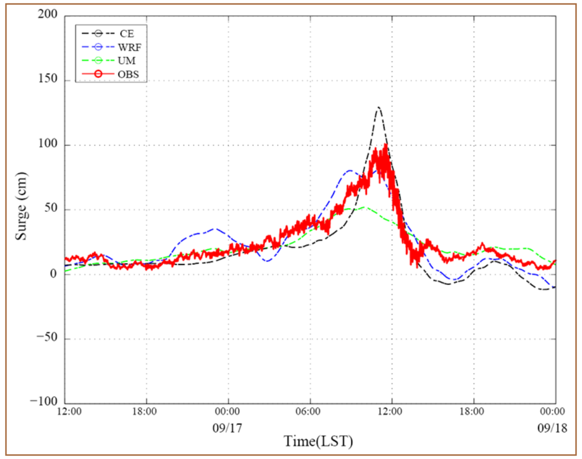


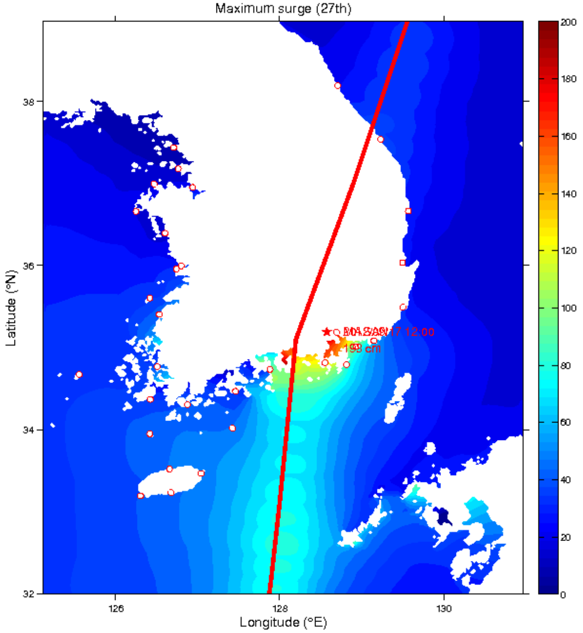

300m

# Storm surge inundation, flood gate management





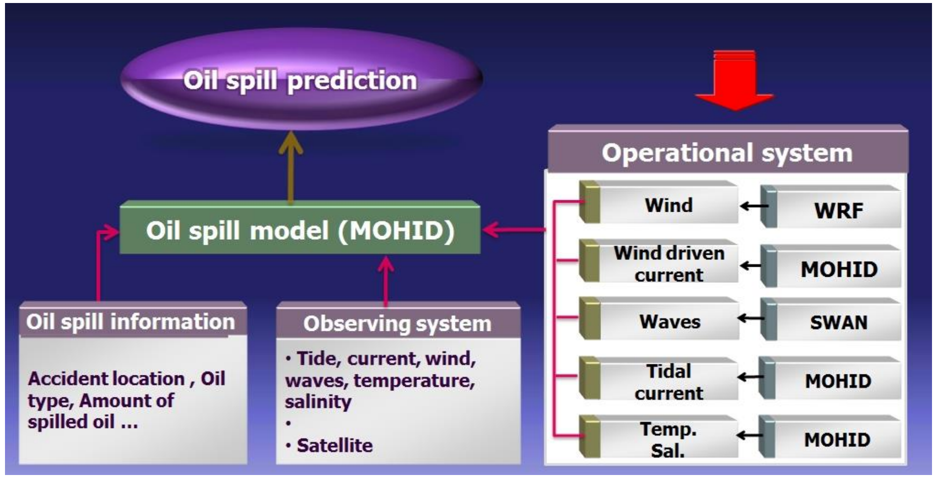



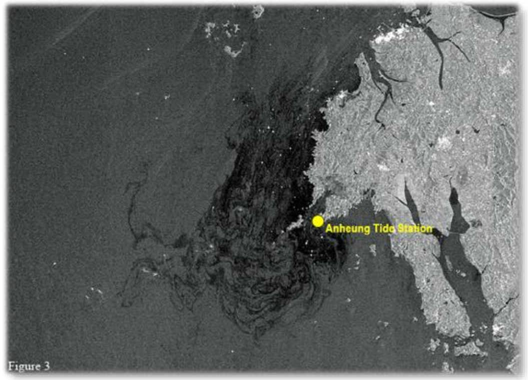




**Typhoon "SANBA" (1216)**

# Oil Spill Model and Response System



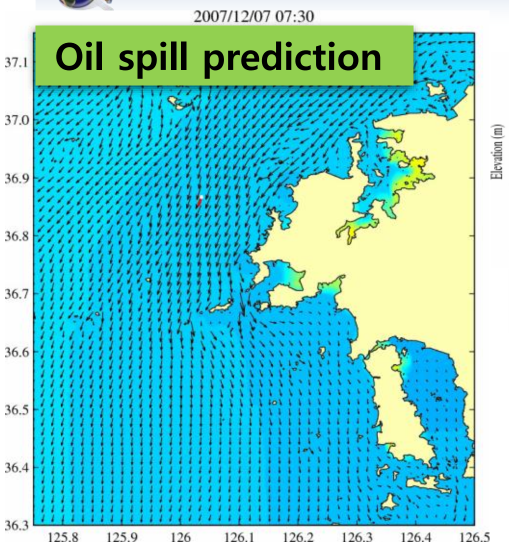


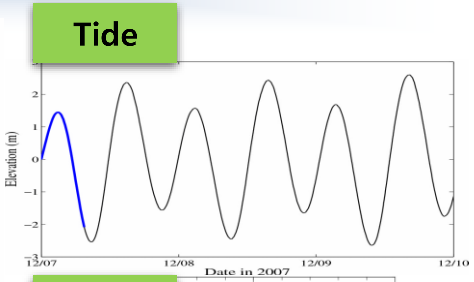



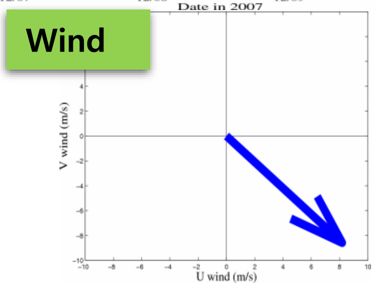


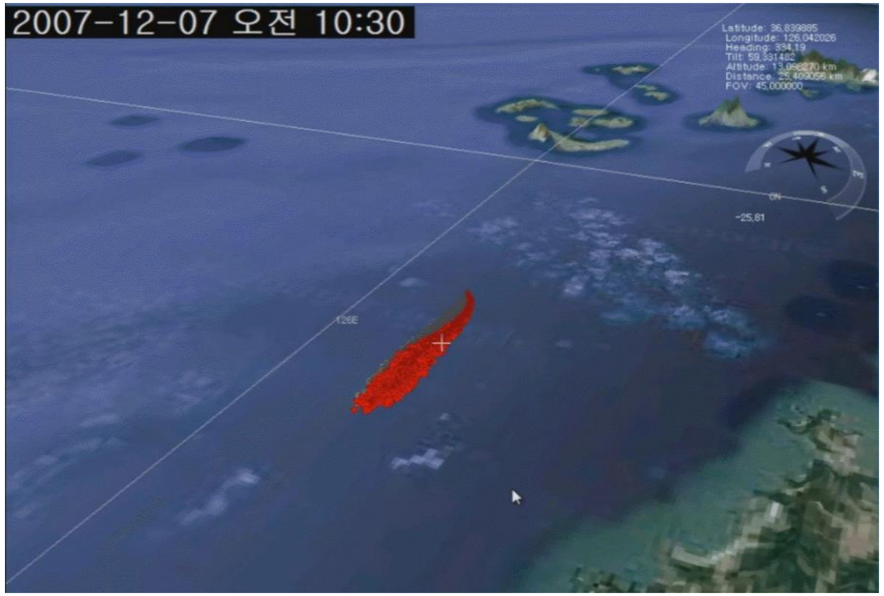
Tanker *Hebei Spirit* leaking crude oi

## Hebei Spirit Oil Spill (Dec/07/2007)

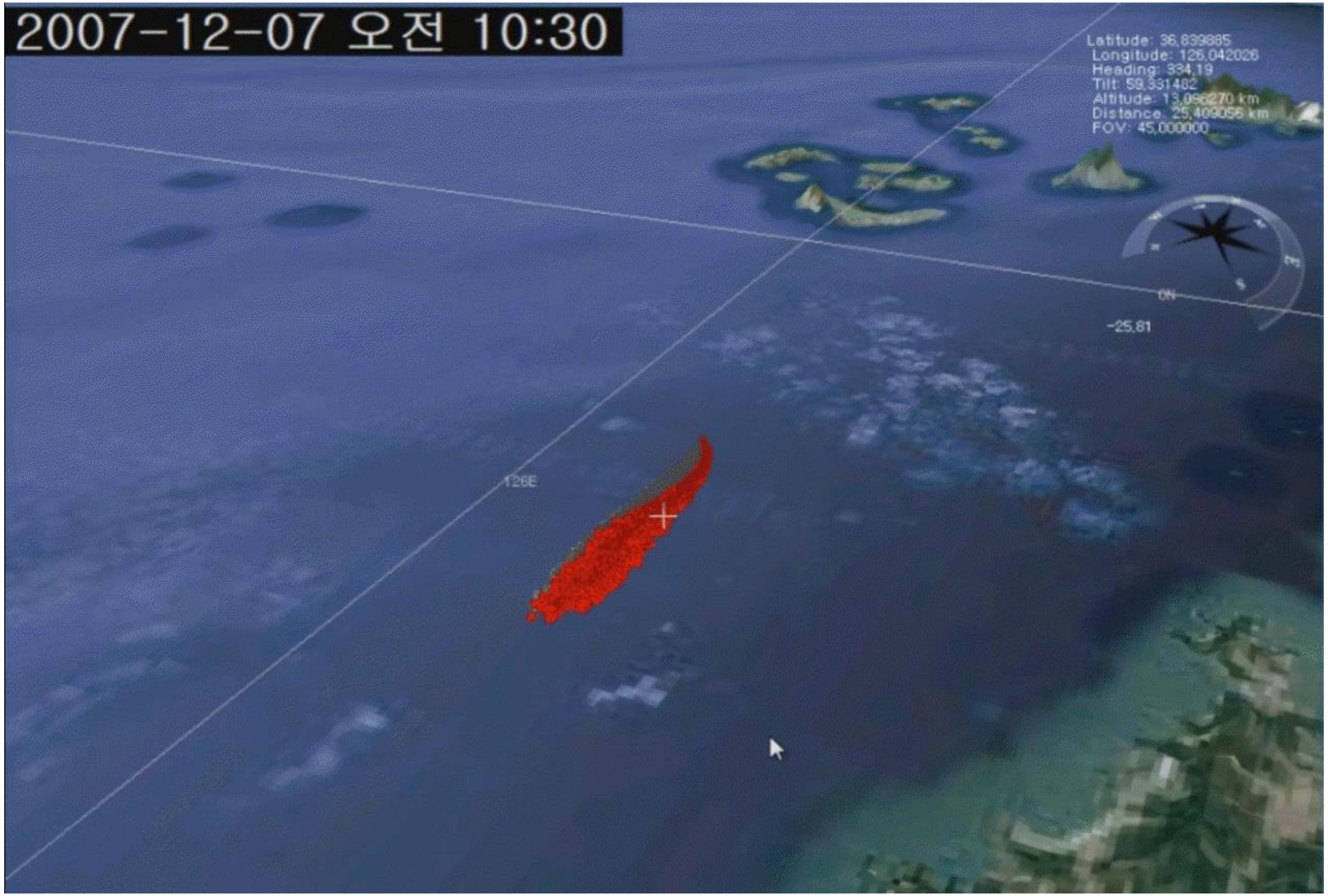


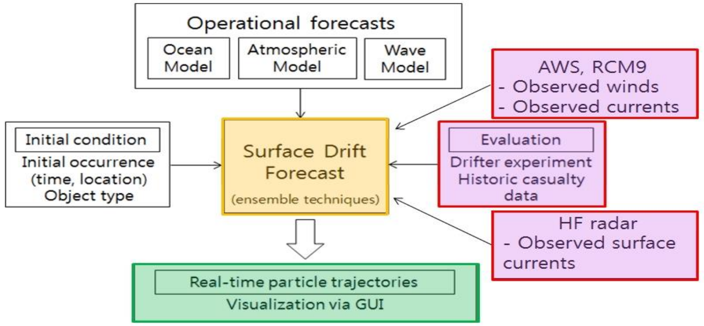



# Oil Spill Model and Response System



OceanPredict '19

# Search & Rescue (SAR) Model and Response System



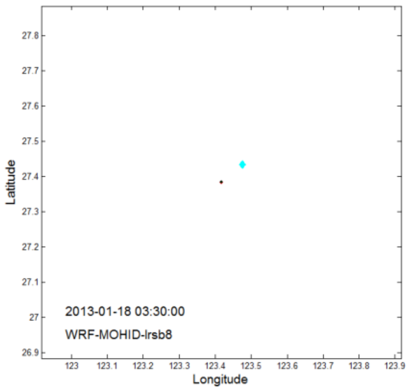

**Stage 1: Establishment of surface drift model (Leeway model)**

**Stage 2: Drifting buoy field experiments and model verification**

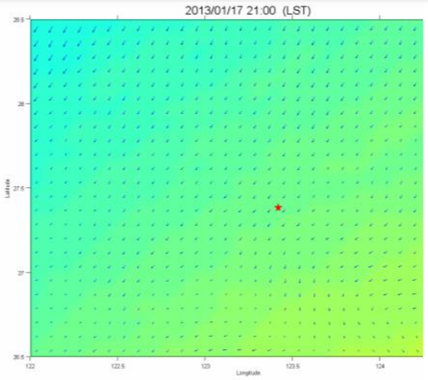
**Stage 3: Development of SAR/Oil-spill Viewer**

SAR support to Korea Coast Guard in maritime accident near Jeju Island (Jan/21/2013) - F/V Hwang-Geum sinking

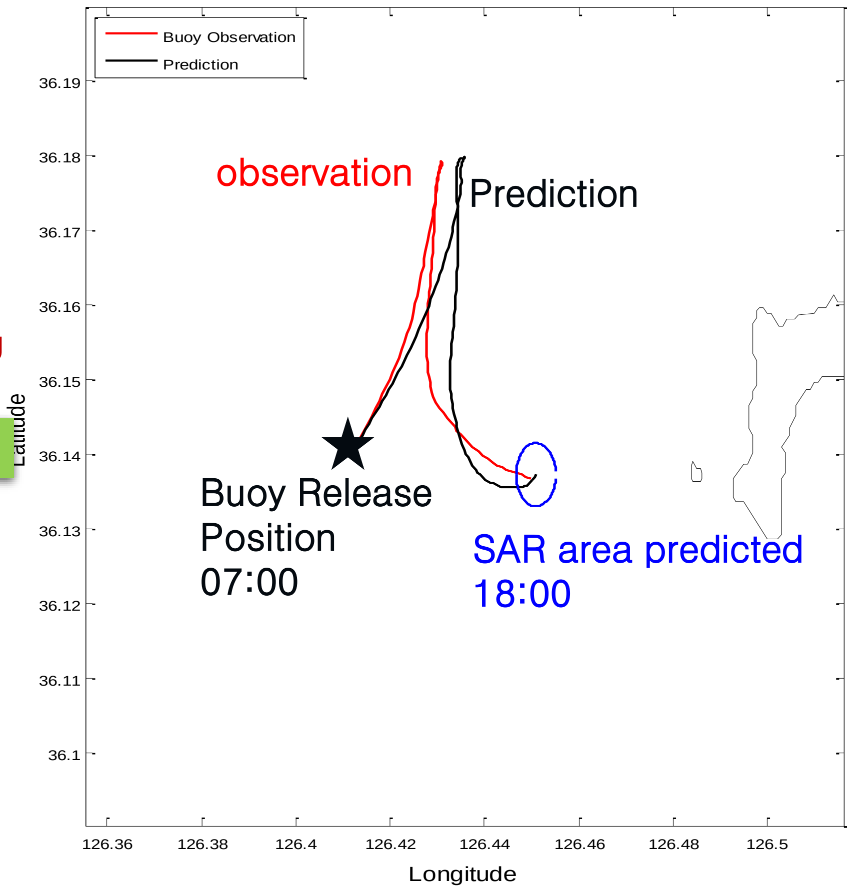
**SAR prediction**




**Surface current vectors**

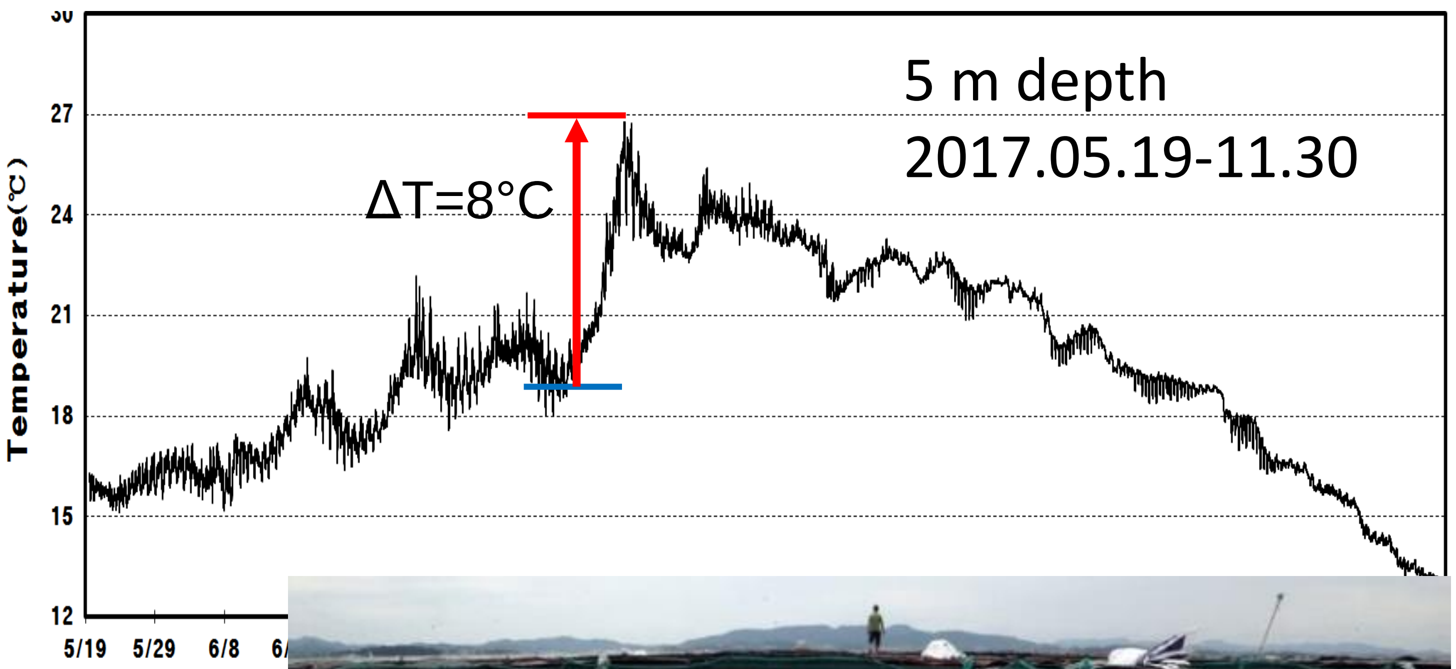


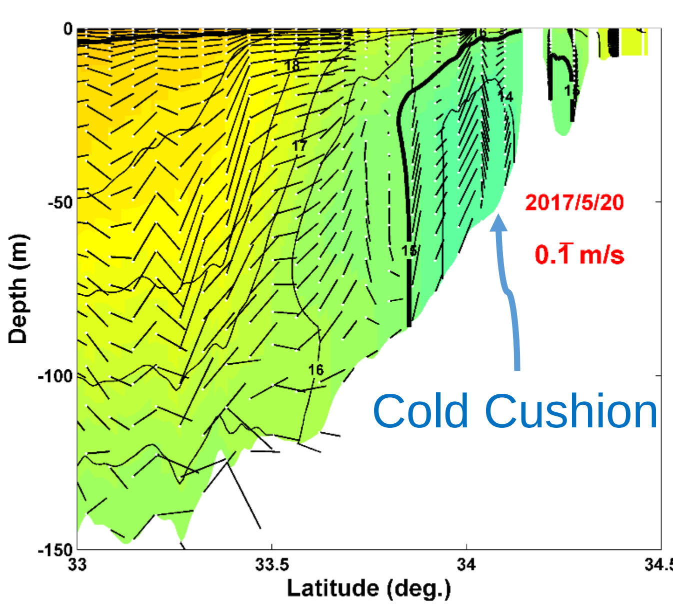

Field experiment (May 25, 2011)

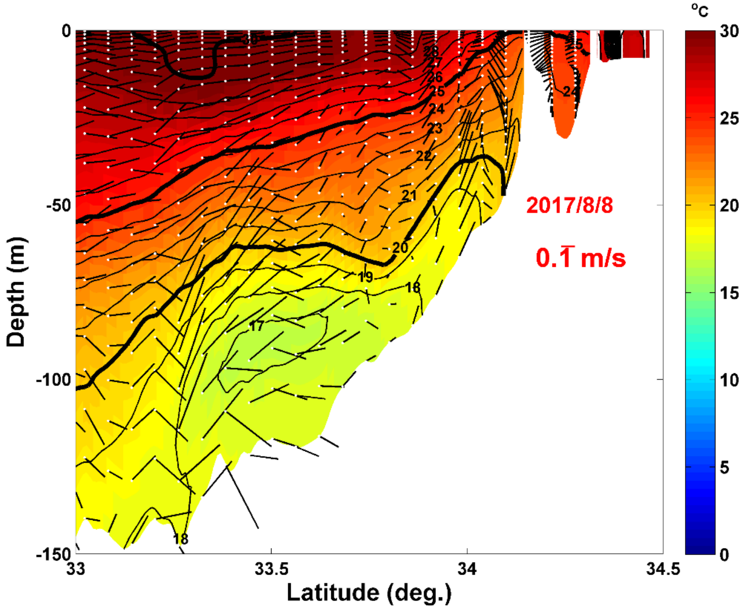


ceanPredict '19

# Fishery management

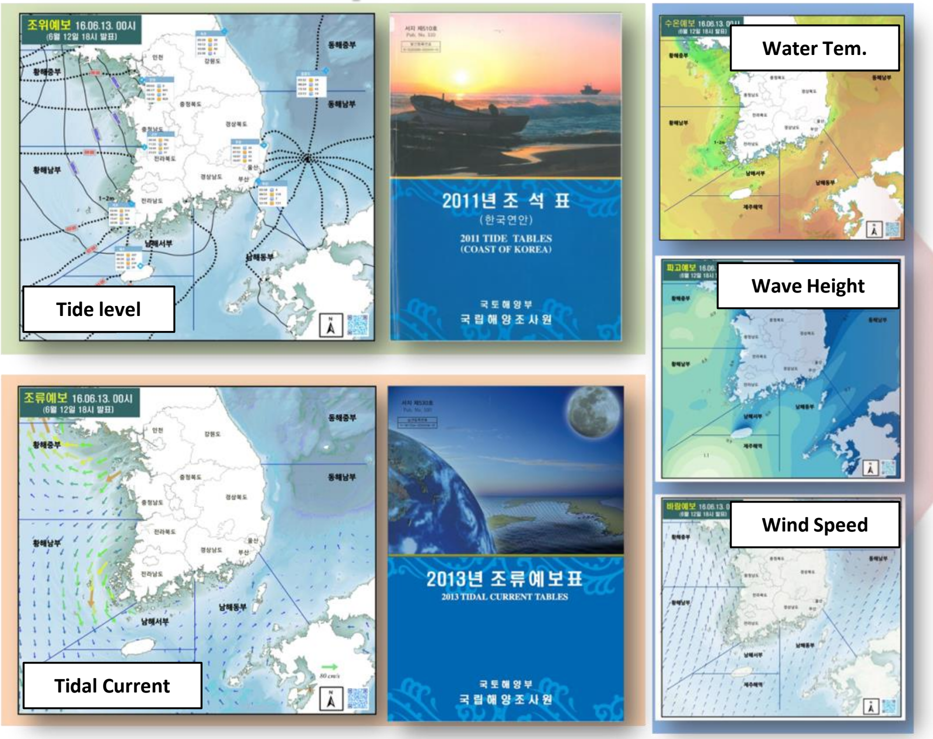



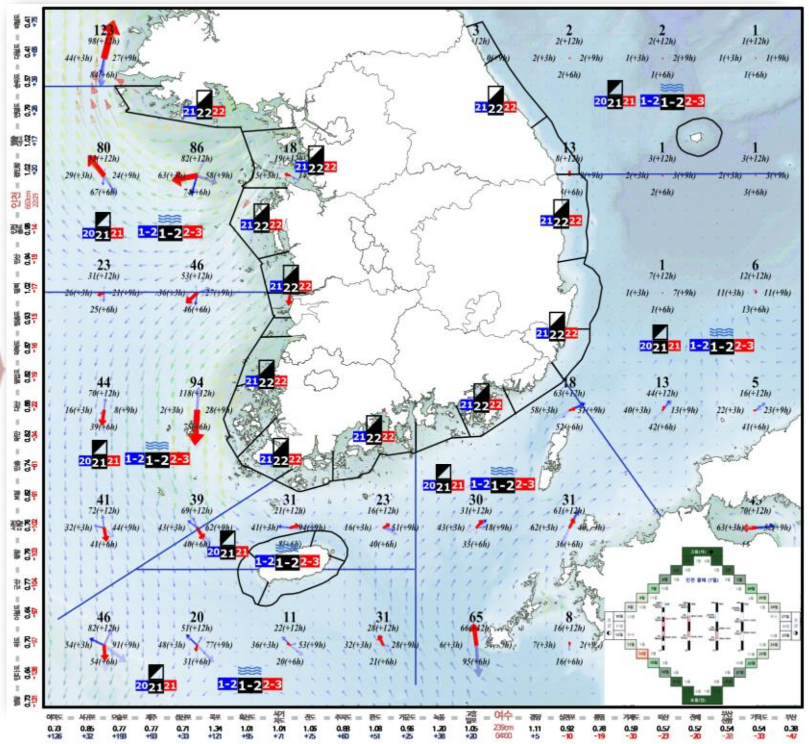

# Information services



Information services **transforming** ocean predictions to information for users (**data** to **information**)

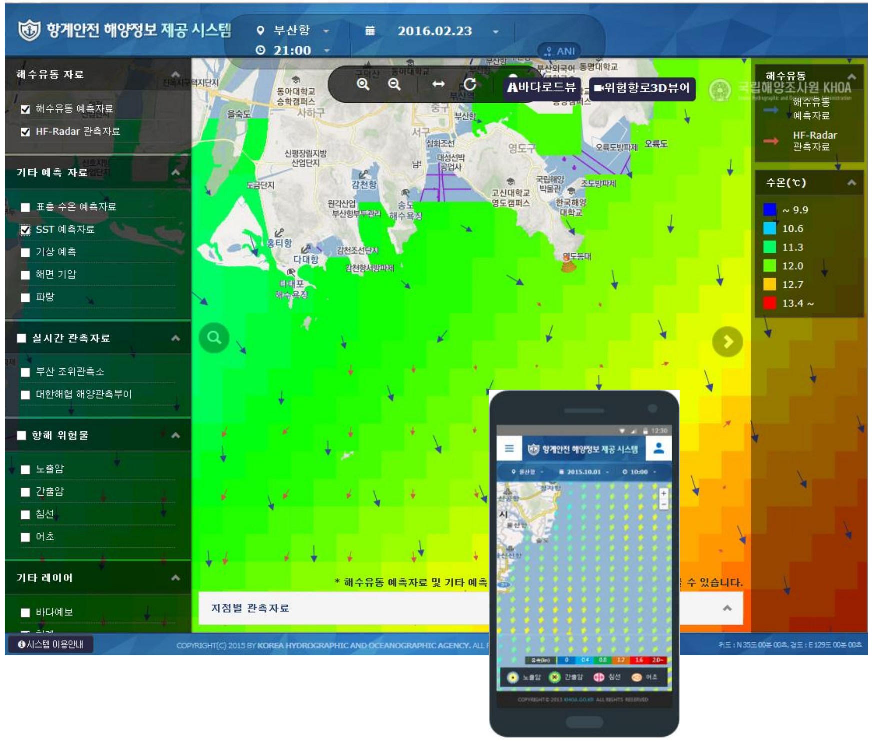
## All the Oceanographic Forecasting Information on a map

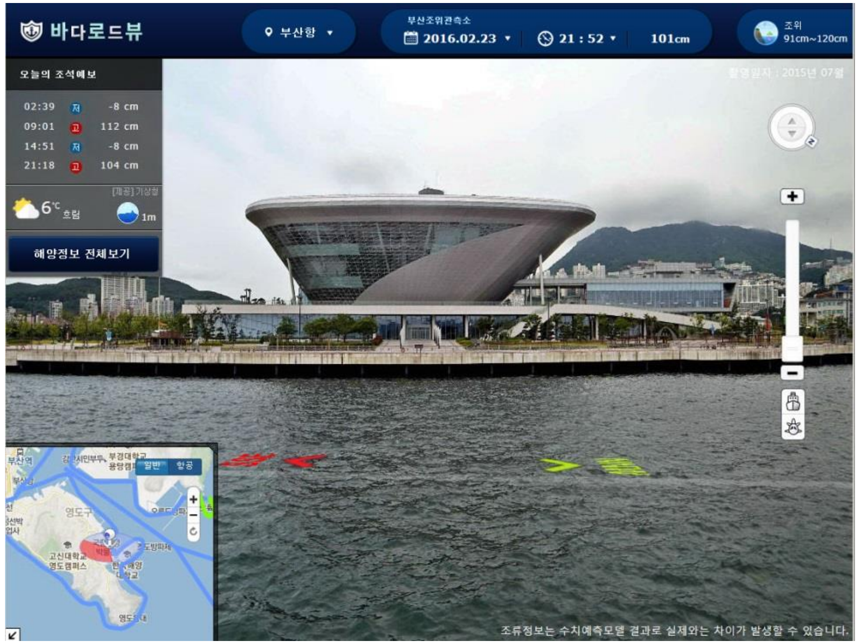


## Ports Oceanographic Information System(POIS)

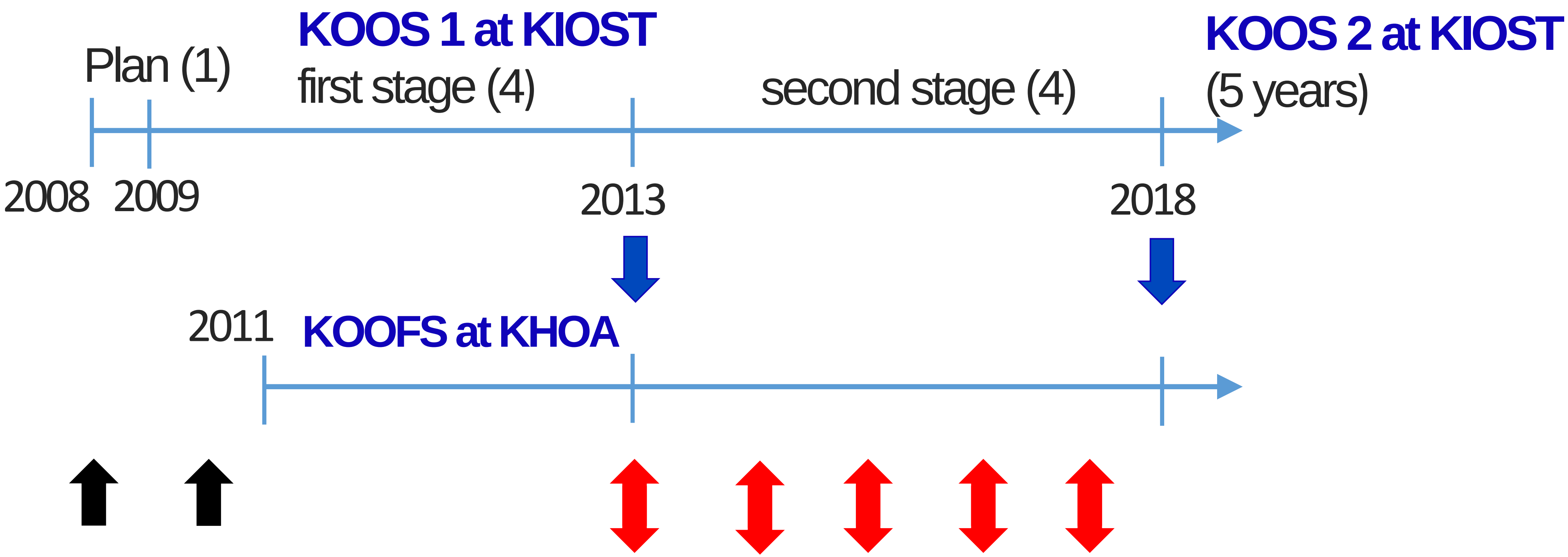
- Providing the ocean information for marine safety and efficient port management
- POIS Webpage (http://www.khoa.go.kr/pois)
- Baroview Webpage (http://www.khoa.go.kr/baroview/)



# 2. KOOFS and KOOS

## Timeline of Korea Ocean Forecasting Systems: KOOS and KOOFS




**GODAE summer school, Final GODAE Symposium (2008),**
**GOV summer school (2010, 2017)**
GOV COSS-TT workshop (2013-), GOV DA-TT workshop (2015-)
Sharing "best practices in prediction" with NMEFC, Met-Office, Bluelink, NOAA, MRI, ….

# 2. Future direction of KOOFS and KOOS

## What we are planning to do in the next years.

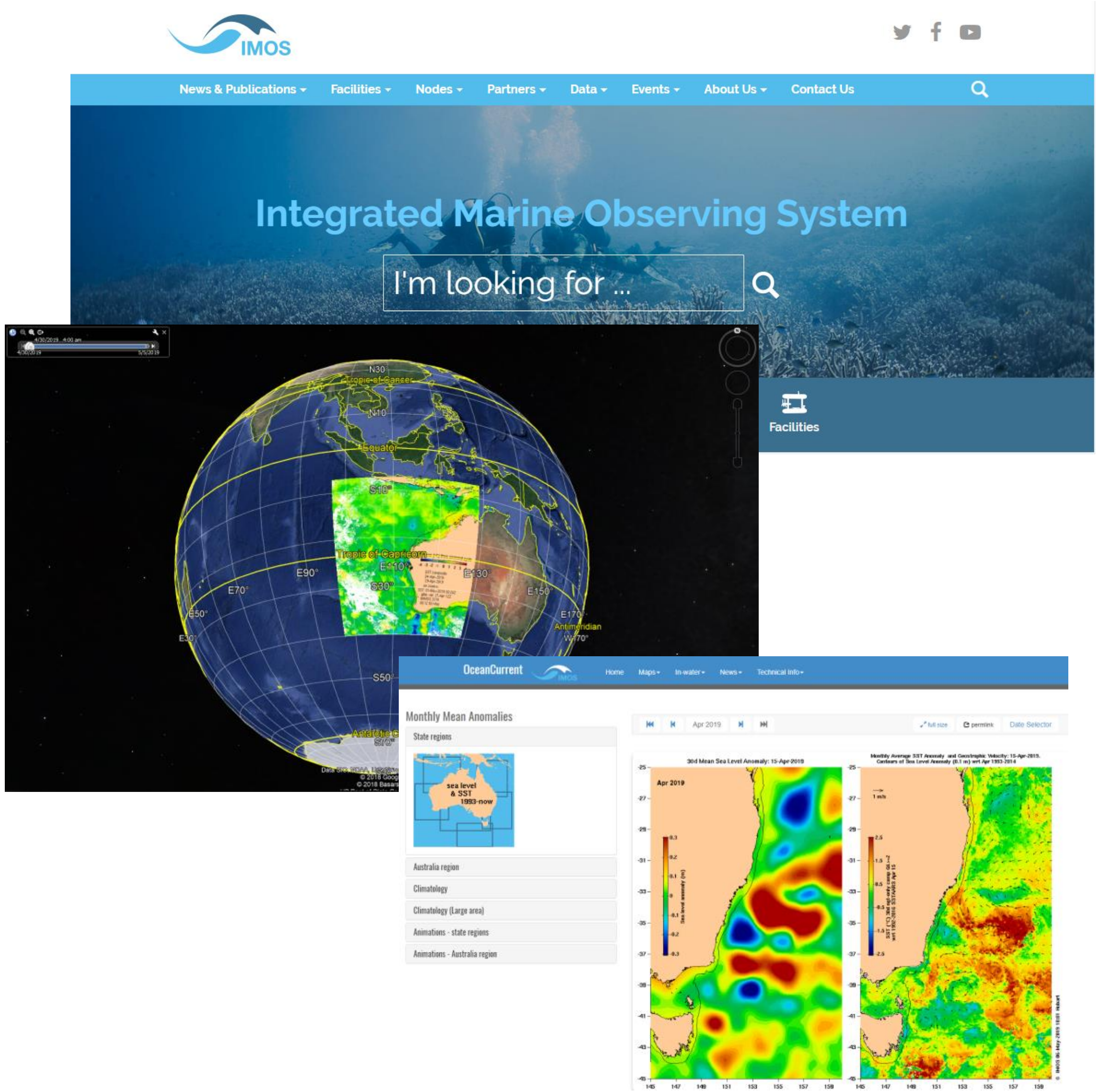
1. Setup a global prediction system based on MOM6 (1/12º) and unstructured grid models for coastal seas
2. Expanding to biogeochemistry (such as red tide issue) and sea ice
3. High-resolution fully coupled modeling (Atmosphere + tide + wave + current + land + river + sea ice)

4. Recruiting next generation: summer/winter school, DA, modeling
5. Assimilation of SSH and HF radar data (Limited Performance). System biases
6. Domestic Coordination Meeting with other groups in Korea
   - Korea Meteorological Administration and NIFS
7. Coordination with observation groups (to have more data)
   - Hydrography (NIFS, KHOA), Ocean Station Data, KOEM
   - Long range HF radar data - Satellite (geostationary satellite data)
8. Sharing "best practices of prediction" with other group.

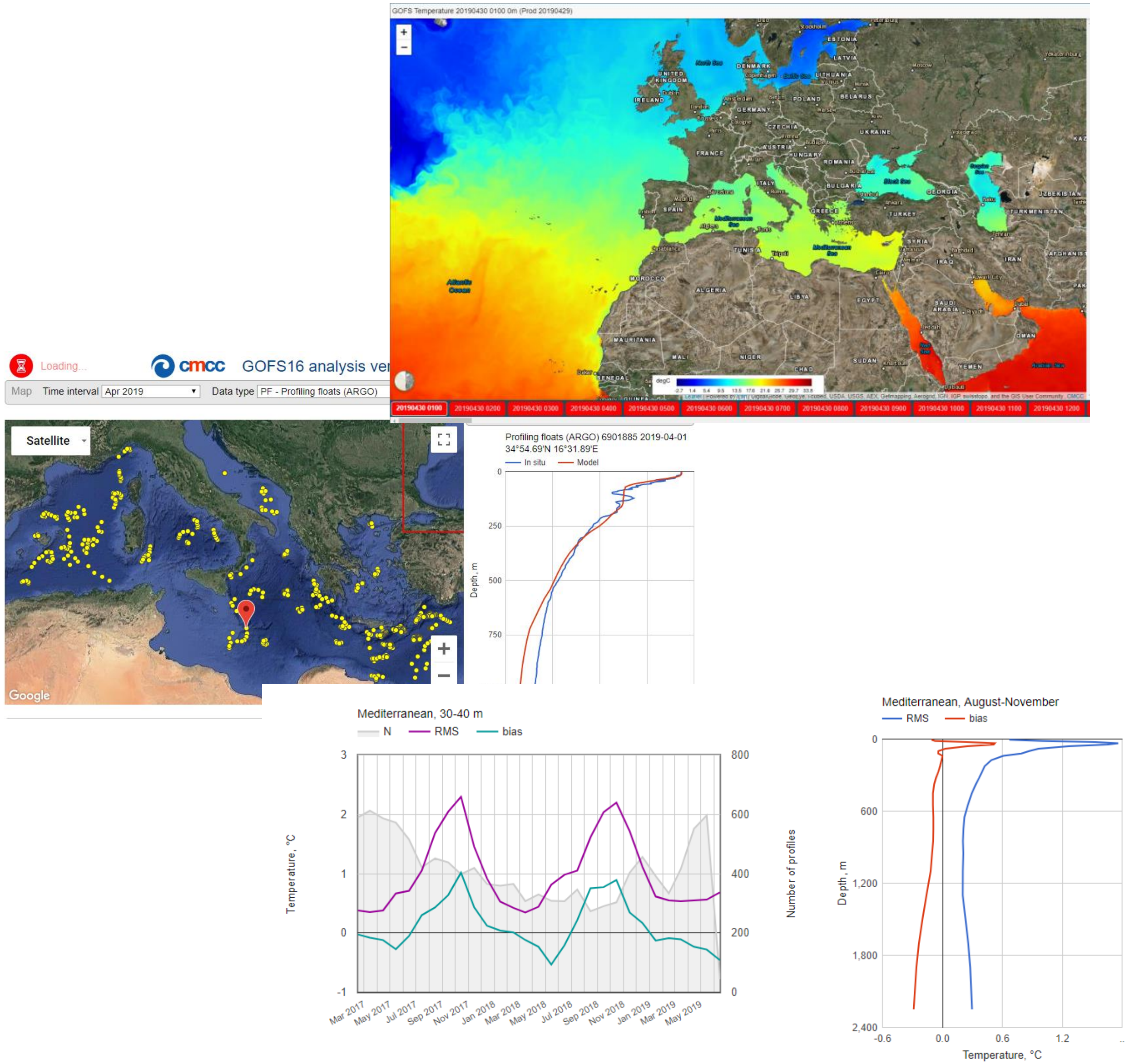
OceanPredict '19

# Capabilities throughout the world

## http://imos.org.au/

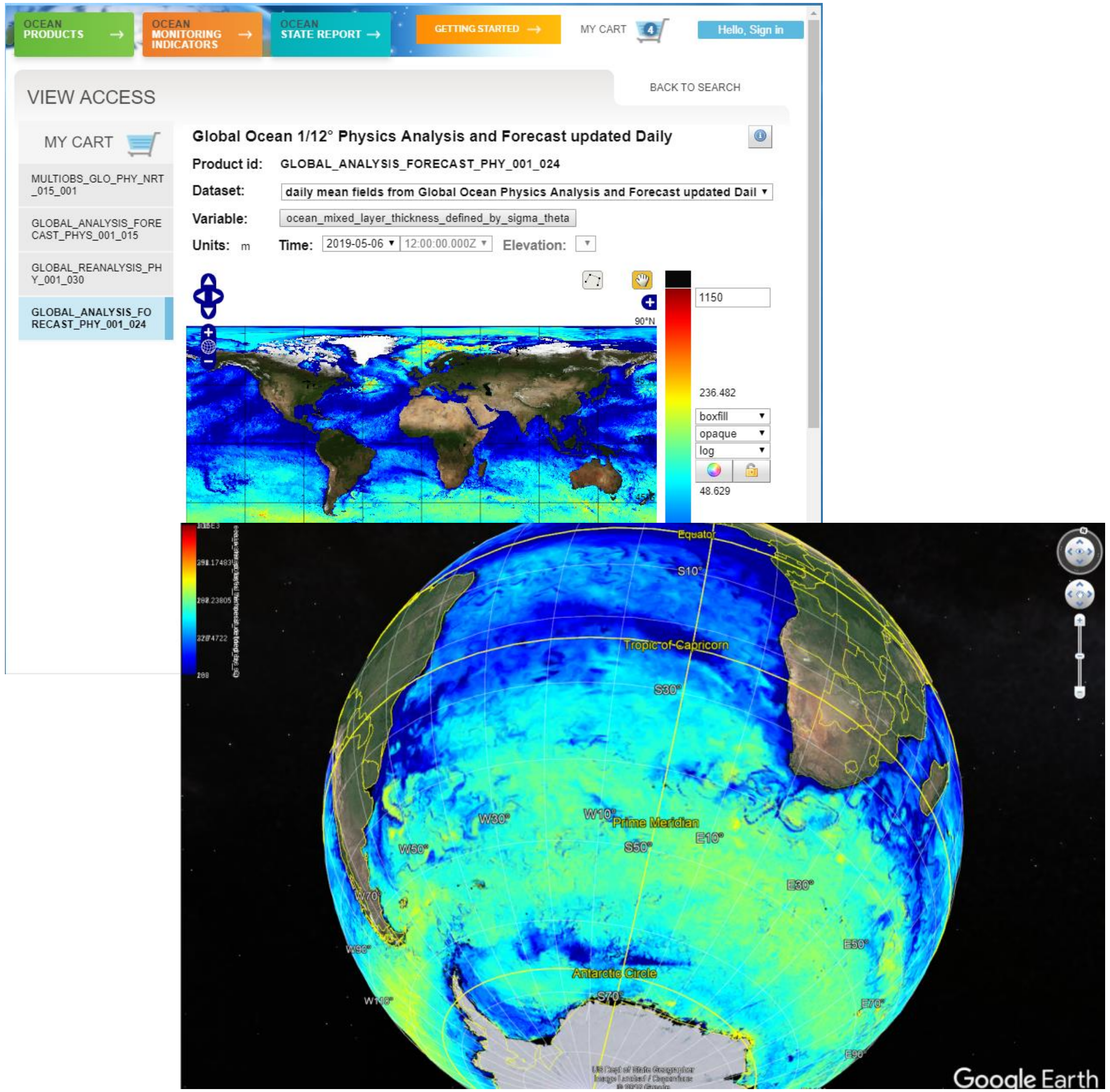



## http://gofs.cmcc.it/

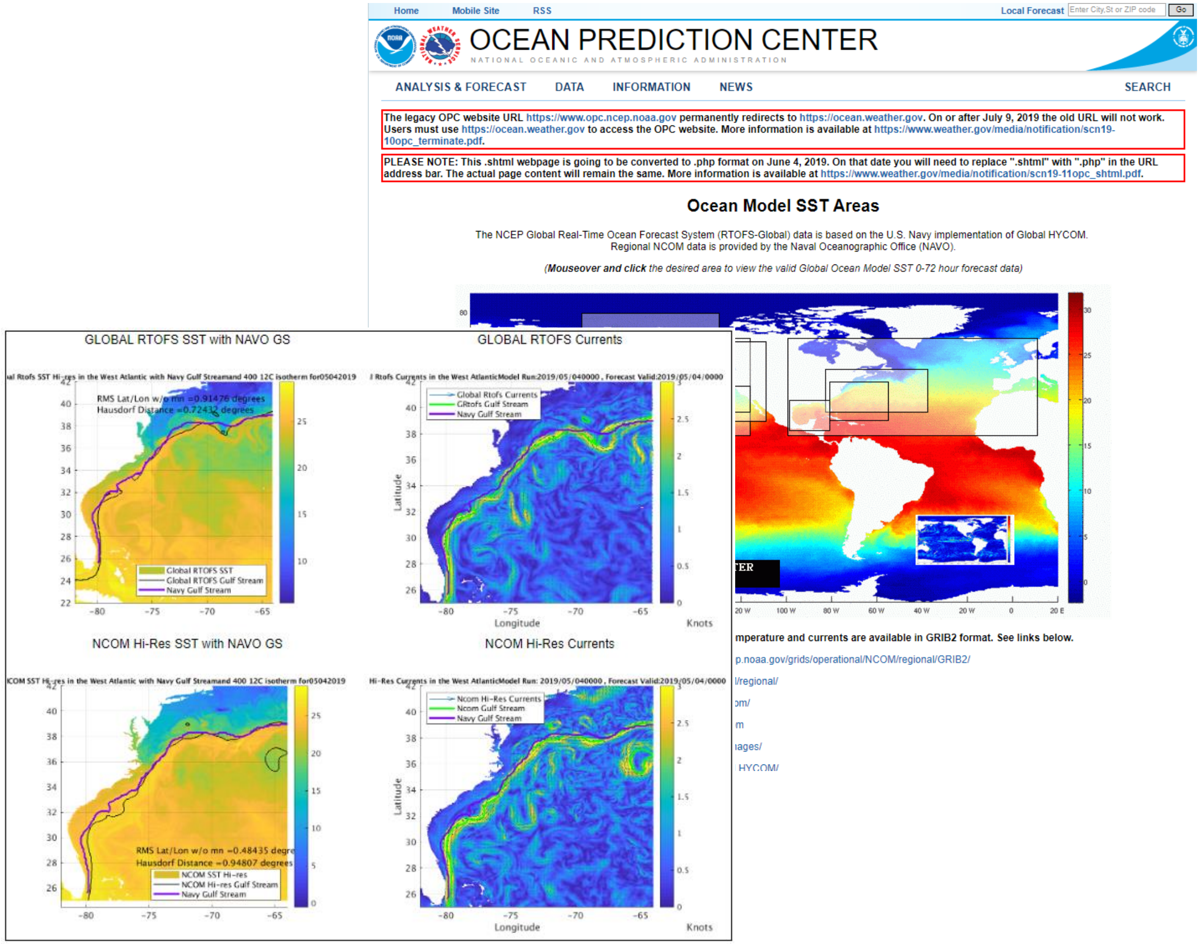


# Capabilities throughout the world

**http://marine.copernicus.eu**

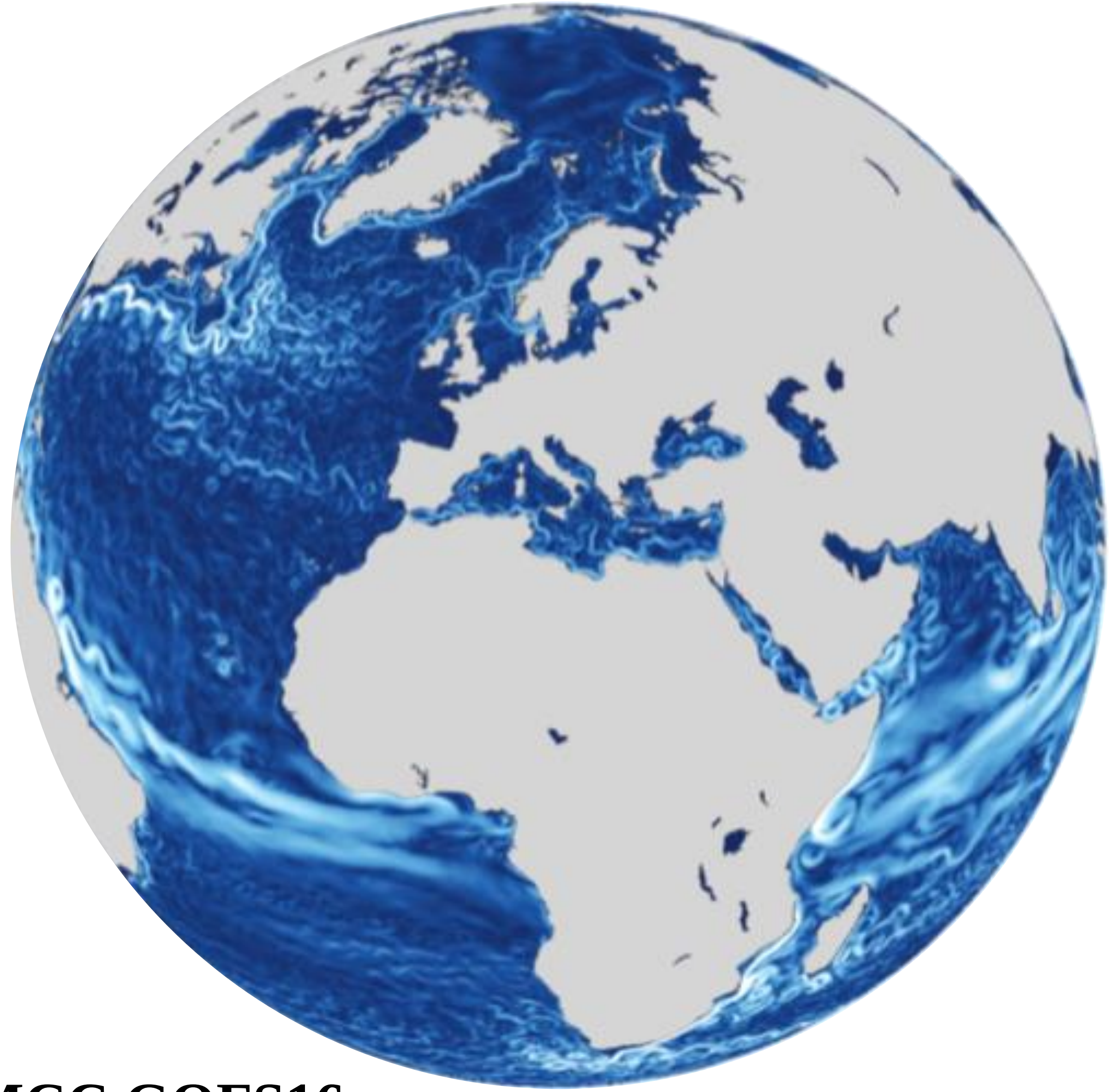



**https://ocean.weather.gov/OceanProd.shtml**



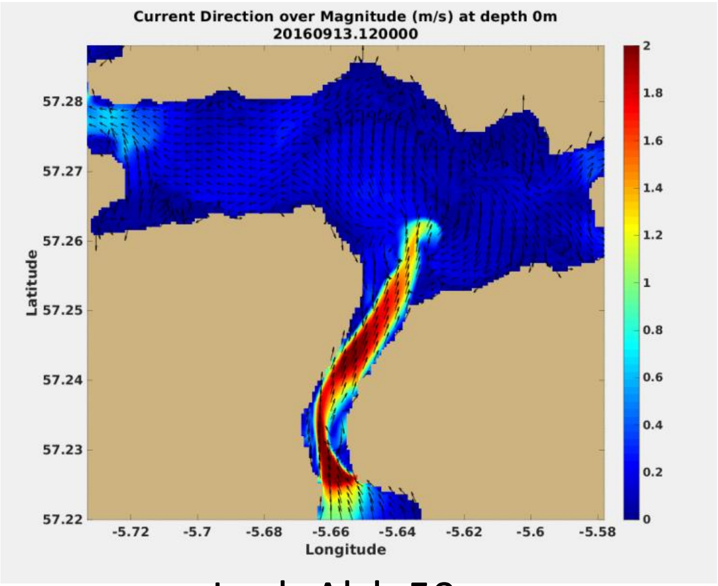
# Global starting point

| | | Horizontal resolution |
|---|---|---|
| Concepts | NEMO 3.1, WW3 | 1/4, 1/4° |
| CMCC | NEMO | 1/16° |
| TOPAZ | HYCOM | 12 km |
| FOAM | NEMO global | 1/4° |
| FOAM | NEMO regional | 1/12° |
| BlueLink | BRAN2018 | 1/10° |
| NCEP | RTOFS HYCOM | 1/12° |
| NCEP | CFS MOM4 | 1/2° |
| KOOFS | MOM5 | 1/24° |
| GOFS | HYCOM | 1/12 – 1/25° |



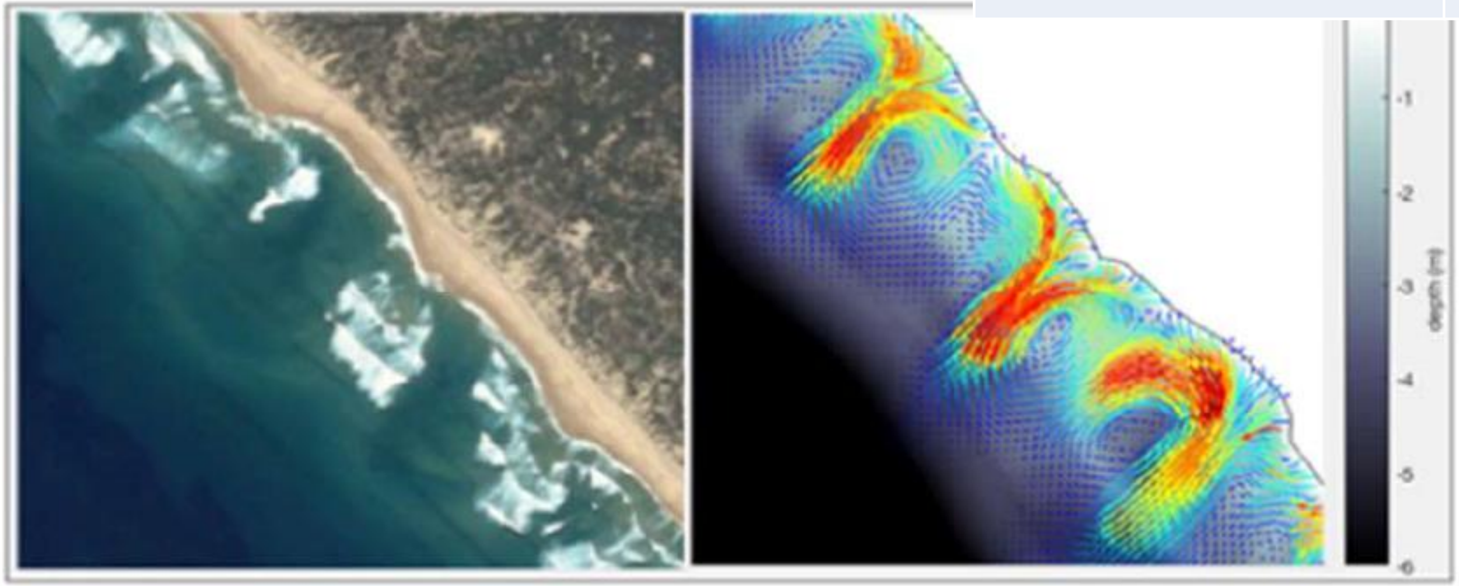
CMCC GOFS16

# Nesting to local forecasts




Loch Alsh 50 m

| | | Resolution |
|---|---|---|
| Concepts S Lawrence | NEMO 3.1 | 5 km |
| Surge | Dalcoast | 1/30° |
| FOAM | NEMO self-seas | 1.5 km |
| BlueLink | Roam, Roam-surf | |
| NCEP | HWRF / MPIPOM / HYCOM | 1/12° |
| Copernicus | NEMO | 1/24-1/32° |
| KOOFS | | 100 m – 3 km |
| COAMPS | NCOM | 10 m + |

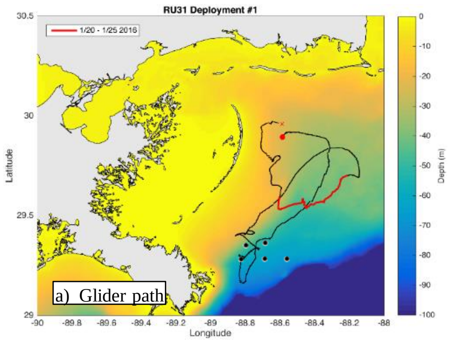


Example of ROAM-Surf rip current prediction. Left: satellite image of Gunnamatta Beach (Australia, Victoria); right: simulated rip currents at the same location, using the XBeach model at 10 m resolution.

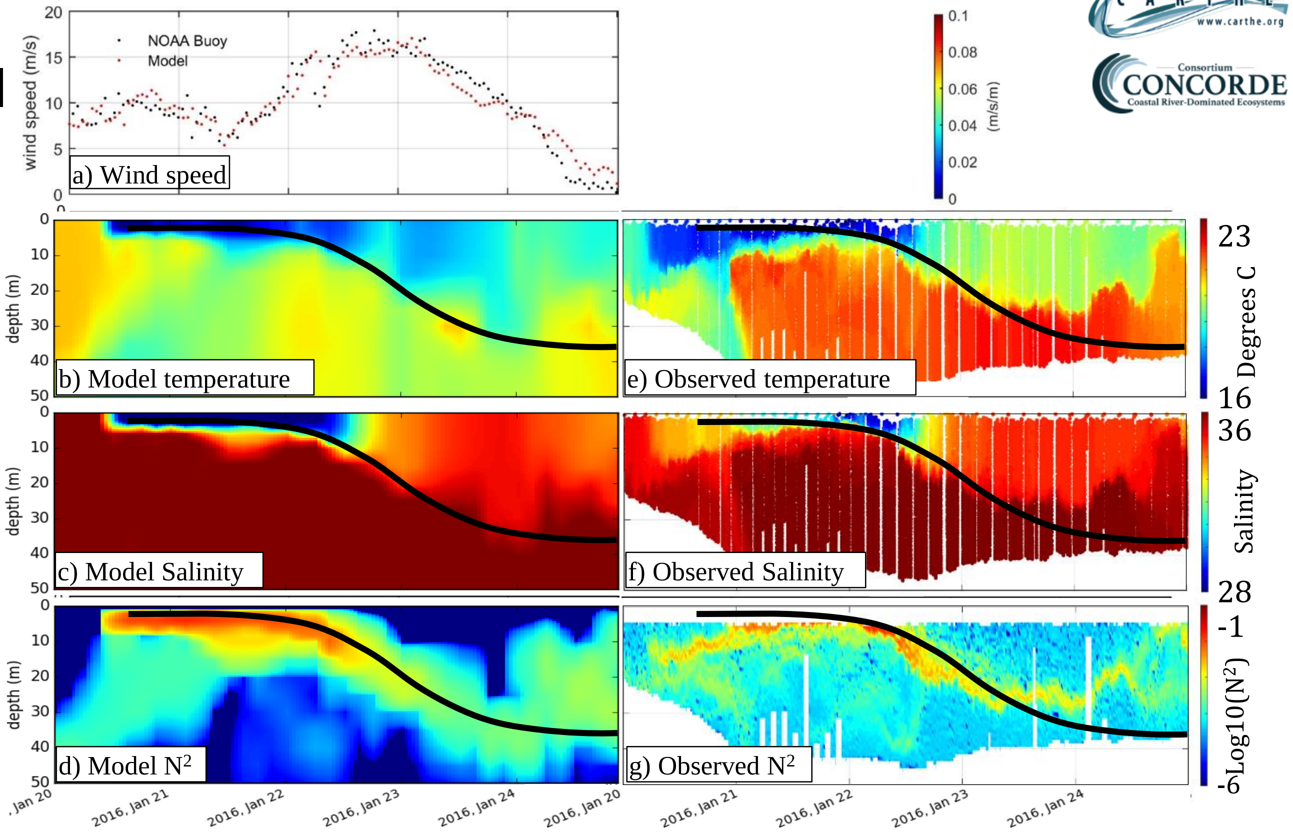
# Directions in ocean model representation

Near term
- Modern coding technology
- Horizontal resolution (surge)
- Vertical resolution
    - Vertical shear
    - Coastal fresh water
- Surface layer physics (Deep mixed layer, diurnal layer, frontal influence, submesoscale, step-layering,…)
- Confidence / uncertainty forecast by ensembles
- Model bias

Long term
- Structured vs unstructured applications
- Nesting vs local refinement in one grid
- Element degree vs element size (driven by computational architecture)
- Scale – adaptive parameterizations
- Computer architecture

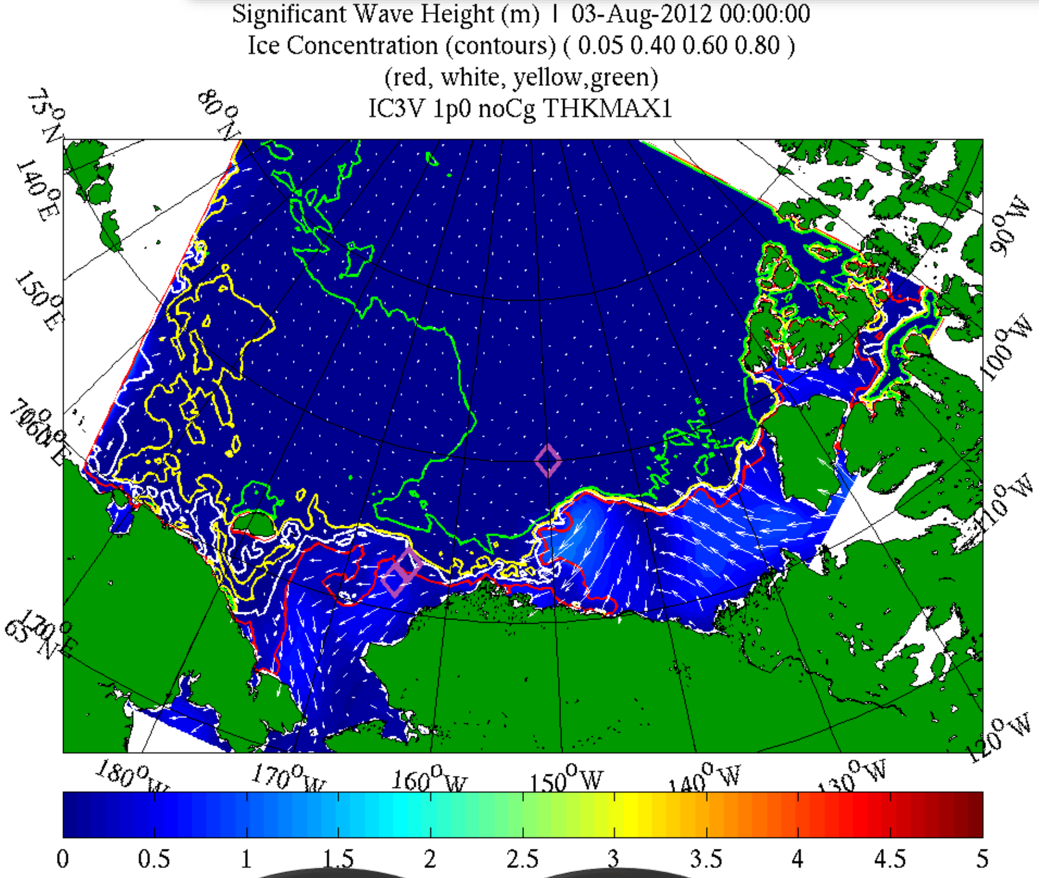


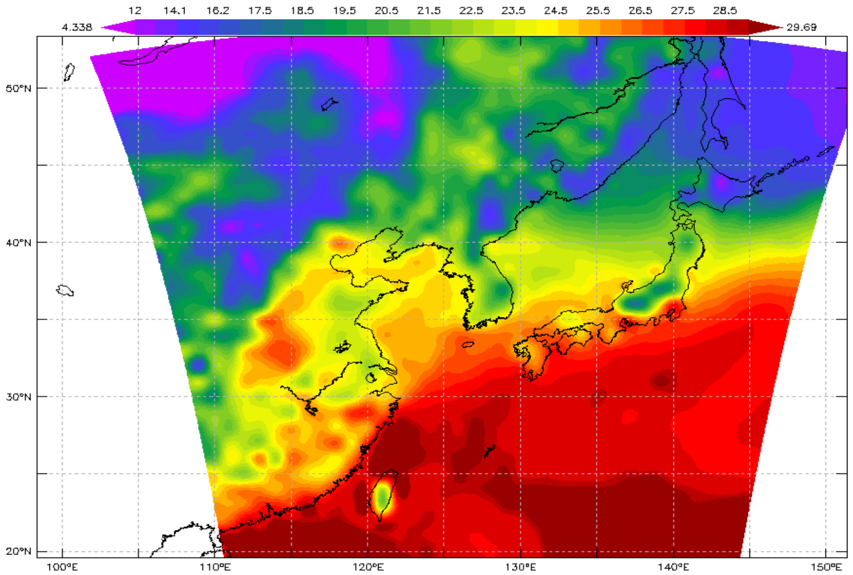

Line: Rutgers University Sea Glider
Red segment corresponds to time period below

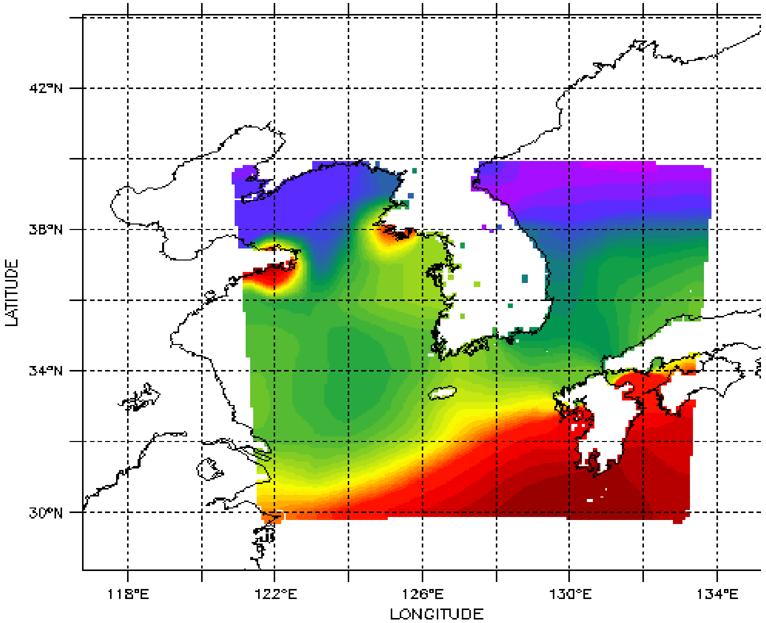


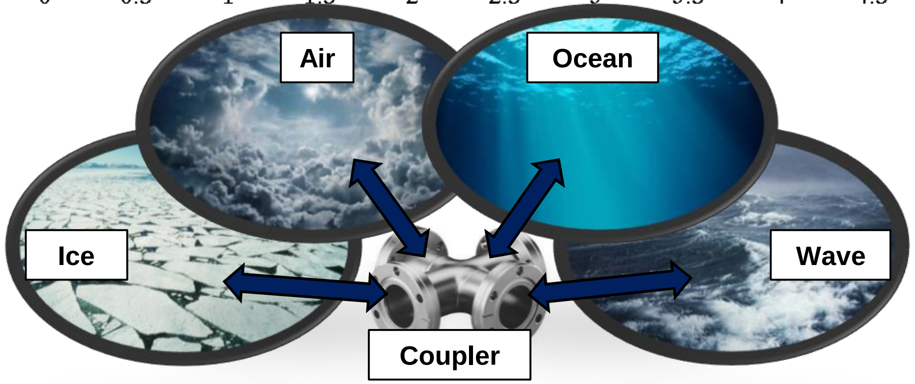

Jacobs, D'Asaro, Ozgokmen, Soloviev, Dean, Harcourt, Bracco, Haza, Bartels, Spence, Book, Parra, Ramos, Miles, Surface Material Transport in the Mississippi River Plume during Wind Events, in preparation

# Coupled systems global and nested



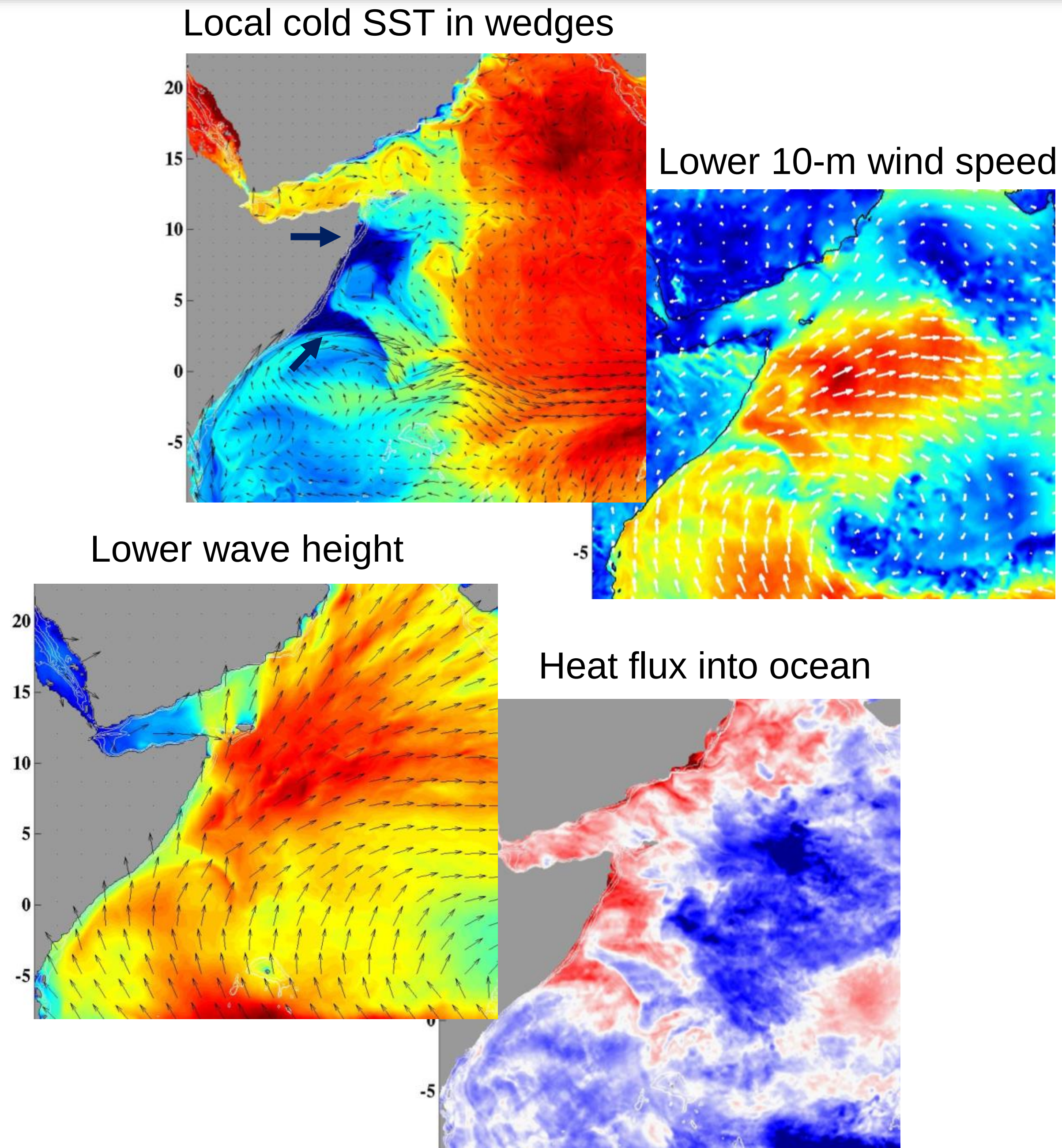




Earth System Model

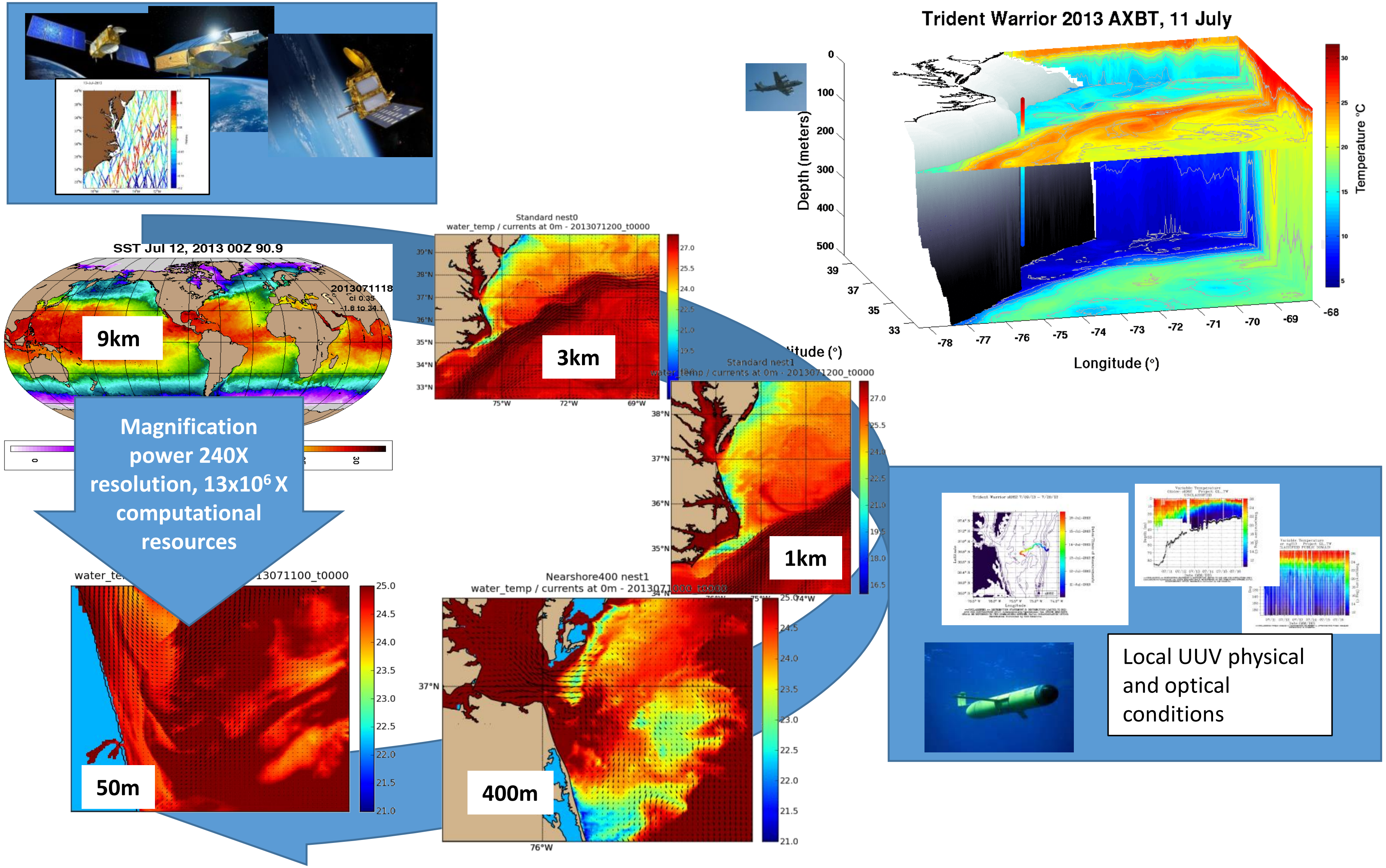
# Directions in coupling

- Software infrastructure
- Conservation
- Fluxes
    - Physical representation
    - Conservation
    - Disparate resolutions of components

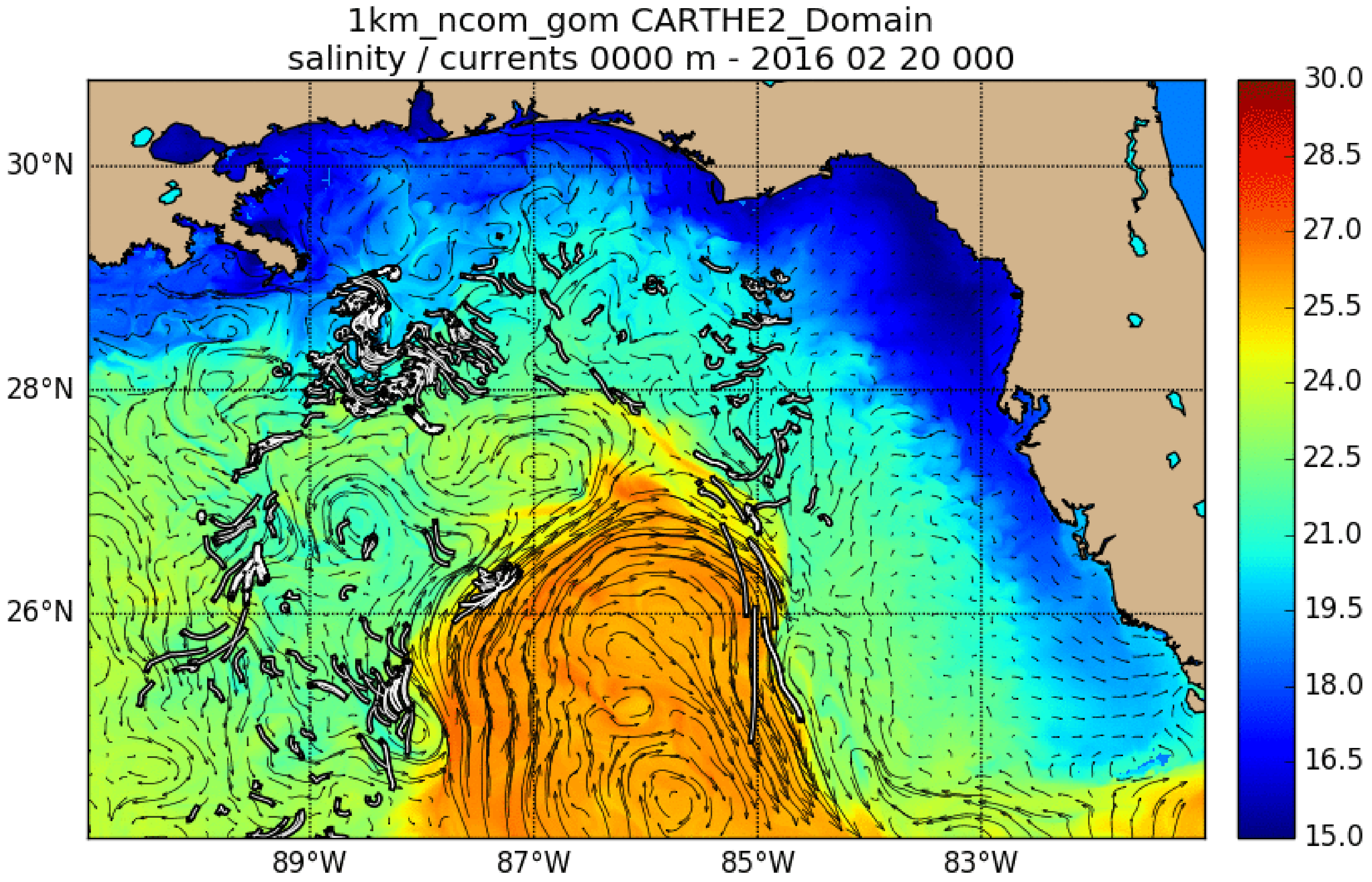
- Hydrology *
- Waves
- Ice
- Biogeochem



# Observing systems nest as well

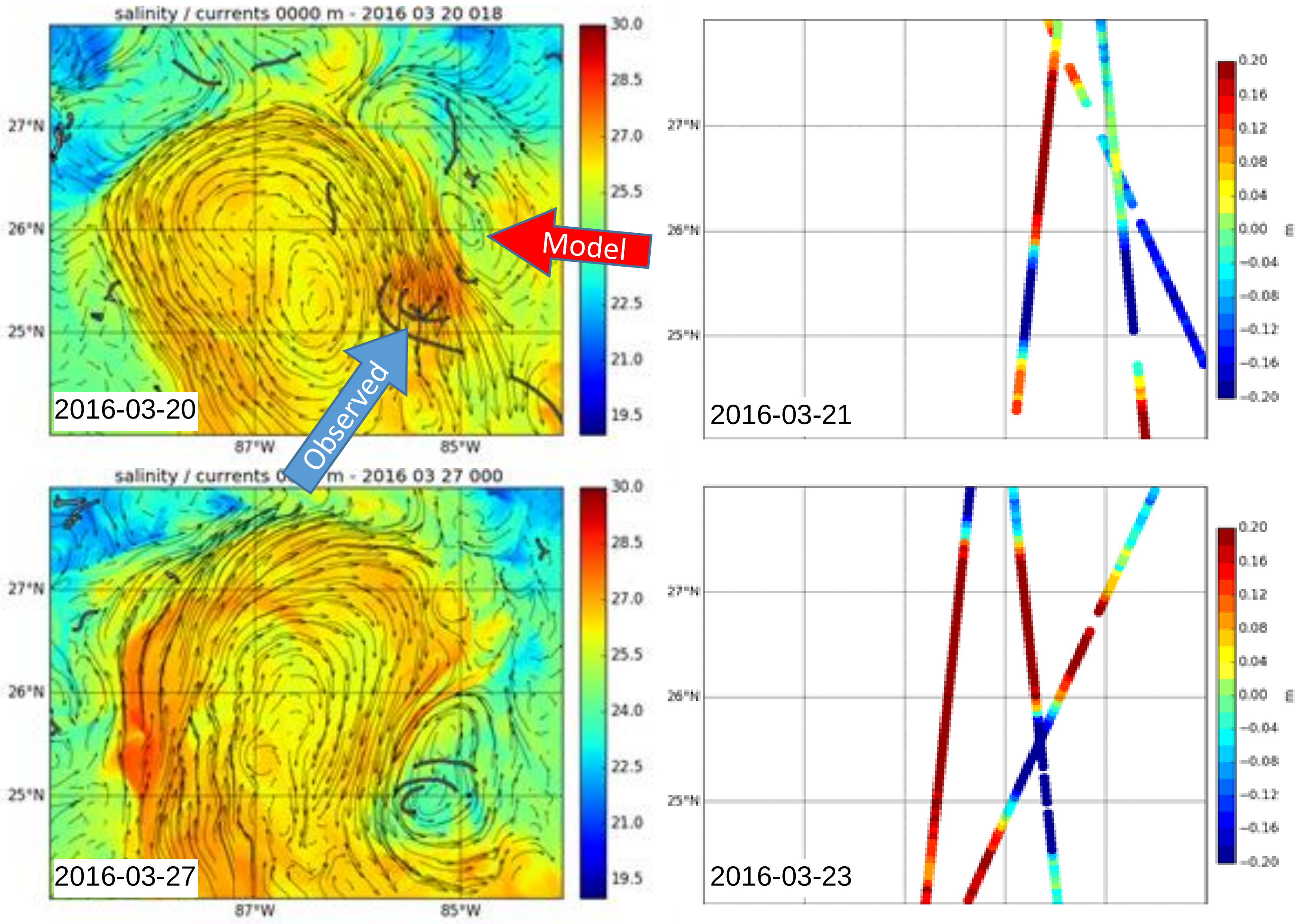


# Insufficient data leads to typical O(100 km) errors



# Insufficient data leads to typical O(100 km) errors

The positioning of 100 km features is often incorrect because of sparse data

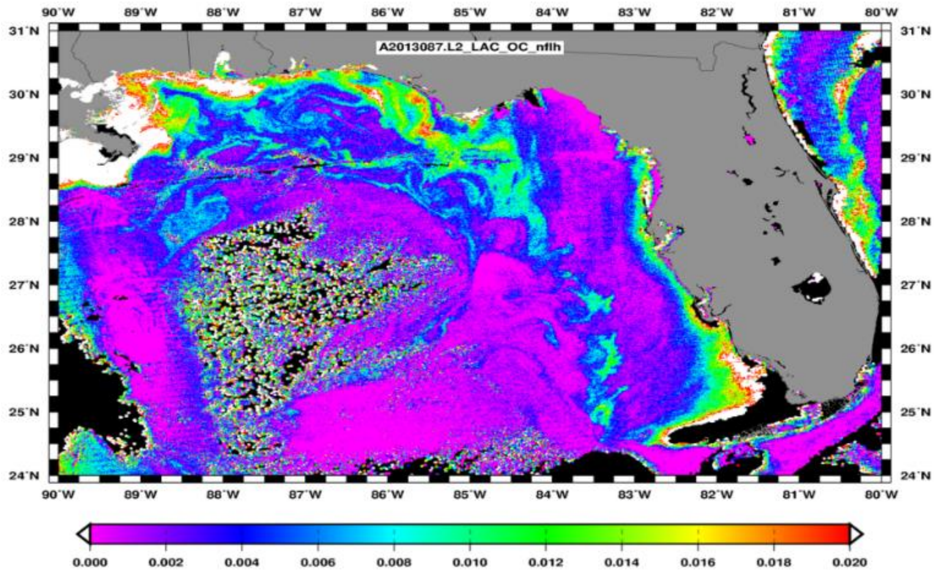



Over a 7 day period, only 2 days have data on the misplaced feature

The data shifts the eddy position in the model solution, but on average it is debatable if the model has skill in predicting this feature

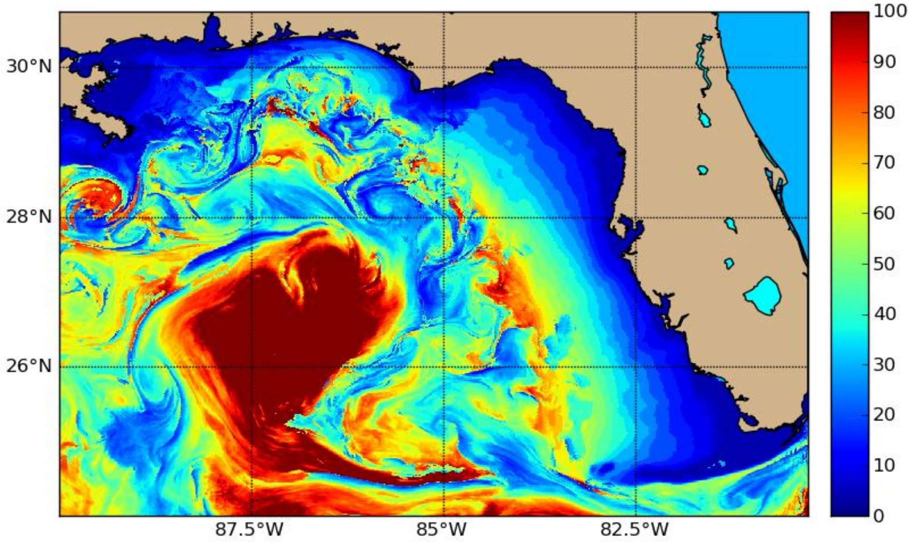
# The need to predict smaller scales

Satellite-observed seaweed March 28, 2013

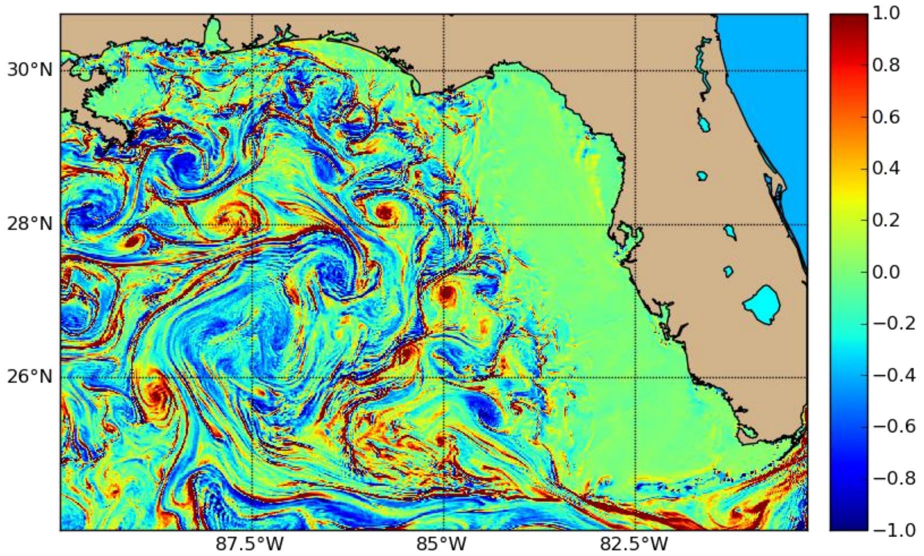



- Ocean prediction to date has focused on mesoscale
- Errors in frontal positions are 50 to 100 km
- Features smaller than 50 to 100 km are not constrained

Mixed Layer Depth



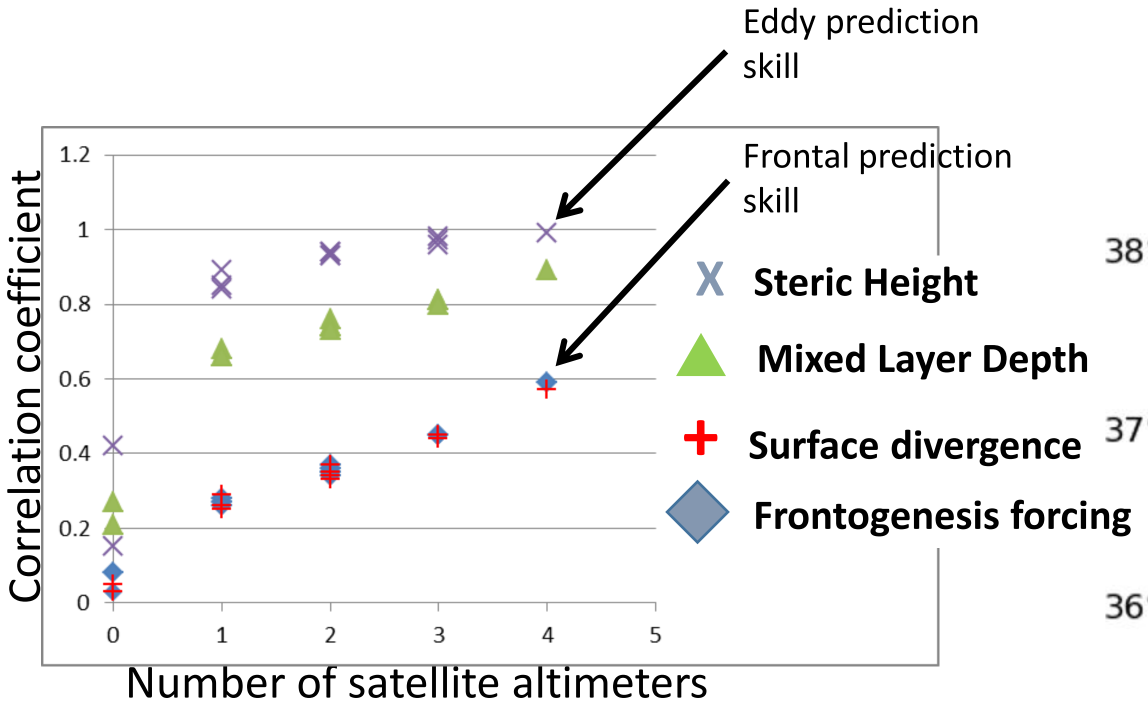

Vorticity / f

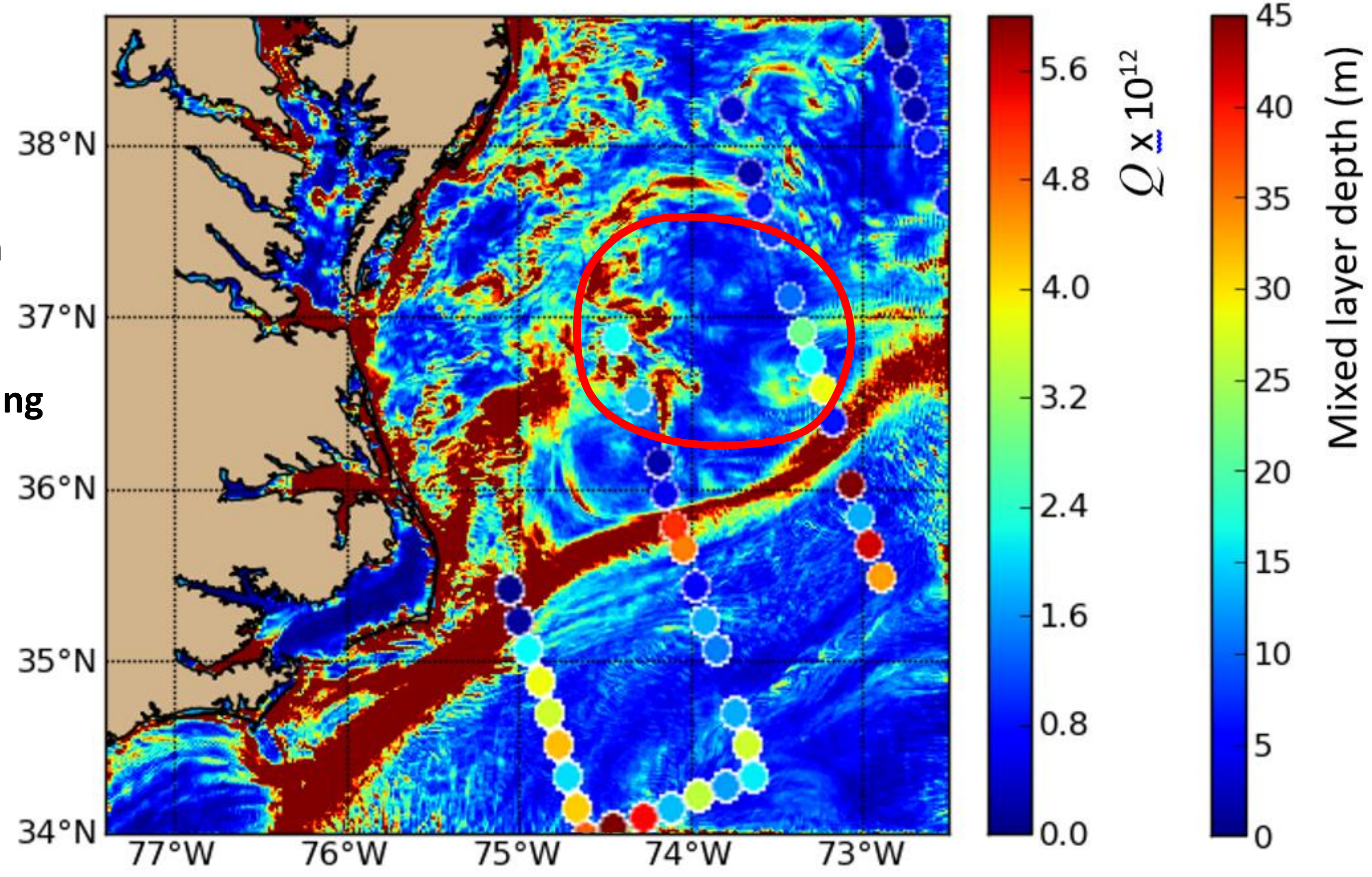



1 km resolution model

Assimilating all regular observations

# Forecast skill as a function of observations

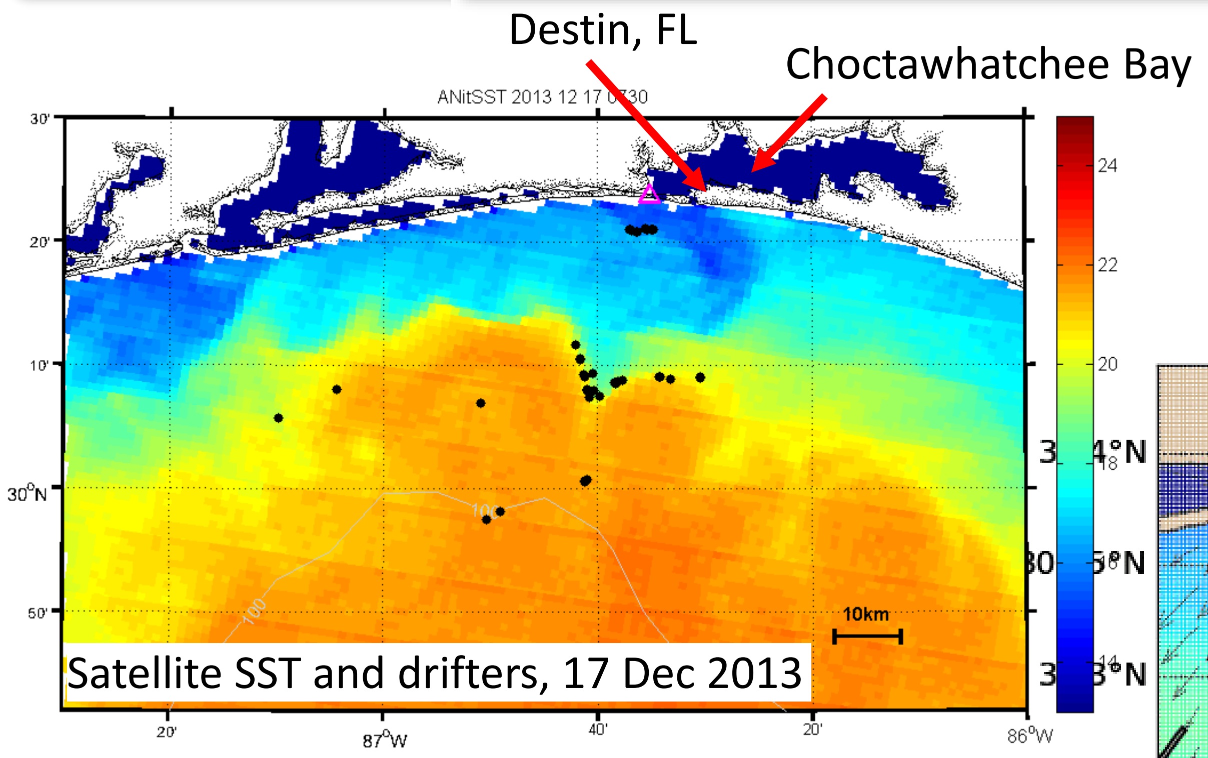


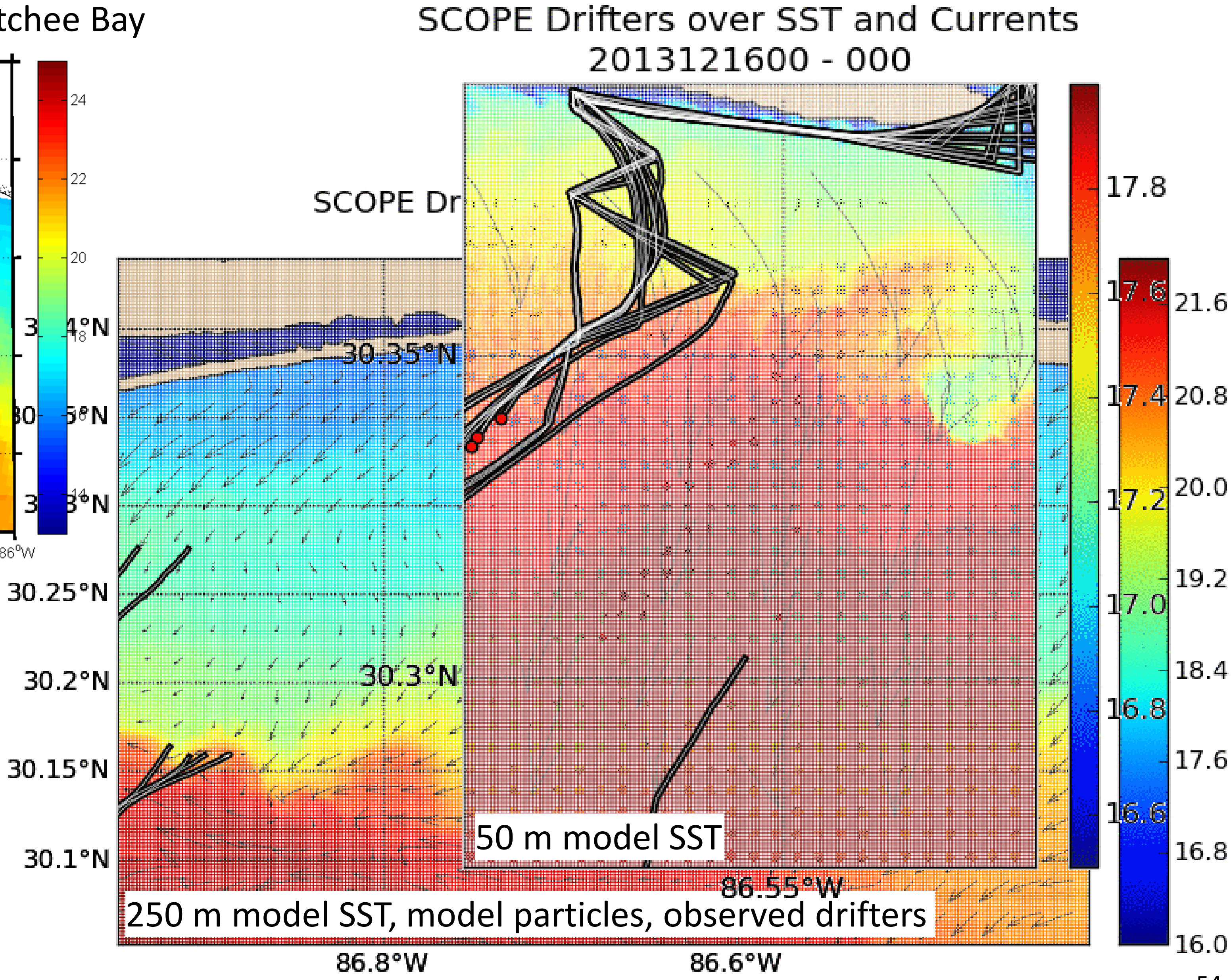

- Observation System Experiments show mesoscale predictability and associated frontogenesis as a function of data quantity
- Mesoscale prediction skill increases quickly
- Frontal prediction skill increases slowly
- Observation density is the limiting factor

Jacobs, Gregg A., James G. Richman, James D. Doyle, Peter L. Spence, Brent P. Bartels, Charlie N. Barron, Robert W. Helber, and Frank L. Bub. "Simulating conditional deterministic predictability within ocean frontogenesis." *Ocean Modelling* 78 (2014): 1-16.

# Frontal effects

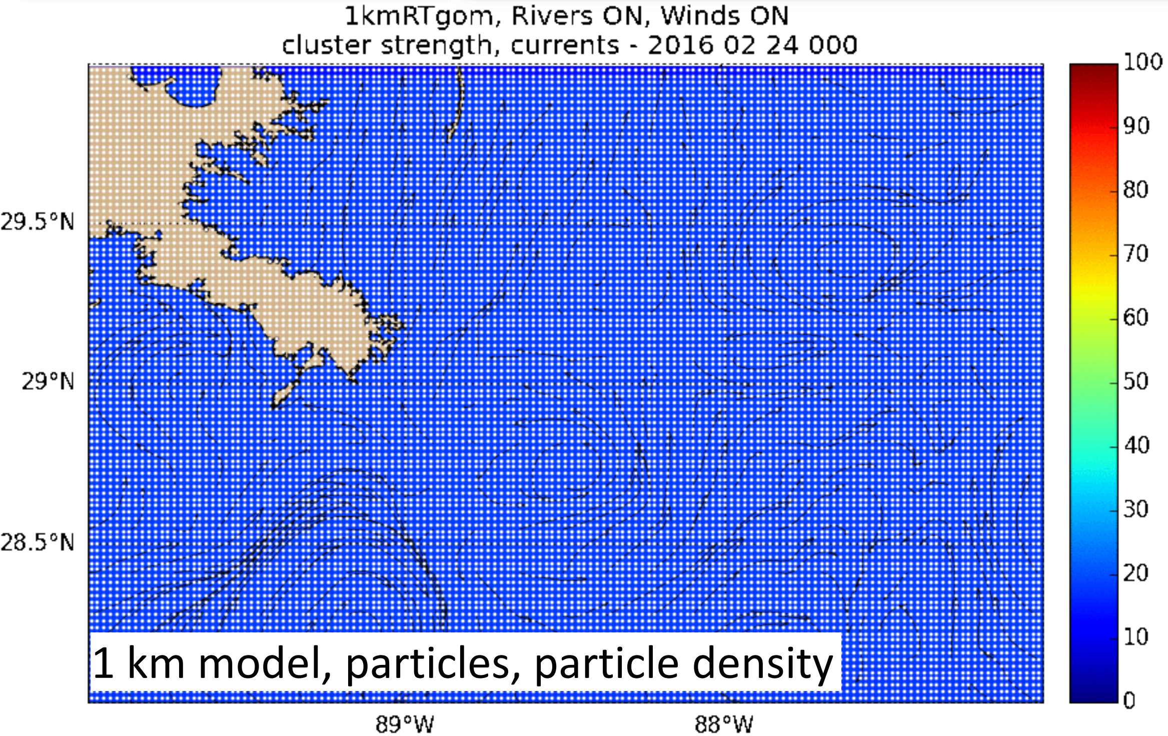



Drifter locations on SST (17 Dec, 2013)

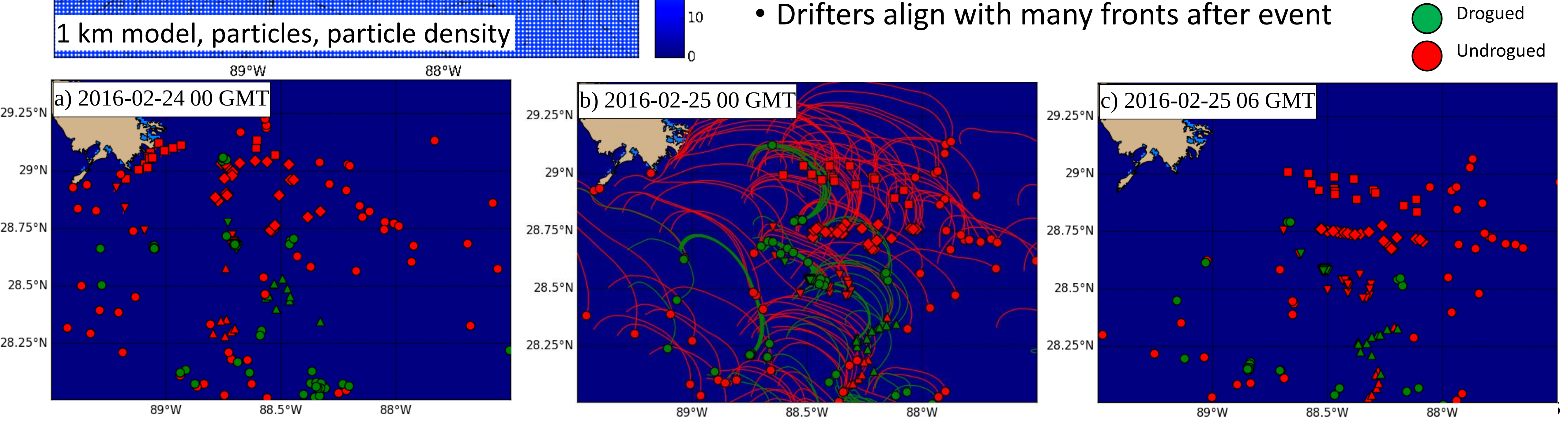



- Frontal effects have been difficult to observe
- Large numbers of drifters have overcome this
- In this case drifters converge on the shelf break front
- The model results show a second front on the shelf that captures some of the drifters as well

# Frontal effects are highlighted around river plumes

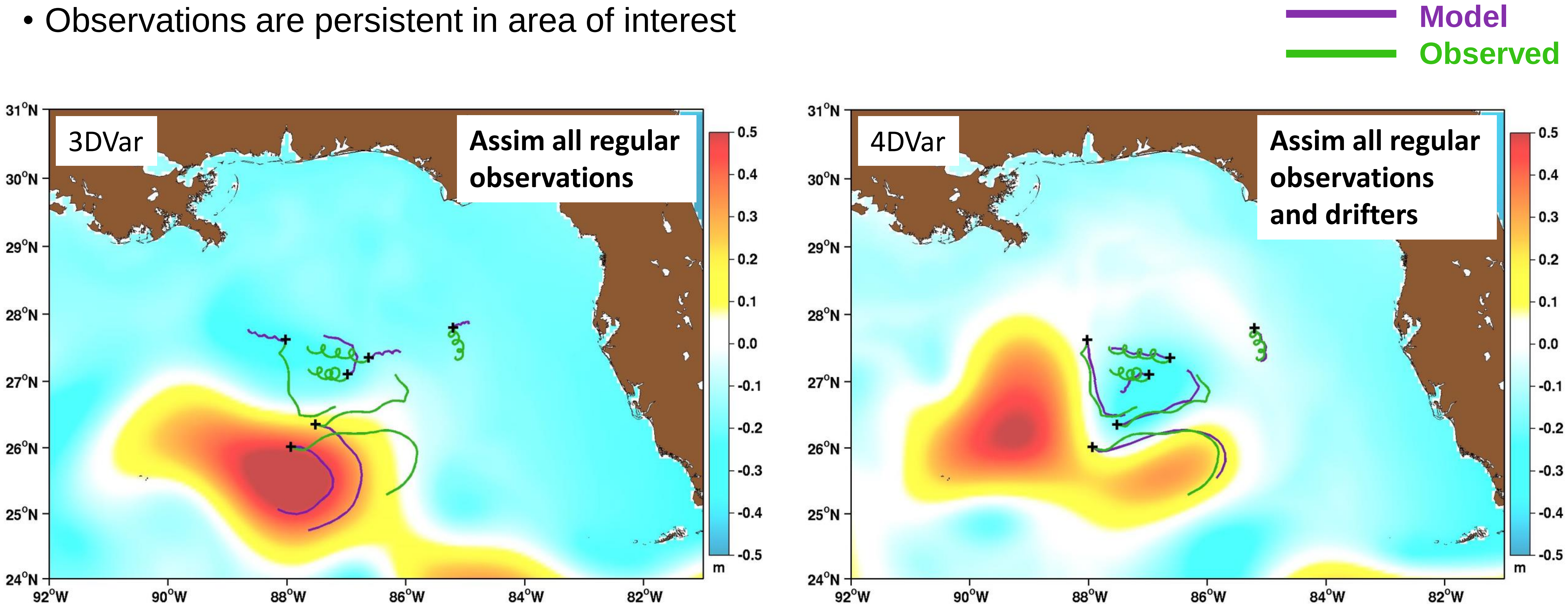



- Deep water fronts are driven by straining of buoyancy
- Coastal fronts occur by fresh water overriding denser water
- This event occurs during the wind event producing the vertical shear in slide 5
- Large distance traveled in 24 hours due to stratification
- Drifters align with many fronts after event



# Using observations

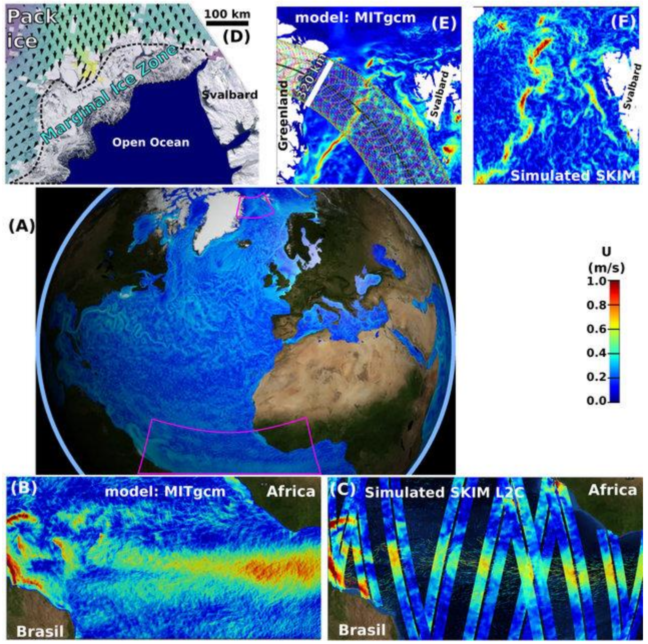
- Drifters inferred as geostrophic currents
- The implied measurement is SSH gradient (little local altimeters)
- Observations are persistent in area of interest

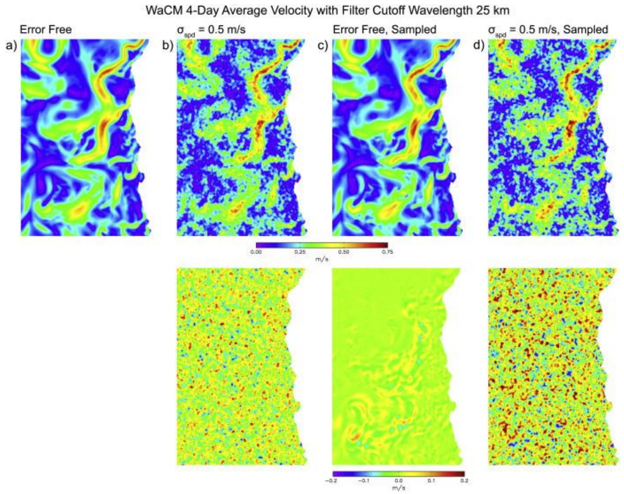



M. J. Carrier, H. Ngodock, S. Smith, G. Jacobs, P. Muscarella, T. Ozgokmen, B. Haus and B. Lipphardt, 2014: [Impact of Assimilating Ocean Velocity Observations Inferred from Lagrangian Drifter Data Using the NCOM-4DVAR](), Monthly Weather Review vol 142 doi:10.1175/MWR-D-13-00236.1

# Extending the satellite systems

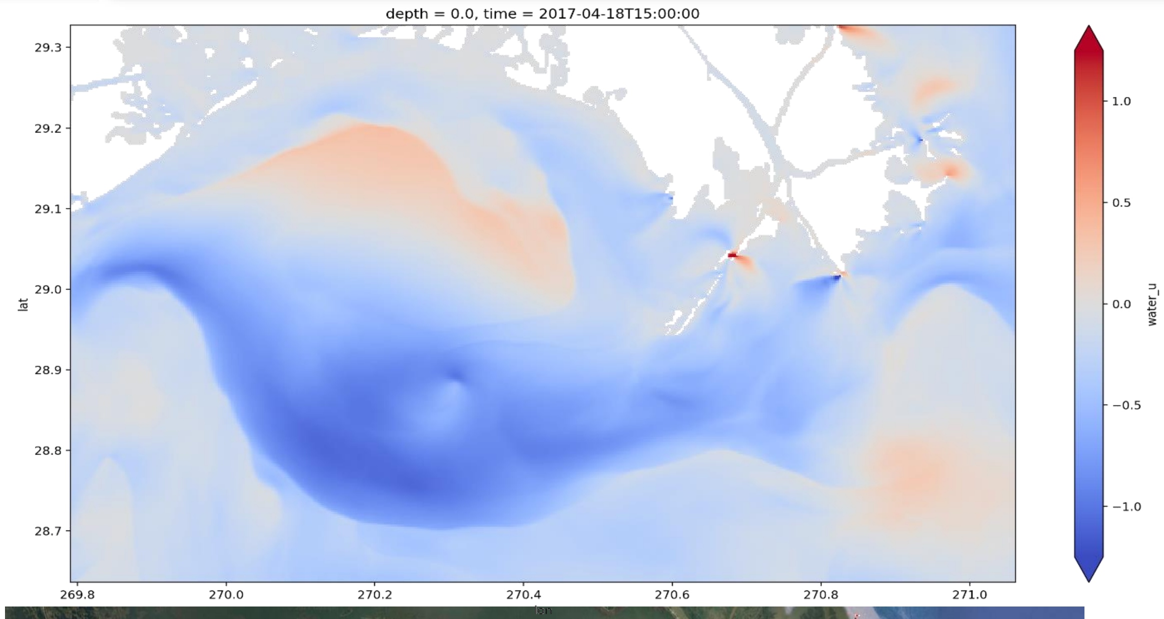
SWOT / COMPIRA



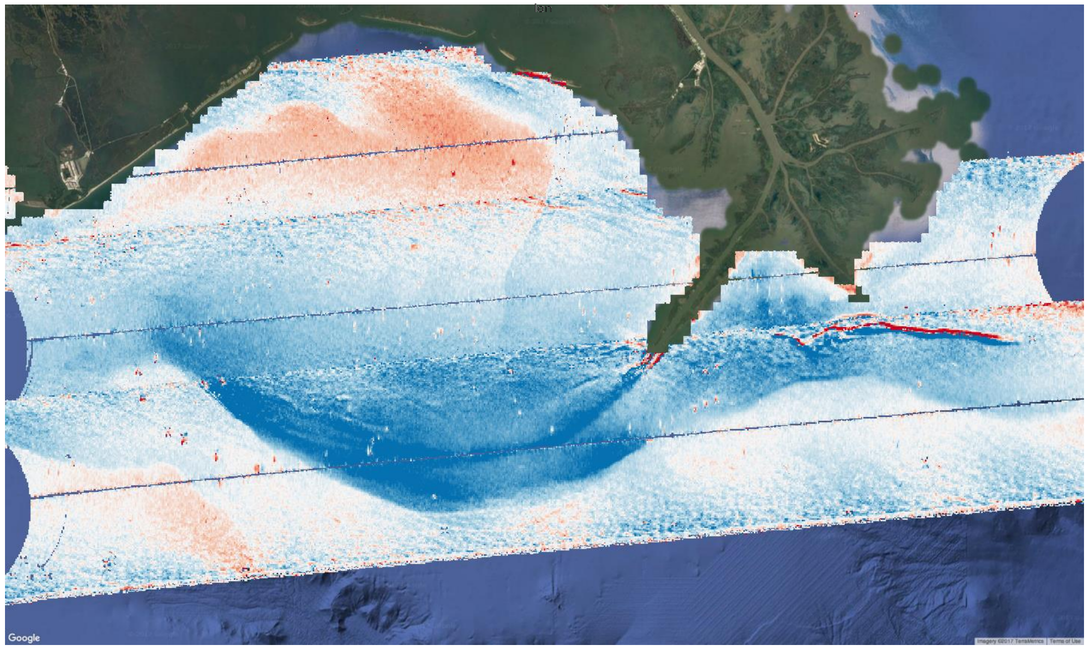

SKIM / WACM

# Dopplerscatt demo




April 18, 15:00 GMT

Ocean model east-west current



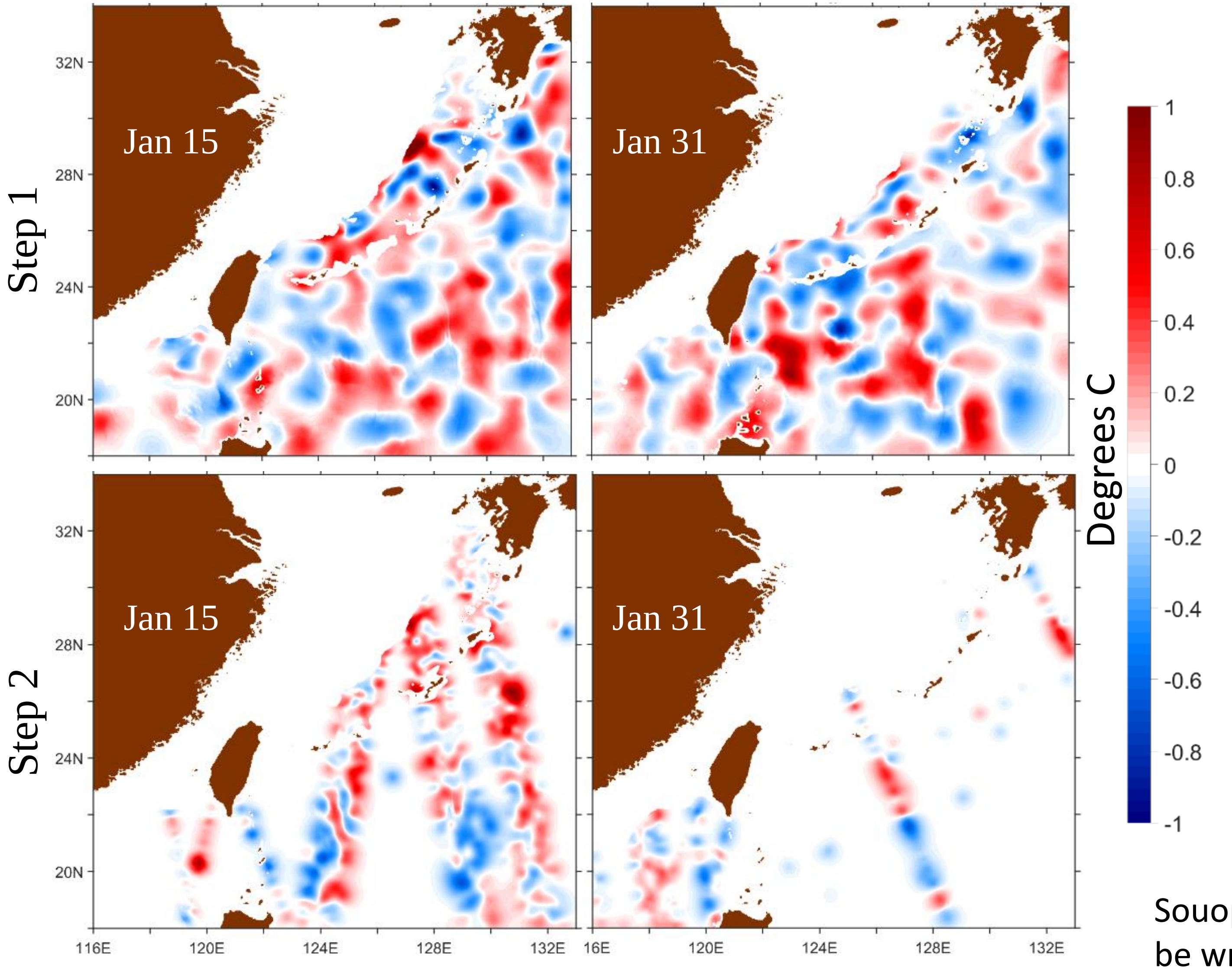

Aircraft Doppler scatterometer
Observed east-west current

Results from Ernesto Rodriguez

# Application of SWOT observations

## Multi-scale-step-physics analysis advances prediction further

### 500 m temperature increments

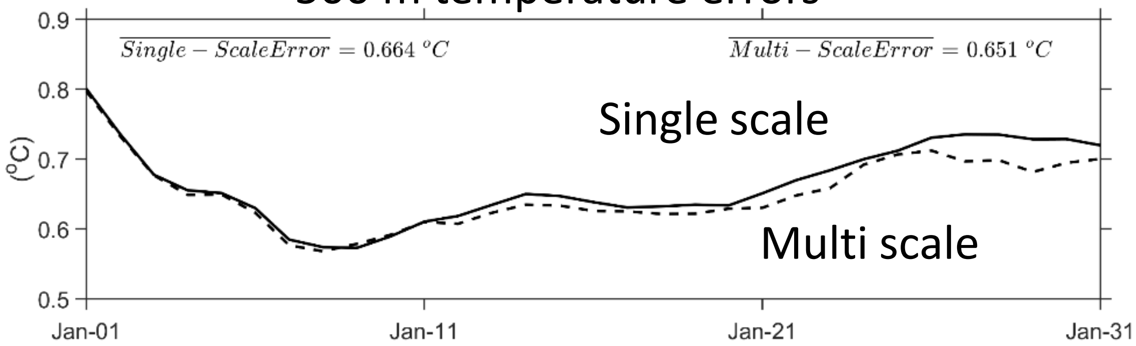



Based on published OSSE experiments

Start Jan 1, IC from 1 year offset

| | Step 1 | Step 2 |
|---|---|---|
| **Observations** | Profiles + SST + Altim + SWOT | Profiles + Altim + SWOT |
| **Profile window** | 288 hours | 72 hours |
| **Altim + SWOT window** | 120 hours | 30 hours |
| **SST window** | 24 hours | None |
| **FGAT** | On for SST | Off |
| **rscl** | 1.2 | 0.5 |

### 500 m temperature errors

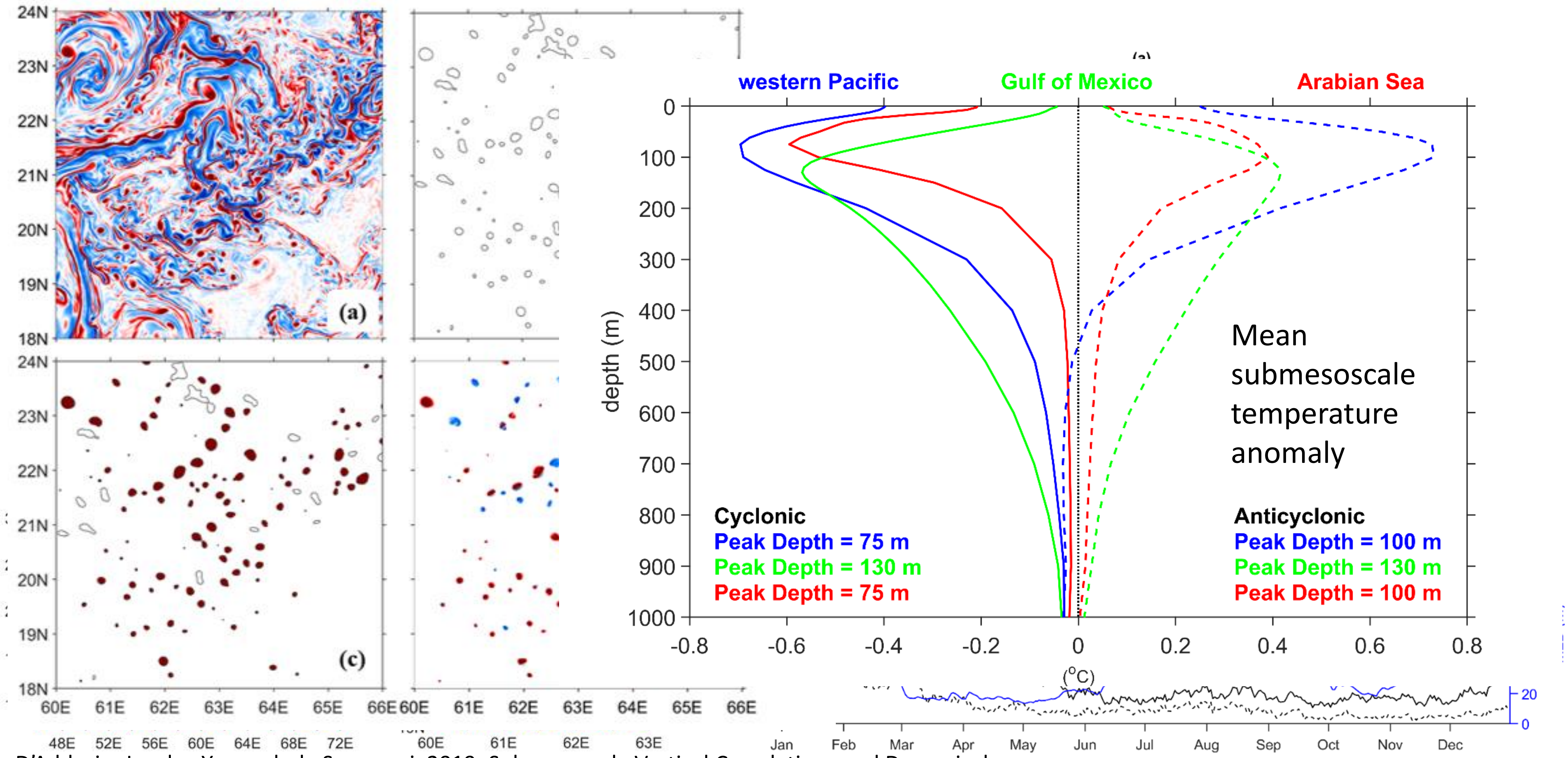



Souopgui, D'Addezio, Multiscale SWOT assimilation skill, to be written

# Application of SWOT observations

1 km – 1 year runs

## Submesoscale physics require different relations than mesoscale




D'Addezio, Jacobs, Yaremchuk, Souopgui, 2019: Submesoscale Vertical Correlations and Dynamical Constraints from High-Resolution Numerical Simulations, submitted

# Directions in assimilation

- Software infrastructure
- 3DVar to 4DVar (adjoint or ensemble)
- Multi – scale / physics
- Databases
- Covariance representation

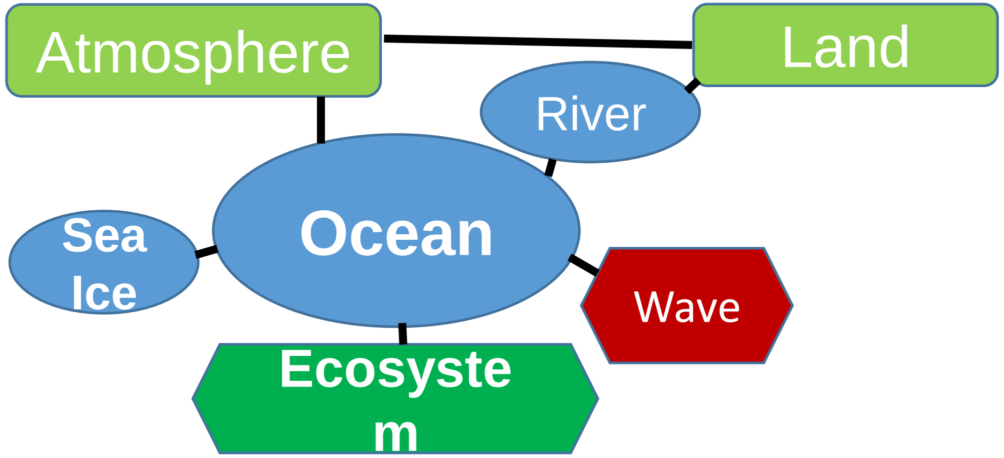
# Personal Summary and Outlook

Transfer "**Information**" to the end users

HPC(High Performance Computing), Software engineering (Big data, AI)
Calibration/Validation and Evaluation w.r.t. end user requirement specification
Sharing best practices with other groups
Recognized in Inter-governmental organizations

**High resolution**
Improved physics and mixing, Two-way nesting
Ensemble prediction
**Coupled (integrated) systems**

National/Regional Systems { Global, Basin, Regional, Coastal }




| Observation Systems | Data Assimilation | Numerical Models |
| --- | --- | --- |

# Conclusions 1

Direction for the future

- Map data to information for end users
  - Understanding how users work and what information affects them
    - Storm surge inundation, flood gate management, …
    - Navy
    - Oil spill response
    - Search and rescue
    - Coral reef stress
    - Fishery management
    - TC potential …)
  - Information services transforming ocean predictions to information for users
  - Data transfer limitations
  - Condensing ensembles to actionable information
  - Big data processing, machine learning, …

# Conclusions 2

Direction for the future

- Ensure the right data exists
    - Coupled systems
        - Model accuracy
        - Hydrology
    - Extend physics, vertical mixing and resolution
    - Modeling architecture and community modelling
    - Computational resources, HPC time, exploiting new computational systems (GPU, cloud services, ….)
    - Ensemble forecasts, advanced postprocessing for uncertainty
    - Ability to rapidly set up a new high resolution area
- Ensure observations are available and used appropriately
    - Real time availability
    - Sharing of observations with defined formats
    - New systems
        - SWOT, SKIM, COMPIRA, WACM, …
    - Assimilation methods (including coupled)
    - Systematic errors
    - On demand observations for rapid response (air, surface, under water)
    - Adaptive sampling for forecast error reduction

- Sharing of best practices
- Computational science problems

*Thank you for your attention!*

Questions or Comments