A numerical study on the winter mixed layer on the shelf-slope region south of Japan

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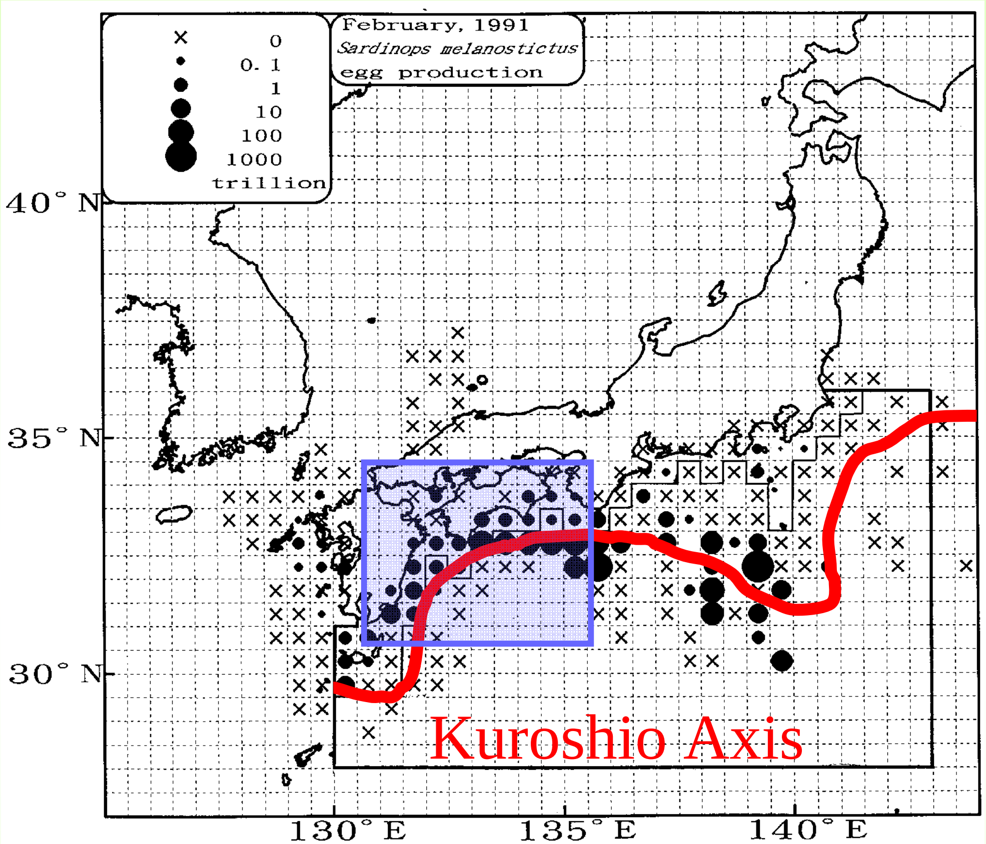
FRA
Fisheries Research Agency

Motivation of this study



Distribution of sardine eggs in February 1991
(Watanabe et al., 1997)

+January to March

Spawning season of sardine

+Main spawning ground

southwest of Japan

Inshore side of the Kuroshio

Missing Link

+Oceanographic condition

Developed winter mixed layer

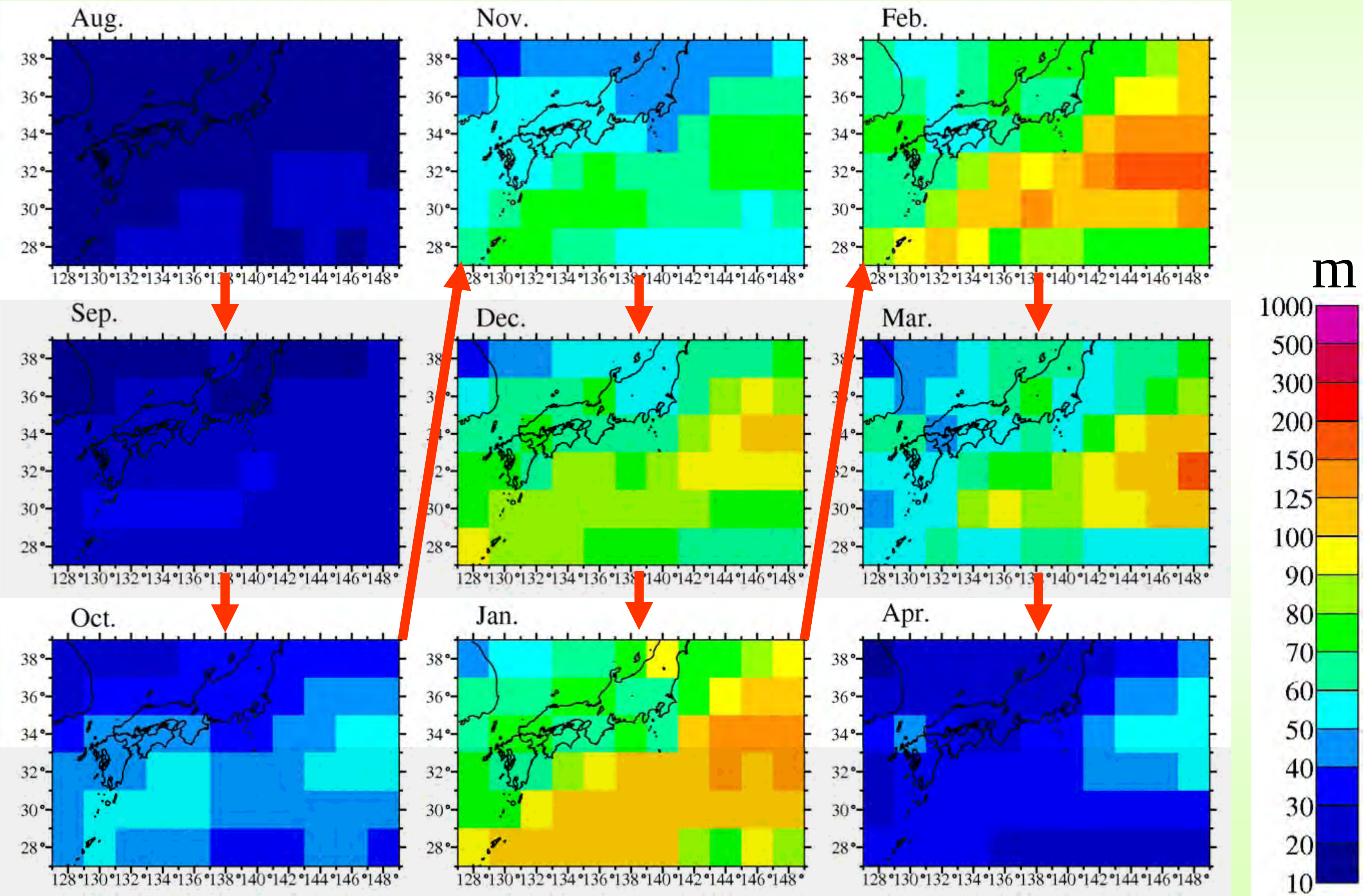
The aim of this study is

to examine properties and dynamics of mixed layer variation

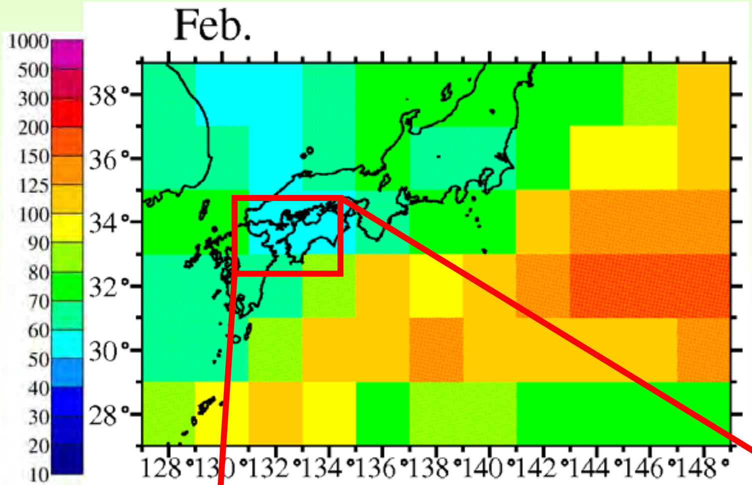
on the basis of high-resolution model

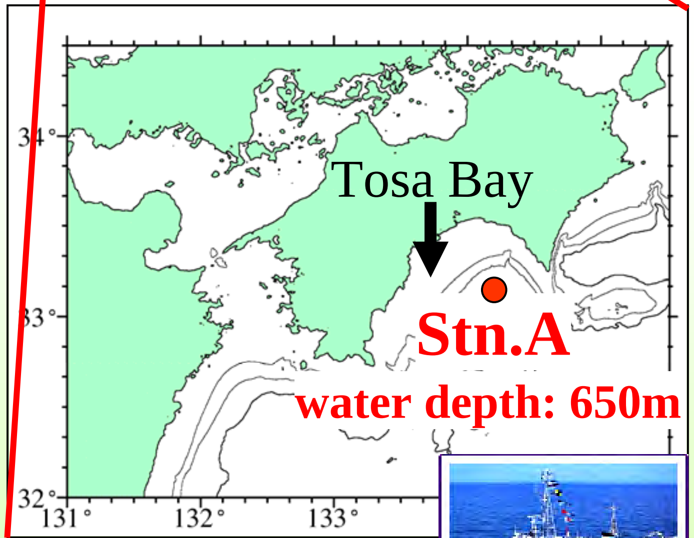
Climatological seasonal cycle of mixed layer depth ($2^\circ \times 2^\circ$)

de Boyer Montégut et al. (2004, JGR)



Data Analysis of monthly temperature profiles on the region southwest of Japan





R/V Kotaka-maru

Analysis Data

Station : Stn.A in Tosa Bay
Period : 1991~2004
Frequency : monthly after 1995
Instrument : CTD&STD&XBT
Vertical resolution : 1m

Definition of Mixed Layer Depth

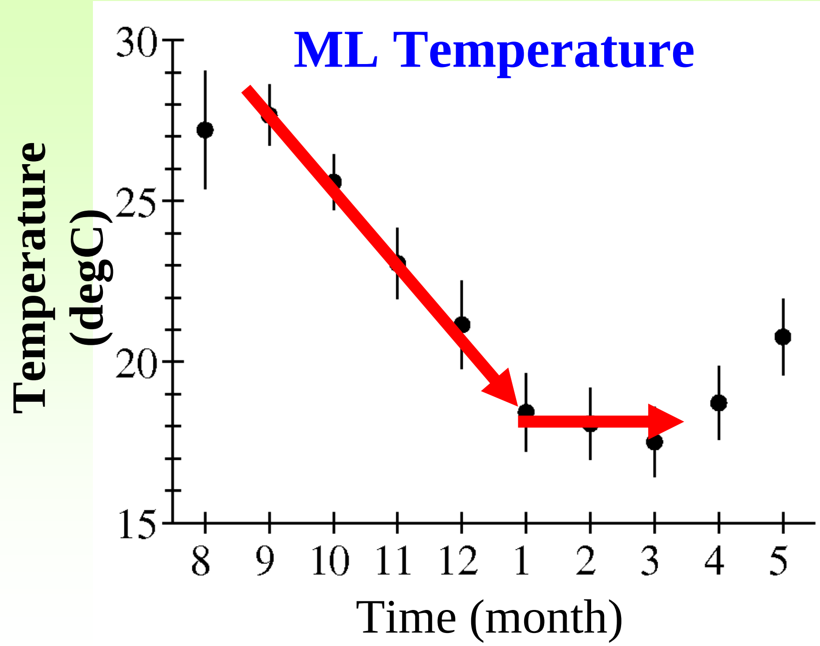
$$\Delta T = 0.2\ {}^{\circ}\mathrm{C}$$

The same criterion is used in de Boyer Montégut et al. (2004)

Monthly ML temperature & depth
at Stn.A in Tosa Bay

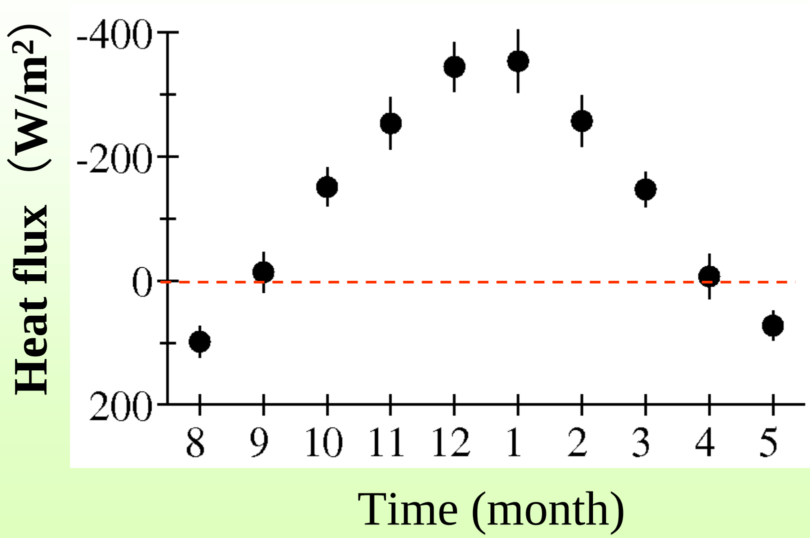
● : monthly mean
vertical bar : ±1 S.D.

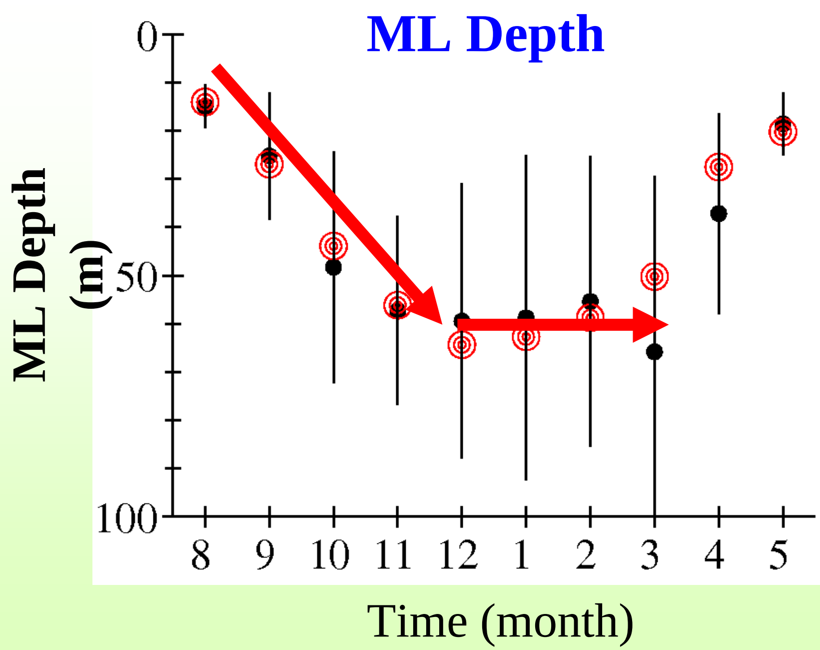
◎ : monthly climatology
de Boyer Montégut *et al*. (2004, JGR)



Net Heat Flux at the sea surface

estimated via bulk formulation (COARE)
using JRA25+GHRSST



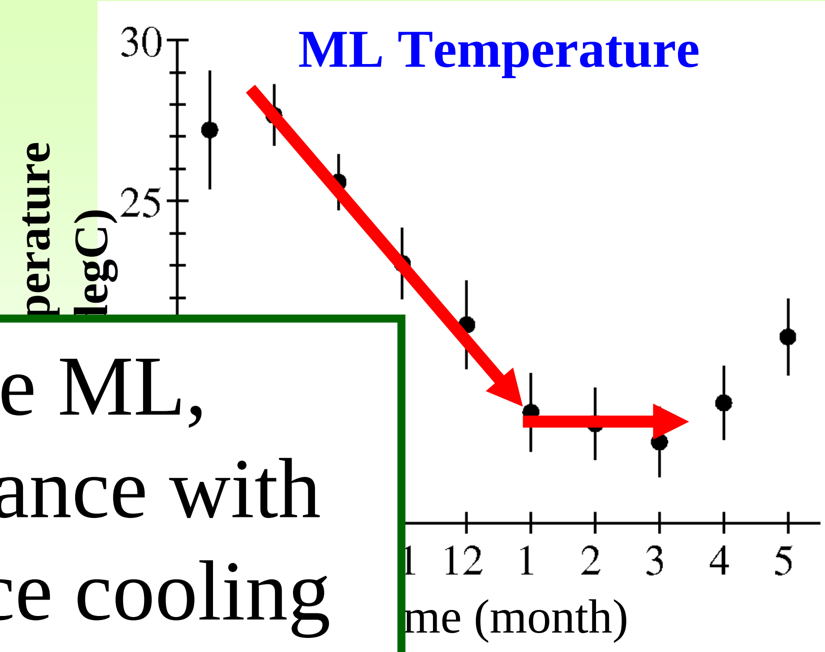


Monthly ML temperature & depth
at Stn.A in Tosa Bay

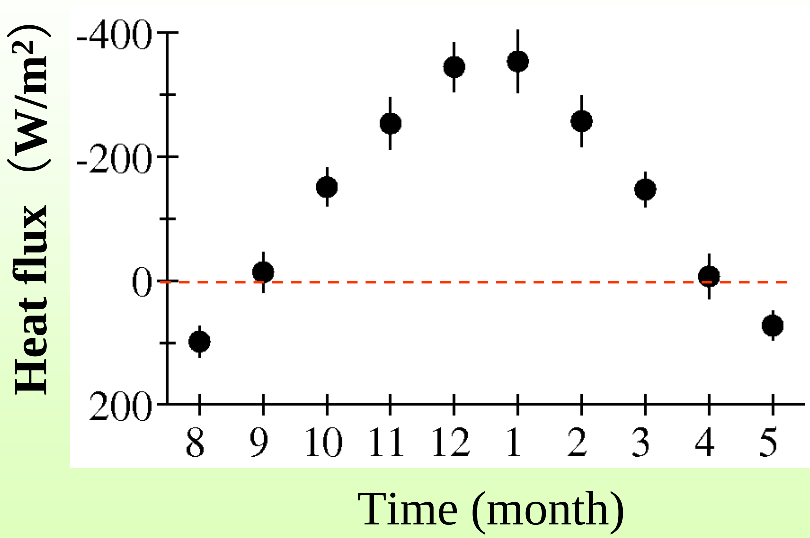
● : monthly mean
vertical b...

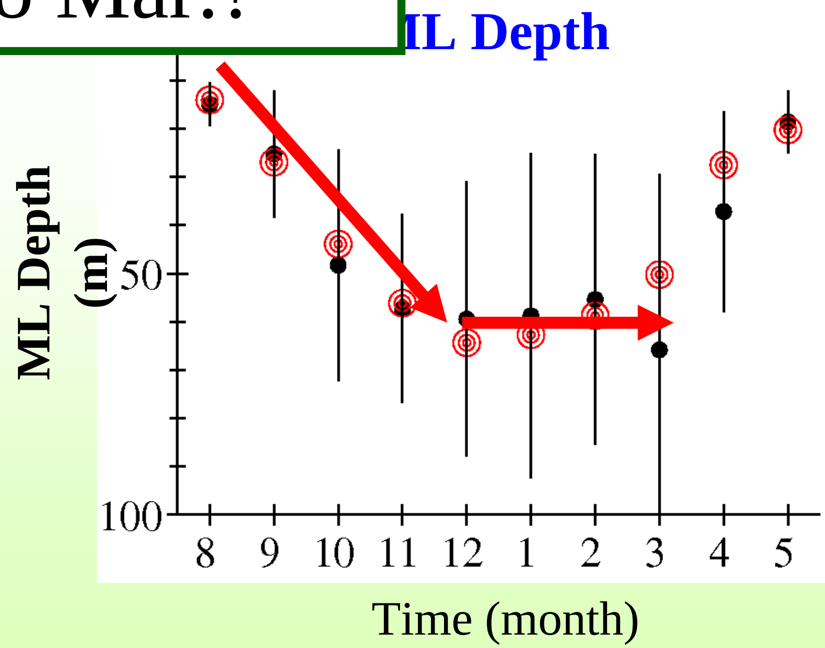
◎ : cl...
de Boyer Monté...

Within the ML, what can balance with the sea surface cooling from Jan. to Mar.?



Net Heat Flu...
estimated via bulk...
using JR...



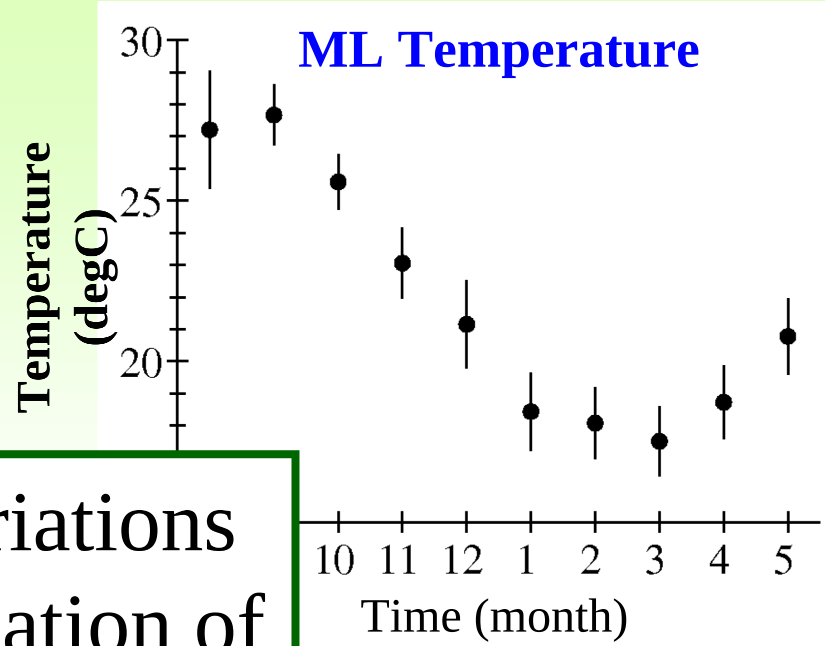


Monthly ML temperature & depth at Stn.A in Tosa Bay

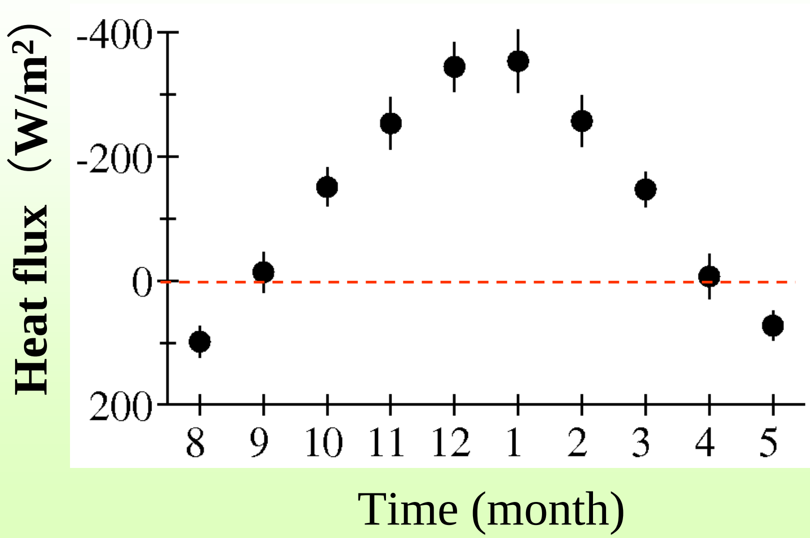
● : monthly mean
vertical bar : ±1 S.D.

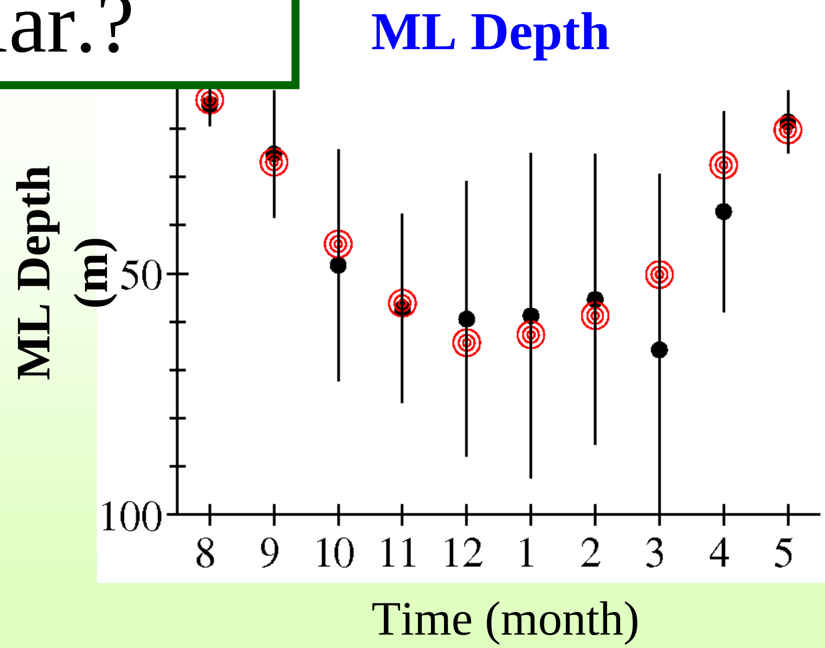
◎ : climatology

Can intra-monthly variations affect the monthly variation of ML from Jan. to Mar.?



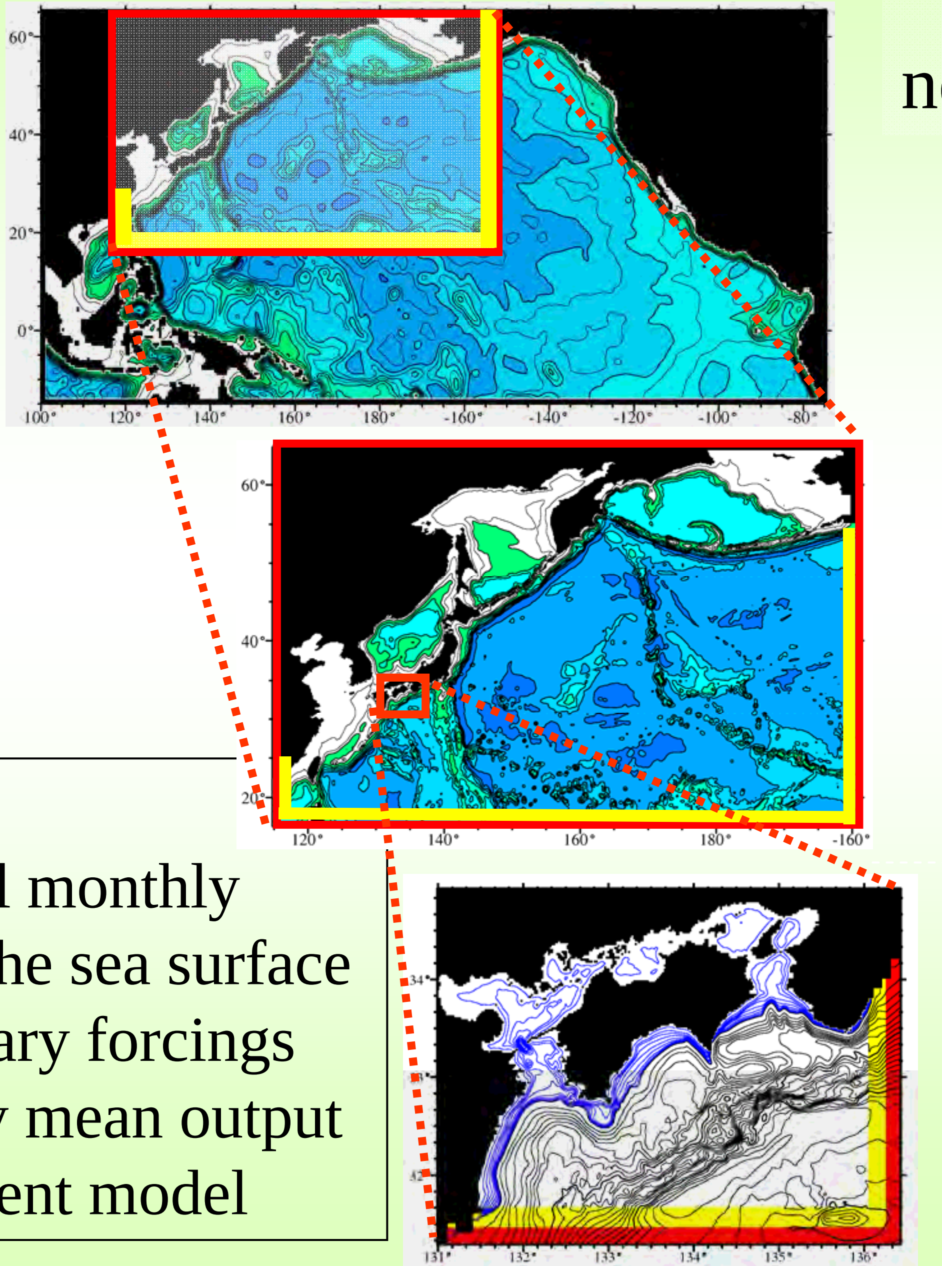
est





Dynamical downscaling system

ROMS
Regional
Ocean
Modeling
System



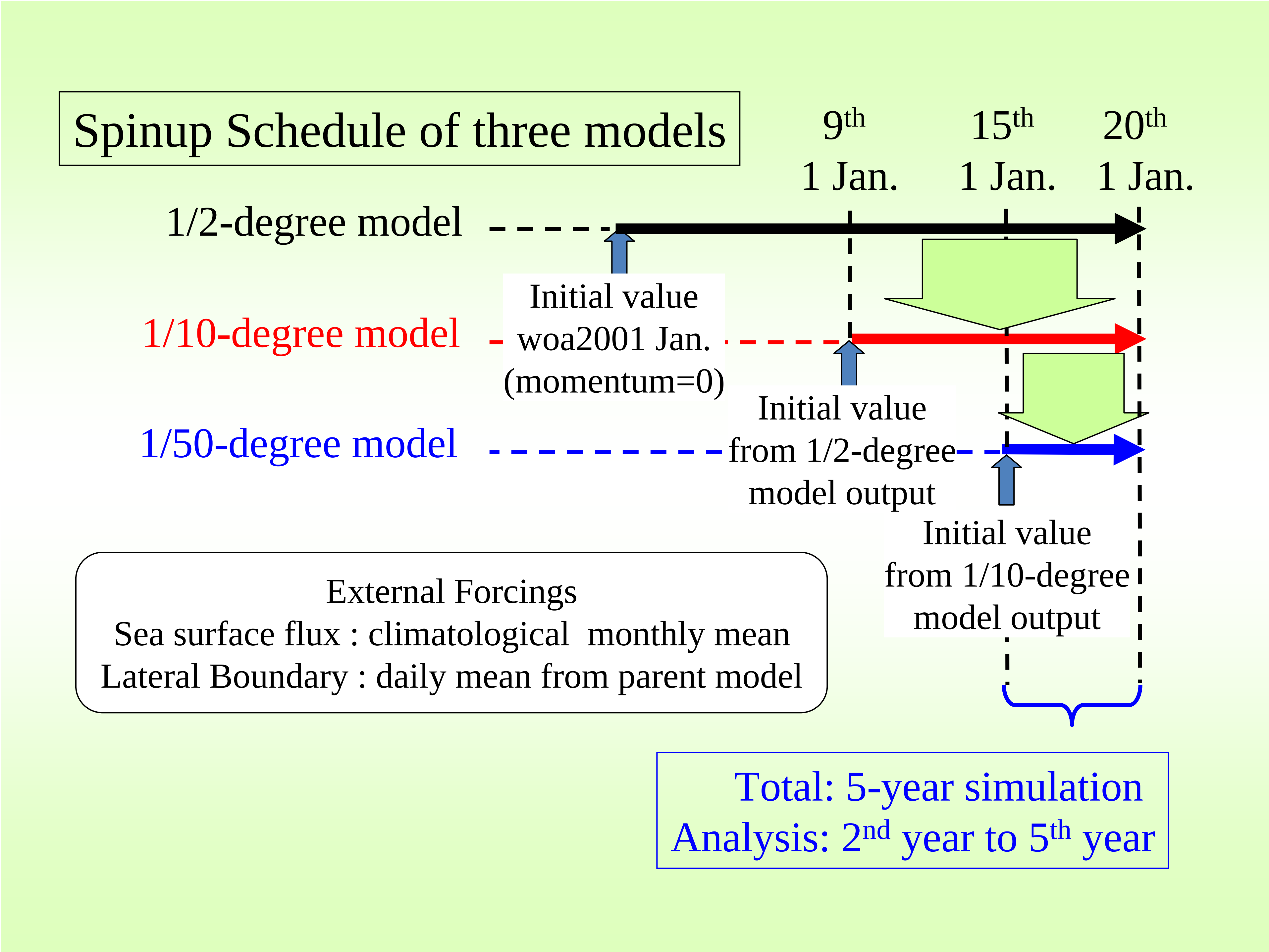
one-way
nesting system

1/2 degree
Basin-scale
(O(10^3) km)

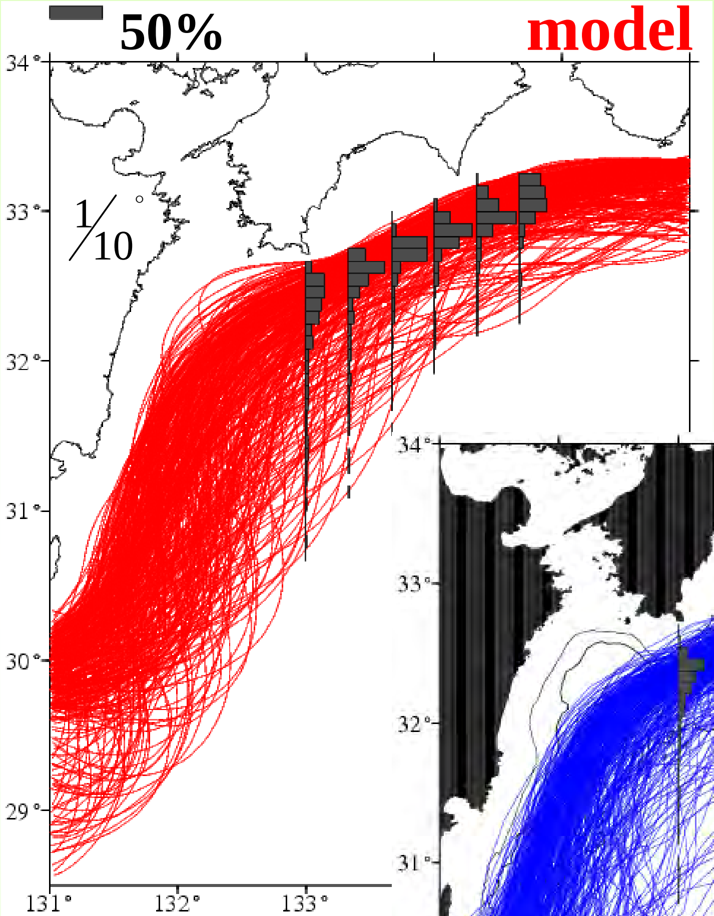
1/10 degree
Mesoscale
(O(10^2) km)

1/50 degree
Submesoscale
(O(10^1) km)

Forcings
1. Climatological monthly mean flux at the sea surface
2. Lateral boundary forcings based on daily mean output from each parent model

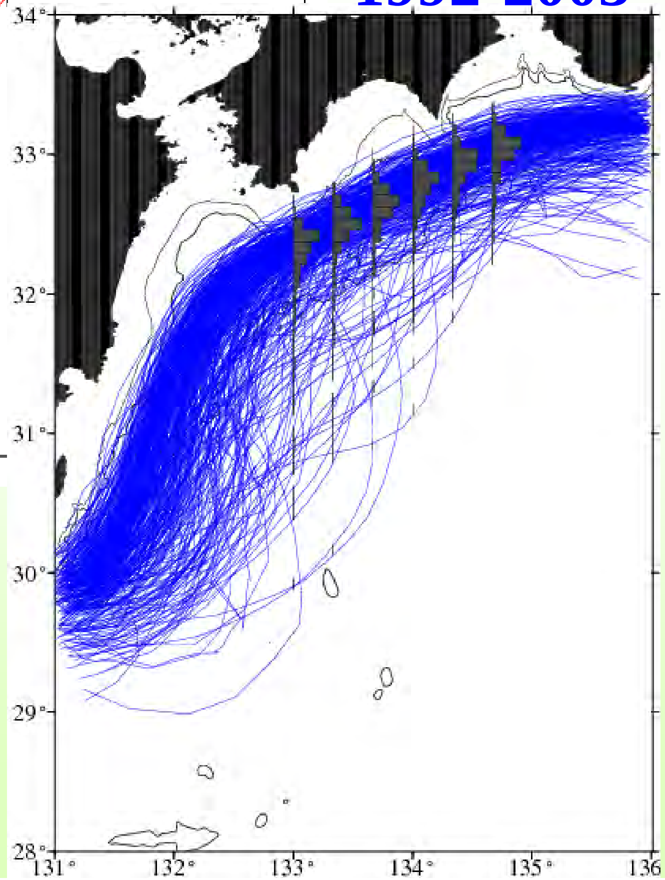

Spinup Schedule of three models
9th
1 Jan.
15th
1 Jan.
20th
1 Jan.
1/2-degree model
1/10-degree model
1/50-degree model
Initial value
woa2001 Jan.
(momentum=0)
Initial value
from 1/2-degree
model output
Initial value
from 1/10-degree
model output
External Forcings
Sea surface flux : climatological monthly mean
Lateral Boundary : daily mean from parent model
Total: 5-year simulation
Analysis: 2nd year to 5th year

Kuroshio axis position

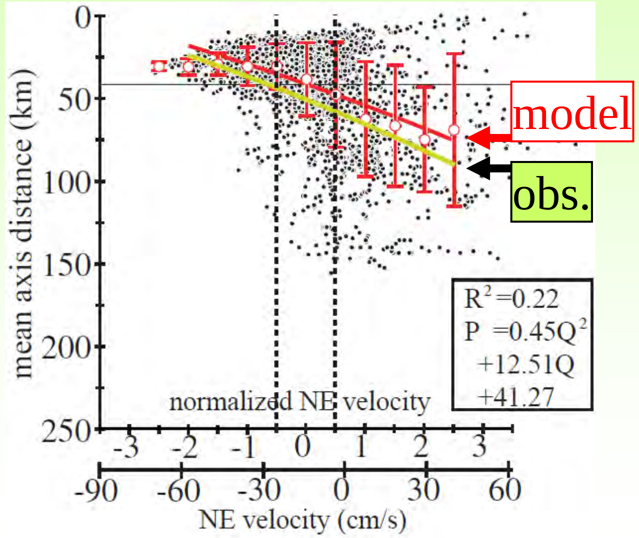


Kuroda et al.
(ready for submit)

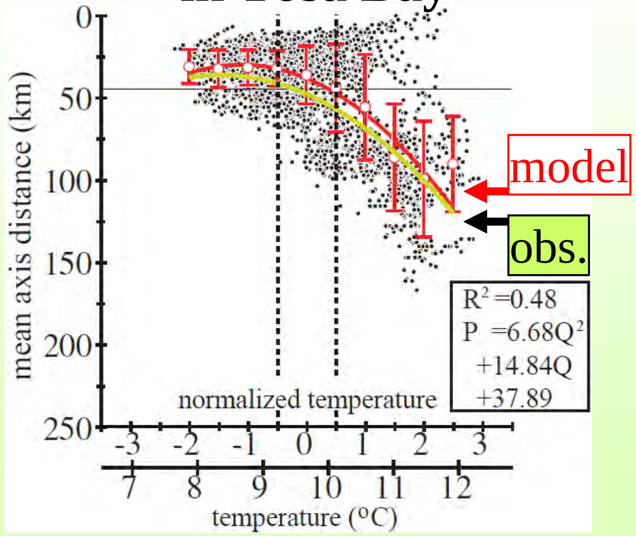
observation
1992-2003



1/50° Kuroshio axis distance vs. Surface current in Tosa Bay

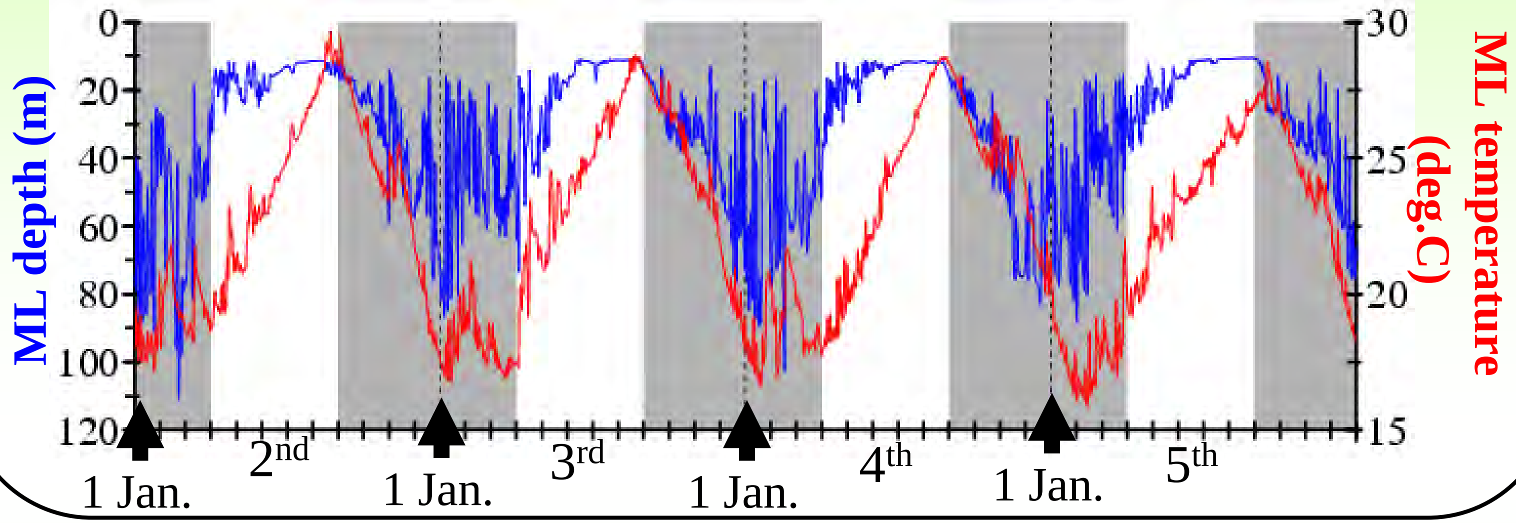


1/50° Kuroshio axis distance vs. Subsurface temperature in Tosa Bay

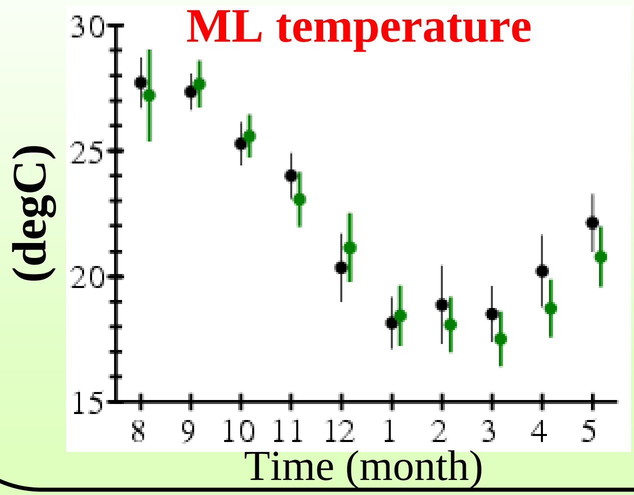


12-hourly time series of mixed layer at Stn.A in Tosa Bay from the 2nd to 5th year

ML depth — ML temperature — gray area: September to March



Monthly mean time series of mixed layer at Stn.A in Tosa Bay

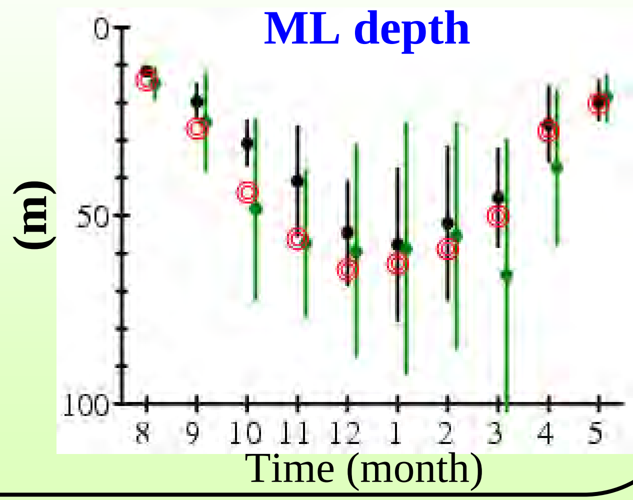


simulation

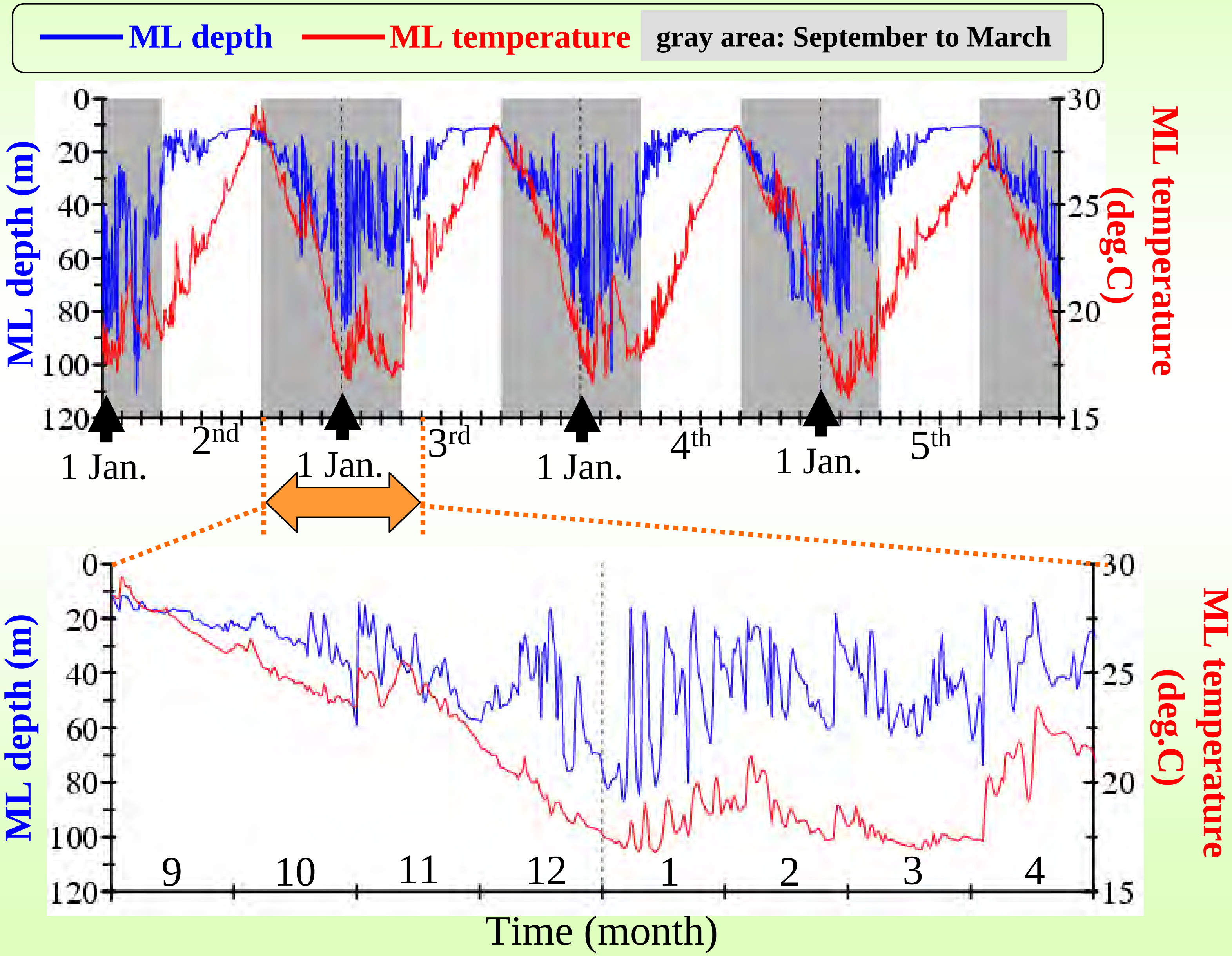
data analysis

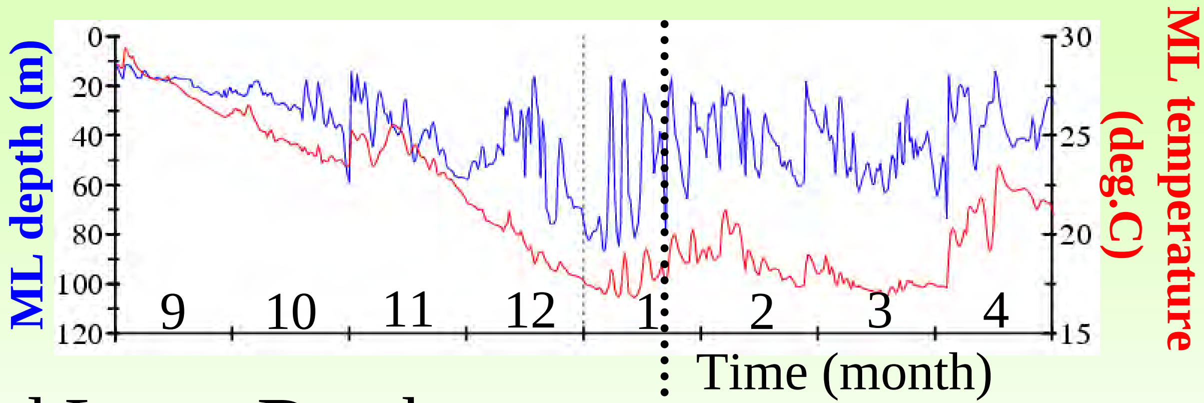
climatology

de Boyer Montégut *et al*. (2004)

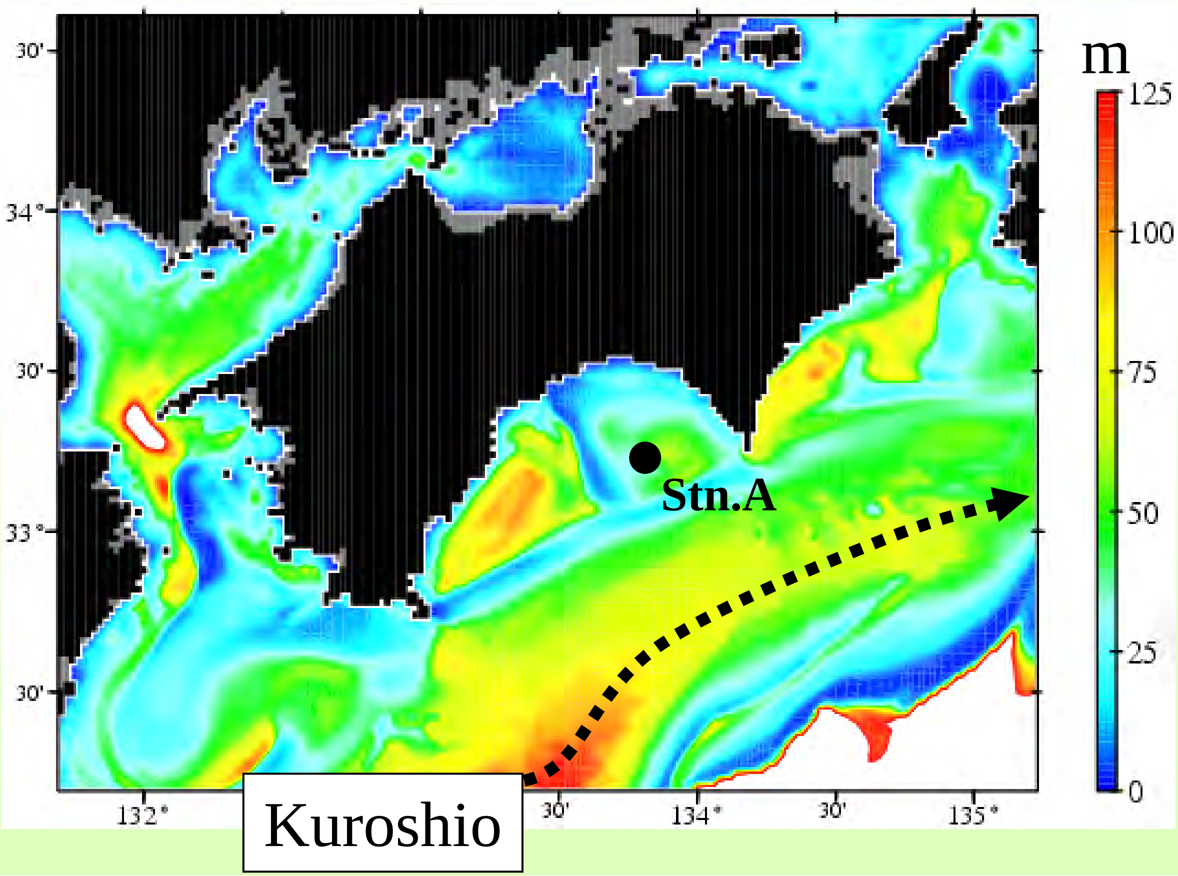


12-hourly time series of mixed layer at Stn.A in Tosa Bay from the 2nd to 5th year





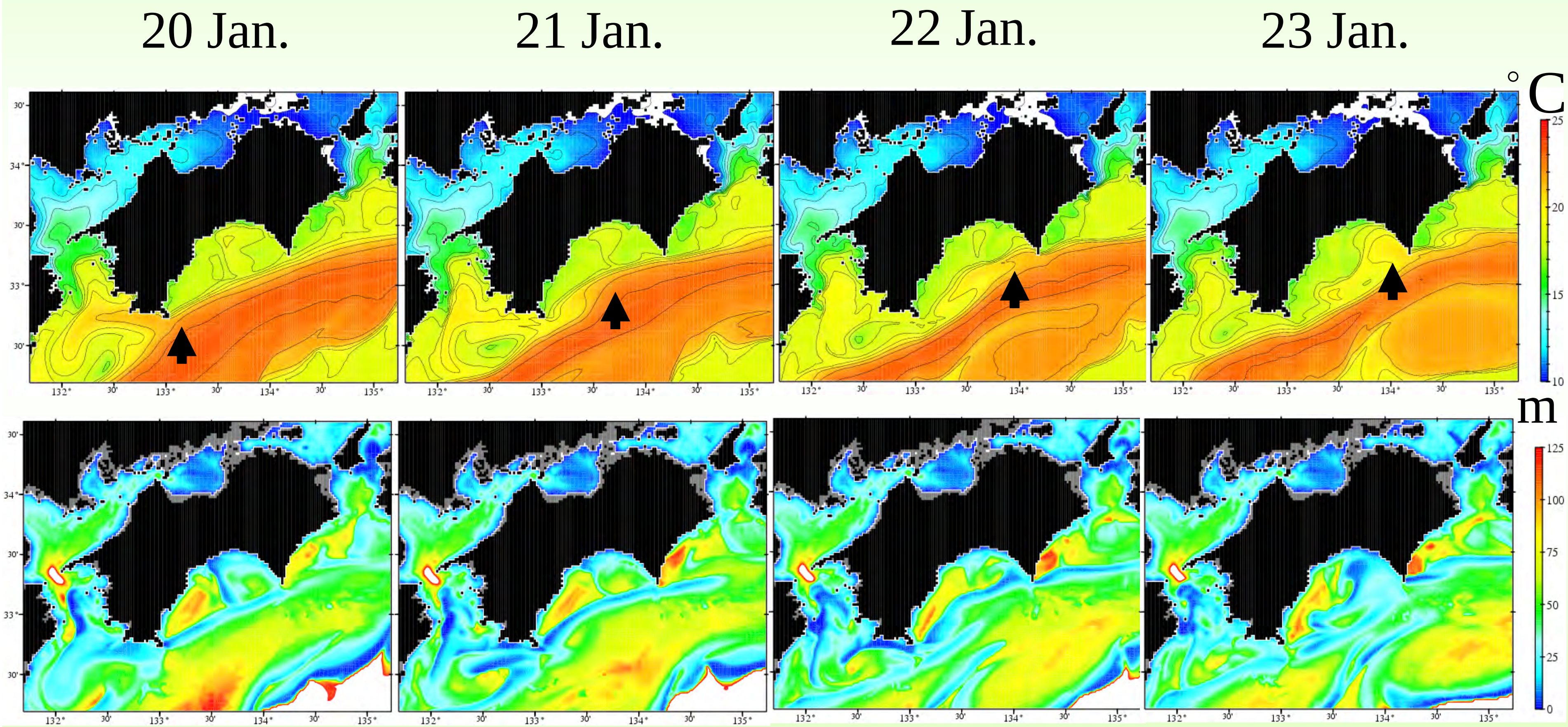
Snapshot of Mixed Layer Depth
20 January in the 3rd year



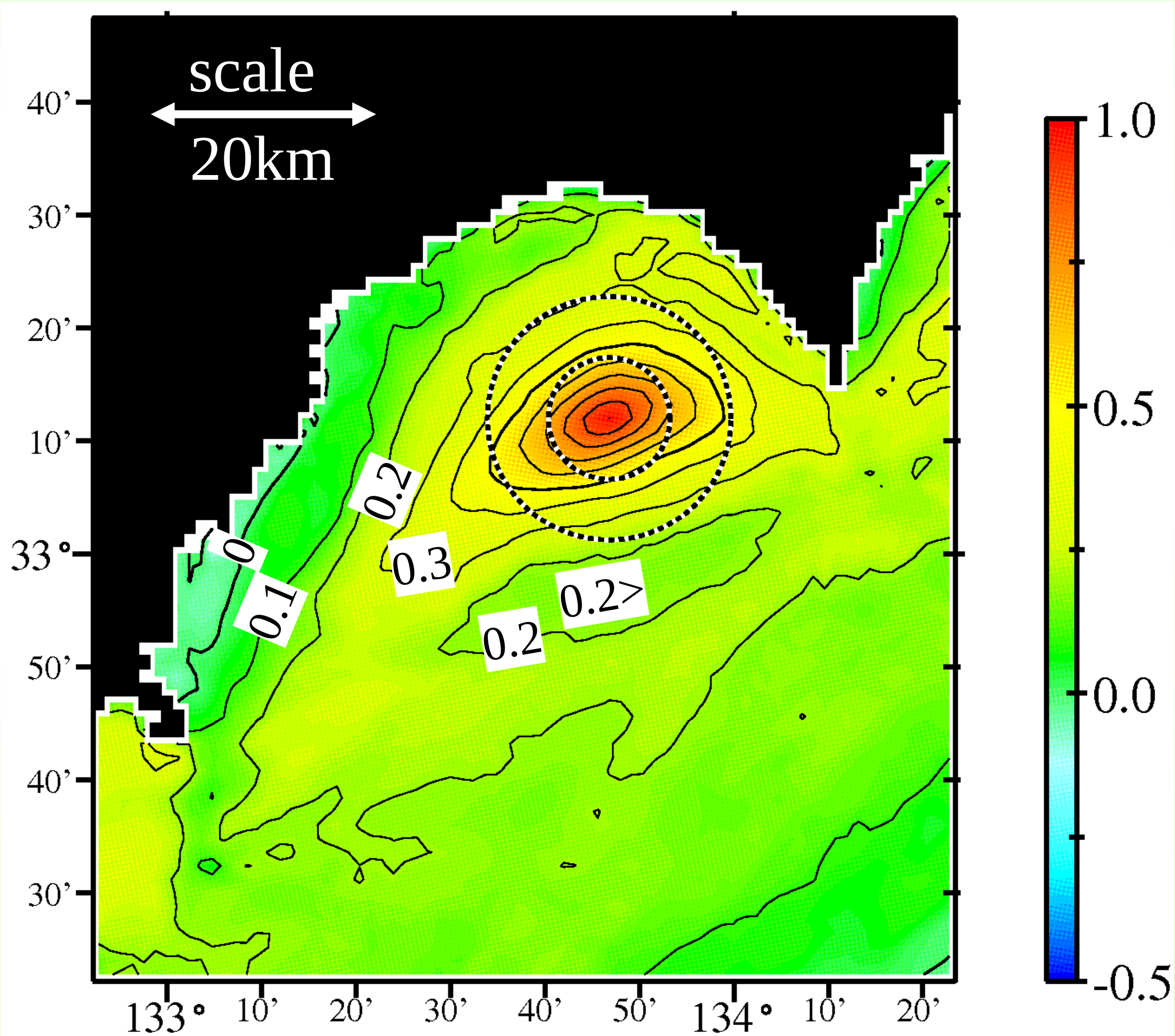
Spatial features

Patch-like deeper ML
Streak-like shallower ML
along the Kuroshio front

Daily snapshots of
SST (upper panels) and ML depth (lower panels)



Correlation coefficient of mixed layer depth for Stn.A
from January to March



dotted circle
around Stn.A
small: radius = 10km
large : radius = 20km

e-folding scale
=10-20km

Heat balance of mixed layer temperature at a fixed station (Stn.A)

$$\frac{\partial T_{\mathrm{ML}}}{\partial t} = \left[\frac{1}{\rho C_{\mathrm{p}}}\frac{\partial q}{\partial z}\right] + \frac{1}{h}\left(\kappa_{\mathrm{z}}\nabla_{\mathrm{z}}T\right)_{z=0} - \frac{1}{h}\left(\kappa_{\mathrm{z}}\nabla_{\mathrm{z}}T\right)_{z=-h}$$

shortwave penetration — **longwave sensible and latent heat fluxes** — **vertical diffusion at ML bottom**

Heat flux through the sea surface

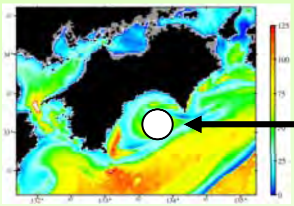
$$-\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}T\right)dz + \frac{1}{h}\left(\nabla_{\mathrm{H}}\left(\kappa_{\mathrm{H}}\nabla_{\mathrm{H}}T\right)\right) - \frac{1}{h}\frac{\partial h}{\partial t}\Delta T$$

advection — **horizontal diffusion** — **entrainment**

$$T_{\mathrm{ML}} = \frac{1}{h}\int_{-h}^{0} T\,dz$$

Each term is diagnostically estimated from model output by a method of Kim et al. (2006, JPO)

Term estimation of the mixed-layer-temperature equation on the slope of Tosa Bay



<u>Part 1: Monthly Mean</u>

$$\frac{\partial T_{\mathrm{ML}}}{\partial t}=\left[\frac{1}{\rho C_{\mathrm{p}}}\frac{\partial q}{\partial z}\right]+\frac{1}{h}\left(\kappa_{\mathrm{z}}\nabla_{\mathrm{z}}T\right)_{z=0}-\frac{1}{h}\left(\kappa_{\mathrm{z}}\nabla_{\mathrm{z}}T\right)_{z=-h}-\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}T\right)dz+\frac{1}{h}\left(\nabla_{\mathrm{H}}\left(\kappa_{\mathrm{H}}\nabla_{\mathrm{H}}T\right)\right)-\frac{1}{h}\frac{\partial h}{\partial t}\Delta T$$

1. Tendency

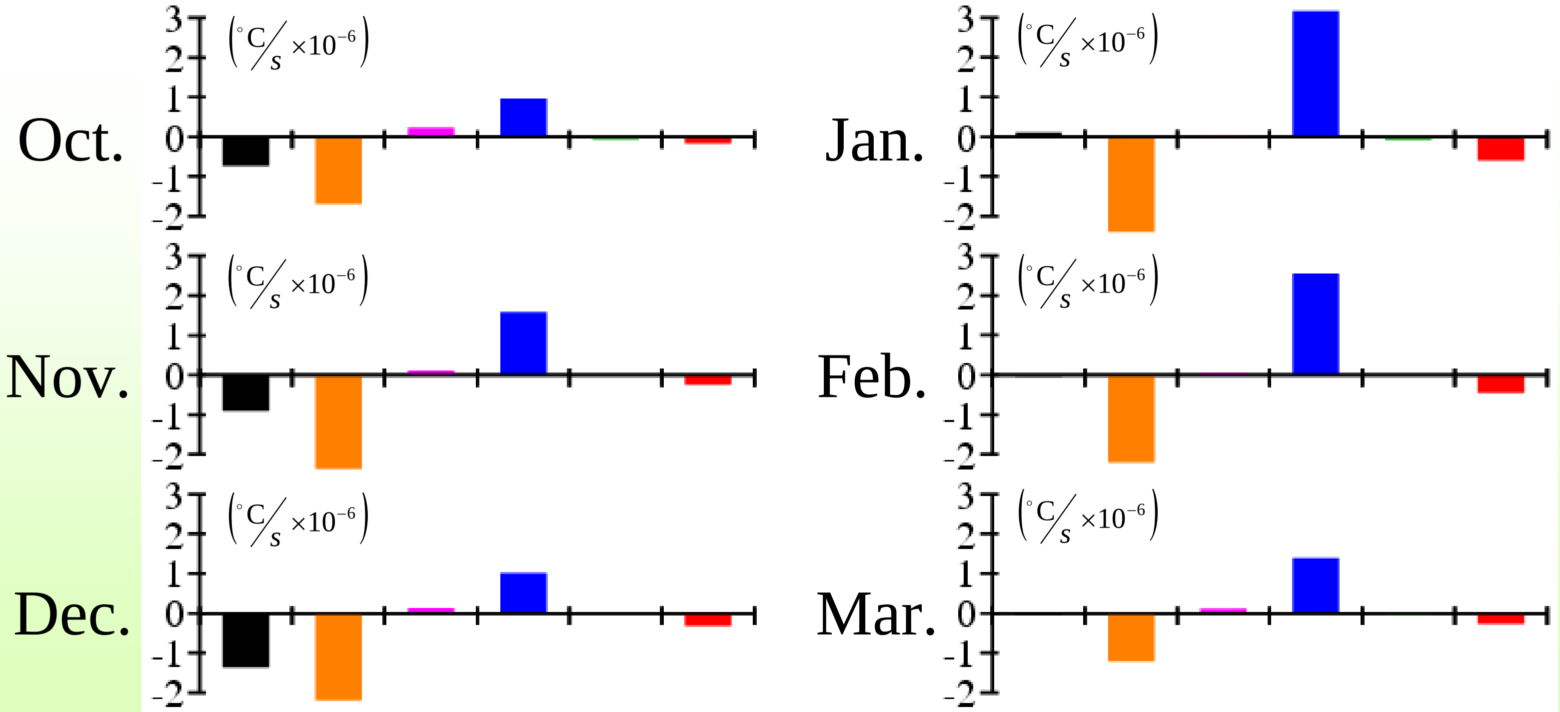
2. Heat flux through the sea surface

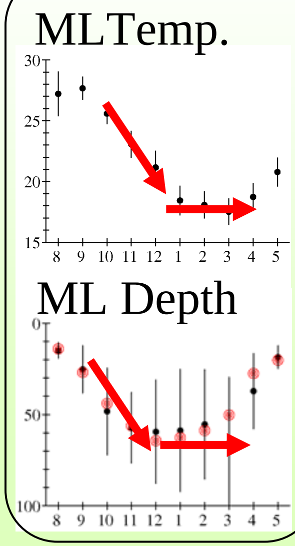
3 Vertical diffusion

4. Advection

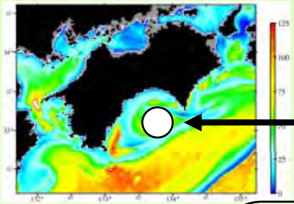
5. Horizontal diffusion

6. Entrainment





Term estimation of the mixed-layer-temperature equation on the slope of Tosa Bay

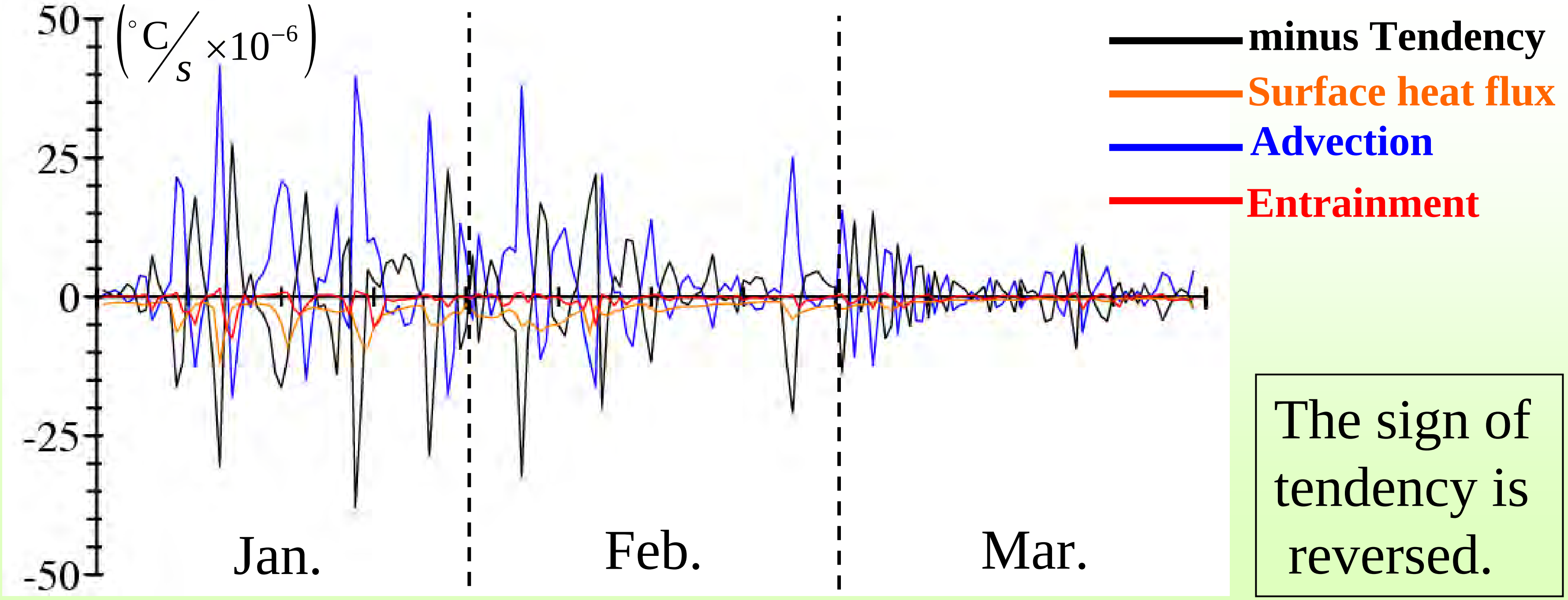


Part 2: 12-hour mean

$$\frac{\partial T_{\mathrm{ML}}}{\partial t} \approx \left[\frac{1}{\rho C_{\mathrm{p}}}\frac{\partial q}{\partial z}\right] + \frac{1}{h}\left(\kappa_{\mathrm{z}} \nabla_{\mathrm{z}} T\right)_{z=0} - \frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}T\right)dz - \frac{1}{h}\frac{\partial h}{\partial t}\Delta T$$

Tendency — **Heat flux through the sea surface** — **Advection** — **Entrainment**

12-hour time series from January to March in the 3rd year



Decomposition of monthly mean advection

Original term

$$-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}T\right)dz}$$

$$\mathbf{u}=(u,v,w)$$

$$\mathbf{u}=\overline{\mathbf{u}}+\mathbf{u}'_{\mathrm{L}}+\mathbf{u}'_{\mathrm{H}}$$

$$T=\overline{T}+T'_{\mathrm{L}}+T'_{\mathrm{H}}$$

Average

Low Frequency (>30-day period)

High Frequency (Intra-monthly)

$$\begin{aligned}\nabla\cdot\mathbf{u}T&=\nabla\cdot\left(\overline{\mathbf{u}}+\mathbf{u}'_{\mathrm{L}}+\mathbf{u}'_{\mathrm{H}}\right)\left(\overline{T}+T'_{\mathrm{L}}+T'_{\mathrm{H}}\right)\\&=\nabla\cdot\overline{\mathbf{u}}\ \overline{T}+\nabla\cdot\overline{\mathbf{u}}\ T'_{\mathrm{L}}+\nabla\cdot\overline{\mathbf{u}}\ T'_{\mathrm{H}}\\&\quad+\nabla\cdot\mathbf{u}'_{\mathrm{L}}\overline{T}+\nabla\cdot\mathbf{u}'_{\mathrm{L}}T_{\mathrm{L}}'+\nabla\cdot\mathbf{u}'_{\mathrm{L}}T'_{\mathrm{H}}\\&\quad+\nabla\cdot\mathbf{u}'_{\mathrm{H}}\overline{T}+\nabla\cdot\mathbf{u}'_{\mathrm{H}}T_{\mathrm{L}}'+\nabla\cdot\mathbf{u}'_{\mathrm{H}}T'_{\mathrm{H}}\end{aligned}$$

$$-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}T\right)dz}$$

$$\begin{aligned}=&-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\overline{\mathbf{u}}\,\overline{T}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\overline{\mathbf{u}}\,T'_{\mathrm{L}}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\overline{\mathbf{u}}\,T'_{\mathrm{H}}\right)dz}\\&-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{L}}\,\overline{T}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{L}}T'_{\mathrm{L}}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{L}}T'_{\mathrm{H}}\right)dz}\\&-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{H}}\,\overline{T}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{H}}T'_{\mathrm{L}}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{H}}T'_{\mathrm{H}}\right)dz}\end{aligned}$$

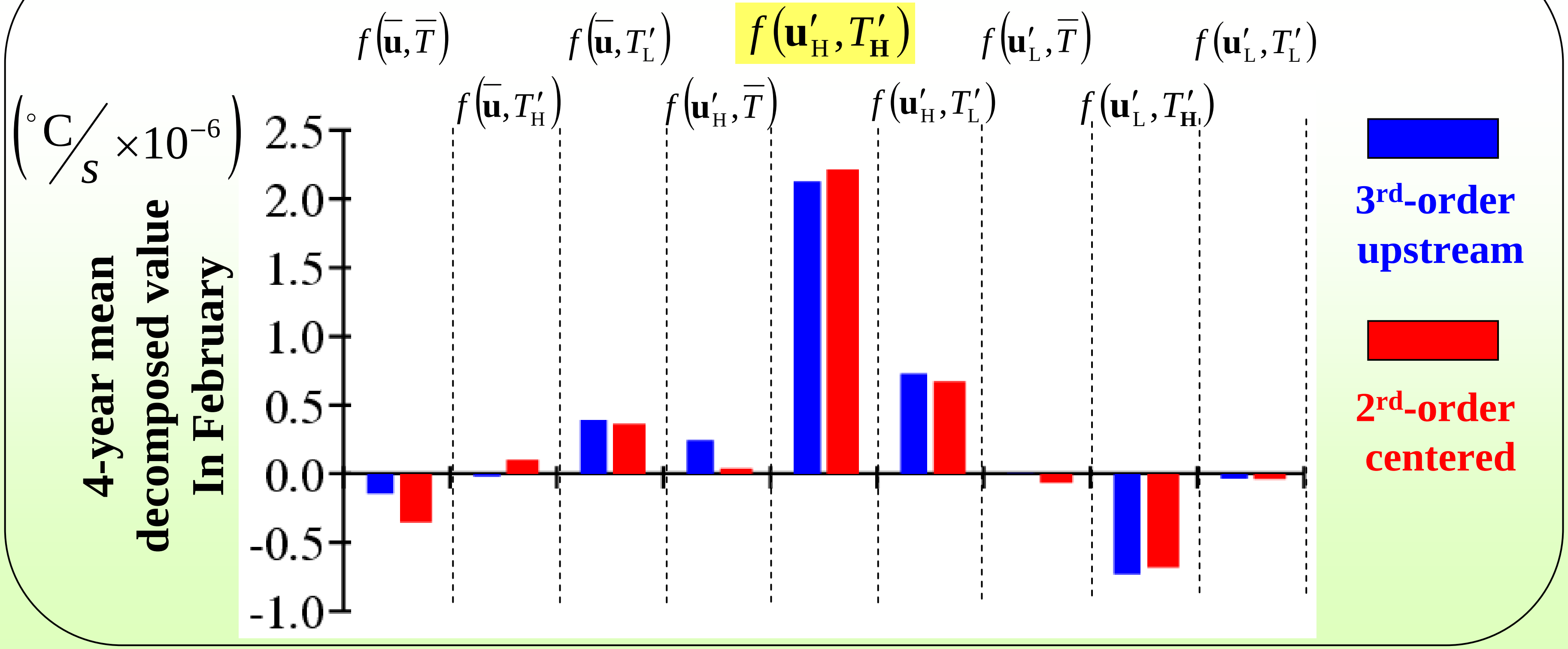
If h is constant,
Orange Terms=0

Contribution of decomposed components (February)

$$
\begin{aligned}
&-\overline{\frac{1}{h}\int_{-h}^{0}(\nabla\cdot\mathbf{u}T)dz}\\
&=-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\bar{\mathbf{u}}\bar{T}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\bar{\mathbf{u}}T'_{\mathrm{L}}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\bar{\mathbf{u}}T'_{\mathrm{H}}\right)dz}\\
&\quad-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{L}}\bar{T}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{L}}T'_{\mathrm{L}}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{L}}T'_{\mathrm{H}}\right)dz}\\
&\quad-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{H}}\bar{T}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{H}}T'_{\mathrm{L}}\right)dz}-\overline{\frac{1}{h}\int_{-h}^{0}\left(\nabla\cdot\mathbf{u}'_{\mathrm{H}}T'_{\mathrm{H}}\right)dz}
\end{aligned}
$$

$$
\begin{aligned}
&f(\mathbf{u},T)\\
&=f(\bar{\mathbf{u}},\bar{T})+f(\bar{\mathbf{u}},T'_{\mathrm{L}})+f(\bar{\mathbf{u}},T'_{\mathrm{H}})\\
&+f(\mathbf{u}'_{\mathrm{L}},\bar{T})+f(\mathbf{u}'_{\mathrm{L}},T'_{\mathrm{L}})+f(\mathbf{u}'_{\mathrm{L}},T'_{\mathrm{H}})\\
&+f(\mathbf{u}'_{\mathrm{H}},\bar{T})+f(\mathbf{u}'_{\mathrm{H}},T'_{\mathrm{L}})+f(\mathbf{u}'_{\mathrm{H}},T'_{\mathrm{H}})
\end{aligned}
$$

Intra-monthly eddy heat advection



Conclusions

Seasonal cycle of ML depth and temperature exhibits two regimes

1. September to November

    Monthly mean ML depth increases & ML temperature decreases

2. January to March

    Monthly mean ML depth and temperature become constant

For the monthly mean heat balance in the ML
Heat flux through the sea surface + entrainment ~ advection

eddy heat advection

There is dominant intra-monthly submesoscale variability associated with the Kuroshio or its frontal disturbances

Intra-monthly variation contributes significantly to the monthly/seasonal variation of heat balance within the ML


Thank you for your attention
34°
33°
32°
131°
132°
133°
134°
135°