海氷生産による中深層水形成とその変動
ー衛星観測から日本南極観測隊観測までー

大島慶一郎（北大低温科学研究所）

1. イントロダクション：海氷生成と中深層水形成
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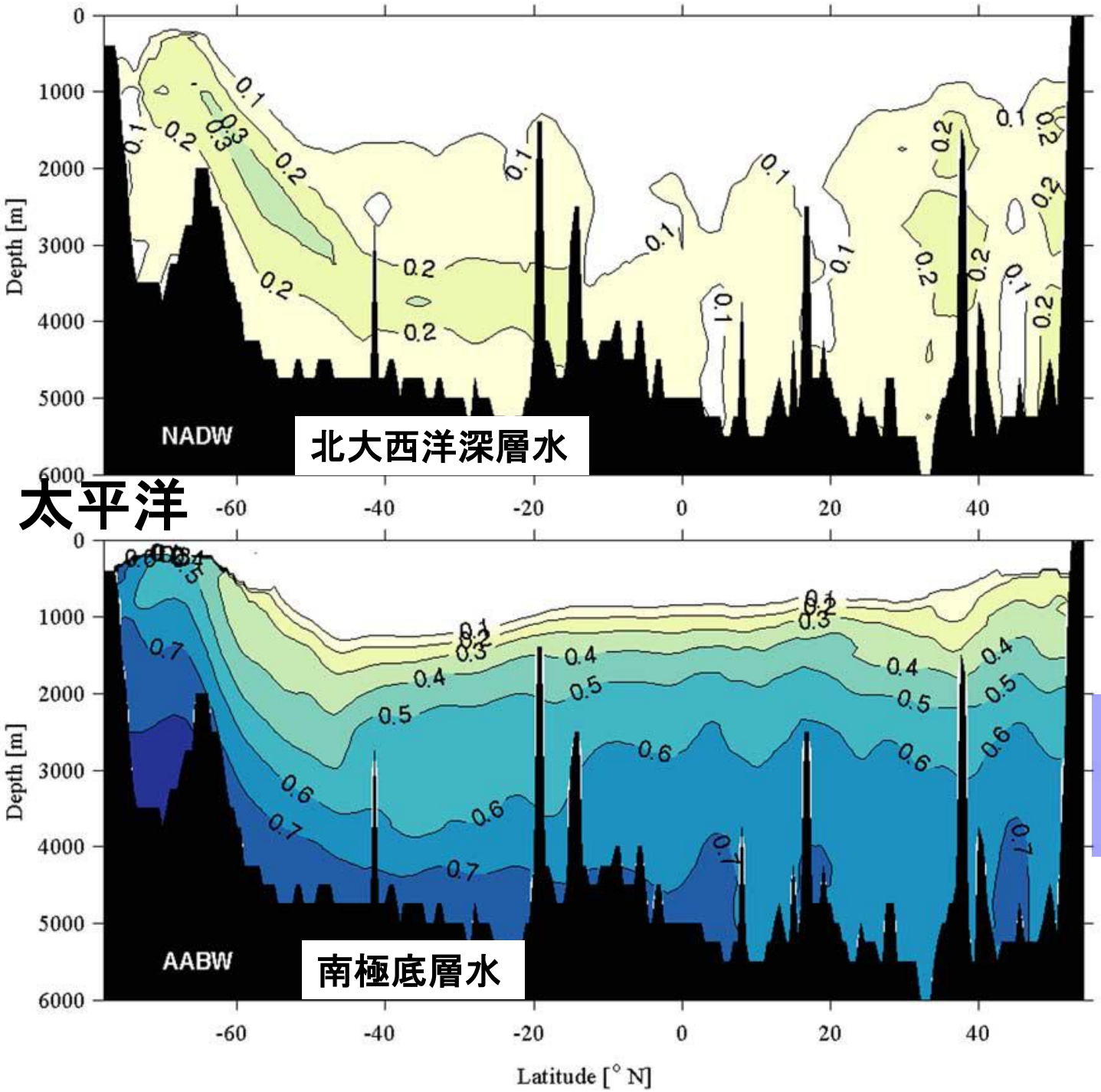


Johnson(2008)

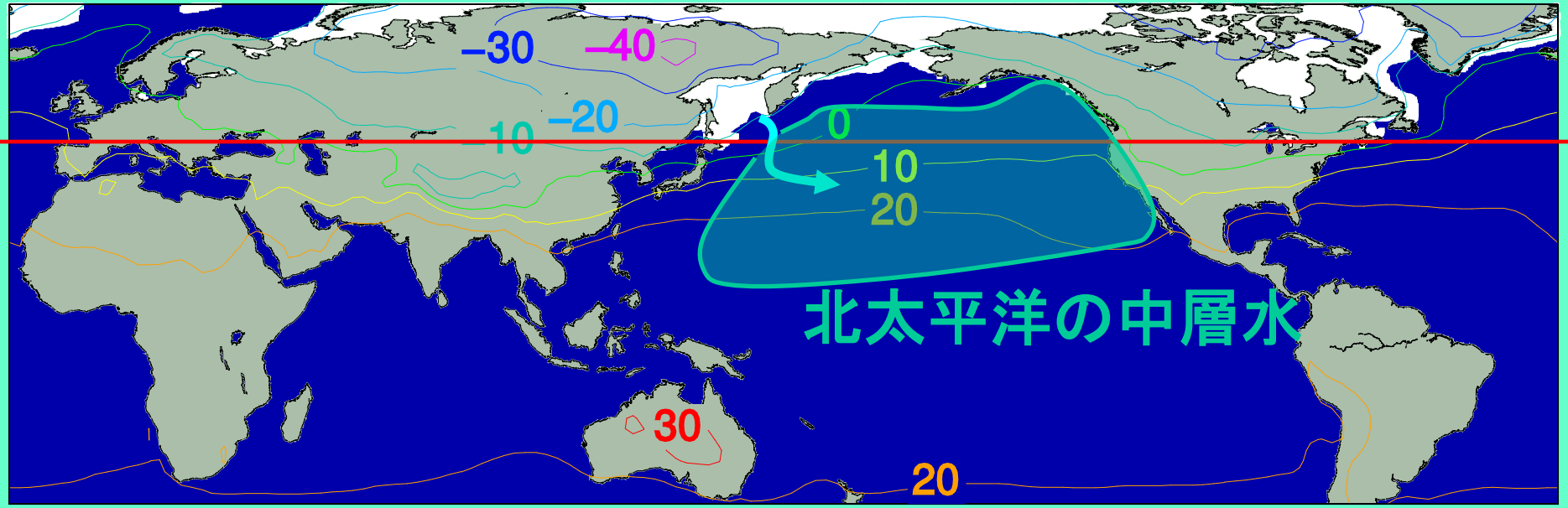
海水の性質から
2つの深層水の
割合を同定

ポテンシャル水温
塩分
渦位
溶存酸素
硝酸
リン
シリカ

南極底層水は
全海水の30－40%
を占める

グローバルな目でみたオホーツク海

2月の海氷分布と平均気温（2001年）

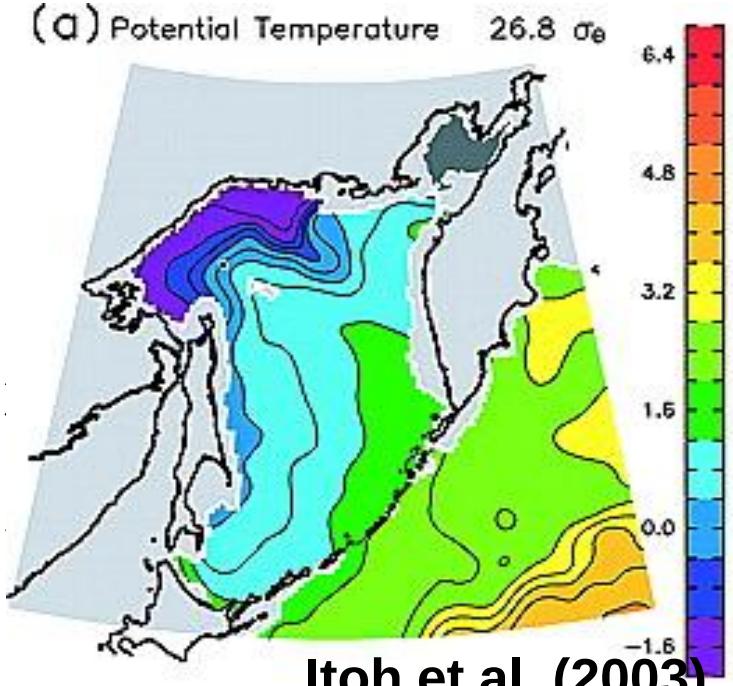


Nihashi et al.,2009

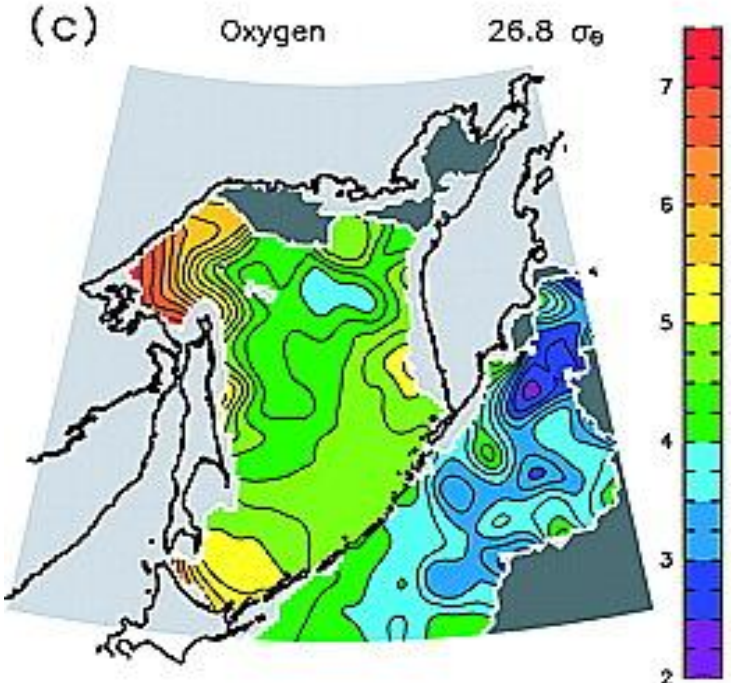
・風上が北半球の寒極 → 北半球における海氷域の南限

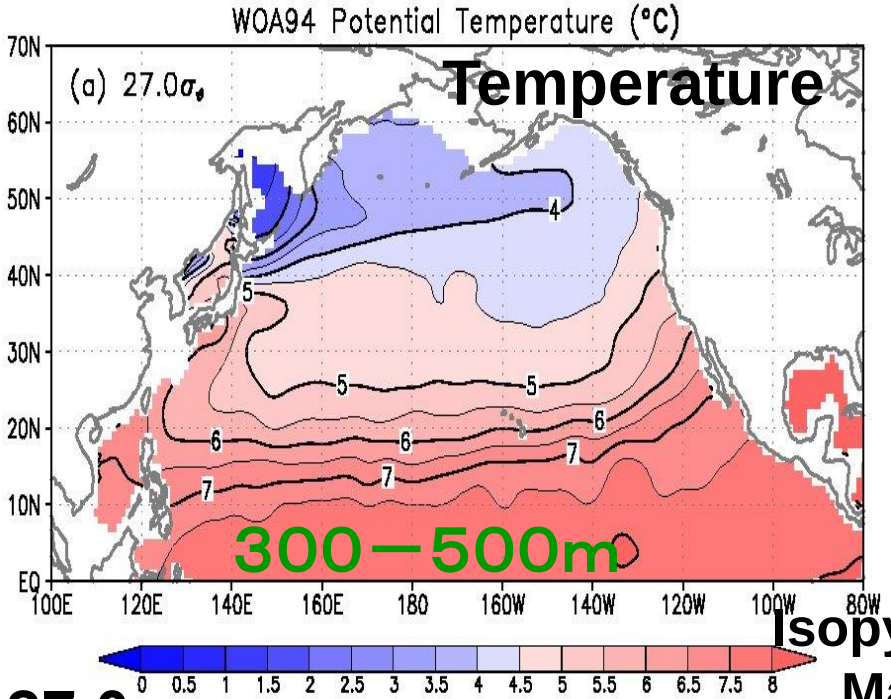
・多量の海氷生産 → 北太平洋で一番重い水ができる場所

→ 大気・陸からの熱・物質を北太平洋中層水(200-800m)へ



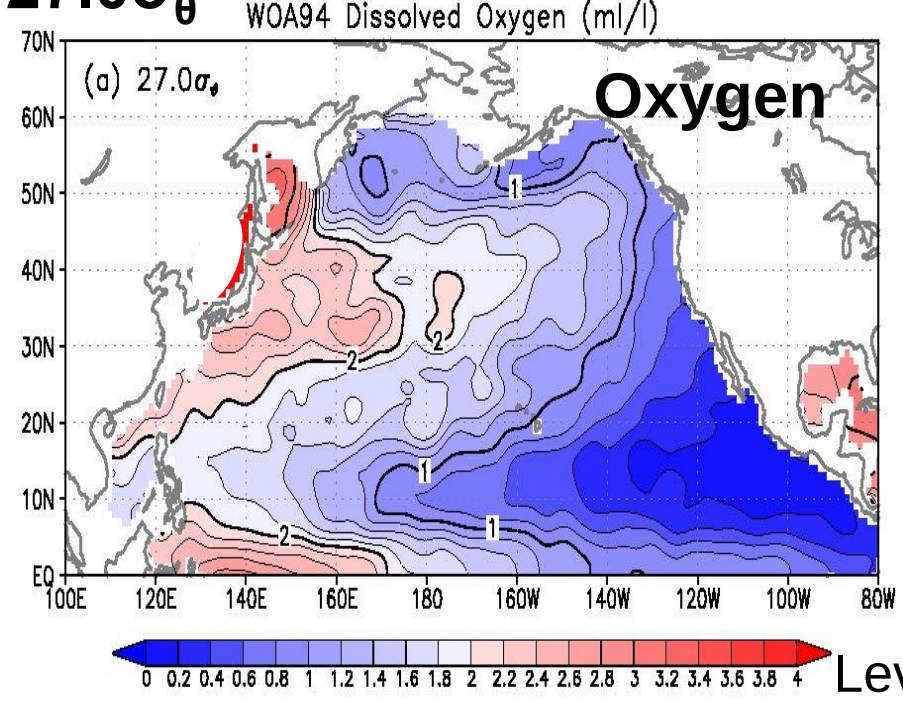
Itoh et al. (2003)





Isopycnal Map

27.0σθ



Levitus

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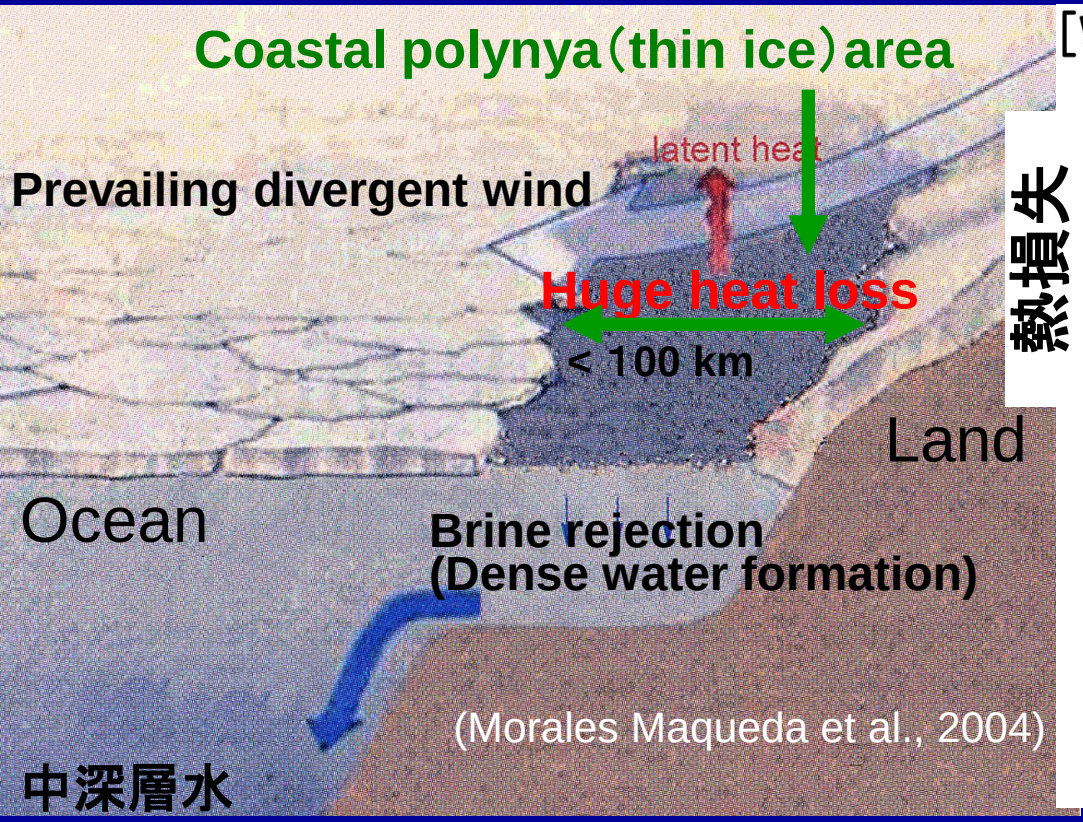
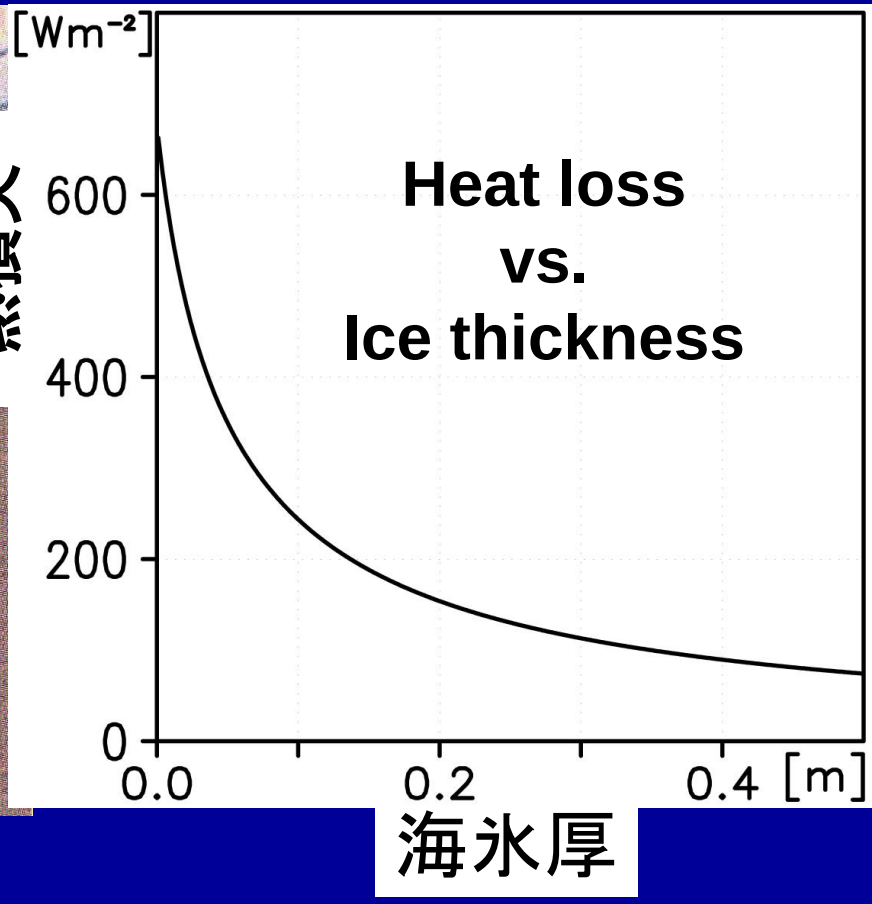
沿岸ポリニヤ → 海氷生産工場



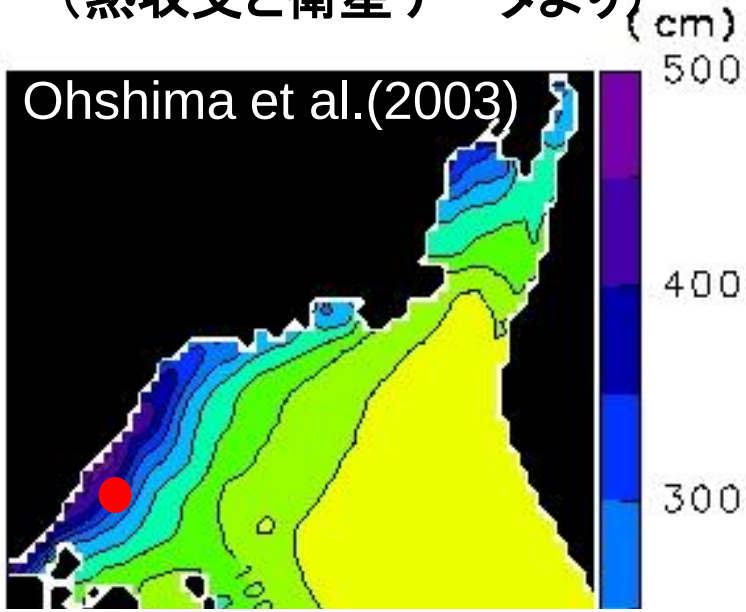


マイクロ波放射計による薄氷厚アルゴリズム

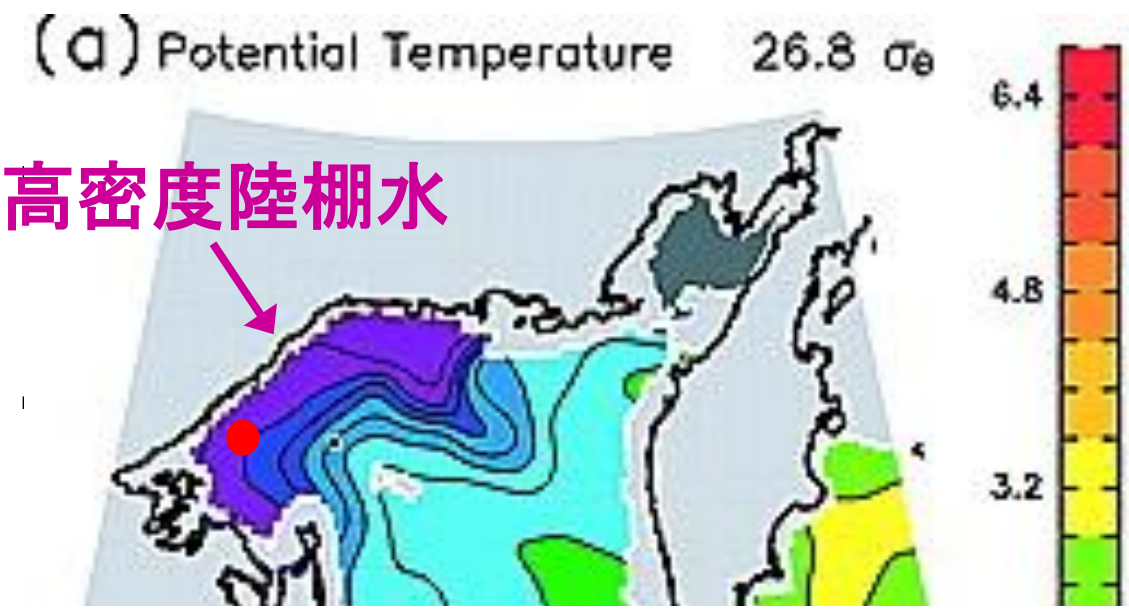
→　熱収支計算による熱損失 ＝ 海氷生産量

海氷生産量の見積もり

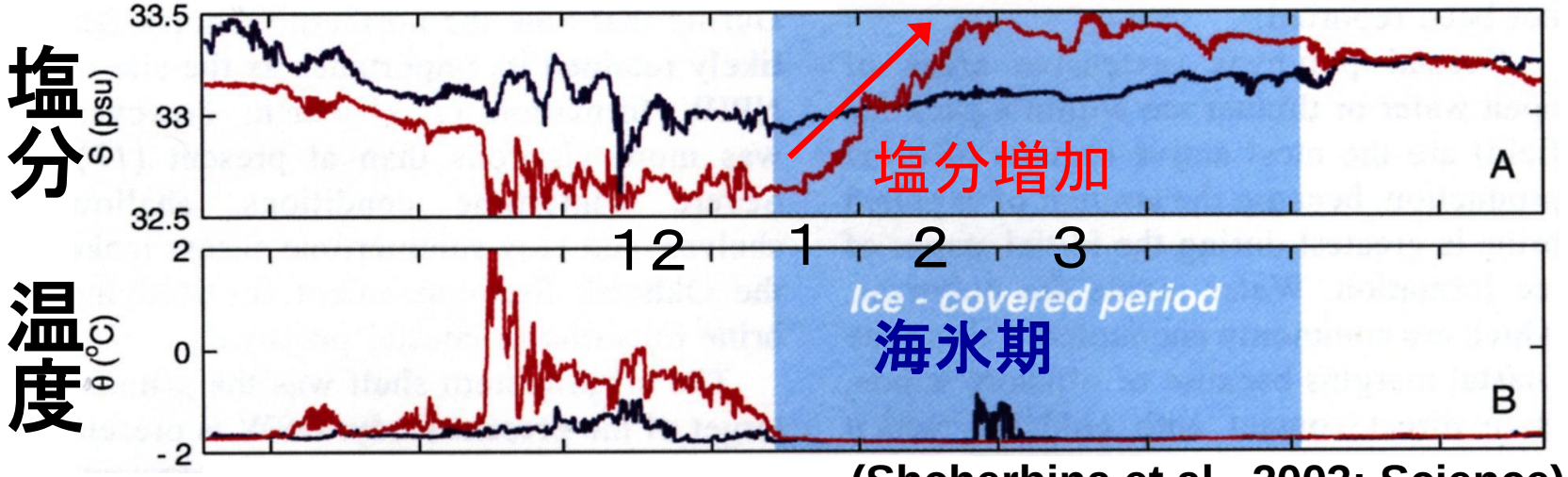
（熱収支と衛星データより）



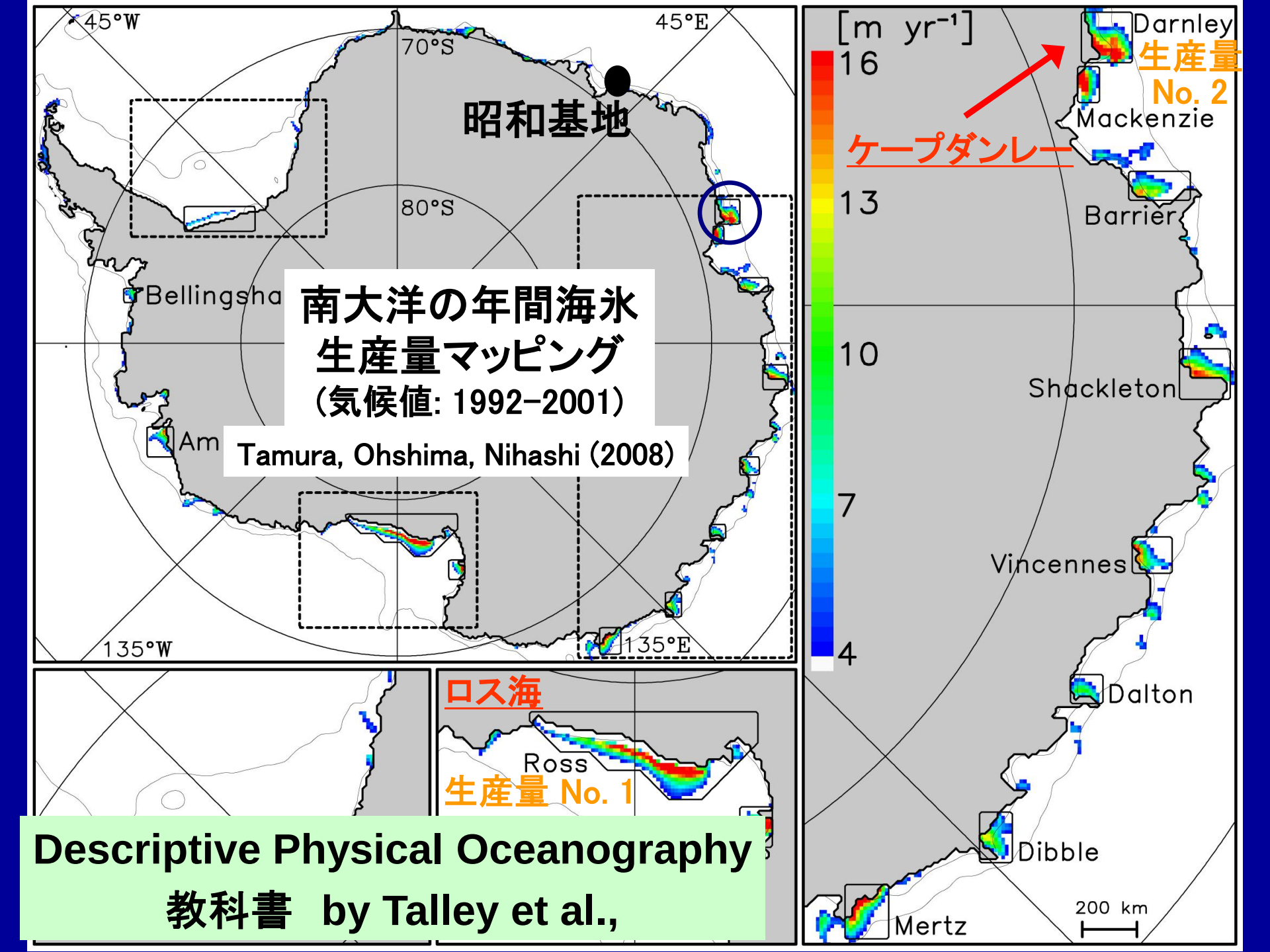
中層(等密度面上)での水温



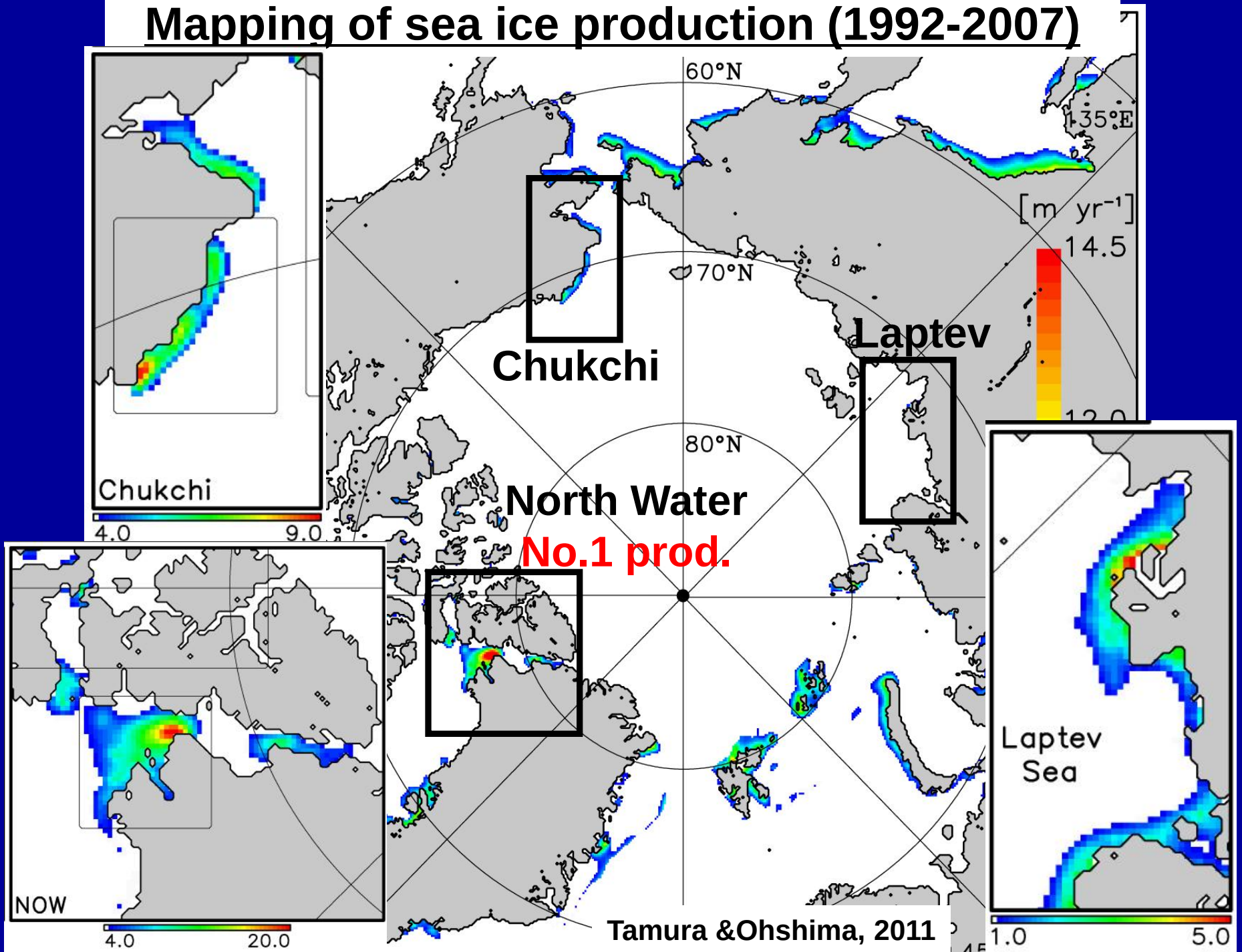
高密度陸棚水生成を捉えた観測



(Shcherbina et al., 2003; Science)

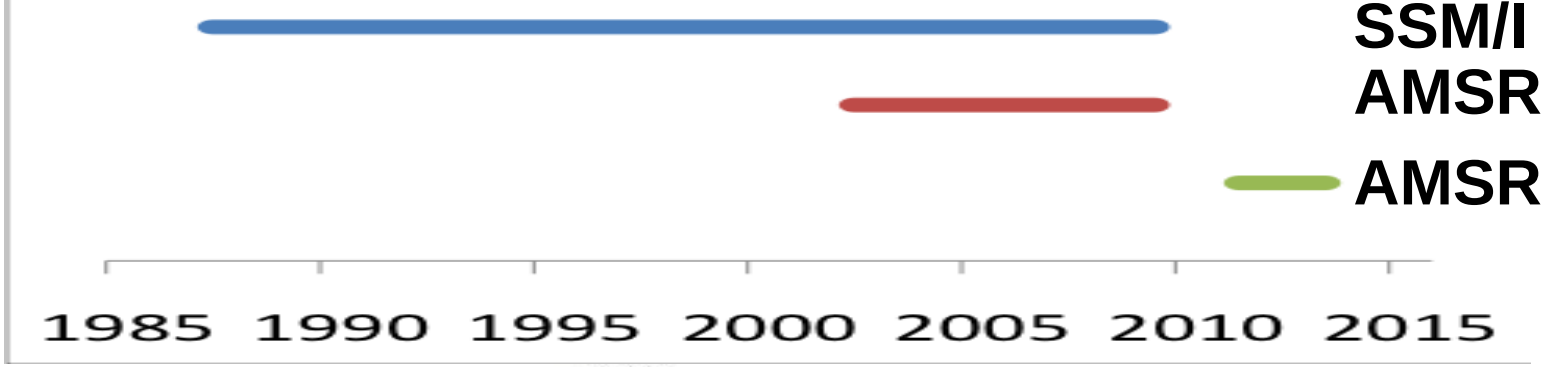

45°W
45°E
70°S
80°S
135°W
135°E
昭和基地
Bellingsha
Am
南大洋の年間海氷
生産量マッピング
（気候値: 1992–2001）
Tamura, Ohshima, Nihashi (2008)
[m yr⁻¹]
16
13
10
7
4
ケープダンレー
Darnley
生産量
No. 2
Mackenzie
Barrier
Shackleton
Vincennes
Dalton
Dibble
Mertz
200 km
ロス海
Ross
生産量 No. 1
Descriptive Physical Oceanography
教科書 by Talley et al.,

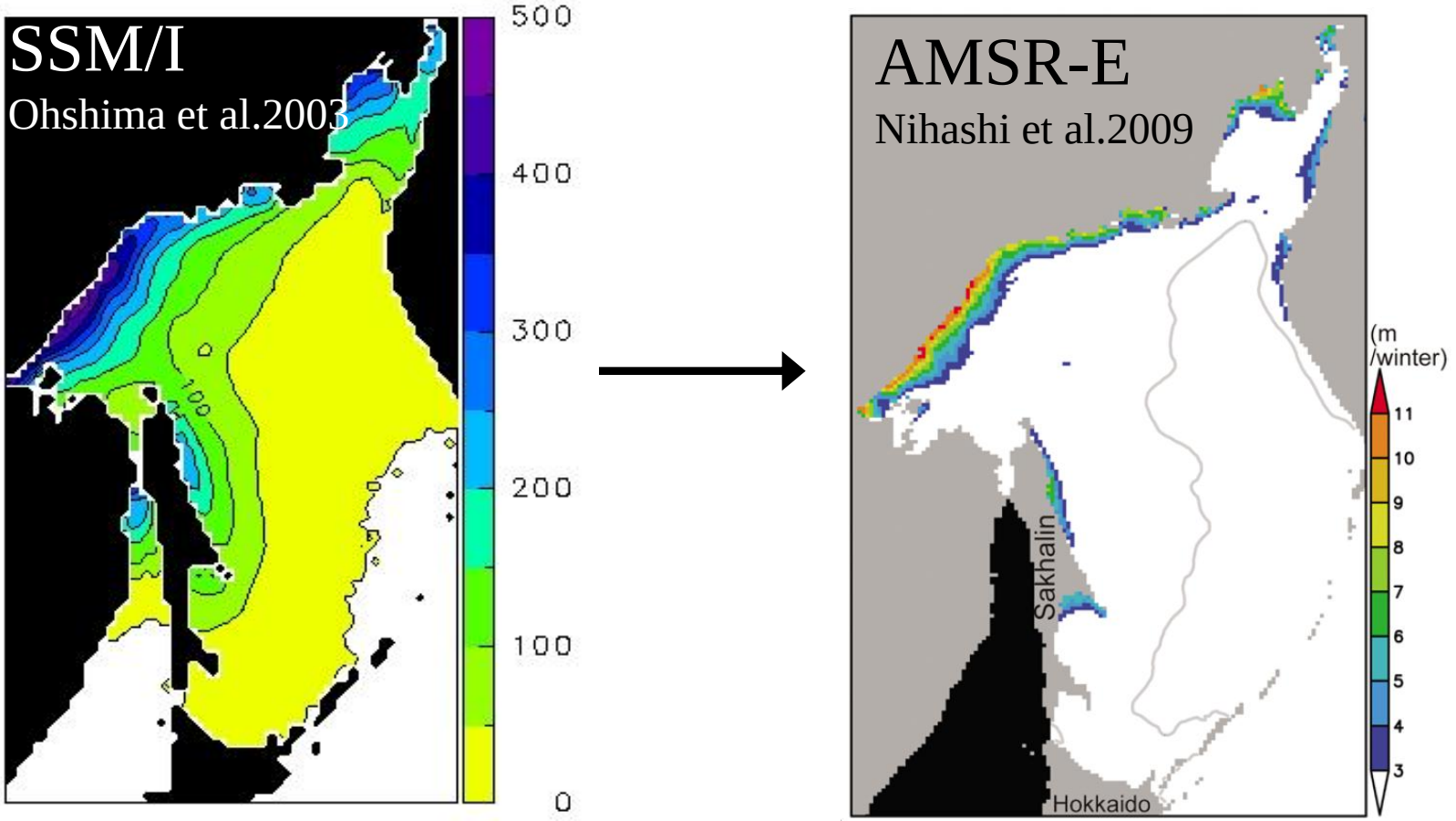
Mapping of sea ice production (1992-2007)



SSM/I 1987-2010 (interannual variations)

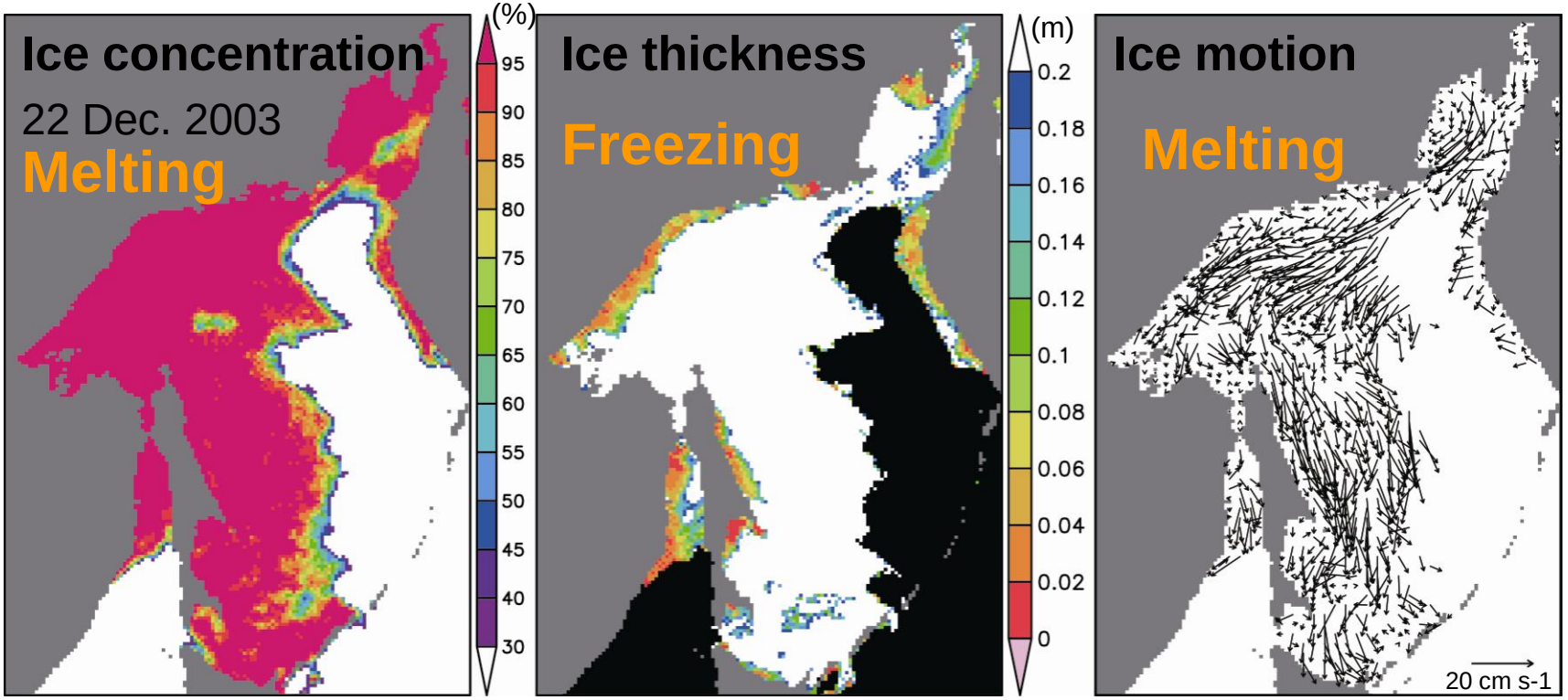
AMSR relatively high spatial resolution (12-6 km))





海氷生成・融解に伴う熱塩フラックスのデータセット作成

Sea ice data are derived from AMSR-E data (daily)



by NT2 algorithm
(Markus and Cavalieri, 2000)

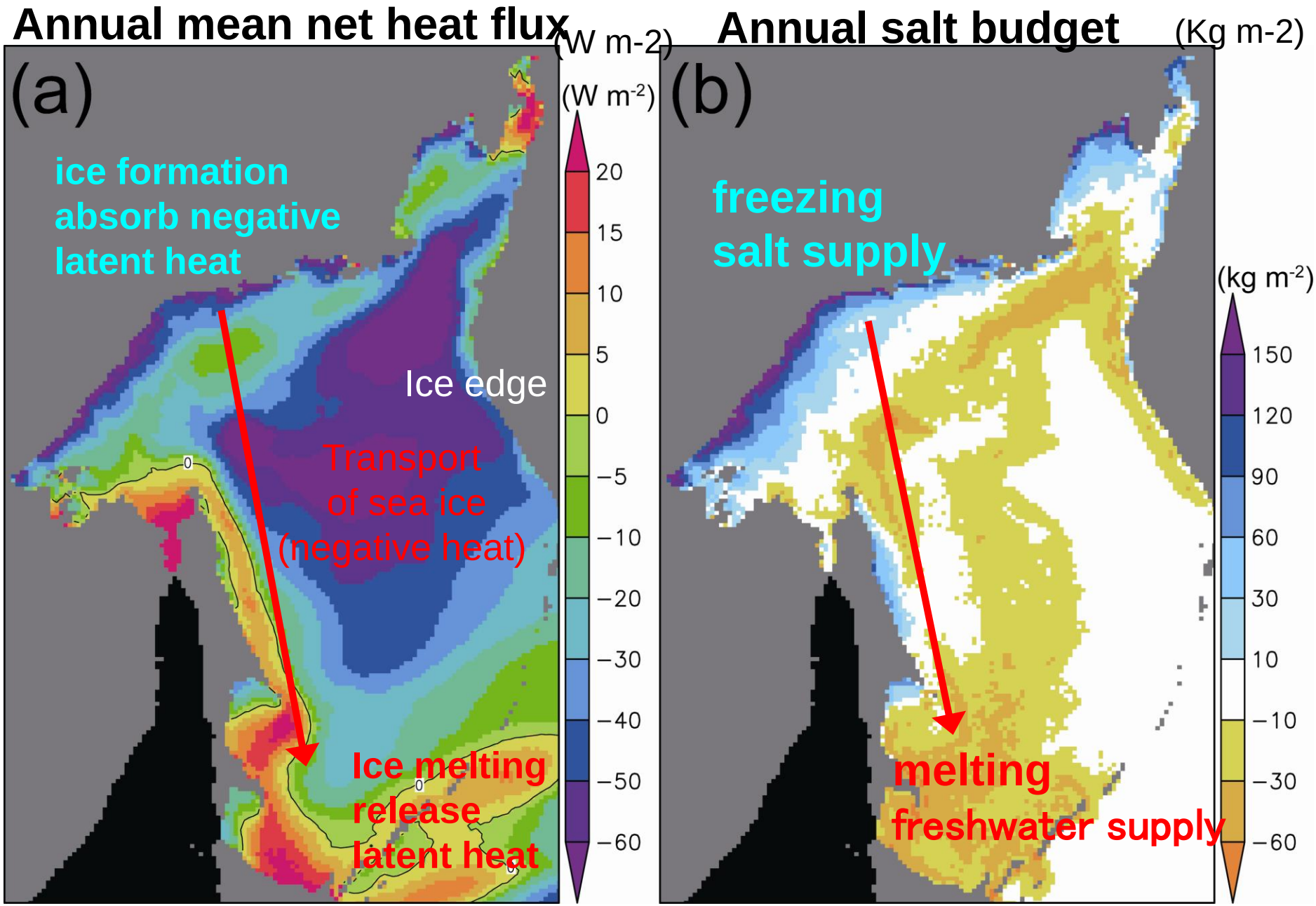
by ice thickness algorithm
(Nihashi et al., 2009)

by maximum correlation method
(Kimura and Wakatsuchi, 2004)

ECMWF: Air temp. Humidity, Wind speed, and SLP (daily)
ISCCP: Cloud (monthly)
HadISST: SST (monthly)

Nihashi, Ohshima and Kimura, J. Climate (2012)

Nihashi, Ohshima & Kimura, J. Climate, 2012



Release plan of the data set (year)

		ice production	heat/salt flux
Southern Ocean	SSM/I	available	available
	AMSR	2013	2014
Arctic Ocean	SSM/I	available	2015
	AMSR	2013	2014
Sea of Okhotsk	SSM/I	2013	2014
	AMSR	available	available

Sea ice production dataset

→ **Validation data for coupled ice-ocean models**

Southern Ocean

Kusahara et al.(2011, Nature-comms.), Kusahara et al.(2010, JGR)

Arctic Ocean

Kawaguchi et al.(2011, JGR)

Surface heat and salt flux dataset incorporating sea-ice growth and melt

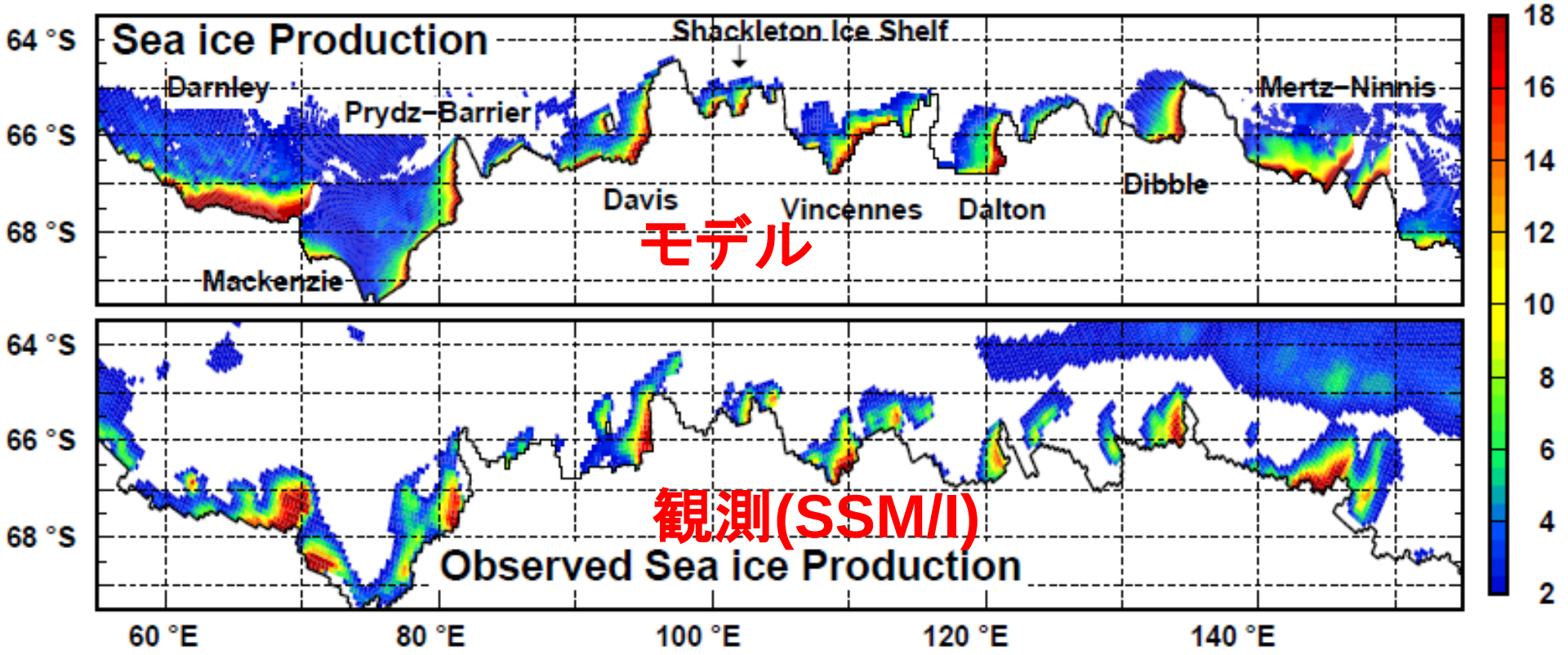
→ **Boundary condition data for various models**

Southern Ocean

ACE CRC ice shelf-ocean coupled model:Galton(2012), Urakawa & Hasumi (2012)

Non-hydrostatic ocean model: Nakayama et al. (preparation)

海氷生産量データセット
海氷結合モデルの検証データ



Kusahara, Hasumi and Tamura (2010)

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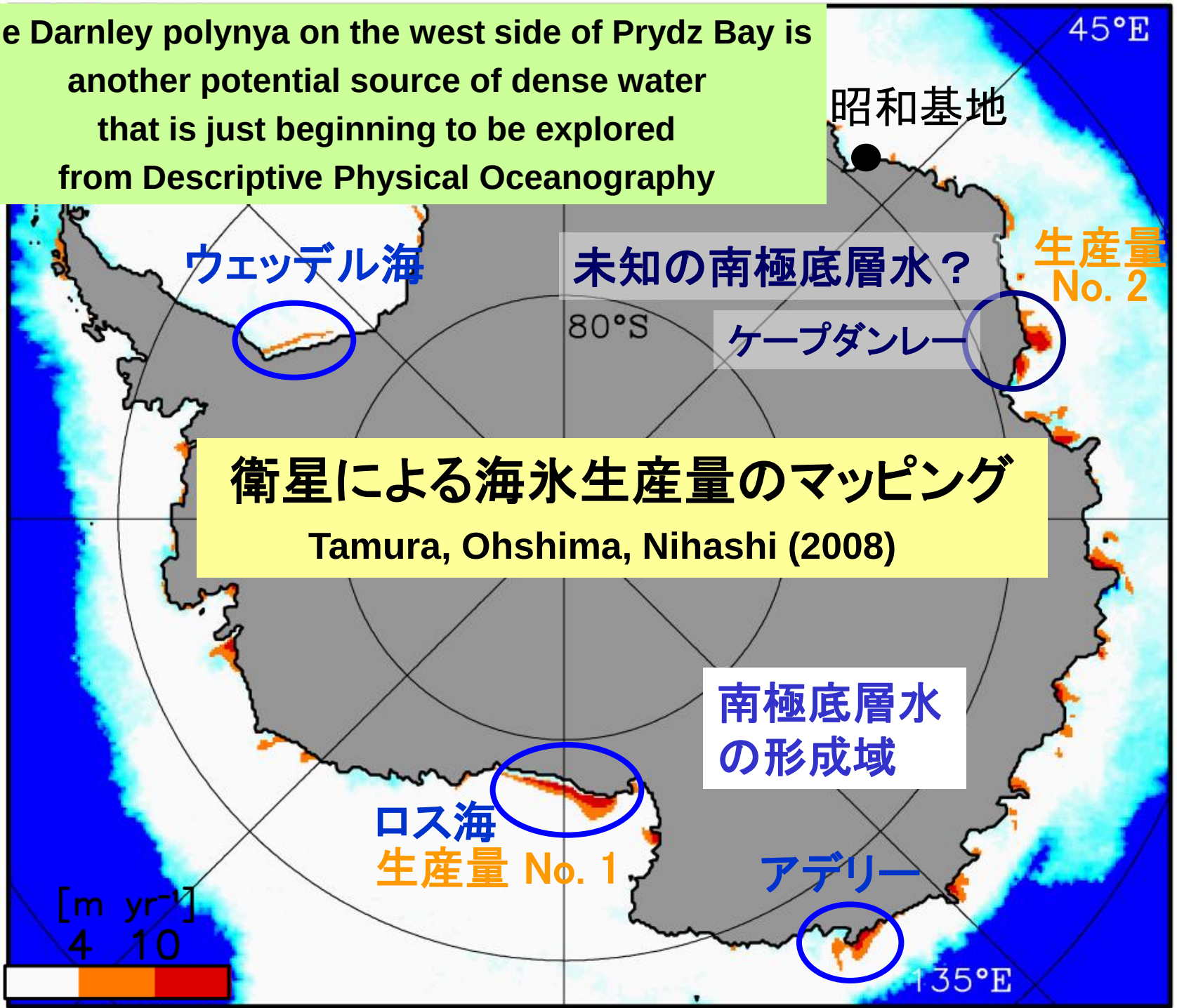
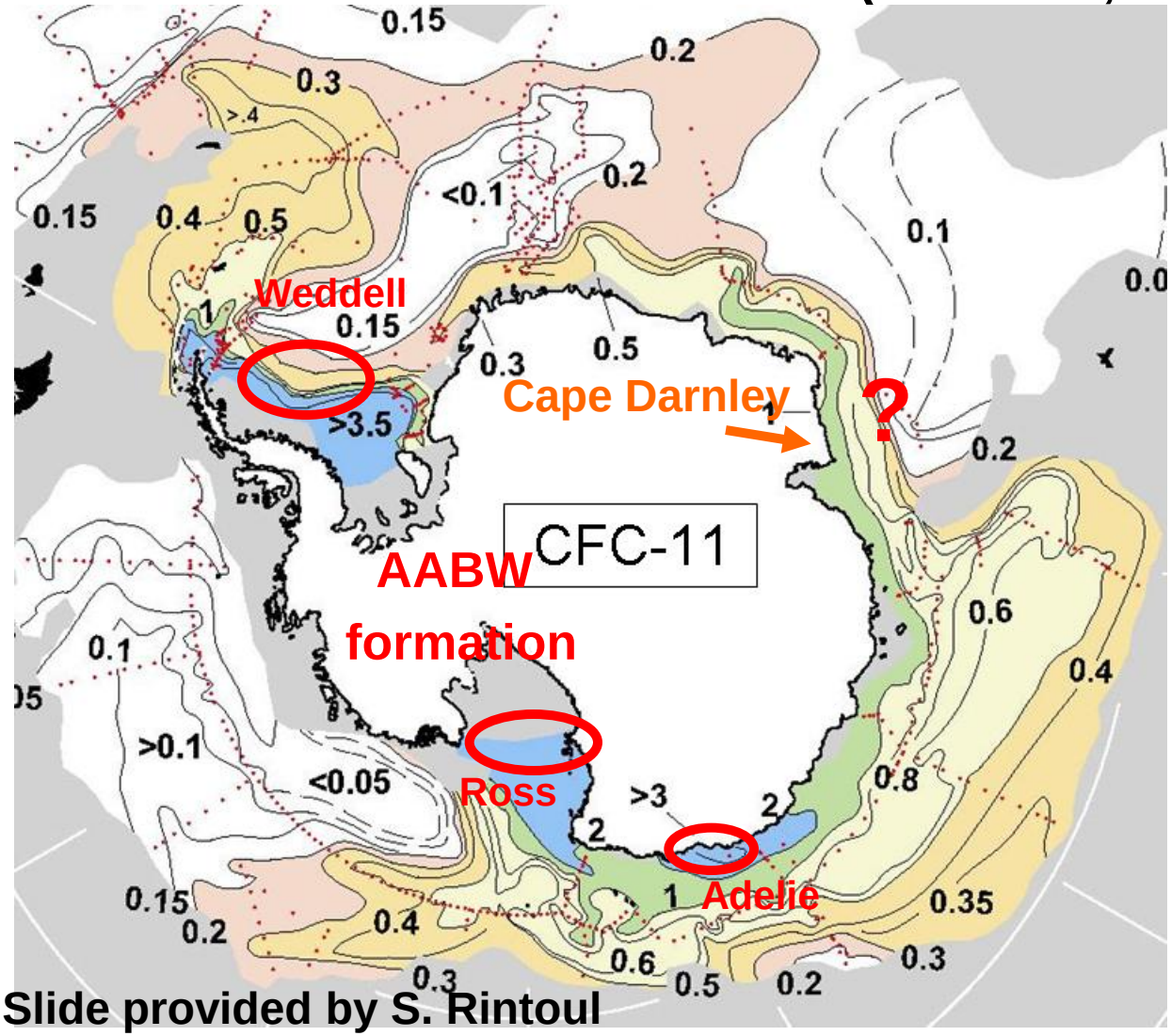
The Darnley polynya on the west side of Prydz Bay is another potential source of dense water that is just beginning to be explored from Descriptive Physical Oceanography



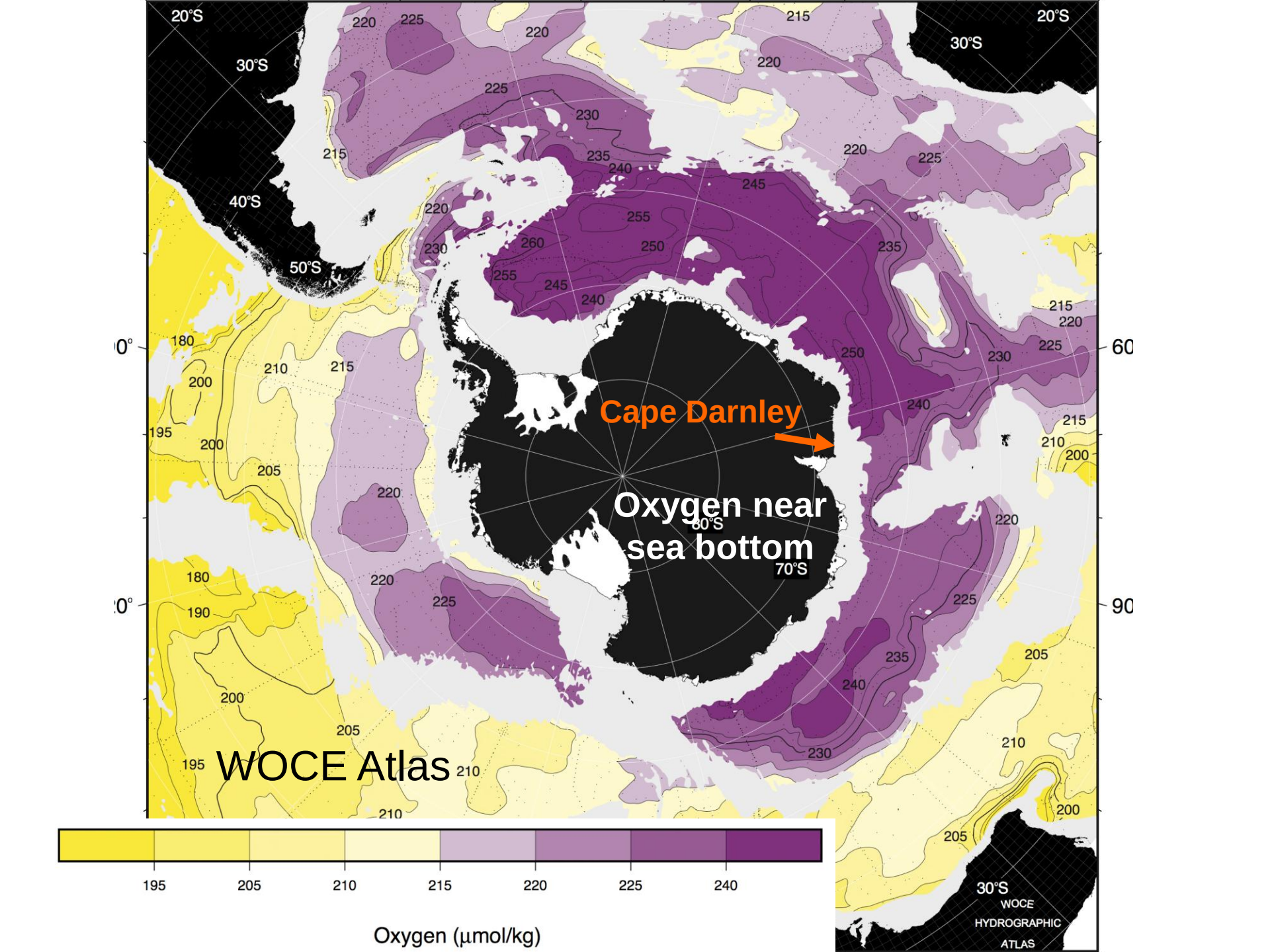
CFC-11 Distribution near bottom (Orsi et al., 1999)

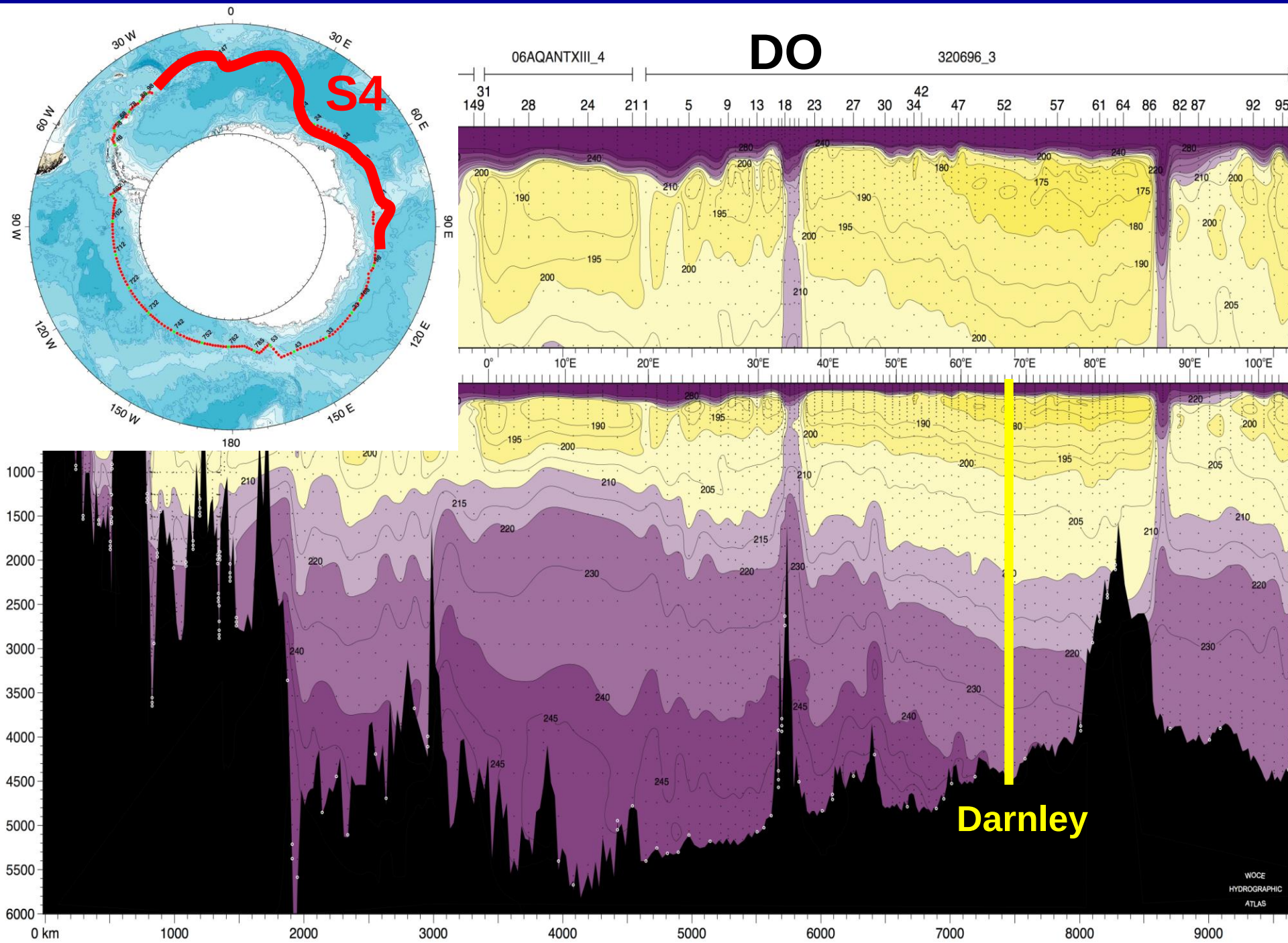


Slide provided by S. Rintoul

Suggestion of AABW formation around 60-70E

- Jacobs and Georgi (1977)
- Middleton and Humphries (1989)
- Mantisi et al. (1991)
- Klepikov et al. (2010, IPY conference)


Cape Darnley
Oxygen near sea bottom
WOCE Atlas
Oxygen (µmol/kg)
195
205
210
215
220
225
240
WOCE HYDROGRAPHIC ATLAS


S4
DO
06AQANTXIII_4
320696_3
Darnley
WOCE
HYDROGRAPHIC
ATLAS
0 km
1000
2000
3000
4000
5000
6000
7000
8000
9000

Darnley Project: CTD Sections & mooring stations

s: Feb. 2008 — Jan. 2009
21 Jan. — 27 Jan. 2009
R/V Hakuho

Line III

Wild Canyon

Line II

M4

M3

M1-M4: Mooring stations

Cape Darnley Polynya

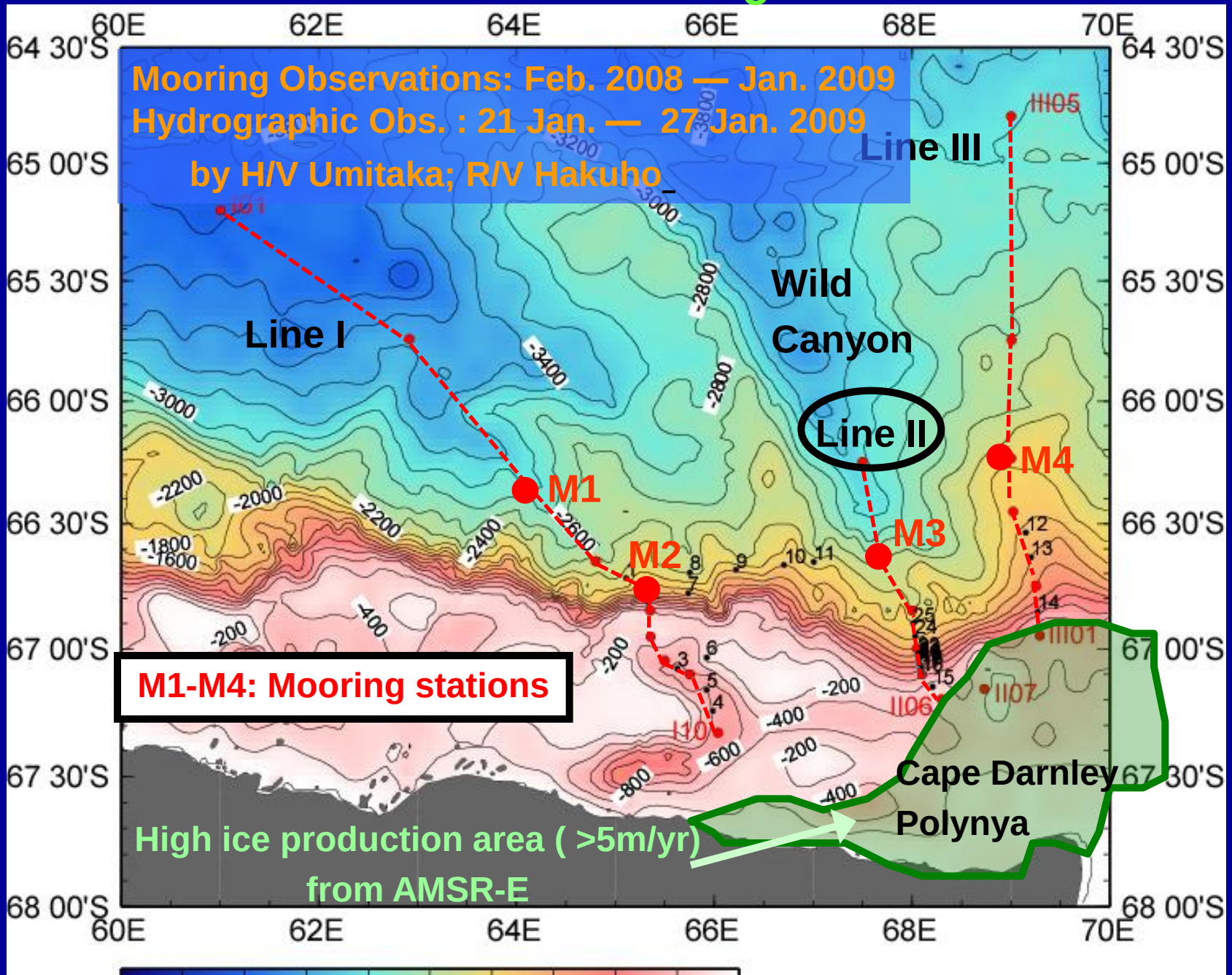
High ice production area (>5m/yr) from AMSR-E

68E 70E

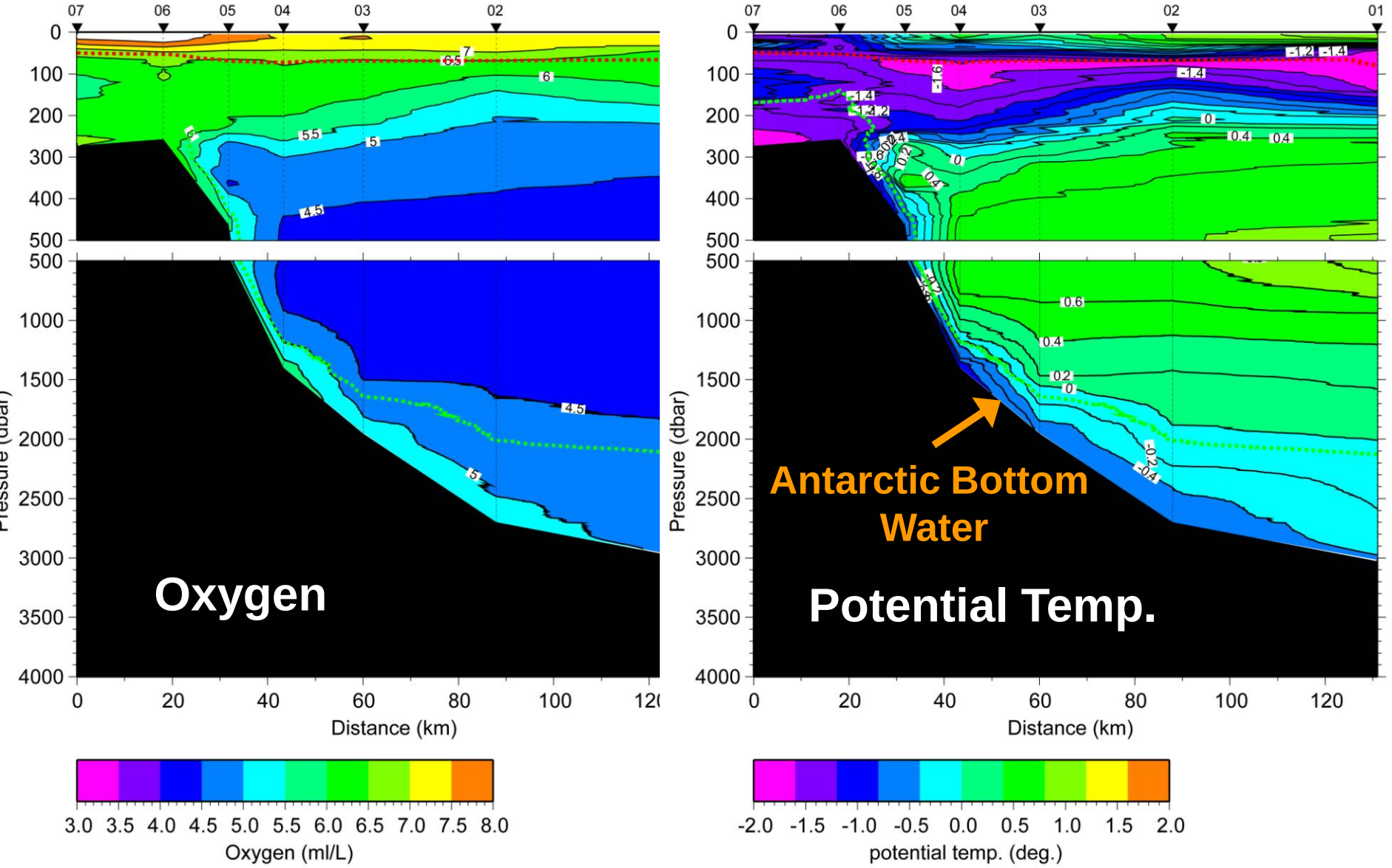
64 30'S
65 00'S
65 30'S
66 00'S
66 30'S
67 00'S
67 30'S
68 00'S

60E 62E 64E 66E 68E 70E

CTD Sections & mooring stations

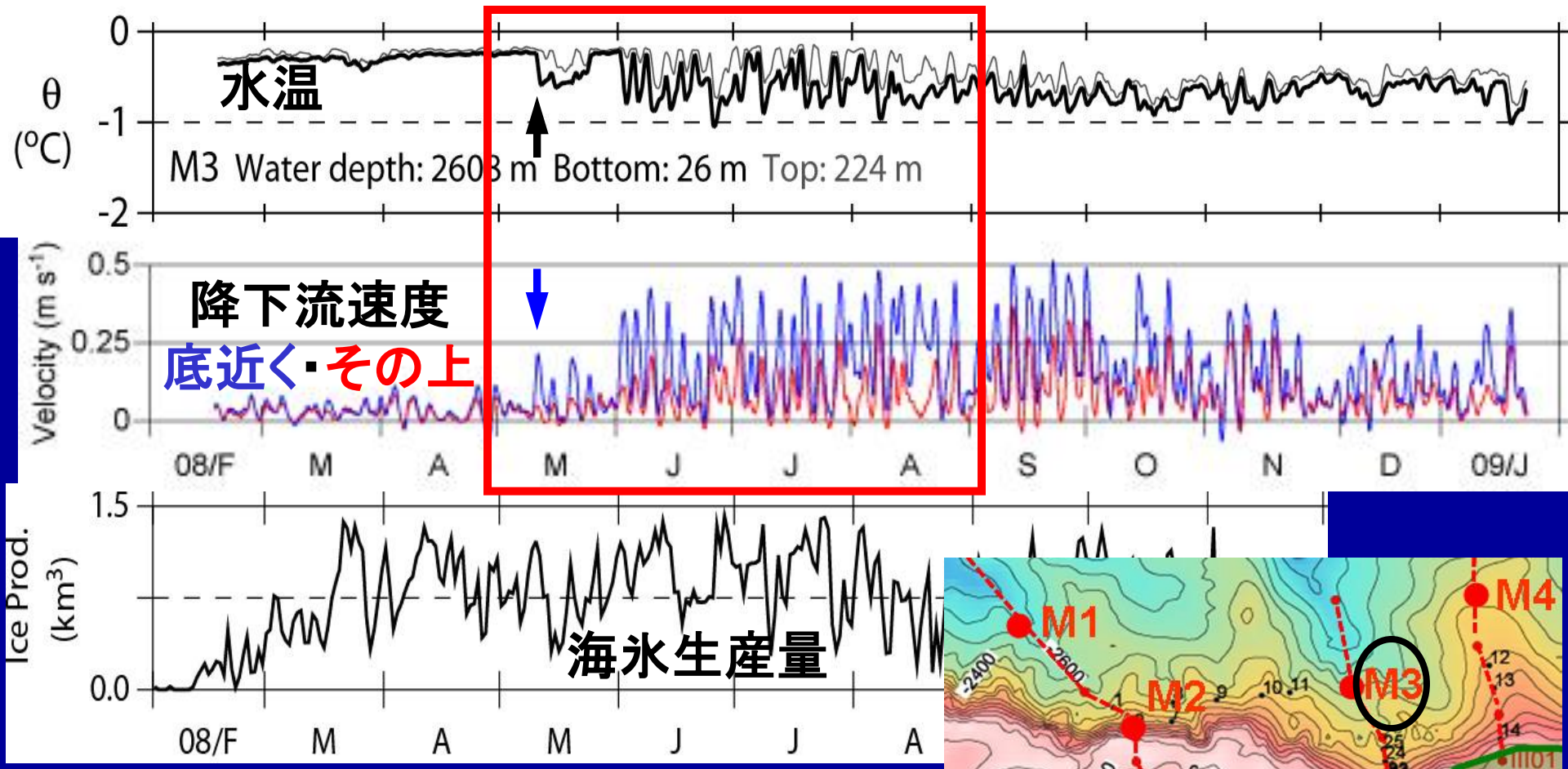


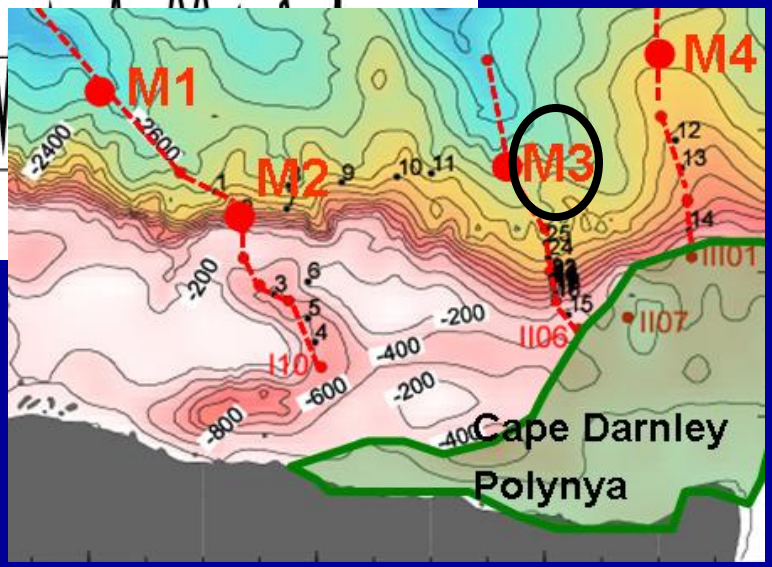
Off Cape Darnley, East Antarctic



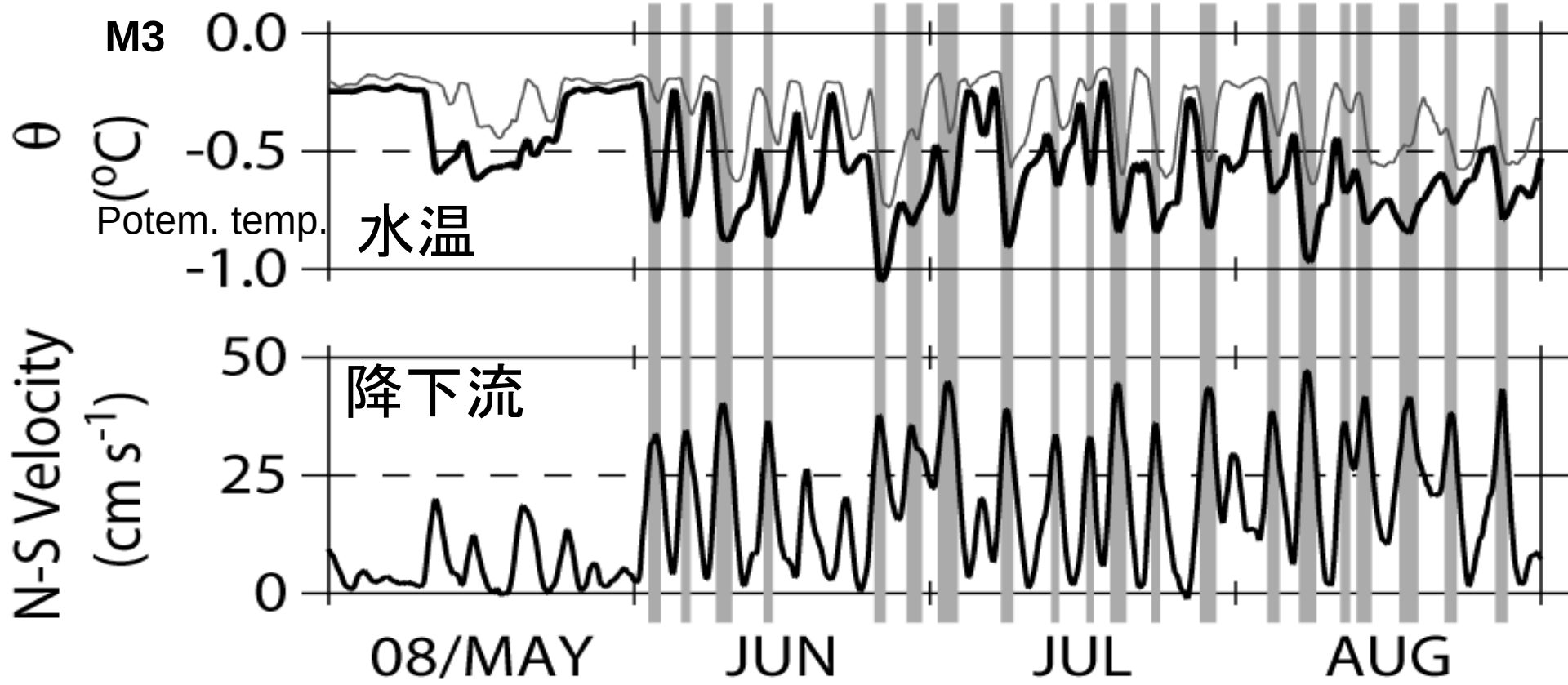
Drawn by Kitade and Hirano

峡谷の底(M3)での水温と流速の1年間の時系列　(水深 2659 m)





・峡谷では、冷たい重い水の到来に
　同期して強い降下流
・流れは底近くほど強い



Thick lines: 20m from bottom

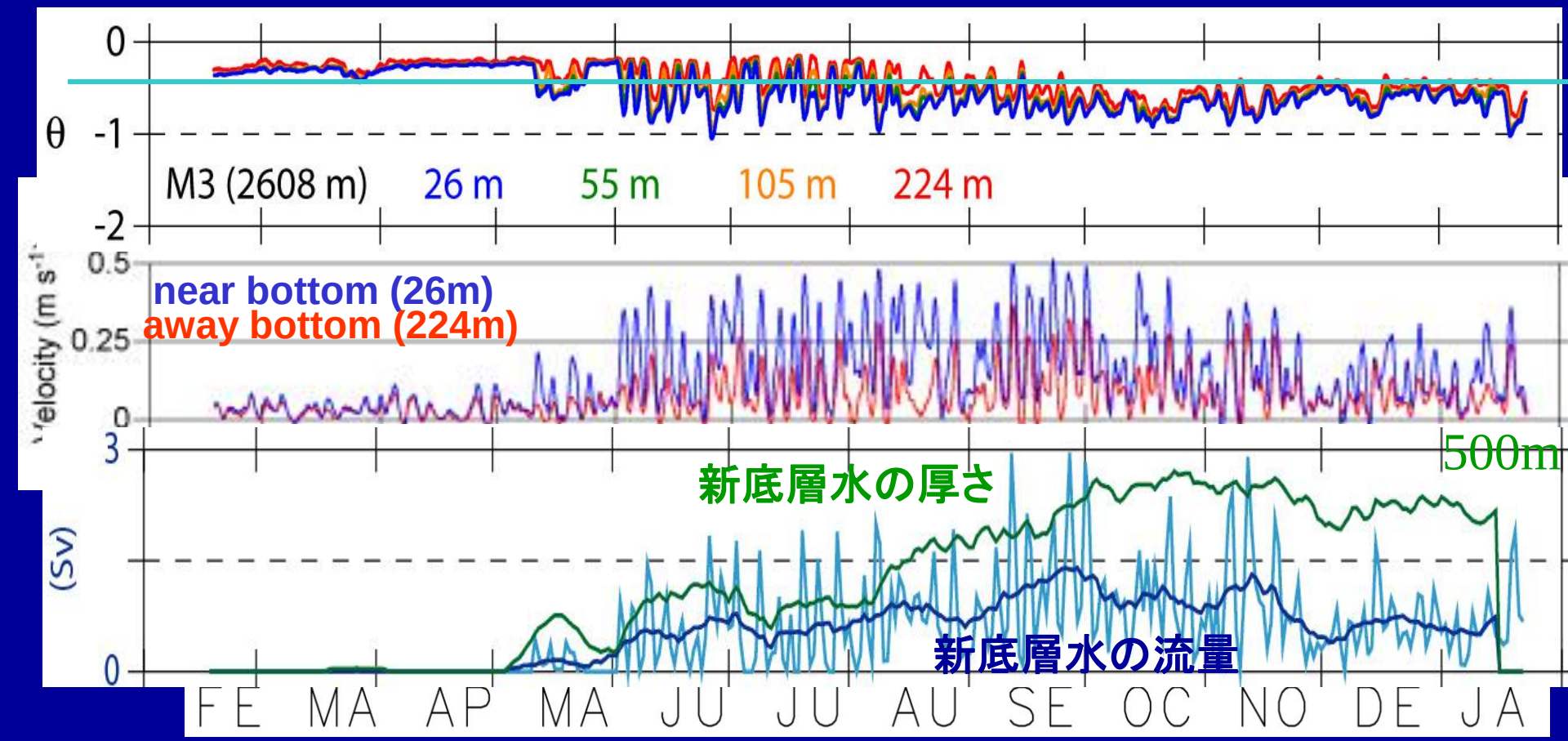
Thin lines: 224m from bottom

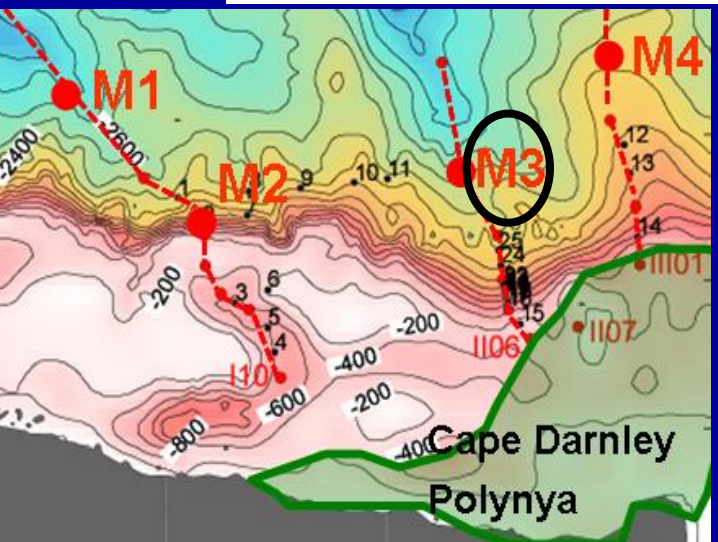
Shaded periods: Northward (Downslope) velocity > 30cm/s

約4日周期で0.4m/s程度の降下流: 冷たい重い水と同期

→ 傾圧不安定？　地形性ロスビー波？

3-day 6-day oscillations occurs associated with dense plume in the Filchner, Weddell Sea (Darelius et al., 2009)

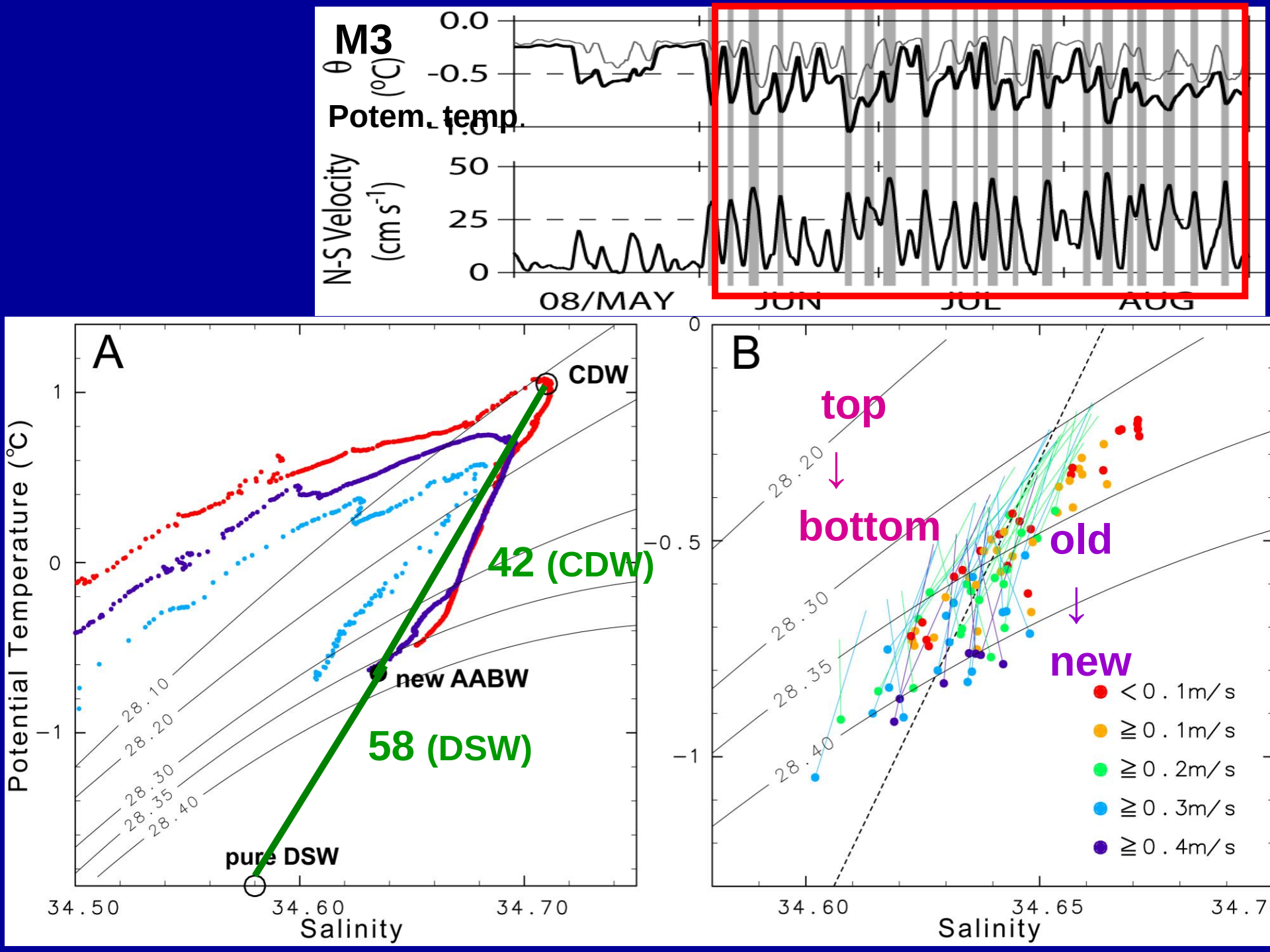




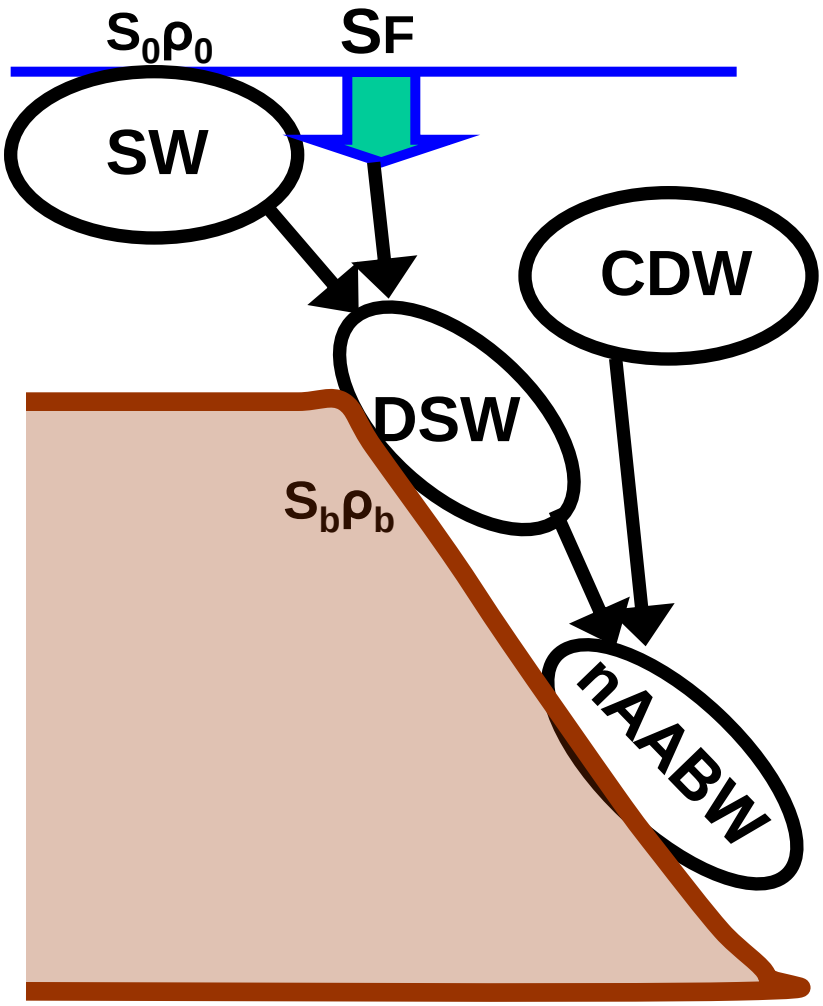
流速・水温を内挿・外挿；-0.4℃以下を新底層水

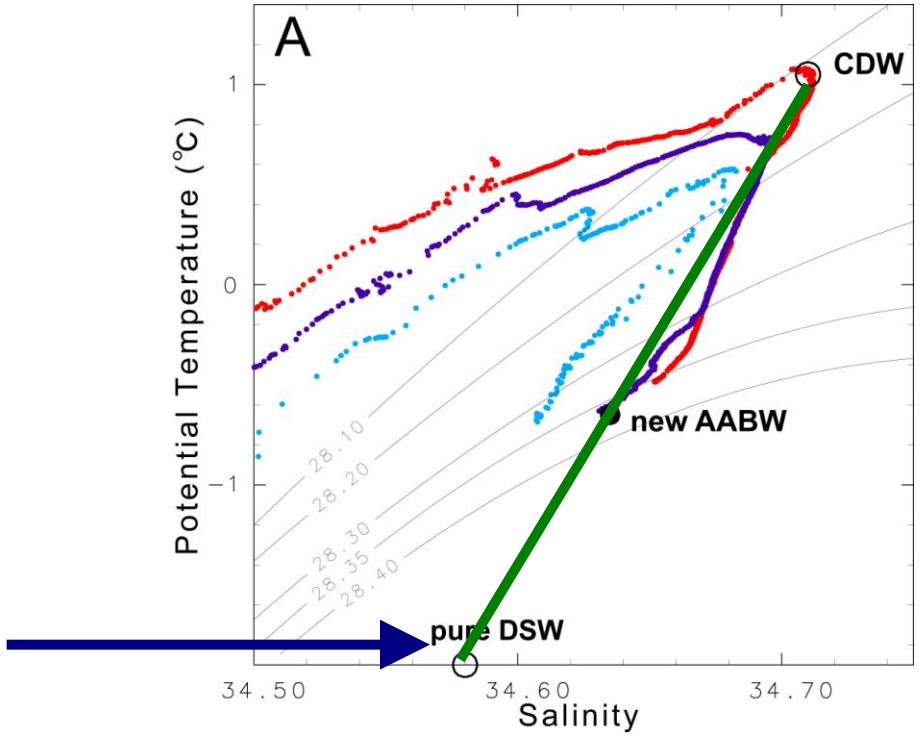
新底層水の厚さは平均 300m：
170m(6月) → 420m(10月) (予想以上に厚い)

流れの幅を20kmと仮定：新底層水の流量 0.52(Sv)


M3
θ (°C)
Potem. temp.
0.0
-0.5
-1.0
N-S Velocity (cm s-1)
50
25
0
08/MAY
JUN
JUL
AUG
A
CDW
42 (CDW)
new AABW
58 (DSW)
pure DSW
28.10
28.20
28.30
28.35
28.40
Potential Temperature (°C)
1
0
−1
34.50
34.60
34.70
Salinity
B
top
bottom
old
new
28.20
28.30
28.35
28.40
0
−0.5
−1
34.60
34.65
34.7
Salinity
< 0.1m/s
≧ 0.1m/s
≧ 0.2m/s
≧ 0.3m/s
≧ 0.4m/s

ポリニヤでの
塩フラックス



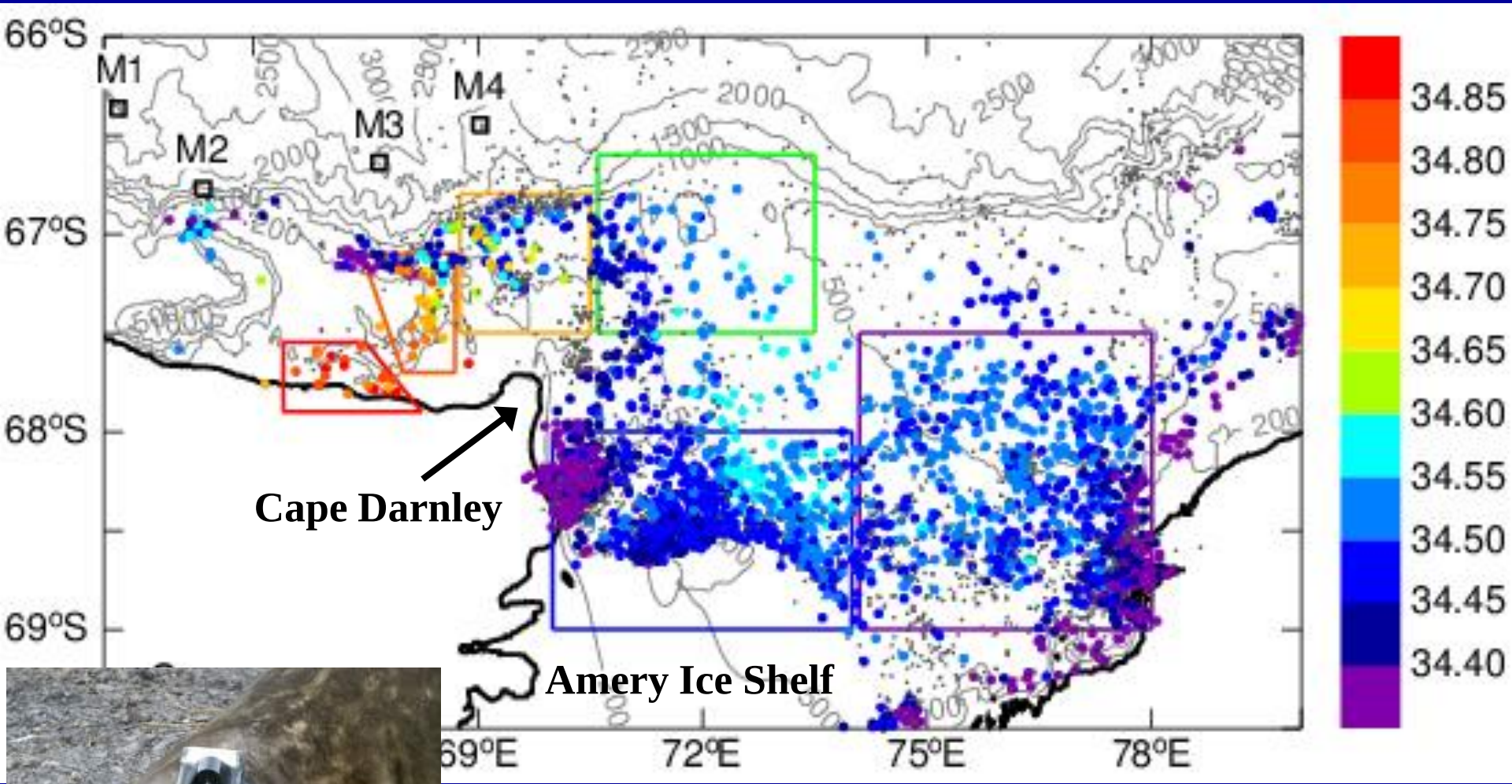


●DSWの潜り込む流量の推定

●係留によるnAABW流量 0.52Svと
DSWとCDWの混合比 (58:42)より
→ 0.30 Sv (Wild Canyonのみ)

●海氷生産による塩フラックスにより
summer SW がwinter DSWとなる
→ 0.70 Sv (上限値)

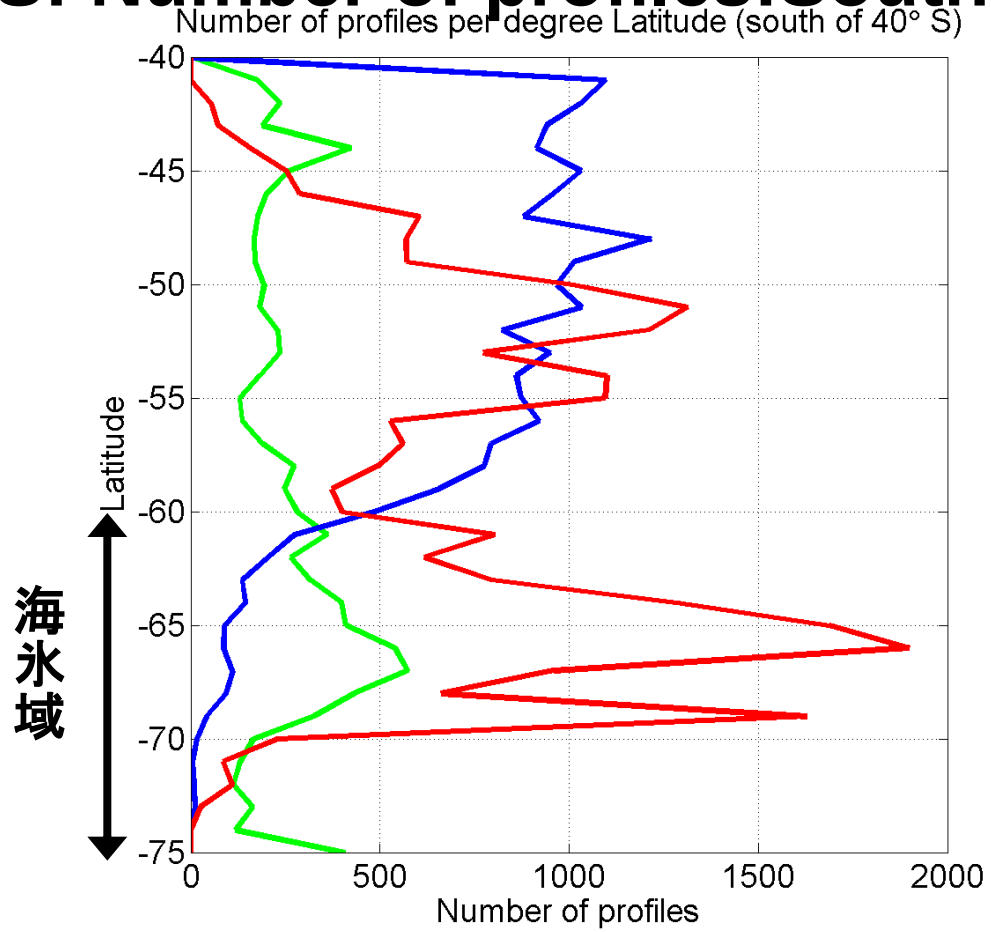
0.3-0.7 Sv: 全南極の5.4 Svの～10%



Salinity of bottom water from instrumented seals

Collaborated with Drs. Williams, Roquet, Field, Hindell

SEaOS: Number of profiles:Southern Ocean



SODB: 10513

Argo: 19463

SEaOS: 22230

→ 150000

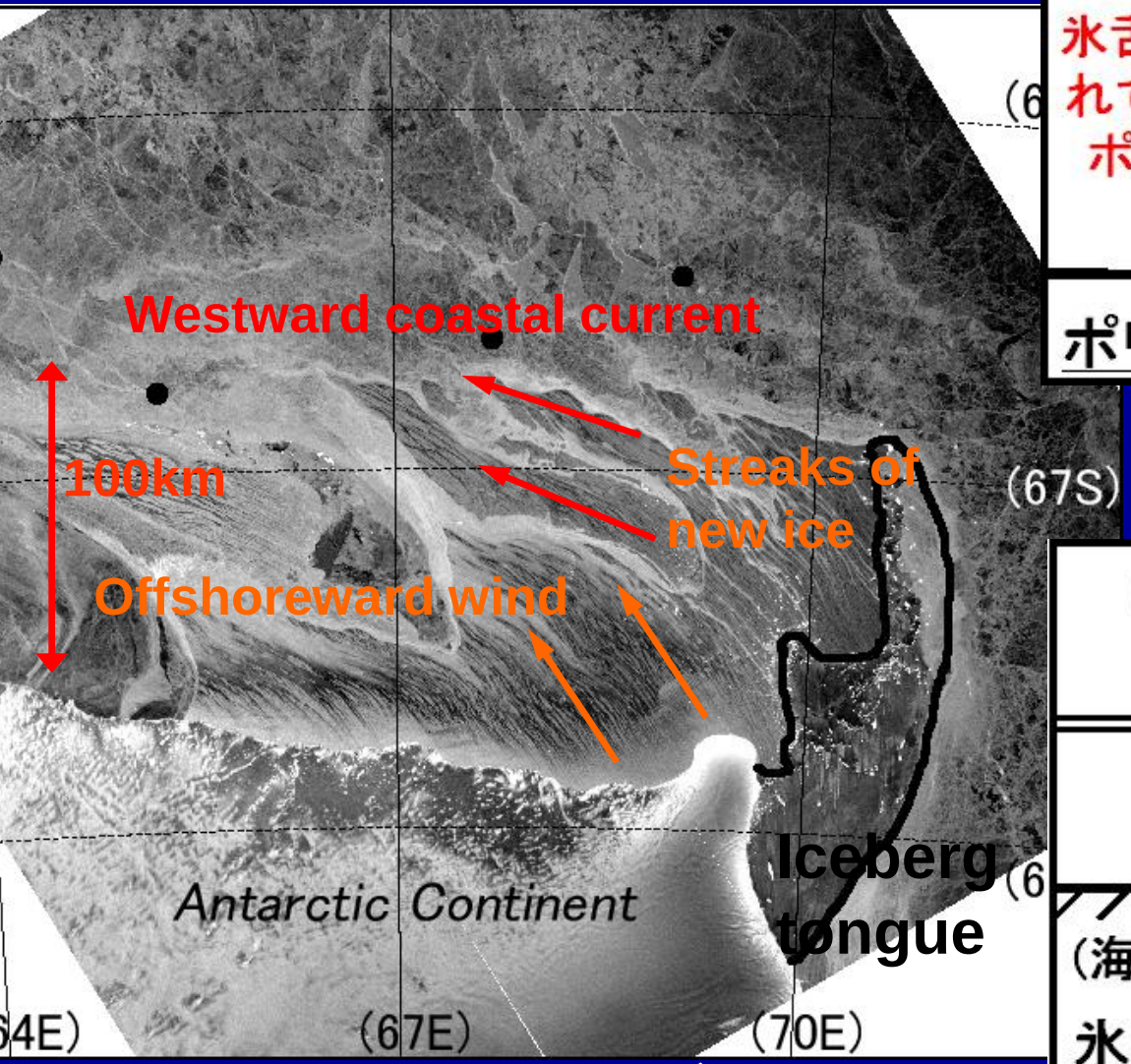
Courtesy L. Boehme

ゾウアザラシ（Elphant seals）の場合：

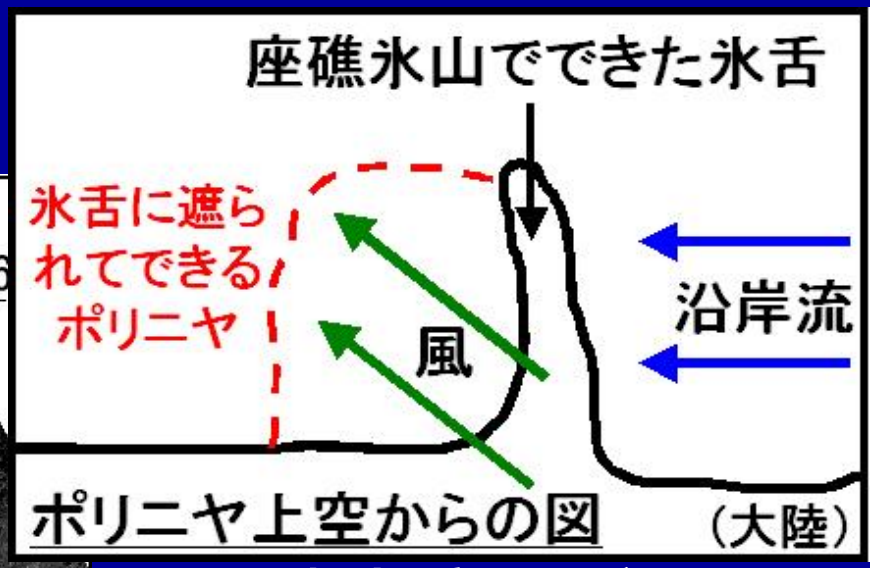
最大2000m まで潜る

底の餌を取りに行くので高密度陸棚水・底層水が観測できる

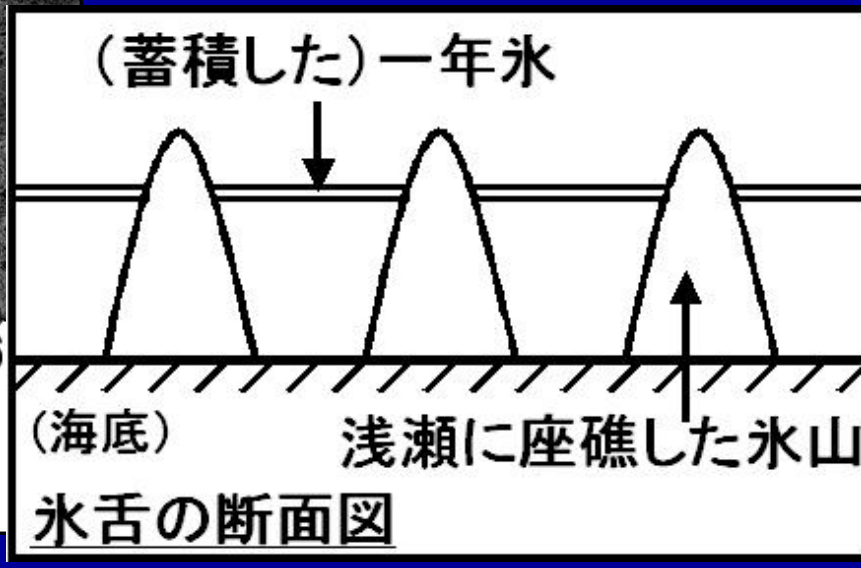
大きな海氷生産量はなぜ？
なぜ巨大なポリニヤができるか？

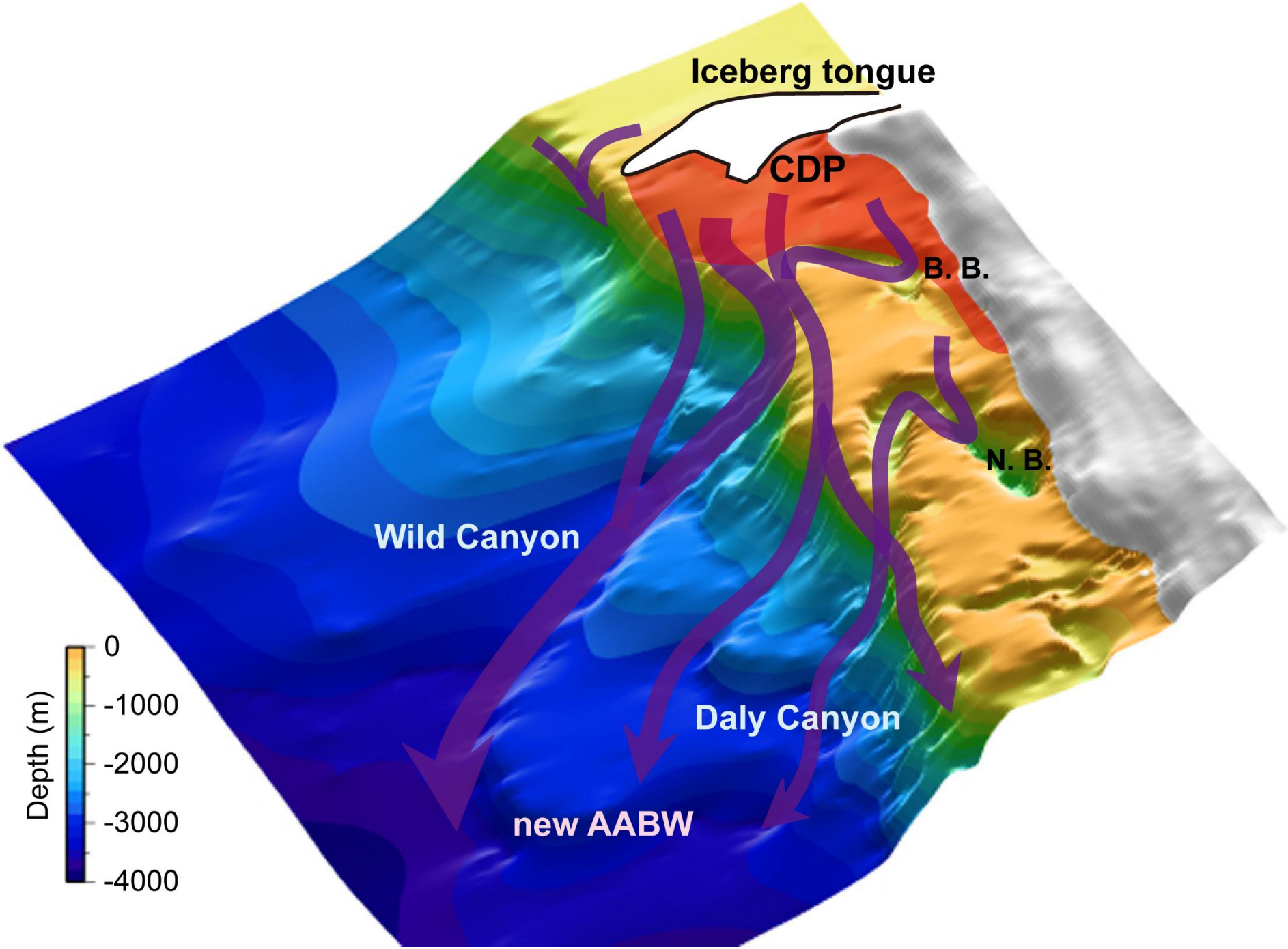


合成開口レーダ

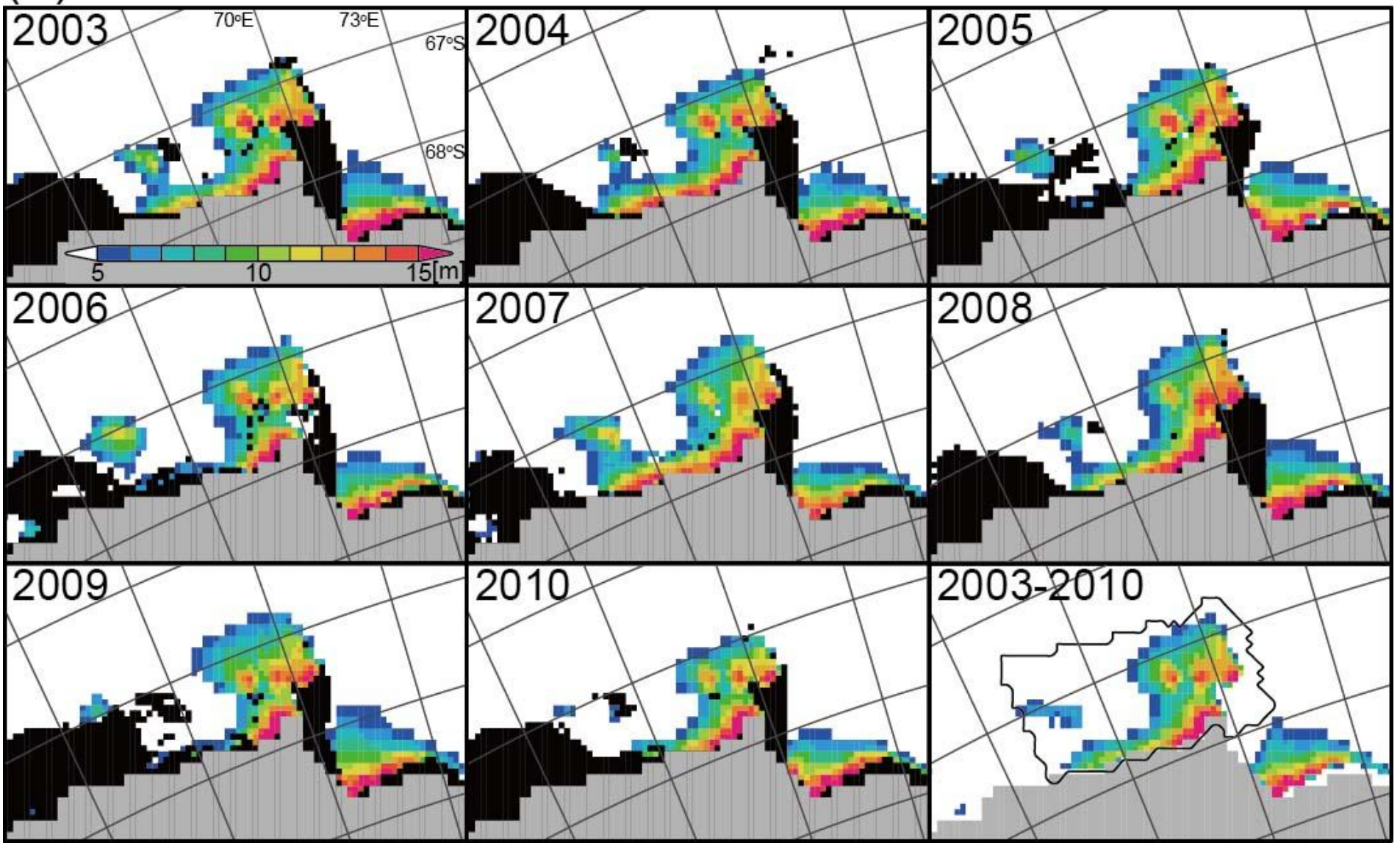


氷山舌による
フィルター効果




Iceberg tongue
CDP
B. B.
N. B.
Wild Canyon
Daly Canyon
new AABW
Depth (m)
0
-1000
-2000
-3000
-4000

Sea ice production (color shading) and iceberg tongue (black) during 2003-2010 (AMSR period)



今回の観測でわかったこと

- やっぱり、ケープダンレー沖では、底層水がガッツリできていた！
- 峡谷では、冷たい重い水の到来に同期して強い降下流
  4-5日周期で間歇的・0.5m/sの降下流 (downslope current)
- 新底層水の厚さは平均300m：170m(6月) → 420m(10月)
  (予想以上に厚い)
- 係留系観測と海氷生産からの見積もりによると、
  表層から底層への水の潜り込むj量は 0.3-0.7 (Sv)
  全南極からの潜り込み量の10%
- 東にある氷山舌によるフィルター効果が高海氷生産を生む

高速非静水圧モデル(Matsumura & Hasumi)による数値simulation

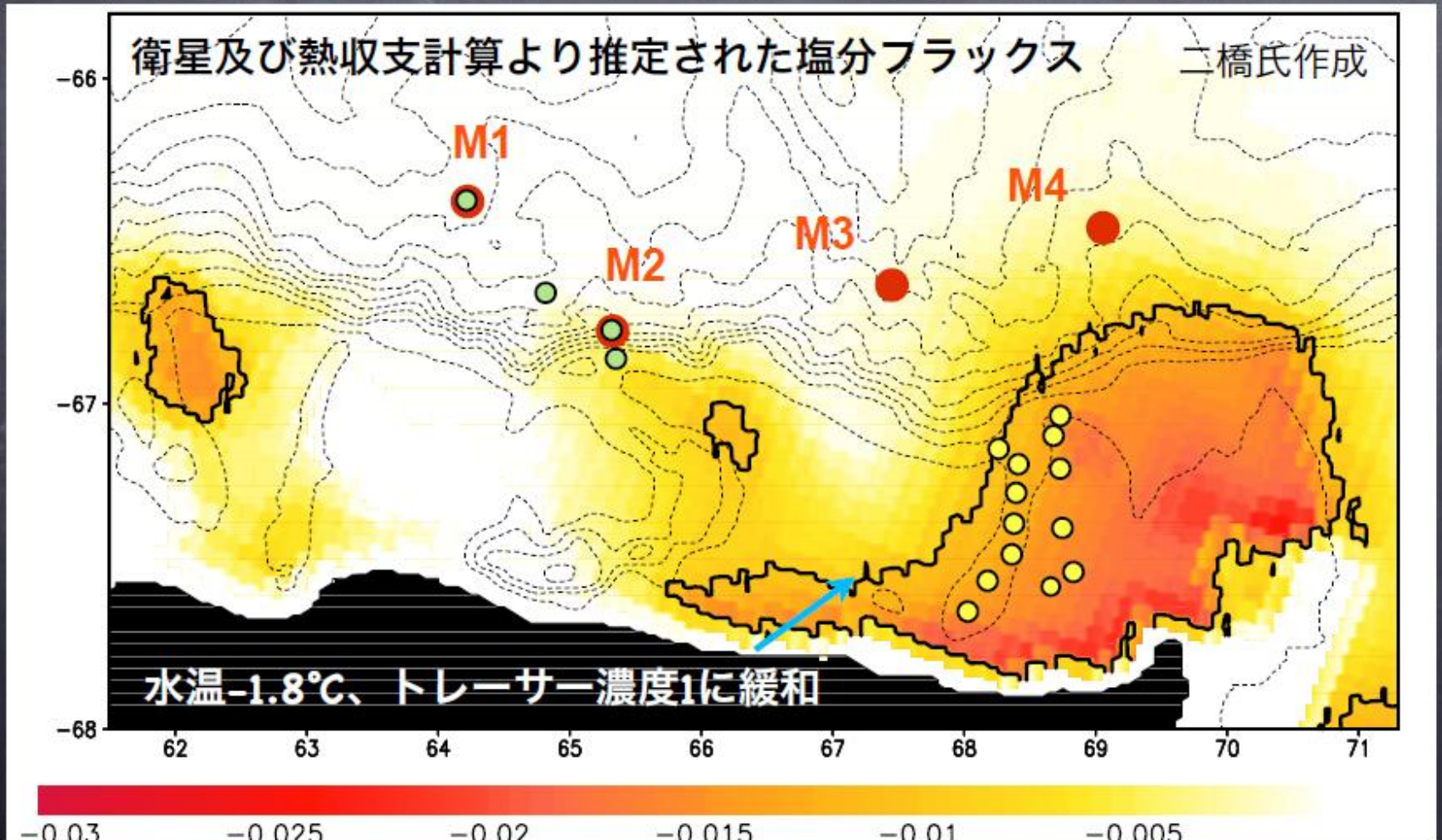
中山修士論文

解像度：1/20°(東西) × 1/80° (南北)　鉛直10m

地形　：GEBCO 1min 地形データ, AAD 0.005deg 地形データ

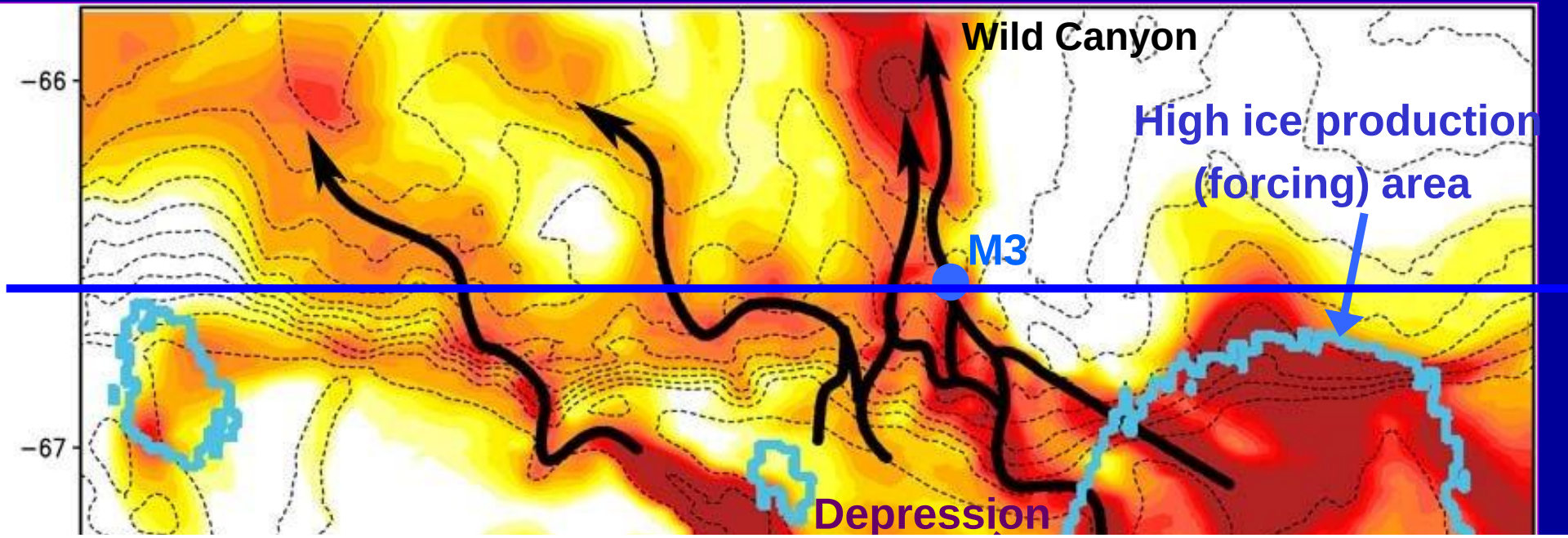
初期値：海鷹丸(緑)、しらせ(黄)の水温、塩分の観測値から補完。

フォーシング：2008年3-10月平均の塩分フラックス。風応力なし。

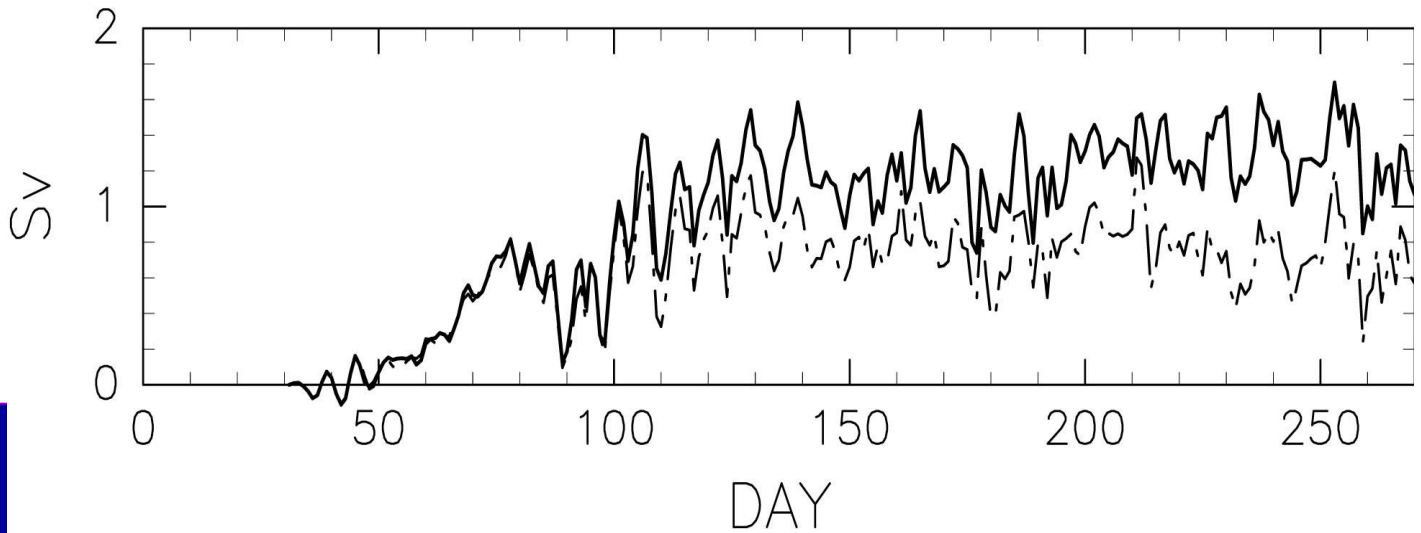


Pathway of AABW from the simulation forced by polynya salt flux

Integrated tracer concentration **DW: Polynya →Depression → Canyon**



Volume flux of dense water which crosses 400m-depth contours



Maximum 1.50 Sv

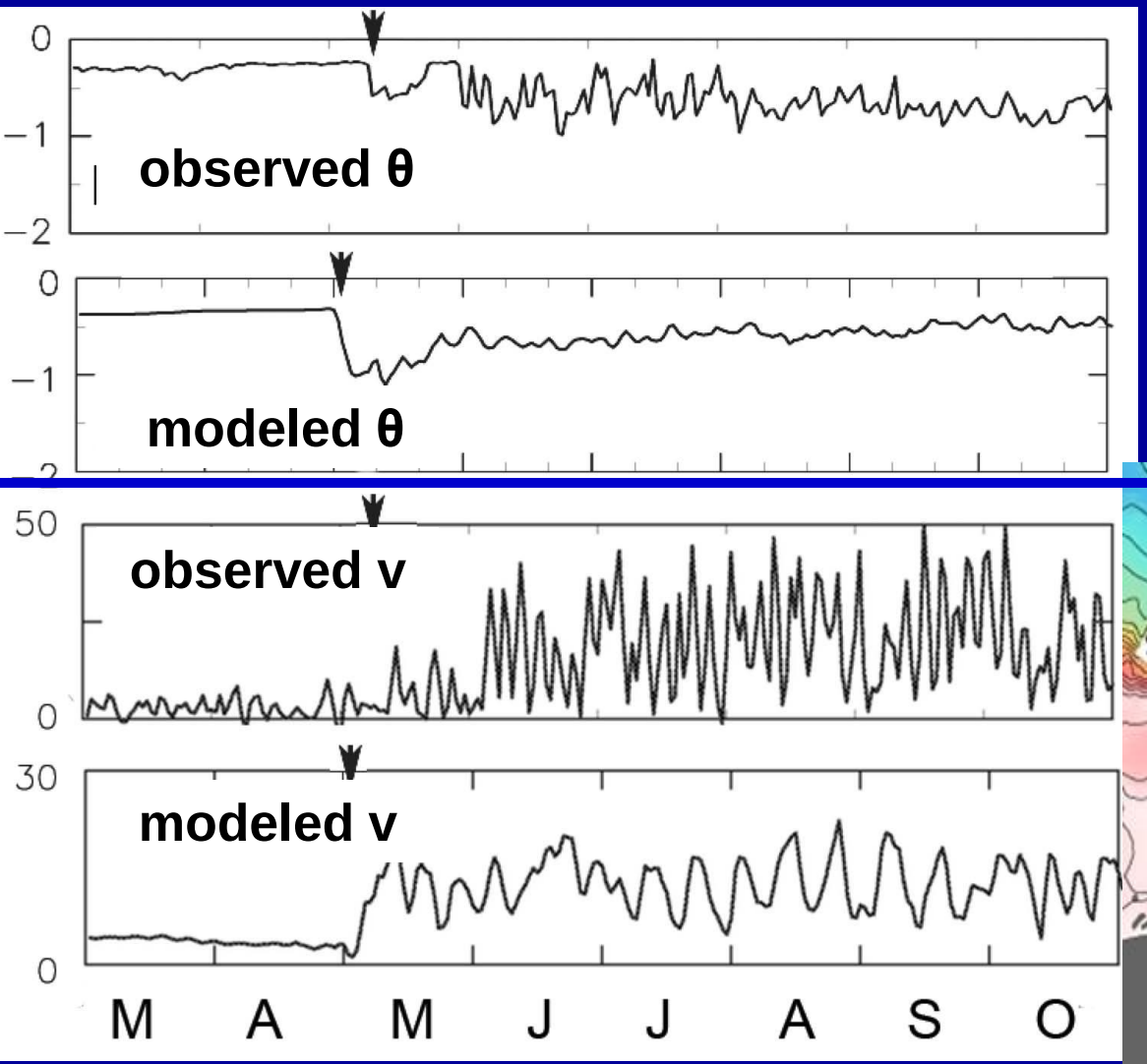
Annual 0.60 Sv

Ice prod. 0.3-.7 Sv

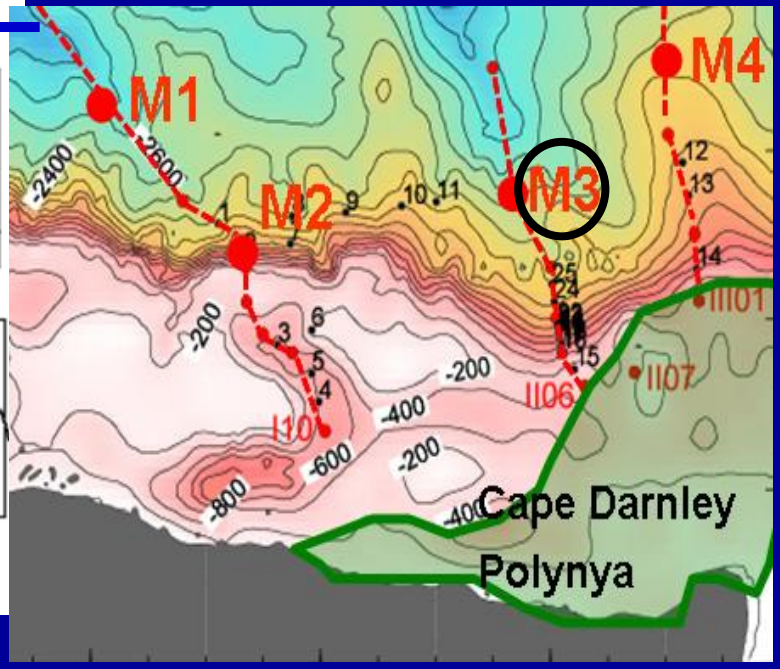
All Antarc. 5.4 Sv

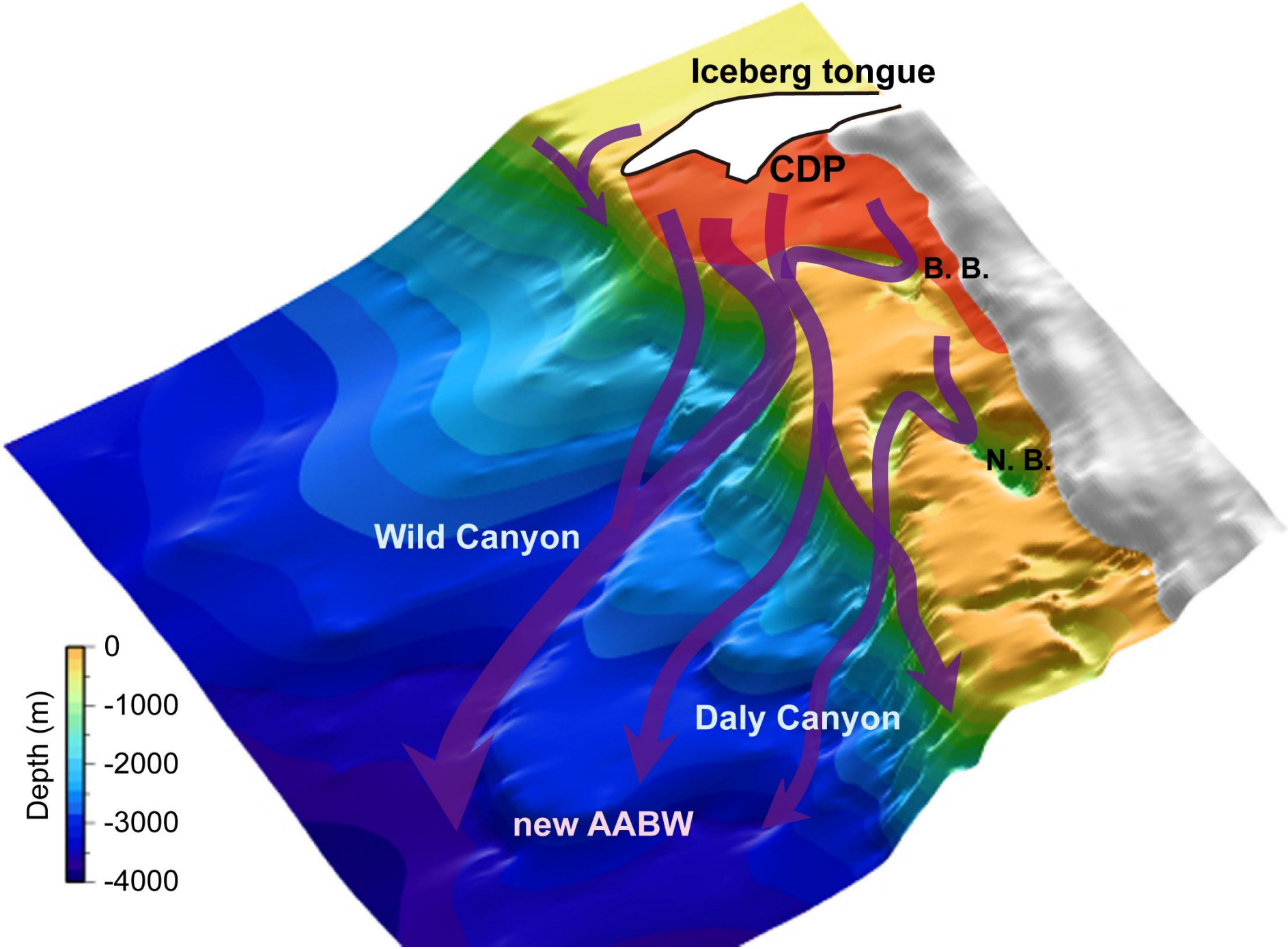
(Orsi et al, 2002)

Reproduction of arrival of dense water and periodic downslope current

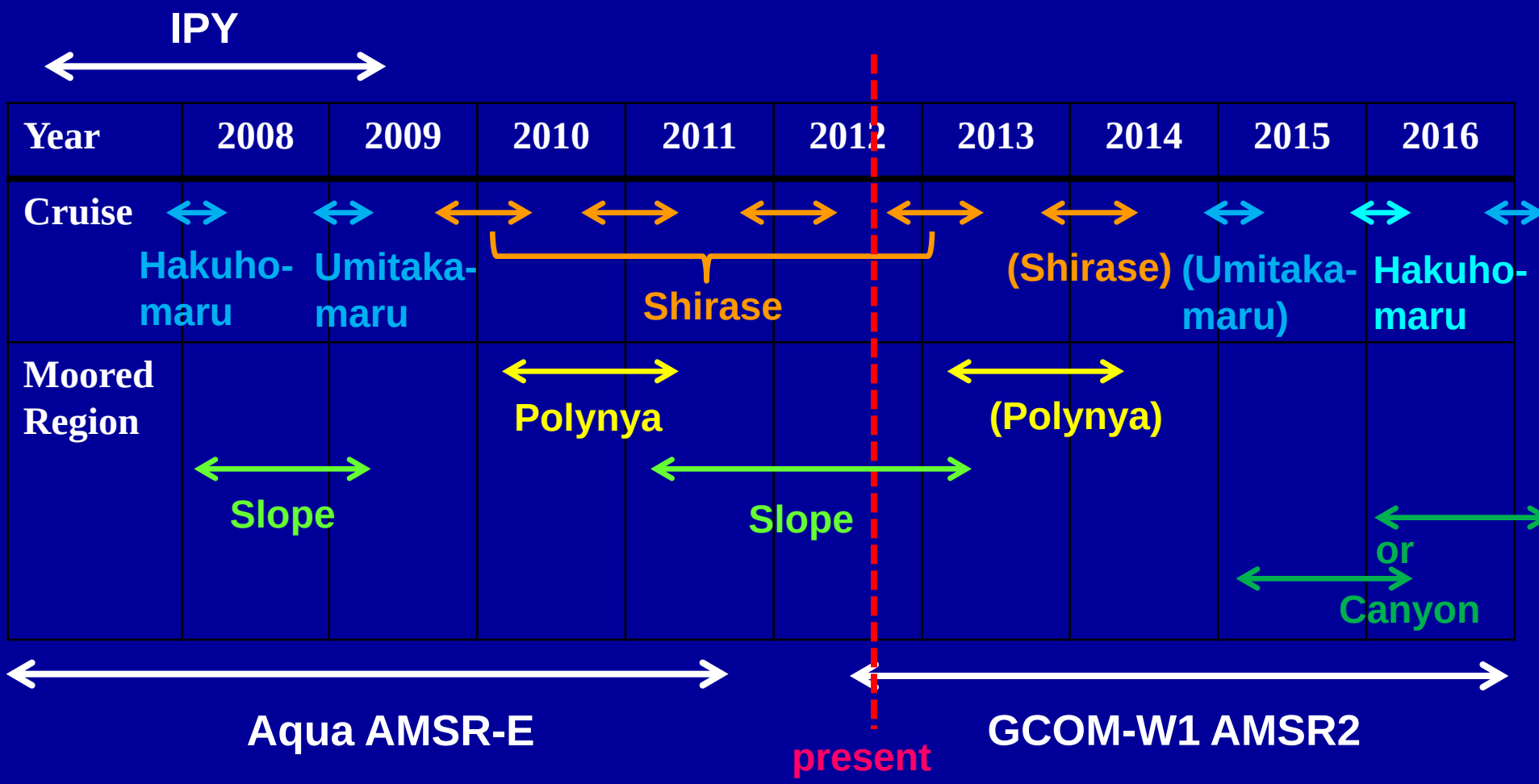


Comparison between observation and model at M3



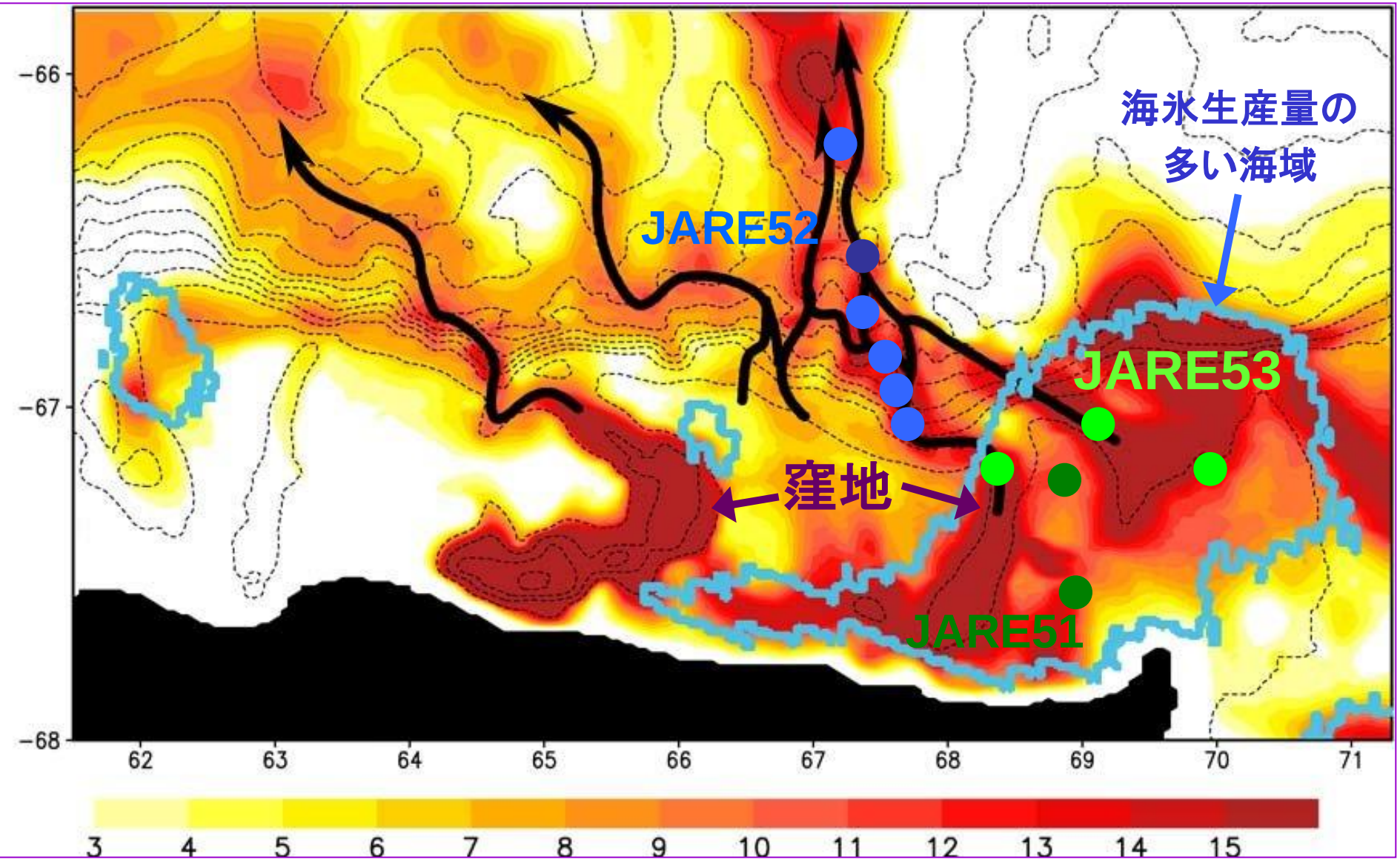

Iceberg tongue
CDP
B. B.
N. B.
Wild Canyon
Daly Canyon
new AABW
Depth (m)
0
-1000
-2000
-3000
-4000

Cape Darnley Project (Cruises)



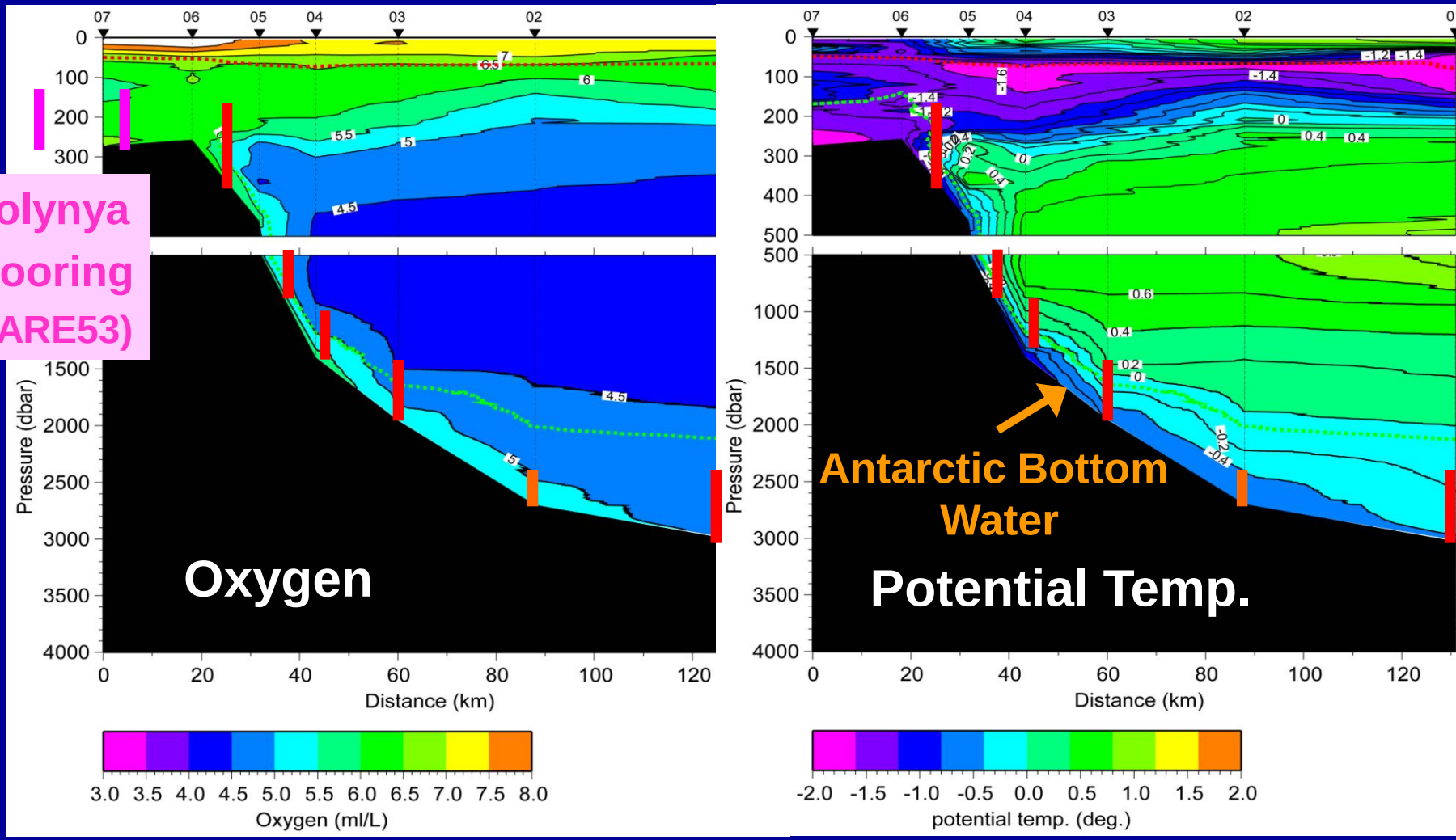
数値シミュレーション：ポリニヤ（水色枠内）での高海氷生産による南極底層水形成

鉛直積分したトレーサー濃度の平均値　窪地から流出、谷に沿って沈み込む



Mooring array off Cape Darnley

Deploy: Feb. 2011 (JARE52) → Recover: Feb. 2013 (JARE54)



JARE51 → JARE54: 未知の南極底層水を探る

Summary for Cape Darnley Bottom Water

In addition to three well-recognized AABW sources, a fourth variety of AABW has been identified east of the Weddell Sea. However, neither its production, nor Dense Shelf Water (DSW) source, has been observed.

Here we show that enhanced sea-ice production in the Cape Darnley Polynya (65−69° E) is the missing source of this AABW.

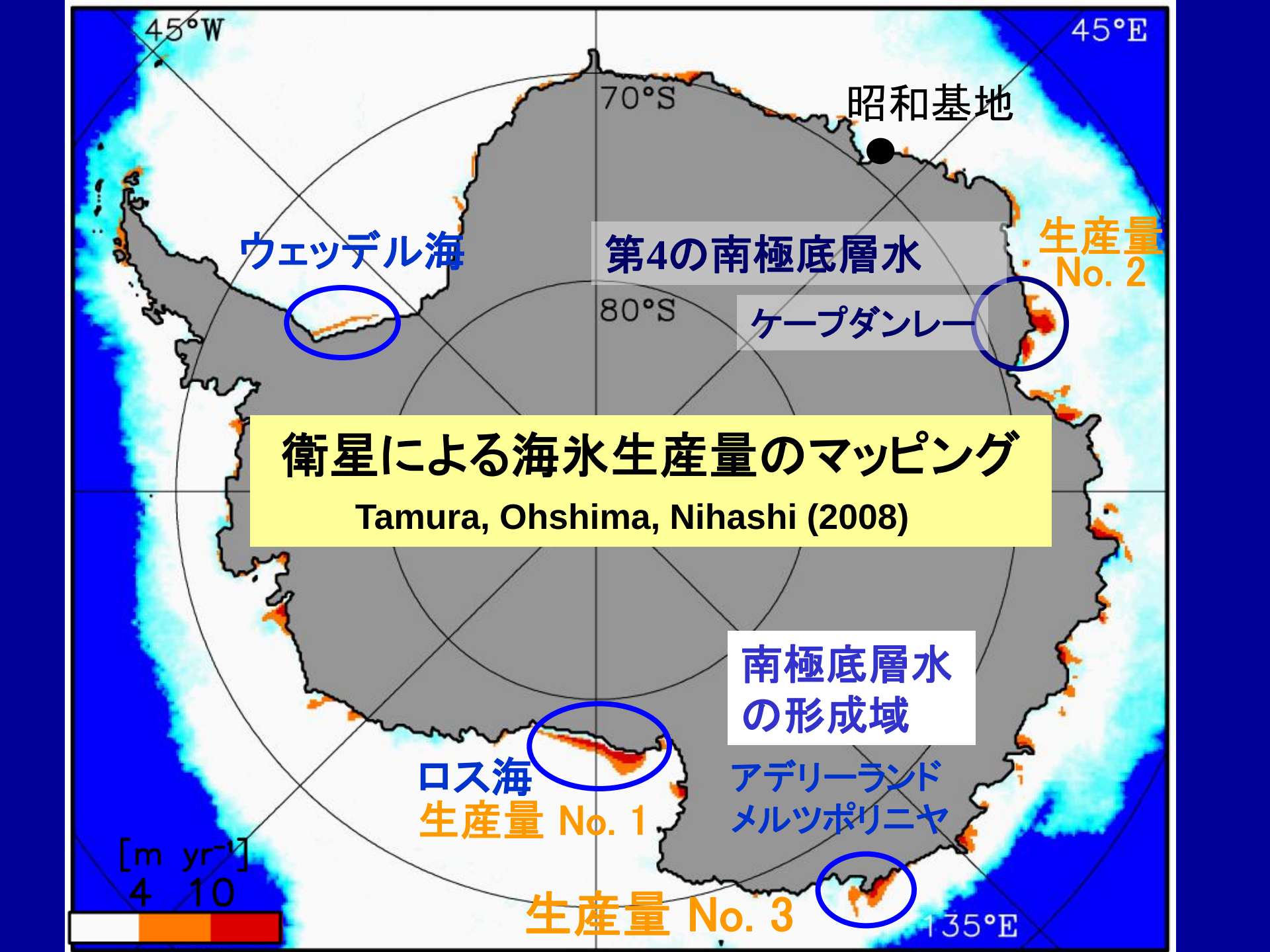
Moored instruments observed overflows of new AABW cascading down offshore canyons, with its DSW source identified by instrumented seals.

That this AABW is produced mainly from sea-ice production without the assistance of an ice shelf and/or large storage volume, challenges the traditional paradigm.

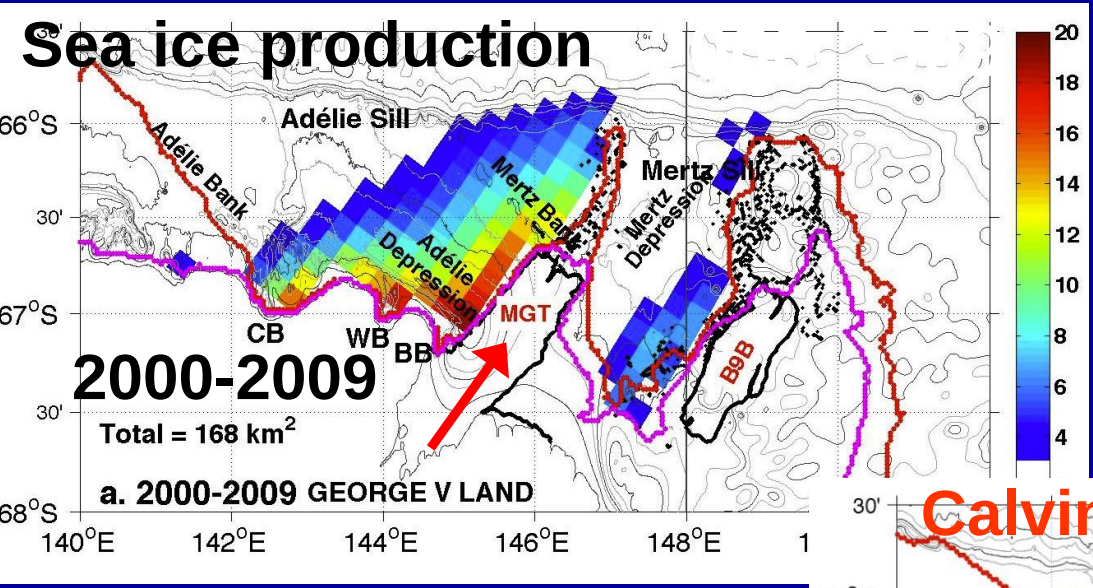
We estimate that 0.3−0.7 Sv (10^6 m^3 s^{-1}) of DSW is transformed into AABW, accounting for 6−13% of the circumpolar total.

Cape Darnley Bottom Water should now be incorporated into the assessment of the global overturning circulation and its variability.

1. イントロダクション：海氷生成と中深層水形成
2. 衛星による海氷生産量・熱塩フラックスの見積もり
3. 未知の南極底層水生成域の発見
4. **中深層水の変動と海氷生産量**
5. 沿岸ポリニヤでの高精度海氷・海洋観測(衛星トゥルース)
6. 中層水の新しいモニター観測


45°W
45°E
70°S
80°S
135°E
昭和基地
ウェッデル海
第4の南極底層水
ケープダンレー
生産量
No. 2
衛星による海氷生産量のマッピング
Tamura, Ohshima, Nihashi (2008)
南極底層水
の形成域
ロス海
生産量 No. 1
アデリーランド
メルツポリニヤ
生産量 No. 3
[m yr⁻¹]
4 10

Sea ice production



Calving of
Mertz Glacier Tongue (MGT)

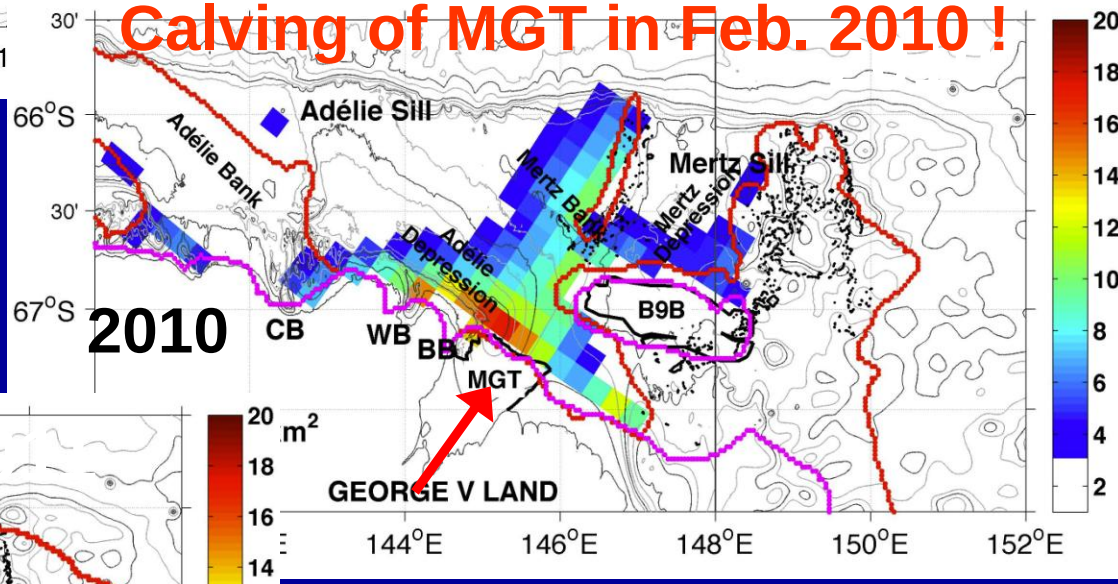
↓

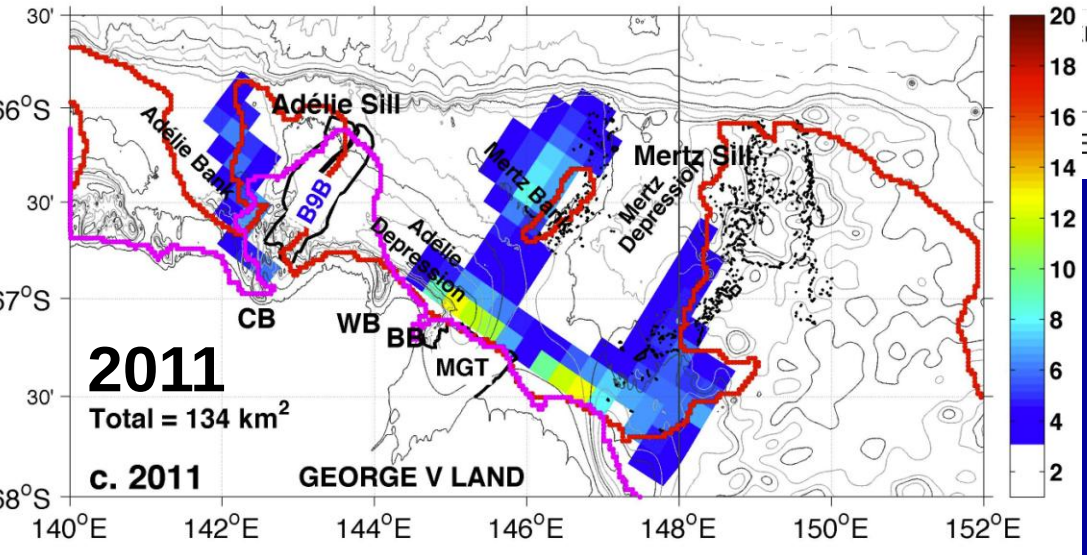
Decreasd sea ice production

↓

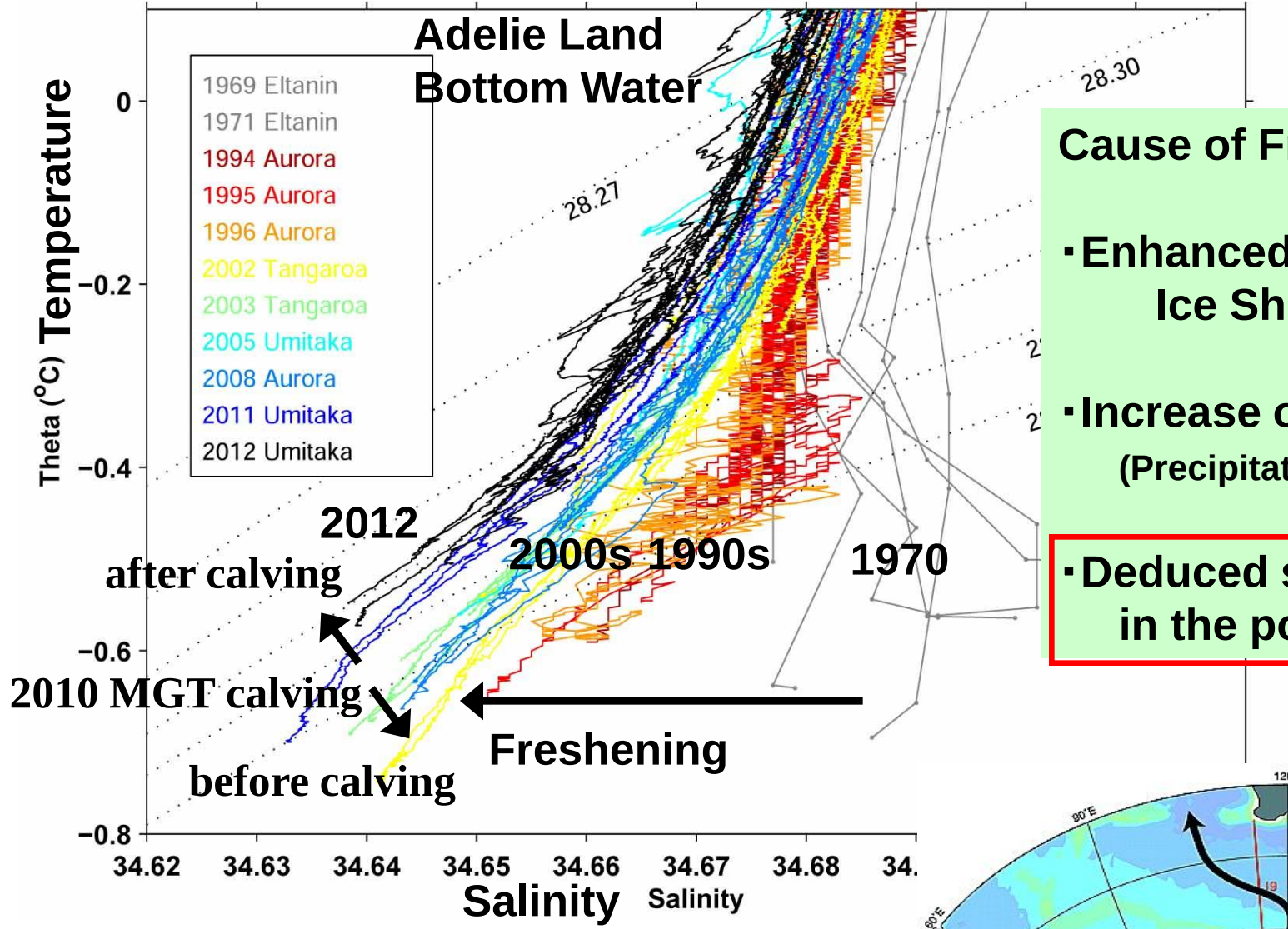
Decreased AABW ?

Calving of MGT in Feb. 2010 !



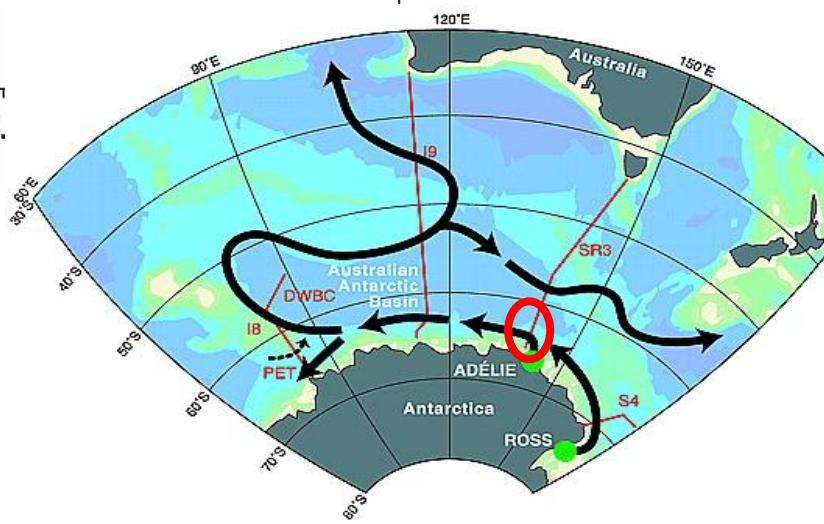


Tamura and Williams, et al., 2012,
Nature Communications



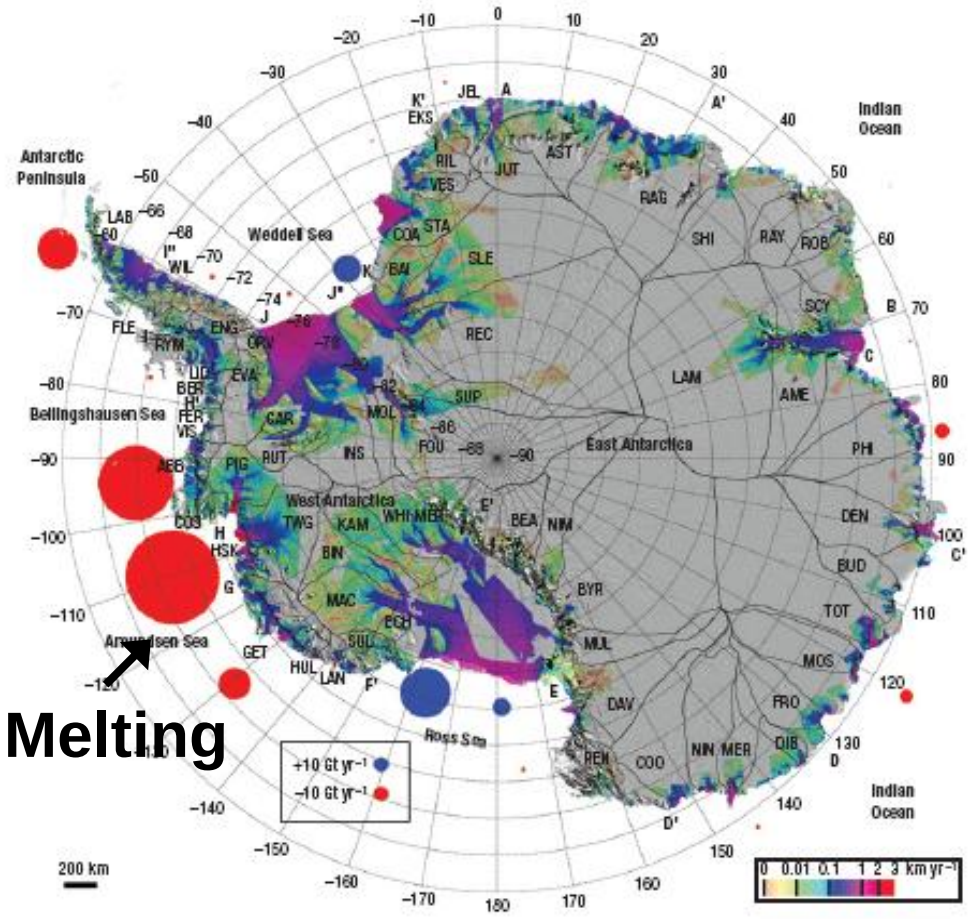
Cause of Freshening

- Enhanced melting of Ice Shelf
- Increase of P-E (Precipitation-Evaporation
- Deduced sea ice prod. in the polynya



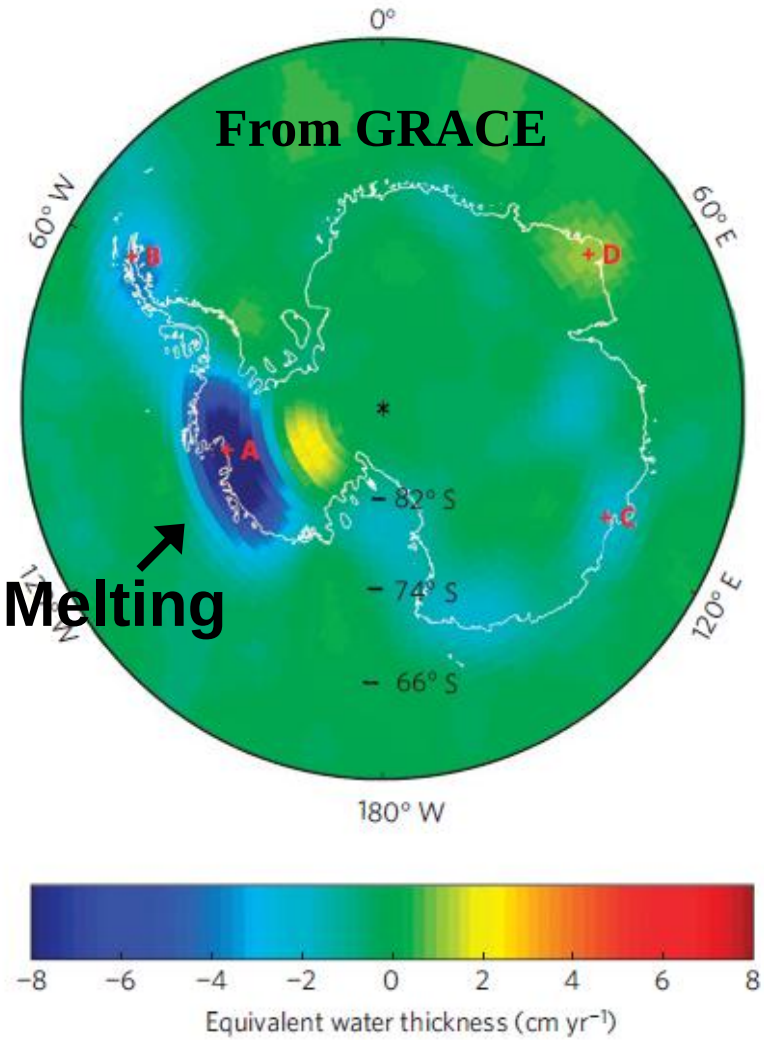
Aoki et al., in preparation

Increase/Decreased rate of Ice Shelf, Ice Sheet



Melting

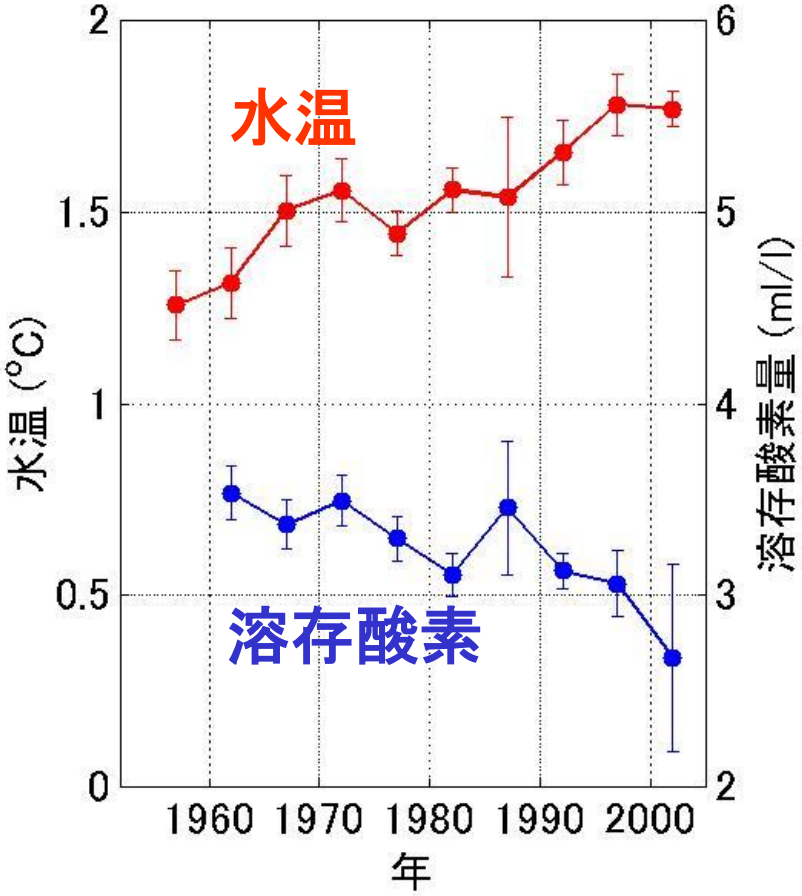
(Rignot et al. 2008)



Melting

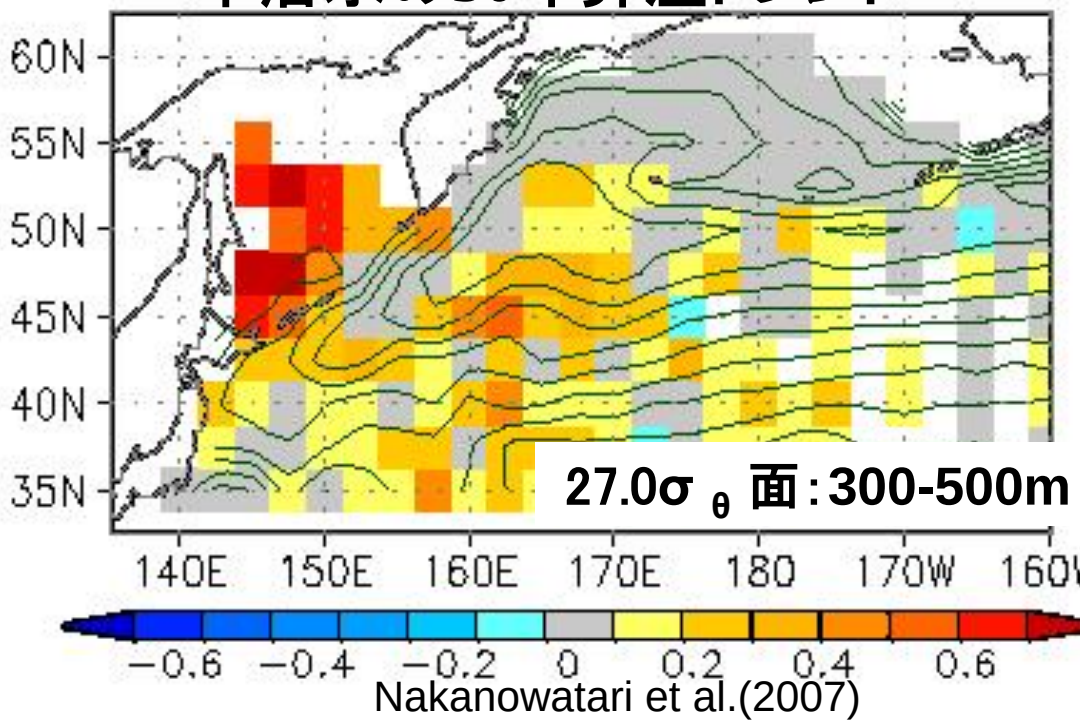
(Chen et al., 2008)

オホーツク海からの熱塩循環：最も弱化が顕著　!?
→　海氷生産量の弱化が原因？

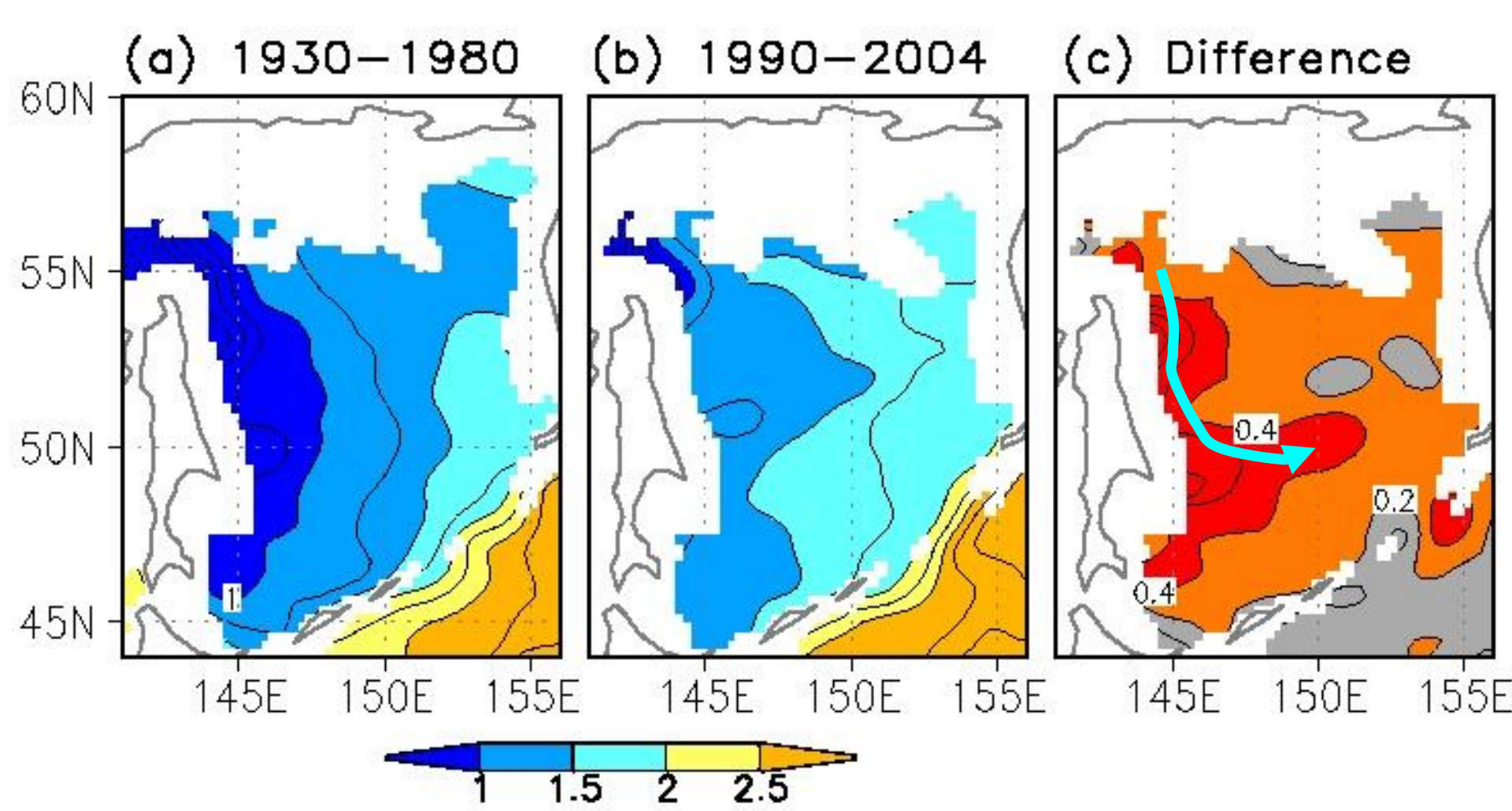


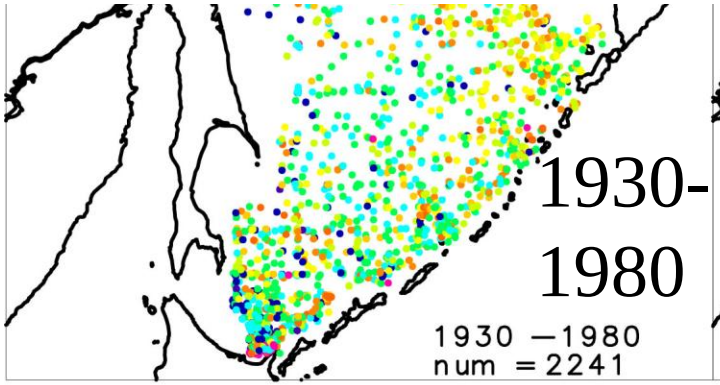
オホーツク海の中層水の50年間の変化

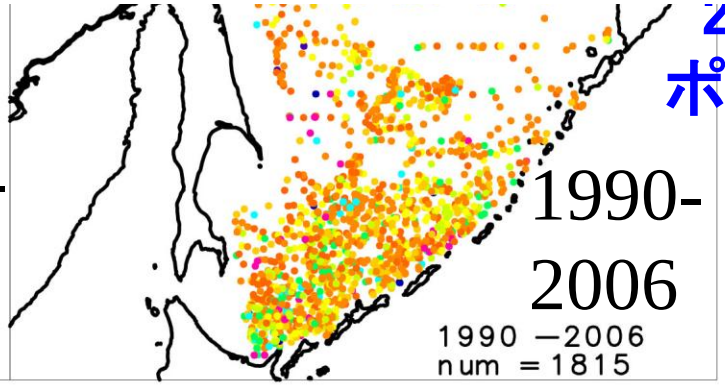
中層水の50年昇温トレンド



Nakanowatari et al.(2007)

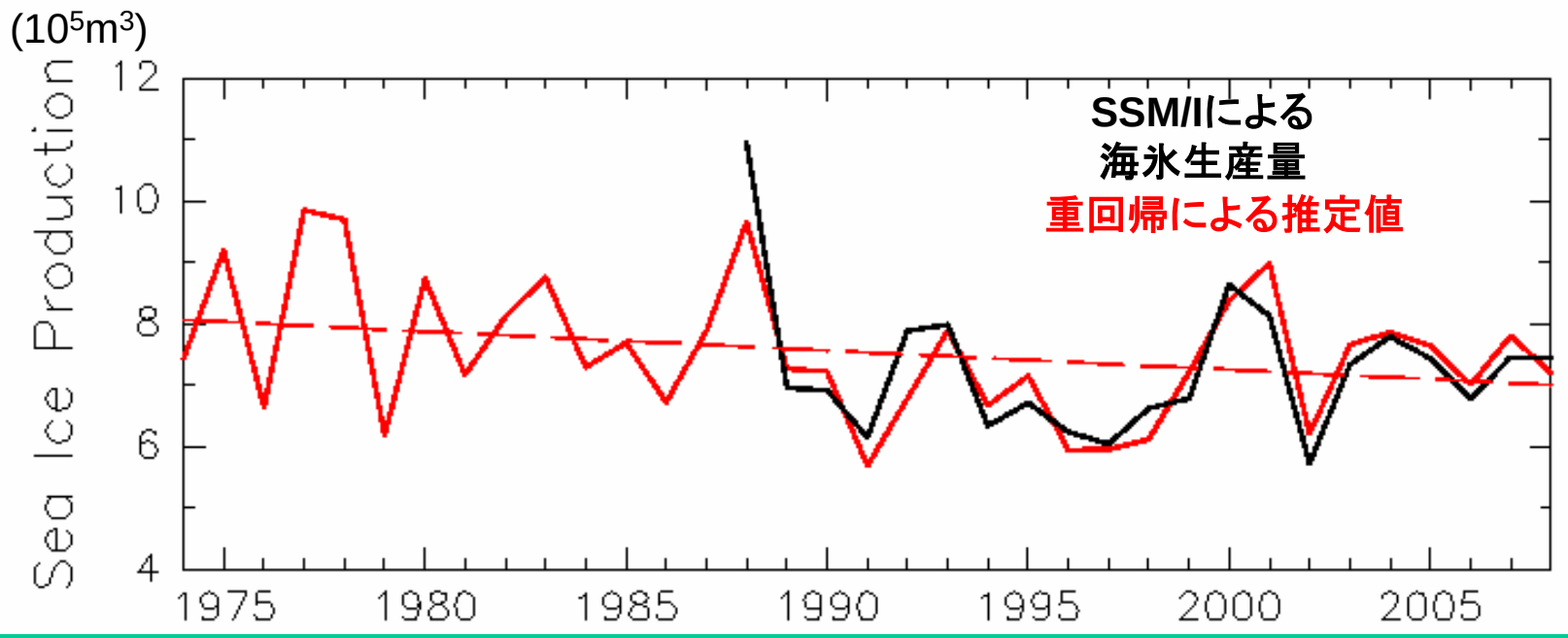




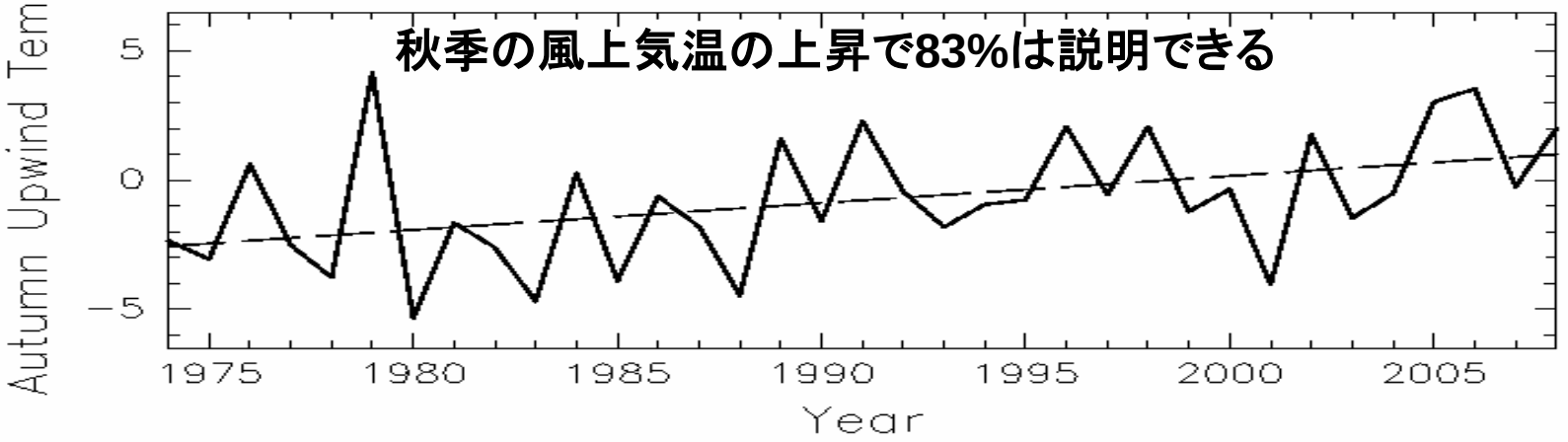


$26.9\sigma_\theta$ 面 での
ポテンシャル温度

海氷生産量の長期変動 •気象要素とSSM/Iデータから推定, 柏瀬修論

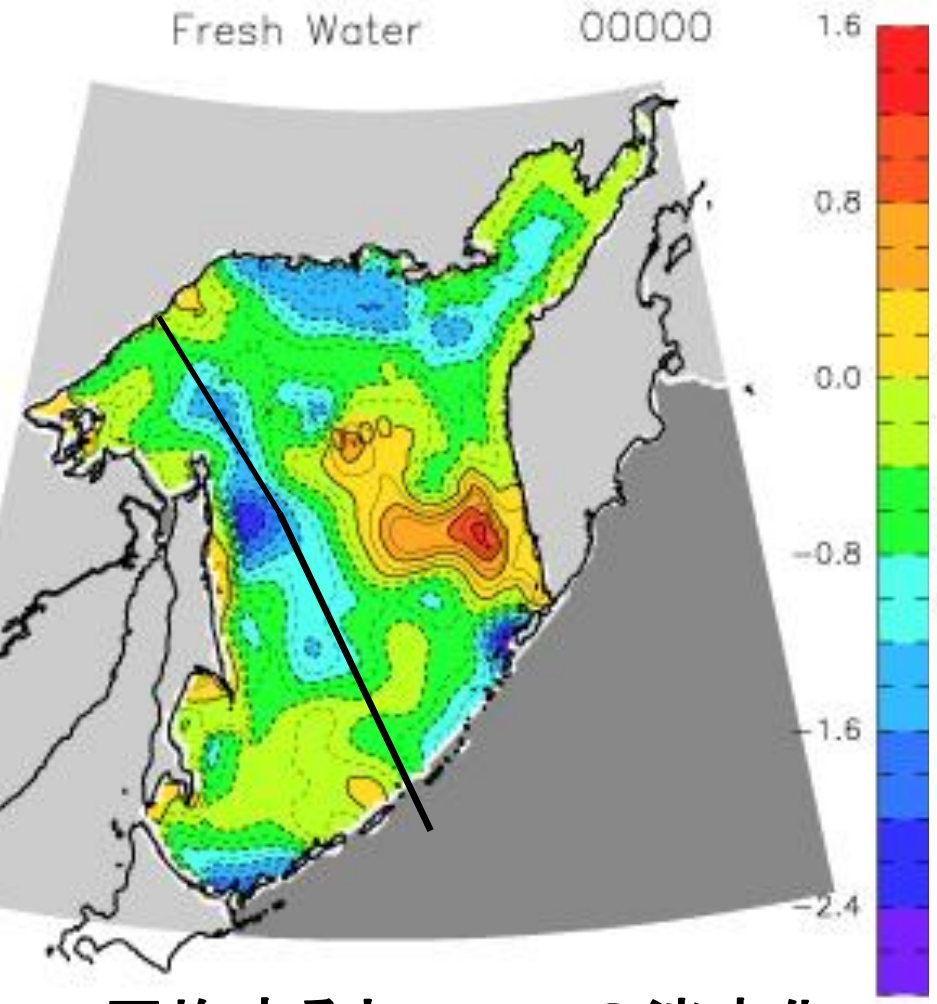


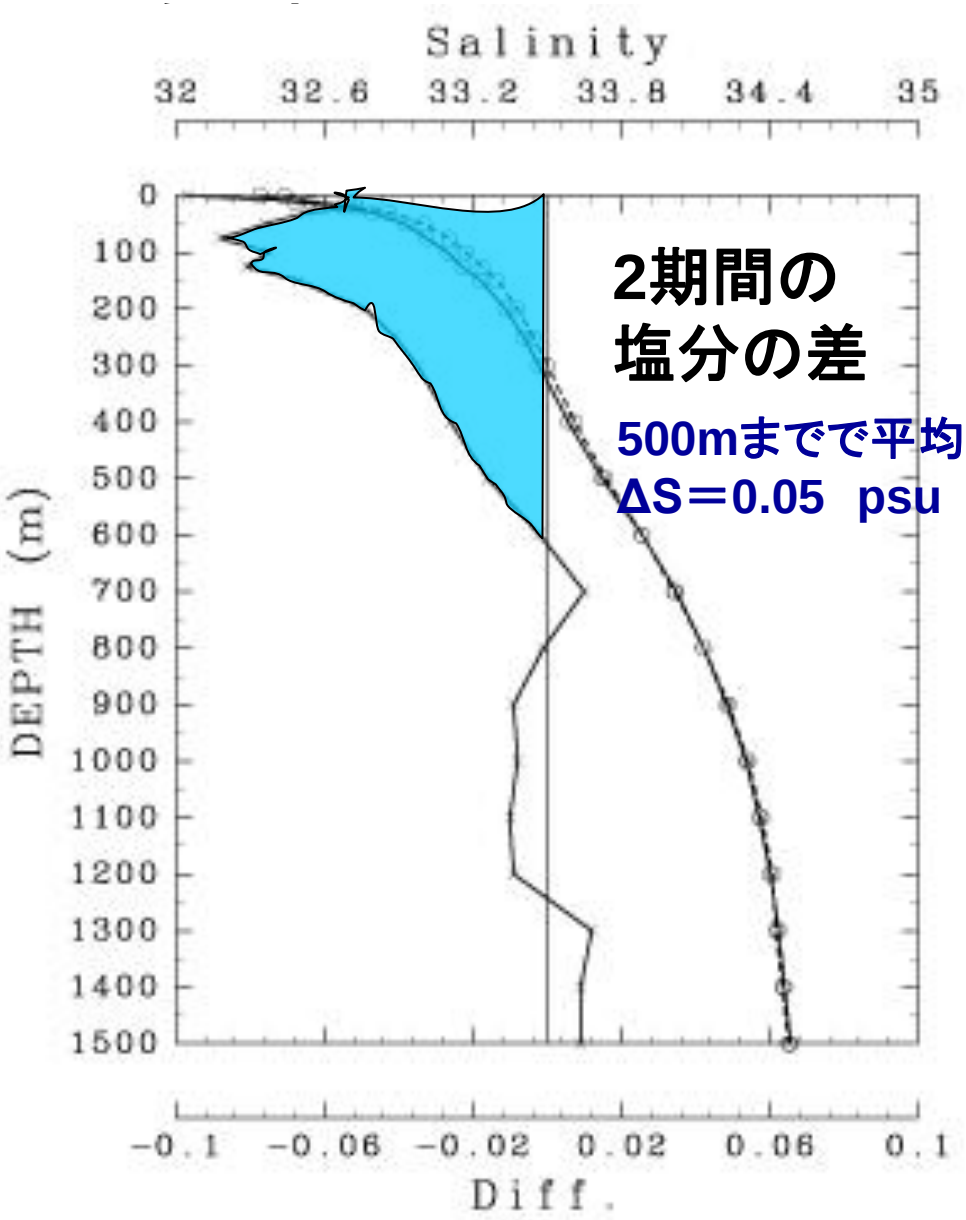
推定した海氷生産量は35年間で約12%の減少トレンドを示した



[(1990-2009) - (1930-1980)]

水柱全体の塩分変化を淡水フラックス(m)に換算

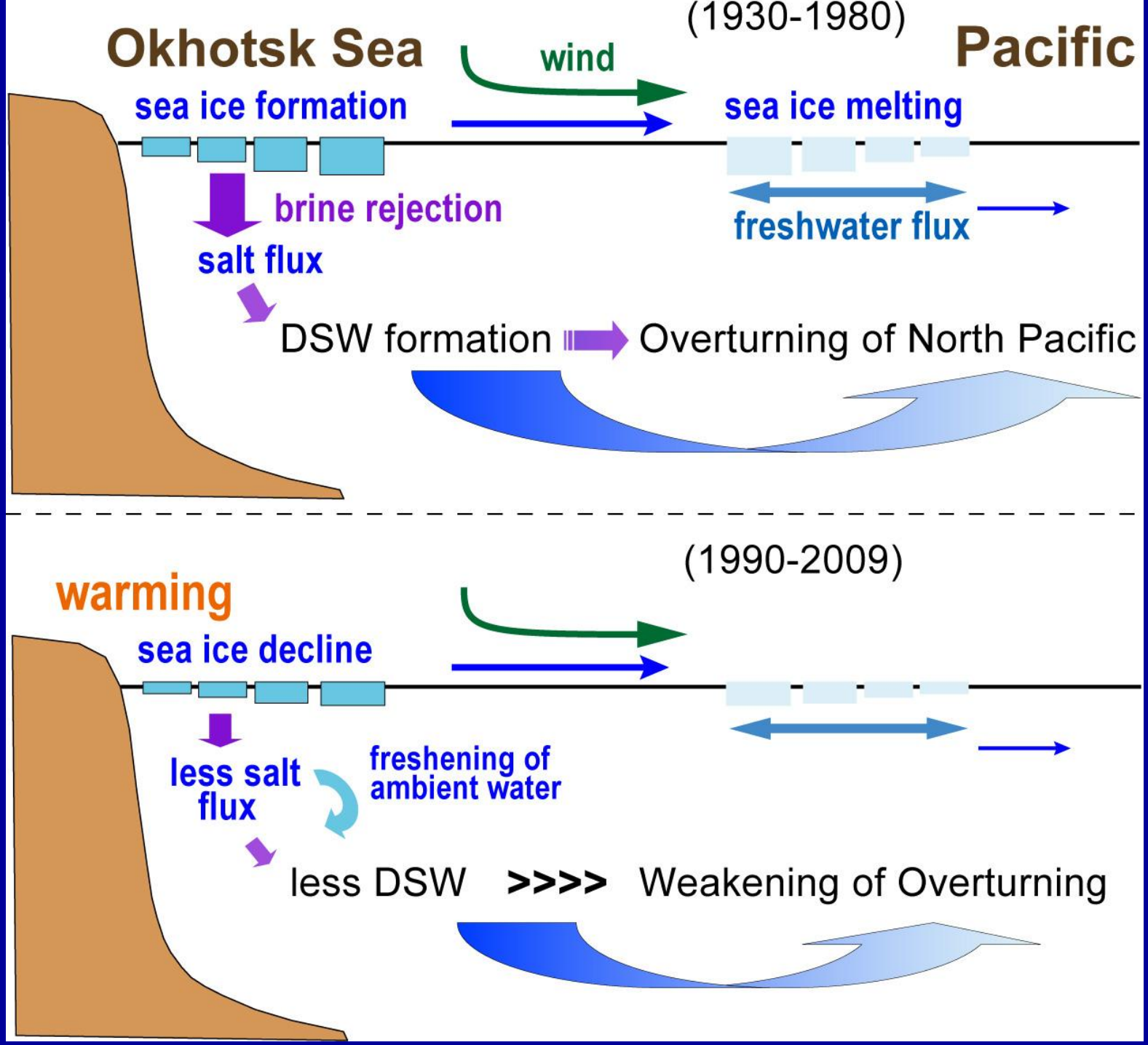




2期間の塩分の差

500mまでで平均
ΔS＝0.05 psu

平均すると0.52mの淡水化


(1930-1980)
Okhotsk Sea
wind
Pacific
sea ice formation
sea ice melting
brine rejection
freshwater flux
salt flux
DSW formation
Overturning of North Pacific
(1990-2009)
warming
sea ice decline
less salt flux
freshening of ambient water
less DSW >>>> Weakening of Overturning

1. イントロダクション：海氷生成と中深層水形成
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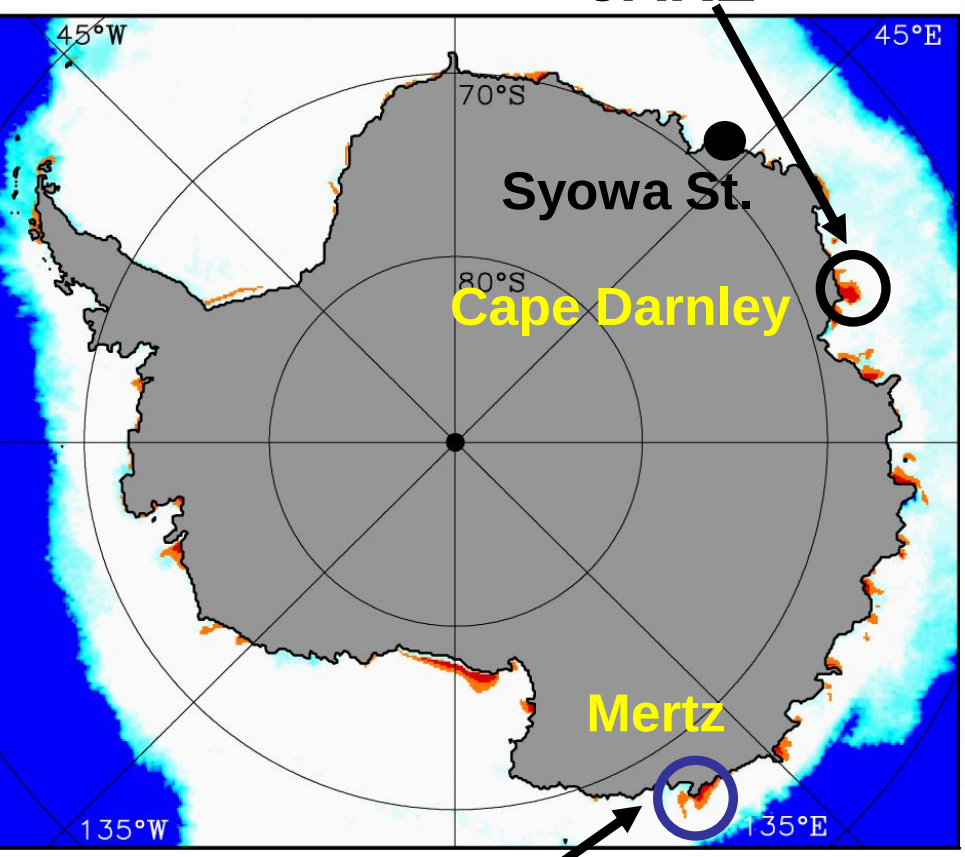
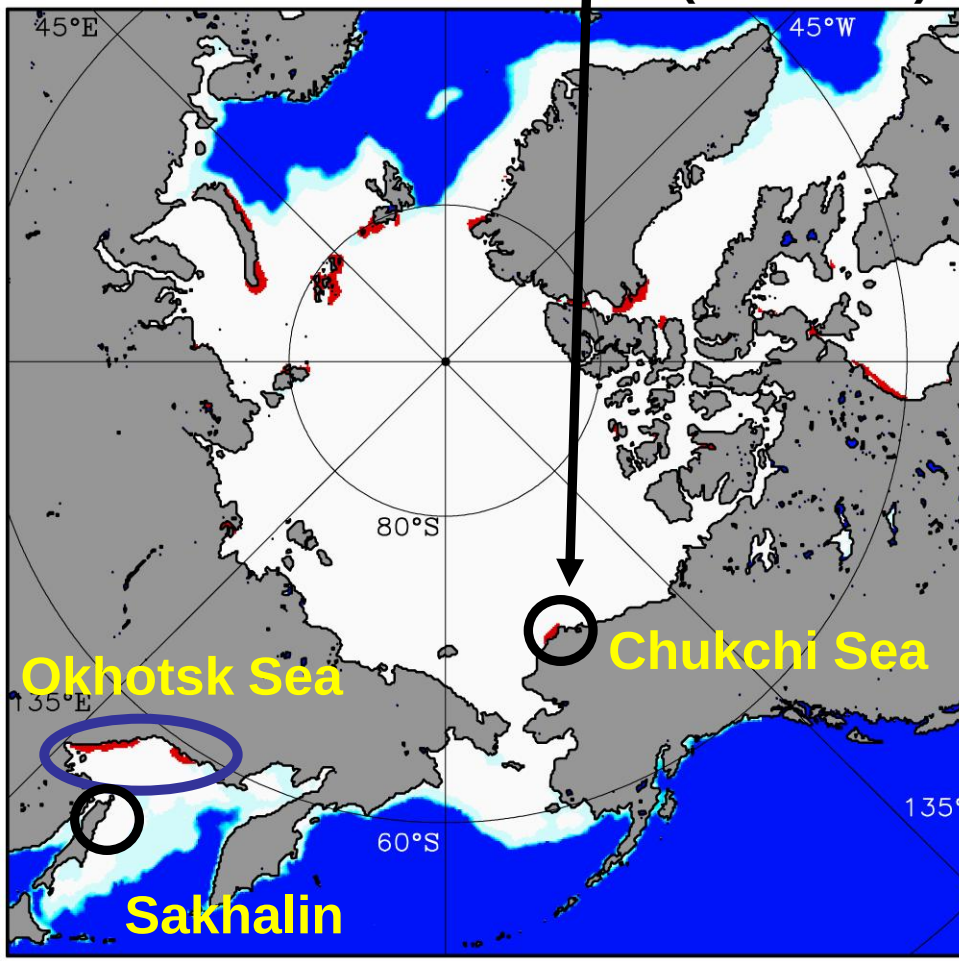
Global mapping of ice production
→ Heat and salt flux data set

JARE



Cooperation with UTAS ?

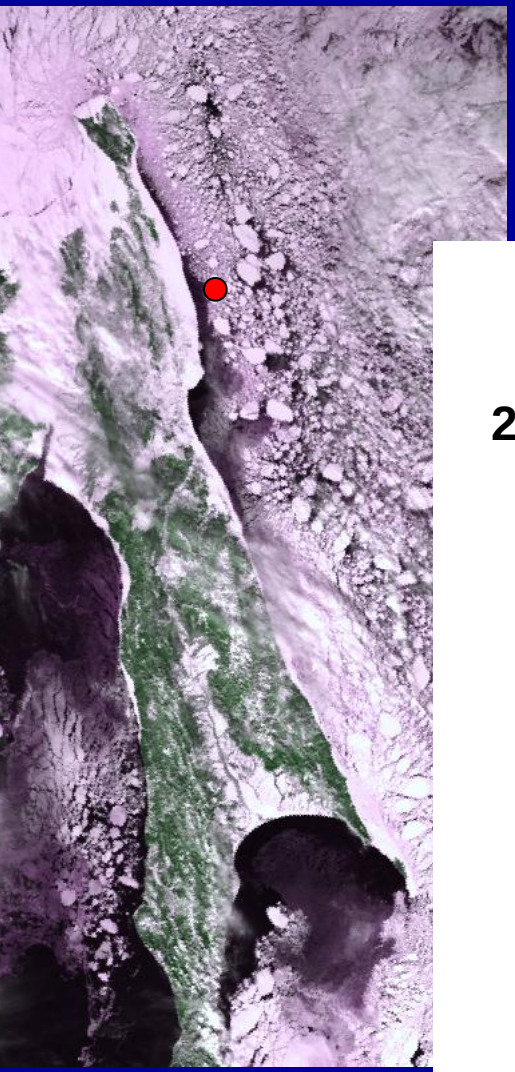
Cooperation with
Univ. Alaska (Dr.Eicken)



Validation by Ice Profiling Sonar (IPS) & ADCP moorings:
We are (will be) making mooring observations in several polynyas in the world to make the ice thickness and production algorithm globally.

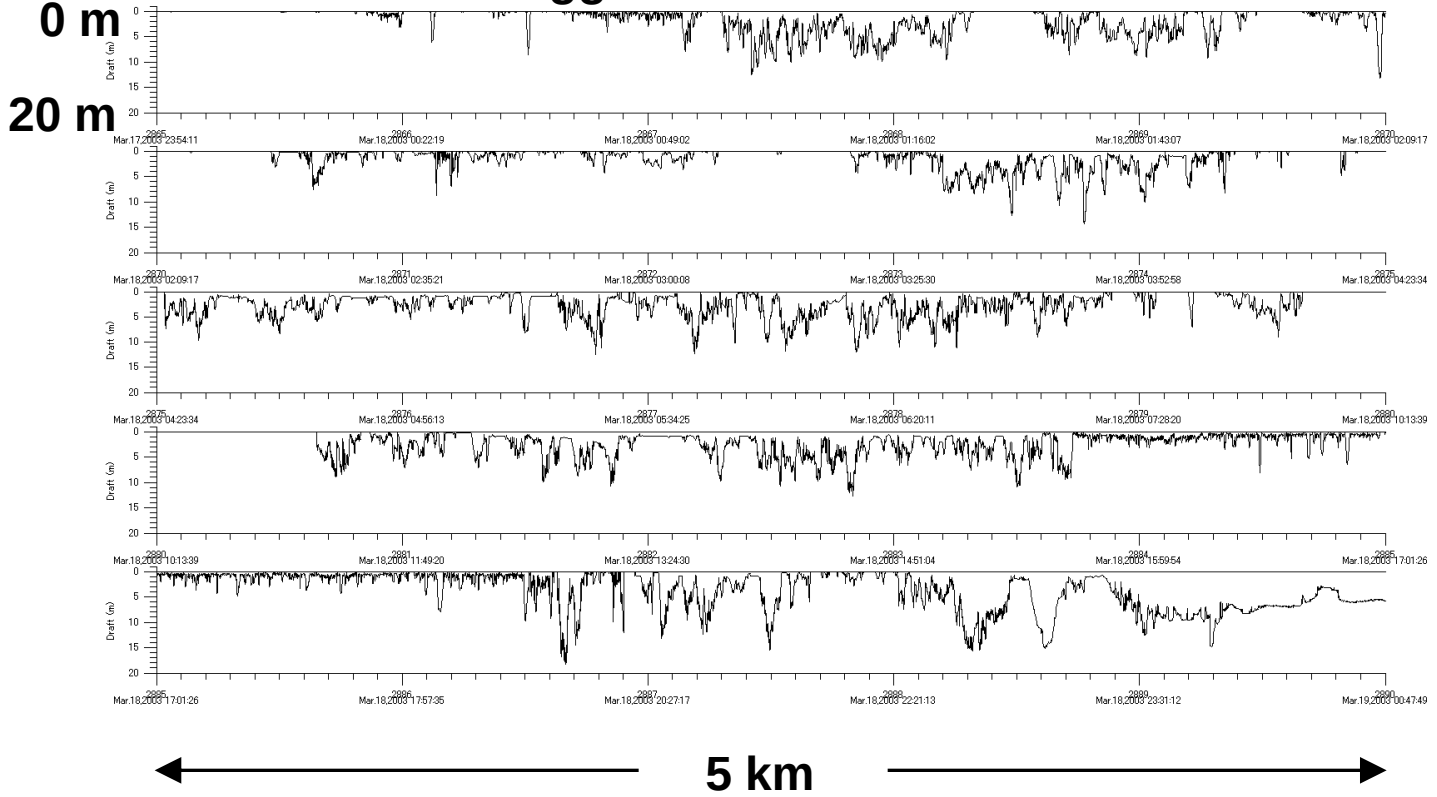
沿岸ポリニヤでの氷厚計(Ice Profiling Sonar), ADCP, CT計の設置

Mar. 18, 2003

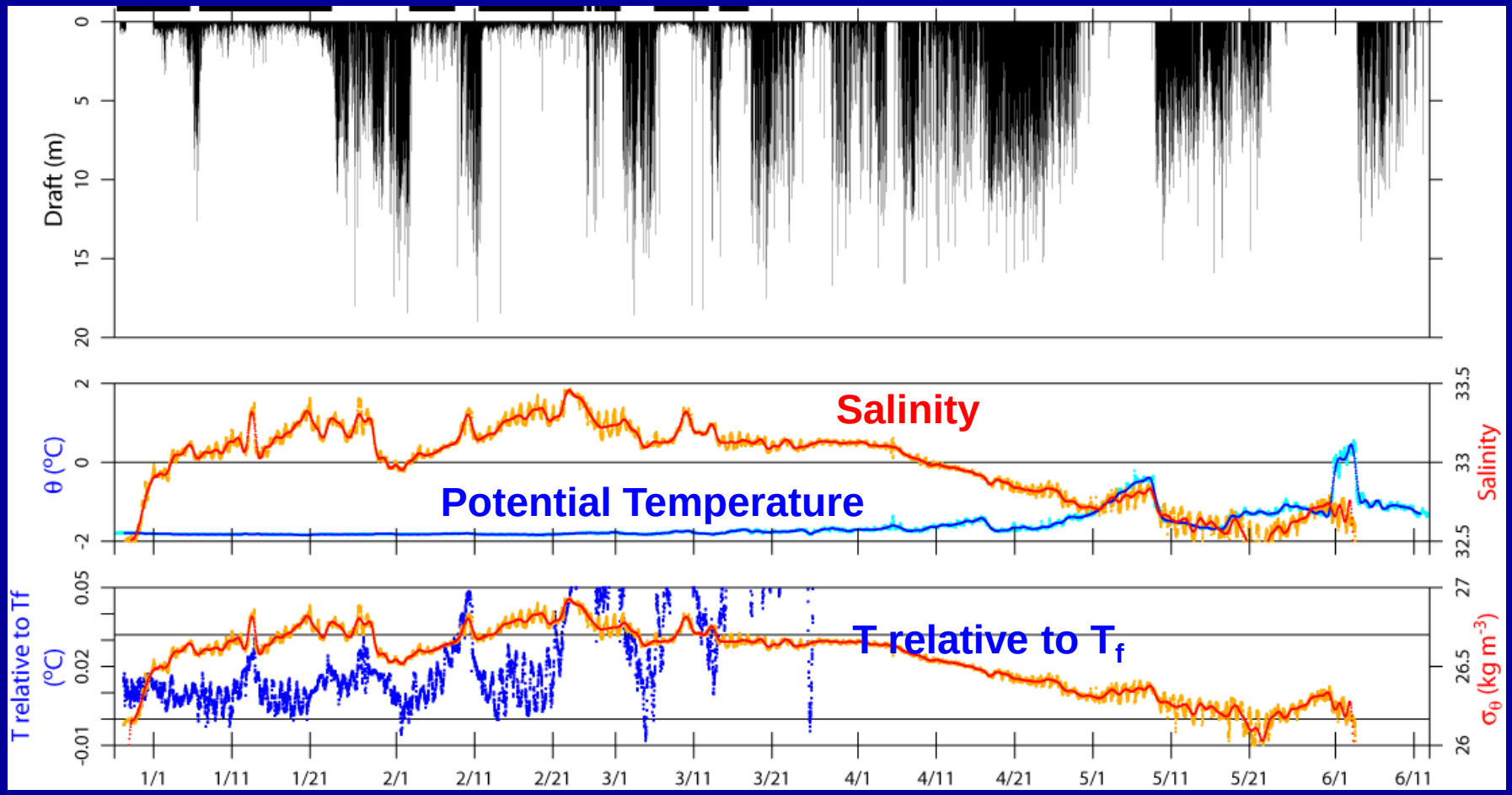


2002年12月～2003年5月

Fukamachi et al., 2009



Ice Draft and Water Properties (at 24-m depth)



1. Salinity increase during thin-ice periods till March
2. Temperature very close to freezing point (T_f)

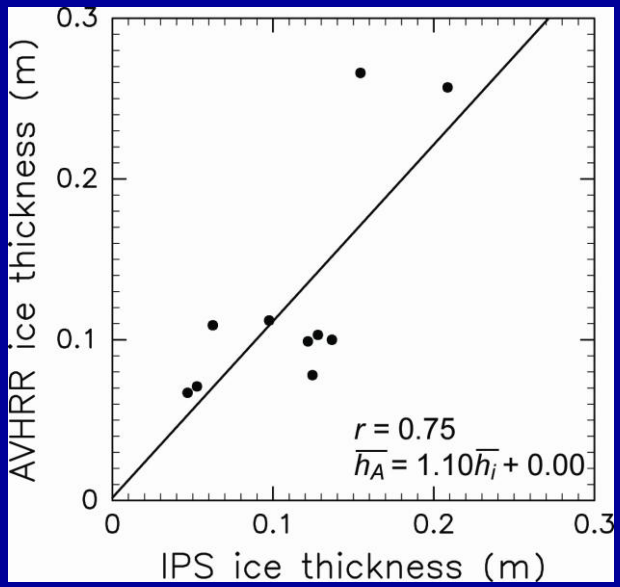
⇓

Brine rejection in polynya

Fukamachi et al., 2009

Validation of thin-ice thickness based on satellite data

Nihashi et al. (2009)



IPS ice thickness

⇓

AVHRR thin-ice thickness

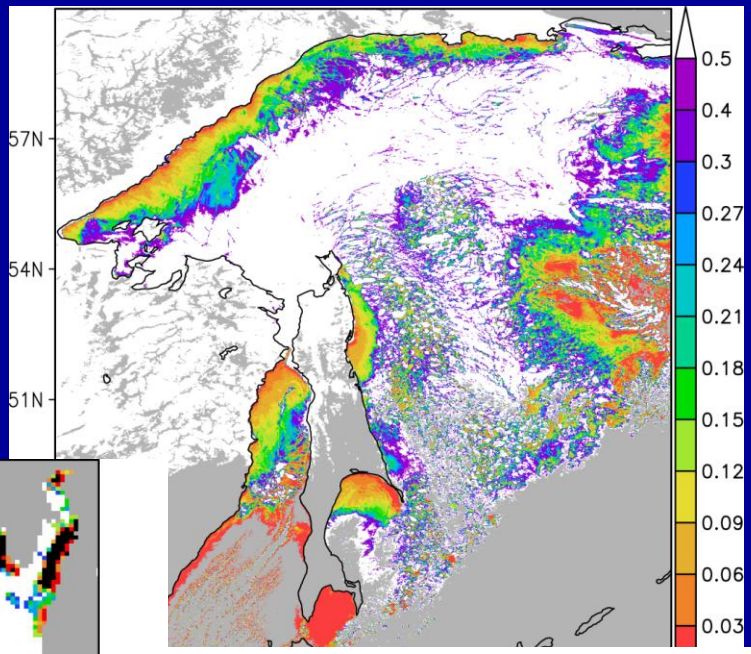
+

AMSR-E data

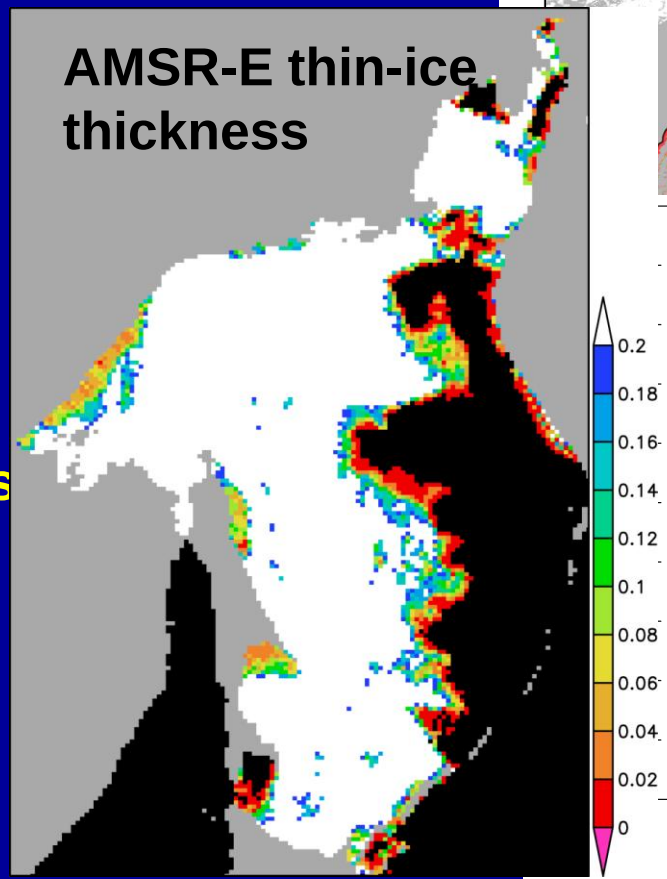
⇓

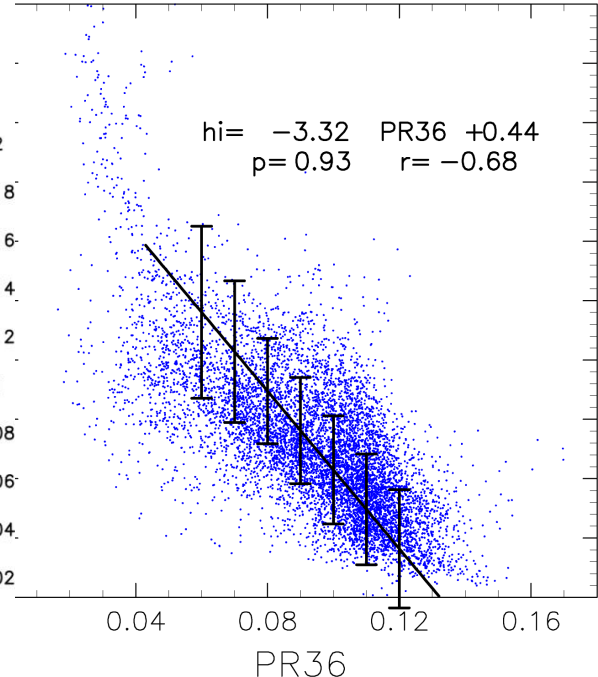
Thin-ice thickness

AVHRR thin-ice thickness

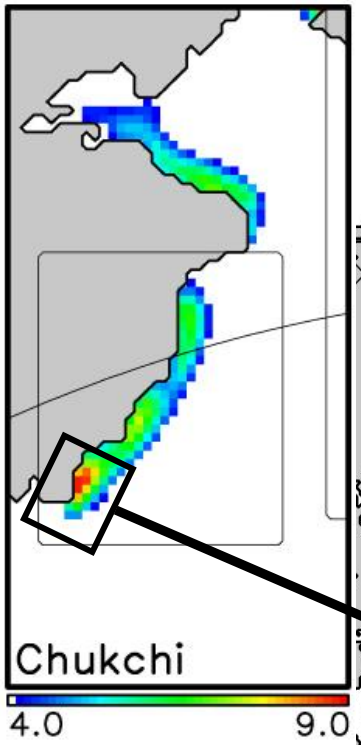


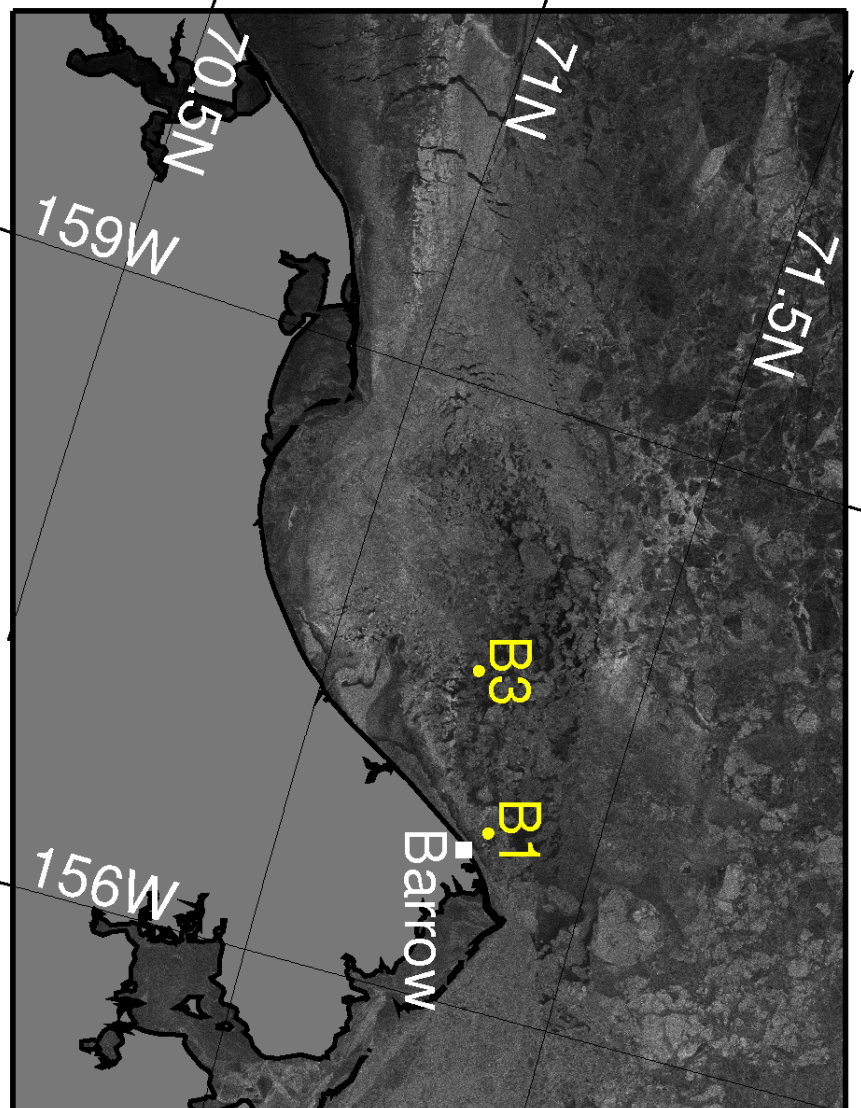
AMSR-E thin-ice thickness





Mapping of sea ice production (1992-2007)





ASAR 20091231 213327

Tamura &Ohshima, in press


ITT-ASI
THEATRE
BARROW ARCTIC
BASC
SCIENCE CONSORTIUM
LOGISTICS

Barrow Arctic Science Consortium (BASC)

世界一cost performance がよい係留観測
小型ボートと手動クレーンでの観測

砂をつめる

重さは次に調整するので持ち上がる程度の重さにしておく

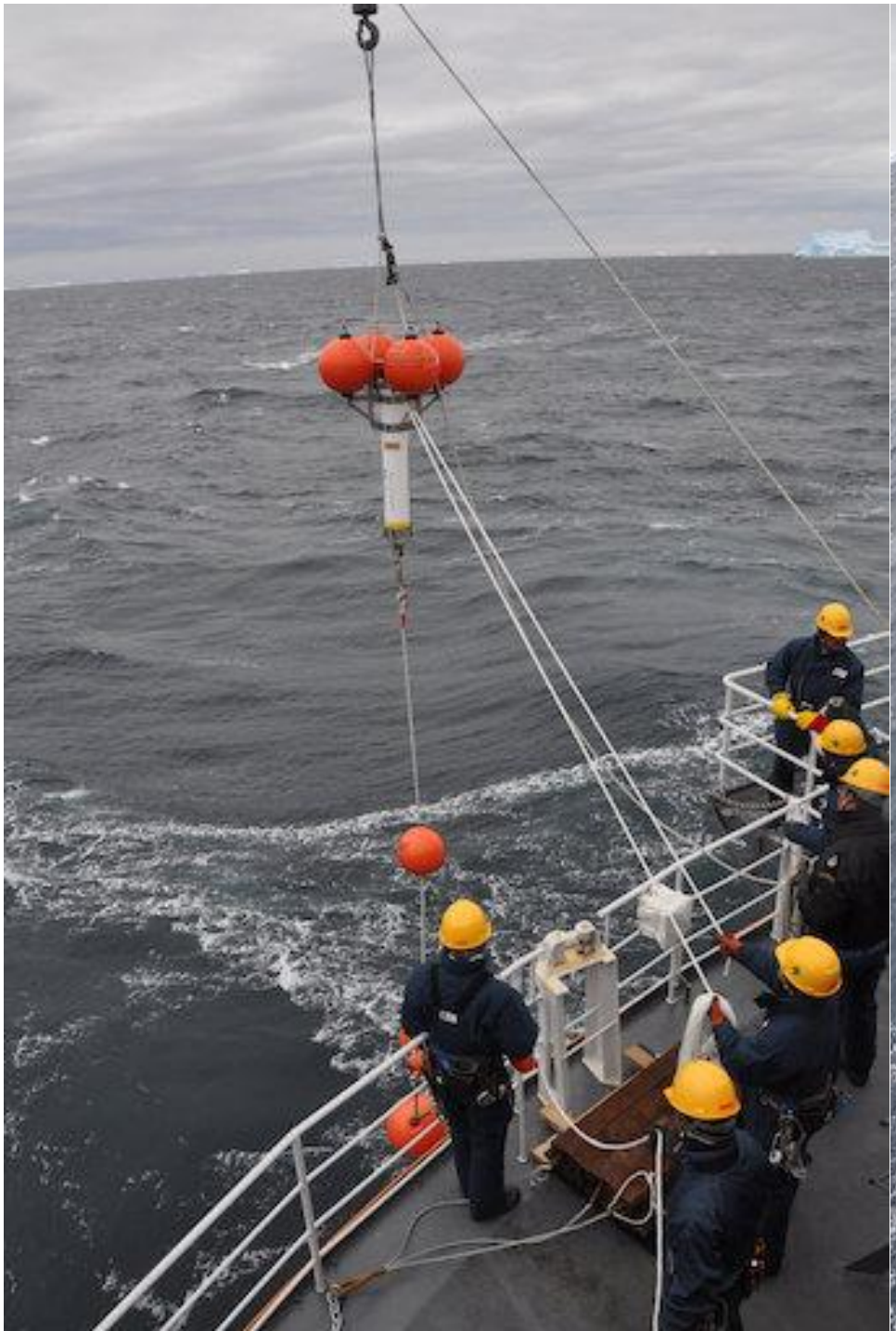
重さを調節する

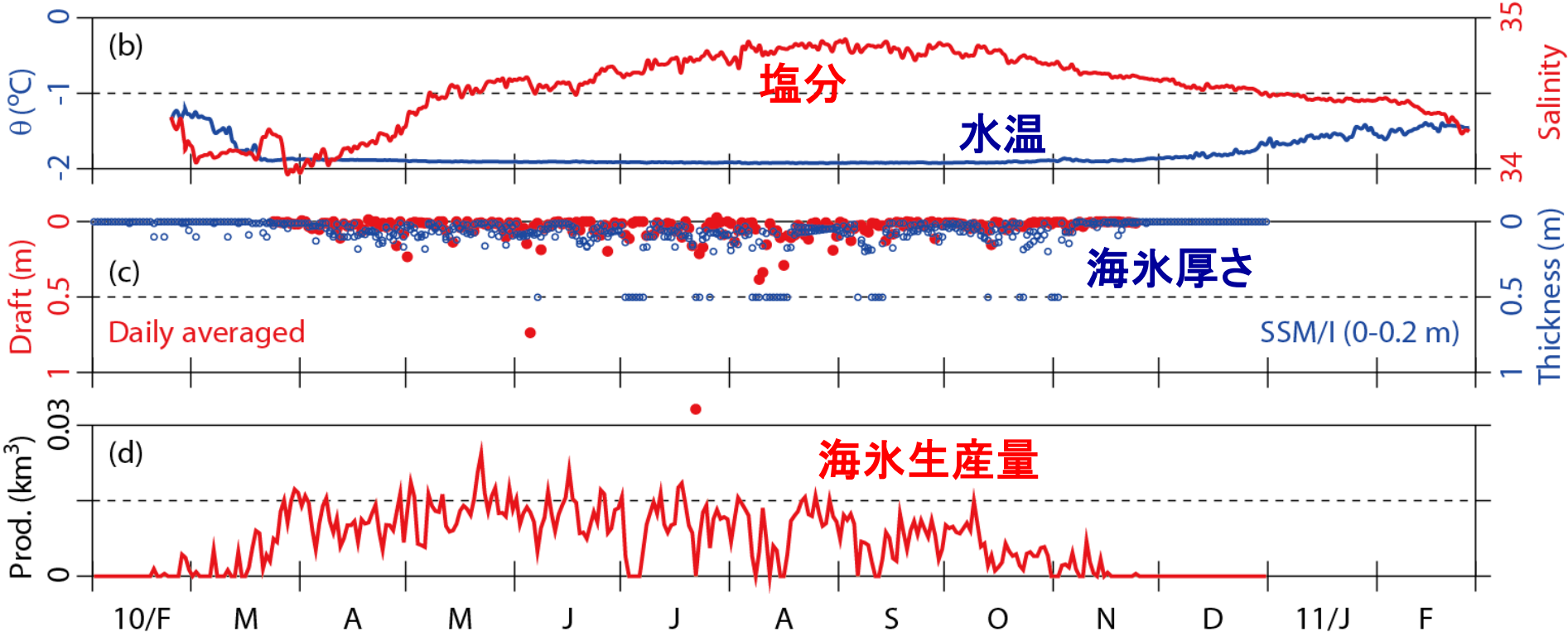
２００９年８月は１系あたり１００ｋｇｘ３を使用した。多めの袋に大雑把に積めた後、ばね秤を使って調節した。

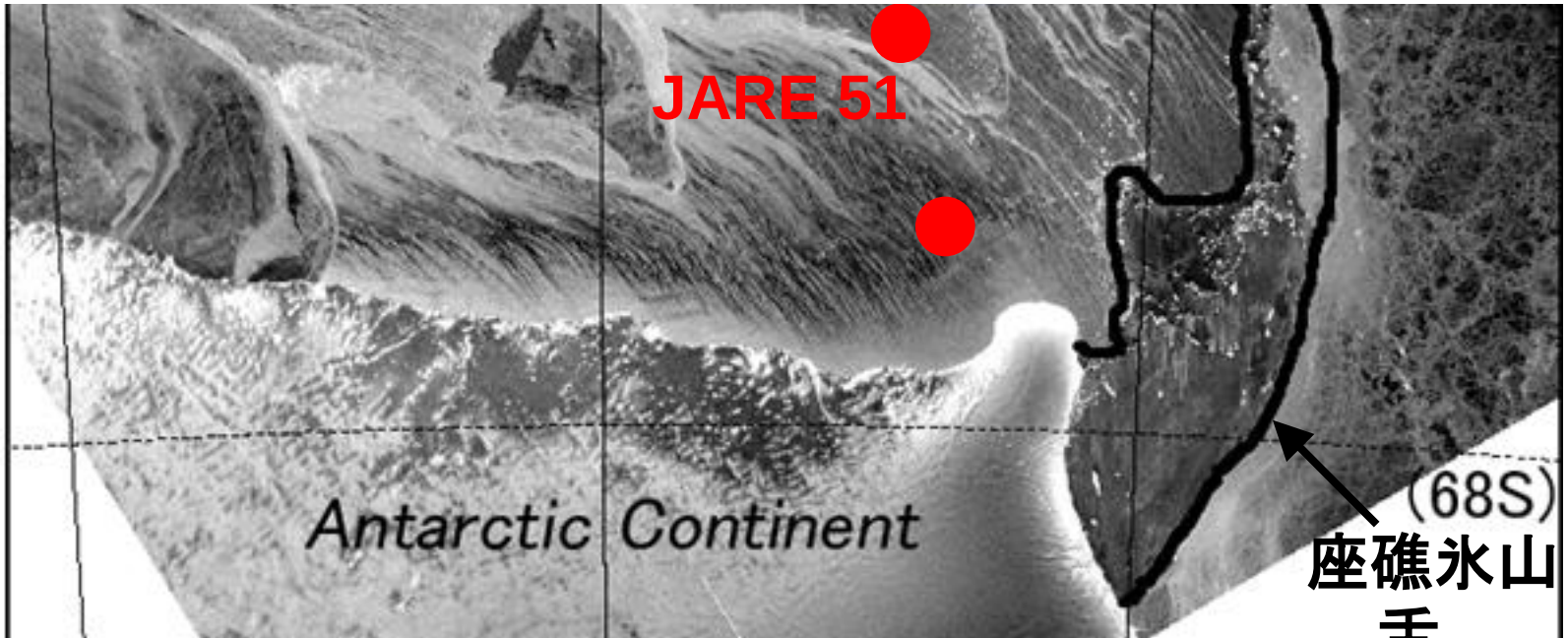
世界最良のcost performanceの
係留観測

世界最悪のcost performanceの
係留観測

日本南極観測隊
砕氷船しらせ
4ヶ月の航海




(b)
θ (°C)
0
-1
-2
塩分
水温
35
34
Salinity
(c)
Draft (m)
0
0.5
1
Daily averaged
海氷厚さ
SSM/I (0-0.2 m)
0
0.5
1
Thickness (m)
(d)
Prod. (km³)
0.03
0
海氷生産量
10/F
M
A
M
J
J
A
S
O
N
D
11/J
F


JARE 51
Antarctic Continent
(68S)
座礁氷山