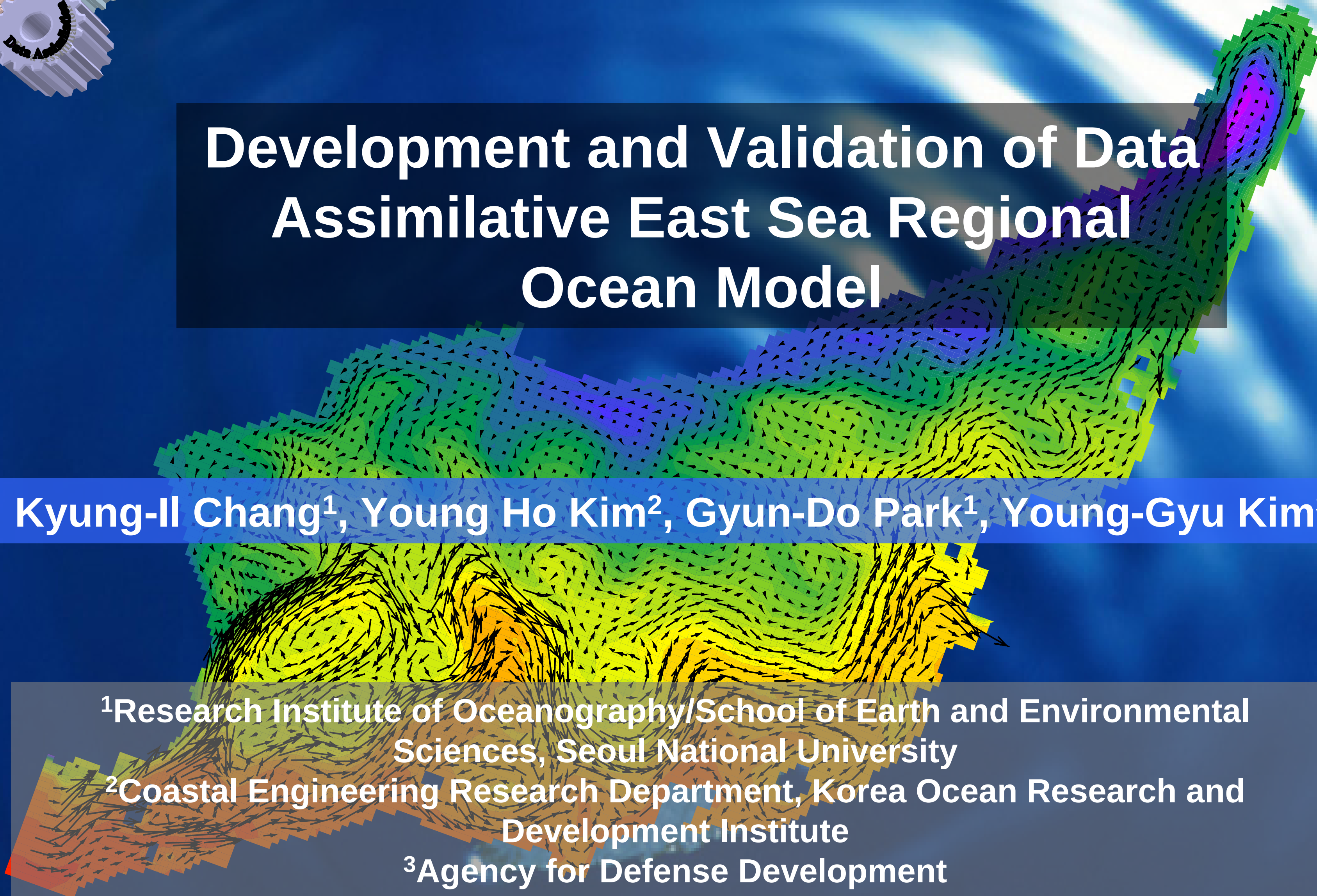
Development and Validation of Data Assimilative East Sea Regional Ocean Model



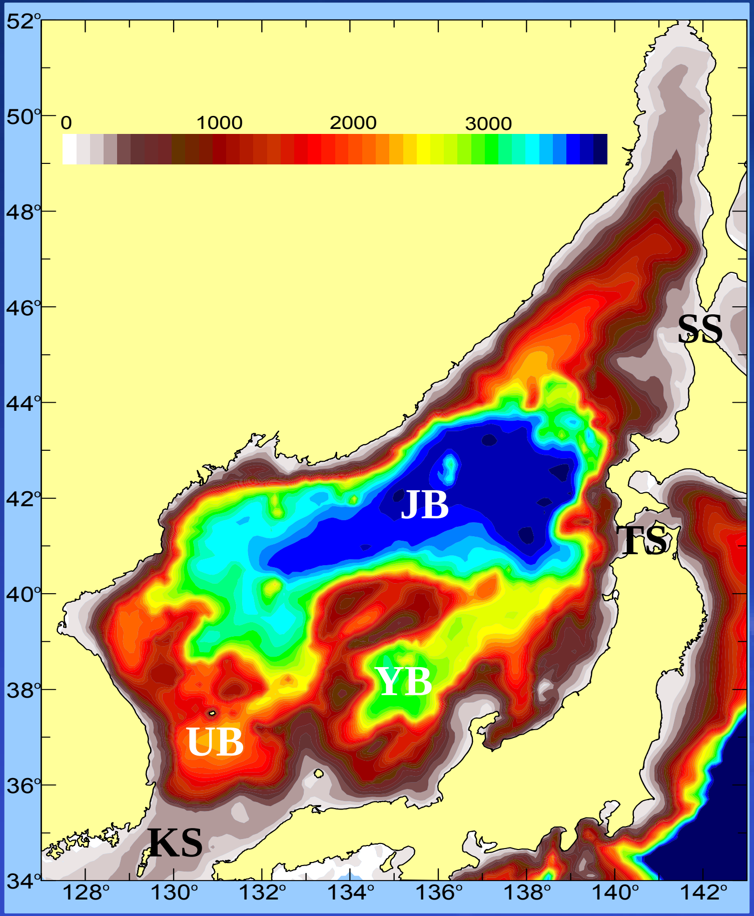
Kyung-Il Chang[1], Young Ho Kim[2], Gyun-Do Park[1], Young-Gyu Kim[3]

[1]Research Institute of Oceanography/School of Earth and Environmental Sciences, Seoul National University
[2]Coastal Engineering Research Department, Korea Ocean Research and Development Institute
[3]Agency for Defense Development

Contents

1. East Sea & Regional Ocean Model
2. Implementation of 3D-Var
3. Validation of 3D-Var system
4. Future Work : Ensemble Kalman Filter
5. Conclusion

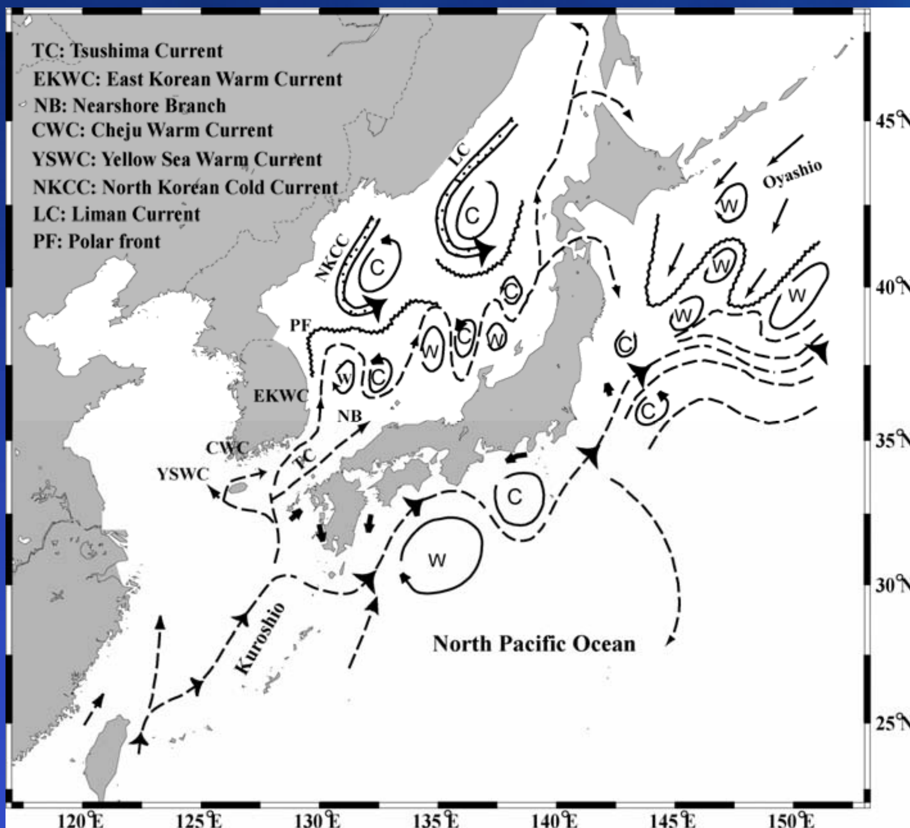
Regional setting: East Sea

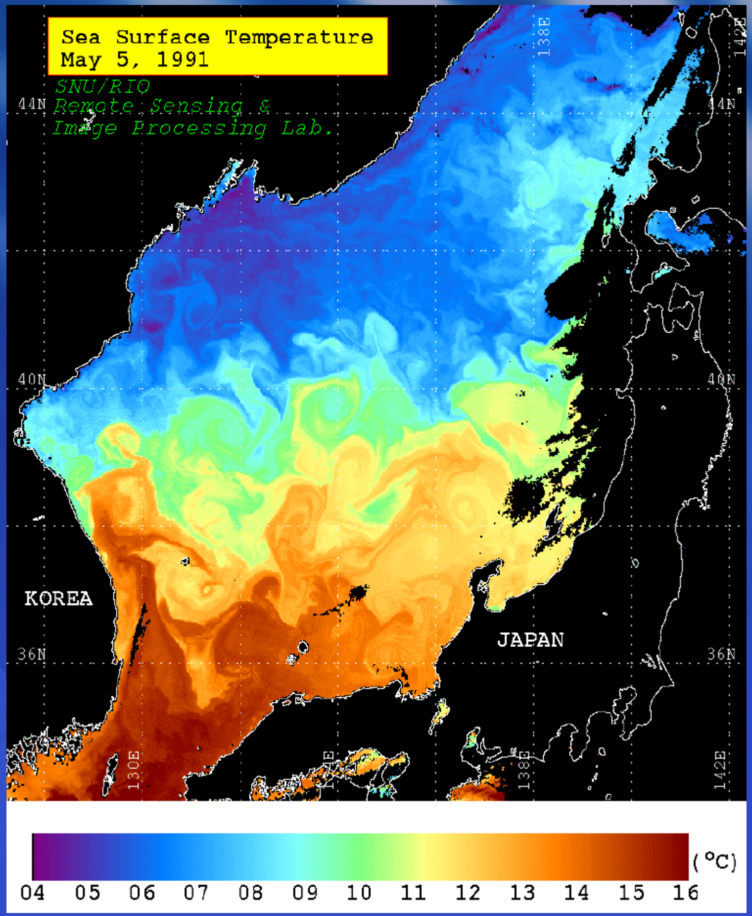


Area: 10^6 km^2
Mean depth: ~1700 m
Max. depth: ~ 4000 m

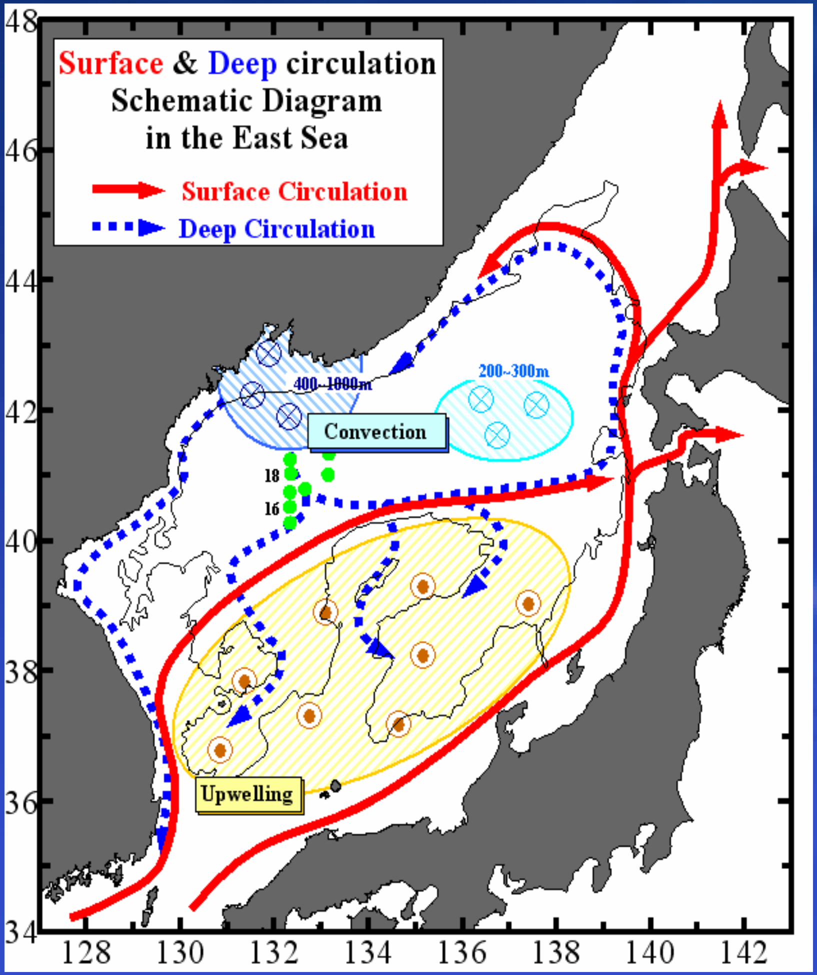
JB: Japan Basin
UB: Ulleung Basin
YB: Yamato Basin
KS: Korea Strait
TS: Tsugaru Strait
SS: Soya Strait

Regional setting: East Sea





Regional setting: Circulation

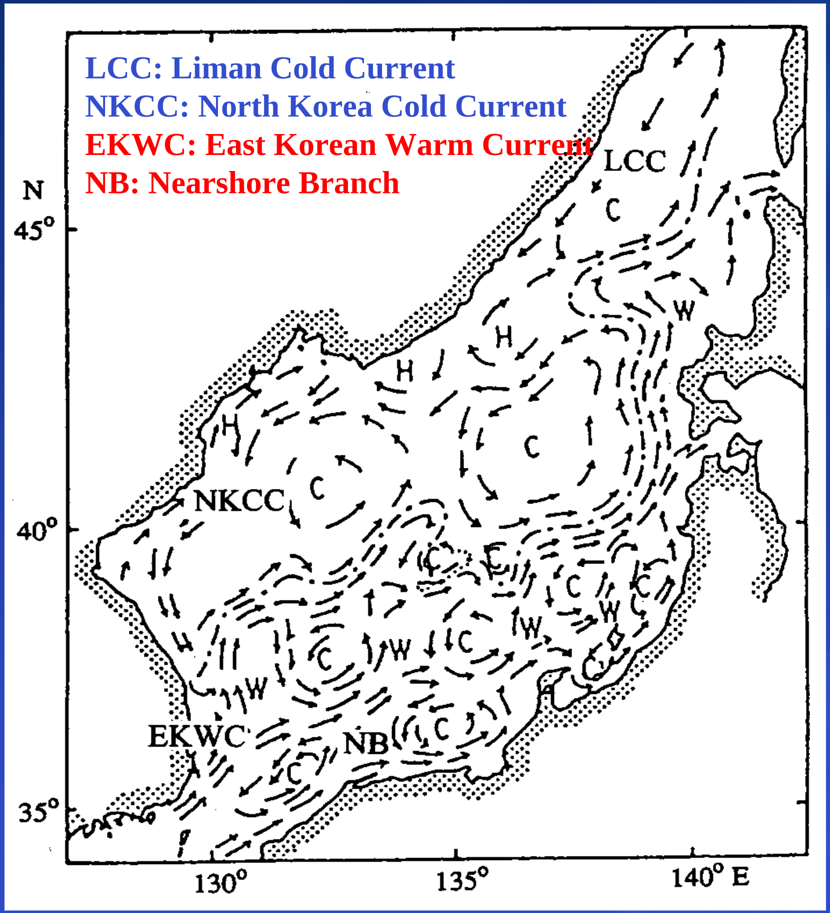


Miniature Ocean

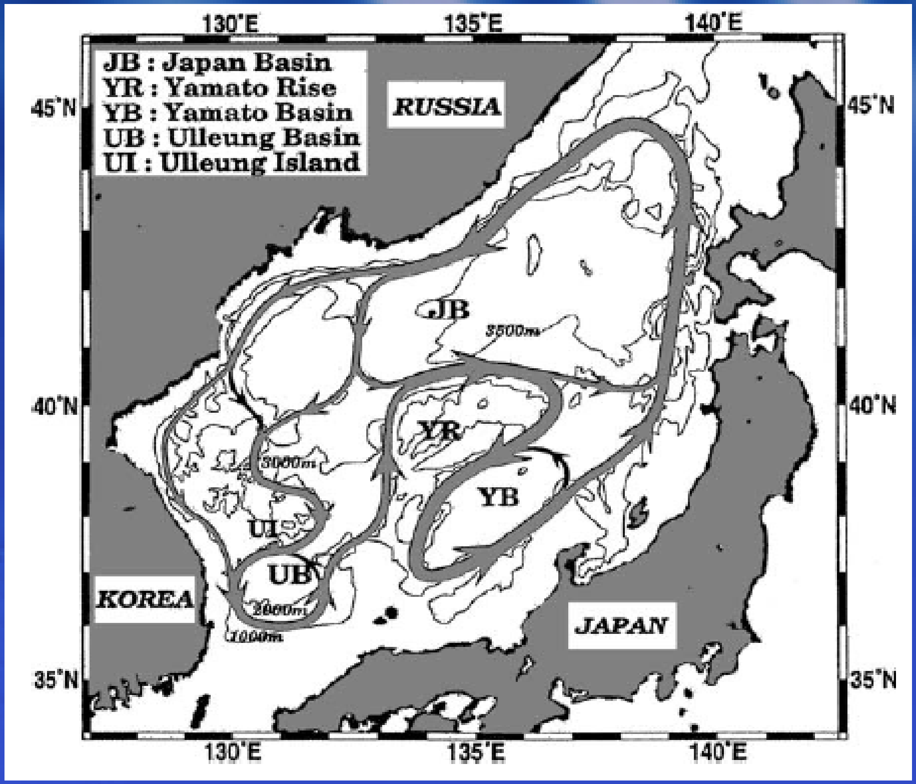
- Warm & cold water regions
- Subpolar front
- Deep water formation
- Deep circulation
- Double-gyre upper circulation
- Mesoscale eddies

Courtesy of Dr. J.J. Park

Regional setting: Circulation

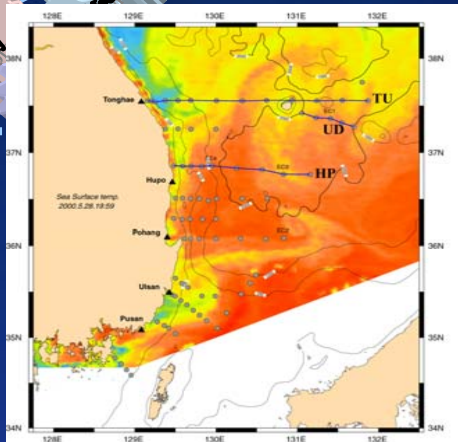


Naganuma (1977)



Senjyu et al. (2005)

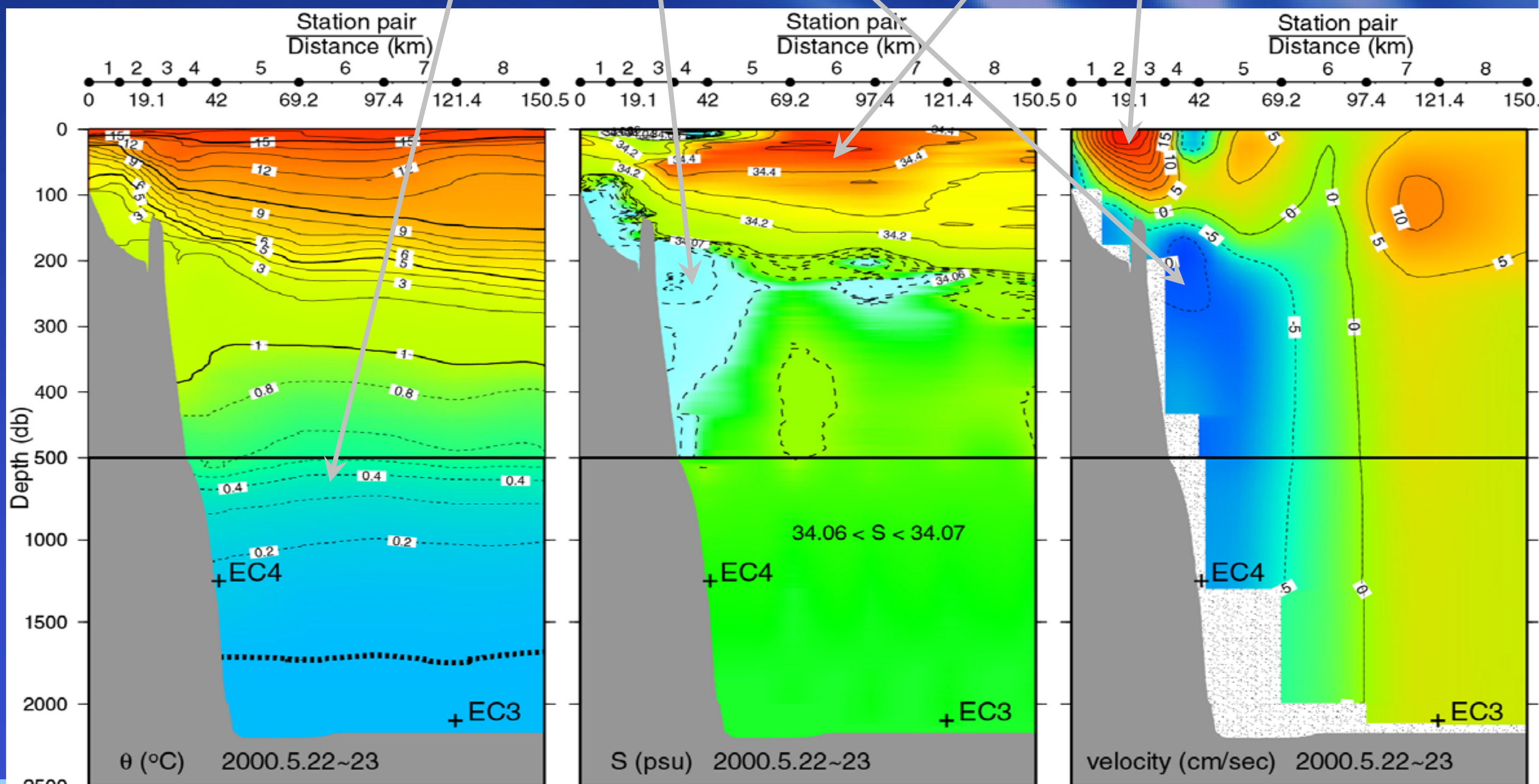
Regional setting: Water Masses



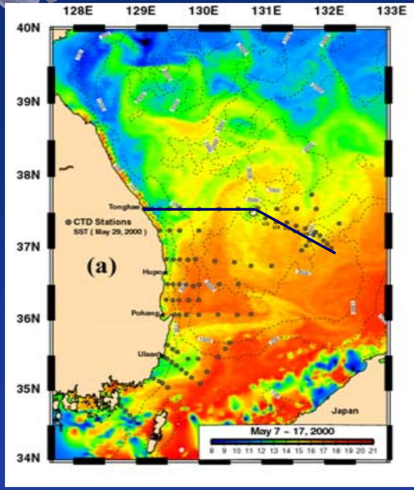
North Korean Cold Water
(Coastal mode of the East Sea Intermediate Water)

Tsushima Current Water

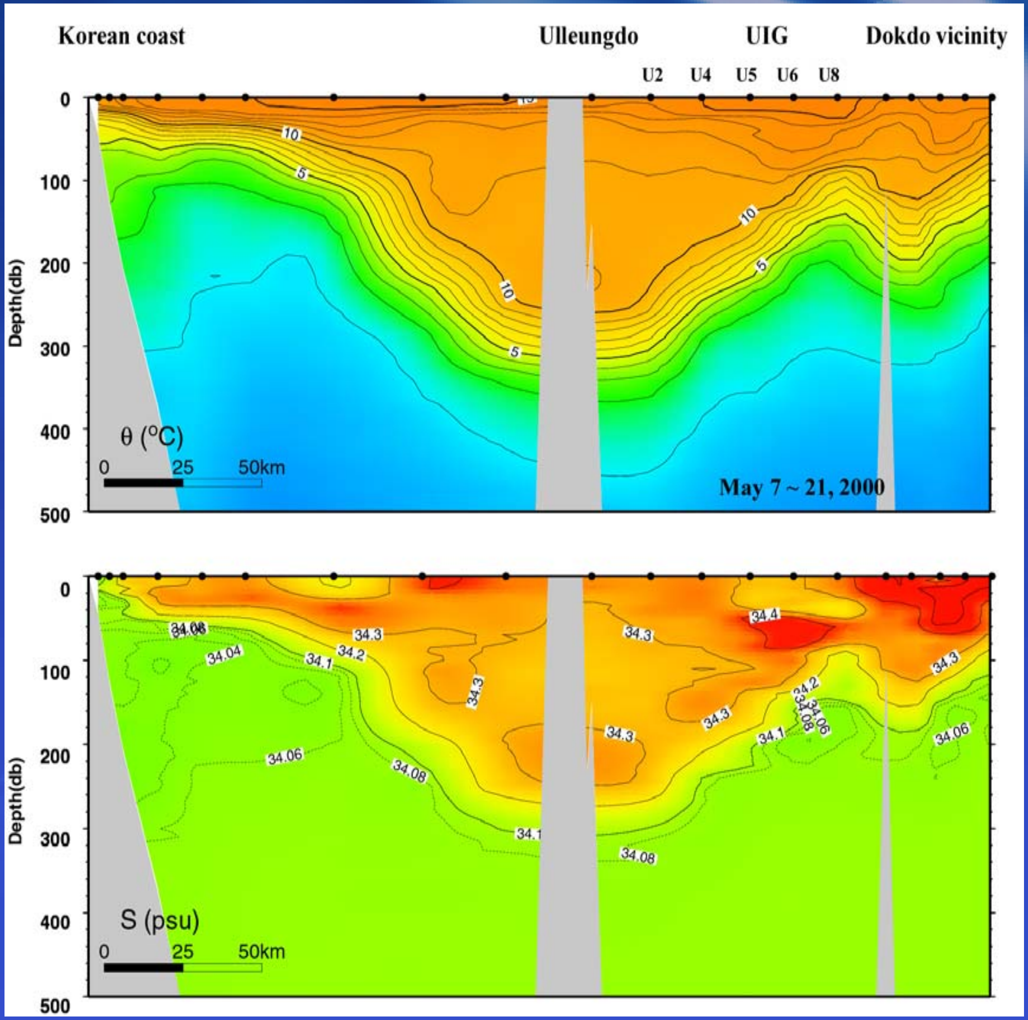
Deep water masses (< 1°C)



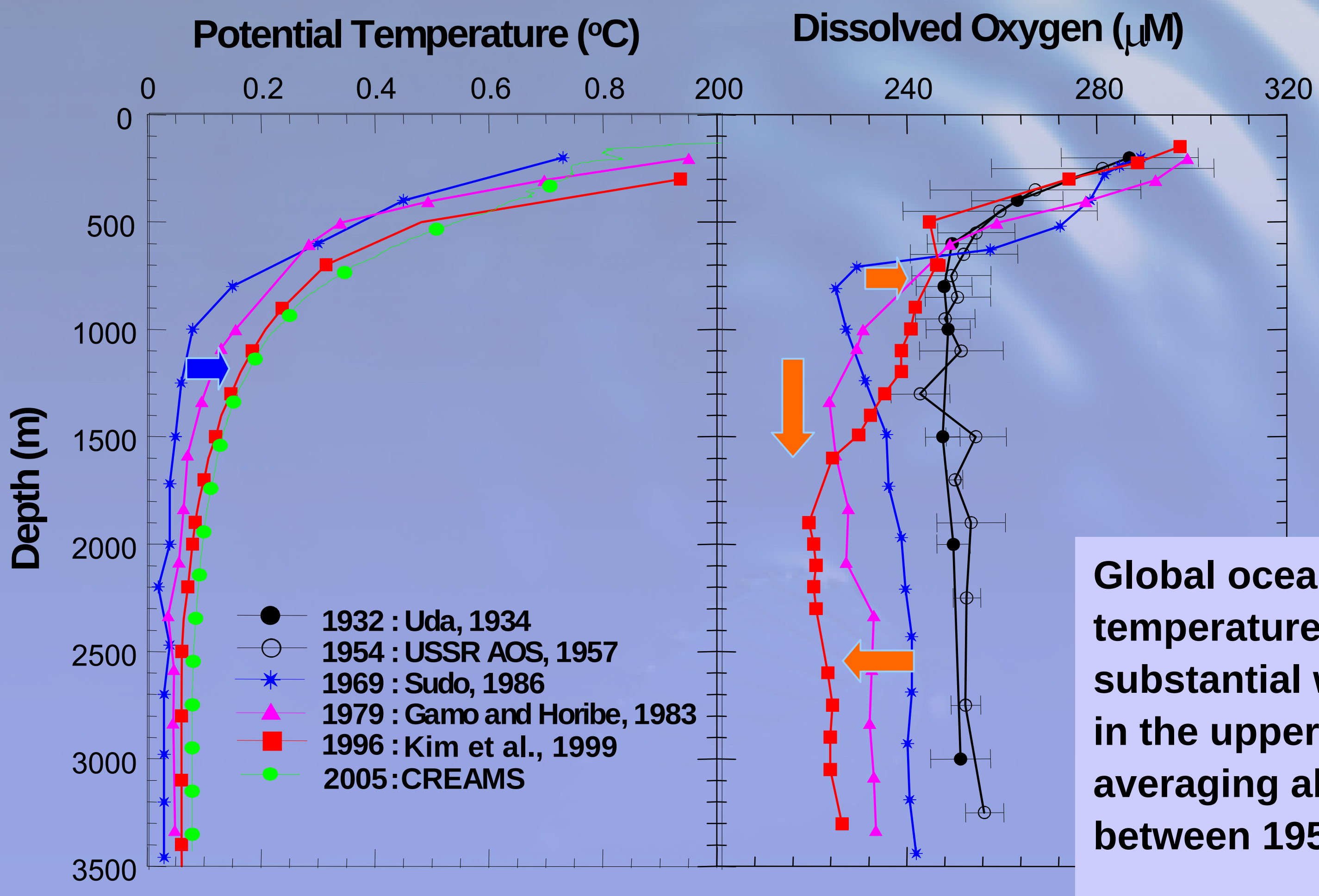
Regional setting: Eddies



Ulleung Warm Eddy



A Miniature Ocean in Change



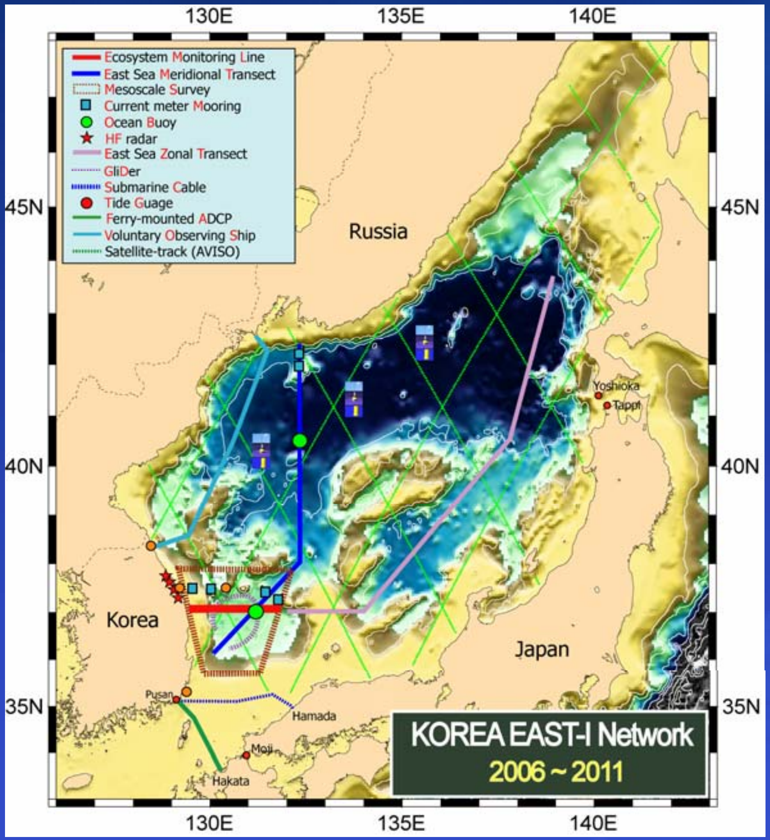
Global ocean temperature change: substantial warming in the upper 3000m, averaging about 0.037°C between 1955 and 1998

Levitus et al. (2005, GRL)

Brief History of International Programs

Before 1981 (1st workshop)	**Cooperative Study of the Kuroshio and Adjacent Regions** (1965-1977)
1981-1992	**Bilateral Collaboration** (Korea/Tsushima Strait submarine cable voltage measurement)
1993-1997	**CREAMS** (Circulation Research of the East Asian Marginal Seas) Multi-national, multi-disciplinary collaboration
1998-2002	**CREAMS II** Japan/East Sea Program (USA/ONR)
2005	**CREAMS/PICES Program** under PICES (North Pacific Marine Science Organization) EAST-I Program (East Asian Seas Time-series: East/Japan Sea)

EAST(East Asian Seas Time-series) - I



- International collaborations

  Joint surveys along meridional and zonal baselines; material flux measurements across the Korea Strait; joint workshops

- Eulerian time-series measurements

  Volume transport monitoring; HF radar; coastal buoy and Super-Station; Volunteer observing ships; Moored observations

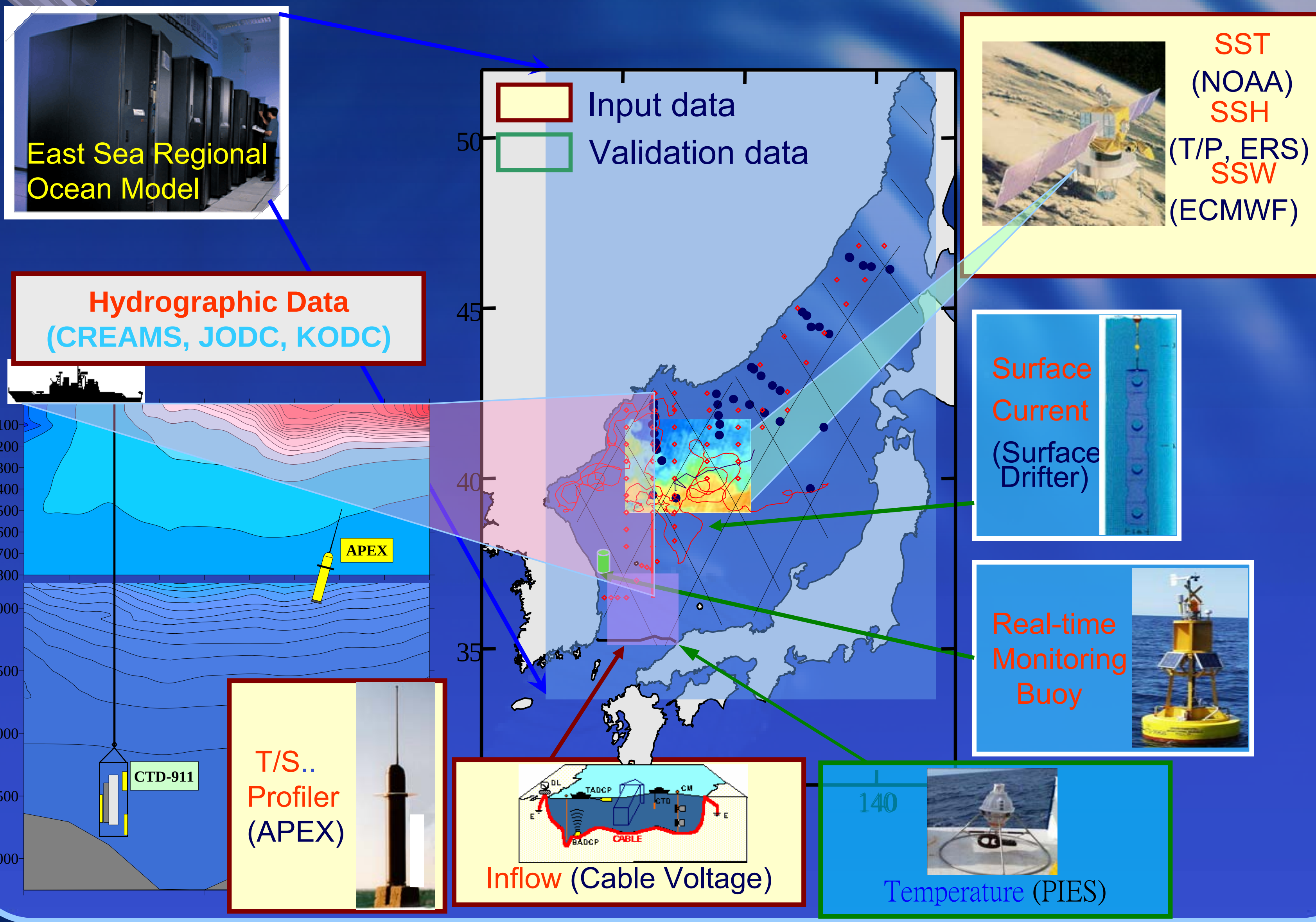
- Lagrangian measurements

  Argo floats; Argos drifters; gliders

Research Tasks (EAST-I)

- Establishment of integrated ocean time-series system
- Ecosystem structure and variability in response to physical forcing
- Air-sea interaction, mixed layer dynamics and ecosystem response
- Monitoring and understanding the thermohaline circulation
- Carbon cycle and its response to climate change
- Role of straits in climate and ecosystem
- Physical-biological coupled modeling & future climate projection

Observation Systems in the East/Japan Sea

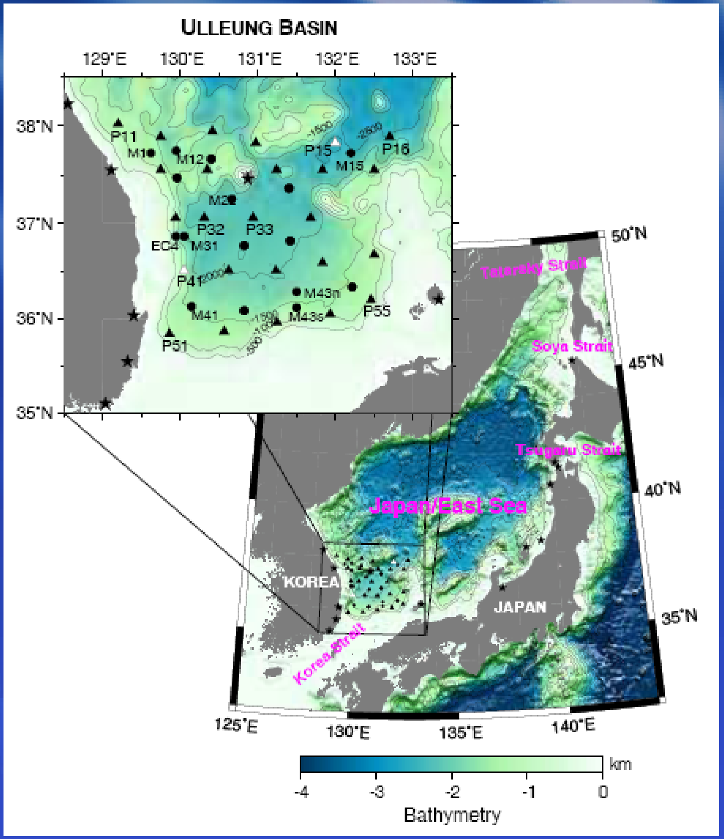


Highly-resolved Observation in the UB

ONR JES Program: URI, KORDI, KU

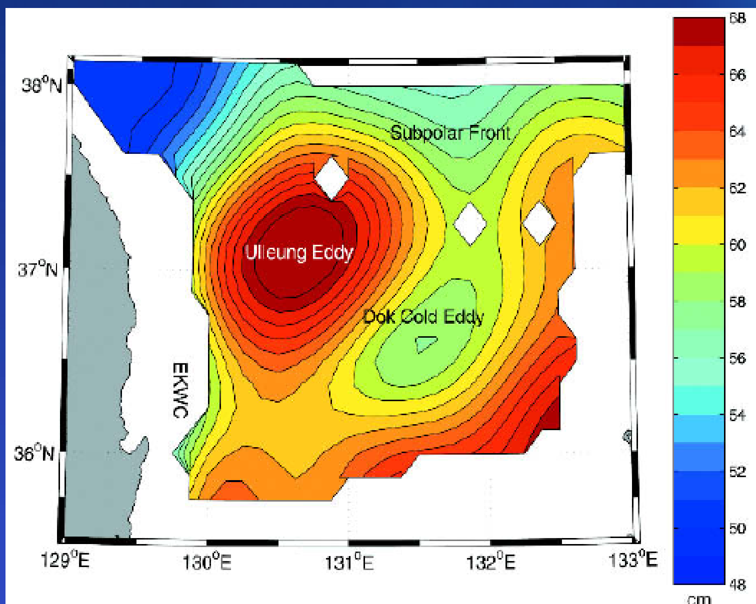
16 current meters, 23 pressure-gauge-equipped inverted echo sounders

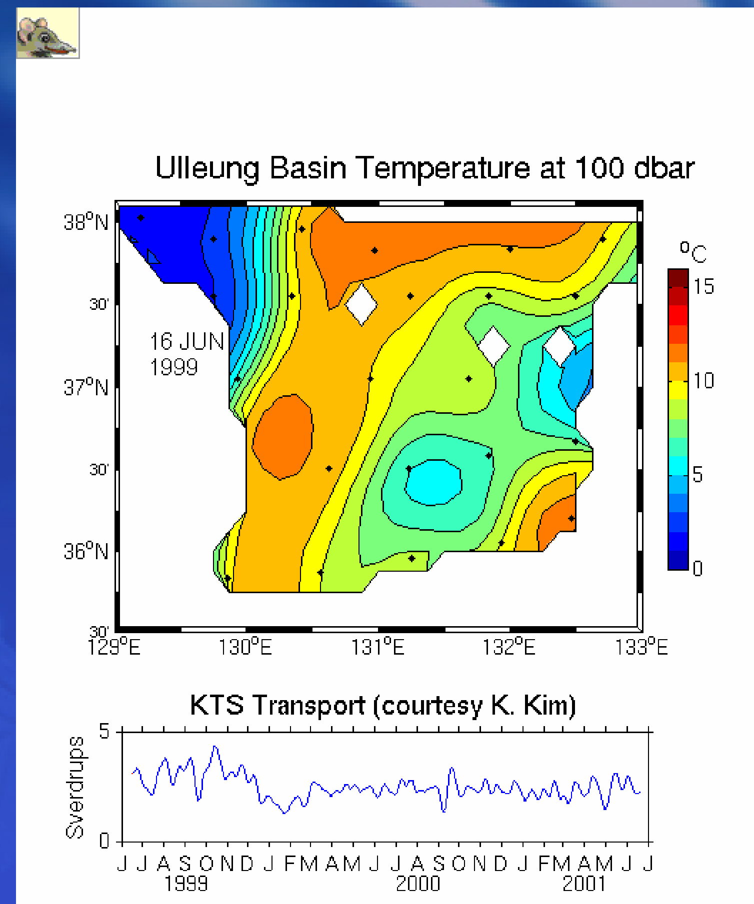
Daily T & dynamic fields between June 1999 and June 2001



Regional setting: Circulation & Variability (UB)

Mitchell et al. (2005); mean surface dynamic height

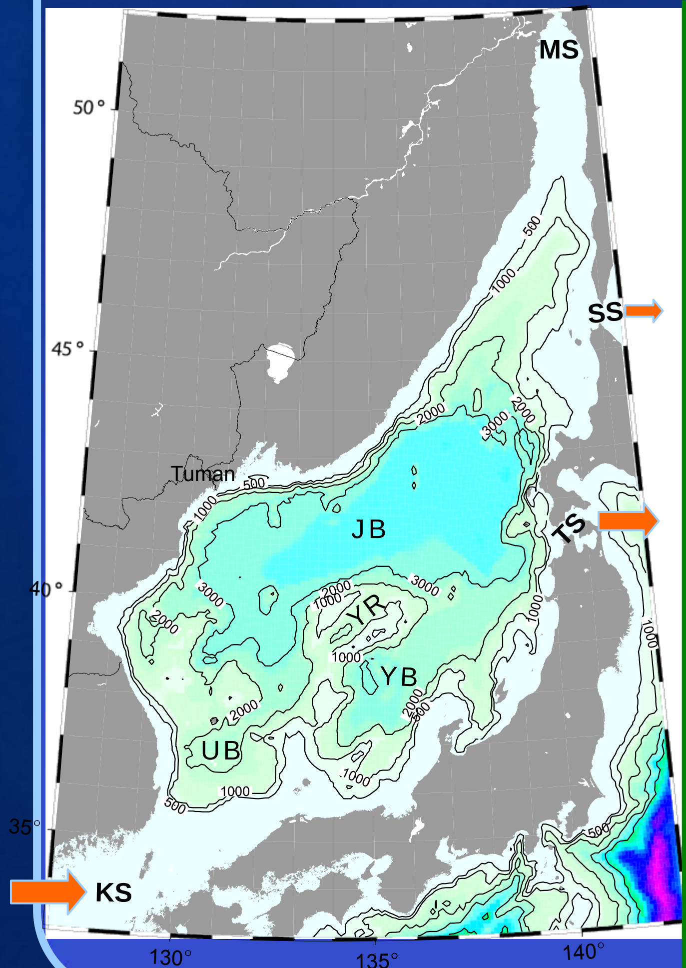




East Sea Regional Ocean Model (ESROM)

ESROM

Horizontal Domain (127.5 ~ 142.5 °E, 33.0 ~ 52.0 °N)
Horizontal resolution: 0.06~0.1º(zonal), 0.1º (meridional)
Modelling periods: 1993~2002



- Based on GFDL MOM3
  - ✓Z-coordinate level model
  - ✓Parallel Processing (MPI)
  - ✓Hydrostatic and Boussinesq approximations
- Open Boundary Conditions
  - ✓Barotropic velocity of inflow and outflow – Estimated from the transport estimated by submarine cable
  - ✓Baroclinic structure of inflow – historical hydrography
- Surface Boundary Conditions
  - ✓Heatflux - Calculated from meteorological variables by Bulk Formula
  - ✓Saltflux - Restoring to observed SSS
  - ✓Windstress - ECMWF
- Features
  - ✓Explicit free surface
  - ✓Smagorinsky SGS for momentum
  - ✓Robert-Marshall Isoneutral SGS for tracers
  - ✓KPP Vertical SGS Parameterization
  - ✓Partial cell

Surface Boundary Condition

ESROM

Forced by monthly mean Surface Boundary Conditions and Open Boundary Conditions

Heatflux – Bulk Formula

$$Q_{net} = Q_{sw} - (Q_{sen} + Q_{lat} + Q_{lw})$$

$$Q_{sen} = \rho_a C_p^a C_h W_{10} (T_a - \theta_1)$$

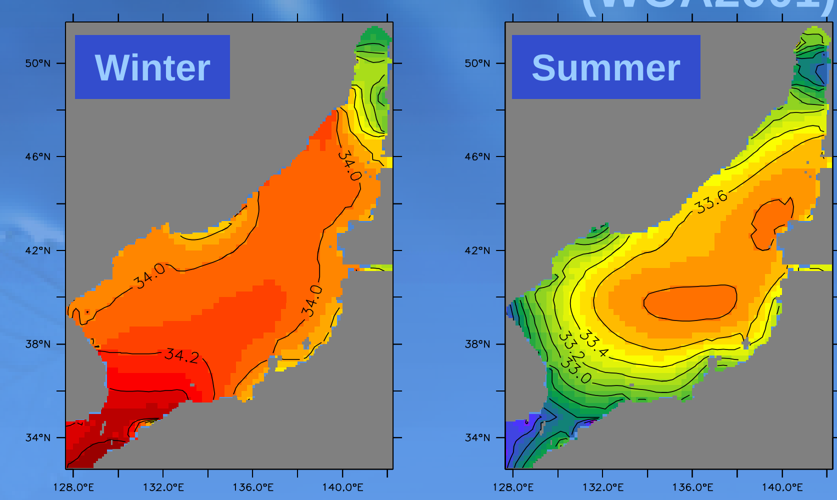
$$Q_{lat} = \rho_a L_e C_E W_{10} (q_a - q_1)$$

$$Q_{lw} = -\varepsilon \sigma_{SB} \left\{ T_a^4 \left[0.39 - 0.05 (e_a)^{0.5} \right] F(c) + 4 T_a^3 (\theta_1 - T_a) \right\}$$

Saltflux – Restoring to SSS

$$S_{surf}^{\tau+1} = \gamma \left(S_{obs} - S_{surf}^{\tau} \right)$$

(WOA2001)

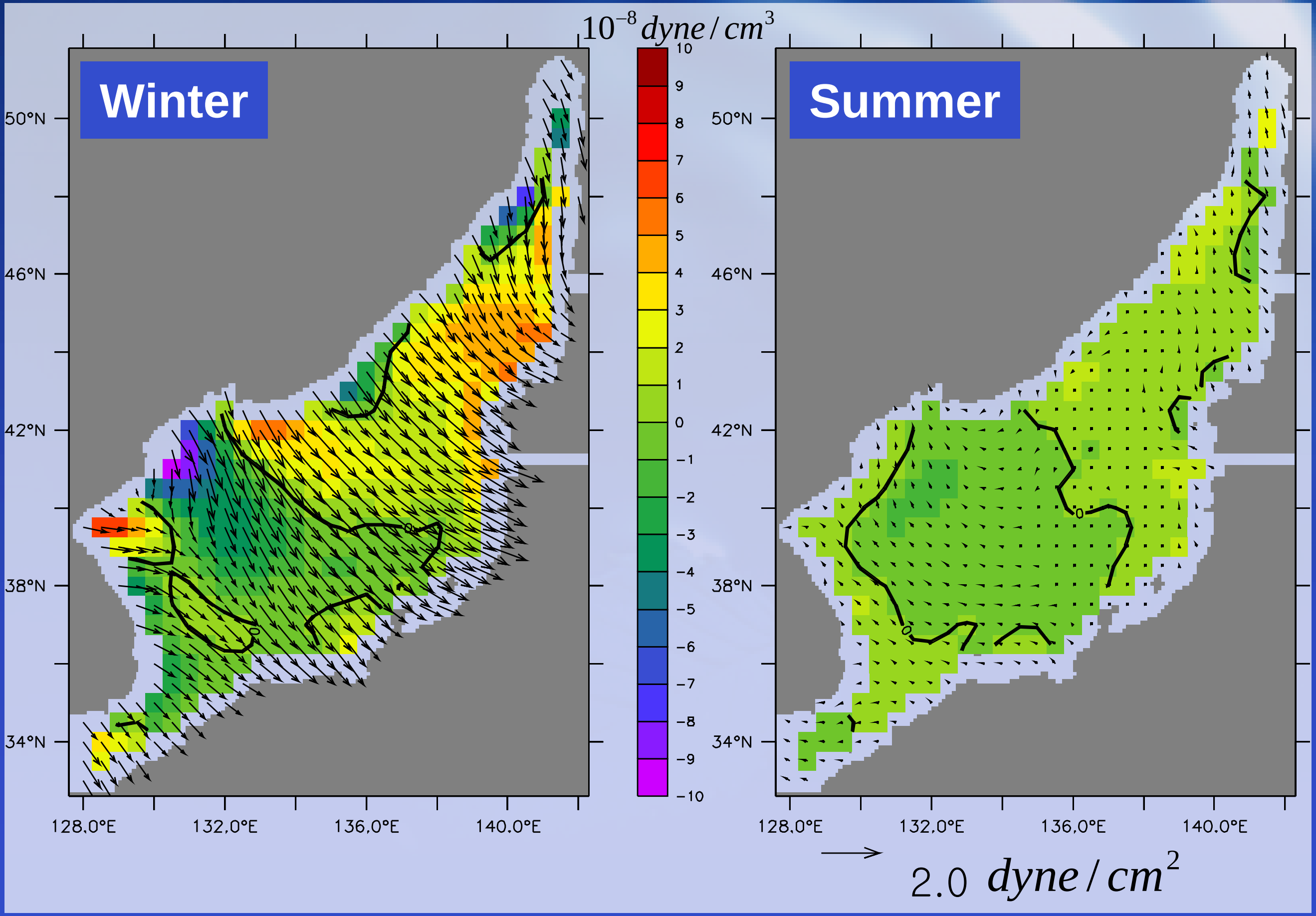


Large, William G., et. al., 1997, Sensitivity to Surface Forcing and Boundary Layer Mixing in a Global Ocean Model : Annual-Mean Climatology, J. of Phys. Oceano., vol. 27, 2418-2447

Surface Boundary Condition

ESROM

Windstress (ECMWF)



Open Boundary Conditions

ESROM

- Radiation condition for the tracers and barotropic velocity

$$\frac{\partial \phi}{\partial t} + C_x \frac{\partial \phi}{\partial x} + C_y \frac{\partial \phi}{\partial y} = 0$$

$$C_x = \frac{\partial \phi}{\partial t} \frac{\partial \phi / \partial x}{\left(\partial \phi^2 / \partial x^2\right) + \left(\partial \phi^2 / \partial y^2\right)}$$

$$C_y = \frac{\partial \phi}{\partial t} \frac{\partial \phi / \partial y}{\left(\partial \phi^2 / \partial x^2\right) + \left(\partial \phi^2 / \partial y^2\right)}$$

- An additional nudging term is added for the influxes

$$\frac{\partial \phi}{\partial t} + C_x \frac{\partial \phi}{\partial x} + C_y \frac{\partial \phi}{\partial y} = -\frac{1}{\tau}\left(\phi - \phi^{ext}\right) \qquad \begin{array}{l} \tau = \tau_{out} \;\; if \;\; C_x > 0 \\ \tau = \tau_{in} \;\; and \;\; C_x = C_y = 0 \;\; if \;\; C_x < 0 \end{array}$$

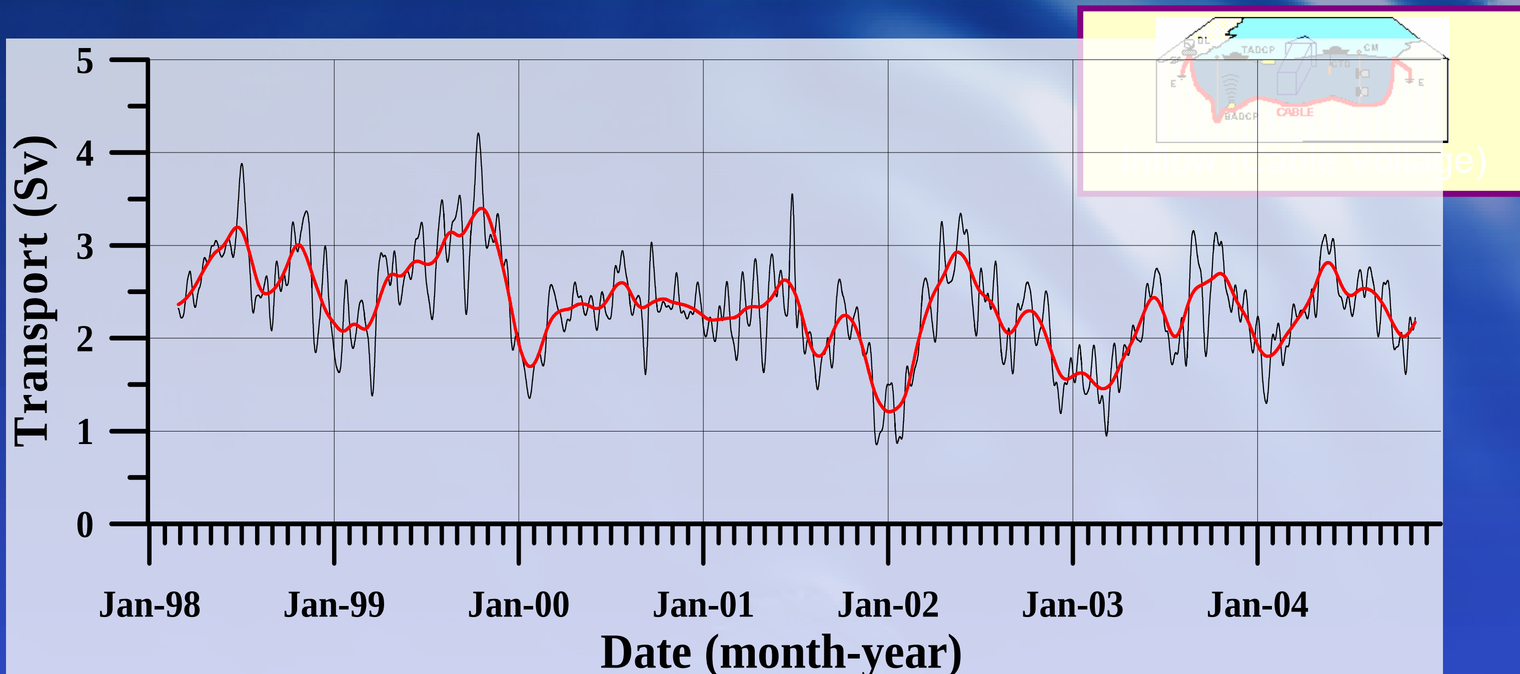
- Volume constraint

$$\frac{dV}{dt} = \frac{d}{dt}\left[\iiint_V dV\right] = \iint_{S_b} \vec{u} \cdot \vec{n} dS = \int_{L_b} h\vec{\bar{u}} \cdot \vec{n} dL$$

Marchesiello, P., McWilliams, J.C., and Shchepetkin, A. (2001) Open boundary conditions for long-term integration of regional oceanic models, *ocean modeling*, 3: 1-20.

ESROM

Open Boundary Conditions



Volume transport through the Korea Strait by a submarine cable between Pusan and Hamada

Theoretical Implementation

3-DVar

Weaver and Courtier (2001)

- A central task in the development of a statistical data assimilation

Estimation of background error covariance

- Size of background error covariance matrix

: ~5 x 10^{11} (x 8 byte) = 4,000 Gbyte – **neither estimated completely nor even stored explicitly**

Modeling B matrix as a sequence of operators.

Correlation modeling on the sphere using a generalized diffusion equation

Theoretical Implementation

3-DVar

- Variational assimilation system with atmospheric models

Background error covariance - Correlation functions in terms of a spherical harmonic expansion

It is not practical for the ocean due to lateral boundary

- Assimilation system with oceanic model

Lorenc(1992, 1997) and Parrish et al.(1997) : Recursive grid-point filters (UKMO)

Derber and Rosati (1989) : Iterative Laplacian grid-point filter (NCEP)

☺ Very efficient and flexible for geographical variations

-_- Limited flexibility in the shape of the correlation function

difficult to make anisotropic

- Objectives : 3D univariate correlation models numerically efficient and sufficiently general; correlation functions with different shape (not just Gaussian), geographically variable length-scale, horizontal/vertical non-separability, and 3D anisotropy.

3D correlation model

3-DVar

- Vertical correlation model

$$L_R^v = \{I - \sum_{r=1}^{R} \kappa_r \Delta t_v (-D^v)^r\}^{M_v}$$, Diffusion equation

- 3D covariance operator

$$L_R^v W_v^{-1} L_P^h W_h^{-1} = L_R^{v\,1/2} W_v^{-1} L_R^{v\,T/2} L_P^{h\,1/2} W_h^{-1} L_P^{h\,T/2}$$
$$= L_R^{v\,1/2} L_P^{h\,1/2} W_h^{-1} L_P^{h\,T/2} L_R^{v\,T/2}$$

$$C_\alpha^{1/2} = \Lambda L_R^{v\,1/2} L_P^{h\,1/2} W_h^{-1/2}, \quad C_\alpha^{T/2} = W_h^{-1} L_P^{h\,T/2} L_R^{v\,T/2}$$

- Sequence of operations for $C_\alpha^{1/2}$, Correlation model

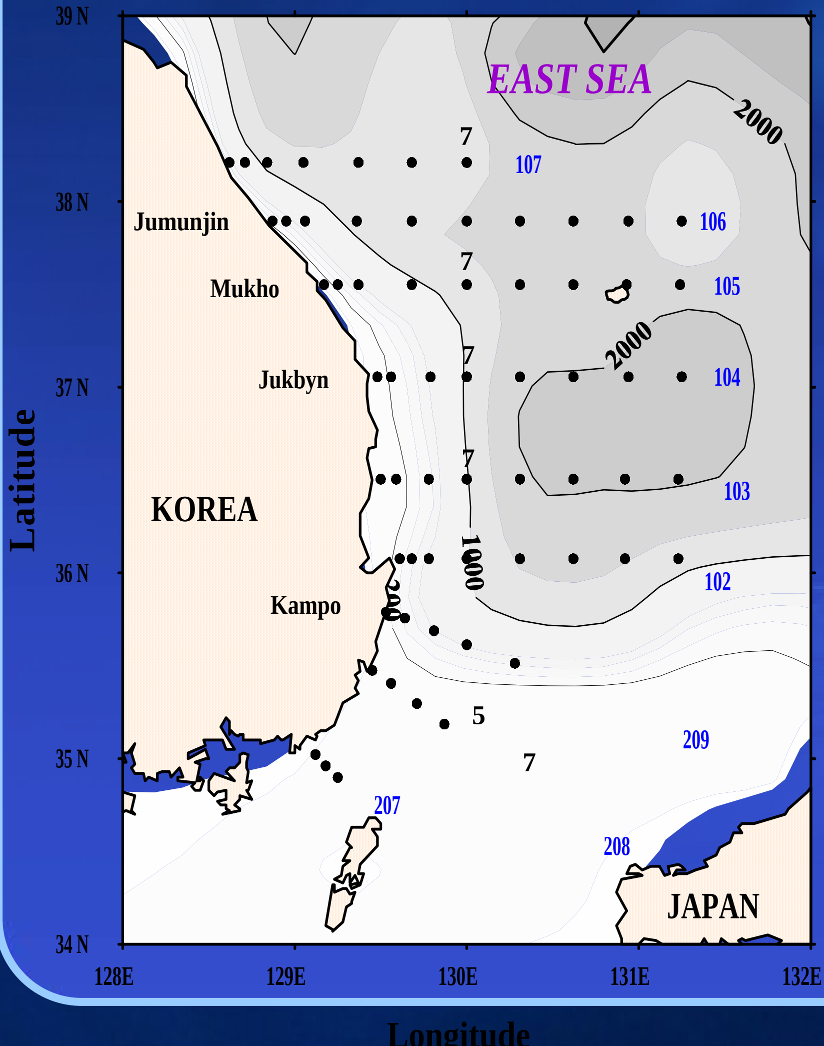
(i) Multiply each element of the input vector by the inverse of the square root of its associated volume element
(ii) Perform Mh/2 integration steps of the horizontal diffusion equation
(iii) Perform Mv/2 integration steps of the vertical diffusion equation
(iv) multiply each element of the filtered vector by it corresponding normalization factor

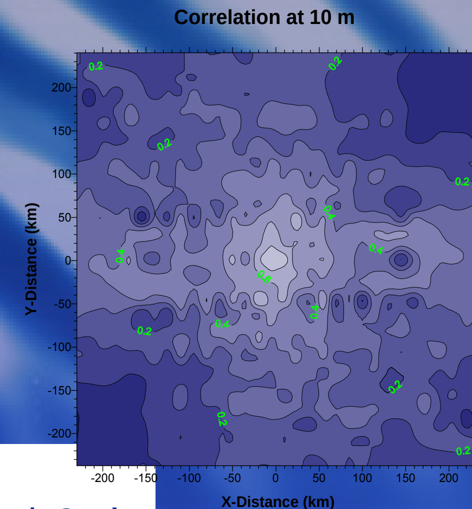
Applied in reverse order for $C_\alpha^{T/2}$ with adjoint code of the diffusion equation

De-Correlation Length Scale

3-DVar

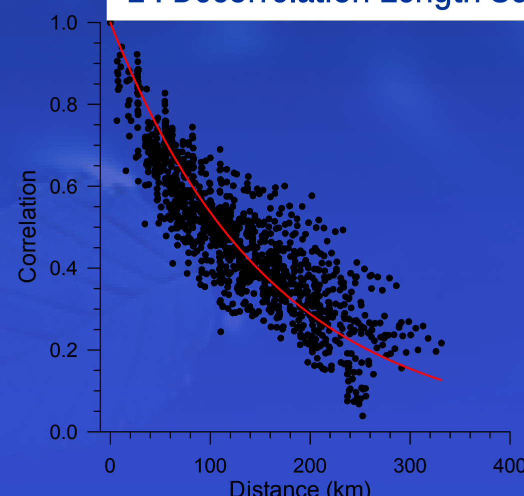
Characteristics of the hydrography taken by the NFRDI, Korea

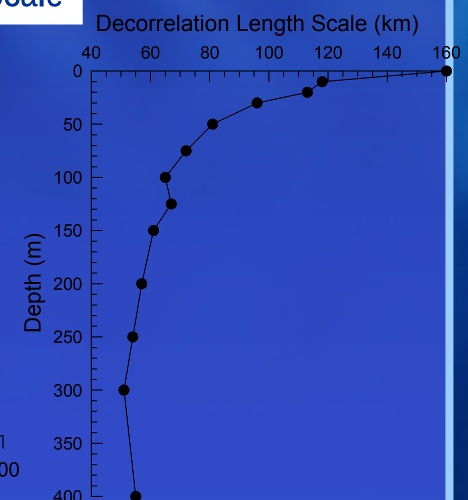




fn(r) = Exp(-r/L)

L : Decorrelation Length Scale





Horizontal Decorrelation Length Scale : 77 km

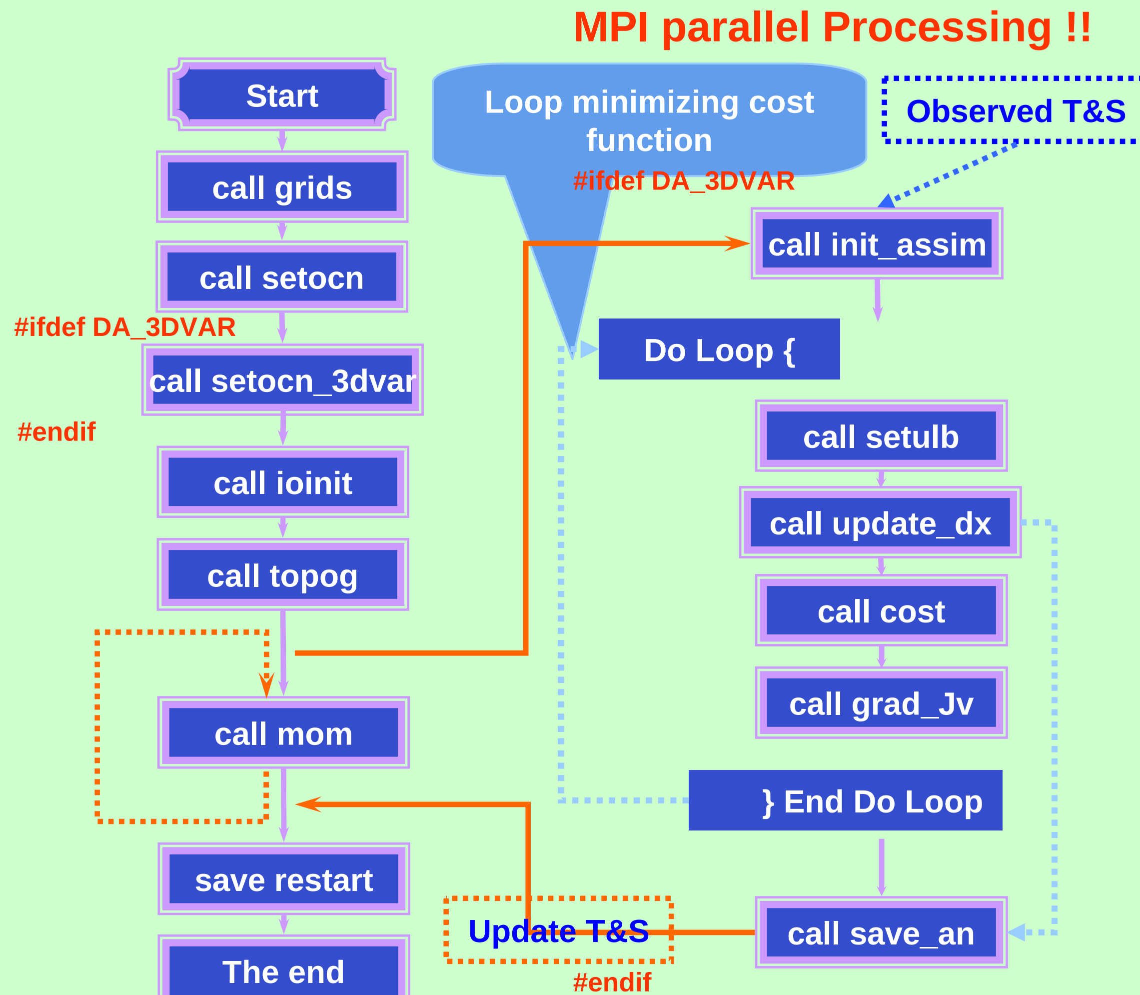
Vertical Decorrelation Length Scale : 77 m

3D-Var Assim. Sys. For East Sea Regional Ocean Model

3-DVar

Ocean Model Structure

Ocean Model & D.Assimilation Structure

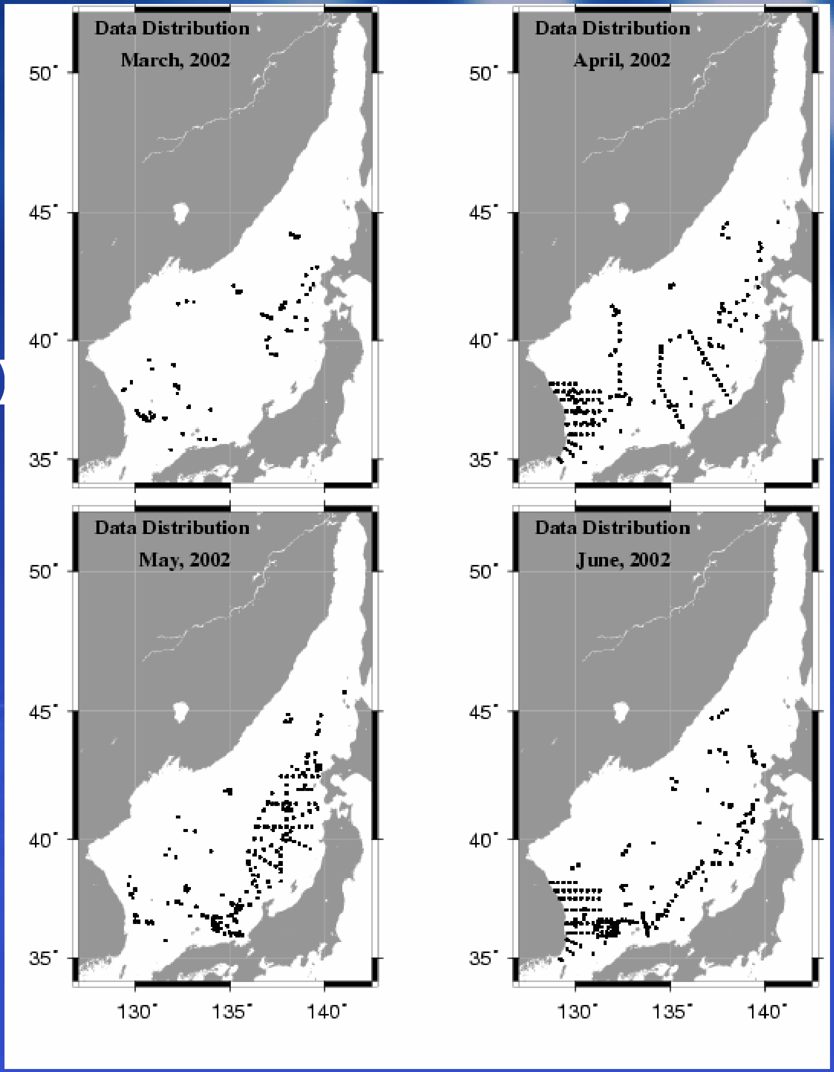


Data distribution

3-DVar

Reanalysis with

1. SST Satellite image
2. Temperature of CREAMS(SNU)
3. Temp. of NFRDI
4. Temp. of JODC
5. Temp. taken by ARGO floats



Theoretical Implementation

Cooper and Haines (1996)

Surface data assimilation problem – Requirement of a rearrangement of water parcels in space without modifying their T,S properties or their potential vorticity.

Hydrostatic connection between Δp_s and subsurface pressure updates,

$$\Delta p(z) = \Delta p_s + g\int_z^0 \Delta\rho dz$$

If we set $\Delta p(z=-H)=0$ as a bottom constraint, this will ensure that the bottom pressure and current distribution (through geostrophy) are not altered.

This bottom constraint gives the relationship

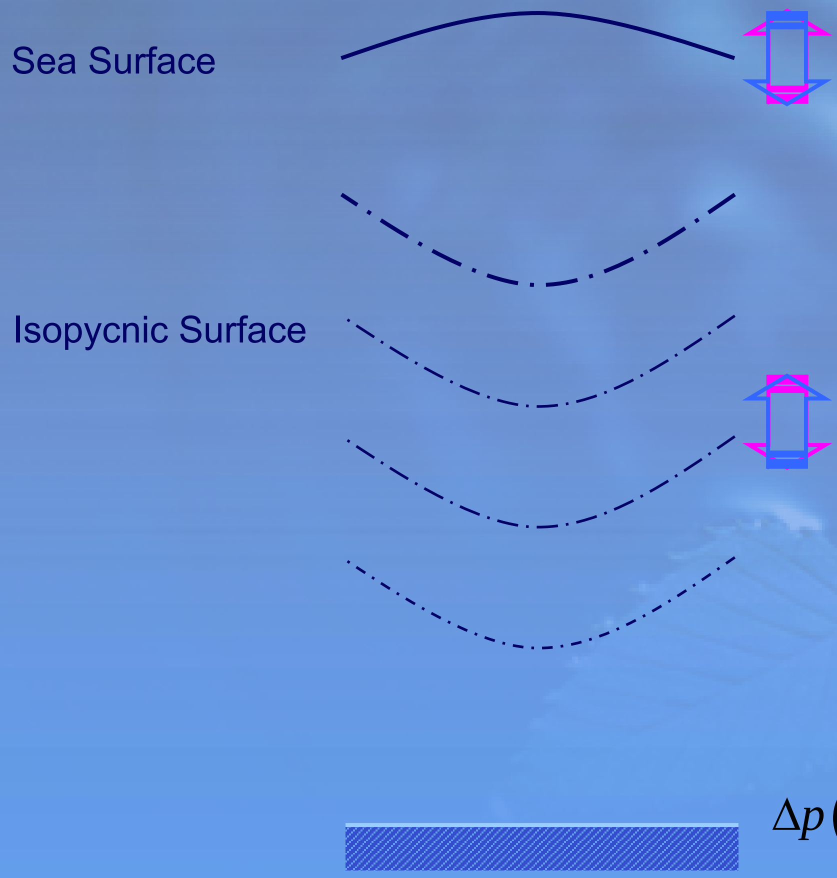
$$g\int_0^{-H} \Delta\rho dz = \Delta p_s$$

the change in weight of the entire water column should compensate for the change in surface pressure observed by the altimeter

3-DVar

Assimilating Sea Surface Height

Cooper and Haines (1996)



$$\Delta p_s = \rho_s g \eta$$

$$g\int_z^0 \Delta\rho dz$$

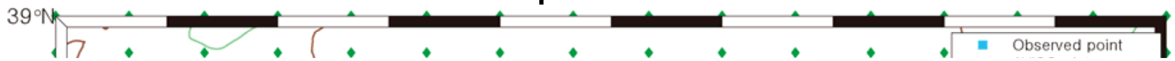
$$\Delta p\left(z=-H\right)=\Delta p_s + g\int_{-H}^0 \Delta\rho dz$$

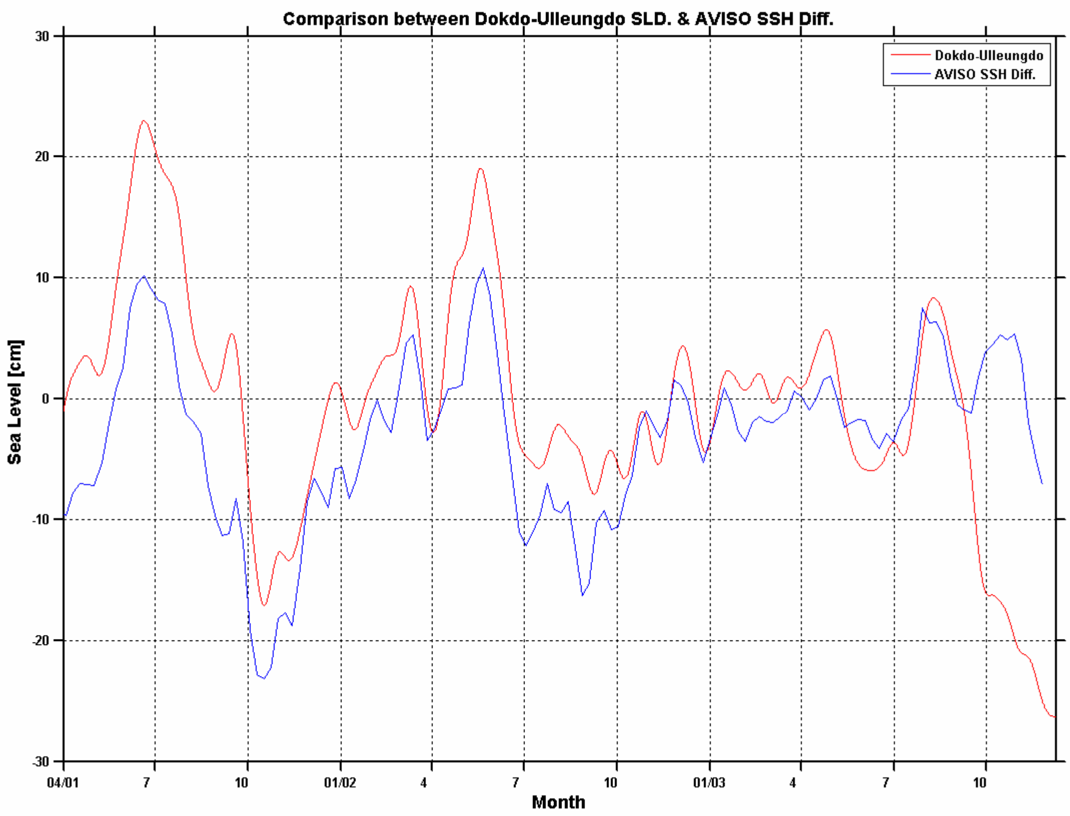
No Change of the Bottom Pressure !!!

Using AVISO Product

3-DVar

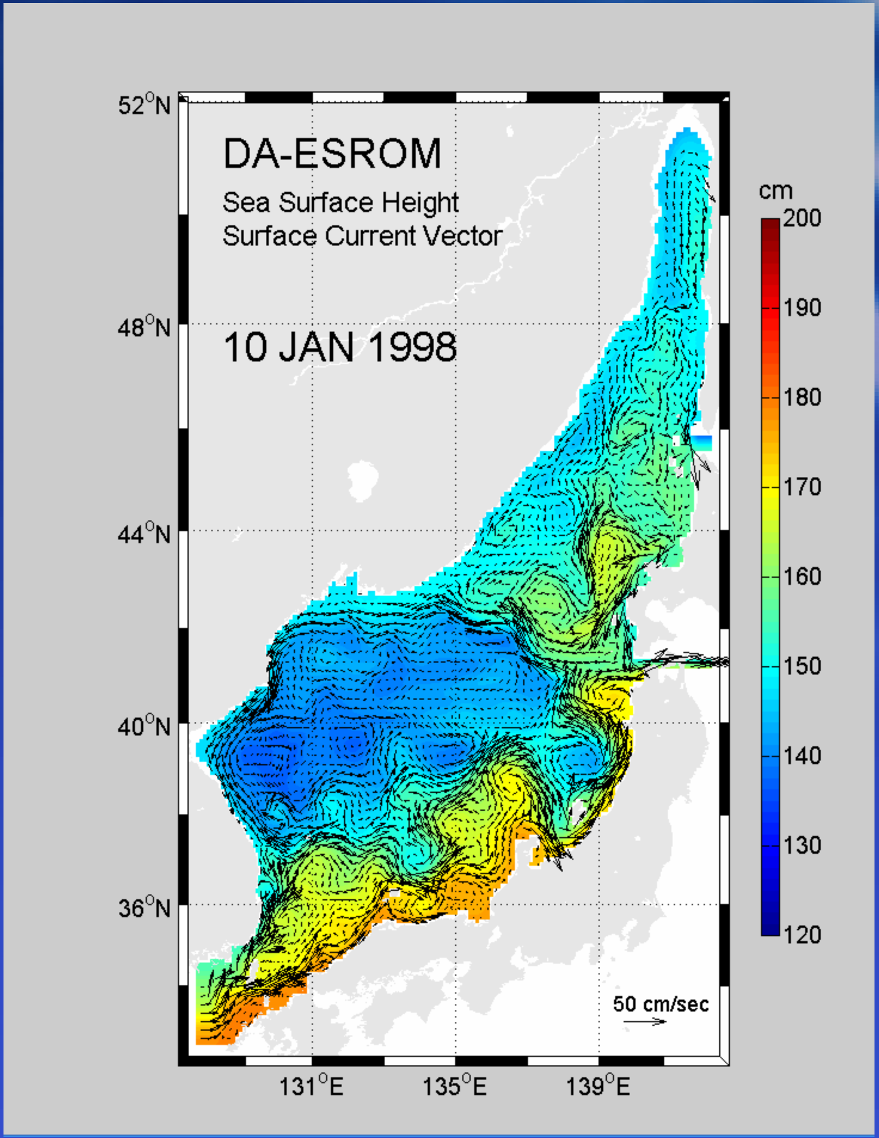
- Sea Level at Ulleung and Dok Islands
- Nearest point of the AVISO from Obs.





Surface current and Height (Model)

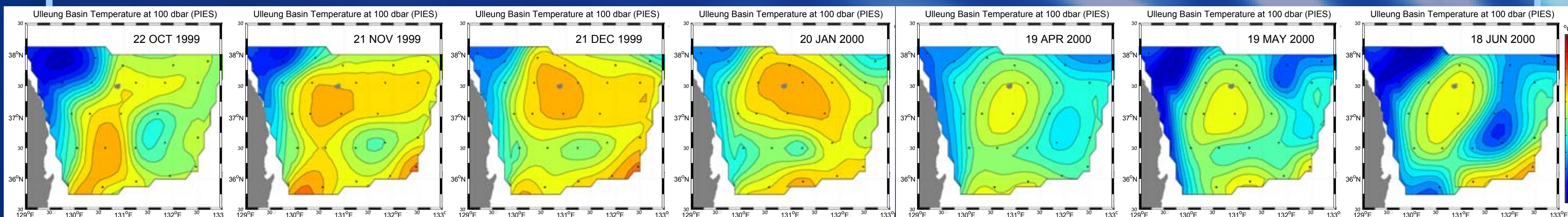
3-DVar



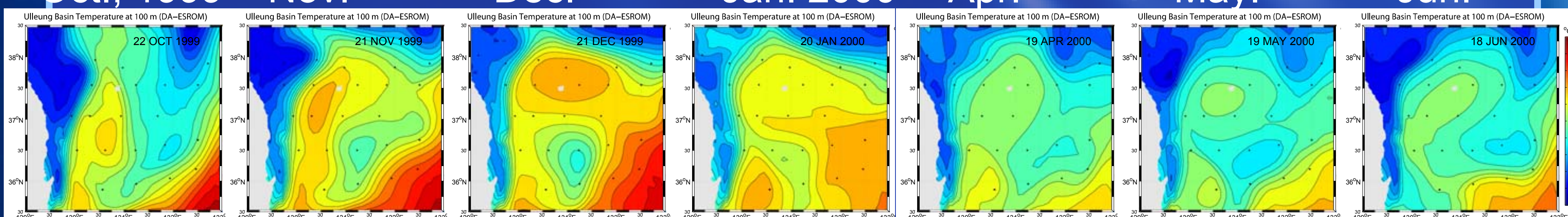
Comparison with Observation (100m)

Validation

PIES measurement



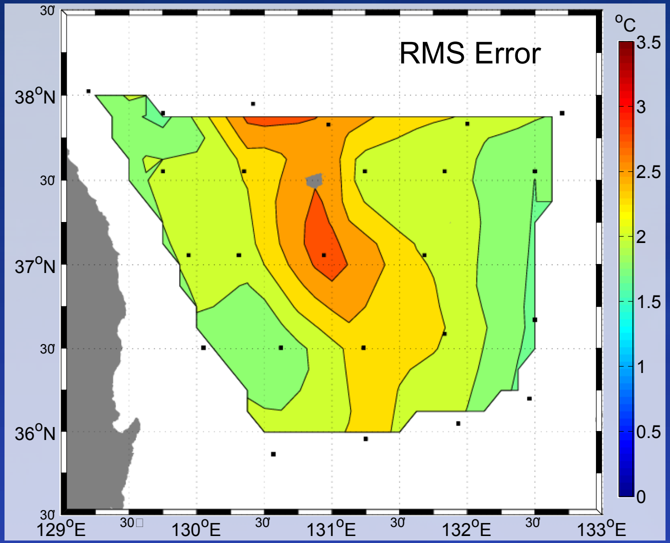
Oct., 1999 Nov. Dec. Jan. 2000 Apr. May. Jun.



Reanalysis Product by DA-ESROM

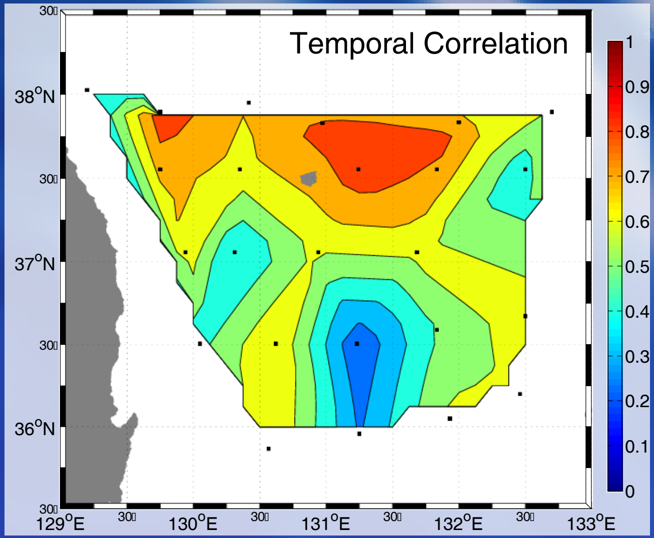
Comparison with Observation (100m)

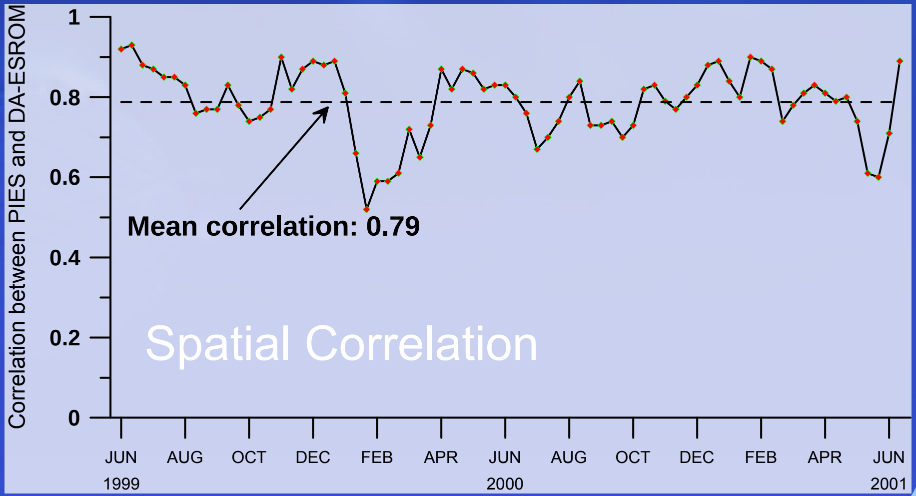
Validation



RMS Error between PIES measurements and reanalysis

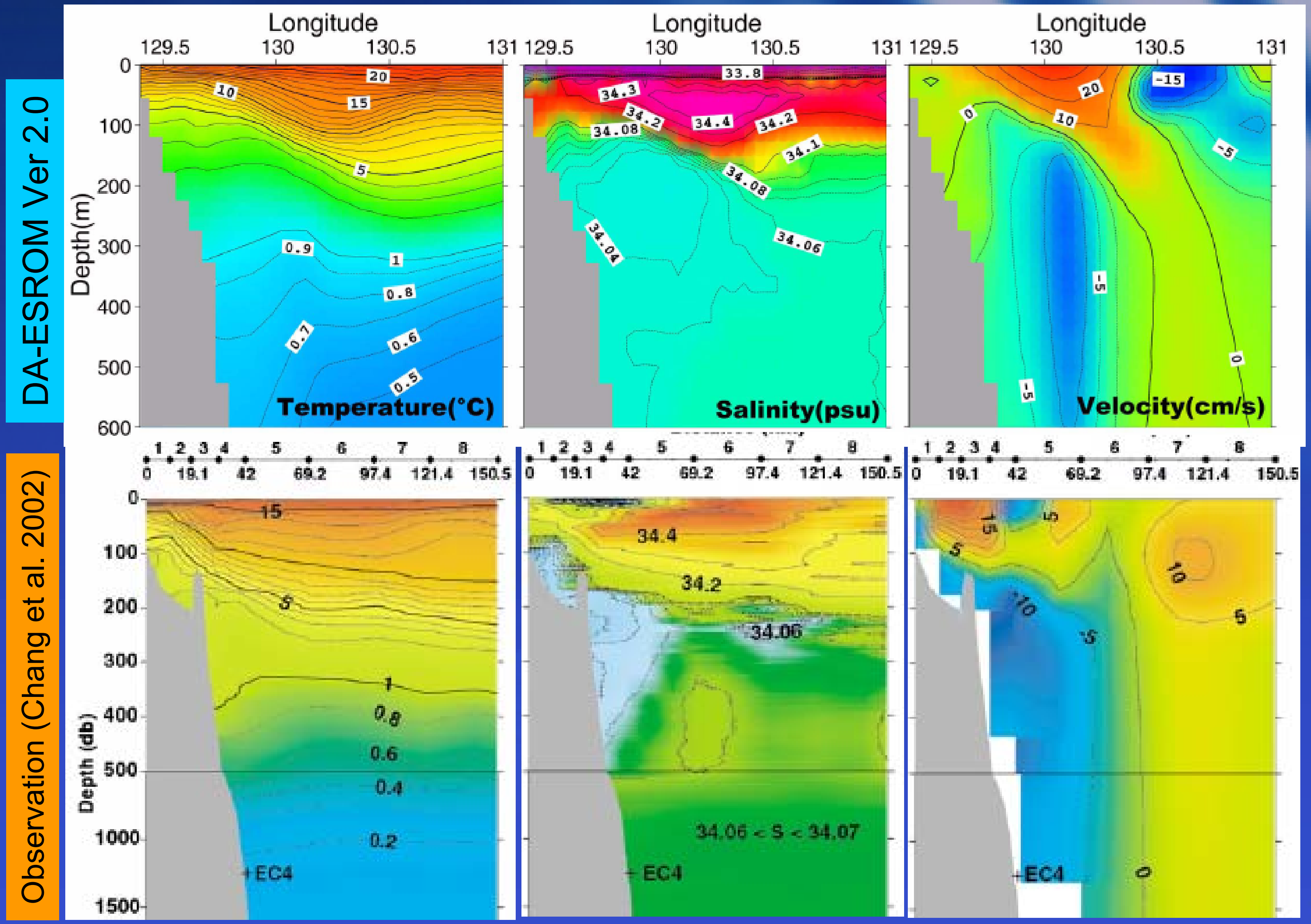
Spatio-temporal correlation





Model & Data Comparison at 36.8˚N (May, 2000)

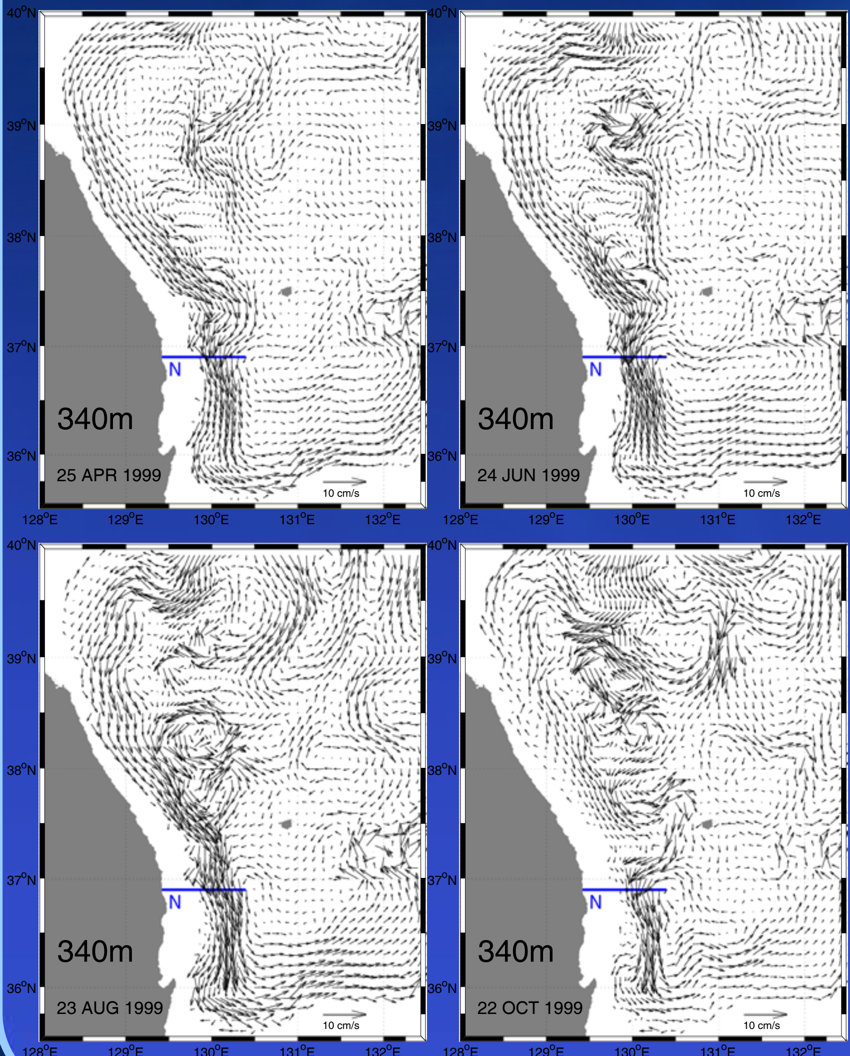
Validation



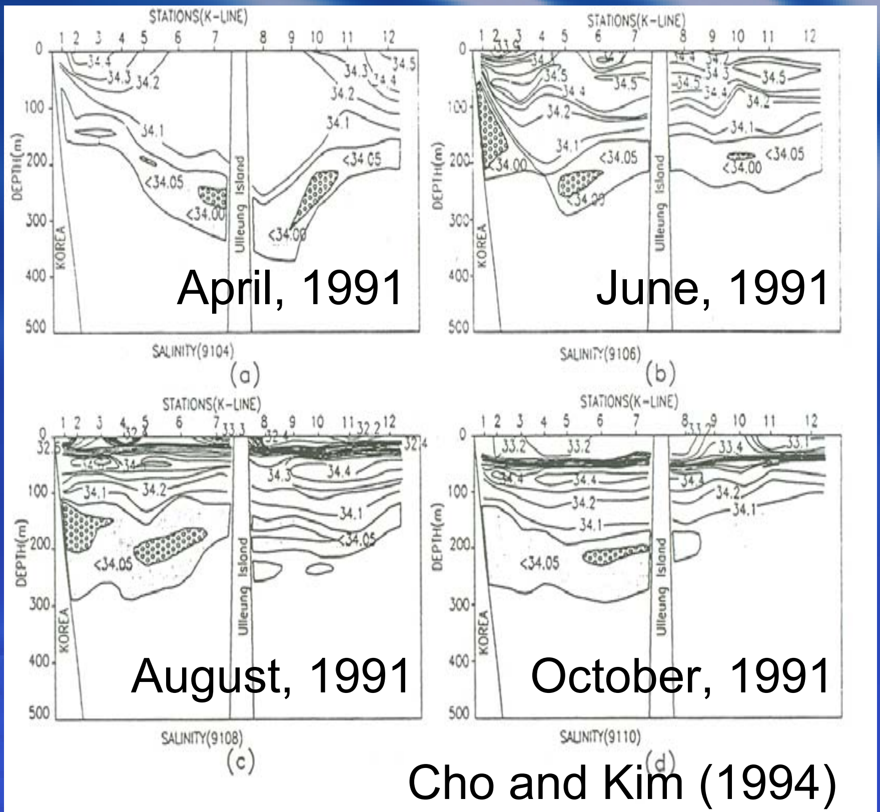
Strengthening of NKCC in summer

Validation

Reanalysis (DA-ESROM)



Salinity section (Observation)

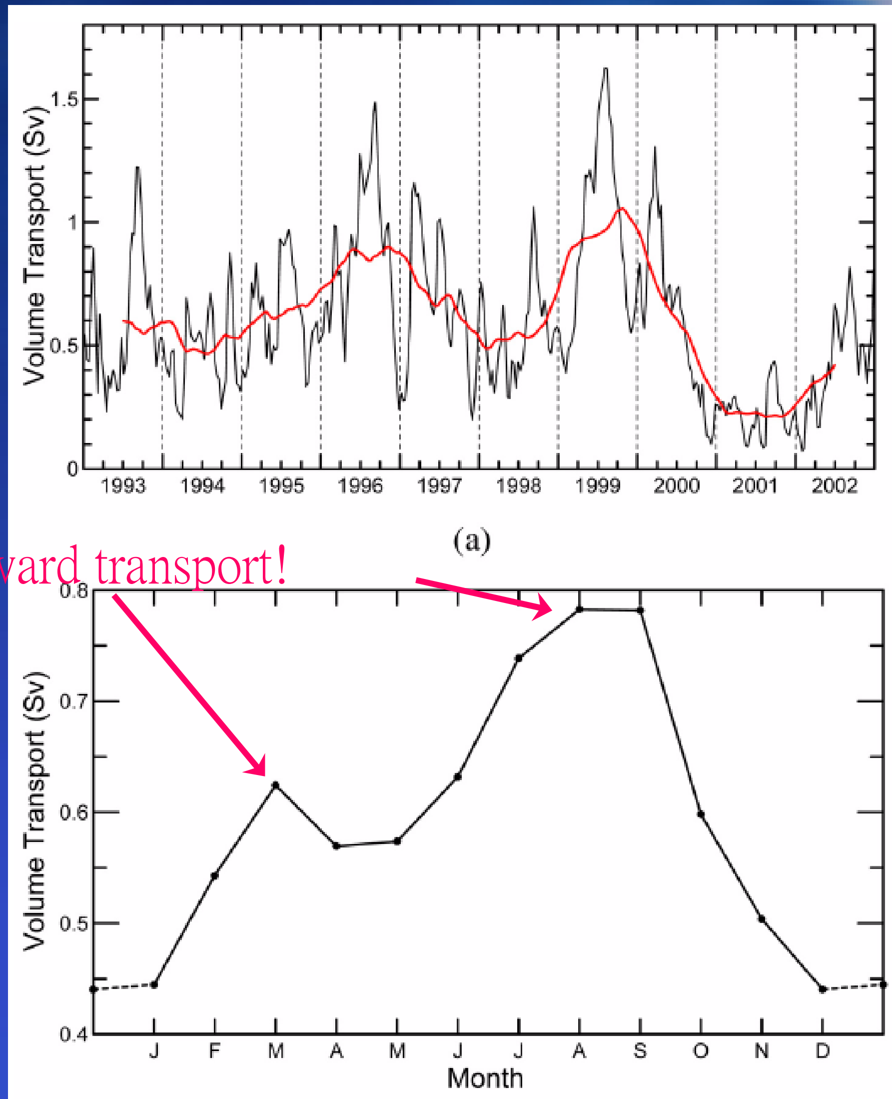


- **Southward advection** of the Low Salinity Minimum Water (**North Korean Cold Water**) **in Summer.** (Kim and Kim, 1983)

Seasonal and Interannual variation

Validation

Maximum southward transport!



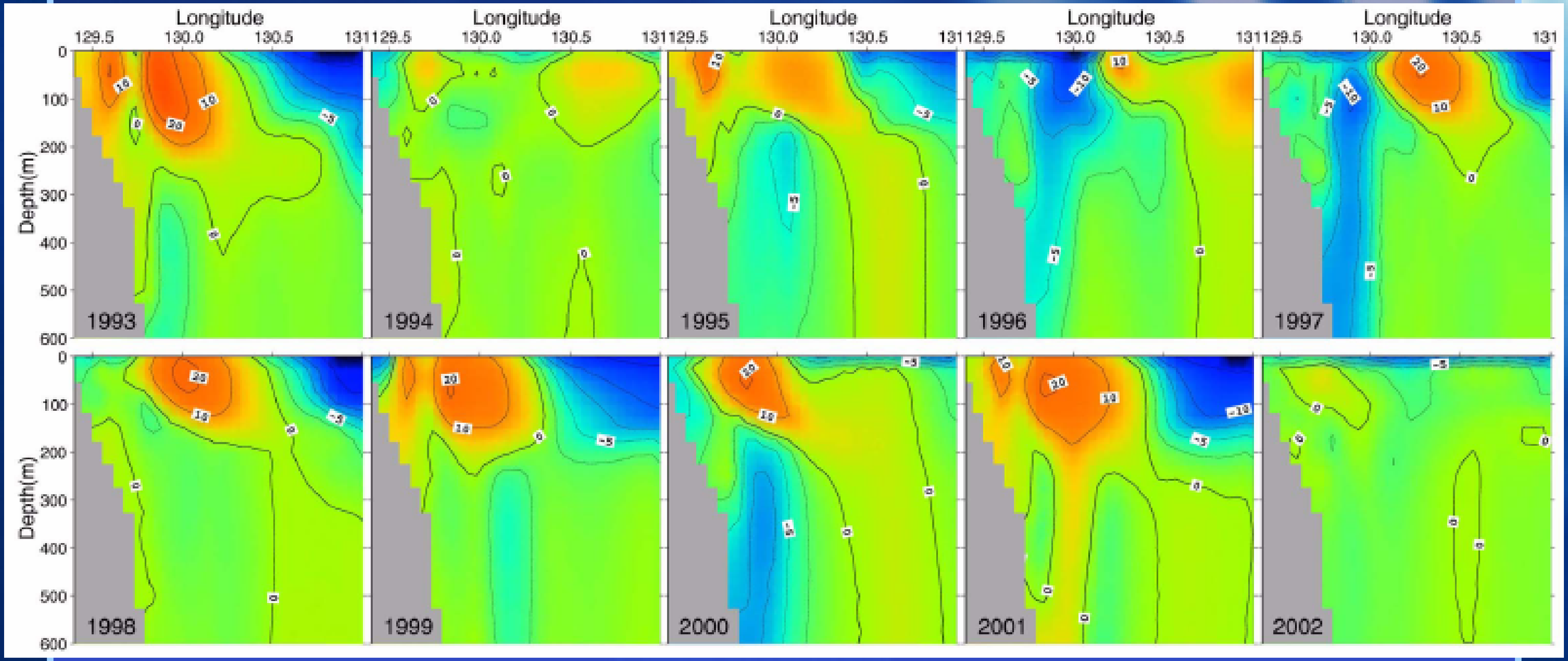
(a)

(b)

Volume Transport of NKCC across N line

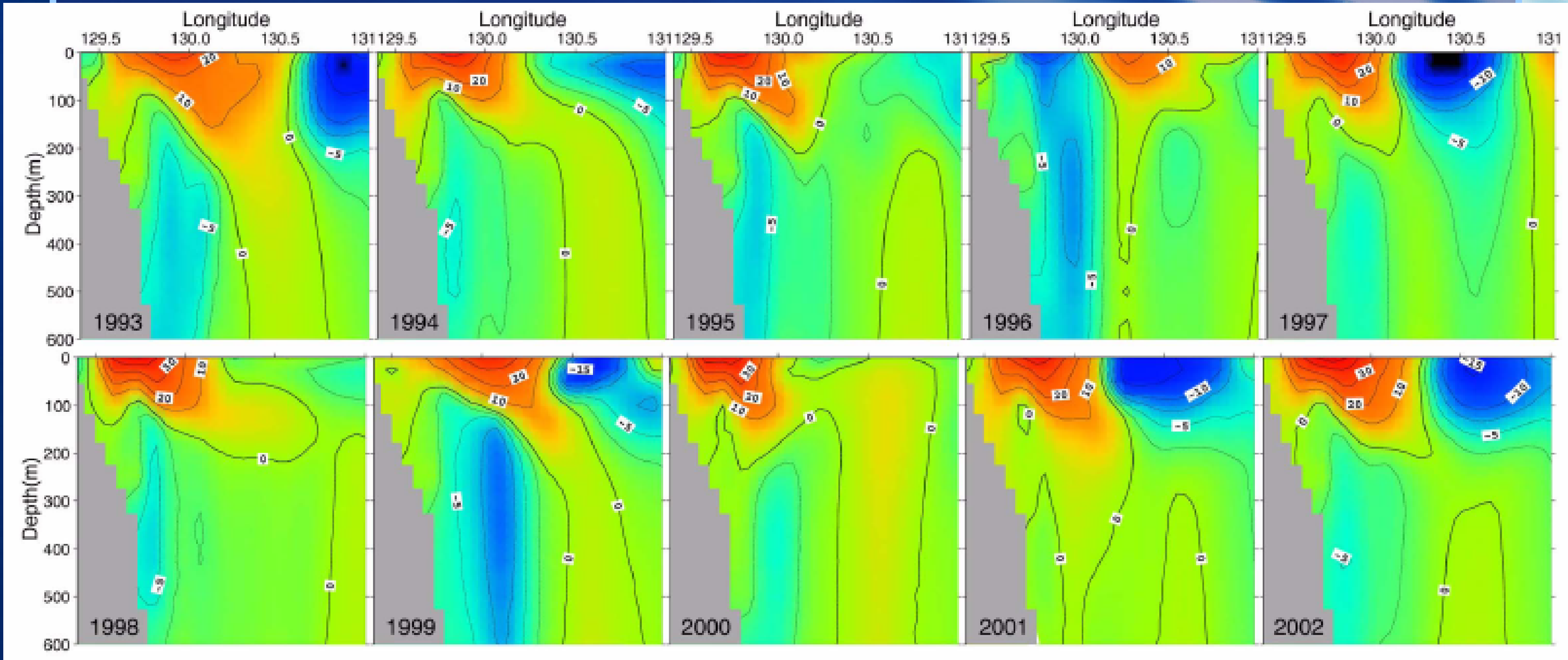
Interannulation variation of NKCC in March

Validation



Interannulation variation of NKCC in August

Validation



4 Future Work : Ensemble Kalman Filter

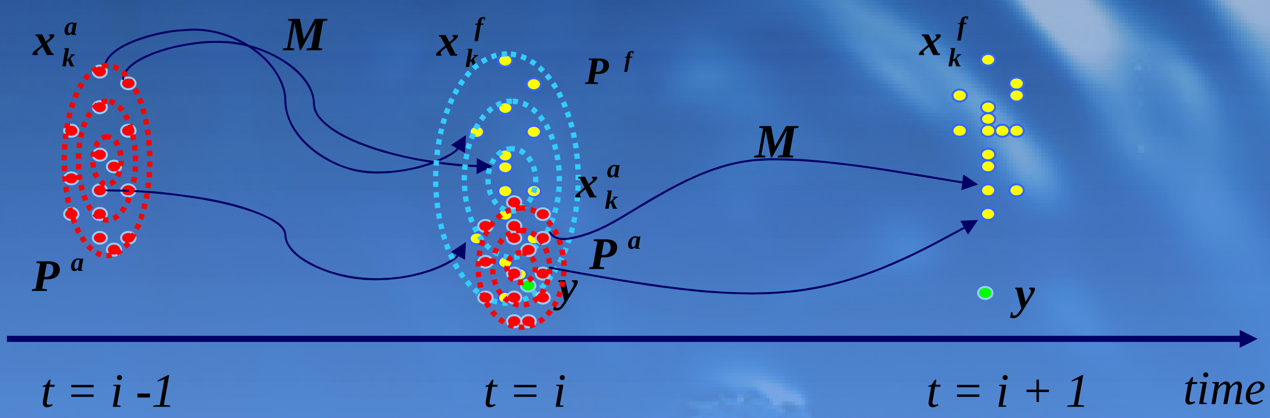
Introduction of Ensemble Kalman Filter

EnKF

P.L. Houtekamer and Herschel L. Mitchell (2001)

$$P^f(t=i) \approx \Psi^f(t=i)\Psi^{f^T}(t=i) : [N \times N_e][N_e \times N]$$

$$x_k^a = x_k^f + \Psi^f \Psi^{f^T} H^T (H \Psi^f \Psi^{f^T} H^T + R)^{-1}(y - Hx_k^f), k = 1, 2, \ldots, N_e$$



Merit

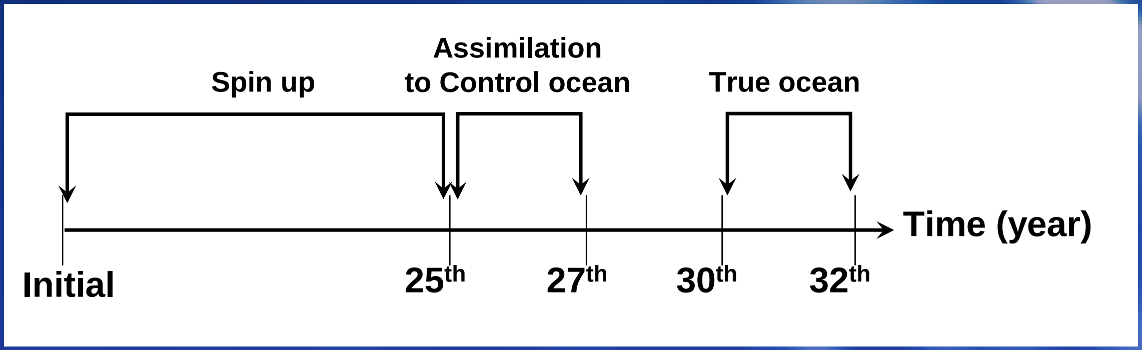
- Direct calculation of background error covariance from ensemble numerical models
- intuitive multi-variate background error covariance

Weak point

- Rank deficiency for not enough ensembles

Sensitivity Test (Twin Experiment)

EnKF

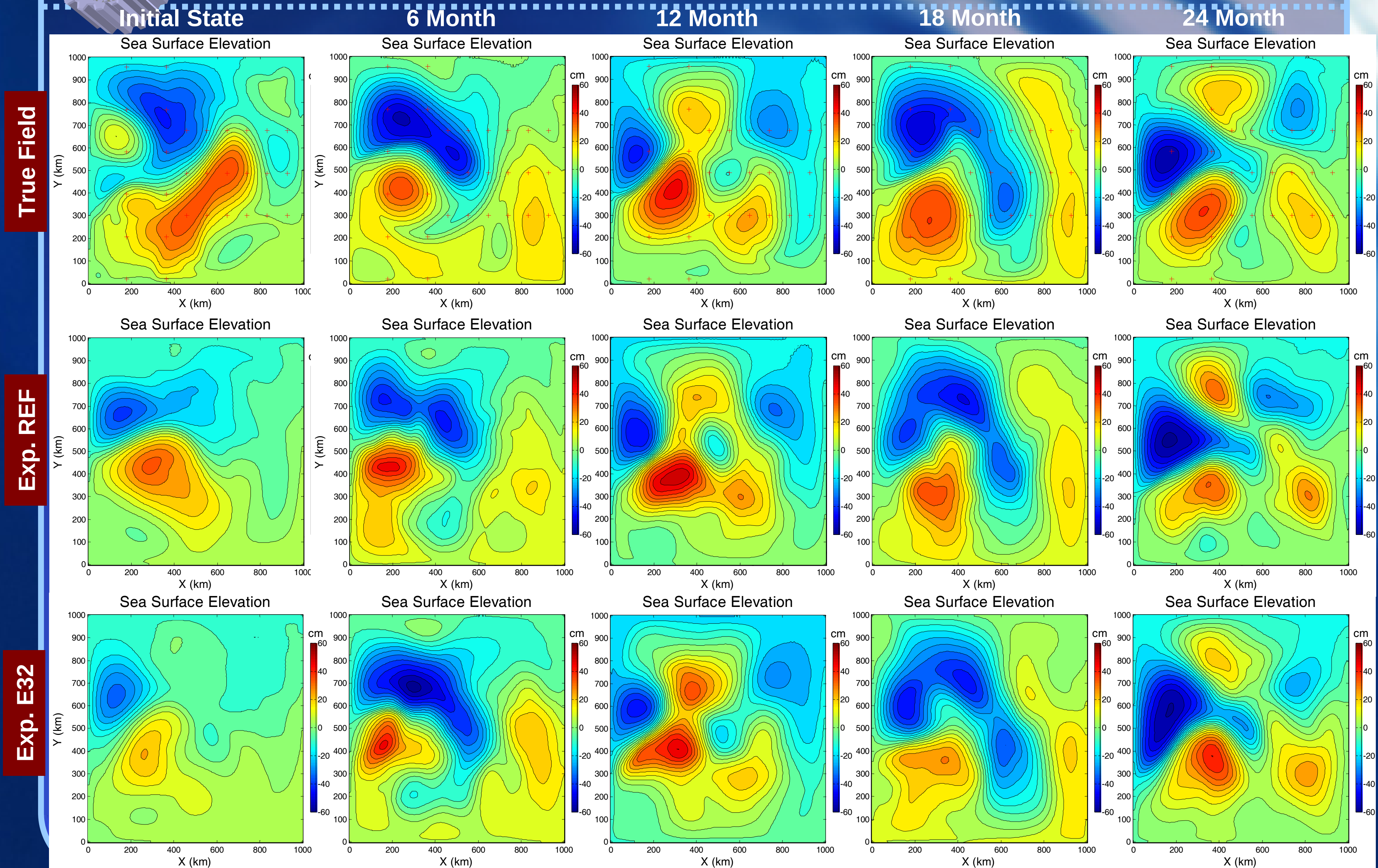


Experiment Design

	Num. of Ens. Mem.	Horizotal Local.	Vertical Local.	Cov. Inflation	SST Assim.	SSH Assim.	etc
E32	32	O	O	O	O	O	Success
REF	16	O	O	O	O	O	Success
HNLC	16	X	O	O	O	O	Overflow
VNLC	16	O	X	O	O	O	Unstable
CNINF	16	O	O	X	O	O	Success
ASSH	16	O	O	O	X	O	Success

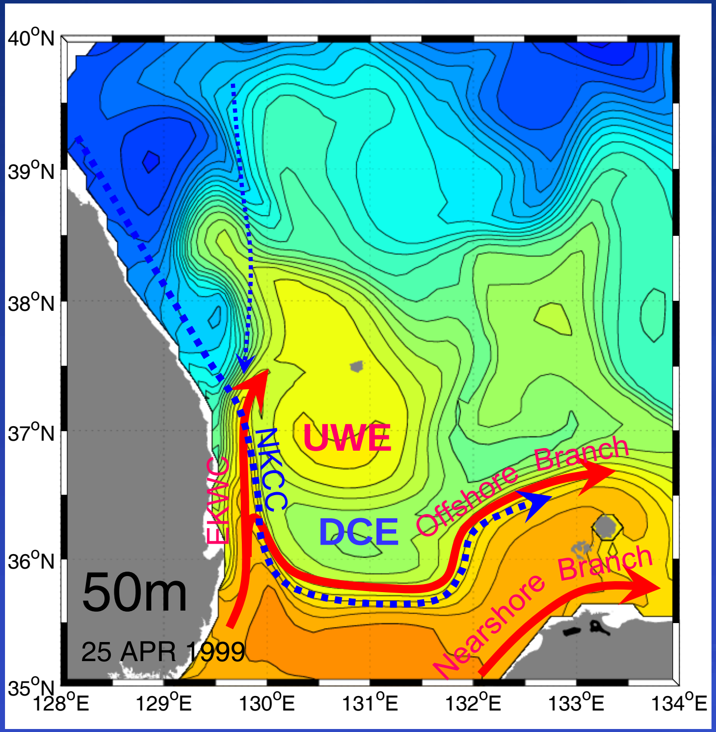
True vs. Model

EnKF



Implementation and validation of 3D-Var System

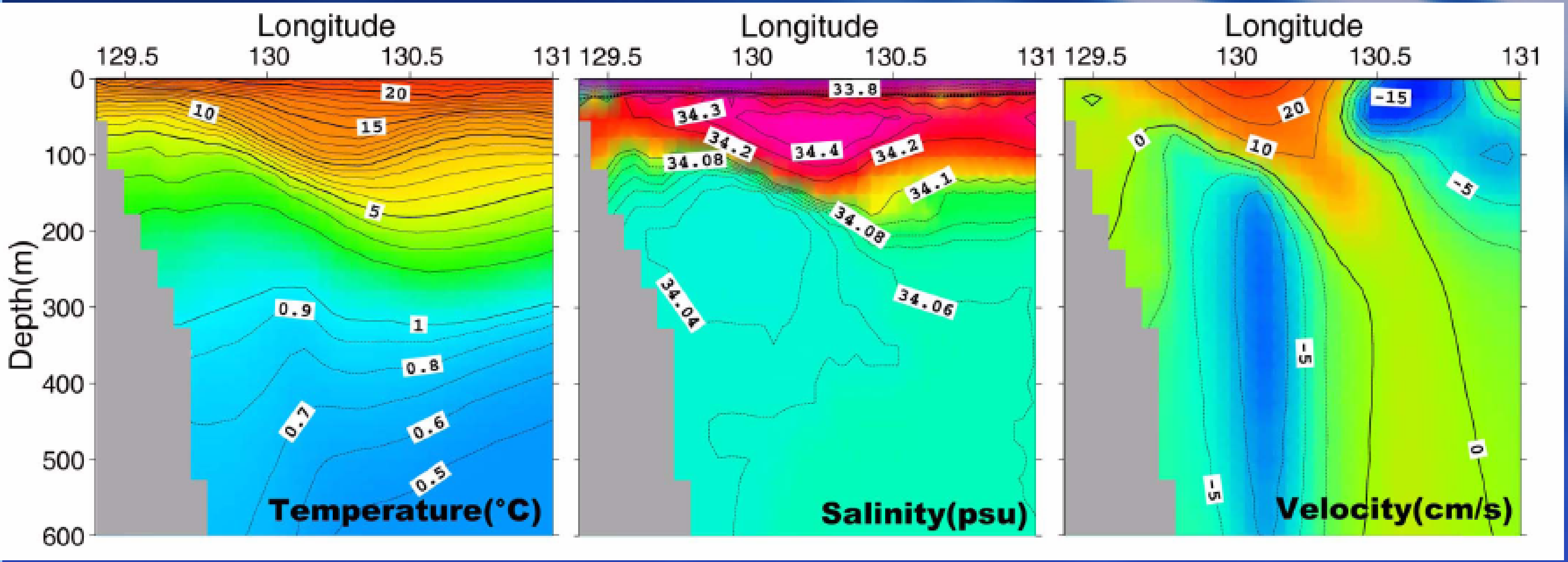
Conclusion

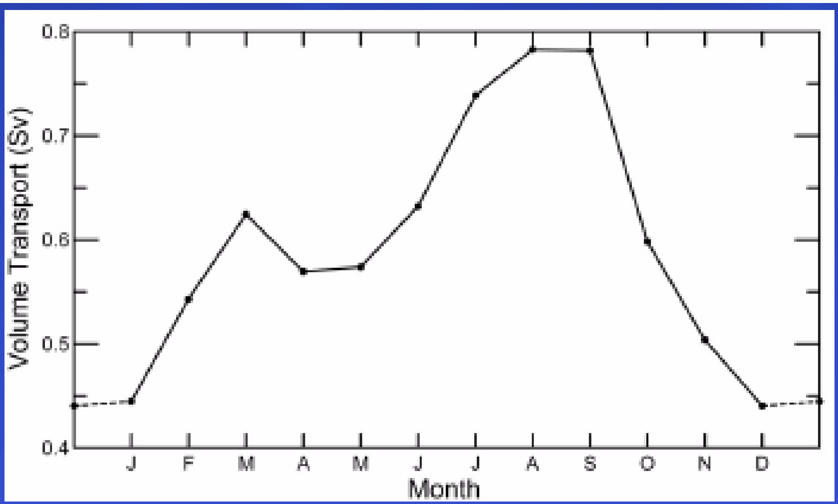


1. New scheme for SSH Anomaly assimilation
2. Reproduction of the NKCC in summer
3. Reproduction of mesoscale eddies in Ulleung Basin
4. Comparision with PIES observation at 100m
   - RMS error : 2.1℃
   - Correlation : 0.79

Spatio-temporal variation of the NKCC

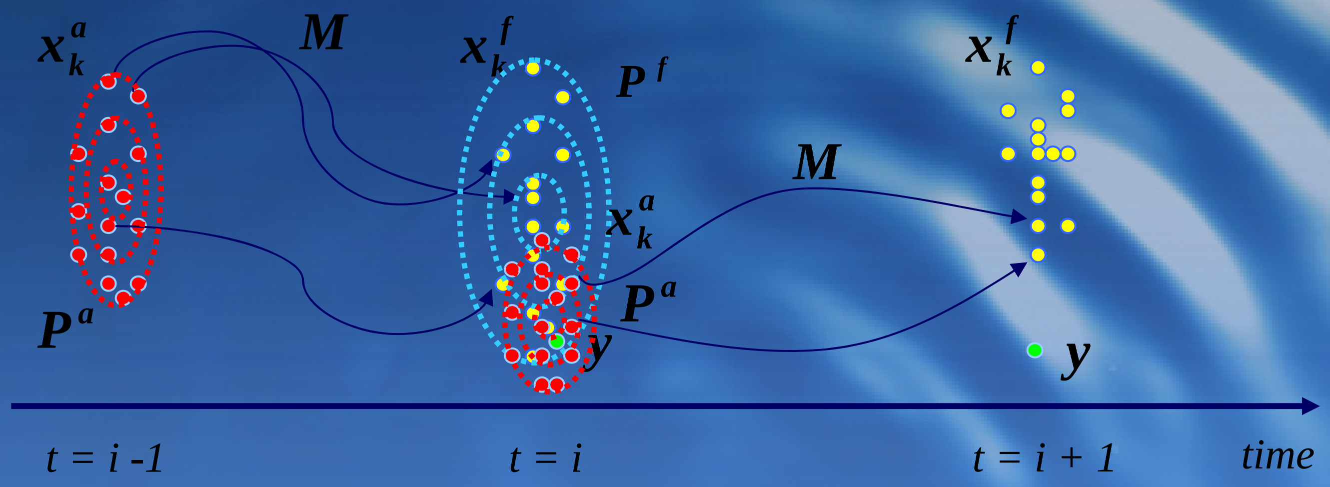
Conclusion





Implementation of EnKF (Ongoing project)

Conclusion



- Implementation of EnKF

1. Direct calculation of Background Error covariance
2. Based on nonlinear ocean model
3. Localization of background error covariance
4. Inflation of background error covariance

Thank you !