Atlantic “Branch Waters” (BW) Fram Strait (FSBW) and Barents Sea (BSBW)

**ATLANTIC LAYER**
- temperature > 0 deg C
- FSBW and BSBW
- usually between 200-1000m in water column
- Tmax usually between 200 and 500m depth

**FSBW**
- temperature max

**BSBW**
- inflexion pt
FSBW
- enters through FS, surface cools (cf first picture), (may melt ice, may freeze). FSBW TRANSFORMED to subsurface Tmax

Along SLOPE
may be capped with ice melt, or perhaps shelf waters

At St ANNA
BSBW outflow mostly comes in at depth, into FSBW core, below it (maybe above)

AW does not really subduct below Arctic Surface Waters. Instead they are formed from AW.

YP = Yermak Plateau
General AW Circulation Schemes

**Aagaard, 1989**
- topographically steered boundary current along slopes and ridges
- interior flow weak, dominated by eddies (based on current meters)

**Rudels et al, 1994**
- mixing off St Anna
- cyclonic (anti-clockwise) circulation (based on T-S and tracers)

Fig. 9. Schematic diagram showing the inferred circulation in the Arctic Ocean of the Atlantic Layer and intermediate depth waters, between 200 m and 1700 m.
Tracers of Atlantic Water

**TEMPERATURE-SALINITY**
- presence of Tmax
- form in TS space
- following a warming (see later)

**CHEMICAL TRACERS**
- usually atmospheric source
- mixed into surface water, and then isolated from the atmosphere

**CFCs (ChloroFluoroCarbons)**
- solvents from 1960s onwards
- CCl4 (“carbon-tet”) is oldest
  then CFC11, CFC12 and newest CFC113
- atmospheric concentrations KNOWN
  - use presence or ratios to give age

**Cs and I from Nuclear Reprocessing**
- on-going,
  - concentrations KNOWN
- use presence or ratios to give age

**Bomb Tritium**
- atomic bomb tests 1950s
  - surface layer of tritium (isotope of H)
- decays to Helium-3 (half-life ~ 12.4 yrs)

**NON-CONSERVATIVE**
(weakness and strength)
- also dissolved oxygen??
- Delta O18?? (not really)
  - N:P ratios (perhaps)

**CONSERVATIVE**
- but mixing important
Renewal and circulation of intermediate waters in the Canadian Basin observed on the SCICEX 96 cruise

William M. Smethie Jr., Peter Schlosser,1,2 and Gerhard Bönisch
Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York

JGR, 2000

Tom S. Hopkins
Department of Marine, Earth and Atmospheric Sciences, North Carolina State Un

Figure 3. Concentration of CFC-11 and CFC-113 Northern Hemisphere troposphere versus time [Walker 1990].

CFCs
Circulation features in the central Arctic Ocean revealed by nuclear fuel reprocessing tracers from Scientific Ice Expeditions 1995 and 1996

JGR, 1999

John N. Smith and Katherine M. Ellis

Marine Environmental Sciences Division, Bedford Institute of Oceanography, Dartmouth, Nova Scotia

Timothy Boyd

College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis

Figure 2. The historical records of $^{137}$Cs and $^{129}$I concentrations in the Norwegian Coastal Current (NCC) have been estimated as outlined in the text and by Smith et al. [1998]. The reconstructed $^{129}$I/$^{137}$Cs atom ratio has three significant ranges: $^{129}$I/$^{137}$Cs < 10 before initiation of major reprocessing plant releases in mid-1960s, 10 < $^{129}$I/$^{137}$Cs < 100 before Chernobyl inputs in 1986, and 100 < $^{129}$I/$^{137}$Cs after Chernobyl. The post-1986 period represents the dynamic range during which $^{129}$I and $^{137}$Cs tracers, together, can provide unique transit time information.

Figure 11. The $^{129}$I distributions on section C (Figure 1) from the USS Pogo cruise show low levels in Pacific halocline water above 200 m extending from station 44 across the Canada Basin to station 30 and relatively high levels in Atlantic boundary current water (below 200 m) flowing along the Lomonosov Ridge (station 28) and along the continental slope of the Beaufort Sea. Elevated $^{129}$I concentrations were also observed in AW and intermediate water at station 38, indicating relatively efficient ventilation of the interior of the Canada Basin, but extremely low $^{129}$I levels were measured at stations 34 and 35, which is consistent with low ventilation rates in the northern Canada Basin and over the Alpha Ridge.
Pathways and “Ages” (transit time?)

.. “ages” much higher than from advection speeds, possibly due to CFC mixing model

Smith et al., JGR, 1999

Smethie et al., 2000

Figure 6. Circulation pathways at Barents Sea Branch Water with tritium/He ages based on the results of this study and previous studies (Rödder et al., 1994; Solozhenko et al., 1997; Swift et al., 1998).
AW circulation very different to PW circulation
- AW follows topography (with exceptions?)
- PW follows ice ??

Jones et al., 2001, Polar Research
How AW varies in the Arctic

45-year mean of Temperature in each box

Does AW cool as it progresses??
- if so, why?
What else might be happening?
The Arctic Ocean Boundary Current

- mean flow weak, but with strong eddies
  - topography following
- equivalent barotropic (i.e. velocity well correlated at all levels)
- NOT SEASONALLY VARYING

- current ~ 50 km wide
  found over ~ 500-3000m isobaths
- centered over ~ 1700m isobath
The Arctic Ocean Boundary Current

Transports – large uncertainties, but consistent with inputs. Advection speeds a few cm/s, consistent with Tmax translation, faster than CFC ages. (? Mixing?)

Flow split by Ridge – one branch N along Lomonosov Ridge, – one branch into Canadian Basin

Some waters cross ridge S of 88N

Small exchange of Deep Waters (CBDW/EBDW – Canadian/Eurasian Basin Deep Water)

BUT STILL DON’T KNOW

= what “type” of current it is
- equivalent barotropic jet? (Killworth and Hughes, 2002)

= what drives it
- “Neptune” – interaction of eddies and topography (Holloway, 1987)

- Potential Vorticity forcing (Karcher et al., 2007)

- Windstress from Greenland Sea (Nost and Isachsen, 2003)
Details still unclear

Figure 2: Published Atlantic layer circulation schemes (black or red arrows) showing (top) anticyclonic (clockwise) flow in the southern interior Canada Basin and a cyclonic (anticlockwise) counter flow (the boundary current) along the Alaskan coast or (bottom) only a cyclonic (anticlockwise) circulation. Flow from the north Northwind Ridge into the interior basin (top left and middle) is also suggested by tracer data [Smith et al., 1999; Smethie et al., 2000].

From Woodgate and Steele, 2006, NSF proposal
Warming in the Arctic

Sir — Climate models predict warming caused by the greenhouse effect to not be distributed evenly. The Greenland ice sheet and the Svalbard glacier, for example, might lose mass at a rate of 100 cubic kilometers per year by 2100 (ref. 3). The Arctic Ocean, however, will experience significant warming.

Quadfasel et al., Nature, 1991

DSR, 1993

1990
Rossiya tourist cruise,
XBT section

Significant Warming of AW

Fig. 4. Summary of observed maximum core temperatures in the Atlantic Water subsurface boundary current along the continental slope. The arrows indicate the path of the boundary current which, according to Perkin and Lewis (1984), bifurcates north of Svalbard. Circled numbers are Rossiya observations, ind.ces on other numbers refer to: (1) Treshnikov (1977), (2) Perkin and Lewis (1984), (3) Anderson et al. (1989), (4) Rudels (1989).
Atlantic Layer warming in 1990s
(collation/model by Karcher et al., 2003)

Modelled (full fields) and observed (circles) AW core temperatures in various years

Warmer since 1990s, ... but slight cooling following the warming ... USE THIS AS TRACER!!
AW warming spreads also into Western Arctic

Tmax from submarine cruises

See warming, but data very sparse

Woodgate et al, 2001, NSF proposal
AW warming .. slow to reach Canada Basin

Figure 1. Study area and temporal sequences of potential temperature on the density surface $\sigma_\theta = 27.90$. Yellow circle in Figure 1a denotes the mooring location used in Figure 3.

Shimada et al., 2004, GRL
Changing Atlantic Inflow

Figure 1. Propagation of warm temperature anomalies into the Arctic Ocean. Large red and yellow arrows indicate two pulses of warm AW. The pathways of AW are shown schematically by black arrows. Red stars show locations of moorings. (Top) Depth–time diagram of water temperature (°C) from the EEB mooring. (Middle and bottom) Time series of water temperature (°C) from Fram Strait and Svinoy moorings. Blue lines show weekly averaged temperature, red lines show six-month running mean temperature. Simulated [Karcher et al., 2003] de-seasoned six-month running mean water temperature anomalies are shown by black dashed lines.
How unique is this warming?

Long-term variability of Arctic Ocean waters: Evidence from a reanalysis of the EWG data set

J. H. Swift
Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA

K. Aagaard
Applied Physics Laboratory, University of Washington, Seattle, Washington, USA

L. Timokhov and E. G. Nikiforov
Arctic and Antarctic Research Institute, St. Petersburg, Russia

Temperature at AW depths in Box 3

EWG data 1948-1993

Have been previous warm periods
Variability of the Intermediate Atlantic Water of the Arctic Ocean over the Last 100 Years

I. V. Polyakov,* G. V. Alekseev,† L. A. Timokov,‡ U. S. Bhatt,* R. L. Colony,* H. L. Simmons, D. Walsh,§ J. E. Walsh,* and V. F. Zakharov*

(Real data, especially sparse real data can be very very messy)

Normalised anomalies of AW Core Temperature
Do these warmings agree??

Swift et al., 2005

Polyakov et al., 2004
Variability of the Intermediate Atlantic Water of the Arctic Ocean over the Last 100 Years

I. V. Polyakov,* G. V. Alekseev,+ L. A. Timokhov,† U. S. Bhatt,* R. L. Colony,* H. L. Simmons,
D. Walsh,# J. E. Walsh,* and V. F. Zakharov+

What are the mechanisms??

SAT – surface Arctic Air Temperature (area?)
HIce – ice thickness at station in Kara

WTM – 10m water temperature at station Mike (66N, 2E)
NAlt SST – North Atlantic Sea Surface Temp
Do these warmings agree?

Swift et al., 2005

AO, courtesy I. Rigor

Polyakov et al., 2004
Relaxation of central Arctic Ocean hydrography to pre-1990s climatology 

J. Morison,¹ M. Steele,¹ T. Kikuchi,² K. Falkner,³ and W. Smethie⁴

- in 2000s, hydrography at NP “returning to pre-1990s state”
- may relate to AO (magenta ~ red marks)

Figure 2. Winter AO Index (NDJFMA) from 1950 to 2005 in blue with a lagged, first-order linear response in magenta and average of North Pole hydrographic section temperature and salinity anomalies from Figure 1 within 100 km of the Pole and to 500m.
On the dynamics of Atlantic Water circulation in the Arctic Ocean

M. Karcher, F. Kauker, R. Gerdes, E. Hunke and J. Zhang

Received 10 April 2006; revised 23 October 2006; accepted 22 February 2007; published 26 April 2007.

[1] We use a subset of models from the coordinated experiment of the Arctic Ocean Model Intercomparison Project (AOMIP) to analyze differences in intensity and sense of rotation of Atlantic Water circulation. We focus on the interpretation of the potential vorticity (PV) balance. Results differ drastically for the Eurasian and the Amerasian Basins of the Arctic Ocean. We find indications that in the Eurasian Basin the lateral net flux of PV is a significant factor for the determination of the sense of rotation of Atlantic Water circulation on timescales beyond pentades. The main source of high PV causing cyclonic circulation in the Eurasian Basin is the Barents Sea, where the seasonal cycle of surface buoyancy fluxes forms stratified water that leaves the shelf and feeds the Atlantic Water Layer (AWL) in the Arctic Basins. However, in the Amerasian Basin vertical PV fluxes are the more important factor. These are closely related to wind field changes. We find an intense response of the AWL flow to wind forcing, approximated by the sea level pressure difference between the Bering Sea and the central Canadian Basin, which describes about half the variance of AWL flow of the Amerasian Basin. An experiment driven with a repeated atmospheric climatology exhibits an extreme case where a permanent high pressure system over the Beaufort Sea dominates the circulation in the Amerasian Basin, demonstrating the potential of the Beaufort Gyre to adjust in such a way as to suppress a cyclonic AWL flow in the Amerasian Basin. In more realistic cases the Beaufort Gyre still modulates the Amerasian Basin AWL circulation significantly.
The Warming of the 1990s

1993 Larsen
- 1 deg warmer on the Mendeleev Ridge
- inversions in temperature and salinity

Carmack et al, '95, and McLaughlin et al, '96
Atlantic Water zigzags AOS94

Line up/ Nest all through the Arctic - ~ 5,000km

Angles of the Zigzags match double diffusive theory

_Carmack et al, 1997_
Mixing and Double Diffusion in T-S Space

Mechanical mixing in TS space creates straight lines between water masses.

In double diffusive processes, heat diffuses faster than salt.

So, in TS space resultant waters are not on a straight line between the parent water masses.
Theories for formation, and for growing to a large amplitude steady state (Turner, Ruddick, Toole, Georgi, McDougall, Walsh, Carmack, Rudels, May ...)

**Diffusive Convection Regime**
Cold Fresh / Warm Salty
*unstable in temperature*

**Salt fingering Regime**
Warm Salty / Cold Fresh
*unstable in salt*

*Temperature unstable*
*Salinity unstable*
“T-S Zigzags” in the Arctic

Interaction of two water columns
- therefore can learn something about origins

Line up throughout Arctic (~ 5000km)
- therefore LOW ENERGY environment

Spread by??
- self propagating? (spread at 90deg to front)
- fossil intrusions? (carried advectively)

Can be used as a tracer of the boundary current???

Many refs,
- most Carmack, Walsh or McDougal
for overview, see Woodgate et al, 2007
Chukchi Borderland
Atlantic Water Circulation

Only shown Fram Strait Branch Water, but Barents Branch very similar

Woodgate et al, 2007, JGR

http://psc.apl.washington.edu/HLD
Atlantic Water

Lars Kaleschke, 1998, Fram Strait North of Spitsbergen, from ~ 500m altitude

FSBW - temperature max

BSBW - inflexion pt

TRACERS
- CFCs, Cs, I
- T, S and Ox
- TS Zigzags

CHANGE DURING TRANSIT, TEMPORAL CHANGE

OPEN QUESTIONS
- pathways, transit times
- driving mechanisms
- why models don’t agree

Fig 2: Schematic circulation of surface water (grey arrows) and the Atlantic Layer plus Upper Polar Deep Water to depths of about 1700 m (black arrows). The straight arrows represent the mouths of major rivers.

Jones et al., 2001, Polar Research

Swift et al., 2005

http://www.zmaw.de/Carbonate_precipitation_explai.93.0.html?&L=1