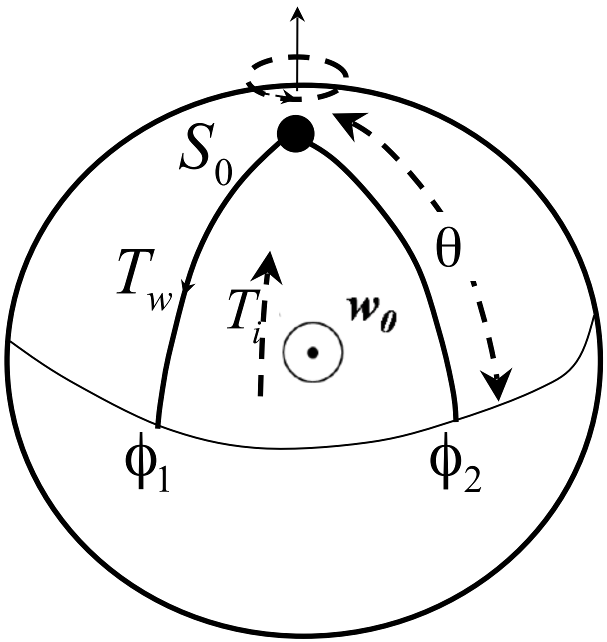
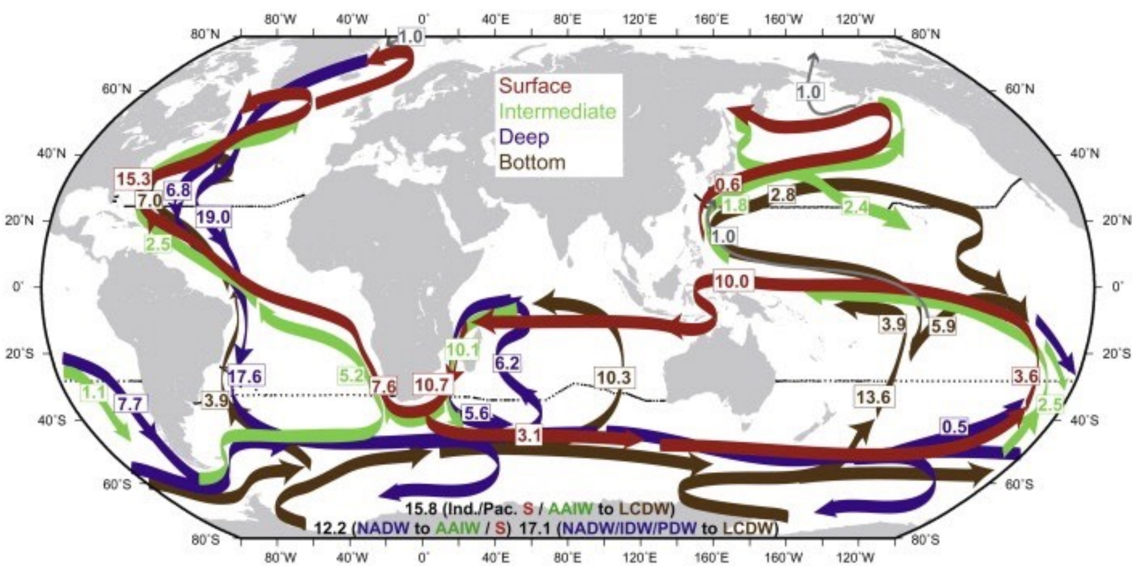
Department of Physics
University of Athens

# 8. Deep convection and the thermohaline circulation

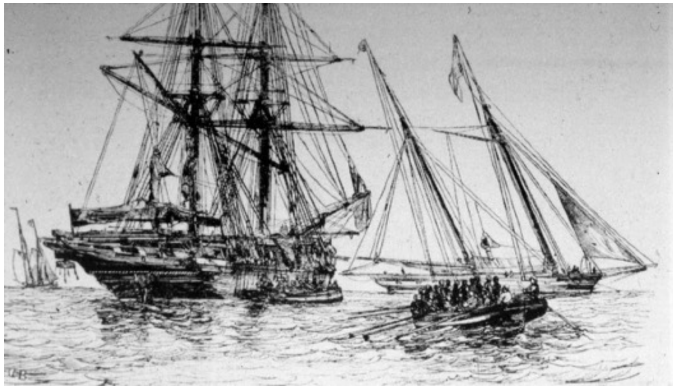



## 8. Η δημιουργία βαθιών νερών και η θερμοαλατική κυκλοφορία

- Βαθιές υδάτινες μάζες - Deep water masses
- Δημιουργία βαθιών νερών - Deep convection
- Θερμοαλατική κυκλοφορία - Thermaohaline circulation




Σ. Σοφιανός & Β. Βερβάτης



1721-1806

In 1751 **Henry Ellis**, the captain of a slave-trading ship, on his route from Africa to America, stopped at the tropical Atlantic and made deep water measurements (asked by the English Reverend Stephen Hales, using wooden bucket equipped with valves to capture water at selected depths). In his letter, he reported that

*"the cold increased regularly, in proportion to the depths, till it descended to 3900 feet: from whence the mercury in the thermometer came up at 53 degrees (*11.67$^{o}$C) …*
*The warmth of the water upon the surface, and that of the air , was at that time by the thermometer 84 degrees (*28.89$^{o}$C)."*

…

*"This experiment, which seem'd at first by mere food for curiosity, became in the interim very useful to us. By its means we supplied our cold bath, and cooled our wines or water at pleasure; which is vastly agreeable to us in the burning climate"*

(Ellis, 1751)



in which I cannot perfectly agree with him, I think ſcarce any body is better acquainted with the ſubject of electricity than himſelf.

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XXXII. *A Letter to the Rev. Dr.* Hales, *F.R.S. from Captain* Henry Ellis, *F.R.S. dated* Jan. 7, 1750-51, *at* Cape Monte Africa, *Ship* Earl of Hallifax.

SIR,

Read June 13. 1751.

I MAKE uſe of this opportunity of writing to you, leſs from the vanity I have of having ſuch a correſpondent, than the deſire of contributing to his ſatisfaction, who eſteems it his greateſt happineſs to promote the intereſt of mankind. At yours and Lord Hallifax's recommendation, I had your ventilators fixed on board of my ſhip, at Briſtol. The following is a detail of the experiments, which I made to prove their utility.

1. I took a wax-candle, of eight to the pound, and drew it thro' a mold, to make it of one thickneſs from end to end: then weighed it exactly, and lighted it in the ſhip's hold; where I found it waſted 67 grains in 30 minutes; that place not being ventilated during 24 hours: but after ſix hours ventilation it waſted $94+\frac{1}{2}$ grains in the ſame time.

2. I carried with me into the hold a plate of ſilver, well poliſhed, and a lantern and candle, all blinded, except a round hole of about two inches diameter. I placed the plate at ſix feet diſtance from it; and with

 ſuch



ſuch obliquity, that the rays from the light ſhould fall on its ſurface at an angle of 45 degrees. I then fixed a white paper ſcreen, at the ſame diſtance from the plate, and under the ſame angle with the lantern, ſo that the reflected rays might fall upon it alſo. This being done, I obſerved, that the reflection from the plate diſtinctly was but 17′ 30″ with an unventilated hold; it being turned the colour of tarniſhed lead; whereas, when the air was replaced by 4 hours ventilation, it continued to reflect light, and retain its brightneſs 4 hours 47 minutes.

3. The ſhip's bell, whoſe diameter is 14 inches, I had brought into the hold, when ventilation had been omitted 12 hours. Having hung it under the lower deck, I took out the clapper; and having ſuſpended it alſo by thread, which, with its own length, made 44 inches; the angle, which the rim of the bell made, with a line let fall perpendicular from the pin, on which the clapper hung, was equal to 34′ 0″. I then held the clapper at the ſame angle, on the other ſide of the line, in order that the ſtrokes at different times might be with the ſame force; when, letting it go, it ſtruck the bell. In its return I catched it, and counting the vibrations, I heard them diſtinctly but three times; whereas, when the hold was well ventilated, it vibrated five times; but its vibrations were not ſo quick in the latter, as in the former caſe. I took all poſſible precautions, that theſe experiments might be fairly tried, to prevent deception; but always found them to produce the ſame effects.

We are at preſent very healthy, tho' our number is 130, not one being ſick aboard. Our hold, which in



in moſt ſhips is very moiſt, in ours is quite dry. Our cargo arms, which are kept there in upright cheſts, without wrappers, come out as bright as from a recent poliſh. Far is a ventilator from being inconvenient aboard of us; on the contrary, 'tis good exerciſe for our ſlaves, and a means of preſerving our cargo and lives.

Upon the paſſage, I made ſeveral trials, with the bucket ſea-gage, in latitude 25′—13″ north; longitude 25′—12″ weſt. I charged it, and let it down to different depths, from 360 feet to 5346 feet; when I diſcovered, by a ſmall thermometer of Fahrenheit's, made by Mr. Bird, which went down in it, that the cold increaſed regularly, in proportion to the depths, till it deſcended to 3900 feet: from whence the mercury in the thermometer came up at 53 degrees; and tho' I afterwards ſunk it to the depth of 5346 feet, that is a mile and 66 feet, it came up no lower. The warmth of the water upon the ſurface, and that of the air, was at that time by the thermometer 84 degrees. I doubt not but that the water was a degree or two colder, when it enter'd the bucket, at the greateſt depth, but in coming up had acquired ſome warmth; for I found, that the water, which came up in the bucket, having ſtood 43 minutes in the air (the time of winding it up) the mercury roſe above 5 degrees. When the air had render'd it equally warm with the water on the ſurface, I tried their weight, by weighing equal quantities very exactly, as alſo by the hydrometer, and found from great depths the heavieſt, and conſequently the ſalteſt water.

This



This experiment, which ſeem'd at firſt but mere food for curioſity, became in the interim very uſeful to us. By its means we ſupplied our cold bath, and cooled our wines or water at pleaſure; which is vaſtly agreeable to us in this burning climate.

I intend, in our paſſage to the Weſt Indies, to ſound a mile deeper than I have done, having a ſufficient quantity of line. But I cannot attempt your method to find the depth of the ſea, for want of apparatus. My buſineſs at preſent affords me very little time for ſpeculation. However, I cannot omit obſerving to you a phænomenon, which I ſaw laſt night, and never before, that I remember; and that was the two arches of the iris, with their colours diſtinct, by moon-light. Having already preſumed much on your patience, and my leiſure,

I am, *&c.*

Hen. Ellis.

*A Letter to the* Preſident, *from* Stephen Hales, *D. D. & F. R. S.*

SIR, Teddington, June 8, 1751.

Read June 13. 1751.

I HAVE here incloſed, at his deſire, a copy of a letter from Captain Ellis, who publiſhed an account of his voyage to Hudſon's Bay.

The bucket ſea-gage, which he mentions, and which I provided for him, to find the different degrees of coolneſs and ſaltneſs of the ſea, at different

 depths,



depths, was a common houſhold pail or bucket, with two heads in it; which heads had each a round hole in the middle, near four inches diameter, which were cover'd with valves which open'd upwards; and that they might both open and ſhut together, there was a ſmall iron rod fixed to the upper part of the lower valve, and at the other end to the under part of the upper valve: ſo that, as the bucket deſcended with its ſinking weight into the ſea, both the valves open'd by the force of the water, which had by that means a free paſſage thro' the bucket. But when the bucket was drawn up, then both the valves were ſhut by the force of the water at the upper part of the bucket: by which means the bucket was brought up full of the loweſt ſea-water, to which it had deſcended.

When the bucket was drawn up, the hole at the bottom was ſtopped with a cork, to keep the water in, when the valves were open'd, to come at the mercurial thermometer, which being tied to an upright ſtick, could readily be unfaſtened, by pulling out a looſe nail, which went into the upper end of ſtick, which was faſten'd at its lower end in the ſame manner.

But great care muſt be taken to make an obſervation of the degree the mercury ſtands at, before the lower part of the thermometer is taken out of the water; elſe it would immediately be alter'd by the different temperature of the air.

In order to keep the bucket in a right poſition, there are four cords fixed to it, which reach about three feet below it, to which the ſinking weight is to be fixed.

Captain



Captain Robinſon, who is lately arrived from India, ſays, he found ſo much benefit by ventilators, that he will never go a voyage without them; and that he loſt but two men in two years.

There are many other inſtances of the benefit of ventilators in ſhips, not only to the health and lives, but alſo to the proviſions, *&c.*

I am, Sir, with great reſpect,

Your obliged humble ſervant,

Stephen Hales.

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XXXIII. *Obſervations on the* Roman Colonies *and* Stations *in* Cheſhire *and* Lancaſhire, *by* Thomas Percival *Eſq*; *communicated by* Hugh *Lord* Willoughby *of* Parham, *F. R. S.*

Read June 13. 1751.

IN the ſecond iter of Antonine's Itinerary, we find, after ſeveral other ſtations mentioned Eboracum

Calcariam M. P. IX.
Camulodunum M. P. XX. Tho' with various
Mamucium M. P. XVIII. readings of the
Condate M. P. XVIII. names.
Devam M. P. XX.

It is agreed, that Deva is Cheſter, and that Mamucium or Manucium or Mancunium, is Mancheſter, by the common conſent of all antiquarians. But where Condate

Ellis, H. 1751. A letter to the Rev. Dr. Hales, F.R.S. from Captain Henry Ellis, F.R.S. dated Jan. 7, 1750–51, at Cape Monte Africa, Ship Earl of Halifax. Philosophical Transactions of the Royal Society of London 47:211–214.

1753-1814

Based on Ellis's temperature profile, **Count Rumford** (Sir Benjamin Thompson), an American-born British scientist, deduced a scheme of the overturning circulation. In 1800, he wrote:

*"It appears to me to be extremely difficult, if not quite impossible, to account for this degree of cold at the bottom of the sea in the torrid zone, on any other sup- position than that of cold currents from the poles."*

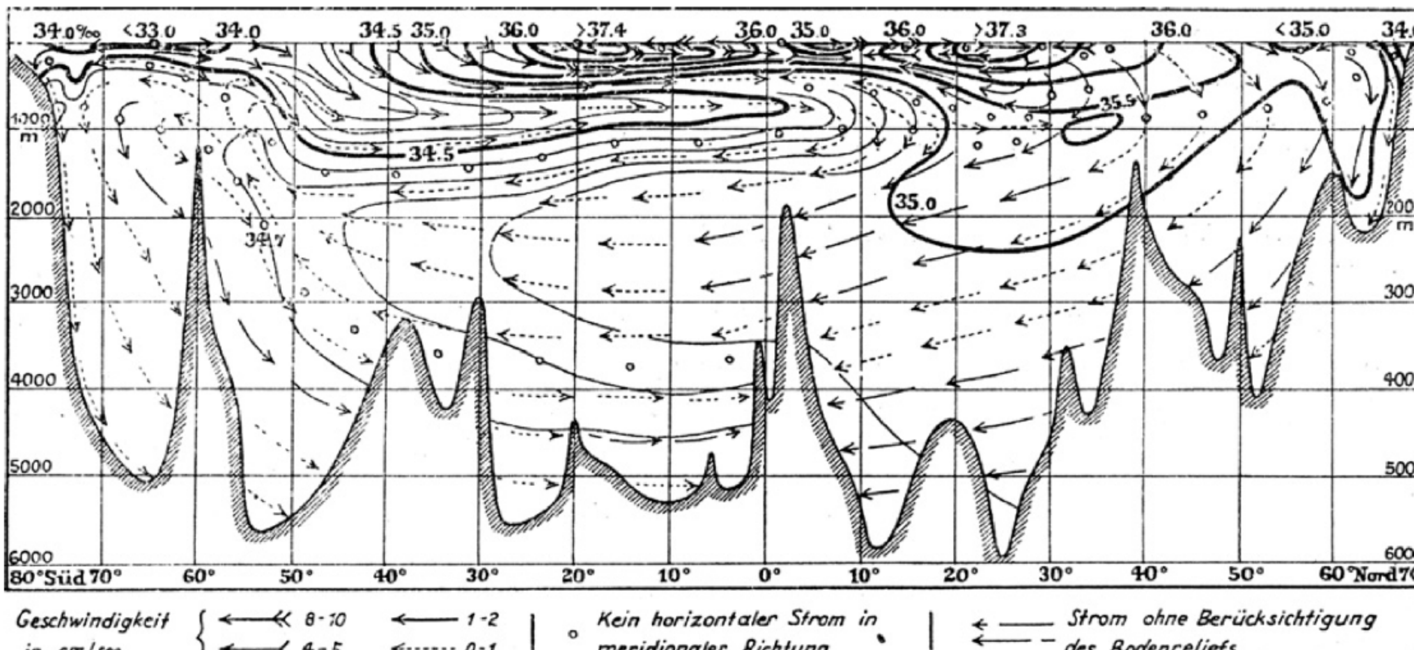
Rumford further reasoned that this cold current at depth

*"must necessarily produce a current at the surface in an opposite direction"*

(Rumford, 1800).

Measurements along 20°W during the German Atlantic **Meteor Expeditions** from 1925–1927, captured plumes of saline waters from the surface waters of the northern North Atlantic and relatively fresh waters of Antarctic origin (Merz, 1925).

METEOR





Rumford, B., Count of. 1800. Essay VII, The propagation of heat in fluids. Pp. 197–386 in Essays, Political, Economical, and Philosophical, A New Edition 2. London.

Merz, A. 1925. Die Deutsche Atlantische Expedition auf dem Vermessungs- und Forschungsschi "Meteor." Bericht. Sitzungsberichte der Preussischen Akademie der Wissenschaften, Physikalische-Mathematische Klasse:562–586.

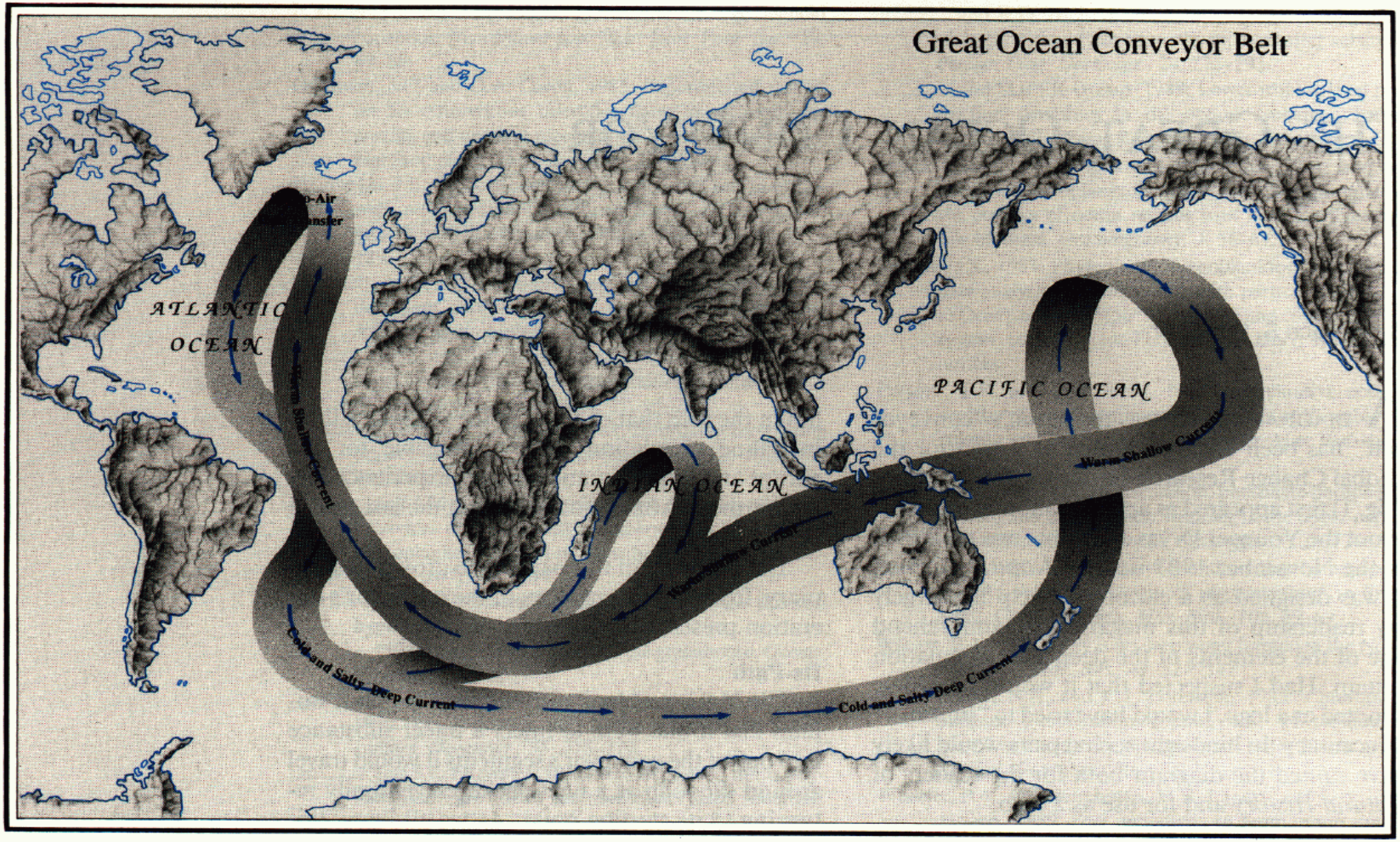
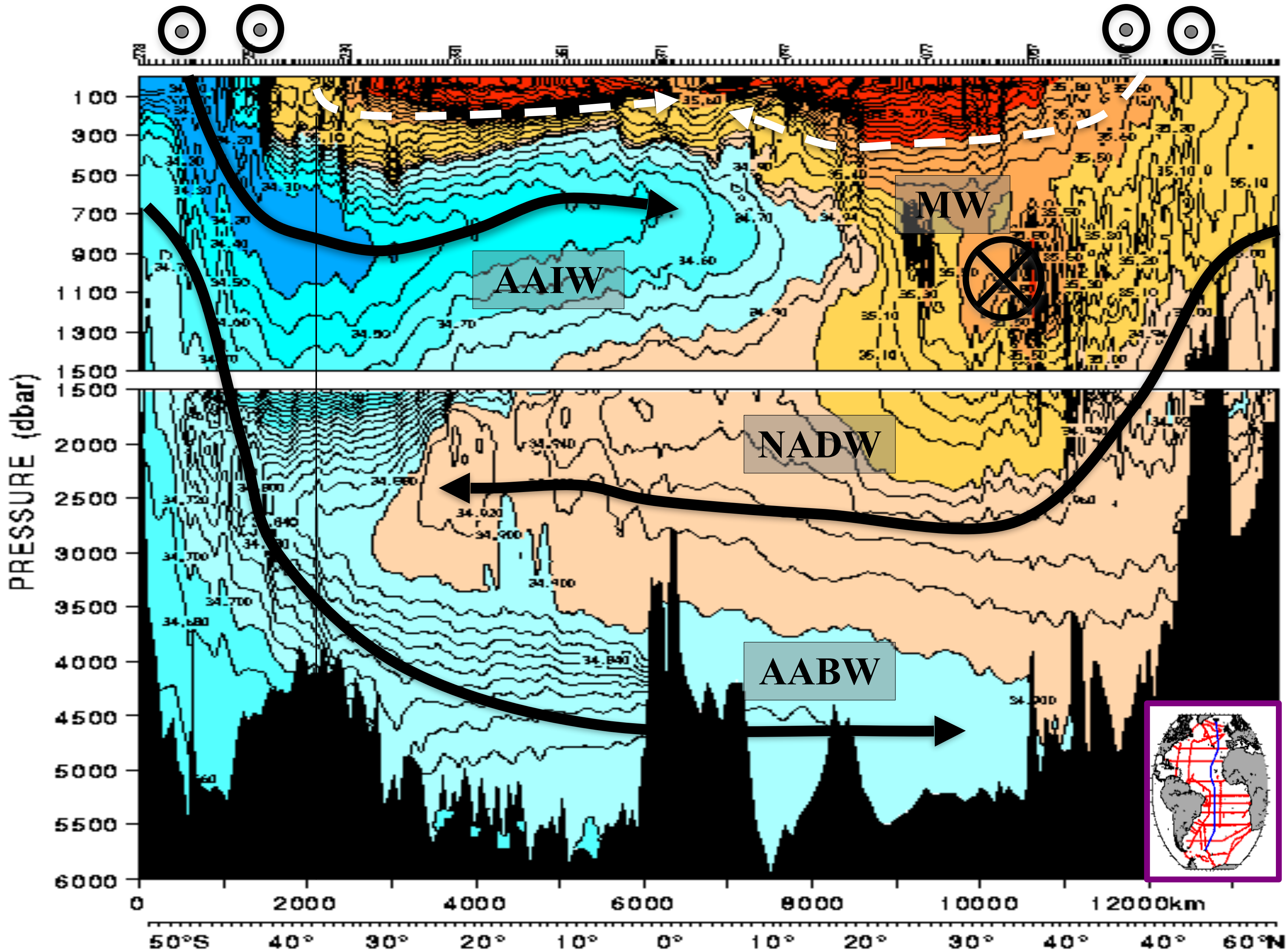
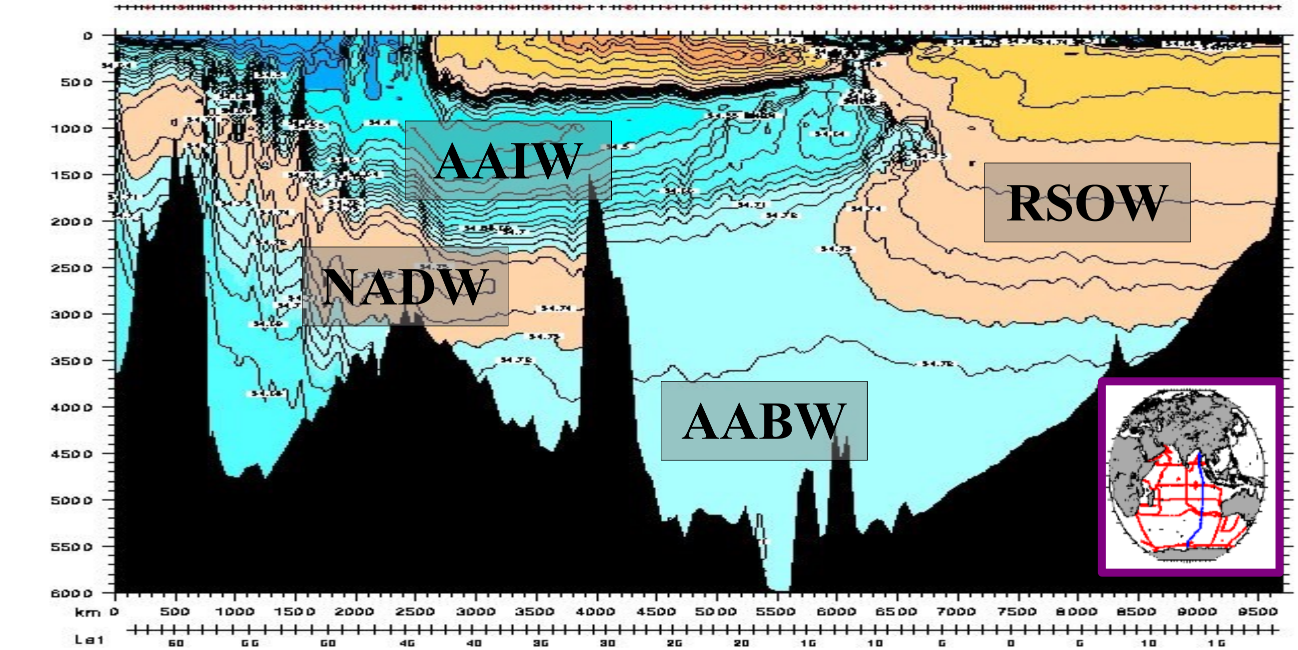



*Fig. 1: The great ocean conveyor logo (Broecker, 1987). (Illustration by Joe Le Monnier, Natural History Magazine.)*

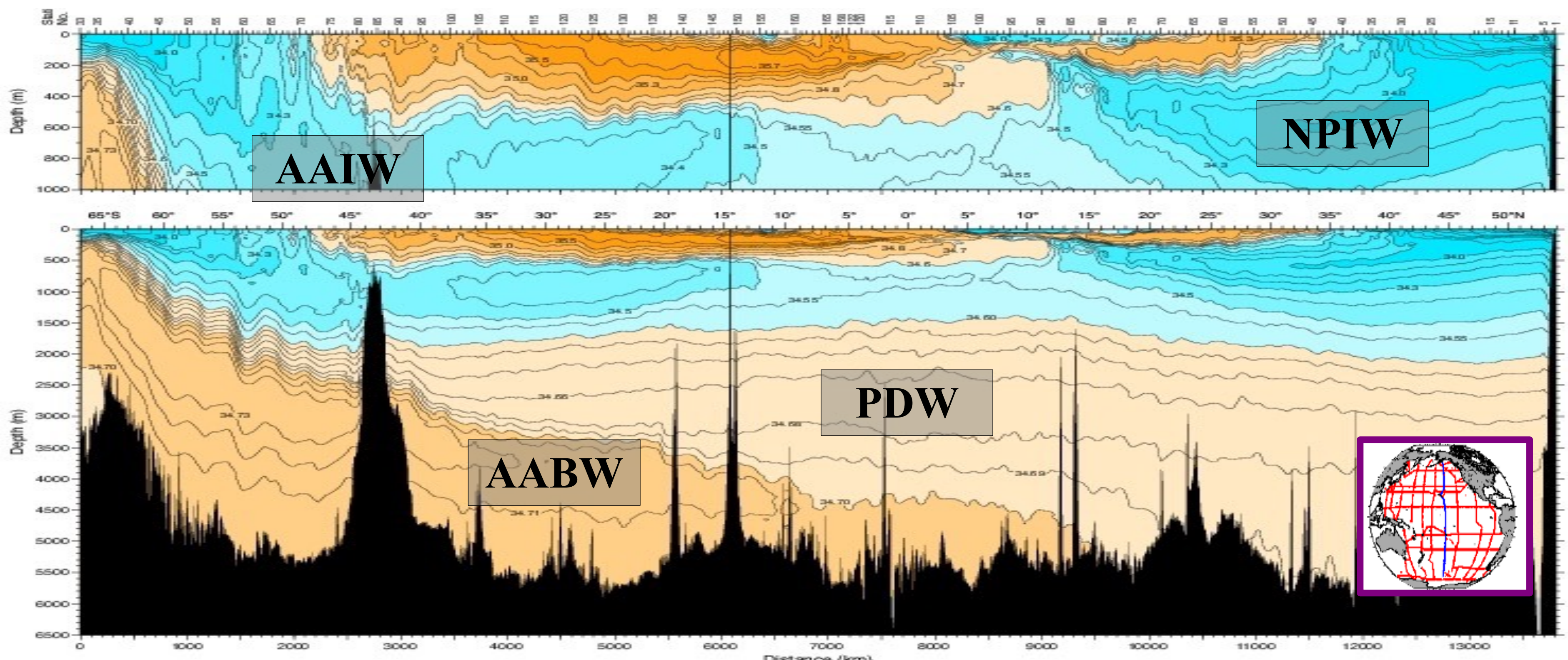
Broecker, W.S. 1987. The biggest chill. Natural History 97(10):74.

# Atlantic Main Water Masses (on salinity section)

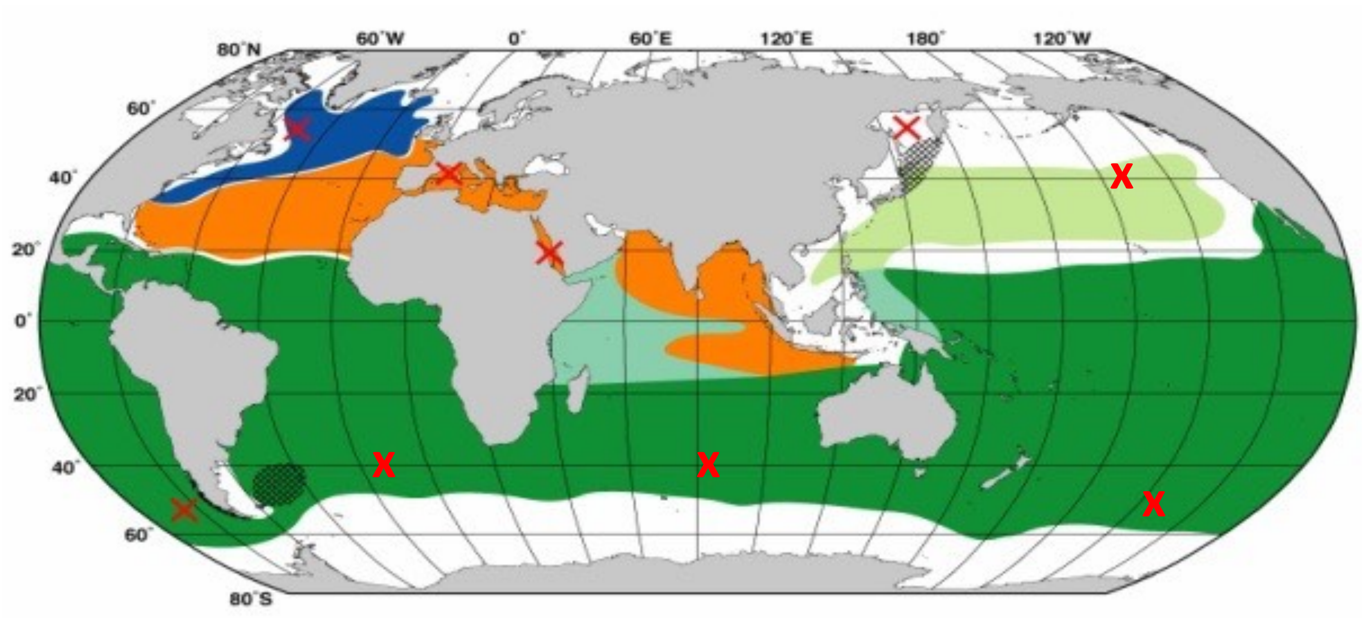





# Indian and Pacific Main Water Masses

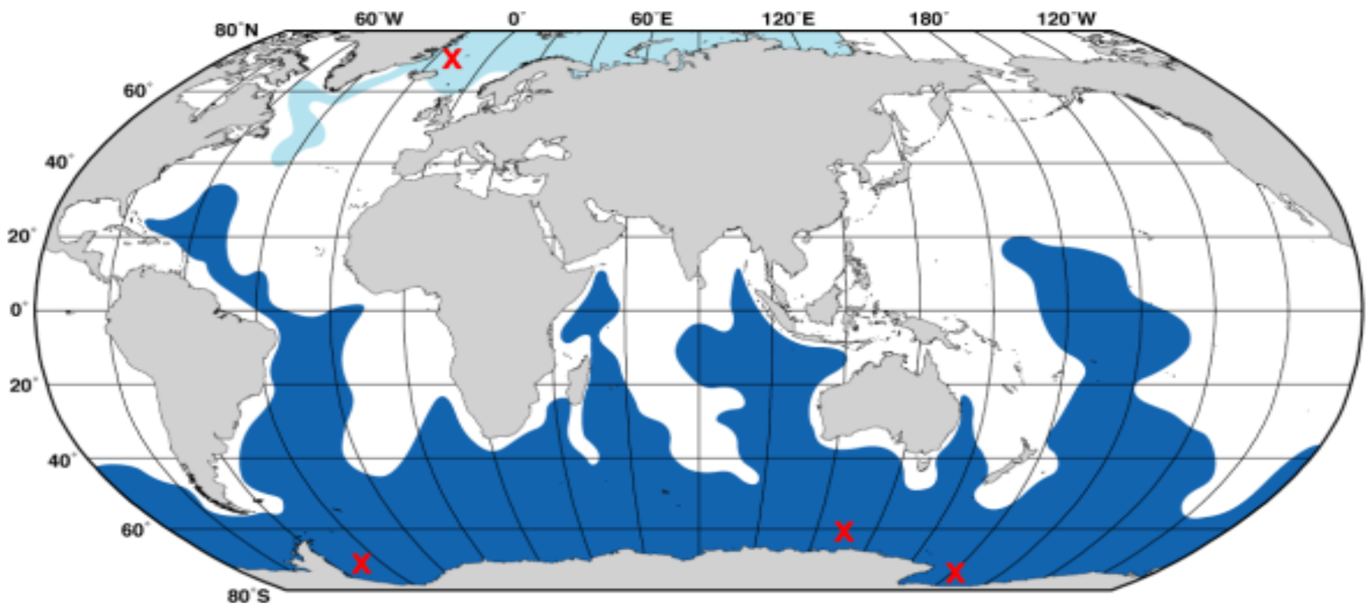


# The Water mass formation processes



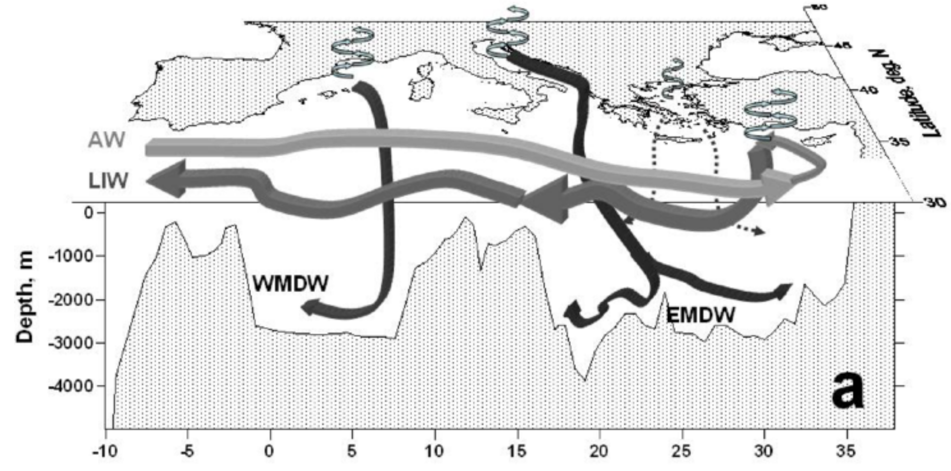

## CONDITIONS

1. Intense heat and freshwater losses
2. Relatively weak stratification
3. Trapping

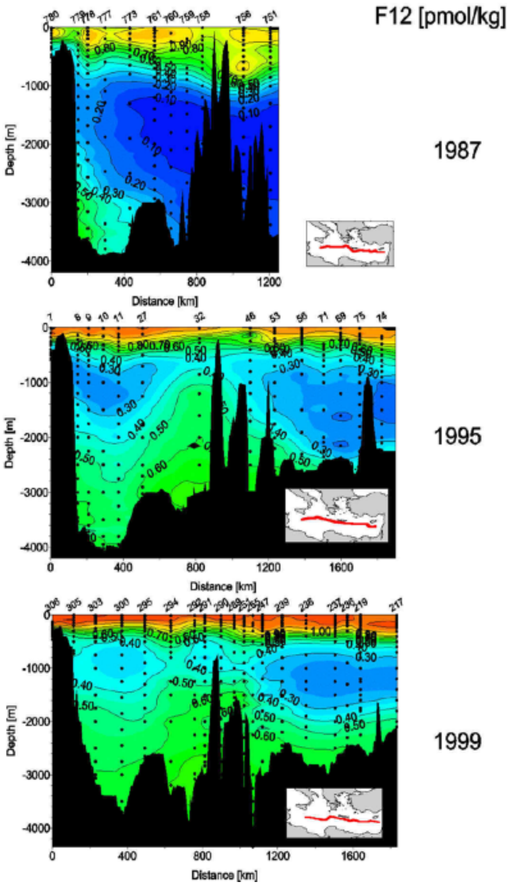


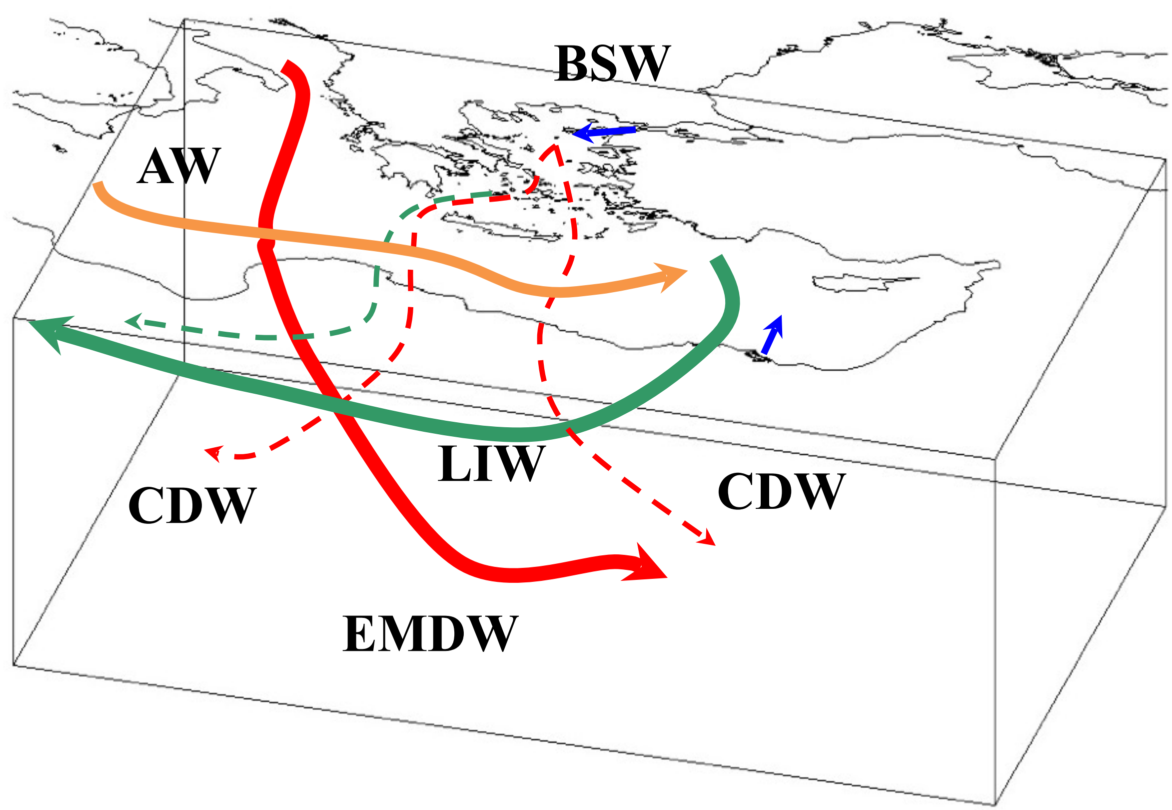

## AREAS

1. Arctic regions
2. Semi-enclosed seas
3. Continental shelf
4. Cyclonic features

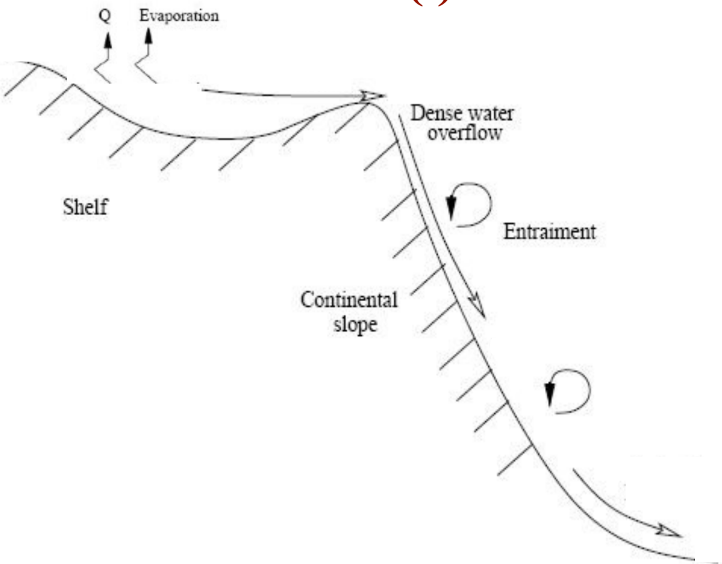


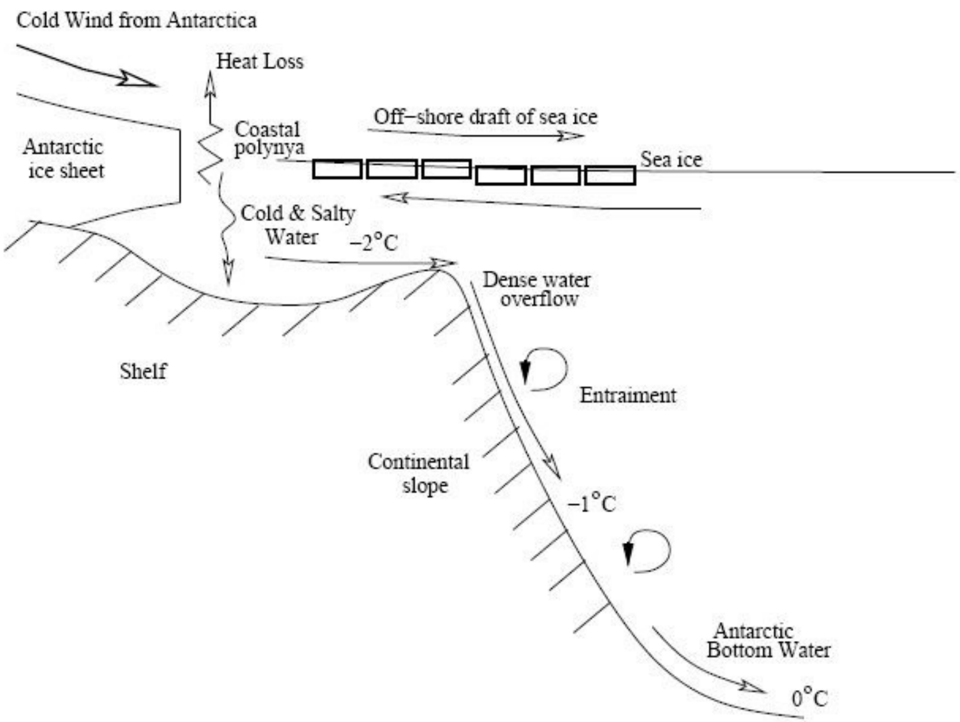

# The Mediterranean Sea water masses



# (i) Shelf convection




**Shelf water mass formation**

•Strong heat loss and/or evaporative rates over the relatively shallow water column on the continental shelf can lead to formation of very dense waters.

•Entrainment on the continental slope changes dramatically the new water mass temperature and salinity properties and gives the water mass its final characteristics.

**Arctic/Antarctic shelf water mass formation**

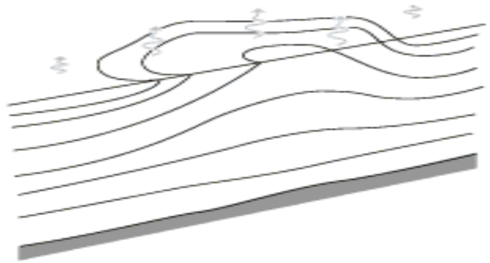
•Winds blowing offshore open the ice sheet, forming a polynya.

•Salt addition to the water column, related to ice formation increases the water salinity.

•Large heat fluxes (~1000 W m-2) from the exposed ocean drives bottom water formation.

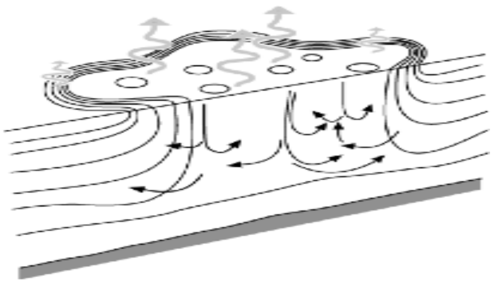
•Entrainment changes the water mass properties.

# (ii) Open ocean convection



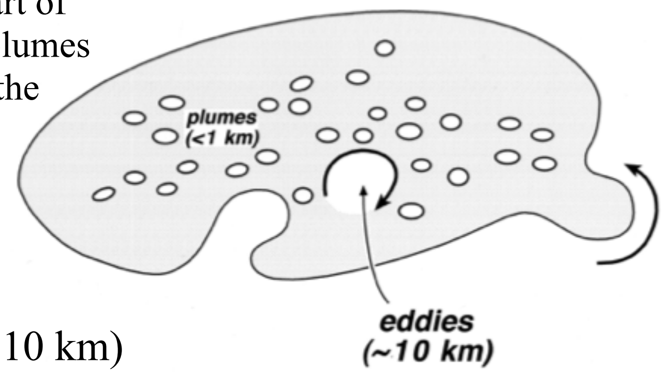
## 1. Pre-conditioning (order of 100 km)

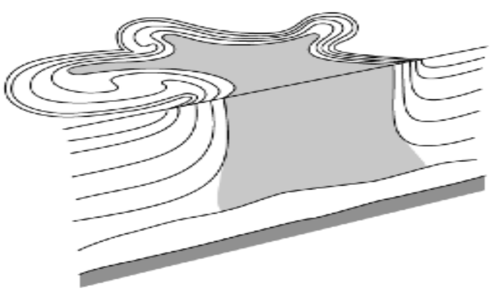
During preconditioning the gyre-scale cyclonic circulation with its “doming” isopycnals, brings weakly stratified waters of the interior close to the surface. Buoyancy loss is preconditioning the “trapped” water.



## 2. Deep convection (order of 1 km)

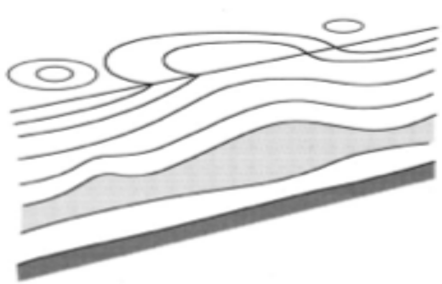
Subsequent cooling events may then initiate deep convection in which a substantial part of the fluid column overturns in numerous plumes that distribute the dense surface water in the vertical.



## 3. Lateral exchange (order of 10 km)

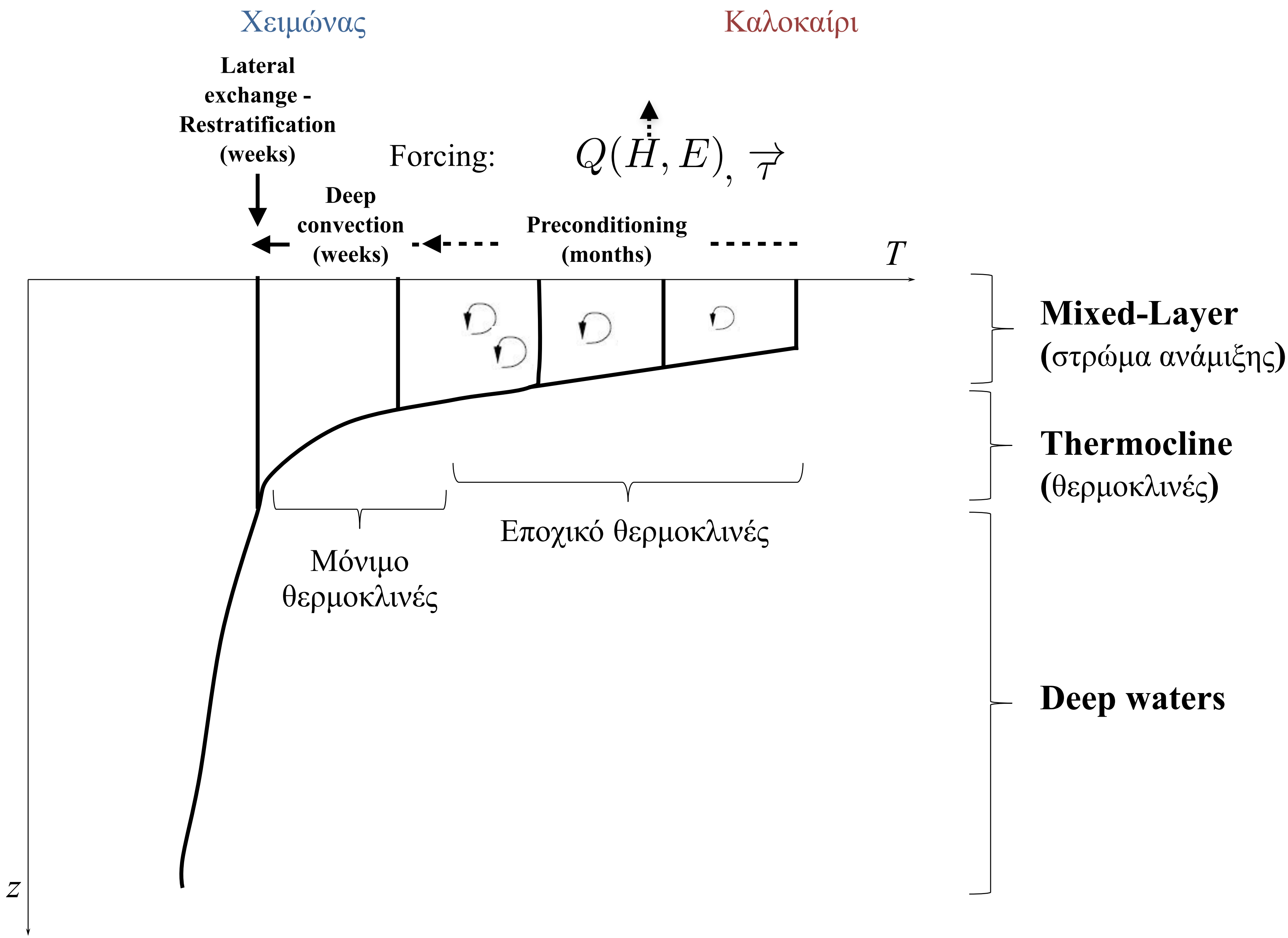
With the cessation of strong forcing, or <u>if the cooling continues for many days</u>, the predominantly vertical heat transfer on the convective scale gives way to horizontal transfer associated with eddying on geostrophic scales as the mixed patch laterally exchanges fluid with its surroundings.



## 4. Re-stratification

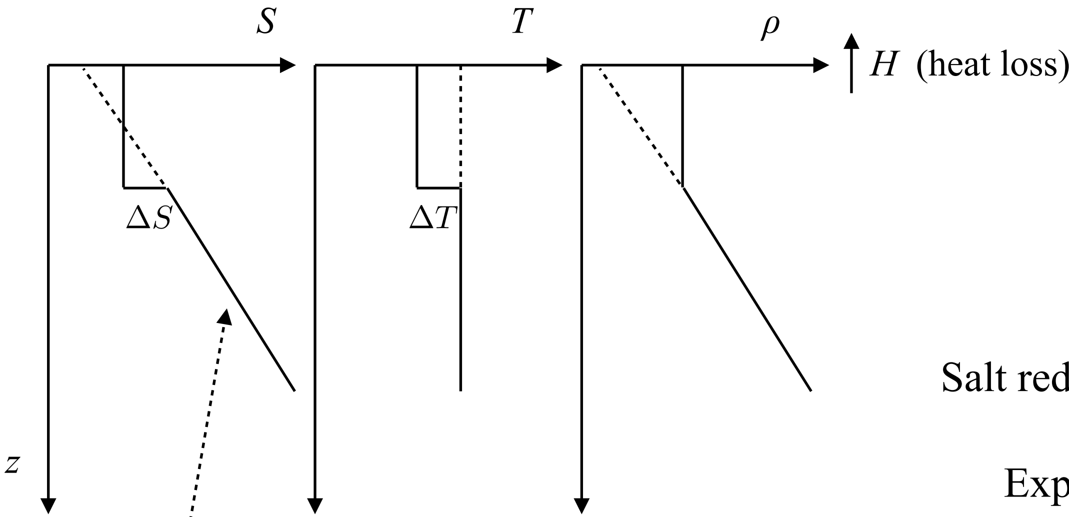
The mixed fluid disperses under the influence of gravity and rotation, spreading out at its neutrally buoyant level and leading, on a timescale of weeks to months, to the disintegration of the mixed patch and reoccupation of the convection site by the stratified fluid of the periphery.

For details: Marshall, J., and F. Schott, Open-ocean convection: Observations, theory, and models, Rev. Geophys., 37, 1–64, 1999.


Χειμώνας
Καλοκαίρι
Lateral exchange - Restratification (weeks)
Forcing: $Q(H, E)$, $\vec{\tau}$
Deep convection (weeks)
Preconditioning (months)
T
Mixed-Layer (στρώμα ανάμιξης)
Thermocline (θερμοκλινές)
Εποχικό θερμοκλινές
Μόνιμο θερμοκλινές
Deep waters
z

**Turner, 1973**

Heat/salt balances in a uniform mixed layer of depth $d$ at time $t$




$$N_s^2 = -g\beta\frac{dS}{dz}$$

Heat loss $\longrightarrow$ $Ht = -\rho c_p d\Delta T \;(1)$

Salt redistribution $\longrightarrow$ $g\beta\Delta S = \frac{1}{2}dN_s^2 \;(2)$

Experimental observations show that:

$$\alpha\Delta T = -\beta\Delta S \;(3)$$

Buoyancy flux (due to heat flux) can be written as: $B = \frac{g\alpha H}{\rho c_p} \;(4)$

Combining (1),(2),(3) and (4): $(1) \Rightarrow d = -\frac{Ht}{\rho c_p \Delta t} \overset{(3)}{=} -\frac{Ht}{\rho c_p\left(\frac{-\beta\Delta S}{\alpha}\right)} =$

$$= \frac{Ht\alpha}{\rho c_p \beta\Delta S} \overset{(2)}{=} \frac{Ht2g\alpha}{\rho c_p d N_S^2} = \frac{2t}{dN_S^2}\frac{g\alpha H}{\rho c_p} \Rightarrow d^2 = \frac{2Bt}{N_S^2}$$

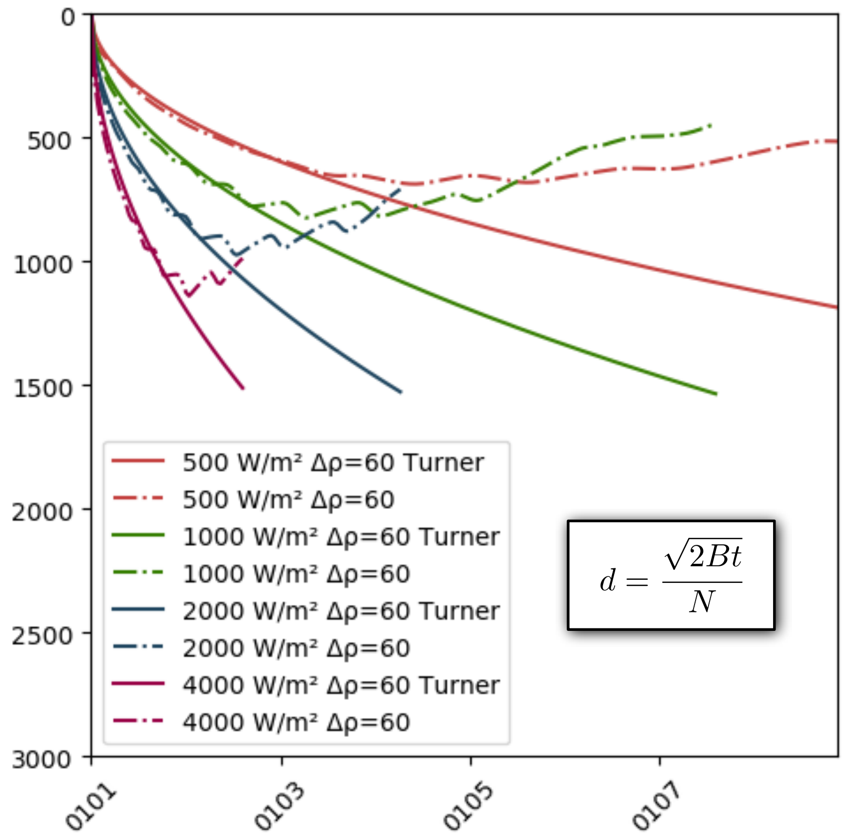
$\frac{g\alpha H}{\rho c_p} = B \;(4)$

$$\Rightarrow \boxed{d = \frac{\sqrt{2Bt}}{N_S}}$$

| | |
|---|---|
| $\alpha \equiv -\frac{1}{\rho}\frac{\partial\rho}{\partial T}$ | Thermal expansion coefficient |
| $\beta \equiv \frac{1}{\rho}\frac{\partial\rho}{\partial S}$ | Haline contraction coefficient |
| $c_p$ | Heat capacity |

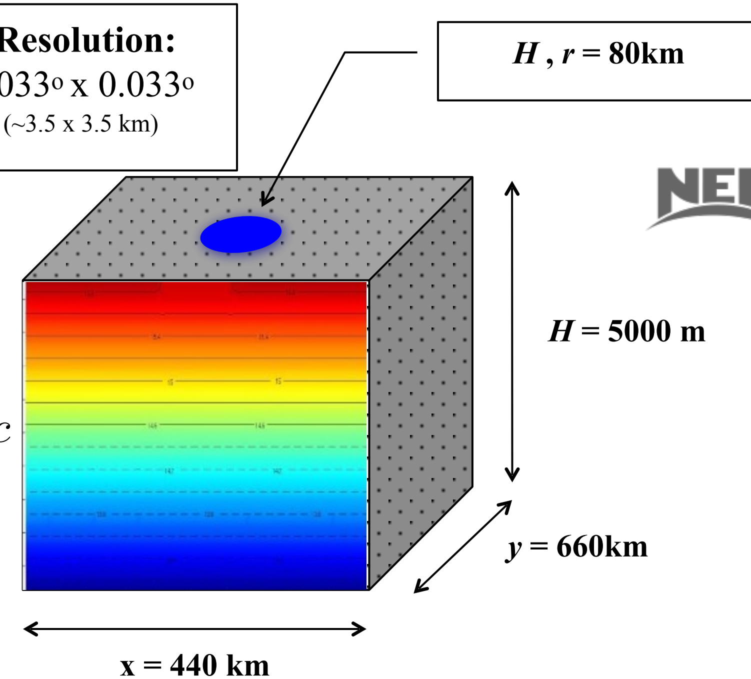
Turner J.S., 1973: Buoyancy effects in fluids, Cambridge University Press.

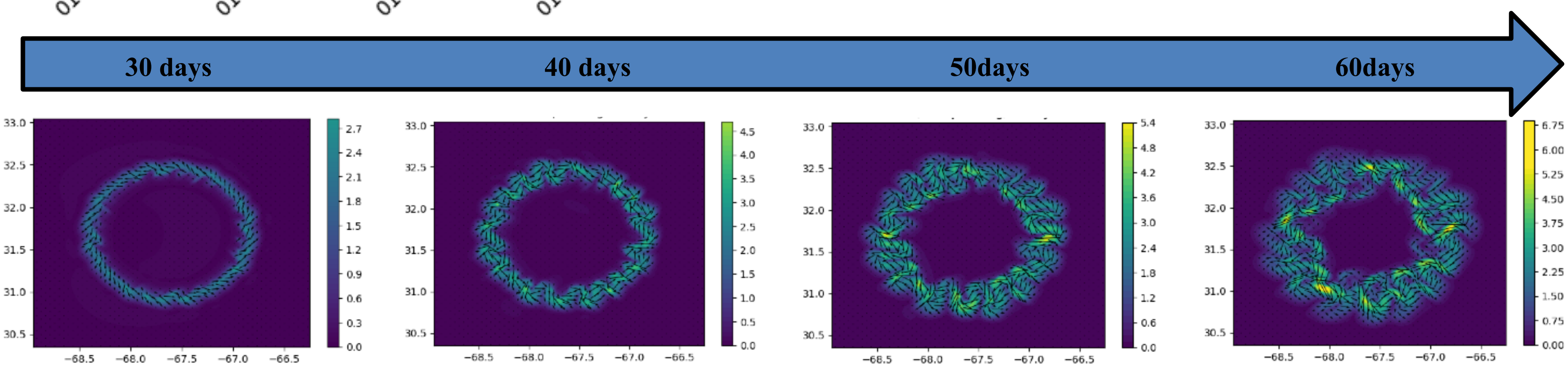
An example: Compare 1-D approach with 3-D results




**Resolution:**
0.033° x 0.033°
(~3.5 x 3.5 km)

$$\frac{\partial \theta}{\partial z} = c$$




S.Stefanou, MSc Thesis, Univ. Athens

**Vorticity** (στροβιλισμός) reduced gravity form

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \upsilon\frac{\partial u}{\partial y} = -g'\frac{\partial h}{\partial x} + f\upsilon \qquad (1)$$

$$\frac{\partial \upsilon}{\partial t} + u\frac{\partial \upsilon}{\partial x} + \upsilon\frac{\partial \upsilon}{\partial y} = -g'\frac{\partial h}{\partial y} - fu \qquad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (3)$$

$$\frac{\partial}{\partial x}(2) - \frac{\partial}{\partial y}(1)$$

$$\frac{\partial}{\partial t}\left(\frac{\partial \upsilon}{\partial x} - \frac{\partial u}{\partial y}\right) + \frac{\partial u}{\partial x}\frac{\partial \upsilon}{\partial x} + u\frac{\partial^2 \upsilon}{\partial x \partial x} + \frac{\partial \upsilon}{\partial x}\frac{\partial \upsilon}{\partial y} + \upsilon\frac{\partial^2 \upsilon}{\partial x \partial y} -$$

$$- \frac{\partial u}{\partial y}\frac{\partial u}{\partial x} - u\frac{\partial^2 u}{\partial y \partial x} - \frac{\partial \upsilon}{\partial y}\frac{\partial u}{\partial y} - \upsilon\frac{\partial^2 u}{\partial y \partial y} =$$

$$= -g'\cancel{\frac{\partial^2 h}{\partial x \partial y}} + g'\cancel{\frac{\partial^2 h}{\partial x \partial y}} - f\frac{\partial u}{\partial x} - u\cancel{\frac{\partial f}{\partial x}} - f\frac{\partial \upsilon}{\partial y} - \upsilon\frac{\partial f}{\partial y}$$

$$\rightarrow = \frac{df}{dt}$$

$(u, \upsilon \not\propto z)$

$f \not\propto x$

$$\frac{\partial}{\partial t}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)+u\frac{\partial}{\partial x}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)+v\frac{\partial}{\partial y}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)+$$

$$=\frac{d}{dt}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)$$

$$+\frac{\partial u}{\partial x}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)+\frac{\partial v}{\partial y}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)=$$

$$=\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)$$

$$=-f\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)-\frac{df}{dt}$$

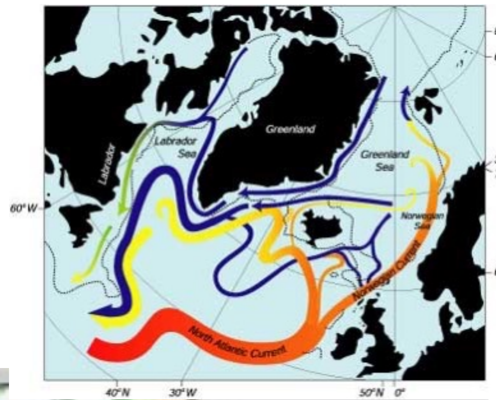
**planetary vorticity**

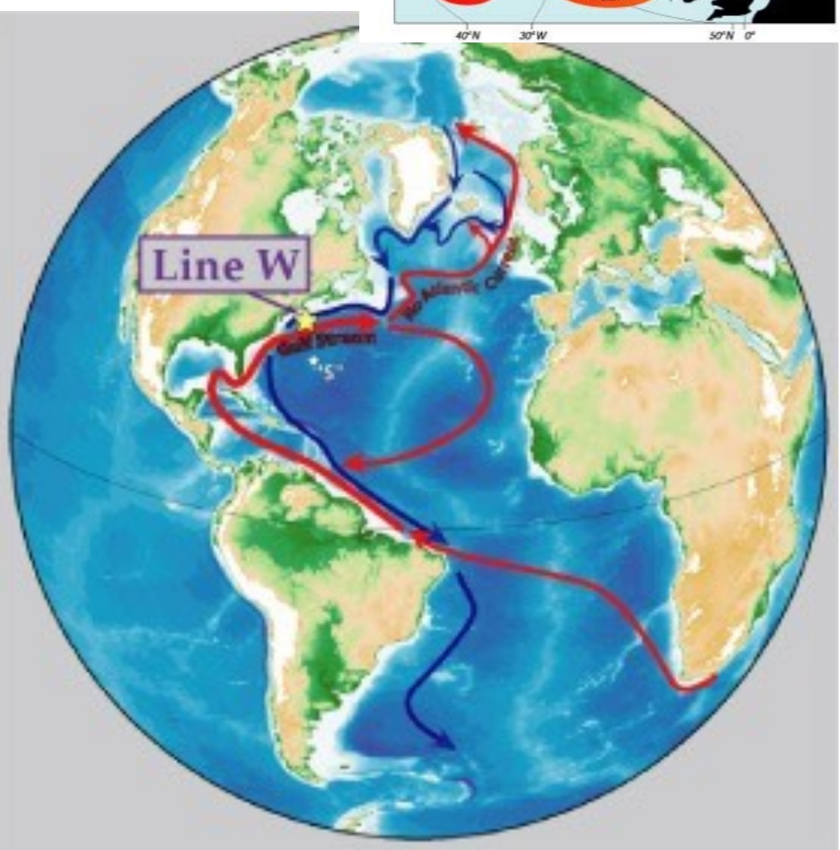
Defining **relative vorticity:** $\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}=\zeta$ (ocean velocity curl)

$$\frac{d\zeta}{dt}+\zeta\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)=-f\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)-\frac{df}{dt}$$

$$\frac{d}{dt}(f+\zeta)=-(f+\zeta)\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)$$

**The pathways of deep waters in the abyssal ocean**




For large scale motions $R_o << 1$

Starting from

$$\frac{d}{dt}(f+\zeta) = -(f+\zeta)\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

and using the continuity equation $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{\partial w}{\partial z}$

$$\frac{d}{dt}(f+\zeta) = -(f+\zeta)\left(-\frac{\partial w}{\partial z}\right)$$

Scaling

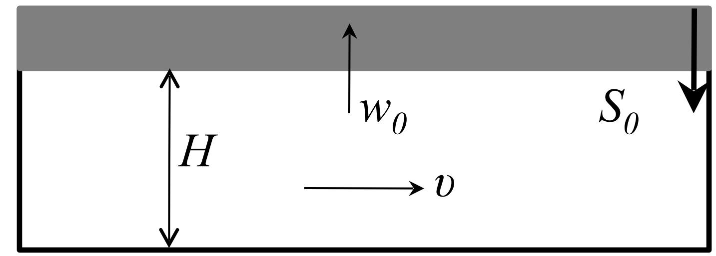
$$\left.\begin{aligned} \zeta &= \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = O\left(\frac{U}{L}\right) \\ f &= O(f_0) \end{aligned}\right\} \frac{\zeta}{f} = O\left(\frac{U}{f_0 l}\right) = O(R_o) << 1$$

Ignoring $\zeta$ and

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} + v\frac{\partial f}{\partial y} + w\frac{\partial f}{\partial z} = \beta v$$

$$\Rightarrow \boxed{\beta v = f\left(\frac{\partial w}{\partial z}\right)}$$

# Abyssal Circulation (Stommel-Arons Theory)



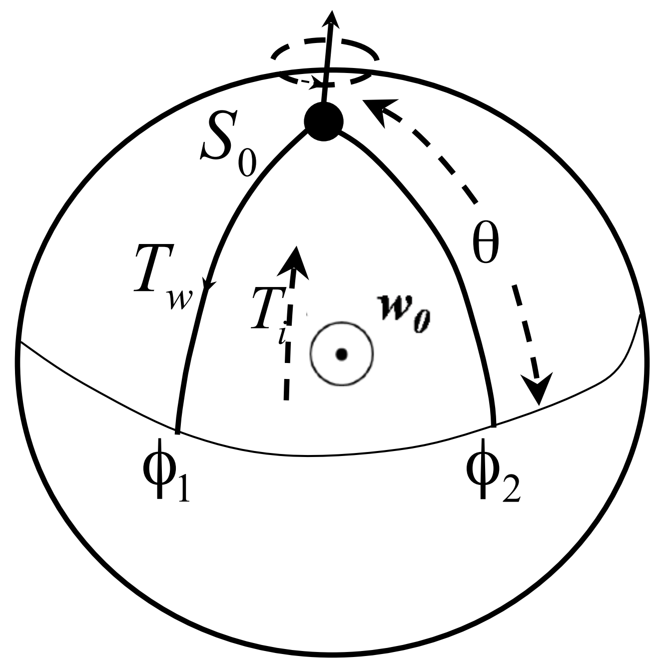

Potential vorticity conservation:

$$\beta v = f\frac{\partial w}{\partial z}$$

$$\frac{2\Omega\cos\theta}{R_{earth}}\, v = 2\Omega\sin\theta\ \frac{\partial w}{\partial z}$$

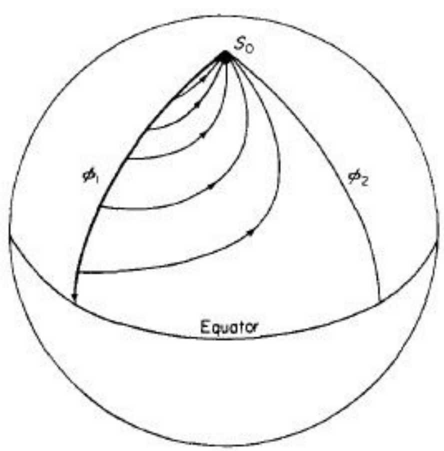
$$\frac{\partial w}{\partial z} \approx \frac{w_{top} - w_{bot}}{H} = \frac{w_0}{H}$$

$$\boxed{v = \frac{w_0 R}{H}\tan\theta}$$



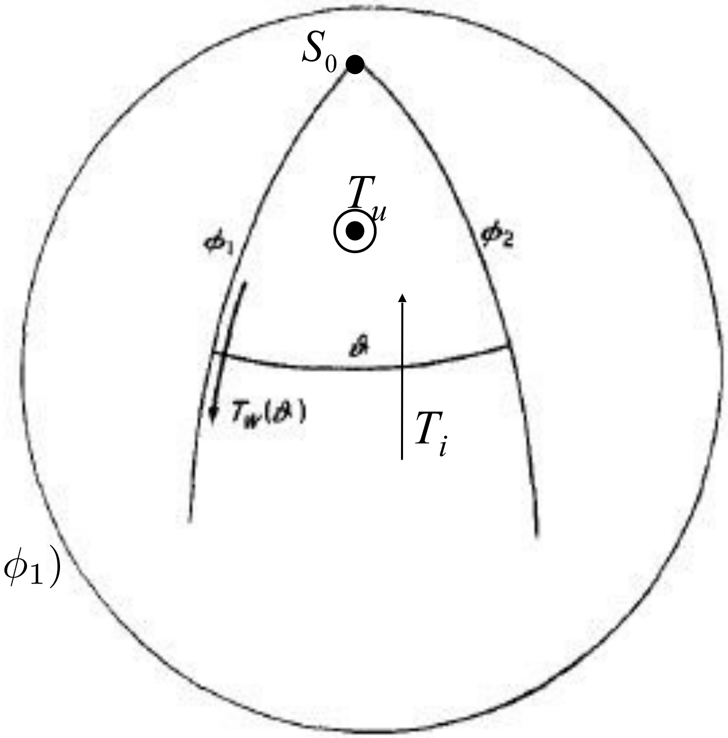

Continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$




Stommel et al.; Stommel & Arons (1958, 1960)

**"Half Ocean solution"**




Conservation of volume:

$$S_0 + T_i = T_u + T_w$$

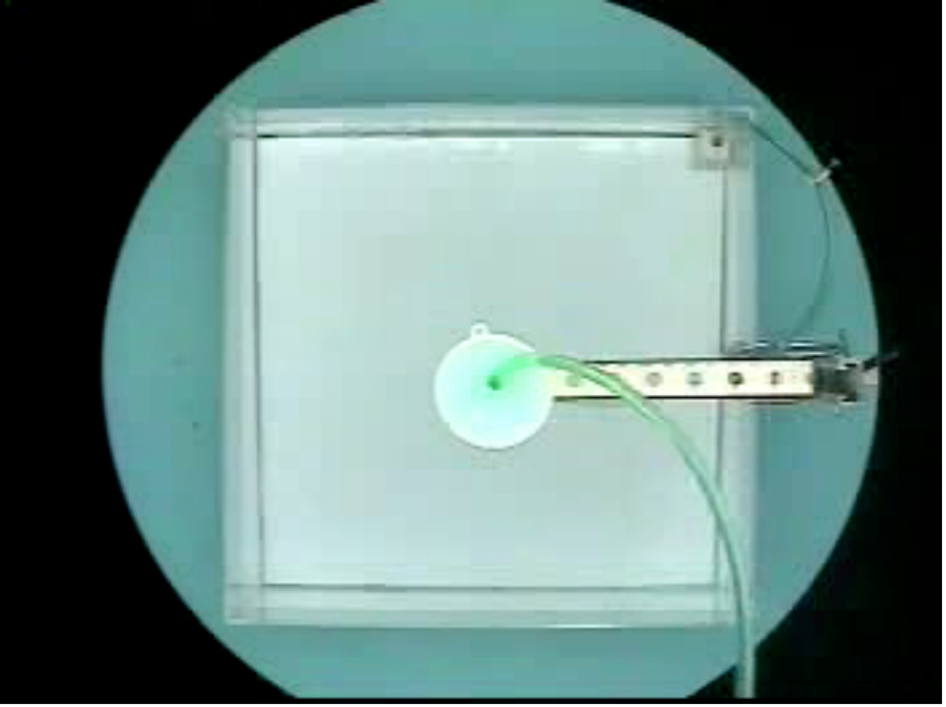
$$T_i = \int_{\phi_1}^{\phi_2} H v R \cos\theta \; d\phi = w_0 R^2 \sin\theta \, (\phi_2 - \phi_1)$$

$$T_u = \int^{\pi/2}_{\theta} \int_{\phi_1}^{\phi_2} w_0 R^2 \cos\theta \; d\phi \; d\theta = w_0 R^2 \, (1 - \sin\theta) \, (\phi_2 - \phi_1)$$

and $T_u(\text{domain}) = w_0 R^2 \, (\phi_2 - \phi_1) = S_0$

$$\begin{aligned} T_w =& S_0 + w_0 R^2 \sin\theta \, (\phi_2 - \phi_1) - w_0 R^2 \, (1 - \sin\theta) \, (\phi_2 - \phi_1) = \\ &= S_0 + \underbrace{w_0 R^2 \, (\phi_2 - \phi_1)}_{S_0} \, (\sin\theta - 1 + \sin\theta) \end{aligned}$$

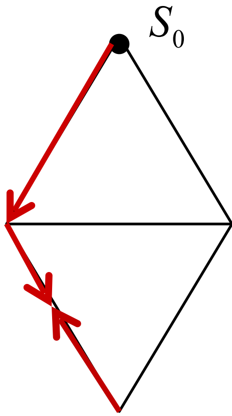
$$\boxed{T_w = 2 S_0 \sin\theta}$$

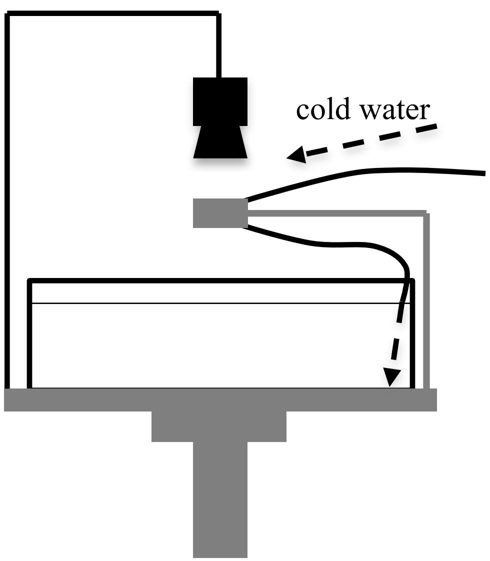


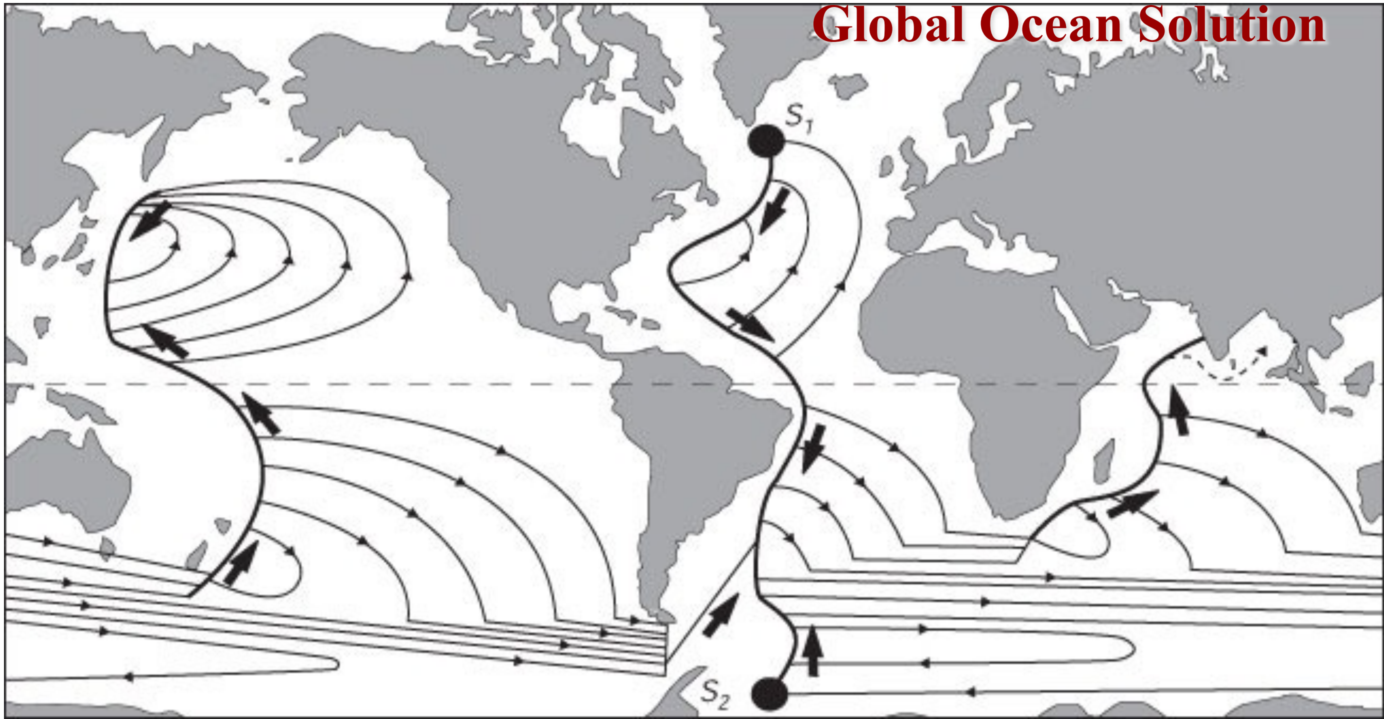
## "Whole" basin solution

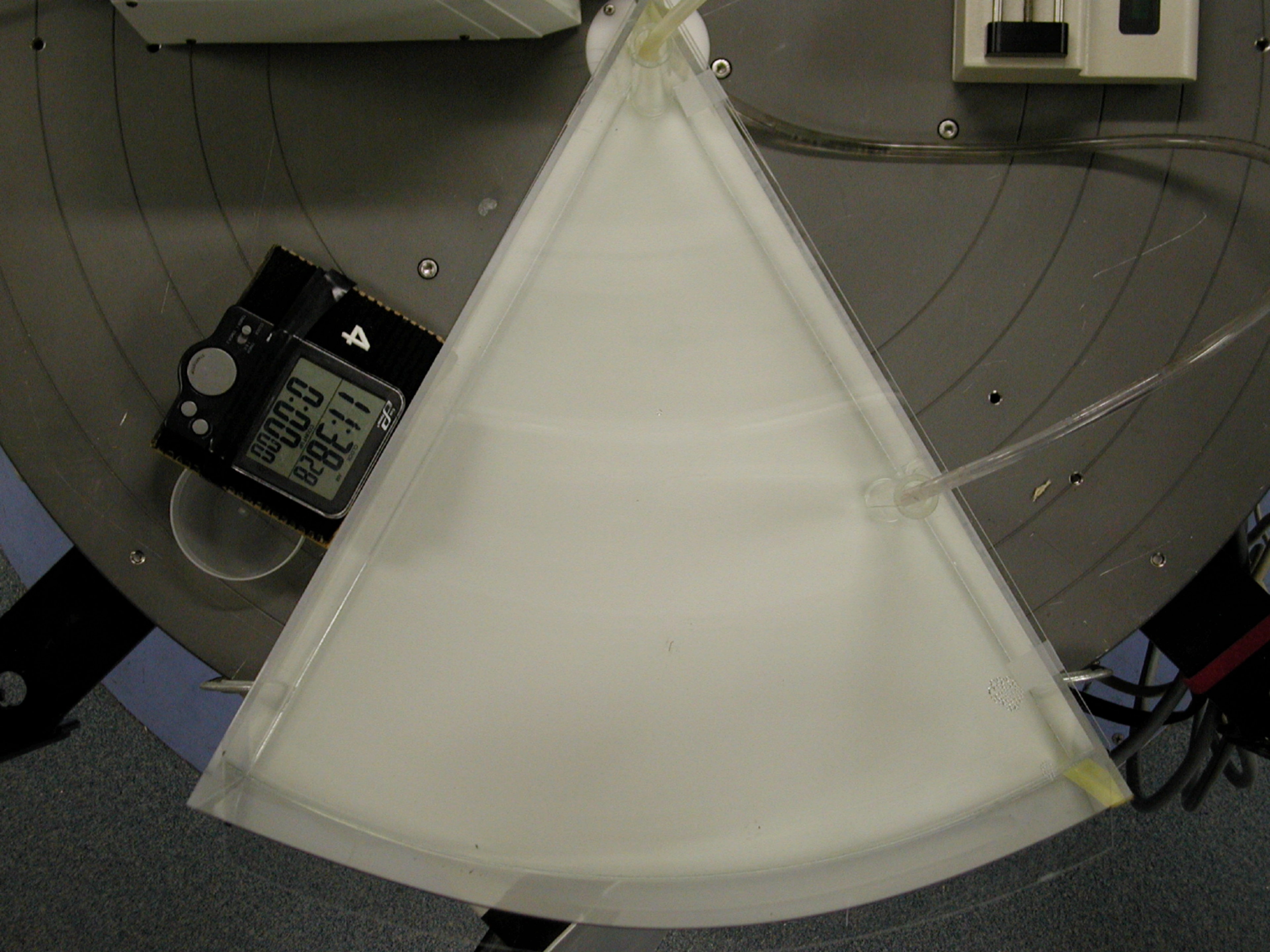
$$S_0 = 2w_0 R^2 (\phi_2 - \phi_1)$$

$$T_w = S_0 \left( \frac{1}{2} + \sin\theta \right)$$

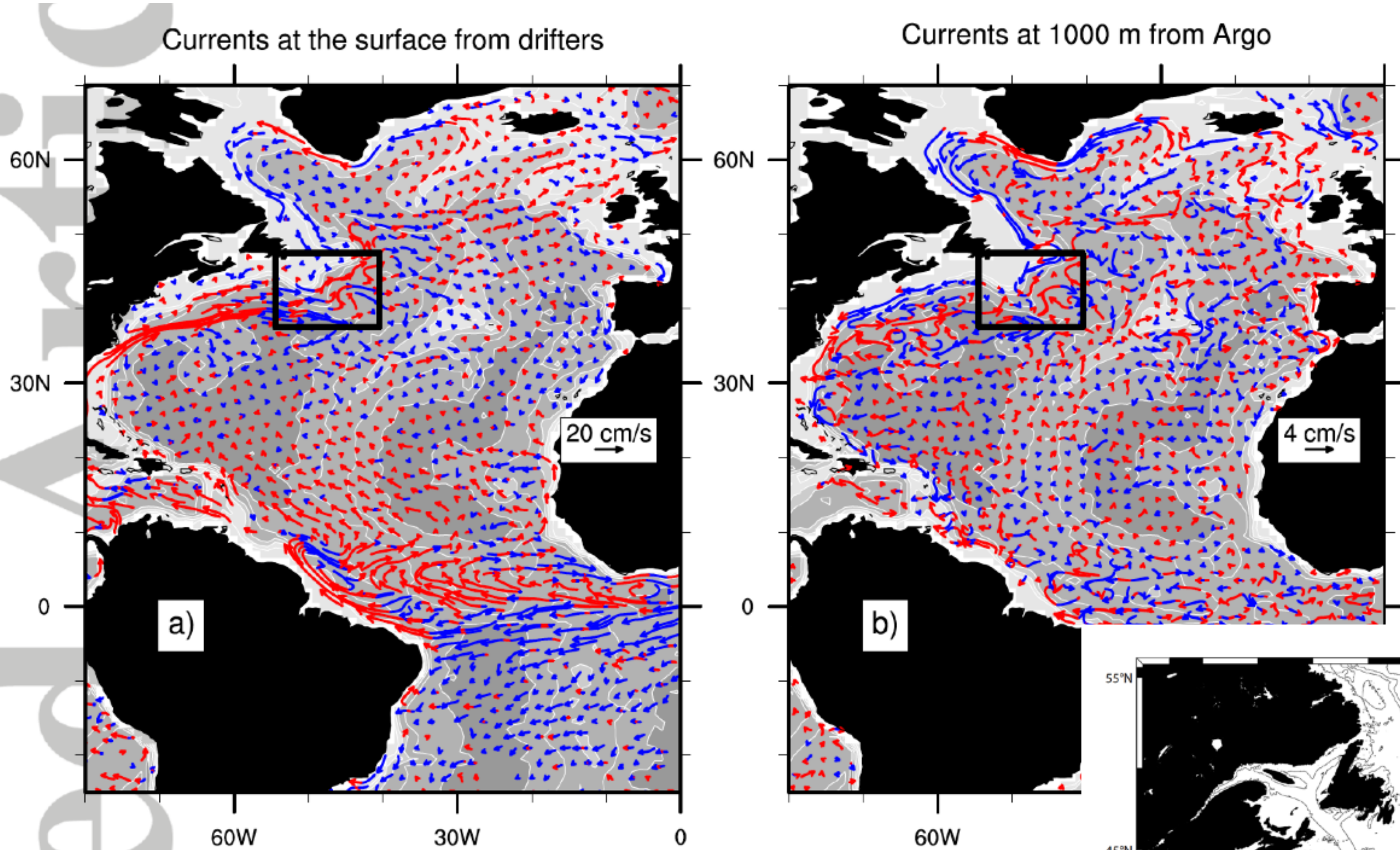


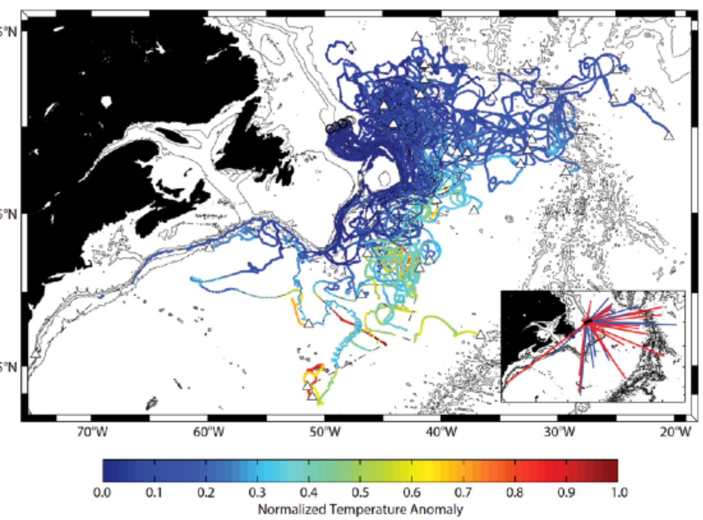



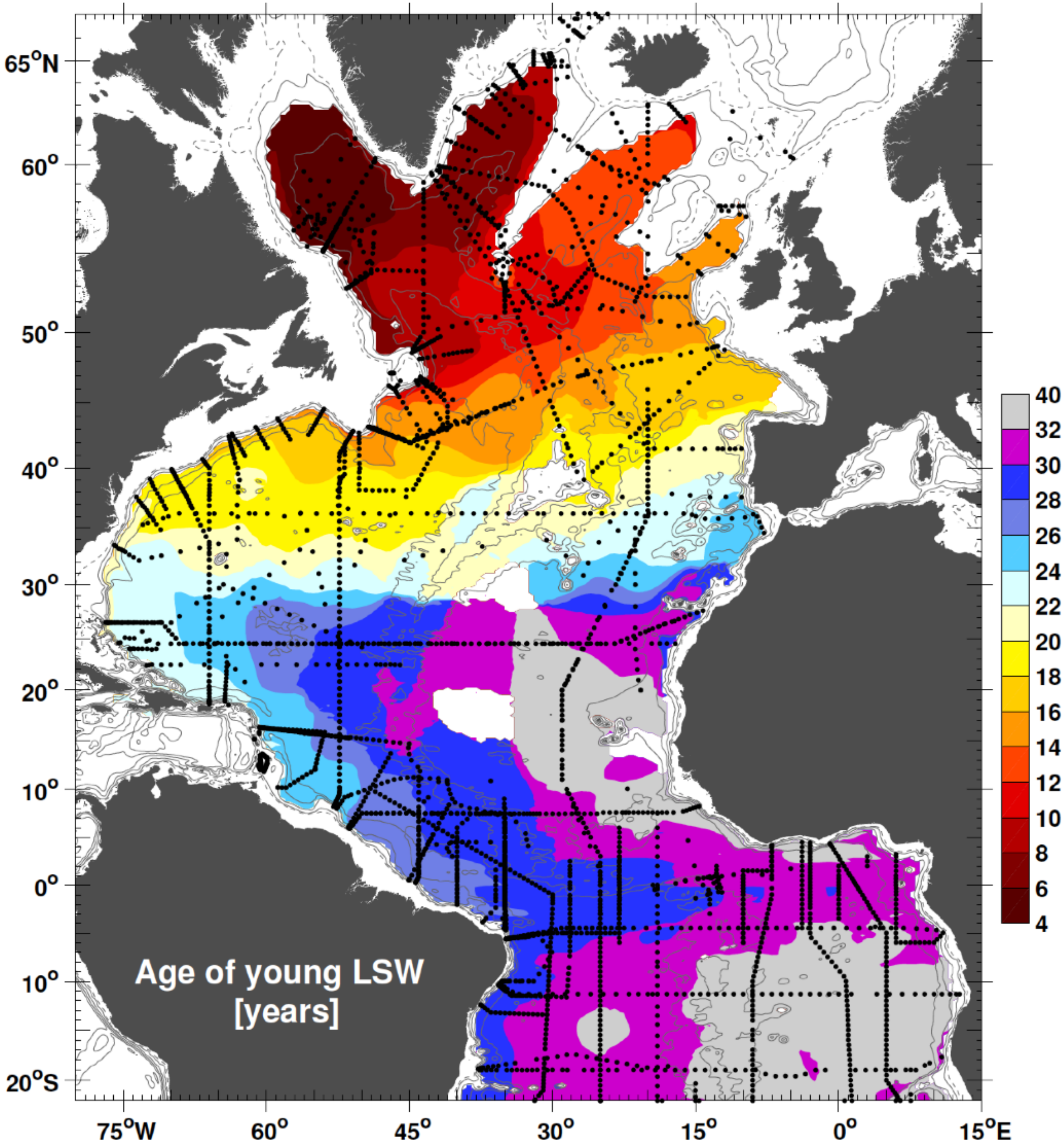


# Pathways



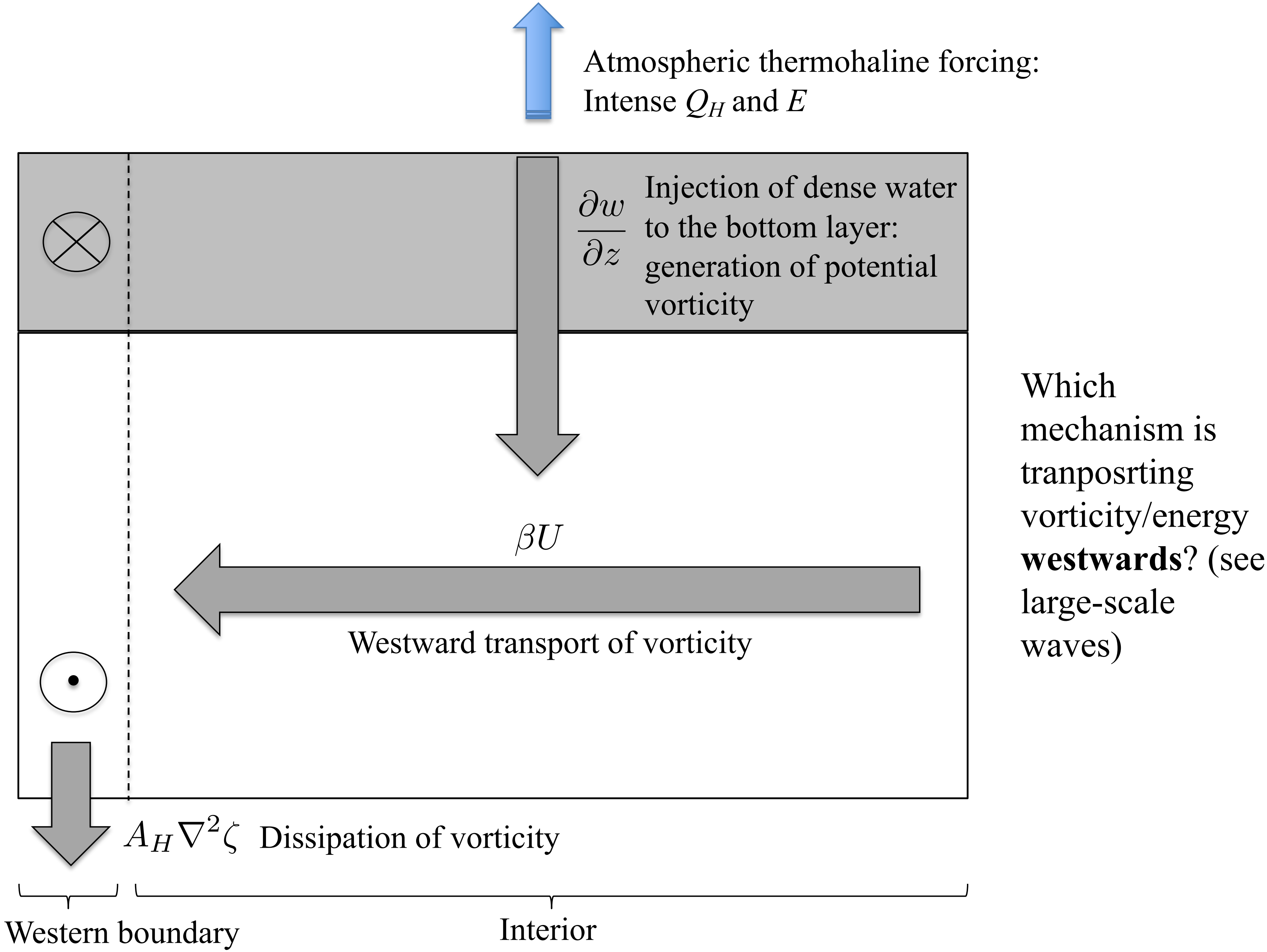

Bower, A. S., M. S. Lozier, S. F. Gary, and C. W. Boning (2009), Interior pathways of the North Atlantic meridional overturning circulation, Nature, 459, 243–247.
Lumpkin, R., S. A. Grodsky, L. Centurioni, M.-H. Rio, J. A. Carton, and D. Lee (2013), Removing spurious low-frequency variability in drifter velocities, Journal of Atmospheric and Oceanic Technology, 30 (2), 353–360.
Ollitrault, M., and A. Colin de Verdiere (2014), The ocean general circulation near 1000-m depth, J. Phys. Oceanogr., 44 (1), 384–409, doi:10.1175/JPO-D-13-030.1.



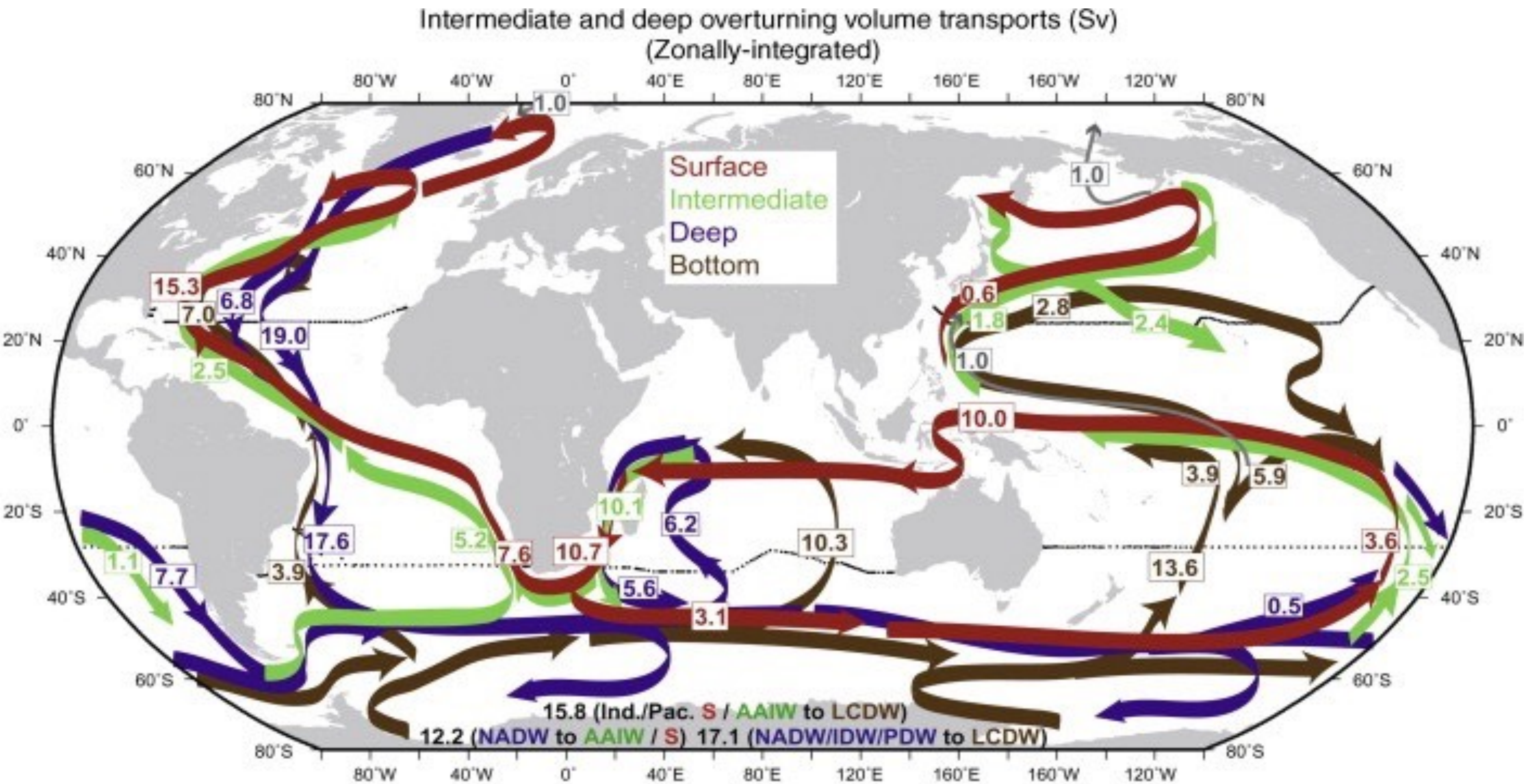

# Tracers

Map of tracer age of the Labrador Sea Water (LSW) layer calculated from CFC concentrations for LSW younger than 40 years.

Rhein, M., D. Kieke, and R. Steinfeldt (2015), Advection of North Atlantic Deep Water from the Labrador Sea to the southern hemisphere, Journal of Geophysical Research: Oceans, 120(4), 2471–2487, doi:10.1002/2014JC010605.


Atmospheric thermohaline forcing:
Intense $Q_H$ and $E$
$\frac{\partial w}{\partial z}$
Injection of dense water to the bottom layer: generation of potential vorticity
$\beta U$
Westward transport of vorticity
$A_H \nabla^2 \zeta$ Dissipation of vorticity
Western boundary
Interior
Which mechanism is tranposrting vorticity/energy **westwards**? (see large-scale waves)

# The "conveyor belt"
# The "overturning circulation"



# The thermohaline routes