The background of the slide is a photograph of an Antarctic landscape. In the foreground, there is a vast expanse of dark blue water. In the middle ground, a long, flat, white ice shelf or glacier extends across the horizon. The sky above is a clear, pale blue with some light, wispy clouds near the horizon.

# Formation process of Antarctic Bottom Water originating from a middle size polynya

Yujiro Kitade and Keishi Shimada

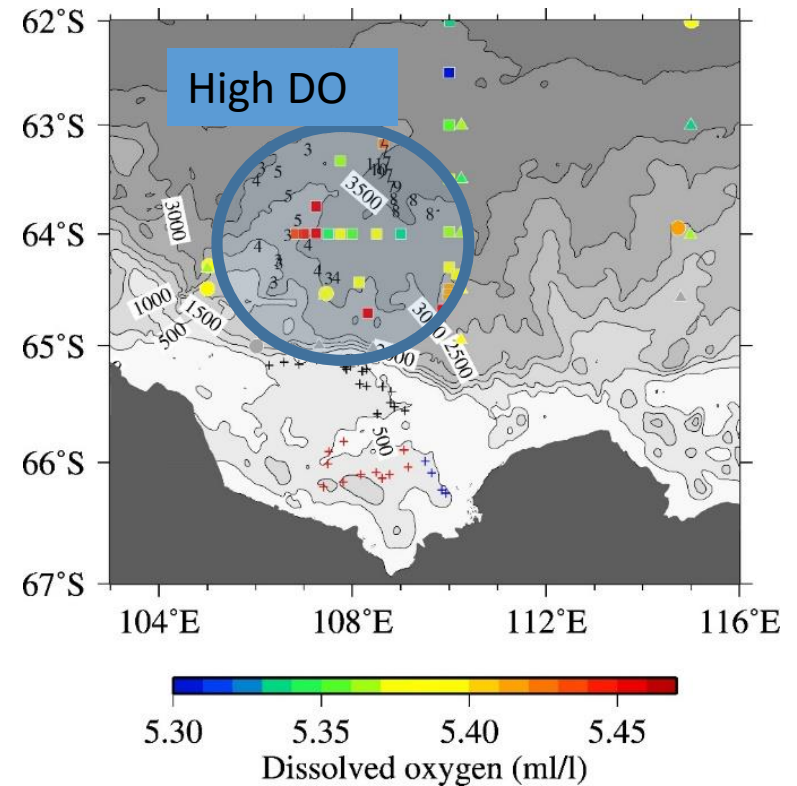
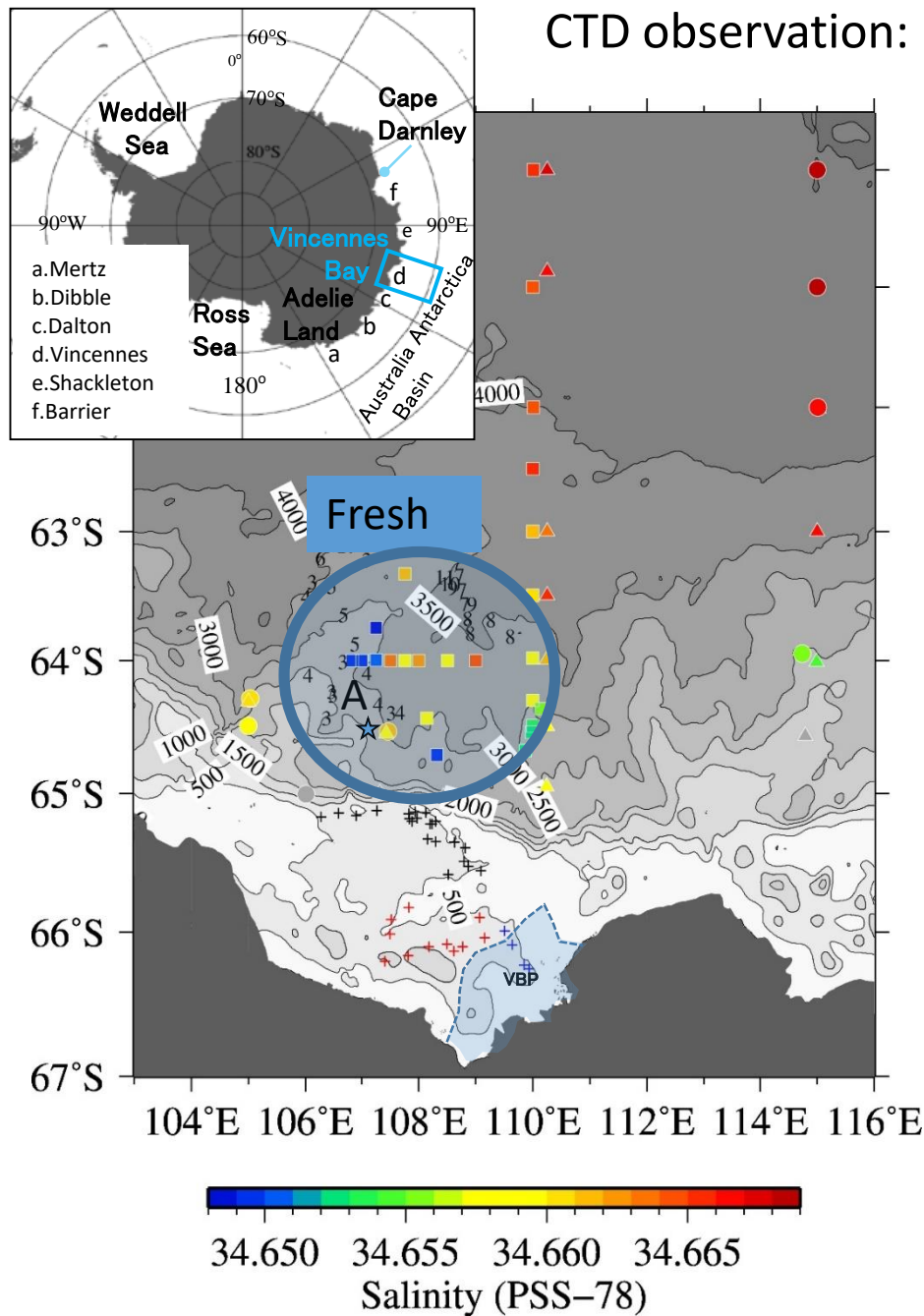
Tokyo University of Marine Science and Technology

*Coast Bordeaux 2017*

# Abstract

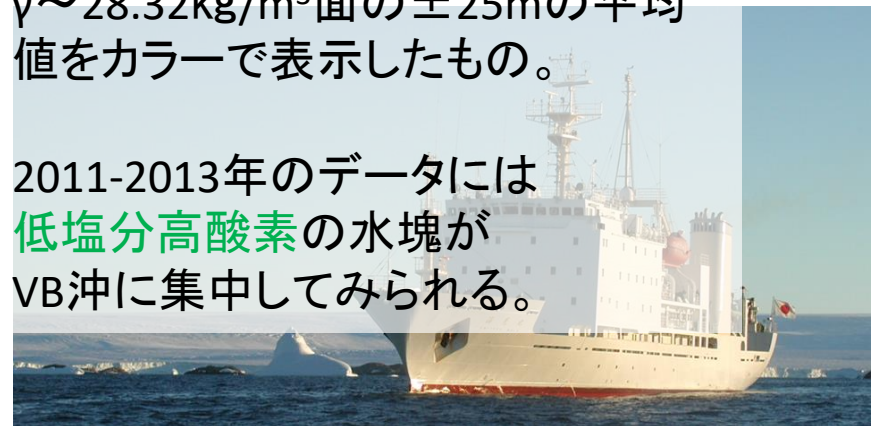
Antarctic Bottom Water (AABW) is the densest water in the ocean and globally significant; its production at the Antarctic margin is a key component of the global overturning circulation. AABW originating from a middle size polynya called Vincennes Bay Polynya (VBP) was discovered recently [Kitade et al., 2014]. Although we found some evidences for AABW formation from the VBP, there are many unknown processes on its formation. Furthermore, recent Deep-float data showed no clear evidence of newly formed AABW off Shackleton Polynya where sea-ice production was more active than that of VBP [Kitade et al. 2016]. Thus, we carried out numerical experiments to explain detail process of the AABW formation off middle size polynya. From data analysis and model results, we finally conclude that not only sea-ice production but also oceanic condition off coastal polynya region is important on the process of AABW formation.

# CTD observation: 2011–2013



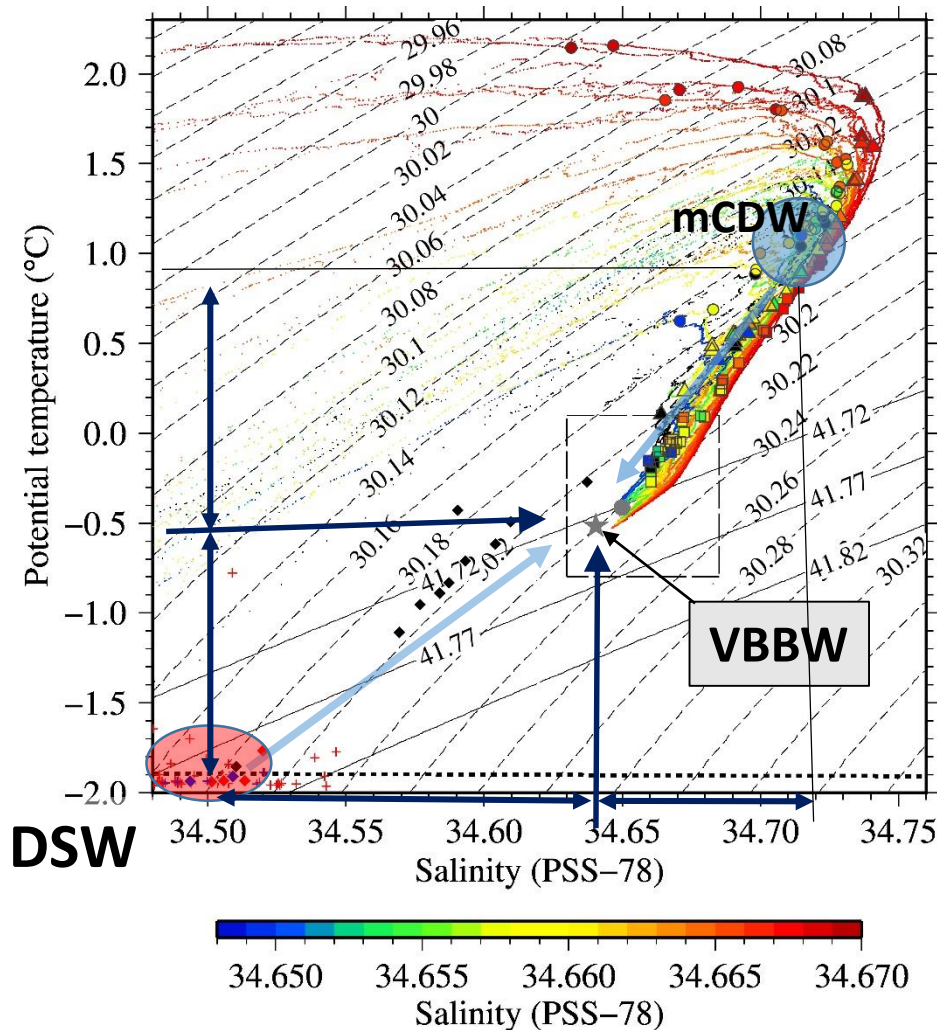
CTD観測より、VBBWの水塊として  
 $\gamma \sim 28.32 \text{ kg/m}^3$ 面の $\pm 25 \text{ m}$ の平均  
 値をカラーで表示したもの。

2011-2013年のデータには  
 低塩分高酸素の水塊が  
 VB沖に集中してみられる。





# Water property of VBBW and mixing ratio



- Potential density at 500 dbar
- Potential density at 3000 dbar ( $\sigma_3$ )

TS relation show that DSW is relatively heavy than the deep water.

However, Mixing ratio of water masses are different by temperature and salinity.

Mixing ratio for temperature  
DSW : mCDW = 1 : 1

Mixing ration for salinity  
DSW : mCDW = 1 : 1.4

What cause such difference?

# Two dimensional model

## Basic Equations

$$\frac{\partial \zeta}{\partial t} - J(\psi, \zeta) + f \frac{\partial v}{\partial z} = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial x} + \nu_h \frac{\partial^2 \zeta}{\partial x^2} + \nu_z \frac{\partial^2 \zeta}{\partial z^2}$$

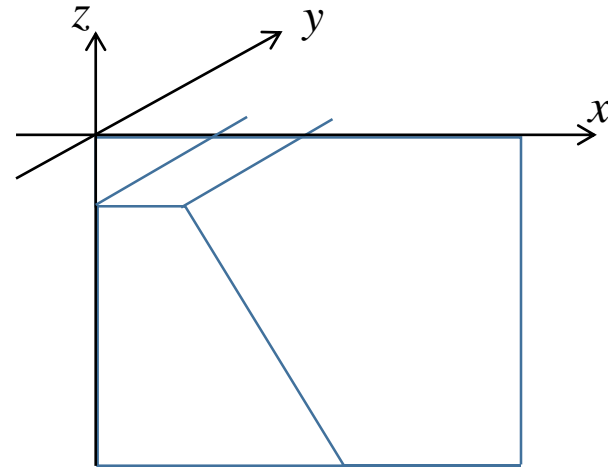
$$\frac{\partial v}{\partial t} - J(\psi, \zeta) + f \frac{\partial \psi}{\partial z} = \nu_h \frac{\partial^2 v}{\partial x^2} + \nu_z \frac{\partial^2 v}{\partial z^2}$$

$$\frac{\partial \theta}{\partial t} - J(\psi, \theta) = K_h \frac{\partial^2 \theta}{\partial x^2} + K_\theta \frac{\partial^2 \theta}{\partial z^2}$$

$$\frac{\partial S}{\partial t} - J(\psi, S) = K_h \frac{\partial^2 S}{\partial x^2} + K_s \frac{\partial^2 S}{\partial z^2}$$

$$J(A, B) = \frac{\partial A}{\partial x} \frac{\partial B}{\partial z} - \frac{\partial A}{\partial z} \frac{\partial B}{\partial x}$$

- $\zeta$  : Vorticity
- $f$ : Coriolis parameter
- $\nu$ : Y component of current
- $\theta$ : P temperature、  $S$ : salinity
- $\psi$ : stream function



$$u = \frac{\partial \psi}{\partial z}, \quad w = -\frac{\partial \psi}{\partial x}$$

$$\zeta = \frac{\partial w}{\partial x} - \frac{\partial u}{\partial z} = -\left( \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} \right)$$

Viscosity

$$\nu_h = 10 (\text{m}^2/\text{s})$$

$$\nu_z = 5 \times 10^{-3} (\text{m}^2/\text{s})$$

# Evaluation of double diffusion effects

## Horizontal diffusivity coefficient

All case

$$K_h = 1.0 (\text{m}^2/\text{s})$$

## Vertical diffusivity coefficient

★ in the case include double diffusion effect

★ Not include double diffusion effect

$$K_s = K_\theta = 0.25 \times 10^{-4} (\text{m}^2/\text{s})$$

\* Density ratio:  $R_\rho = \alpha\theta/\beta S$

Where  $\alpha$  is thermal expansion,  $\beta$  is haline contraction

\* diffusive coefficient in back ground

$$K_b = 0.1 \times 10^{-4} (\text{m}^2/\text{s})$$

$$A = 10 \times 10^{-4} (\text{m}^2/\text{s})$$

I) Finger type: Schmitt(1981)

$$1 < R_\rho < 100$$

$$K_s = A / (1 + R_\rho / R_c)^{32}$$

$$K_\theta = 0.7 K_s / R_\rho$$

II) Diffusive type: Kelly(1990)

$$0 < R_\rho < 1$$

$$K_\theta = 0.909 * 0.015 \exp(4.6 \exp(0.54(1/R_\rho - 1)))$$

$$K_s = K_\theta (1.85 - 0.85/R_\rho) R_\rho$$

$$K_s = K_\theta (0.15 R_\rho)$$

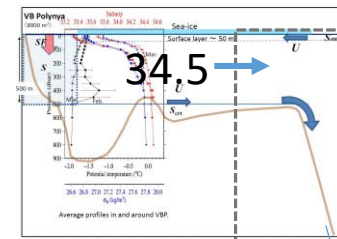
# Model

- Two dimension, non-hydrostatic level model (domain:  $400 \times 300$ )
- Grid size: 200m in horizontal, 10m in vertical
- Bottom topography : slope  $1/10$ 、 $1/20$ 、 $1/40$

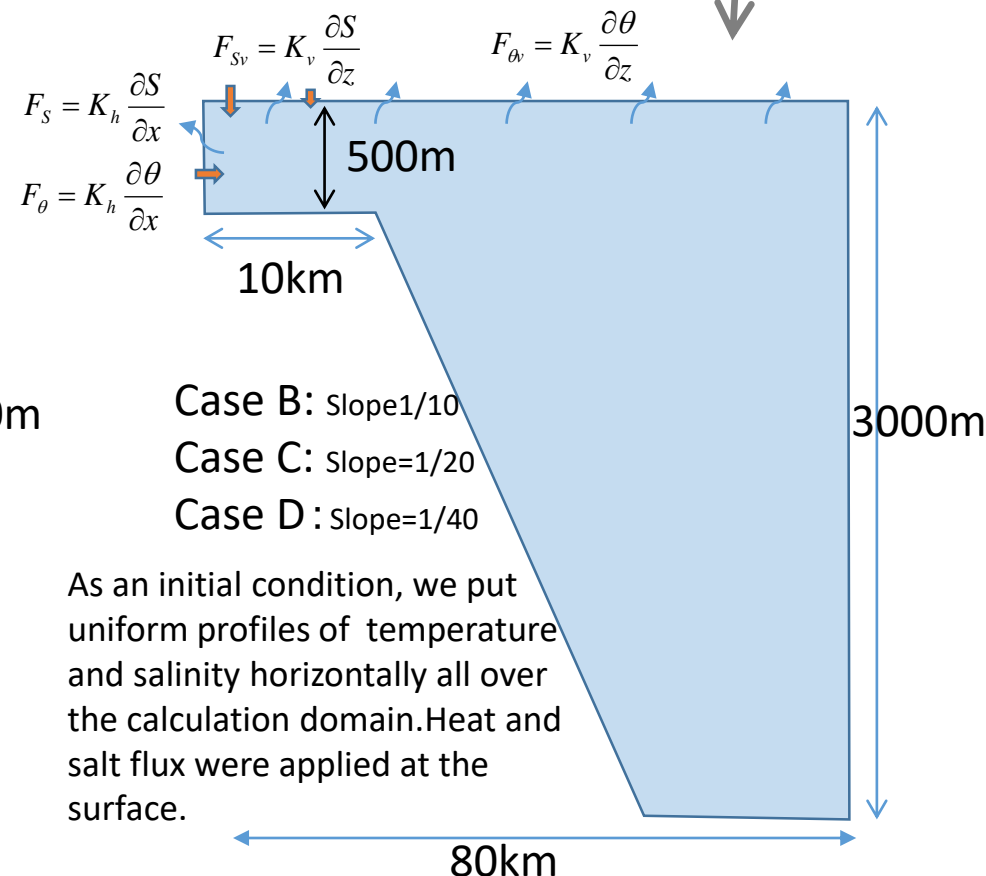
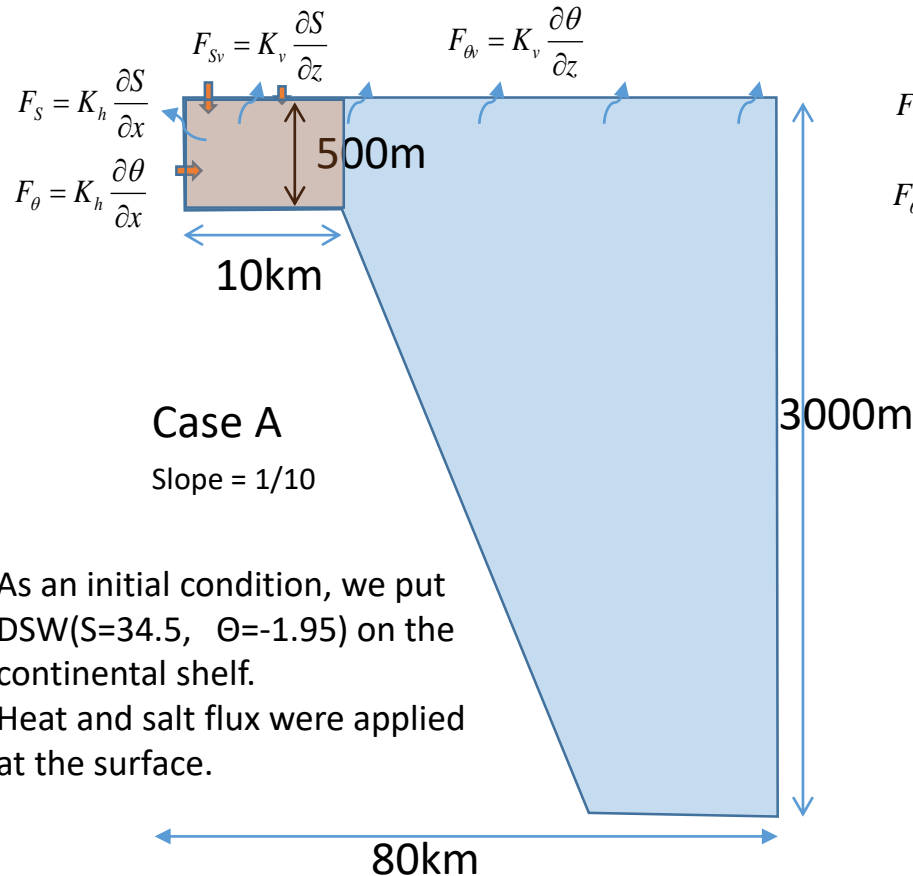
Heat flux =>  $-1.95^\circ\text{C}$

Salinity flux 6 km=> 34.5

6-10 km=> 34.5 → from observational result



We modeled this area to see sinking process of DSW and modification of water property



# Cases of experiments

As an initial condition, we put DSW( $S=34.5$ ,  $\Theta=-1.95$ ) on the continental shelf.  
Heat and salt flux were applied at the surface.

Case	Coriolis	Compressibility	Double diffusion	topography
A1	○	○	○	1/10
A2	×	○	○	1/10
A3	○	×	○	1/10
A4	○	○	×	1/10
A5	×	×	○	1/10

As an initial condition, we put uniform profiles of temperature and salinity horizontally all over the calculation domain. Heat and salt flux were applied at the surface.

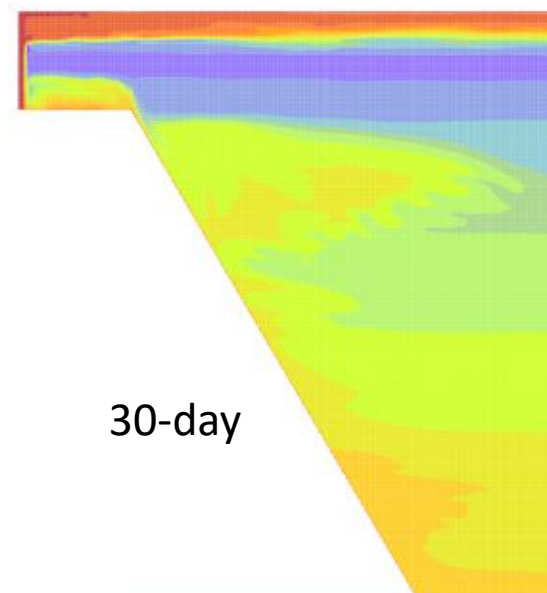
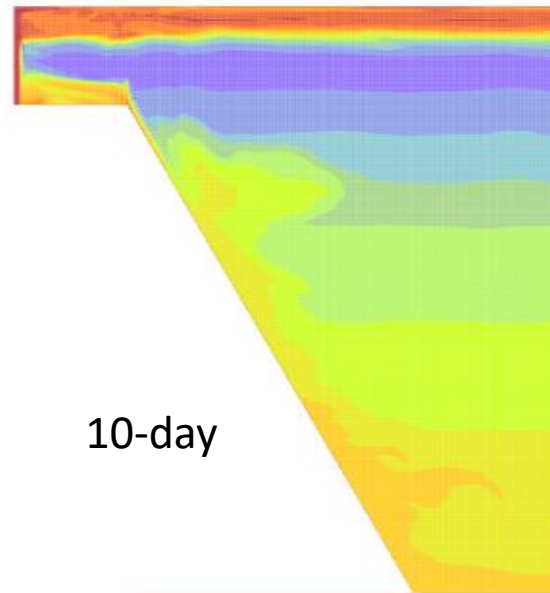
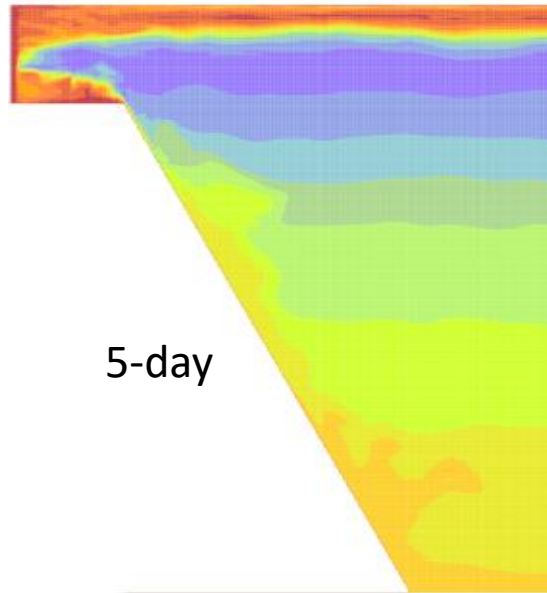
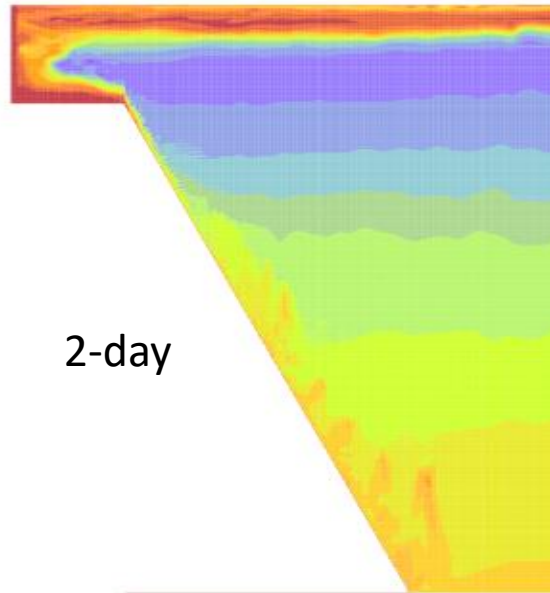
Case	Coriolis	Compressibility	Double diffusion	topography
B1	○	○	○	1/10
B2	×	○	○	1/10
B3	○	○	×	1/10
B4	×	○	×	1/10
C1	○	○	○	1/20
C2	×	○	○	1/20
D1	○	○	○	1/40
D2	×	○	○	1/40



Results

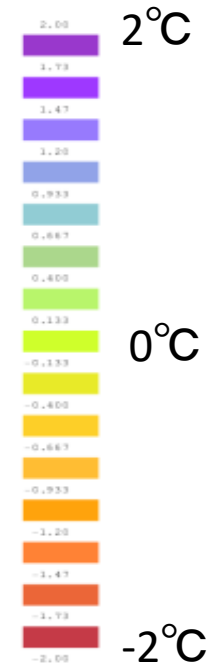
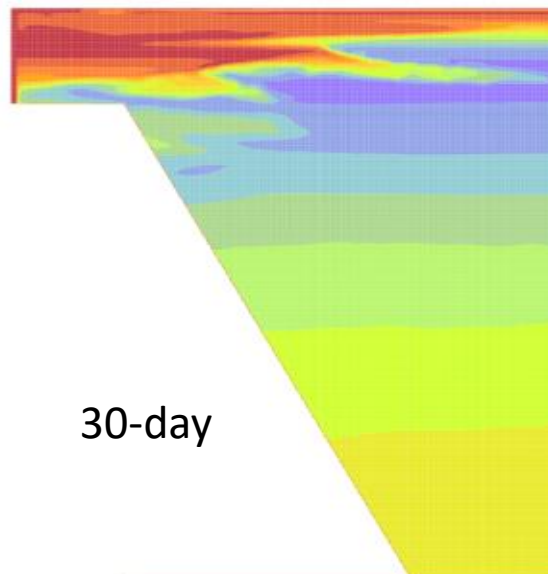
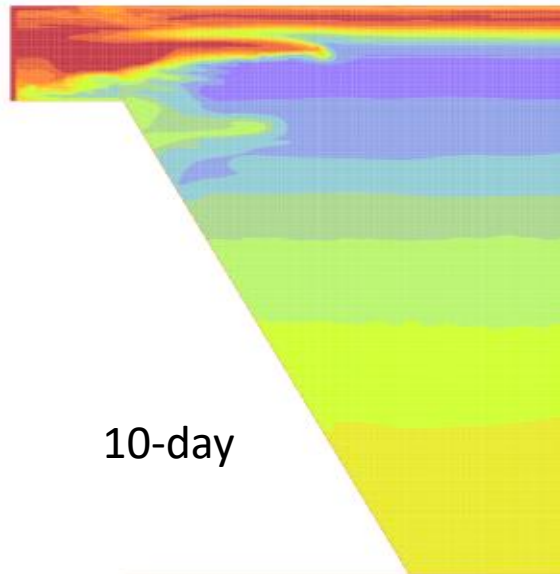
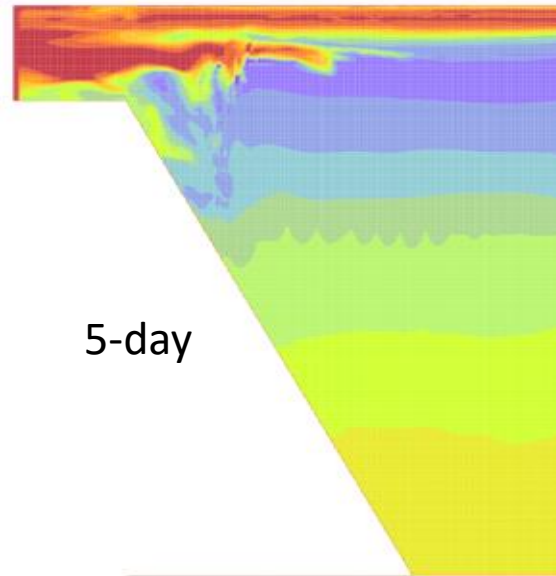
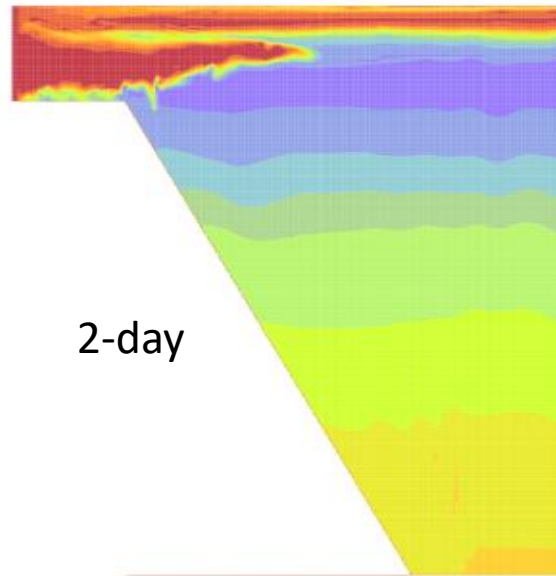
# Temperature distribution

Case A2



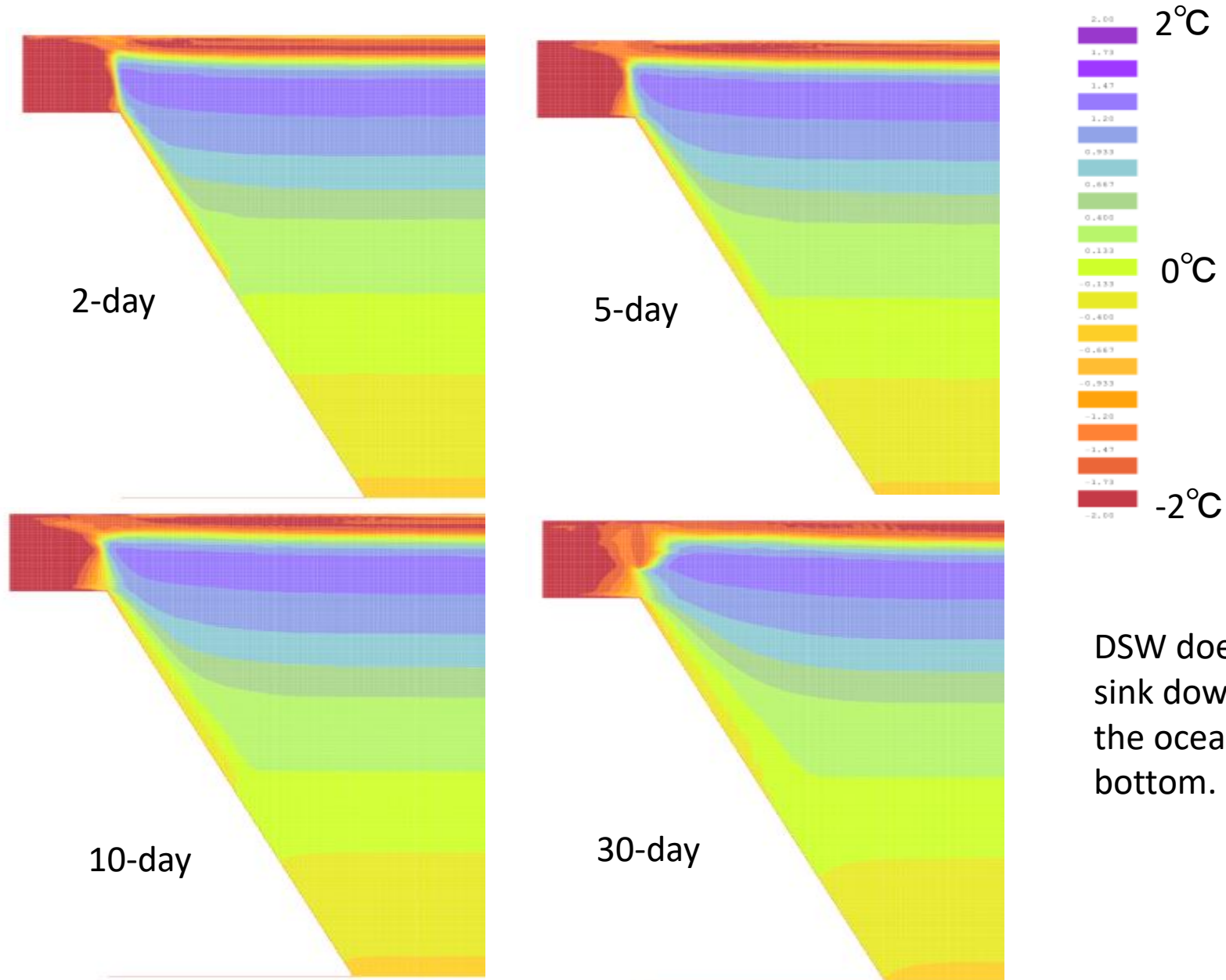
DSW sink down up to the ocean bottom within two days.

# Result Temperature distribution Case A5 Non-compressibility



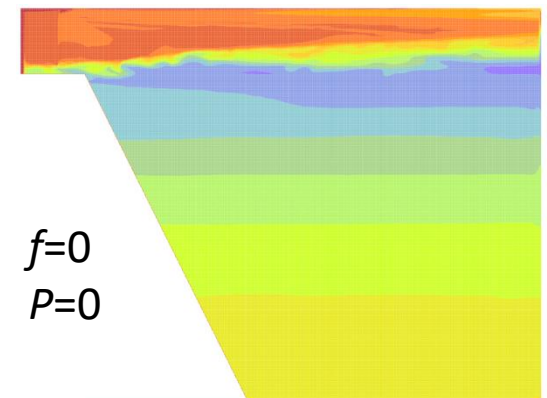
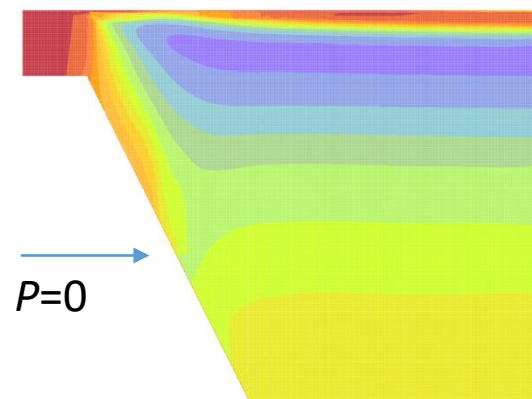
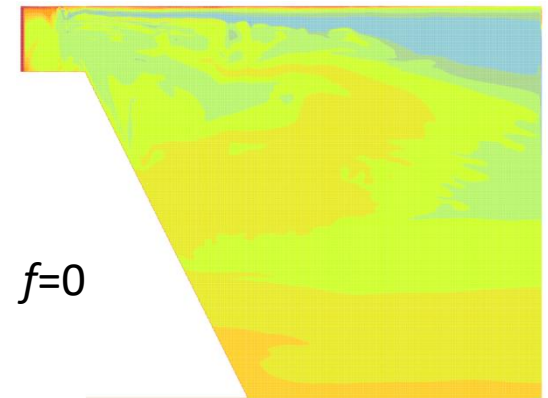
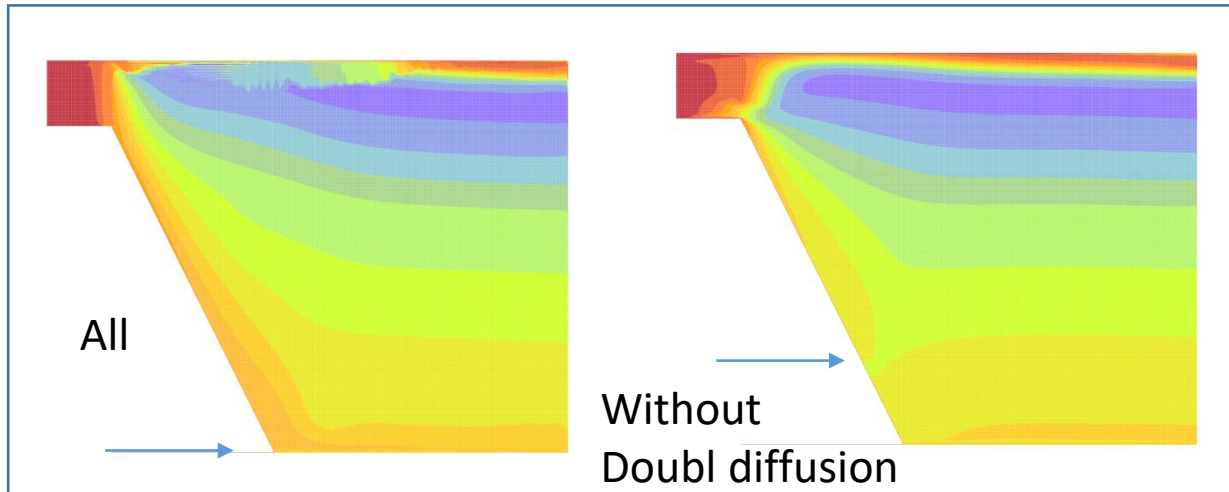
DSW spread horizontally.

# Temperature distribution Case A1 ( $f \neq 0$ with double diffusion effect)



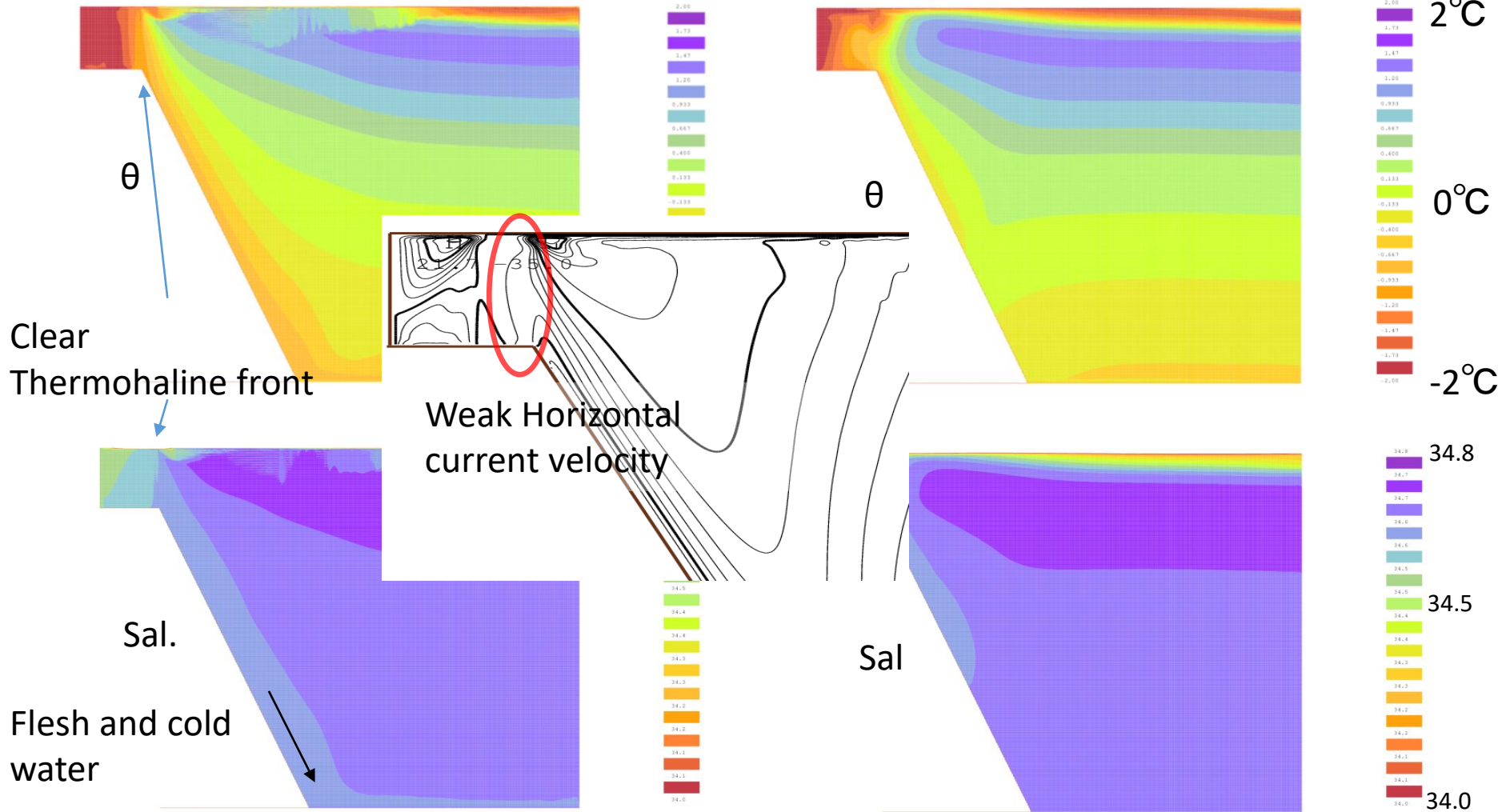
DSW does not sink down up to the ocean bottom.

# 150-day



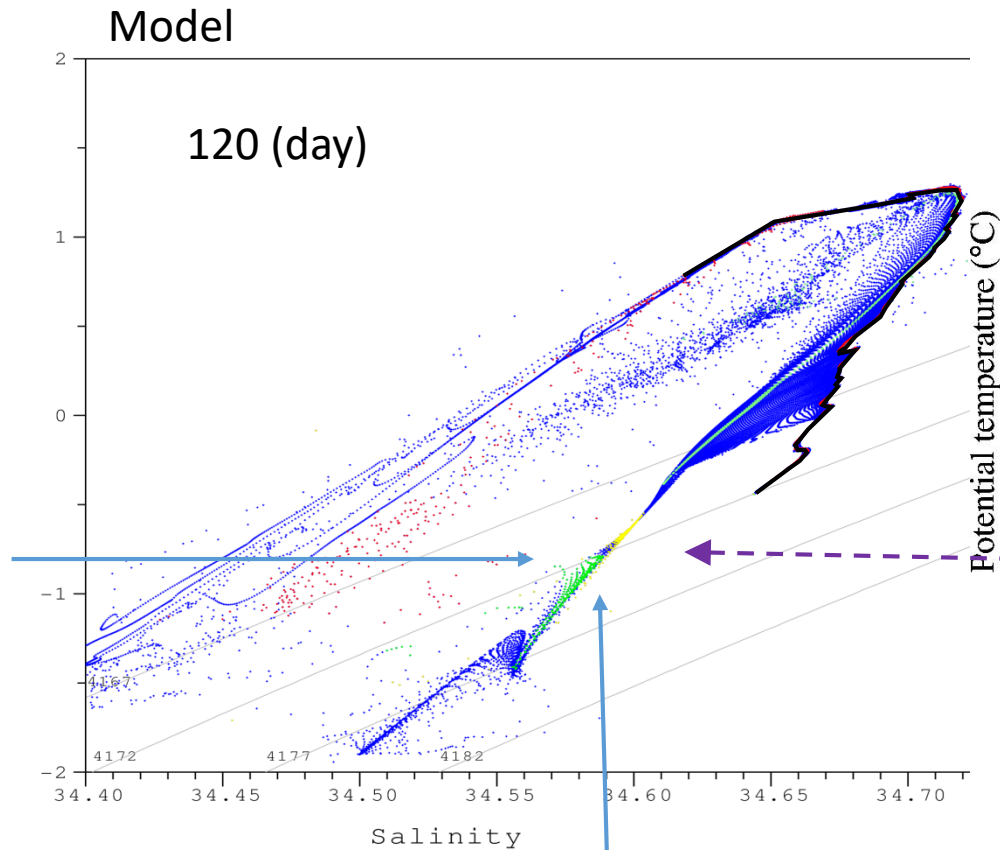
180-day with Double diffusion

without double diffusion

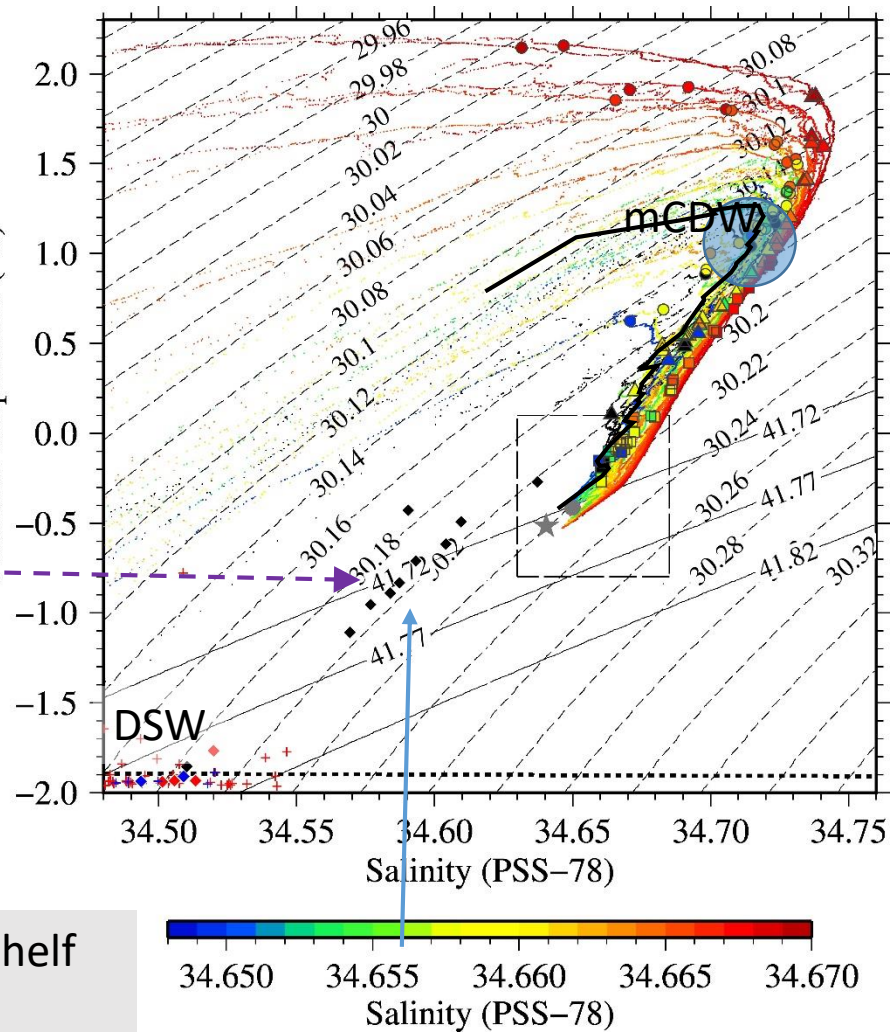




# $\theta$ S relations



## Observation



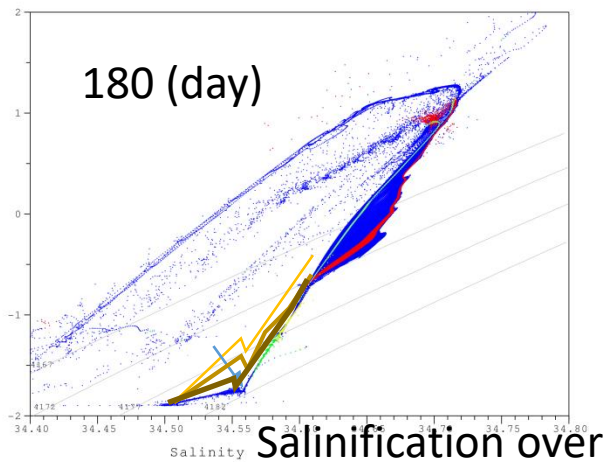
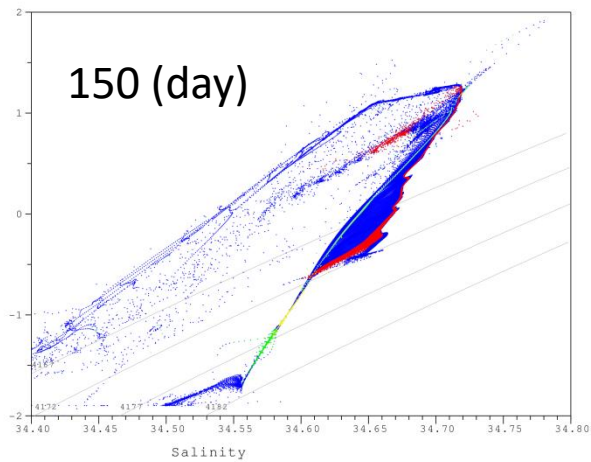
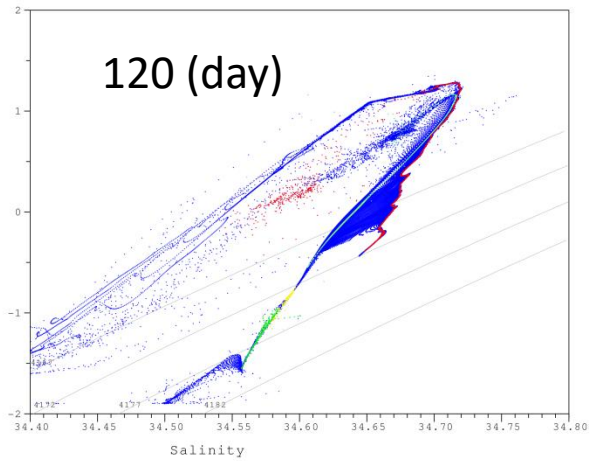
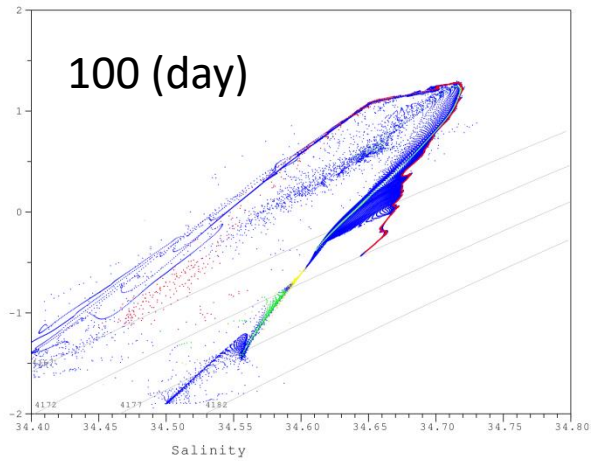
Green: continental shelf

Yellow: middle depth of continental slope

Red: bottom of continental slope



# CaseB $\theta$ S relations



Salinification over  
the continental  
shelf

# Summary of numerical experiment

We have well reproduced  $\theta$ S-relation observed off VB.

**Important process on the formation of VBBW are all of “Compressibility”, “Coriolis effect” and “Double diffusion”.**

- **Compressibility:** Quite important on the formation of dense water off the middle size polynya.
- **Coriolis effect:** formation of density front at the shelf edge. Conservation of potential vorticity induce deepening of cold water its self at the shelf edge.
- **Double diffusion:** important to form cold and saline water

Possibility of AABW source originating from meddle size of Polynya along the coast of Australian-Antarctic Basin

\*Yujiro Kitade<sup>1</sup>, Keishi Shimada<sup>1</sup>, Yuki Ogata<sup>1</sup>, Shigeru Aoki<sup>2</sup>, Taiyo Kobayashi<sup>4</sup>, Kohei Mizobata<sup>1</sup>, Takeshi Tamura<sup>3</sup>, Toshio Suga<sup>5</sup>, Kay I. Ohshima<sup>2</sup>  
1. Tokyo University of Marine Science and Technology, 2. University of Tokyo, 3. National Institute of Polar Research, 4. Japan Agency for Marine-Earth Science and Technology, 5. Tohoku University



### Introduction

Antarctic Bottom Water (AABW) is the densest water in the ocean and globally significant; its production at the Antarctic margin is a key component of the global overturning circulation [eg. Marshall and Speer, 2012]. AABW originating from a middle size polynya called Vincennes Bay Polynya (VBP) was discovered recently [Kitade et al., 2014]. The fact that a middle size polynya can be a formation site of AABW suggests the possibility that the unknown formation area further exists along the coast of Australian-Antarctic Basin (AA-Basin).

A deep profiling float, called "Deep NINJA" which is able to observe temperature and salinity at depths up to 4,000 m, was developed by Japan Agency for Marine-Earth Science and Technology and Tsurumi-Seiki Co. [Kobayashi et al., 2015].

Fig. 1. Locations of major polynyas in the East Antarctica and location of the study area.

[bindoff et al., 2000]

### Observation

Fig. 2. Locations of CTD data obtained by Ninja float, TR/V Umitsuka and R/V Mimi. Colored circle (pink) and diamond (estimated) are location of Ninja profiled data. Black and white squares: TR/V Umitsuka; Brown triangle: TR Mimi; Black cross: Biologging

Because the Ninja profilers drifted westward, we had expected discovery of unknown formation area of AABW. However ...

Fig. 3. Photo of Deep NINJA

Five deep floats were deployed along 110°E in Jan. 2014. Two of them drifted west most along the continental rise. Ninja 14 has been observing 40 profiles within two years, while Ninja 13 had obtained 23 profiles.

Fig. 4. Vertical sections of  $\theta$  and Salinity. Dashed horizontal line indicate lower criteria of density of AABW.

Ninja profiler successfully captured data up to depth level of AABW. Effects of VBBW (relatively cold signal) were not clear in the western region. Strength of MCDW signal varies largely with location. This transition in MCDW signal implies the existence of recirculation gyre, roughly consistent with Bindoff's schematic view. Furthermore, relatively low salinity (34.3) was observed in the western region, which is consistent with density driven current and its recirculation.

Fig. 5.  $\theta$ -S relation for all of CTD data obtained in Fig. 1. Black dot: TR/V Umitsuka; Brown dot: TR Mimi; Black cross: Biologging; colored dot: Ninja as same color indicated in Fig. 1.

Variety of water property near the Antarctica in AA-Basin are shown in the figure. Ninja profilers observe typical water masses, e.g. AABW, Modified CDW, and cold dense water. Dense Shelf Water (DSW) with fresher property were obtained by biologging in shackleton area.

### Characteristics of AABW obtained by Ninja Float

Fig. 6.  $\theta$ -S relation for AABW. Dark gray: 110°E TR/V Umitsuka; light gray (Vincennes Bay Bottom Water) : Near VB TR/V Umitsuka. Colored line: Data from Ninja floats. The light gray contour denotes neutral density. Data by Ninja13 showed Vincennes Bay Bottom Water (VBBW) signals at first few casts. Because Ninja13 were near VB than Ninja14 at first, strong effect of VBBW has been appeared in profiles of 13. Since the temperature and salinity increase gradually with distance from VB, we may say that no signal of newly formed AABW has been observed except in the region off VBP.

Fig. 7.  $\theta$ -S relation of bottom water obtained by mooring and hydrographic data during 2011-14 (after Kitade et al. [2014]). New mooring data from 2015 Jan. to 2014 Jan. are indicated by crosses. Dark and light gray line indicate same as shown in Fig. 6. The  $\theta$ -S profile obtained from 2011 to 2014 are color coded by salinity value, which is averaged in the range of  $\pm 25$   $\sigma_{\theta}$  of neutral density surface of 28.32 kg/m<sup>3</sup> (See Kitade et al. [2014]).

Fig. 8. Vertical profiles of  $\theta$  and S. Red vertical line indicate  $\theta = -0.3^{\circ}\text{C}$  in temperature and  $S = 34.35$  in salinity. Cold and fresh VBBW ( $\theta < -0.3^{\circ}\text{C}$ ,  $S < 34.65$ ) has been found in Region 1. In region 1(off VB), cold and fresh signal, implying interleaving layer, appeared throughout water column. While interleaving layer was not clear in region 2, it appeared again in upper 2000m in region 3 (off SK). Temperature maximum, implying MCDW, was found at almost 300m depth in region 1, but at around 600m depth in region 3.

### Summary

Ninja profiler successfully captured signals of VBBW. Because the Ninja profilers drifted westward, we had expected discovery of unknown formation area of AABW. However, no signal of newly formed AABW has been observed except in the region off VBP, which is consistent with the BROKE results [eg. Bindoff et al., 2000]. Although these observations do not completely negate the additional formation of AABW originating from middle size polynyas located west of VBP, their formation volume of AABW is suggested to be much smaller than that from VBP.

There is a possibility that the lower salinity DSW, which is not heavy enough to sink down to the bottom, is formed in SK.

The candidates to explain the differences in VB and SK are

- (1) Depth of MCDW and circulation off SK,
- (2) Possibility of glacier melting.

To confirm AABW formation, long period mooring off SK is also needed as future subjects.

### Characteristics of DSW

Fig. 9. Dense Shelf Water obtained by biologging are compared with Ninja14. Pink is VB, Blue is SK. The TS obtained by Ninja 14 is indicated by the color at the right end. The black solid line in the figure indicates the  $\sigma_{\theta}$  contour line.

We can see DSW in both of VB and SK, while their salinity are not so high as shown in other AABW production region. Nevertheless, DSW in VB shows a value close to  $S = 34.5$  at freezing temperature. This DSW can become more heavy due to the compression effect, so it is considered that it has a potential to sink down to about 3000 m [Kitade et al. 2014].

When DSW and MCDW mix on the shelf a water mass of higher salinity than DSW called Modified Shelf Water (MSW) is formed. Although MSW is frequently observed in VB, it is likely uncommon in SK. The related structure appears in the depth of the MCDW observed by Ninja floats off the shelf edge. In the region off VB, the depth of MCDW is shallow, and hence, able to spread over the shelf. In the region off SK, however, it is too deep to be supplied on the shelf. Also, core salinity of DSW's in SK is lower as  $\sim 34.3$ .

### Discussion

Fig. 10. Time series of ice production in SK and VB for 2014 and 2015.

In order to investigate the cause of salinity difference on the shelf, we examined salt flux due to sea ice production. The sea ice production amount is higher in SK in 2014, but it is almost the same in 2015. Therefore, as a total, there is no big difference in the amount of salt supply induced by sea ice production. Thus, in VB and SK, the difference in salt content of DSW can not be explained by salinity flux associated with sea ice production.

Fig. 11. Distribution of MCDW off the shelf edge of VB and SK, and the relationship between offshore circulation.

Cold and fresh signal, implying interleaving layer, appeared throughout water column off VB, while it appeared only in upper 2000m off SK.

DSW close to 34.3 and MSW were abundant in VB, but in SK, where the salt content of DSW was low and water mass indicating MSW was hardly observed. We can think that this will make a difference in the depth of ventilation into the offshore stream.

Despite the comparable sea ice production, what is different between VB and SK? As a factor of this, from this data set, what is considered is the presence and/or absence of inflow of MCDW from offshore. In SK, since the depth of MCDW is deeper than the shelf edge, salinity supply accompanying advection is small, but in VB it is considered shallow, so salt is likely to be supplied onto the shelf because it is shallow. The source of high temperature and high salt water off VB corresponds well with the distribution of circulating flow.

Fig. 12. AVISO absolute dynamic topography from Oct. 2013 to Mar. 2014.

Effects of glacier melting: In recent years, melting of glaciers has been rapidly advanced, and the melting amount of SK ( $\sim 80$  Gton) is much larger than VB ( $\sim 50$  Gton).

This poster show that no clear evidence of newly formed AABW off Shackleton Polynya where sea-ice production was more active than that of VBP.



# Conclusion

- From these results, we may conclude that not only salinity flux by sea-ice production but also surrounding water conditions are important to form AABW.
  - These studies should also be taken into account for more good estimation of total volume of AABW formation around Antarctica.
- ⇒ Good estimation of parameters on Global Ocean Circulation increases accuracy of long period prediction of climate change.

**Further study including detailed observation is necessary to clarify the mechanism of AABW modification in Global warming age.**