Transit Times in the North Atlantic DWBC Measured Using the Tracer Pair $^{129}I/CFC\text{-}11$

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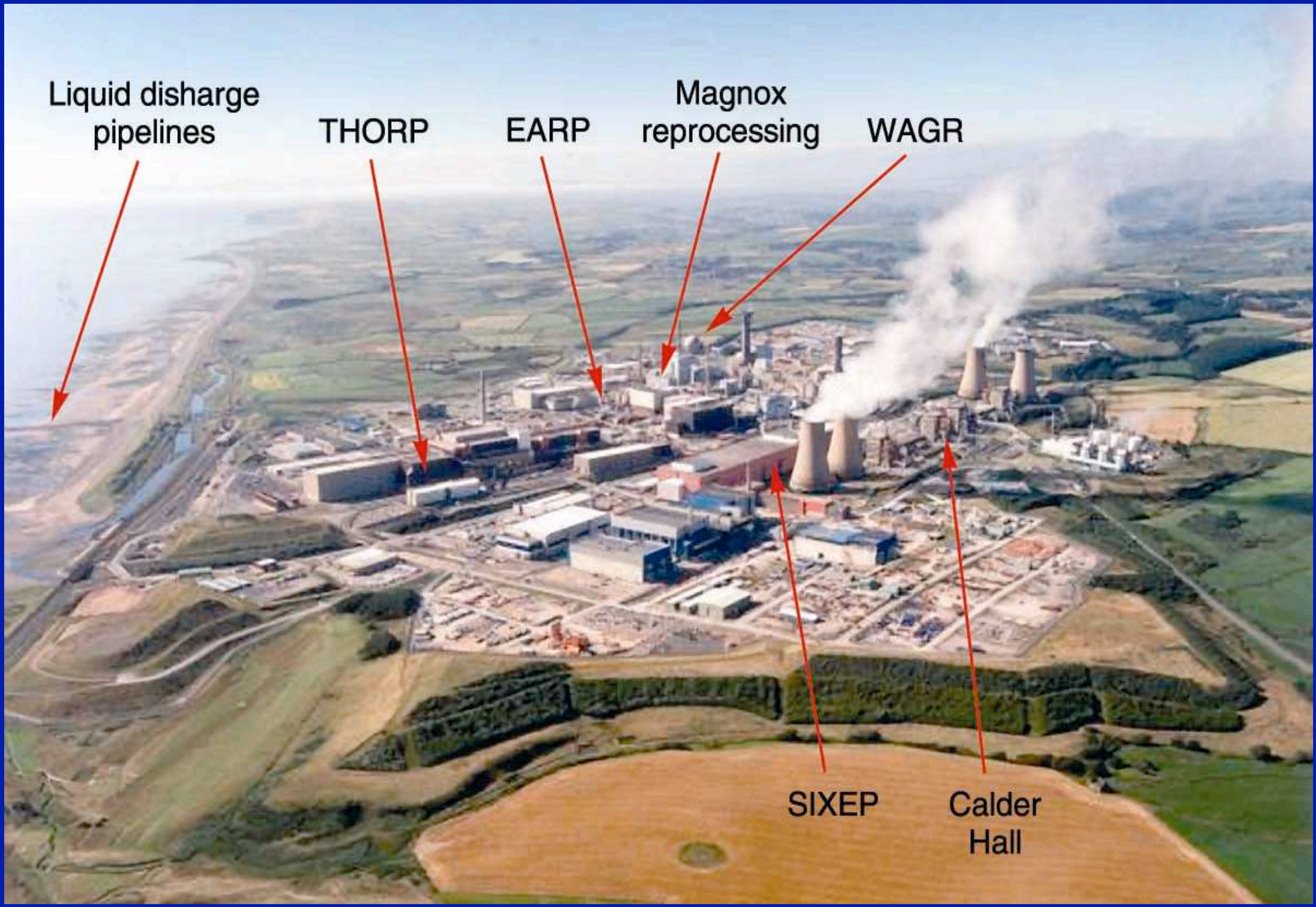
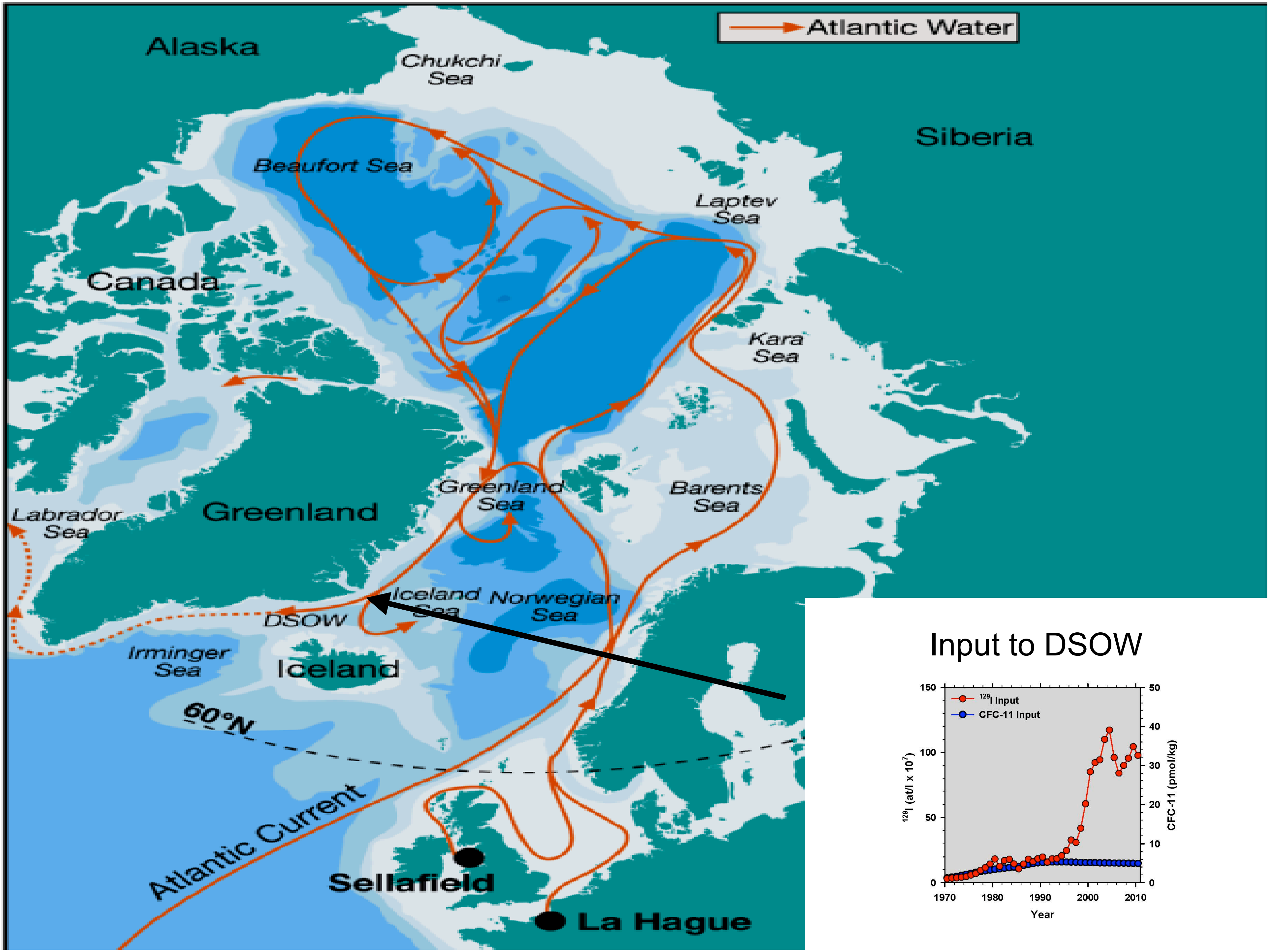
^{129}I Tracer Characteristics

- $t_{1/2} = 1.6 \times 10^7$ y
- Measured by AMS (IsoTrace: Univ. Toronto)
- 250 ml samples
- $200/sample for AMS
- Sample collection; cheap
- Nuclear fuel reprocessing plant source – Sellafield (UK) & La Hague (France)

BNFL Sellafield




Atlantic Water
Alaska
Chukchi Sea
Siberia
Beaufort Sea
Laptev Sea
Canada
Kara Sea
Greenland Sea
Barents Sea
Labrador Sea
Greenland
Iceland Sea
Norwegian Sea
DSOW
Irminger Sea
Iceland
60°N
Atlantic Current
Sellafield
La Hague



Atlantic Water
Alaska
Chukchi Sea
Siberia
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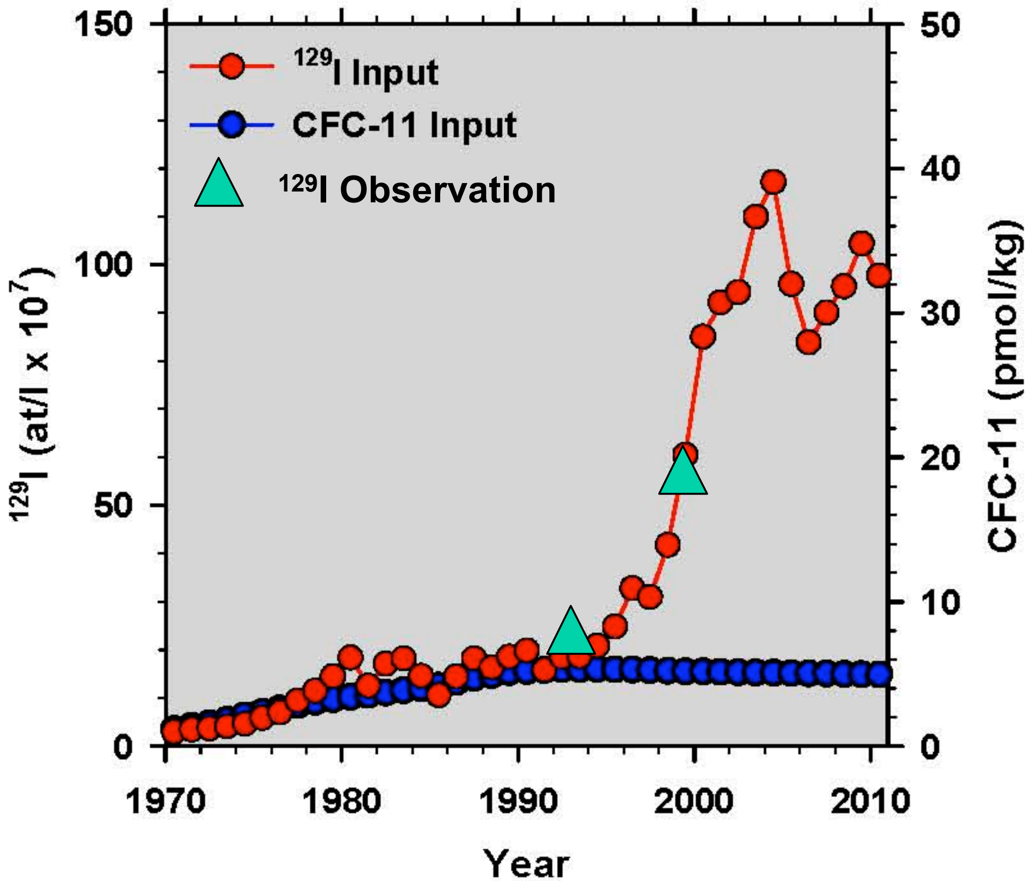
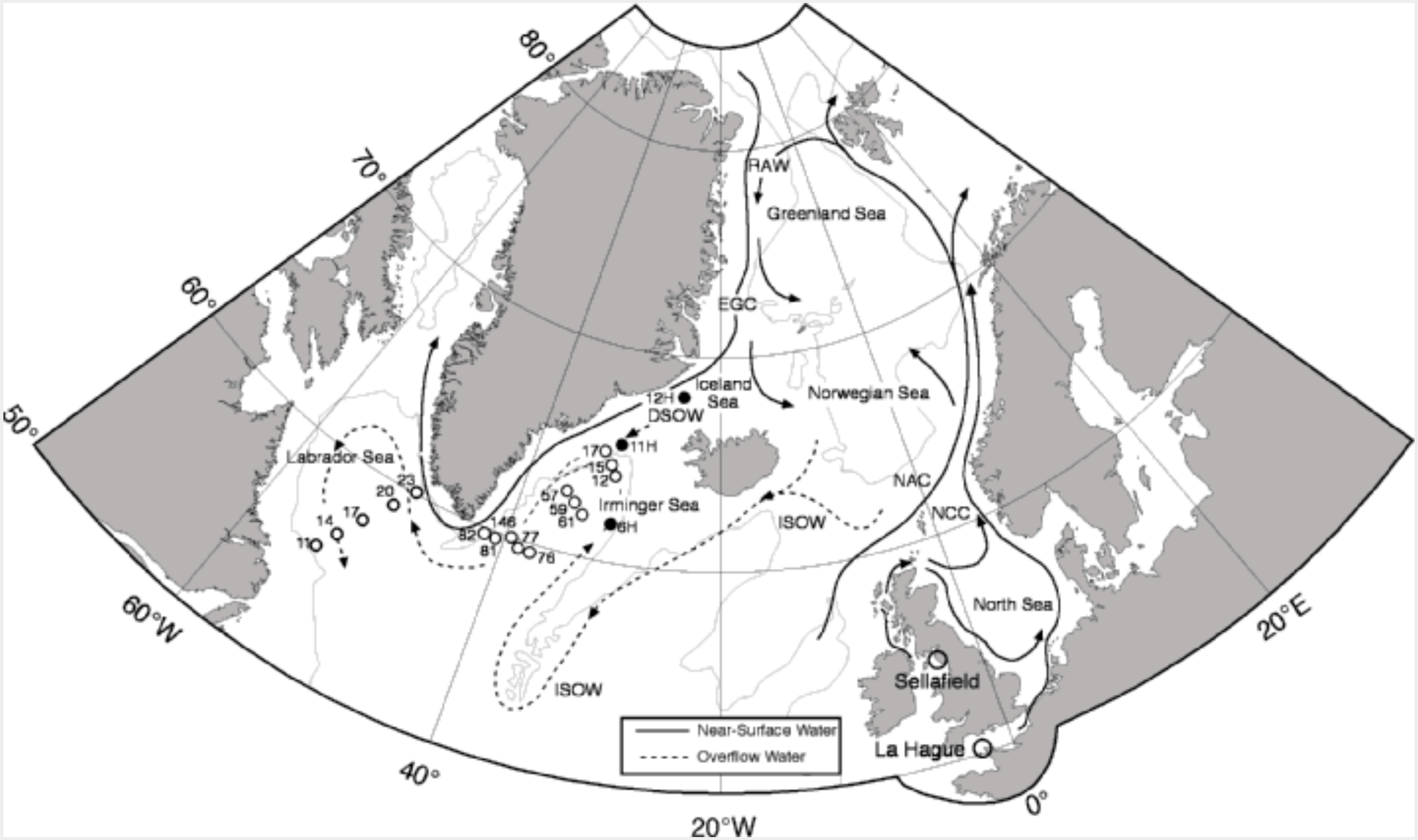
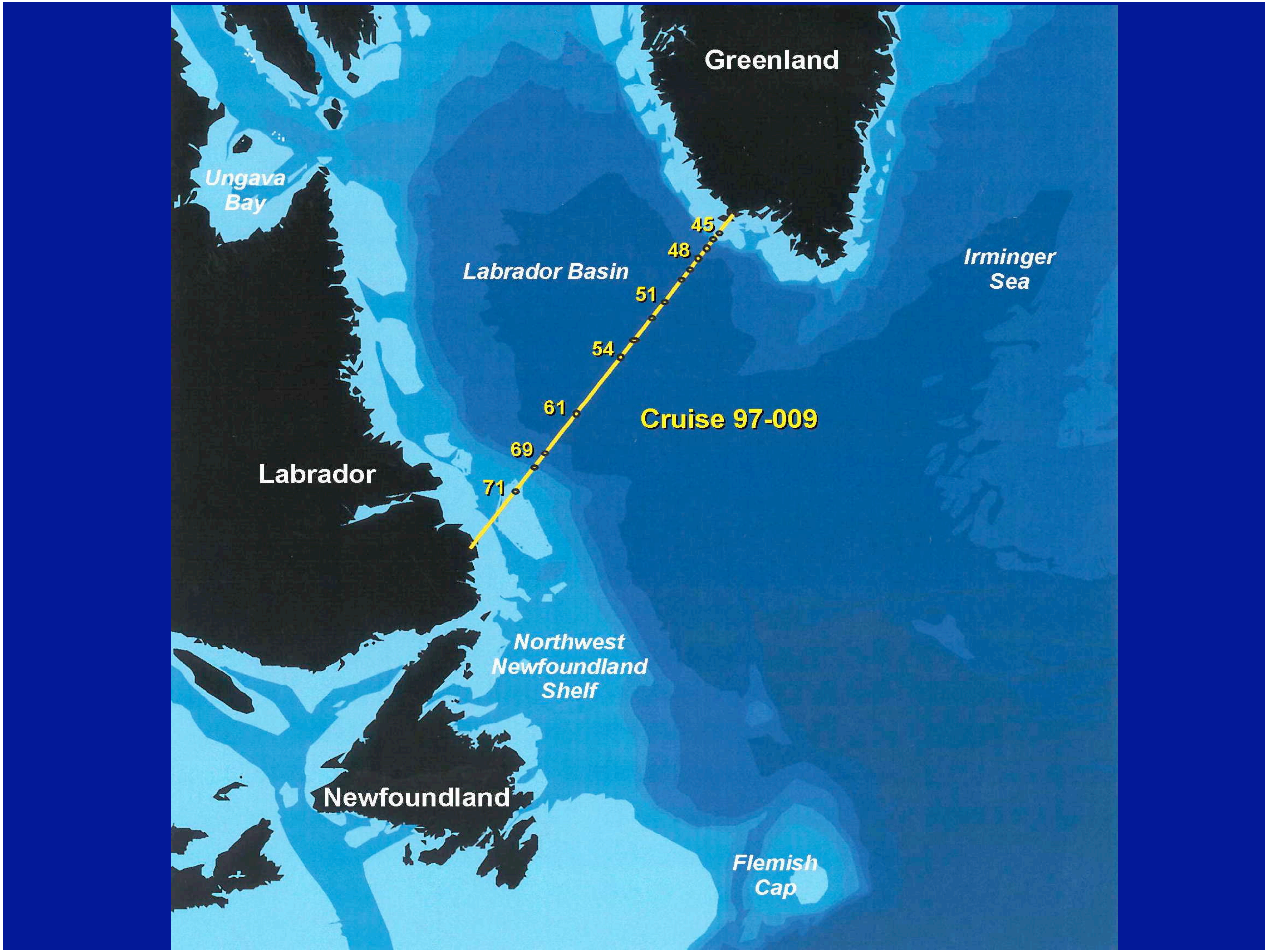
Laptev Sea
Canada
Kara Sea
Greenland Sea
Barents Sea
Labrador Sea
Greenland
Iceland Sea
Norwegian Sea
DSOW
Irminger Sea
Iceland
60°N
Atlantic Current
Sellafield
La Hague
Input to DSOW
129I Input
CFC-11 Input
129I (at/l x 10^7)
CFC-11 (pmol/kg)
Year

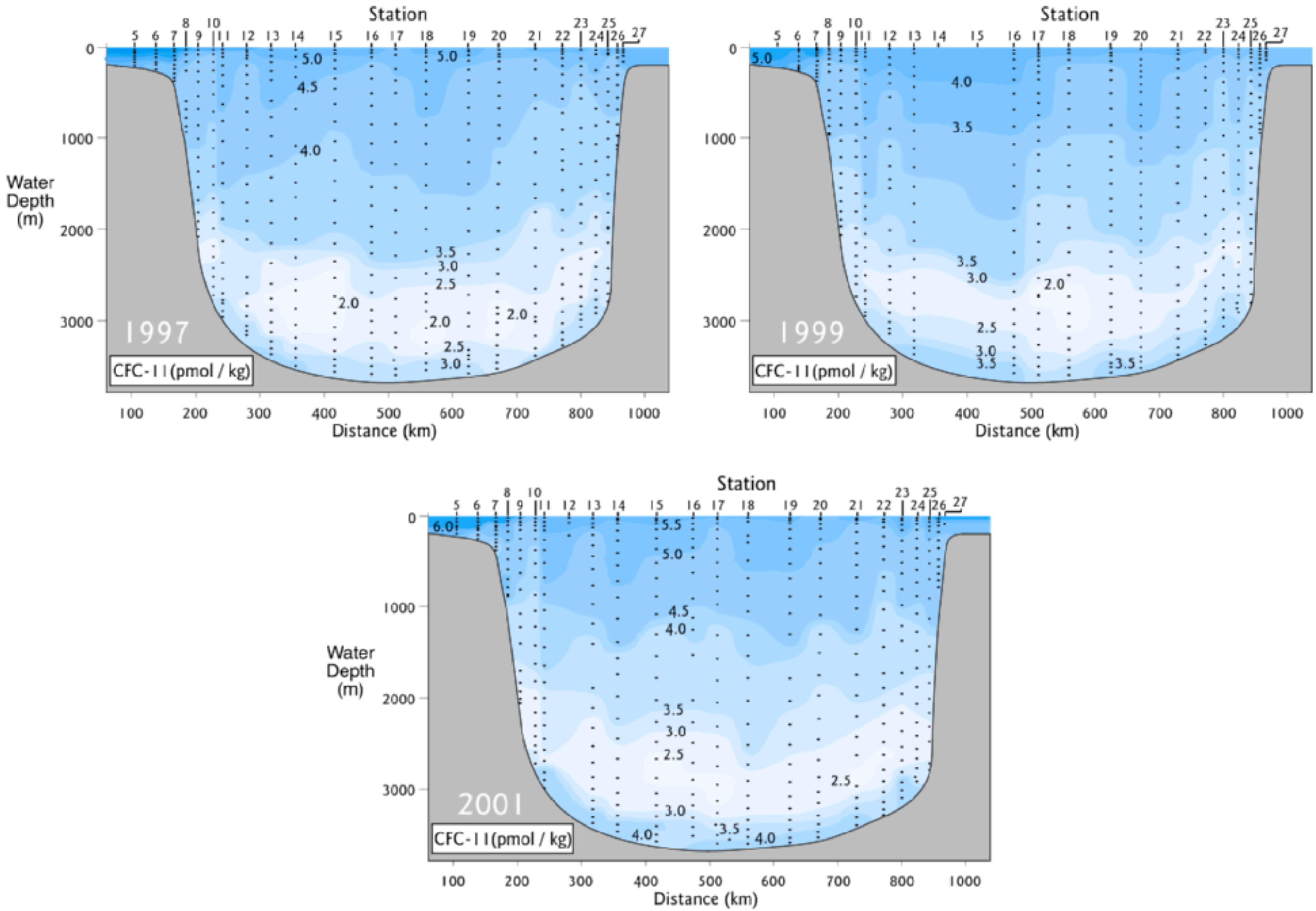


150
100
50
0
50
40
30
20
10
0
1970
1980
1990
2000
2010
Year
129I (at/l x 10^7)
CFC-11 (pmol/kg)
129I Input
CFC-11 Input
129I Observation

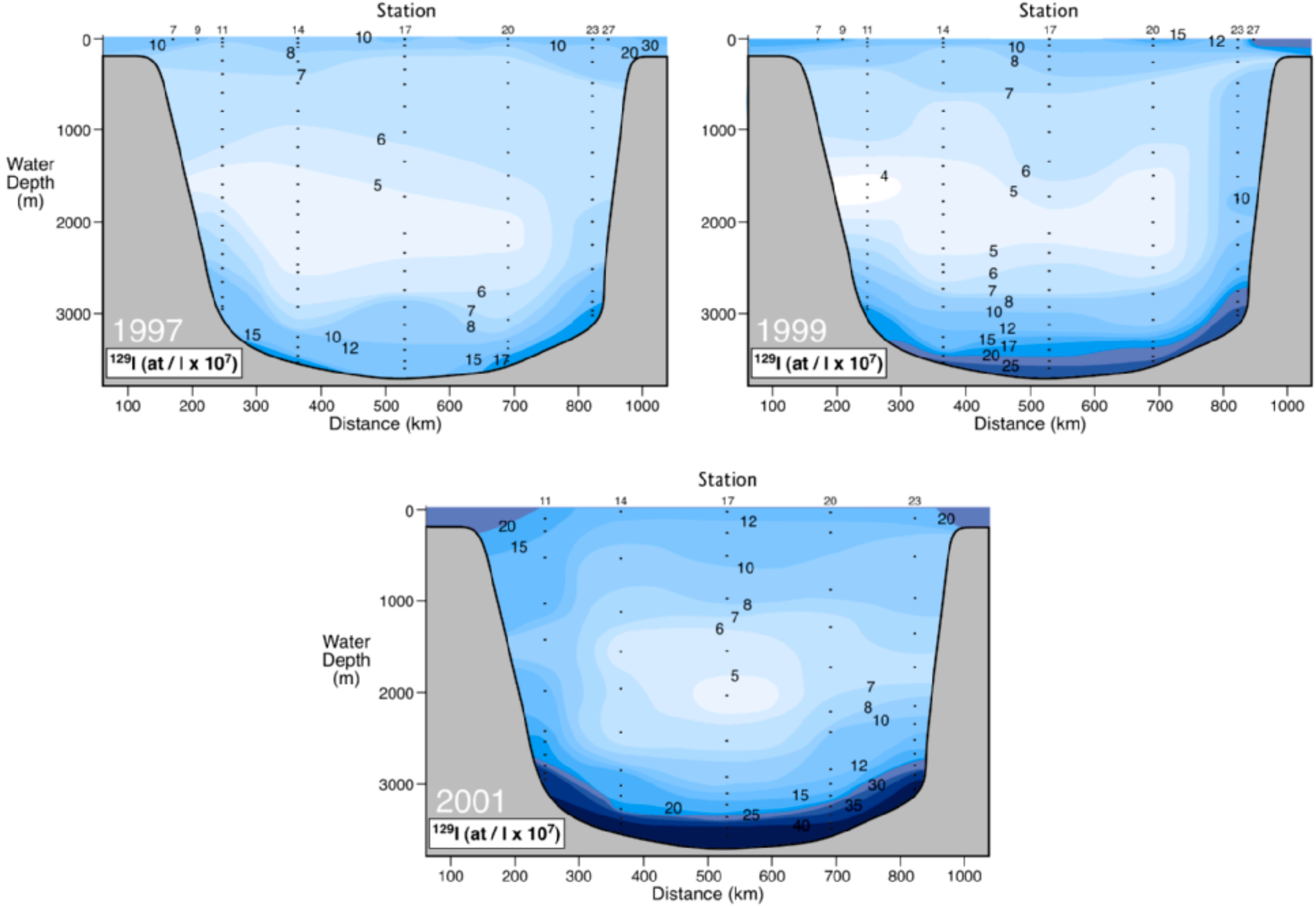


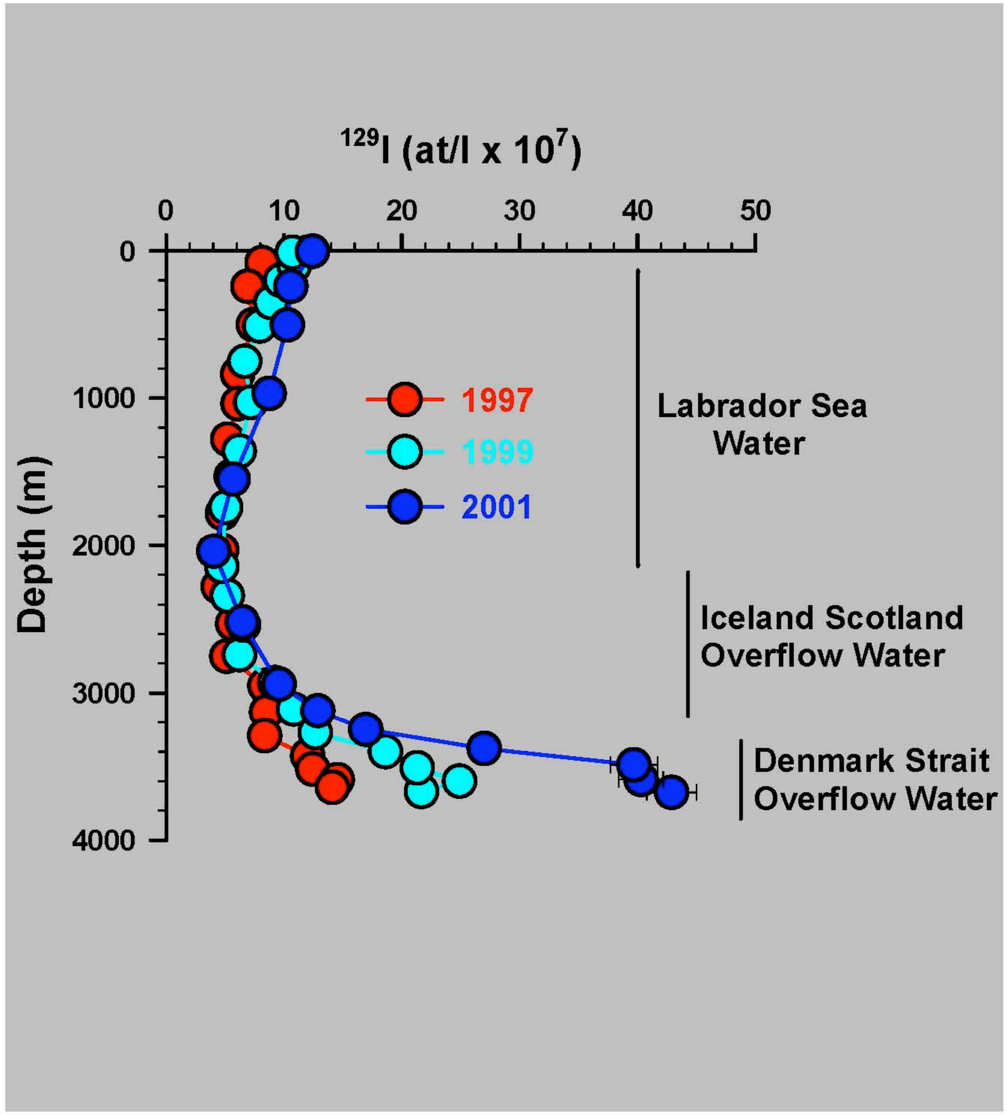
80°
70°
60°
50°
60°W
40°
20°W
0°
20°E
RAW
Greenland Sea
EGC
Iceland Sea
12H
DSOW
Norwegian Sea
11H
17
15
12
Labrador Sea
23
20
17
14
11
57
59
61
Irminger Sea
6H
146
82
81
77
76
ISOW
NAC
NCC
North Sea
Sellafield
La Hague
ISOW
Near-Surface Water
Overflow Water


Greenland
Ungava Bay
Labrador Basin
Irminger Sea
45
48
51
54
61
69
71
Cruise 97-009
Labrador
Northwest Newfoundland Shelf
Newfoundland
Flemish Cap

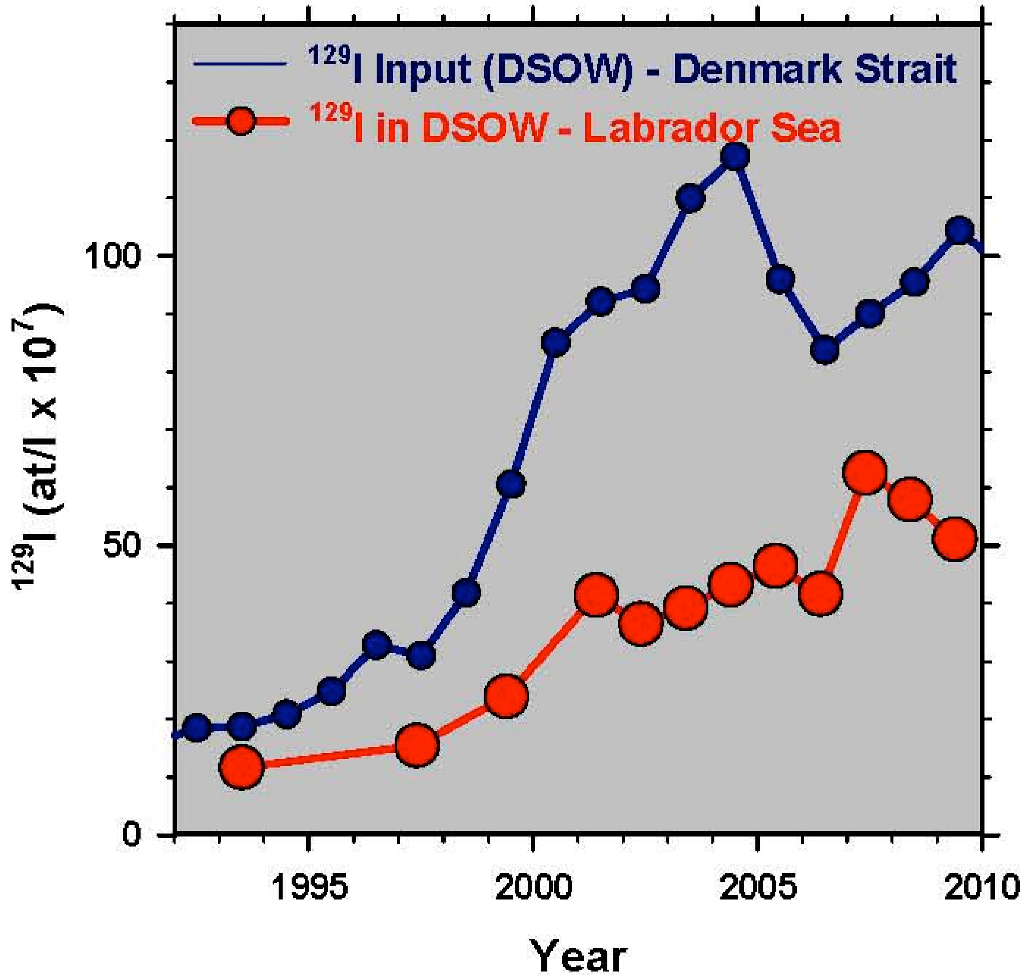


Station
Water Depth (m)
Distance (km)
1997
CFC-11(pmol / kg)
1999
CFC-11(pmol / kg)
2001
CFC-11(pmol / kg)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
5.5
6.0

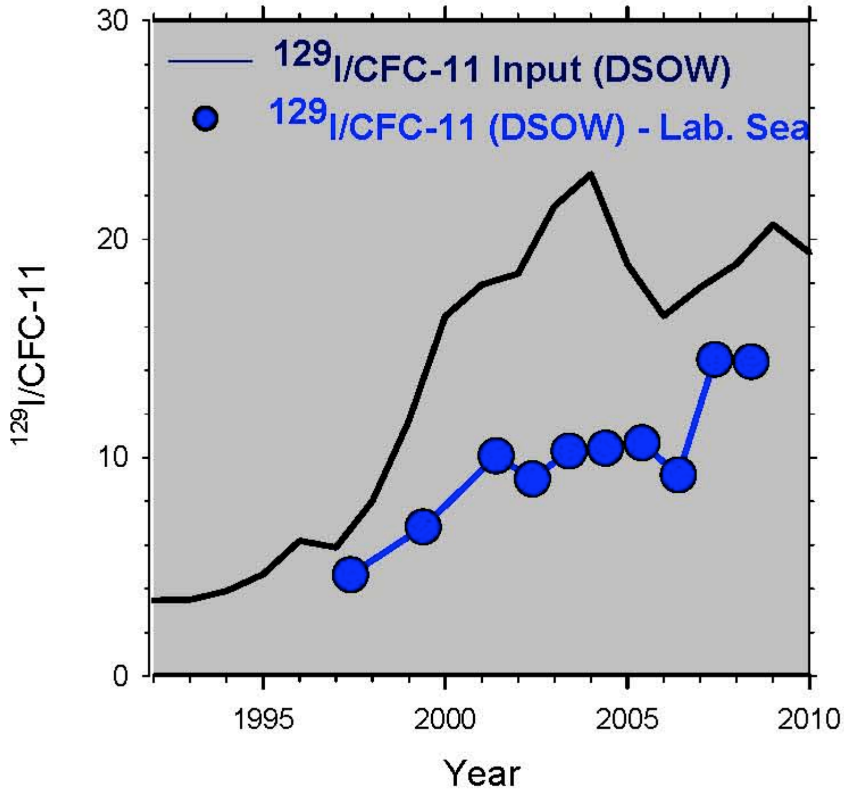

Station
7 9 11 14 17 20 23 27
Water Depth (m)
0
1000
2000
3000
Distance (km)
100 200 300 400 500 600 700 800 1000
1997
^{129}I (at / l x 10^7)
Station
7 9 11 14 17 20 23 27
Water Depth (m)
Distance (km)
1999
^{129}I (at / l x 10^7)
Station
11 14 17 20 23
Water Depth (m)
Distance (km)
2001
^{129}I (at / l x 10^7)



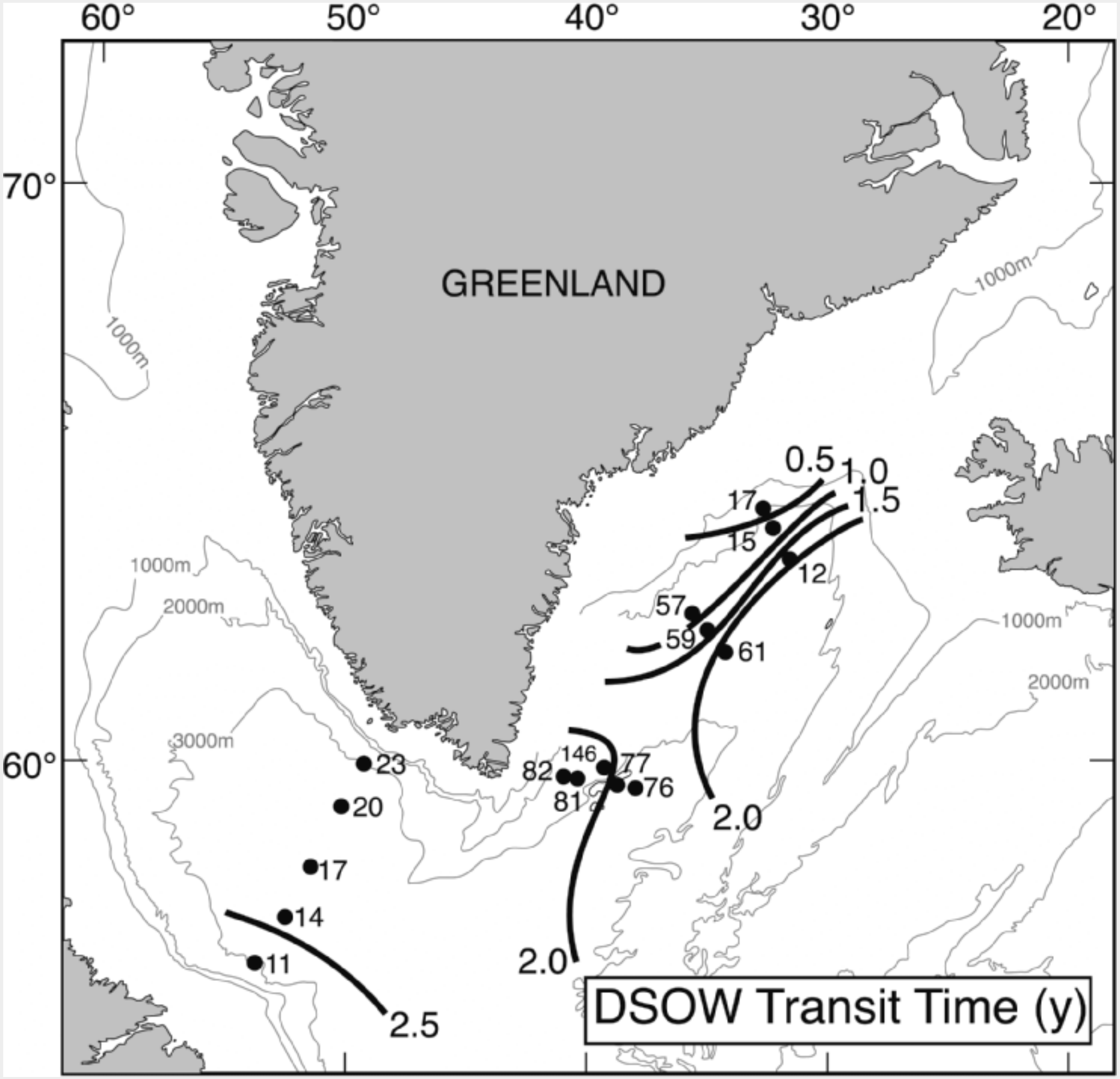
^{129}I (at/l x 10^7)
0
10
20
30
40
50
0
1000
2000
3000
4000
Depth (m)
1997
1999
2001
Labrador Sea Water
Iceland Scotland Overflow Water
Denmark Strait Overflow Water



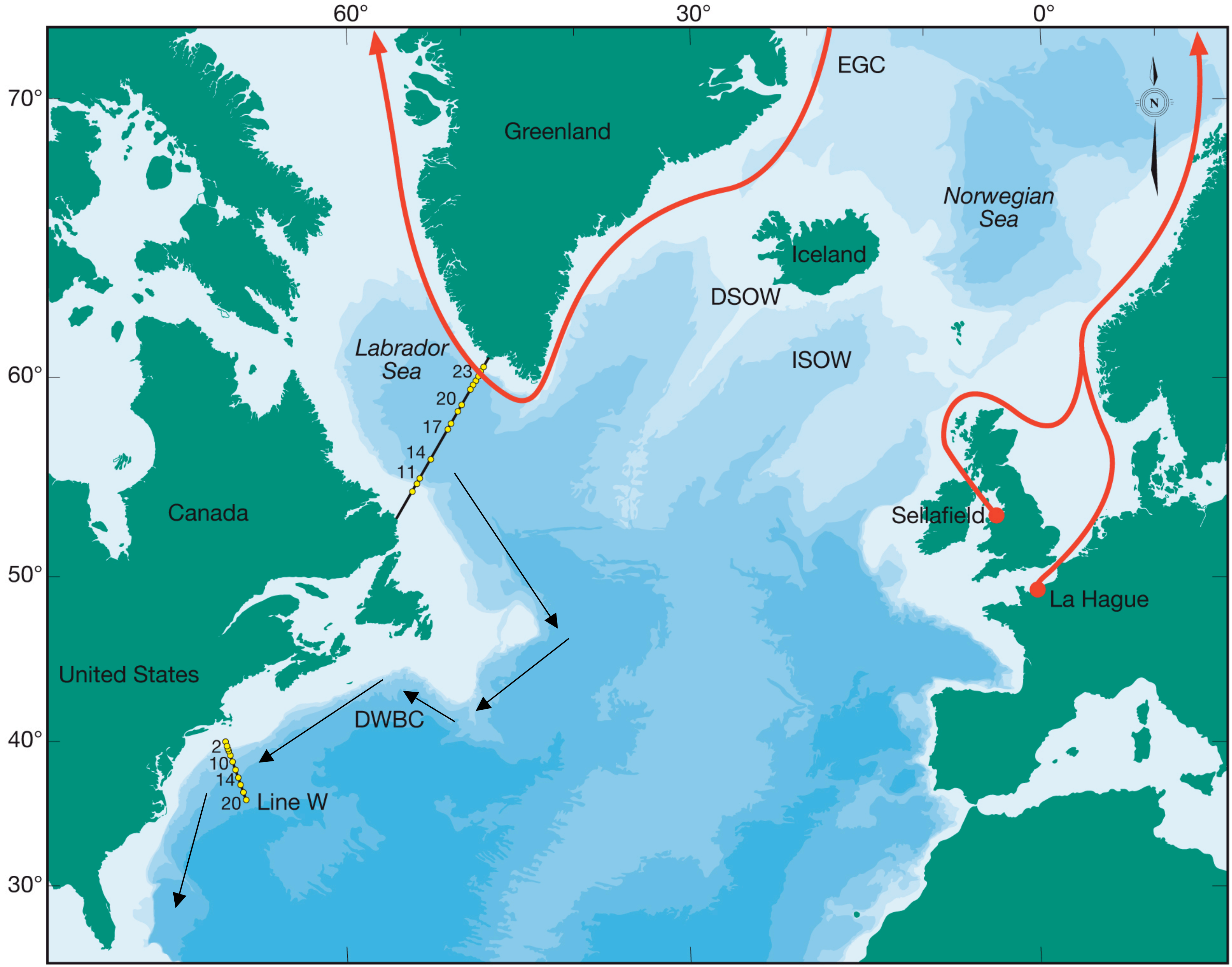
129I Input (DSOW) - Denmark Strait
129I in DSOW - Labrador Sea
129I (at/l x 10^7)
0
50
100
1995
2000
2005
2010
Year



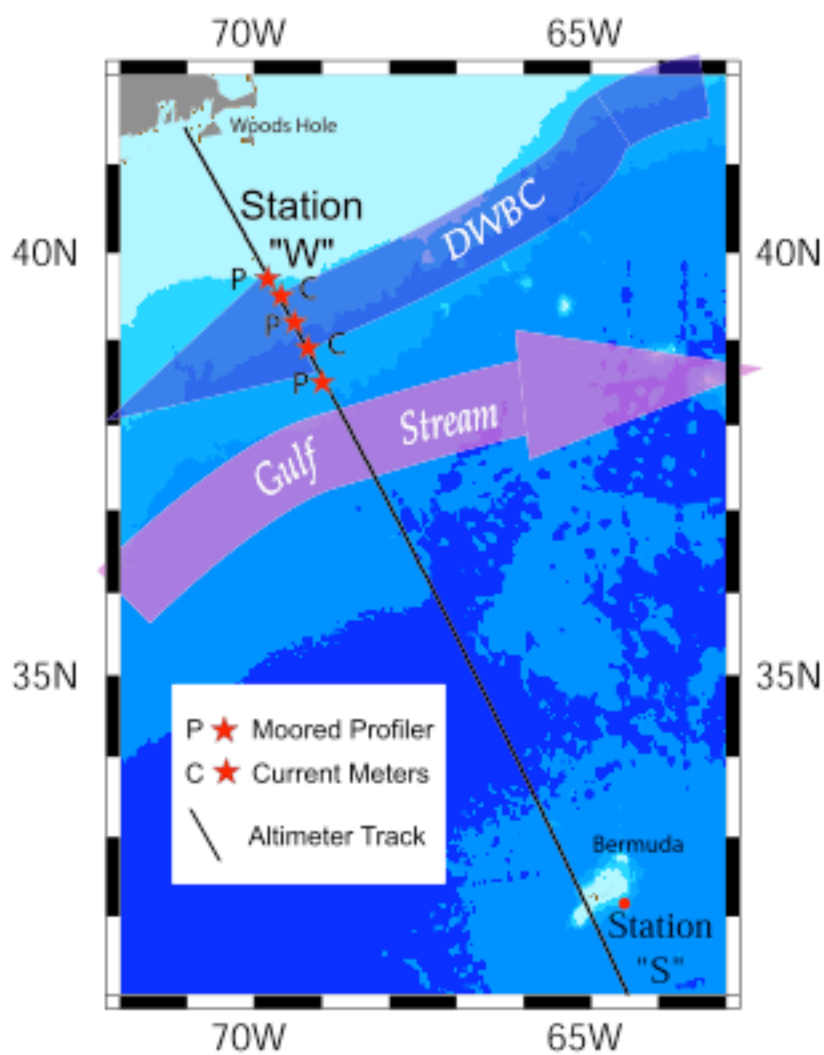
129I/CFC-11 Input (DSOW)
129I/CFC-11 (DSOW) - Lab. Sea
129I/CFC-11
Year
0
10
20
30
1995
2000
2005
2010

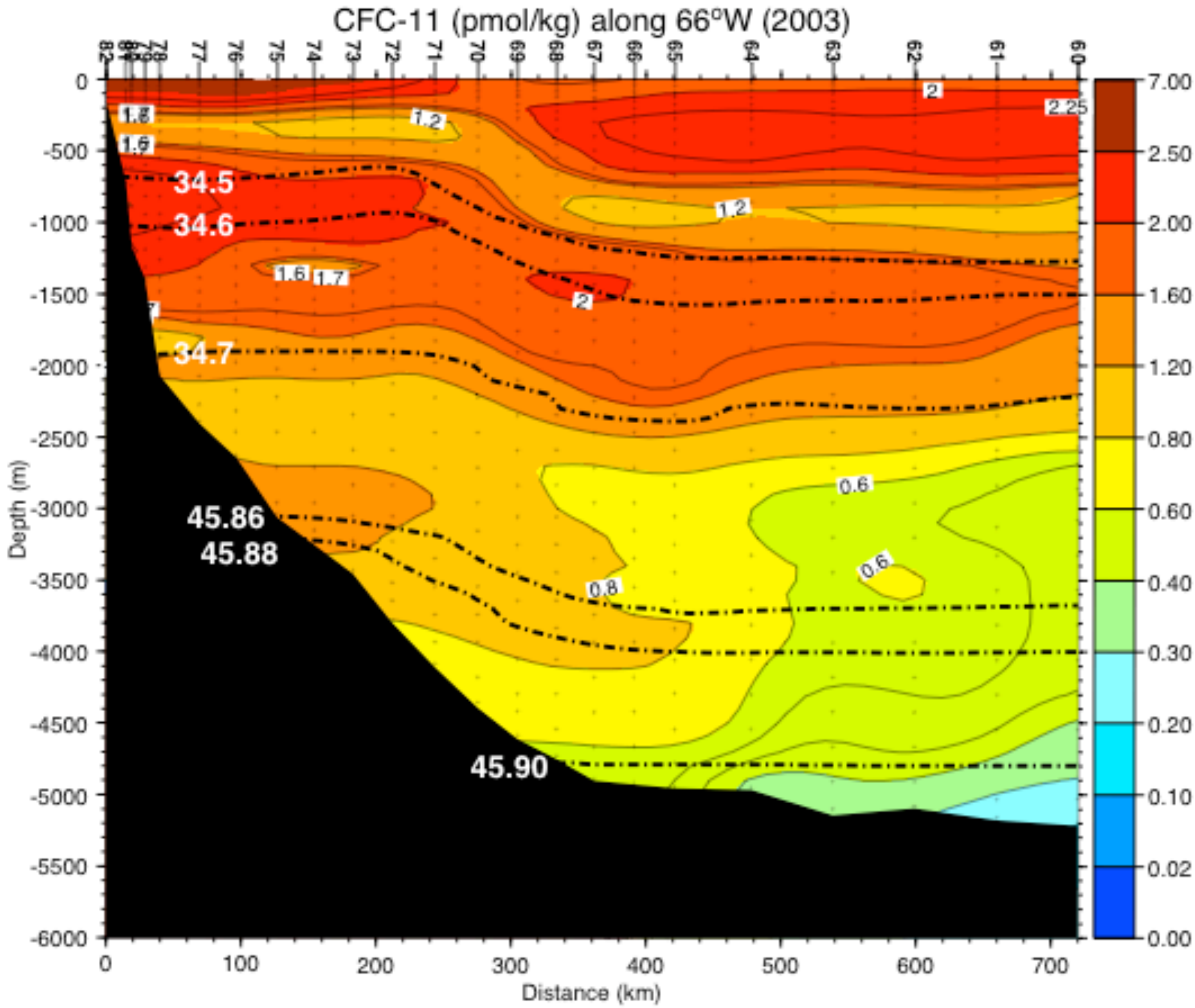


Smith et al., *JGR*, 2005

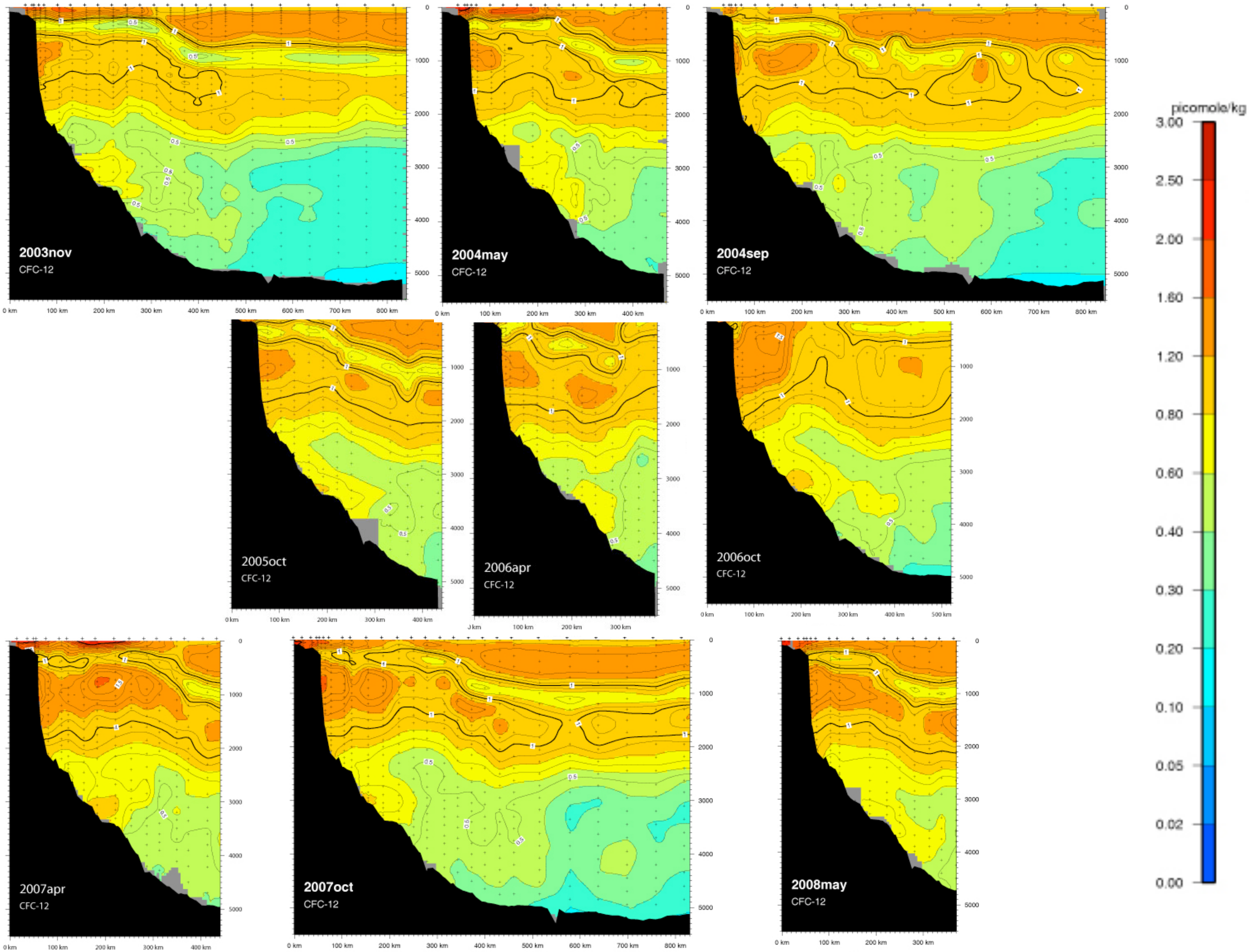


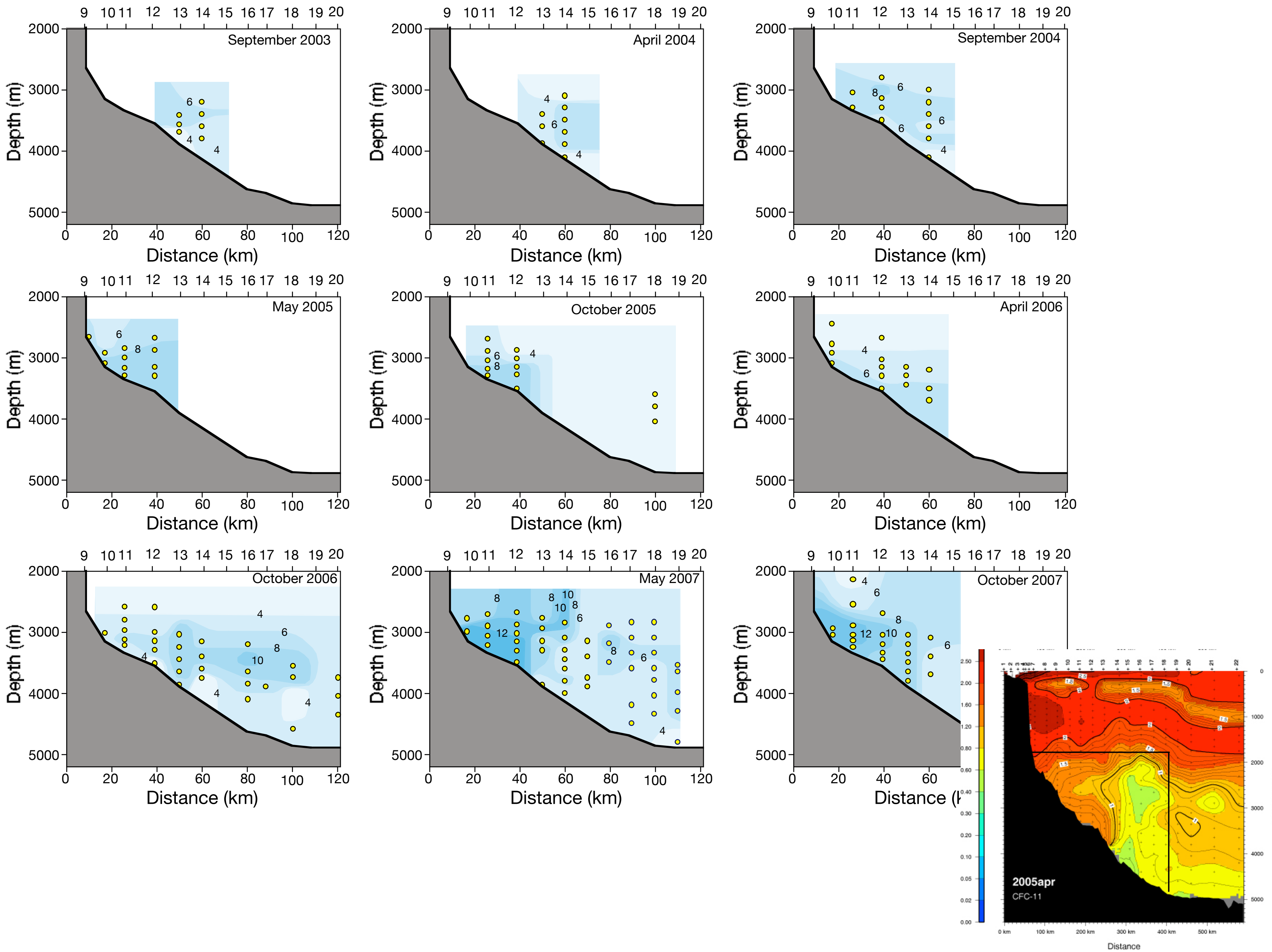
60°
30°
0°
70°
60°
50°
40°
30°
EGC
Greenland
Norwegian Sea
Iceland
DSOW
ISOW
Labrador Sea
23
20
17
14
11
Canada
Sellafield
La Hague
United States
DWBC
2
10
14
20
Line W
N


70W
65W
40N
35N
Woods Hole
Station
"W"
DWBC
P
C
P
C
P
Gulf
Stream
P Moored Profiler
C Current Meters
Altimeter Track
Bermuda
Station
"S"



CFC-11 (pmol/kg) along 66°W (2003)
Depth (m)
Distance (km)
34.5
34.6
34.7
45.86
45.88
45.90

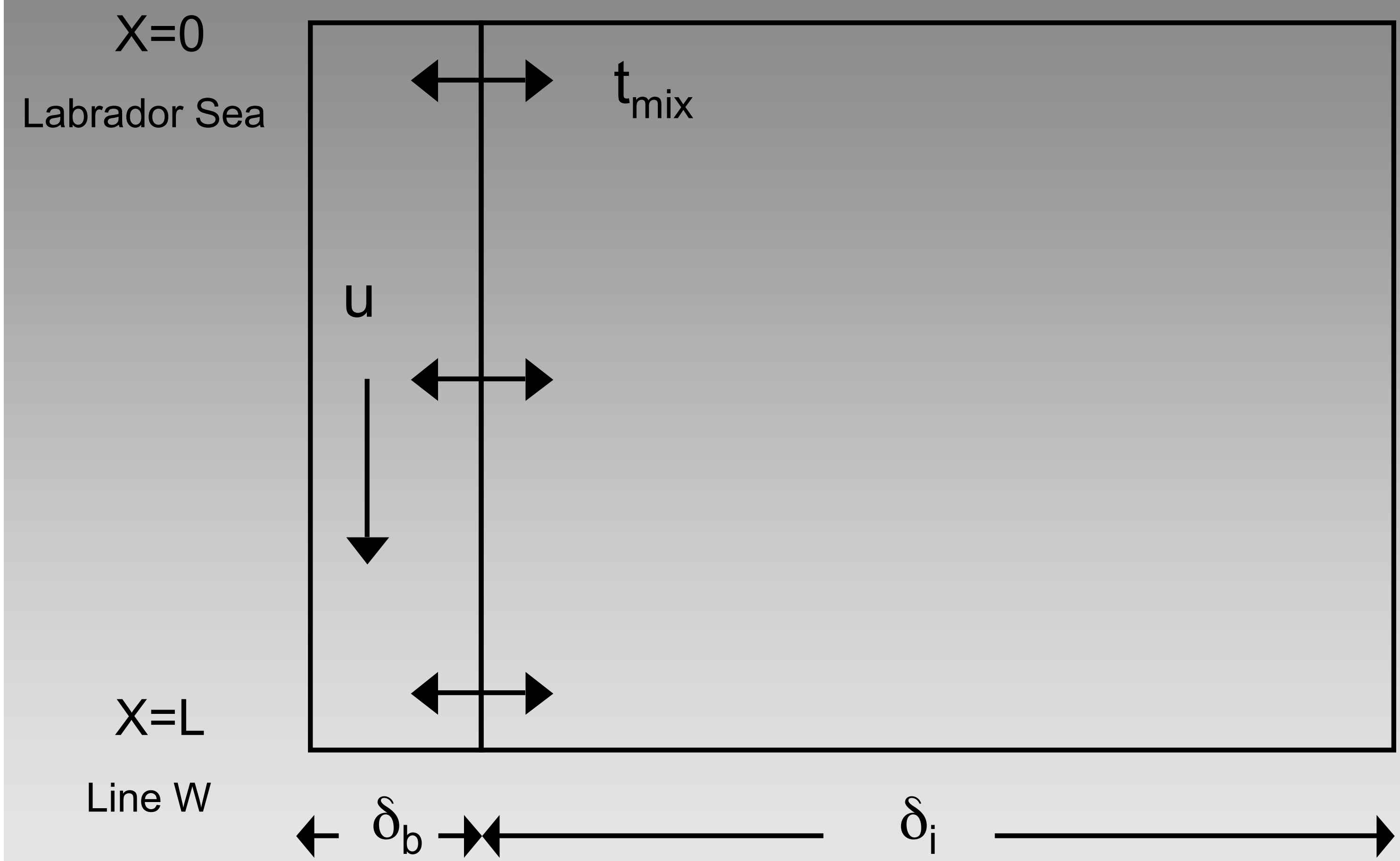

2003nov
CFC-12
2004may
CFC-12
2004sep
CFC-12
2005oct
CFC-12
2006apr
CFC-12
2006oct
CFC-12
2007apr
CFC-12
2007oct
CFC-12
2008may
CFC-12
picomole/kg
3.00
2.50
2.00
1.60
1.20
0.80
0.60
0.40
0.30
0.20
0.10
0.05
0.02
0.00



September 2003
April 2004
September 2004
May 2005
October 2005
April 2006
October 2006
May 2007
October 2007
Depth (m)
Distance (km)
9 10 11 12 13 14 15 16 17 18 19 20
2005apr
CFC-11
Pressure (db)
Distance

Boundary Current Model

Waugh and Hall, JPO, 2005



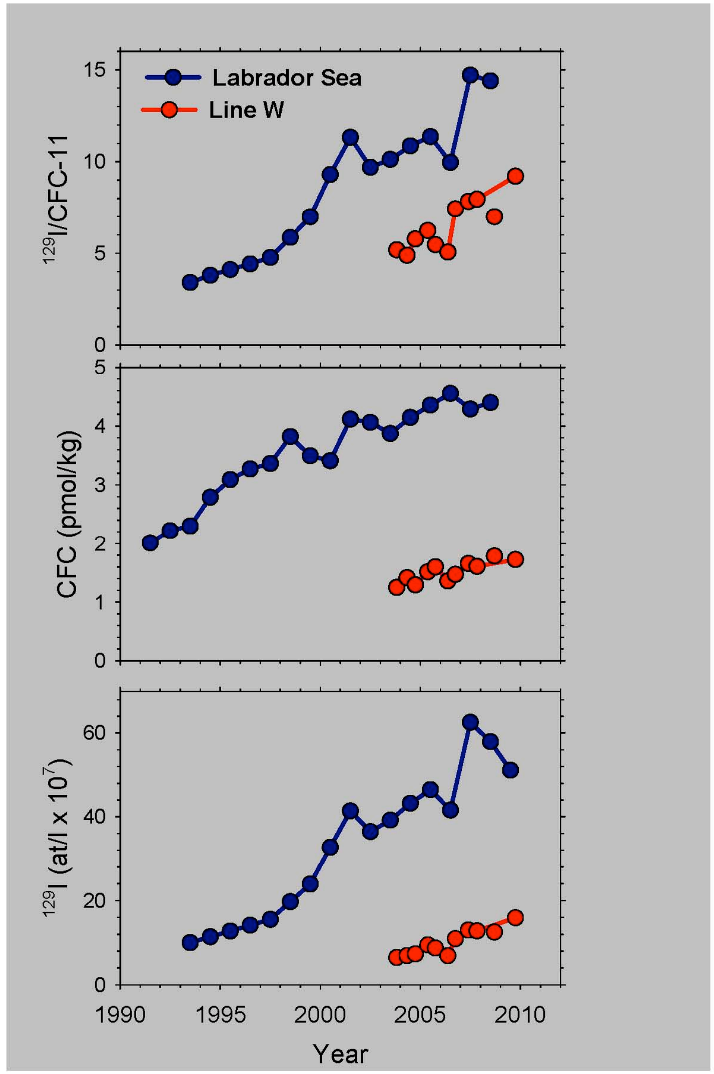
Core has uniform flow, u; interior has zero flow; mixing between regions is parameterized as relaxation with time scale, t_{mix}; $\alpha = \delta_b/\delta_i$ (= 0.1 in DWBC).

Tracer continuity equations:

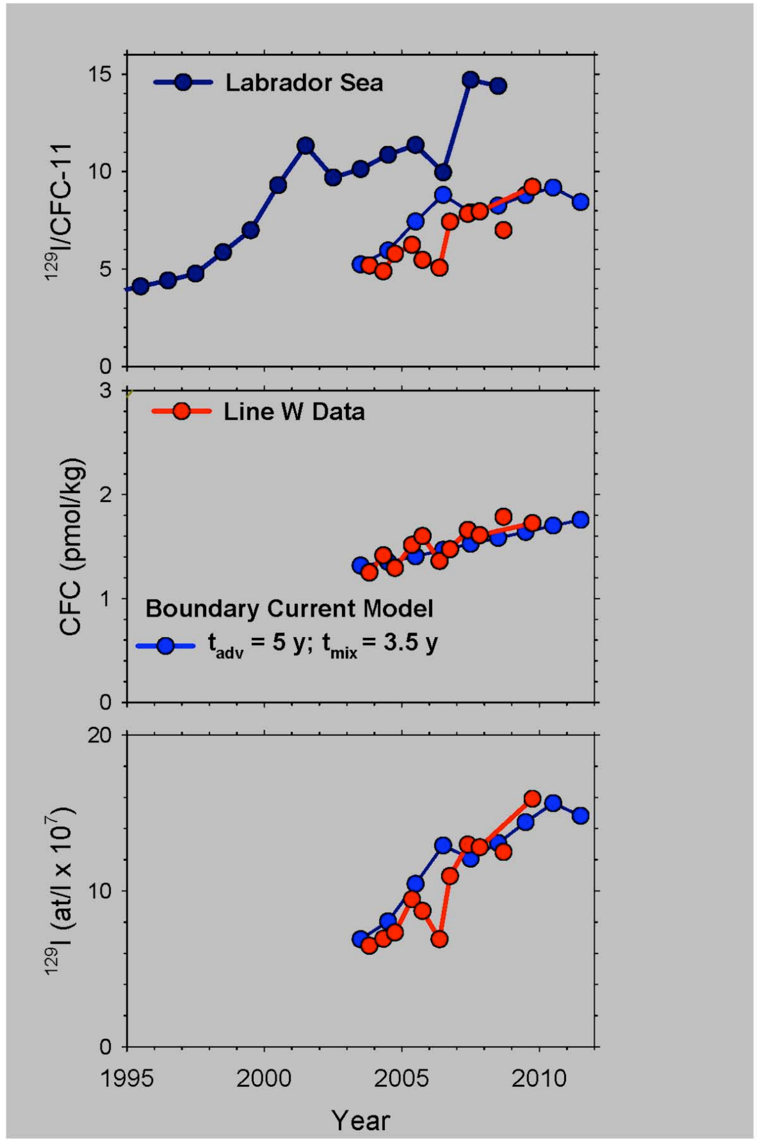
$$\frac{\partial c_b}{\partial t} + u\frac{\partial c_b}{\partial x} + \frac{1}{t_{mix}}(c_b - c_i) = S$$

$$\frac{\partial c_i}{\partial t} - \frac{\alpha}{t_{mix}}(c_b - c_i) = S$$

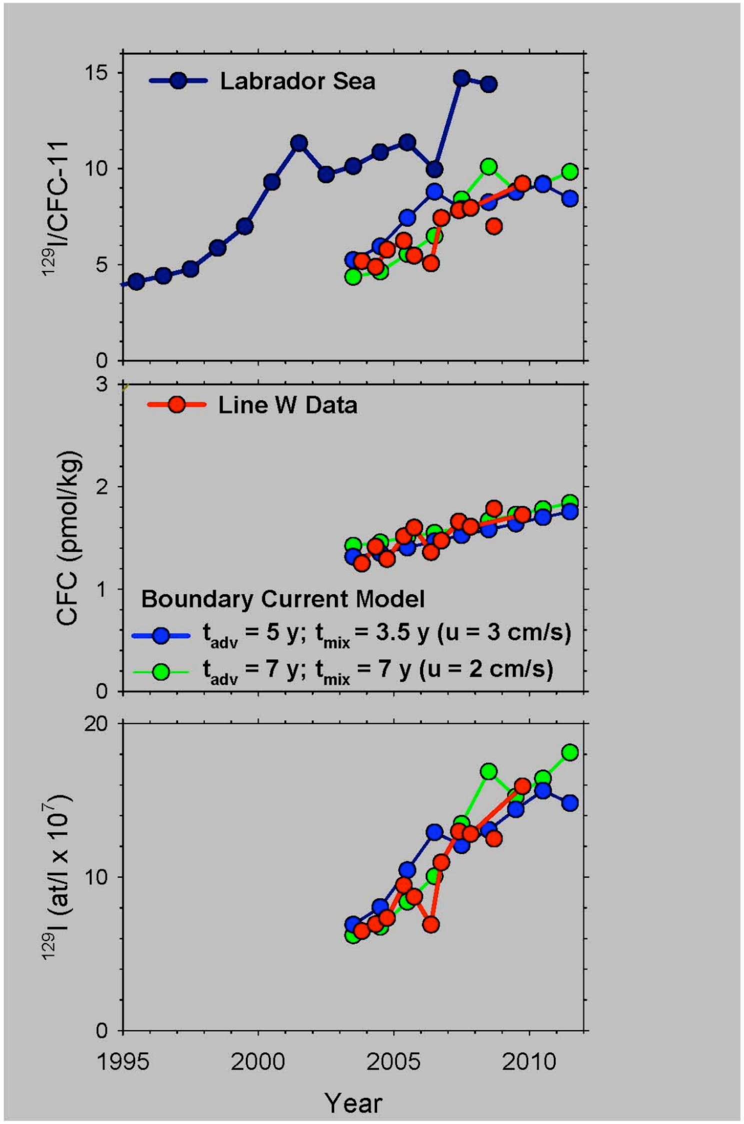
C_b and C_i are tracer concentrations in boundary current and interior, respectively; S is tracer source or sink. Similar to Pickart et al. (1989); Rhein (1994); Doney and Jenkins, 1994.



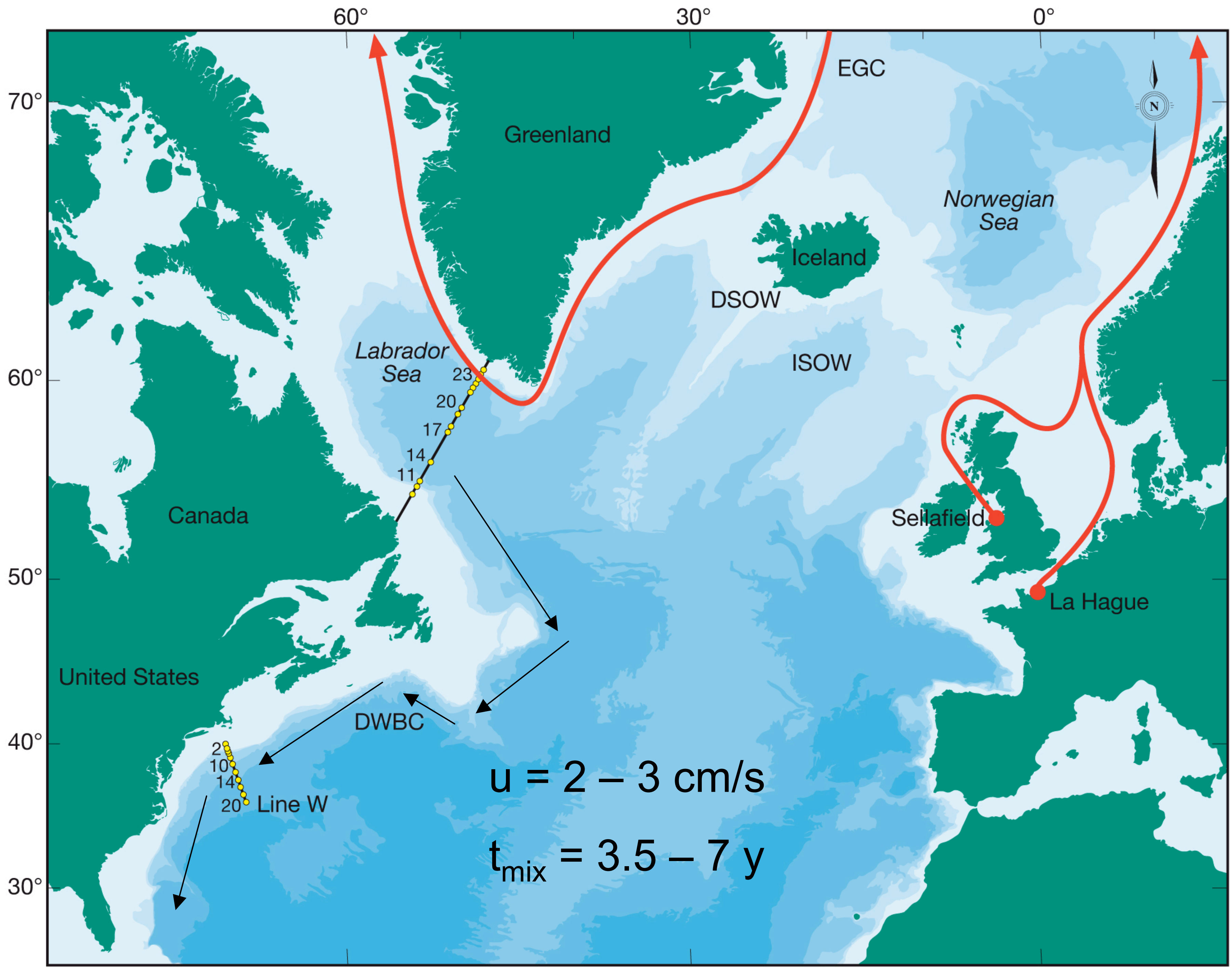
Labrador Sea
Line W
^{129}I/CFC-11
CFC (pmol/kg)
^{129}I (at/l x 10^7)
Year
0
5
10
15
1
2
3
4
20
40
60
1990
1995
2000
2005
2010



Labrador Sea
$^{129}I/CFC\text{-}11$
Line W Data
CFC (pmol/kg)
Boundary Current Model
t_{adv} = 5 y; t_{mix} = 3.5 y
^{129}I (at/l x 10^7)
Year



Labrador Sea
^{129}I/CFC-11
Line W Data
CFC (pmol/kg)
Boundary Current Model
t_{adv} = 5 y; t_{mix} = 3.5 y (u = 3 cm/s)
t_{adv} = 7 y; t_{mix} = 7 y (u = 2 cm/s)
^{129}I (at/l x 10^{7})
Year



60°
30°
0°
70°
60°
50°
40°
30°
EGC
Greenland
Norwegian Sea
Iceland
DSOW
ISOW
Labrador Sea
23
20
17
14
11
Canada
Sellafield
La Hague
United States
DWBC
2
10
14
20
Line W
u = 2 – 3 cm/s
t_{mix} = 3.5 – 7 y

Conclusions

- Boundary current model advection times (t_{adv}) of 5–7 y (u = 3 and 2 cm/s, respectively) and mixing times (t_{mix}) of 3.5–7 y (intermediate to low mixing regimes) are all consistent with ^{129}I/CFC-11 results for the DWBC at Line W and the Labrador Sea.
- Values of u = 5 cm/s; t_{mix} = 1 y are consistent with best-fit values in models of Pickart et al., 1989; Doney and Jenkins, 1994; core velocity is similar to mean velocities from direct measurements. However, other tracer studies imply lower spreading rates.
- Line W ^{129}I/CFC-11 results (2010-2012) will further constrain advection and mixing times.

Transit Time Distributions for Boundary Current Model:

$$c(x,t) = \int_0^\infty c_0(t-t')G(x,t')dt'$$

$c_0(t)$ = time varying, tracer concentration at r = 0
$c(x, t)$ = interior tracer concentration
$G(x, t)$ is the TTD at location x

$$G(x,t) = G_1\delta(t-t_{adv}) + G_2\Theta(t-t_{adv})$$

$$G_1 = e^{-t_{adv}/t_{mix}}$$

$$G_2 = \frac{\alpha}{\zeta t_{mix}} e^{-(1+\zeta^2)t_{adv}/t_{mix}} I_1(2\zeta t_{adv}/t_{mix})$$

$t_{adv} = x/u$ = advective time to reach point x

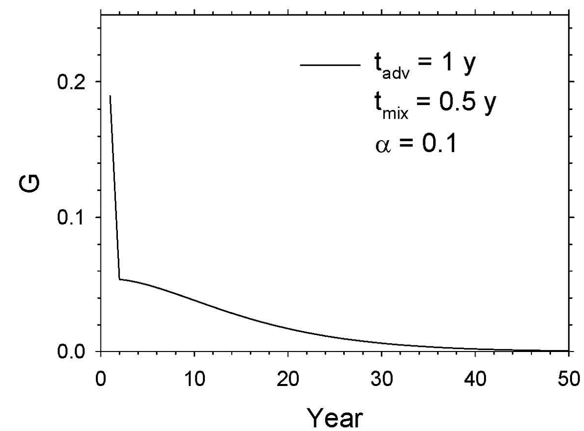
$\zeta^2 = (\alpha u/x)(t - x/u)$

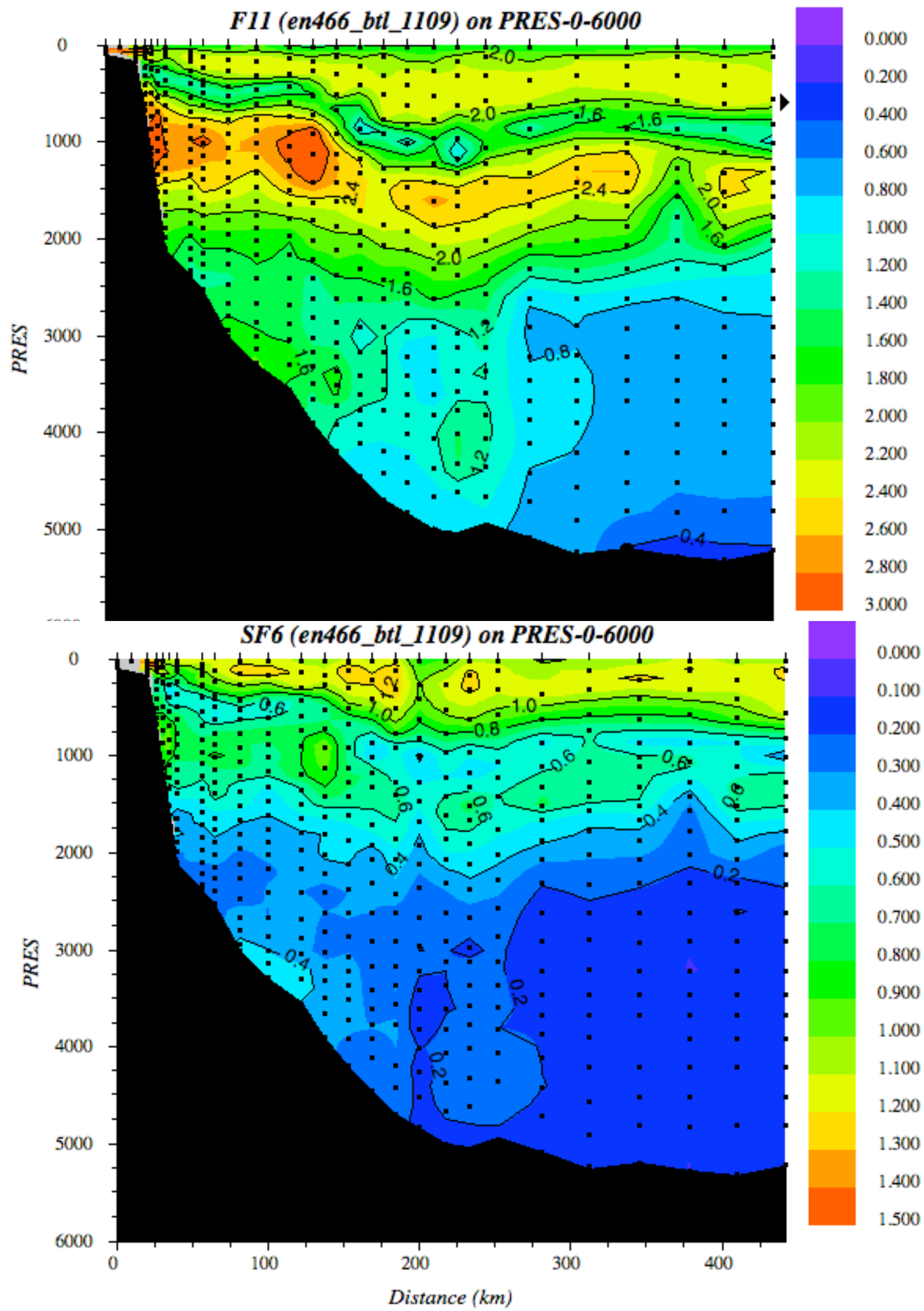
I_1 = modified Bessel function of first order,

δ = Dirac delta function

Θ = Heaviside function

Waugh and Hall JPO 2005




F11 (en466_btl_1109) on PRES-0-6000
SF6 (en466_btl_1109) on PRES-0-6000
PRES
Distance (km)
0.000
0.200
0.400
0.600
0.800
1.000
1.200
1.400
1.600
1.800
2.000
2.200
2.400
2.600
2.800
3.000
0.100
0.300
0.500
0.700
0.900
1.100
1.300
1.500

Transit Time Distributions for Boundary Current Model:

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$c_0(t)$ = time varying, tracer concentration at r = 0
c(x, t) = interior tracer concentration
G(x, t) is the TTD at location x

$$G(x,t) = G_1\delta(t-t_{adv}) + G_2\Theta(t-t_{adv})$$

$$G_1 = e^{-t_{adv}/t_{mix}}$$

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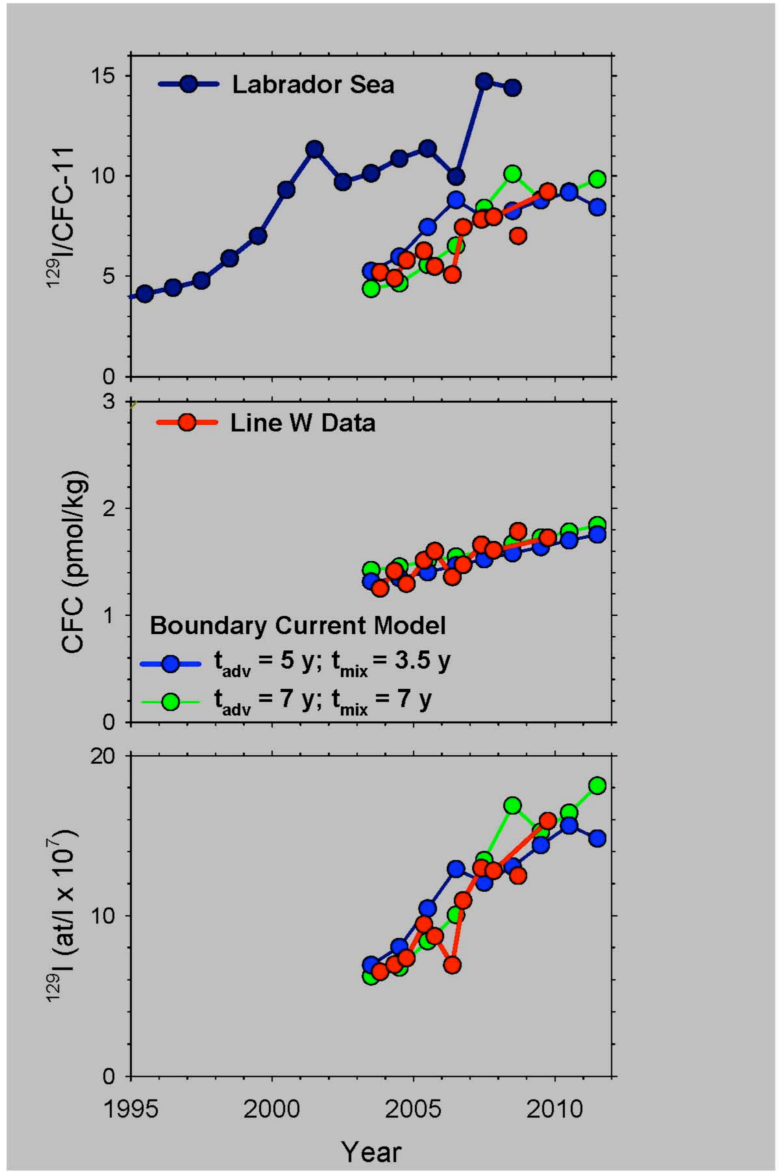
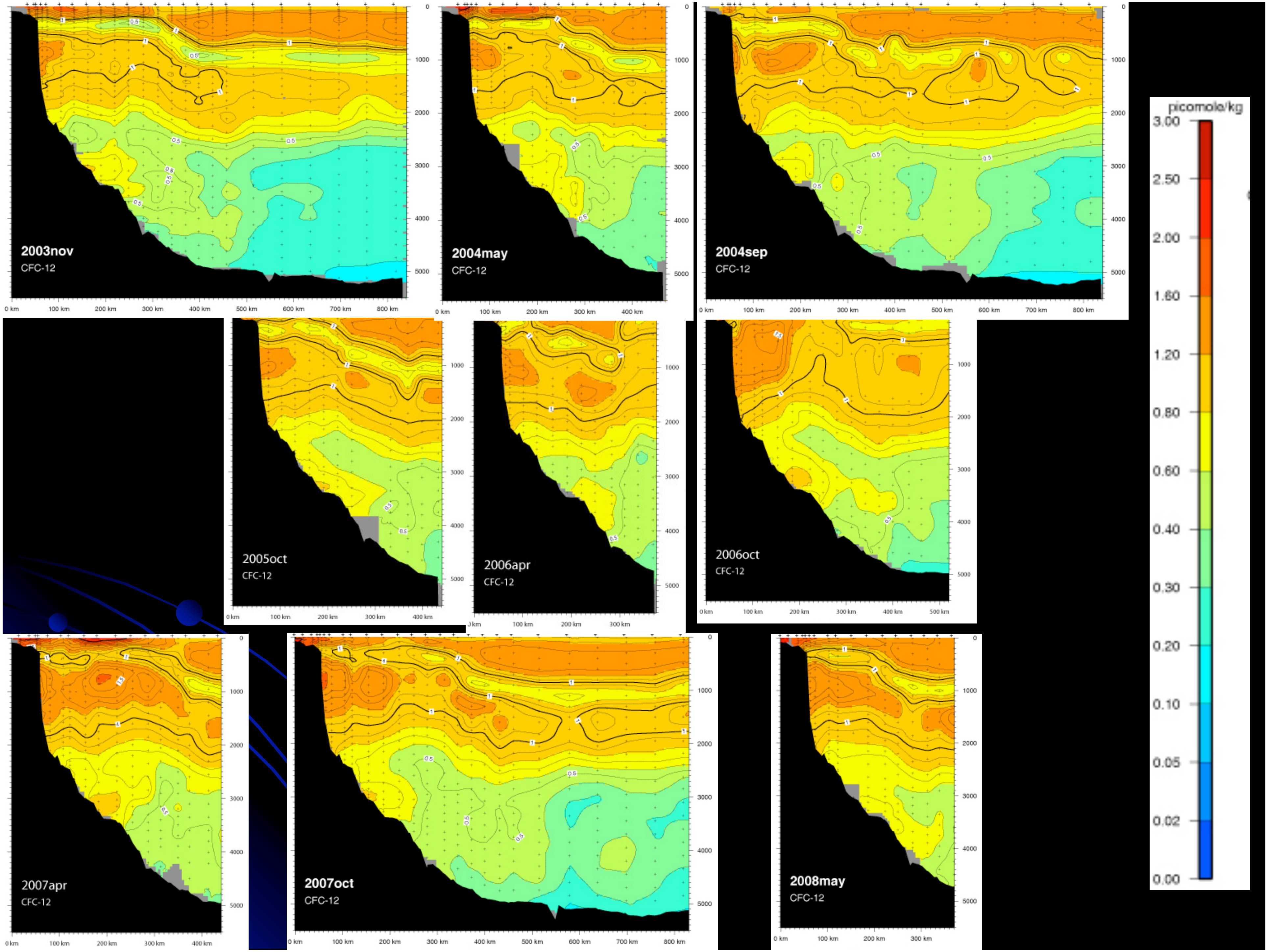
Waugh and Hall JPO 2005


Labrador Sea
^{129}I/CFC-11
Line W Data
CFC (pmol/kg)
Boundary Current Model
t_{adv} = 5 y; t_{mix} = 3.5 y
t_{adv} = 7 y; t_{mix} = 7 y
^{129}I (at/l x 10^7)
Year
1995
2000
2005
2010


2003nov
CFC-12
2004may
CFC-12
2004sep
CFC-12
2005oct
CFC-12
2006apr
CFC-12
2006oct
CFC-12
2007apr
CFC-12
2007oct
CFC-12
2008may
CFC-12
picomole/kg
3.00
2.50
2.00
1.60
1.20
0.80
0.60
0.40
0.30
0.20
0.10
0.05
0.02
0.00