Report on the IASC workshop on internal mixing processes in the Arctic Ocean

Woods Hole, October 21-22, 2013

Compiled by: Bert Rudels & Tom Haine

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Summary
The deep Arctic Ocean is a low energy environment and the processes determining the mixing and water mass transformations may be different from the mechanically generated turbulence dominating in most of the world ocean. Although often invoked, few hard numbers about the efficiency of these internal processes exist. To identify and examine these mechanisms and determine if they play a major role in the physics and the circulation of the Arctic Ocean a two-day workshop on internal mixing processes was held in Woods Hole October 21-22, 2013 in combination with the second FAMOS (Forum of Arctic Modelling and Observational Synthesis?) meeting. The workshop was arranged by IASC and co-sponsored by WHOI and FMI. Close to 40 scientists attended the workshop, which was organised thematically with introductions (25 min.) by invited speakers, presenting different processes present in the Arctic Ocean, followed by discussions and questions (20 min.). The presentations were organized into four themes: The upper Ocean, Mixing in the interior, Mixing at the boundaries and interaction with the interior, and the Large-scale Picture (see the workshop programme). After the talks, and to put the present workshop into a larger perspective, results and insights from the 1st Norbert Unstersteiner workshop, held in Fairbanks, Alaska in March 2013 were presented by Laurie Padman and Barry Ruddick. The workshop ended with a general discussion to identify which were the most urgent problems to approach and examine possible approaches to their study. Special sessions devoted to Arctic Ocean mixing processes could be proposed for AGU and/or EGU annual meetings. The possibility to introduce mixing and process studies as a theme for the upcoming ICARPIII conference was also examined. The special feature of the Arctic Ocean mixing processes is the weakness of the directly forced mixing by wind and atmospheric motion. Is this weakness due to the presence of a permanent ice cover, or to the characteristics of the atmospheric forcing, or is it primarily due to the strong stratification caused by the excess input of freshwater? A study of this question is vital to determine what changes are expected, if the ice cover in the Arctic Ocean no longer is permanent but becomes seasonal in the near future. The possible consequences of a seasonal ice cover for the Arctic Ocean mixing processes and for the Arctic in general were singled out as one of the urgent themes for Arctic research to address in the next ten years.

Rationale
The Arctic Ocean is strongly stratified in its upper part and in spite of the strong mechanical and thermohaline forcing present at high latitudes the direct local effect of the energy input from wind and heat exchange is limited to the upper 100-150m at the most. The Arctic Ocean is thus essentially an area dominated by advection. Nevertheless, the properties of the deeper layers are distinct and different from those in the neighbouring seas, indicating that other processes than direct surface forcing are active and of importance in the Arctic Ocean. Such internal mixing processes have often been brought up to explain specific and unique features observed in the Arctic Ocean water column.

The sharp temperature steps alternating with homogenous layers observed in the Arctic Ocean thermocline have been suggested to enhance heat transport, through double-diffusive convection, from the subsurface Atlantic layer to the Polar mixed layer and possibly contribute to reduction of the sea ice cover.

Extensive interleaving layers are present in the Arctic Ocean intermediate and deep waters. These layers, as well as subsurface sub-meso-scale eddies, have been proposed to enhance the spreading of heat advected from lower latitudes from the continental slopes into the basin interiors.

Interaction between tides and topography generate disturbances that can be dissipated locally, or propagate away as internal tides and increase mixing at the basin boundaries. Similarly, wind events generate inertial motions in the ice and/or in the upper ocean, which may also contribute to mixing the water column. While both these processes are generally weaker in the Arctic than in the rest of the World's oceans, they might be locally (or regionally) dominant.

Ice formation and brine rejection over the shallow shelves and accumulation of saline bottom water eventually lead to slope convection. The sinking, entraining boundary plumes bring salt from the shelves and heat from the intermediate Atlantic layer into the deep Arctic Ocean, ventilating the deep waters and provide the high temperatures and salinities observed in the deep layers.

Geothermal heating has also been proposed to explain the high temperature and the temperature increase observed in the bottom layer. The deep bottom layers could then be stirred and homogenized by thermal convection. The further transport of heat upwards would be through double-diffusive convection and/or through enhanced mixing at the continental slopes.

These, and other, processes are important in creating the characteristic Arctic Ocean water column and water masses. However, although often invoked, these processes are still not adequately described and understood, and few hard numbers exist to quantify their influence and fluxes they generate.

In response to these outstanding questions the IASC Marine Working Group (AOSB) planned and arranged a workshop dedicated to mixing processes in the Arctic Ocean. The workshop, originally to take place at the Finnish Meteorological Institute (FMI) in Helsinki together with the Arctic Subarctic Ocean Fluxes (ASOF) meeting in November, 2013, was eventually moved to Woods Hole Oceanographic Institute (WHOI) and held in connection with the annual FAMOS meeting.

The principal aim of the workshop was the exchange of ideas and its format therefore consisted of different topic, all introduced by invited speaker, specialists in the field. After the introduction (25 min.) ample time (20 min.) was given for questions and discussions before the next topic was introduced. The topics were collected under four general headings; 1) the upper ocean, 2) mixing in the deep interior, 3) mixing at the boundaries and interaction with the basins, and 4) the large-scale picture, to catch the many-facetted nature of the Arctic Ocean mixing processes.

At the end of the workshop the outcome of the Untersteiner workshop: "on the Role and Consequences of Ocean Heat Flux in Sea Ice Melt" held in March 19-21, 2013, at the University of Alaska Fairbanks, AK was presented to get additional input to the concluding discussion. The final discussion concentrated on how the efforts to better understand the Arctic Ocean processes initiated by the workshop should be continued. One suggestion was to propose a dedicated session to AGU and/or EGU on Arctic, or Polar, Ocean mixing processes. This would stimulate the interest and the future research. Another event that could promote future work on the Arctic Ocean processes and also examine their role in the Arctic climate in general is the upcoming ICARPIII conference in 2015. These meetings would serve to identify and evaluate priorities for the next ten years of Arctic research. A theme, relevant in this context, would be to examine how conditions and the mixing processes in the Arctic Ocean would change, if the ice cover from being permanent become seasonal.

Summary of presentations.

Observations of turbulence in the upper ocean.
Takashi Kikuchi, JAMSTEC

After an introduction, setting the scene of how changes in e.g. ice conditions in the Barents Sea might affect the climate on a global scale, causing strong cooling in Siberia and leading to snowy winters in Japan, different approaches to study the seasonal and annual variations in the upper layer of the Arctic Ocean and the exchanges between ocean, ice and atmosphere were reviewed. Mooring observations were judged as less satisfactory because of the danger of being destroyed by ice motion. Ships and drifting buoys, tethered to the ice are preferable. Results from expeditions with the ice strengthened R/V Mirai in the marginal ice zone were presented, especially a large (100km) warm (7^oC) core eddy in the western Beaufort Sea in fall 2010. JAMSTEC fieldwork in the interior Arctic Ocean has been conducted in cooperation with Canada, Germany and US. JAMSTEC has been using drifting buoys since 1990s, J-CAD (Jamstec Compact Arctic Drifter) and many have been deployed in collaboration with the North Pole Environmental Observatory (NPEO) near the North Pole and drifting towards Fram Strait. In the period 2000-2006 the Transpolar Drift was fastest in 2000 and slowest in 2004.

Ocean to ice heat flux: J-CAD measures ΔT (temperature above freezing) below the ice. Typical values of ΔT range between 0.07 and 0.16°C and the friction velocity is used to compute heat flux. Peak heat fluxes are about 10 Wm^{-2} and mean annual fluxes 1.4-3.1 Wm^{-2}, leading to a basal ice melt of 15-30 cm. Values are much higher for floats put in open water. What determines ΔT? Sea ice drift speed might influence ΔT. Fast ice drift causes strong mixing and high ΔT and small drift speed the reverse (Inoue & Kikuchi, 2006).

Ship based turbulence (microstructure) measurements: Rainville & Winsor (2008) from the Oden cruise 2005 across the Arctic Ocean, Kawagachi (JAMSTEC) using Turbu-MAP turbulence probe during three years from R/V Mirai in the Canada Basin (unpublished). Interleaving structure observed in the warm core eddy seen in 2010.

Ongoing and future observations: RV Mirai made two weeks stationary observations September 11 to September 25 2013 on the Chukchi shelf, launching radio sondes every third hour, making CTD casts every 6th hour and conducting turbulence measurements every 8th hour as well as other biogeochemical observations. Similar observations will be made in 2014, depending upon ice conditions.

Mooring observations: Multi-frequency acoustic zooplankton fish profiler (AZFP – 4 frequencies) on mooring. One year long echogram (Amakasu). Record shows lots of activity in summer and a strong diurnal cycle but very quiet in winter.

Questions:
Laurie Padman: Which frequency are you showing in your echograms? Are you seeing biology or turbulence when you see backscatter patches moving around? Turbulence can be imaged in acoustic data at specific frequencies.

Lars Umlauf: Dissipation you see is due to double diffusion? Look at chi/epsilon ratio?

? You saw a positive correlation between mean ice speed and temperature anomaly. Is it possible that ice speed is faster because ice concentration is lower therefore solar absorption is higher (i.e. not due to enhanced mixing)? Takashi says something about storminess too (?)

? Friction velocity depends on ice speed and ocean current? Yes, the J-CAD data measure both ice speed and surface flow, which are very similar.

? You assume neutral stability in the upper water mass to estimate ocean to ice heat flux.

Wieslaw Maslowski: Your J-CAD measurements are in multi-year ice – what about other areas? What technology would work here? Mike Steele is working on this (?).

Bert Rudels: Melting is due to seasonal heating. NCEP & ERA heat input is greater than what you infer from the basal melt estimates, especially in the Nansen Basin. The problem is that in the Nansen Basin. it appears that the atmosphere supplies more heat than goes into melting ice – where does the extra heat go? In the western Arctic it seems to balance as expected, but not in the Nansen Basin.

How ocean heat flux is melting sea ice?
Jari Haapala, FMI

How might mixing and transfer of heat from below affect the ice cover? One approach to investigate is by using models to see how the ice melt affects different ice categories. Sea ice exists in many forms and shapes, rafted ice, ridged ice, rubble piles (comprising up to 30% water filled “voids”). Observations of melting of different ice types usually exclude ridges. 10-15% of the area consists of ridges, which may comprise 70% of the volume (Wadhams, 1992 (from submarine sonar data); Wadhams and Doble, 2008 (from AUV scanning sonar)). The heat flux and the melting should preferentially go into melting the thick ridged ice. Sea ice drag estimates show a 10 times variability between smooth ice (low C_D) and ridged ice (high C_D) promoting the heat flux to the ridged ice (Lu et al.??).

The evolution of sea ice thickness and compactness were described and a “toy” model was used to determine the evolution of the ice cover for the cases when oceanic heat goes to all categories and when the heat only goes to the ridged ice. The heat input to the surface is equal for both categories. Stronger melting smoothes and reduces the ridges, removing the thicker ice categories. Since no process for forming thick ice is present in the model no steady state is possible.

JH speculated about the effects of a less compact and extensive ice cover on mixing and vertical heat transfer. Although wind mixing is likely to increase the energy input to a more open Arctic Ocean the roughness of the ice floes contributes with a substantial drag. Weakest mixing and entrainment is expected for a compact ice cover with little drift of the ice, while a less compact ice cover allows for more rapid motion of the ridged ice and enhanced mixing. The possibility thus exists for a, for mixing, optimal ice

cover compactness for transfer heat from the ocean to the sea ice. To this should be added the concomitant increase in open water and increased radiation heat input.
Conclusions:
Ice/ocean interaction depends strongly on ice thickness.
Realistic calculations of heat & momentum fluxes need coupled ice thickness distributions and ice-ocean boundary models. This will permit depth dependent mixing rates. The largest ridges are 50m deep, which imlies ice imbedded in the upper ocean.
Toy model shows that depth-dependent melting gives enhanced melting of ridges ice.

Questions:
Benoit Cushman-Roisin: Melting is a surface process. More fundamentally it's connected to roughness of ice available to melting (fractal dimension of surface).

? Snow cover is important for sea ice too.

? Ridges are preferentially melted but also have impact on surroundings, which may not be ridged themselves. Ridge spacing is important.

Bert Rudels: Heat source in the ocean comes from where? Radiative heat from the summer or advected heat from the Atlantic? Is it seasonally added heat? Is there a relation between depth of the ridges and compaction of the ice to give optimal entrainment of heat from below? Or is the optimal situation no ice and just wind mixing? Would also depend on underlying currents? What are the characteristics of the ice that give optimal heat flux out of the ocean? The same question must also apply to stress (also freshwater flux?). Is there any reason to believe that the optimum ice conditions would simultaneously optimize both? Is it right to think that removing the ice will increase the heat flux and the stress on the ocean?

Sea ice formation and brine rejection
Andrew Wells, Oxford

The growth of sea ice has been studied for than 100 years and the problem was formulated by Stefan (1891). He considered ice floating on water at the freezing point. Stefan’s balance gives a first order picture of freezing driven by heat loss to the atmosphere: the latent heat released by basal freezing is mostly conducted through the ice and balances the upper surface fluxes. The growth rate of ice then decreases as the ice becomes thicker. This picture ignores many aspects of ice formation in the ocean, including the effects of supercooling, the presence of salt and the need for brine rejection, and of wind mixing. It also ignores the initial state of ice formation, when frazil ice is formed inside the water column.

The recently observed reduction in ice extent in the Arctic Ocean enhances the importance of formation of first year ice. First year ice comprises an initial granular (frazil) ice layer, and the columnar ice formed by freezing from below. Granular ice forms a fairly thin skim in the Arctic, but provides up to 60-80% of the ice observed in some regions of the Antarctic. Since salt cannot be accommodated in the ice crystals, it has to be expelled as the ice crystals grow. Initially salt is rejected into the highly saline liquid brine network and is retained within the sea ice matrix, but eventually some of this salt drains into the ocean and the ice desalinates over time (Malmgren, 1927). The dominant mechanism for expelling brine in winter is gravitational drainage. The upper part of the ice is colder due to heat loss to the atmosphere, and this enhances freezing and increases the salinity and density of the interstitial brine. The dense interstitial brine will sink through the ice as part of a convective circulation, and is eventually rejected into the ocean (Notz & Worster, 2008). In summer, flushing with melt water (mainly due to drainage of surface melt ponds) can remove the saline brine and replace it with low salinity melt water. This effect occurs when the temperature of the ice increases and the brine pore space becomes wider, allowing the ice to be sufficiently permeable for melt water flushing to occur. Ocean modelling studies show that using different representations of brine rejection from sea ice can lead to substantial differences in ocean mixed layer depths in certain regions, such as changes in the mixed layer deepening by as much as 400m in some areas around the Antarctic coast.

Further insight into the process of gravity drainage is gained by thinking of sea ice as an example of a mushy layer, comprising of a mixture of ice and brine. Observations in the laboratory and in models indicate that fluid circulates through the ice, with dense saline fluid sinking through narrow brine channels and a slow upward return flow of warmer and fresher brine rising from the ocean through the interior of the porous ice. The brine channels form narrow chimney-like structures, which are kept ice free because the high salinity of the sinking brine causes dissolution of the ice. Brine channels form the primary conduits for salt fluxes from sea ice into the ocean. Theoretical considerations provide a way to predict salt fluxes during steady-state ice growth, and also suggest that the length scale between brine channels scales with the thickness of the layer of active convection (Wells et al. 2010, 2011, 2013). However, the depth of active convection may evolve depending on the thermal conditions in the ice. In laboratory experiments this initially scales with the ice thickness during early stages of growth, and is of order 10cm. However, there is some evidence of convection localizing in the lower region of the ice at later stages of growth. A variety of contrasting parameterisations have been proposed to describe this gravity drainage mechanism, although developers are hampered by the limited data available that is suitable for testing and distinguishing between them. In particular, the impact on brine drainage of time dependent growth conditions and ocean heat fluxes are poorly quantified.

The vigorous plumes of concentrated brine leaving the brine channels might penetrate deep into the mixed layer in winter and contribute to mixing. In a heterogeneous ice cover, rapidly freezing leads can cause enhanced convection and stronger stirring of the mixed layer, perhaps penetrating to the pycnocline.

Questions:
Q: What is the importance of gravity drainage versus melt water flushing?
A: Gravity drainage will get you about 6/7th of the way, and melt water flushing will do the rest later in the growth cycle.

Q from Laurie Padman: You showed a big difference between time-dependent brine rejection and instantaneous salt dumping (Vancoppenolle et al. 2010). What is going on here?
A: Loosely speaking, the difference is due to dumping salt versus slowly dripping salt out into a weakly stratified layer. Because the ice is advected by winds, slower brine drainage will provide a different spatial distribution of salt which leads to differences in the mixed layer depth.

Q from Bert Rudels: How high can the salinity be leaving brine channels?
A: I haven't calculated this and the result would depend on the amount of mixing in the brine channels, but an upper bound on the maximum possible value comes from the salinity of brine at the top of the ice being up to ~200 g/kg.

Q: What is the spacing and size of channels?
A: The channels have widths of order mm to cm. The spacing scales with thickness of the convection cells in ice, with a spacing of 10cm scale in the lab. This spacing evolves in time according to the growth conditions, and could be of order m scale if there is full depth convection in spring in thick ice.

Q: Can the brine plumes drain through the mixed layer and penetrate the halocline?
A: Unknown. If the plumes encounter shear-driven turbulence in the mixed layer, one could imagine them being rapidly mixed and contributing as a general surface buoyancy flux to the mixed layer. However, Bert Rudels pointed out that if the plumes are sufficiently narrow they may lie below the turbulent Komogorov scale and remain as coherent fluid parcels for a longer time. The plumes will likely be supercooled and this will cool the mixed layer. We would need a coupled ice/mixed layer model to explore the full impact on the upper ocean.

Double-diffusive interfaces; formation, extent and possible importance for the vertical heat flux.
Laurie Padman, ERS, Corvallis

In spite of, or perhaps because of, the Arctic Ocean being a low energy environment many mixing processes are active and of importance, as is shown by a mixing schematic (Padman, 1995). Double-diffusive convection (DDC) is just one, albeit important, of these processes. Double-diffusive convection also affects, and is affected by, internal wave propagation, shear instabilities and breaking internal waves. DDC requires that the vertical temperature and salinity gradient have the same sign and that the diffusion coefficient of heat is larger than the diffusion coefficient of salt. Mixing requires no external energy source and the buoyancy (density) flux is up gradient. DDC has temperature and salinity increasing with depth and are therefore prominent in the high latitude β-oceans, where the upper layer stratification is due to salinity and freshwater input (Carmack, 2007?). Saltfingers require that temperature and salinity decreases with depth and dominate in the mid-latitude α-oceans (α is the coefficient of heat expansion and β the coefficient of salt contraction). This is clearly shown in a global map compiled by Kelley (Kelley et al., 2003).

In the Arctic Ocean DDC has the potential to transfer heat upward from the Atlantic layer and from the geothermal heating at the sea floor. The effective diffusivities in DDC is different from that of ordinary turbulent mixing because heat and salt are transported differently and the flux ratio $Rf = F_{\beta S}/F_{\alpha T}$ is close to $(\kappa_S \kappa_T^{-1})^{1/2}$, the square root of the ratio of the diffusion coefficients, at least for stability ratios $R_\rho = \beta\Delta S/\alpha\Delta T$ between 2 and 10 (Turner, 1973). The transports decrease with increasing stability ratio.

DDC is manifested in the ocean by thin (5cm) sharp interfaces with strong temperature and salinity gradients and thicker, homogenous layer. Heat diffuses through the interfaces faster than salt. Instabilities form above and below the interfaces, which, when they become critical, lead to convection and stirring of the layers and the interfaces become re-sharpened. The heat, and salt, is then transported by a combination of molecular diffusion and convection. The different diffusion coefficients are essential for the convection and for the difference in the transports of heat and salt. The heat flux is commonly assumed to depend upon the temperature step as $\Delta T^{4/3}$ which makes the transport independent upon the layer depth (Turner, 1965). Shear might increase the transport by sharpening the interfaces but to strong shear could make the interfaces overturn and thus cut of the double-diffusive transfer.

The most numerous layers and interfaces are found above the Atlantic layer in the Canada Basin. The steps are, however, much smaller and the stability ratios generally higher than in the Nansen Basin, suggesting that double-diffusive transports are larger in the Nansen Basin than in the Canada Basin. The heat transport in most part of the Arctic Ocean ranges between 0.05 and 0.2 Wm^{-2} based on microstructure measurements. In the Nansen Basin higher transports are expected. The laboratory flux laws usually indicate higher values, but this may be due to insufficient resolution to identify individual temperature steps.

The extent of the individual layers is open to debate. Padman and Dillon (1988) could identify individual layer over 1 km and the observations of Sirevaag and Fer (2012) suggest a similar extent. This is contrasted with 800km deduced by Timmermans et al (2008) from ITP observations in the Canada Basin. This would imply that Atlantic water entering the Canada Basin has, or forms, layers that line up with layers already present in the Atlantic water that arrived in the Canada Basin 20 years earlier. At the Eurasian continental slope off Laptev Sea, persisting layers were observed from moorings in spite of water in the boundary current being advected passed the mooring (Polyakov et al., 2010?). This would then suggest that the layer structure might propagate upstream and influence the newly entered Atlantic water.

What will be the effects of expected changes in the Arctic Ocean like changes in salinity of the upper layer or increased temperature in the Atlantic layer? What would be the effect of less ice cover and more wind mixing? Would the importance of the diffusive layer diminish?
Needed and potential future activities:
Map of DDC characteristics, dye release experiments, establish better flux laws and determine their validity.

Questions:
Wieslaw Maslowski: How much heat gets into cold halocline (isn't DDC focused at 150-300m)? In the Atlantic layer, how about the continental slope? Is DDC more active there? Not really. Other processes overwhelm it.

Mike Spall: DDC active in small boundary eddies? Mary-Louise T sees active DDC in both Pacific and Atlantic eddies. Could be important for eddy dissipation (?). Turbulent dissipation seems to peak at the edges of the eddies.

? Adjustment timescale for change in surface forcing (thought experiment). Don't know, but easy to work out.

Mary-Louise Timmermans: Interface thicknesses. See thick interfaces that aren't growing. Doesn't seem to be intermittent. Contradicts Laurie's thin interface arguments (?). Spun-down interfaces (for some unknown reason they've spun down)? How does flux law apply in that case? Lateral differences? Slanting layers?

DDC must always apply at the bottom of beta oceans.

Bert Rudels: The heat and salt fluxes become more equal for $R_\rho < 2$. Is that an artifact of the laboratory experiments used to measure them?

Intrusions and Interleaving
Barry Ruddick, Dalhousie

Stommel and Fedorov (1967) observed density compensating temperature and salinity anomalies and assumed, correctly, that they were produced by lateral advection and eventually dissipated by vertical mixing. Subsequent observations have shown that intrusions are found almost everywhere in the ocean. The first model of intrusive exchanges across a laterally density compensating front in temperature and salinity was created by Stern (1967). The background stratification was assumed to be unstable in the saltfinger sense, warm saline water above cold and fresh and Stern parameterised the heat flux with the flux ratio $Rf = F_{\alpha T}/F_{\beta S} < 1$ for saltfingers, which is obtained from theory and laboratory experiment. Stern formulated a stability problem and found that a disturbance would grow if saline, warm intrusions rise (becoming lighter) and fresh, cold intrusion sink (becoming denser) as they pass across the front.

Many models have been constructed based on Stern's initial approach. Toole & Georgi (1981) added friction to circumvent the high wave number catastrophe present in Stern's model and baroclinic effects were added by Kuzmina & Rodionov (1992) and May & Kelley (1997). In the case of a background diffusive stratification, cold, fresh water above warm, saline water, the situation was the opposite and warm, saline intrusions would sink and cold, fresh intrusions would rise (Ruddick, 1992). In the case of a basic stratification stable in both components intrusions could still form as was observed in the laboratory (Ruddick & Turner, 1979) but finite disturbances or differential turbulent mixing (Gargett, 2003) are then required to create the initial inversions to drive the vertical saltfinger and diffusive fluxes. Another possibility could be differential diffusion that can create intrusions in a situation when both components are stably stratified (Merryfield, 2002).

The key question is if the intrusions, which in the Arctic Ocean appears to be very extensive, extending over entire basins, contribute to the heat exchange between the warm Atlantic water in the boundary current and the deep ocean interior. Such processes cannot be directly included in large-scale numerical models and estimates of effective lateral diffusion coefficient are needed. The range of existing estimates from different intrusion models extends from 10 to 3000 m^2s^{-1}, but 20 – 100 m^2s^{-1} might be a reasonable value (Walsh & Carmack, 2003; Kuzmina et al., 2011).

In the Arctic Ocean Walsh & Carmack (2003) compared the exchanges between the boundary and the interior with the heated wall experiments with salinity stratified water performed by Thorpe et al. (1969), which describe cells rising at the boundary and, when stopped by the stratification, leave the boundary and enter the interior, forcing a return flow below towards the wall. Walsh & Carmack assumed that several such cells could exist along the intrusive layers, generating the "nested" appearance of the intrusions in TS diagrams.

The most promising method to determine the effective lateral diffusion coefficients appears to be the approach suggested by Joyce et al. (1977). The lateral advection is related to the vertical diffusion and if the vertical diffusion coefficient can be determined from microstructure measurements of the dissipation rate, using the Osborne-Cox (1972?) approach the lateral diffusion can be estimated. Observations from the meddy Sharon indicate that this works (Ruddick et al., 2010).

Among recent methods introduced for studying intrusions the use of sound and seismic observations of the ocean temperature structure appears to be promising. Observations of meddies indicate that the known meddy structure is captured, but also that previously unnoticed and still unknown features have been detected. "Tendrils" having slopes not in agreement with intrusions, and also detached features resembling spiral arm on galaxies. Unfortunately the use of acoustic streamers in the Arctic Ocean is severely restricted by the presence of sea ice.
Question for discussion: How & where does Atlantic heat rise to affect the ice?

Questions:
Mary-Louise Timmermans: Physics of process at the base of the meddy? Features slope too steeply to be thermohaline intrusions. Woods papers.

Talks about Phillips instability (?).

Mike Spall: Importance of interleaving vs. eddy fluxes for getting Atlantic water off the boundary? Eddy fluxes are bigger?

Laurie Padman: Intrusions coming off E. Eurasian slope and Lomonosov ridge towards each other. Why do they match up? Or would one see if they do or don't.

Observations of Mixing Processes in the interior of the Arctic Ocean
Luc Rainville, UW-APL

Direct dissipation measurements show that the mixing level is low in the interior of the Arctic Ocean, giving $\kappa_T \sim 10^{-6}\ m^2 s^{-1}$. The system is forced in winter by convection confined to the upper polar mixed layer and by advection of denser shelf outputs. Melting of sea ice re-stratifies the upper ocean in summer. Only close to topographic features, continental slopes and ridges are high dissipation rates detected. The internal wave energy is also low and breaking internal waves is a weak source of mixing.

The main reason for the weak mixing in the interior is the presence of the ice cover and the strong stratification. The stratification also attenuates internal waves between the ice cover and the halocline and little wave energy is radiated to the deep interior. The primary energy source at the continental slopes is the tides, which also generate internal tides through interaction with the topography.

A reduction in ice cover would lead to more wind energy being transferred to the ocean and observations show that more inertial waves are generated in ice free conditions, which can be radiated to the Arctic Ocean interior (Rainville & Woodgate, 2009). A marked deepening of the upper layer also takes place during severe storms in spite of the strong stability. The largest effects of a reduced ice cover is expected at the continental slopes, which may become more frequently ice free and experience higher wind mixing than beneath the ice. However, the wind stress is larger over ice and largest in the marginal ice zone. Ice is better to impart momentum and energy into the ocean than an open sea surface. Patchy ice cover also leads to variation of the air-sea-ice fluxes and to generation of lateral density gradients and fronts that go unstable and lead to eddy formation.

Strong sub-surface mixing is observed where the two inflows from the Norwegian Sea, through Fram Strait and over the Barents Sea meet north and east of St. Anna Trough and when Pacific water flows down the Barrow Canyon or just crosses the shelf break.
Big Questions:
How best capture episodic events? Integrated impact of episodic events? Wind stress over the Marginal Ice Zone? High frequency ice dynamics?

Questions:
Benoit Cushman-Roisin: How long does energy last when strong summer forcing is applied? A week or two?

Rebecca Woodgate: Something on ice over SBI moorings.

John Toole: doesn't like the 40N winds experiment (Arctic winds aren't resonant with Arctic inertial period, but mid-latitude winds are).

It seems very unclear how air/sea/ice interaction works. Details sketchy.

Mesoscale eddies and their role in the Arctic System
Wieslaw Maslowski NPS

Mesoscale eddies can affect:
The Main Currents
Inter basin and shelf-basin exchanges
Sea ice melting,
Deep ocean convection
Eddy Kinetic Energy EKE and total Kinetic Energy EK in the ocean
But we do not know the role of mesoscale eddies in the Arctic Ocean although it is significant.
Sea surface height anomalies in Bering Sea indicate eddies along the Aleutian arc (Alaskan Stream), otherwise only barotropic waves.
The EKE is large compared to the total kinetic energy in Bering Sea. Eddies in the Chukchi Sea can be seen in models with 9km resolution.
Fram Strait and Nordic Seas described with fully coupled model (9km ocean and 50km atmosphere: RASM). Marginal Ice Zone air-sea monthly mean heat fluxes of 350Wm^{-2}. Labrador Sea, radar satellite image shows sea ice dipole leaving shelf.
How to identify eddies? Okubo-Weiss parameter?

Observation of mixing processes at the continental slopes and shelves of the Arctic Ocean
Yeung-Djern Lenn, Bangor

The stratification in the interior of the Arctic Ocean strongly influenced by processes active at the boundaries. The most prominent of these processes are the formation and export of dense water, sinking down the continental slope (Ivanov et al., 2004), and mixing with the boundary current and the interior waters forming eddies (Woodgate et al., 2005) or interleaving (Rudels et al., 1999). Strong mixing also occurs over prominent bathymetric features such as the Chukchi Cap (Woodgate et al., 2005) and over the Yermak Plateau (Padman & Dillon, 1991). At the Yermak Plateau Padman & Dillon find a heat loss from the Atlantic water reaching 25 Wm^{-2}, while (Fer et al., 2010) estimate weaker heat loss ranging between 2 and 4 Wm^{-2}. Thus interannual variability in the boundary current Atlantic Water may be due to the path taken by around the Yermak Plateau. Double-diffusive convection is active over the slopes and less turbulence dissipation is observed when double-diffusive layers are present.

Three sections taken across the continental slope north of the Laptev and East Siberian seas show large downstream changes in the properties of the Arctic Ocean halocline and the Atlantic water core that do not vary between the years. The vertical mixing is dominated by double-diffusive convection through diffusive interfaces, but microstructure measurements indicate that the heat fluxes are not large enough to explain the observed changes. They are one order of magnitude too low. Splitting of the boundary current at the Lomonosov Ridge is also found wanting in explaining the lower temperatures and salinities observed north of the East Siberian Sea. A possible mechanism is input of colder, less saline water from the shelves, not necessarily from the Laptev Sea and East Siberian Sea shelves. This could then imply input from the Kara Sea and the Barents Sea branch inflow.

The dissipation on the shelves is enhanced and bottom intensified. A drift northward across the Laptev Sea with microstructure measurements October 2008 showed intensified bottom mixing and strong dissipation in the surface layer. The dissipation in the bottom layer was higher, when the current was directed on shore. The dissipation cycle could be explained if a steady on-slope current of 2 cms^{-1} was added to the rotating tidal current vector and assuming the dissipation in the bottom boundary layer is governed by the vertically integrated bottom stress times the velocity.

Intense but varying mixing also took place in the pycnocline (20m) with peak heat fluxes of 52 Wm^{-2} that dominate the tidally-average fluxes of 12 Wm^{-2}. The shear production was balanced by dissipation and the shear might be enhanced either by increased surface stress or by interaction between the surface stress and barotropic and baroclinic tides. The observations in 2006-2007 were made close to the critical latitude, where the M2 and the inertial frequencies are equal. The strong burst in mixing occurred just after the surface drift shear was aligned with the tidal shear. A theory by Burchard & Rippeth (2009) suggests that enhanced mixing takes place when surface and bottom stresses and shear vectors are aligned. Such strong bursts could inject freshwater into the halocline and the Atlantic water. The dissipation as well as the shear follows the alignment of the tidal currents and the NCEP winds and over the seasons the maximum shear follows the stratification.

At the slope tides may modify the down and up slope exchanges similar to effects observed in the Ross Sea (Padman et al 2009) or Ekman layer upwelling or draining from the slope can also have an impact (Wåhlin et al., 2013).

Questions:
John Toole: sub-inertial current...?

Barry Ruddick: You focus on epsilon only, why not chi? Hard.

Laurie Padman: Why is shear-spiking not valid in deeper water? It should be.

Lars Umlauf: Law of the wall scaling for dissipation rates?

Dynamics of entrainment into thin, dense boundary current descending from the shelves into the deep basins
Lars Umlauf, Warnemünde

The transports of dense water down the continental slope require either friction, which breaks the dynamical balance between gravity and the Coriolis force that makes the flow follow the isobaths, or the presence of depressions or ridges enhances the downward channelling of fluid into the deep (Darelius, 2008). In a downward flow in a depression it is possible to have an along stream balance between friction and gravity and a cross stream balance between the Coriolis force, and the pressure gradient due to the lateral interface tilt. This is due to the downstream slope of the bottom and the interface, assumed to have similar slopes. Furthermore, it is possible to formulate a cross stream volume balance between the Ekman transport at the bottom and the geostrophic flow in the interior of the gravity current, leading to no net transport across a vertical plane parallel to the flow (Wåhlin, 2002, 2004).

The bottom drag coefficient C_D is expected to be much larger than the drag caused by the entrainment E, but also a large E can be accommodated. A Froude number can be defined based on the ratio of the bottom slope, b, the drag coefficient and an Ekman number and then a nonlinear ordinary differential equation for the interface height can be derived. In a vertically varying description with the coordinate system directed along the canyon the entrainment can be computed, using the GOTM turbulence model. Larges density differences lead to stronger entrainment. However, a less dense plume flows more slowly and when it reaches the same depth level the entrainment might be similar, provided that a density contrast still exists.

The cross flow structure of the gravity current is such that the interface is lower and thinner on the left side, away from the ridge. A secondary circulation is set up, bringing the entrained water towards the ridge, where it is forced down. This flow is geostrophic and at the bottom the Ekman transport brings the entrained water towards the centre of the gravity current. The accumulation of less dense water close to the ridge might, however, reduce the downstream pressure gradient to generate a bottom Ekman transport towards the ridge to make the bottom velocity become zero. This structure has been noticed in the Arkona Basin in the Baltic Sea, where the dense inflow from the Danish Straits (the North Sea) enters and renews the bottom water of the Baltic. There are no tides in the Baltic and the density contrast is 10 times that of the Arctic Ocean gravity currents, while the slope is about 1/10 of the continental slope around the Arctic Ocean deep basins.

Questions:
Benoit Cushman-Roisin: Why no KH instabilities? Ozmidov scales are 10-20cm so you wouldn't see them.

Benoit Cushman-Roisin: Strong bottom flow. Related to sediment erosion? Turbidity? Bottom is bare rock – already eroded,

Bert Rudels: What happened to 3-layer flow at thick end of the concluding schematic? Yes, it should be there.

Bert Rudels: Transfer your buoyancy differences to salt differences.

? Slope is corrugated in some places. What happens when slope is much steeper? More entrainment? What is a typical slope steep? Steeper slopes result in higher Froude numbers (higher entrainment rates) but also in a quicker descent, and thus less time for entrainment. Net effect is non-trivial.

Andrew Wells: Asks about entrainment parameterization details and dependence on velocity scale. The point here is that entrainment is a complex non-local process, so it cannot be described by local parameters like Fr.

Laurie Padman: Why is Cd variable? Cd is based on bulk velocity. Model is built on bottom roughness, not on specifying Cd.

Laurie Padman: Role of lateral mixing? Not well-known but it seems most lateral mixing is done via shear dispersion.

Tom Haine: Do you see static instabilities on the thick side of the plume? No because the Ekman layer thickness exceeds the plume thickness. In cases where that is not true, yes, you see static instabilities and overturning. E.g. Ilker Fer sees it in the FBC.

Stability of boundary currents and eddy formations
Mike Spall, WHOI

Input from the boundaries is essential for maintaining the stratification and the halocline in the interior. The mechanisms controlling the boundary-interior exchanges in the halocline are not well known but eddies are probably important. Eddies are common, but are mostly observed in the Canada Basin. They are mainly anti-cyclonal and located in the halocline. Cold core eddies suggest input from the shelves or from the Bering Sea winter water. Observations north of the Barrow Canyon show cold, nutrient rich shelf water in the halocline at 170m. The expected life time of an eddy is 1-2 years and 100-200 are formed every year.

From mooring time series obtained in the deep Canada Basin three types of eddies have been seen; Small eddies located around 80m probably formed by instabilities at surface fronts (Timmermans et al., 2008). Slightly larger eddies are observed in the halocline at 150-200m both warm and cold core eddies, suggesting both Bering Sea summer water and Bering Sea winter water. Finally deep anticyclonic eddies 1200m deep (Carpenter and Timmermans, 2012) could be detected. Mooring observations from the Eurasian Basin also show both shallow and deep eddies at the boundaries as well as in the interior of the deep Eurasian Basin. They appear to originate in the boundary current.

Many formation mechanisms have been suggested; baroclinic instability (Hart & Killworth, 1976; Hunkins, 1981), local buoyancy forcing, formation at topographic features such as submarine canyons, where they may attain anticyclonic vorticity by friction against the boundary (D'Asaro, 1988). The number of canyons is nevertheless limited and cannot explain all observed eddies.

Watanabe (2011) identified three types of eddies in the Beaufort Sea: 1) eddies formed in the Barrow Canyon, 2) bottom intensified jets in winter, and 3) surface intensified shelf break jets in summer. Different models capture many of the observed features. An idealised model of low potential vorticity shelf break jets produces many anticyclonic eddies in the halocline, consistent with observations. No slip conditions as well as steeper slopes lead to shedding of more eddies. Observations show sign of reversal of the lateral potential vorticity gradient with depth, a necessary condition for baroclinic instability. Also the eddy density flux and the net conversion rate from potential to kinetic energy is consistent with baroclinic instability. The model indicates that tracers are fluxed offshore by the eddies but that mass transport in the boundary current is not diminished (exchange rather than diversion).

The importance of eddies in the large-scale circulation of the Arctic Ocean as shown from an idealised numerical and analytical model. Freshwater is added at the rim. Atlantic water enters through Fram Strait and follows the slope around the basin. Constant wind and cooling are applied. The analytic model has three layers representing the shelf water, the Atlantic Water, and the halocline. The main assumption in the analytic model is that the vertically integrated salt flux between the boundary and the interior is carried by eddies and integrates to zero. Eddies transport low salinity water into the halocline at the surface and they transport saline Atlantic water into the interior at depth. These fluxes create the halocline in the interior. The density of the halocline then becomes intermediate between the surface water and the Atlantic water. Vertical diffusion then balances the eddy fluxes generated and driven by baroclinic instabilities at the rim.

The numerical model compares well with theory and a vertical diffusion coefficient of 10^{-5} to 10^{-6} m^2s^{-1} leads to a 200m thick halocline. The conclusion is that lateral eddy fluxes are essential in maintaining the halocline. The transport in the boundary current driven by the thermal wind balance can stop if the halocline becomes too dense and deep. Eddy transport and diffusion not only control the halocline formation but also the circulation of the Atlantic water. Small diapycnal fluxes may be important to ventilate the basins since the eddy fluxes take long time to flush the basin since the mean flow is along the slope.

Outstanding questions:

How large is the eddy tracer flux in the Arctic interior compared to mean flow, Ekman transport, interleaving, etc? Are eddies formed all along the boundary or preferentially near topographic features (canyons, steep slopes)? Relative influences of baroclinic, barotropic instability, singular catastrophic events? How do eddies decay? How might eddy fluxes change in a changing climate?

Questions:

Laurie Padman: Canada Basin eddy production rate is really every 1-2 days? This is not well constrained by observations.

Mary-Louise Timmermans: Observations show unrealistically large baroclinic conversion rate?

RebeccaWoodgate: Why does 7Sv recirculate in Fram Strait? Don't know, it is largely constrained by SSH but I do not have a theoretical understanding of what controls that (yet).

Depth of shelf water is cubed in the analytic model. Why? Yes, it's strongly dependent on that because of baroclinic instability parameterization.

Influence of the slope on the AW circulation and eddy fluxes? Yes, it is contained in eddy flux parameterization.

Laurie Padman: Effect of resolution on the scaling? Don't think it's converged yet, but not very important to overall result because scaling only depends on getting the cross-shelf fluxes right, not the decay of the eddies.

Laurie Padman: Vertical diffusivity dependence: is this sensitive to resolution? The model has not converged, but the primary point is that such a balance between shallow and deep eddies, and vertical diffusion, can produce a reasonable halocline and circulation of AW.

By construction the model omits many other processes that may compete with the eddies, such as Ekman transport.

Recreating density differences in the sea – The Adriatic case

Benoit Cushman-Roisin, Dartmouth

Mixing removes differences between water masses. To recreate differences in temperature and salinity energy must be supplied and the entropy reduced. This requires an open system. To reduce the entropy over a cycle requires that heat is added at the higher temperature and removed at the lower temperature of the cycle. This is the case on the global scale. The earth is heated at low latitudes and cooled at high latitudes. It applies to the ocean as well as to the atmosphere, and it may also occur on smaller scales.

Question: For a given warming-cooling rate, what is the created temperature difference?

Start by considering salinity. The open ocean generally evaporates water increasing the salinity, while in the coastal ocean the salinity is reduced by freshwater input from e.g. rivers and runoff. For a given evaporation Q_e and river runoff Q_r, what is the salinity difference?

Example the Adriatic Sea – and enclosed bay with exchanges with the Mediterranean through the Strait of Otranto and forced by the cold and dry Bora winds in the open northern part and by the freshwater input from the Po river close to the coast. The water transformations change the inflow into both low salinity surface and saline deep outflows. The freshwater input, 32 cm/year is about twice the evaporation rate, 15cm/year.

To quantify the transformations one part, α, is subject to freshening, while the rest (1−α) becomes more saline. Knudsen's relations then give:

$$Q_1 = \alpha Q_0 + Q_r; \quad Q_2 = (1-\alpha)Q_0 - Q_e$$
$$\alpha Q_0 S_0 = Q_1 S_1; \quad (1-\alpha)Q_0 S_0 = Q_2$$

The salinities of all components are known as well as the evaporation and the runoff, which makes it possible to compute α and Q_0. α becomes 0.65 and $Q_0 \approx 0.05$ Sv. With Q_0 known, vary α and compute ΔS for every α. The curve describing ΔS has a minimum for α = 0.57 giving ΔS = 3.87.

Now make the assumption that the solution tends to the one with the smallest ΔS. Knudsen's relations can then be augmented by the requirement $\frac{d\Delta S}{d\alpha} = 0$. Do the same for temperature, one part is heated and one part is cooled and minimize ΔT, the temperature difference between the two outflowing waters, with respect to α. Again the minimum is found for α = 0.57. Why?

Does the ocean, or any system, resist lowering the entropy and try to keep entropy at a maximum, and the separation of other variables at a minimum? Can this approached be used in the Arctic Ocean, which also acts as a double estuary, producing both less dense and denser water? Can it be extended by other, more dynamical constraints?

Questions:
Barry Ruddick: Could minimize other quantities. Yes, entropy (slightly different to T or S), potential energy.

Mary-Louise Timmermans: Like Stommel & Farmer on over-mixed case for exchange through a strait.

Mike Spall: Kinematic model, no dynamics? Yes. Is geostrophic balance an extra constraint? In the real Adriatic, do the currents follow topography?

John Toole: Global scale balance must constrain global mixing rates somehow (Terry Joyce?).

Relation to large scale circulation, heat and freshwater transports & to modelling: processes and parameterisations.
Andrey Proshutinsky, WHOI

The focus is on four issues:
Tide related mixing and its contribution to hydrography and transports.
Counter currents or counter forcing and their effects on large scale processes.
Freshwater accumulation in the Beaufort Gyre.
Role of landfast ice in the intensification of mixing processes.

Tides influence ocean heat budget through formation and deformation of sea ice and affect the mixing in the ice ocean and the ocean land/bottom boundaries. Tides mix oceanic heat to melt ice but also create open water and ridges allowing for regrowth and thickness increase. Strong dissipation takes place at bathymetric features such as the Yermak Plateau, at the continental slope and on the shelf seas. Mixing and transformation of Atlantic water is stronger in the interior in models including tides.

The most significant example of counter currents is the path of the runoff following the coasts around the Arctic Ocean, leading to intercontinental connections, “the Carmack hypothesis”. This feature can be found also in low resolution barotropic models.

The cyclonic and anti-cyclonic regimes defining the Arctic Ocean Oscillation (AOO) index were presented. After a long period of approximately equal length of the positive and negative AOO periods the anti cyclonic, positive, AOO state has now prevailed for 16 years leading to continuous accumulation of freshwater in the Beaufort Gyre. Are the Beaufort Gyre anti-cyclonic circulation and the freshwater accumulation irreversible? The wind (Ekman) accumulation during the last years is the strongest ever recorded. What will be the fate of the Beaufort Gyre if this state prevails? Model inter comparison experiments have been conducted, first anti-cyclonic, then cyclonic. The expected outcome is that increased mixing can force the freshwater to penetrate into the underlying ocean.

Land fast ice and mixing: East Siberian Sea has fast ice from mid-October to mid-May. Models have no fast ice and show biases in areas with fast ice. A very crude parameterization of land fast ice, put the ice velocity to zero, leads to improvements and many differences throughout the Arctic domain. Fast ice might have a large effect on the state of the Arctic.

Questions:
Andrew Wells: How large is internal variability in model compared to the model-model differences. Andrey doesn't know how to compare the model signal with internal variability. These results aren't trustworthy. Often there's open water beyond the edge of the fast ice. Or very thin ice.

Jari Haapala: Grounding points (“stamukies” (?)) are important for fast ice. Fast ice edge is dynamic.

The Arctic Ocean under sea ice: Ekman veering, internal waves, turbulence.
Sylvia Cole, WHOI

Data from ITP_V equipped with velocity sensors, were presented. During a drift period of 6 month, 9th October 2009 to 31st March 2010, in the Beaufort Gyre 2-3 eddies were observed. Strong internal wave and inertial motions were present in the upper layer and turbulent fluctuations caused vertical momentum, heat and freshwater (salt) fluxes, usually connected with strong events. Internal generated upward heat and salt fluxes while brie rejection caused downward salt but upward heat fluxes.

Ekman veering was observed underneath the ice. Ice drifts 28 degrees to the right of the wind and the drift angle between ice and ocean was 35 degrees to the right when the ice drift was fast.

The M2 period was close to the inertial period and the internal wave field had a peak at this frequency. An increase in M2/inertial frequency energy was observed through the winter. However, also changes in ice-ocean shear can generate internal waves. The observed internal waves had upward phase velocity indicating downward energy transport. There is little difference between the many existing methods for parameterize the momentum flux.

Questions:
Laurie Padman: Drag coefficient (ice/water) of 0.01 is the best fit.

Wieslaw Maslowski: Did the ice evolve after deployment? Unclear

Bill Williams: Mixed layer and internal waves is there a pattern? Not much data to tell.

Jari Haapala: Amplitudes of the internal waves? See upward propagating internal wave packet near eddy.

Lars Umlauf: Periodic structure in N^2 plot within the surface layer? Looks interesting.

The Arctic Ocean Climate – a balance between local radiation, advected heat and freshwater
Bert Rudels, FMI (Physical Oceanography seminar held in connection with the workshop)

Could there be an ice free ocean north of Eurasia and N. America? Discussed in 19th century. Bent (1972 – in Hayes, 2003). Strange idea considering failure to find NE and NW passages (Barents died in his Sea and Hudson died in his Bay). It was known that the air temperature was below freezing north of 70N. Why did they believe there was open water? Polynya north of Laptev Sea was observed. Sea ice is fresh: maybe seawater cannot freeze? Beyond the frozen river water it would be open. Or maybe the warm water from the Gulf Stream would keep the Arctic Ocean open.

1884 wreck of the Jeanette led to Nansen's idea about drifting with the ice across the Arctic Ocean, the Fram expedition 1893-1896. Nansen (1902) found a deep ocean (harder to freeze?). He also observed warm Atlantic water, but it was covered by low salinity surface layer and local brine rejection could not penetrate to the Atlantic water. The bottom layer was highly saline (actually an observational error, but it gave Nansen the idea that bottom water could be supplied by salty shelf drainage).

Sandström (1908) experiment with thermally driven ocean circulation and Nansen (1912) experiments on the effect of cooling through melting of ice. Put a bowl of ice on warm seawater. The ice melts and loses heat to the water, which convects thermally and generates a deep convective layer (the melt water stays in bowl). Without the bowl convection briefly occurs then switches off because low salinity surface water and a halocline form. Essential principles were known 100 years ago. Arctic Ocean climate is a balance between transport and mixing.

Early observations in the Arctic:

Successes and failures:
1931 Nautilus submarine expedition (Sverdrup was the oceanographer: WHOI contribution #1). Failure.
1937-1938 Soviet ice station 1. Success.
1941 Wüst deep water circulation. Didn't worry about the variability.
1950s Soviet airborne hydrographic stations
1960s-1970s manned drifting ice stations.
Ice camps and air-borne expeditions increased knowledge of the bathymetry.

Radiation & heat balances:

Serreze et al. (2007) heat balance north of 70N. Heat lost to space is provided mainly by meridional atmospheric fluxes.

Atlantic Water:

1980 Ymer-80 was an early scientific ice-breaker expedition. It didn't penetrate far into Arctic but obtained full cross sections in Fram Strait. One research topic was: could reduced river runoff lead to a decreased ice cover, raised by the plans of the Soviet Union to divert one or two of the Siberian rivers to central Asia for agricultural purposes.
1991 Oden got across the Lomonosov Ridge.
T/S diagram of the Eurasian Basin. Mixing arguments about shelf water and AW.
Mixing of AW T/S signal in Laptev Sea. See thin interleaving evolving into thick intrusions. 3 sections from Polarstern in 1990s. Talks about Fram Strait inflow branch and Barents Sea inflow branch.

How is heat in the Fram Strait branch lost? Need to lose 44TW. Can melt ice, store it, lose some heat in St. Anna Trough, lose to the ML in the Nansen Basin. Mechanism for vertical heat transfer in the interior of the Nansen Basin.: Filling box haline convection and heat transfer through diffusive interfaces.

Rudels (2010). Need to know the fraction of heat going into ice melt. Minimize this fraction to find a solution. It's about 30% in practice. The rest goes to the atmosphere.

Freshwater balance and fluxes:

Serreze et al. (2006) budget. Ice export is mainly controlled by the wind. Look at the liquid part. Buoyant baroclinic coastally trapped outflow (Rudels, 2010). Can compute the freshwater layer thickness needed to support the flow. The average thickness of the freshwater layer in the Arctic Ocean for a steady state is 8.5m If no ice is exported the mean thickness of the freshwater layer would be 10.1m. Freshwater storage increases as $\sqrt{F}$, F is the liquid freshwater export, and residence time decreases as $1/\sqrt{F}$. Barotropic exchanges in Fram Strait probably only add about 10% to freshwater fluxes. The freshwater export depends on the wind. Accumulation of freshwater in BG reduces its thickness in passages and reduces the fluxes.

Double estuary: forming/exporting less dense and denser water:

Eddy Carmack note on reference salinity. Discussion of brine rejection and penetration through halocline to Atlantic Water. 1980s Greenland sea deep convection. Since then salinity and temperature in deep water has increased due to advection through Fram Strait.

Exchanges through Fram Strait: inflow & outflow. Is it possible to have Arctic processes that change the density of the outflowing water to match the inflow without any barotropic circulation? Doesn't know but has a partial answer. Rudels (2012). Budgets volume, heat, freshwater. No purely baroclinic flow appears possible, and a barotropic component is necessary.

Global ThermoHaline Circulation:

Stommel 2 box model. Walin (1985). Neshyba (1986).

During LGM ice covered large part of NH and Nordic Seas. Albedo higher. Less OLR. Arctic ocean exports cold water and ice. Ocean heat transport keeps ice edge in place at low(er) latitudes. During LGM, ocean had to export ice southwards. Arctic controls climate (?)

Today: Little ice export is required to maintain the heat balance. Currently, have enough heat coming to the Arctic to melt ice more or less in place. Advent of seasonal ice cover?

Open Questions:

How does AW lose heat in the Nansen Basin. How much does this reduce ice production in Nansen Basin?
Why does minimum heat going to ice melt appear to give realistic salinities in the upper layer?
How well can freshwater export and storage be estimated by geostrophic flow in passages?
What drives Atlantic water inflow? Large-scale wind systems or local mixing processes?
What about Bering Strait opening/closing? How important is that for the Arctic ocean? During LGM it was closed.

Norbert Untersteiner Sea Ice Workshop summary:

Barry Ruddick & Laurie Padman

Agenda:

"An Untersteiner Workshop: On the Role and Consequences of Ocean Heat Flux in Sea Ice Melt"
March 19-21, 2013, University of Alaska Fairbanks, AK

Specific objectives for the workshop

1. Identify principal mechanisms for ocean heat flux to the sea-ice and ocean surface (includes "recycling" of atmospheric heating through the year, and an assessment of uncertainty in atmosphere/ocean/ice fluxes).
2. Quantify uncertainties in heat fluxes for individual ocean transport processes, and prioritize processes for further research.
3. Develop research methodologies for addressing processes identified as likely to play significant roles in ice heat and mass budget variability. This could include both current technologies and instrument development, and both in situ and remote sensing.

Day 1. Presentations by experts giving overviews (sea ice, atmospheric forcing, fluxes…
Day 2. Express presentations on specific issues.
Discussions of specific issues:
Double Diffusive Convection, Thermohaline Intrusions, Vertical shear of velocity (including tidal velocity), Internal waves, Lateral advection, Eddies, Measuring DD fluxes in the presence of shear
Measuring/mapping IWs/IntTides, and seasonal variability
Design of ice camp experiments
How accurately can we get the atmospheric fluxes? Measuring fluxes through sea-ice/snow
Day 3 (AM) Breakout groups
- BG#1 Atmosphere & ice (Room 417)
- BG#2 Ocean (Room 407)

Summary of workshop

Uncertainties in air-sea heat fluxes (10's Wm^{-2}) are far larger than likely contribution from deep ocean.

Ice mechanics, dynamics and thermodynamics (incl. snow load, melt ponds, etc.) dominate the picture.

Hypothesis that hasn't been eliminated yet: even if the Arctic Ocean were capped just beneath the halocline, little change would occur to the heat budget. But as Eddy says: The Atlantic carries lots of heat.

We propose to submit to *BAMS* a manuscript "*The emerging new Arctic Ocean: The role and consequences of ocean heat flux in sea ice melt*" by E. Carmack *et al*. This is a very timely contribution as there is great public and scientific interest in the rapid changes occurring in the Arctic Ocean.

This article will provide a broad overview of high-latitude changes to demonstrate that a new Arctic system has emerged. In the paper, we will:
define the new normal state for all components of the Arctic climate system,
demonstrate the increasingly important role of the upper ocean in shaping Arctic ice changes,
emphasize the critical need for emerging technologies and experiments for assessing the observed changes,
and outline a plan of future, integrated research.
We will provide a thorough description of questions centered on processes, magnitudes and spatial and temporal variability in the atmosphere and ocean and their relative impact on Arctic sea ice.

Our paper will guide general *BAMS* readership through the most exciting and important changes, providing a systematic view on major drivers governing these changes. In particular, this analysis will develop insight into the mechanisms responsible for redistribution of heat beneath the ice pack and its impact on bottom ice melt, lateral melt, and slowing of fall freeze up.

These processes change as sea ice volume declines; therefore, this study will make an important contribution to current knowledge of the ongoing high-latitude changes and the relative role of atmospheric and oceanic heat fluxes in diminishing Arctic ice cover.
Where are the big uncertainties? Especially for sea ice projections.
Accuracy of atmospheric fluxes. Errors are O(10) Wm^{-2}, far larger than flux up from AW.
Ice mechanics is very important. And snow load, melt ponds.
Ocean interior processes maybe secondary compared to the uncertainties in these surface processes.
But as sea ice disappears, the ocean becomes more important.

Final Discussion

The discussion at the end of the meeting was meandering but some specific inputs were given.

Near-surface temperature maximum (Jennifer Jackson) in western Arctic, but also seen in eastern Arctic.

What do we do next? Focus on how the Arctic ocean works with a seasonal ice cover (Bert)? Or, what is the role of the ocean in a seasonally covered Arctic ocean?

What diagnostics? What processes?

What about other changing inputs? Meteoric water? Atlantic Water? Winds?

Atmospheric response?

Arctic could move towards looking like: Southern ocean? Nordic Seas? something else?

Barry: Given that Arctic is changing, is monitoring technology sufficient?

Arrange a session on EGU/AGU meetings – how would such session be formulated? 4000€ have been allocated in the Marine Working Group budget for 2014, which can be used to prepare a proposal for a special section on Arctic Ocean mixing processes at one of these meetings.

Email input from Arild Sundfjord:
Mixing processes connecting the ice-ocean boundary layer with the underlying pycnocline and Atlantic Water
The largest immediate effects on the ocean in an Arctic Ocean changing from predominantly ice covered to partially seasonally ice covered will be seen near the surface. A thinner, more mobile ice cover with different drag characteristics will change the magnitude and vertical distribution of momentum from wind. Less ice will likely result in different fresh water content in the upper ocean, which implies altered

stratification. The combined effects of these two factors are difficult to predict and require further study if we are to assess the future development of the upper-ocean stratification, the halocline, and any drastic changes in the heat flux from AW to the surface.

Well-planned process studies in FYI areas, the MIZ, and in open water after ice melt, should be carried out. The deep basin, continental slope and representative shelf areas should be studied. Some of the open questions relevant for future ice free AO scenarios might be partially answered by looking at previous open-ocean studies from strongly stratified (coastal) regions at lower latitudes. New campaigns must be planned in close collaboration with the AO modeling community to ensure that the data obtained cover the appropriate temporal and spatial scales as well as the required forcing and diagnostic parameters that can be used to run parameterized processes in the various models.

Email input from Yeung-Djern

It seems to me that as a community we aren't at the stage of having a proper integrated view of the Arctic Ocean system yet. Perhaps it was because of the way we discussed each process separately and highlighted how each was important, but I didn't come away with a good feel for how each mixing process worked in combination with others to set the Arctic stratification, circulation and ocean-ice balance we observe. What we really need is a much better handle of relative fluxes because this is the key to understanding climate change. We have been in the habit of looking at balances within the global ocean in order to understand processes, but the Arctic is not a system in balance. We are still somewhat playing catch-up, having identified some, but perhaps not all the important mixing processes, without having adequately quantified the fluxes each process drives. Only by focusing on the roots of the imbalance within the Arctic ice-ocean system will we be able to predict the impact on future climate.

ICARPIII initiative

Based on the discussions a proposal for a workshop to explore the consequences of an Arctic Ocean with a seasonal ice cover has been sent to IASC with the aim to make this a theme in the ICARPIII conference 2015 and for the next 10 years. The decision on the proposal has not yet been made. The title and the work description are given below.

Seasonal Ice Cover in the Arctic Ocean: changes and consequences

The ice cover in the Arctic Ocean has gradually diminished during recent decades. The minimum ice extent in fall has decreased and the mean thickness has been reduced. Climate models also show that the arrival of a seasonal ice cover could occur by mid-century, perhaps earlier. Whether the present trend is irreversible or not, the fact remains that an almost ice free Arctic Ocean is a real possibility in a not too distant future. How would this change the physical processes active in the Arctic Ocean and the interactions with sea ice and the atmosphere? What would be the effects of ocean acidification, caused by uptake of CO_2, on the biological communities and on the ecology of the Arctic Ocean?

Some changes have not yet happened, and may not even take place. However, when considering research priorities in the Arctic extending ten years into the future, the moment, when the climate projections indicate a possible change to a seasonal ice cover, comes uncomfortably close. It might therefore well be worth to seriously address such questions as: What will change, and how, and what will essentially remain the same? The proposal is focussed on the ocean and on ocean processes, but interaction with sea ice and the atmosphere as well as causes and consequences of a changed radiation balance will be essential parts in the analysis.

The key parameter dominating the processes in the Arctic Ocean is the stability. It is caused by the net precipitation and the excessive continental runoff occurring in the Arctic, and it is the reason why the Actic Ocean is permanently ice covered. The stratification limits the vertical mixing depth in winter and the upper layer is cooled to freezing temperature and heat advected from lower latitudes becomes isolated from the sea ice and the atmosphere in most part of the Arctic Ocean.

An open Arctic Ocean allows for more wind mixing and wave breaking in the surface layer than in an ice covered ocean. However, a looser ice cover with ice keels present could transfer a substantial amount of wind energy into the ocean and the optimal state for transferring kinetic energy from the atmosphere to the ocean is not necessarily one without sea ice. Furthermore, the melting of ice will increase the stratification and the advected heat stored in the Atlantic layer might well be as inaccessible as today.

The annual freezing and melting cycle is expected to increase, more ice is formed in the open water in winter and more is melted in summer. It is an open question, if the increased freezing might, at least locally, compensate for the larger amount of freshwater in the upper layer and allow for increased ventilation of the deeper layer, or if these layers will become even more isolated. The ice growth will involve more frazil and less columnar ice, becoming more like the Southern Ocean.

The increased open water affects the albedo, making the surface water warmer and increases the evaporation, thus raising the water vapour and freshwater contents in the atmosphere. This leads to trapping of heat radiated from the ocean and a larger long-wave back radiation from the atmosphere to the sea surface, further increasing the temperature. A more compact cloud cover could, at least in principle, increase the albedo and partly compensate for the loss of sea ice, but are the clouds high enough, or will the effect on the long-wave back radiation dominate?

The increased water content in the atmosphere is likely to cause heavier snowfall in winter, which might lead to higher albedo in spring and the early part of summer before the ice disappears. The increased sensible heat loss and evaporation and the subsequent condensation in the atmosphere will promote a more energetic, locally driven atmospheric circulation in the Arctic.

The diminished Arctic Ocean ice cover is usually considered a consequence of the present increase in greenhouse gases in the atmosphere. How will the uptake of CO_2 in the Arctic Ocean, presently a net sink for CO_2, change when the ice cover is seasonal? Will the uptake be reduced by the warmer surface water or increased by the larger area of open water? If the production of dense water in winter increases, will this be connected with a transfer of more CO_2 into the deep Arctic Ocean? The CO_2 uptake in the Arctic Ocean is double-edged. An increased CO_2 concentration in the ocean will lead to stronger acidification. A situation that already is critical for the marine life in the Arctic Ocean.

The biology and ecology of the Arctic Ocean will be seriously affected. The increased stratification in summer is likely to inhibit nutrient supply from below and thus reduce the production in spite of stronger mixing and more light being available. Will the production be concentrated to continental slopes and topographic features, where enhanced vertical mixing is present? What will be the effects on ice algae and the communities thriving in the ice, when they cannot retain their habitats over summer?

The proposal aims at identifying and evaluating the likelihood and the effects of these, and other, changes that might occur. It will also confront the issues why and when the Arctic Ocean might become ice free in summer, and if it does, under what circumstances can it revert back to an permanently ice covered ocean (multiple equilibria). The work during the first part of the 10 years period will mainly be conceptual and concentrate on what consequences possible changes might have and how these changes could be observed, should they take place. Where are similar conditions to be seen today, in the marginal ice zone, in the southern ocean, along high latitude shelf breaks? The second part of the period will encompass more field work and tests of concepts.

Acknowledgement: We want especially to thank Anne Doucette and Andrey Proshutinsky for making this workshop a pleasant and fruitful event.

Appendices:

A1: Programme

IASC workshop on Internal Mixing Processes in the Arctic Ocean
Carriage House, Woods Hole Oceanographic Institute
Co-sponsored by WHOI & FMI
Conveners: Bert Rudels, Sheldon Bacon, Thomas Haine, Barry Ruddick, Michael Spall

Programme

Monday 21/10

8:30 Bus from Falmouth (Holiday Inn) to WHOI

9:00 Welcome, introduction, why are we here etc.

9:15 – 12:00 The Upper Ocean *Chair: Bert Rudels*

9:15 – 10:00
Observations of turbulence in the upper ocean and its importance for the heat flux to sea ice.
Takashi Kikuchi

10:00-10:30 Coffee

10:30 – 11:15
How ocean heat flux is melting sea ice?
Jari Haapala

11:15 – 12:00
Sea ice formation and brine rejection.
Andrew Wells

12:00 – 13:00 Lunch

13:00 – 17:15 Mixing in the interior *Chair: Bert Rudels*

13:00 – 14:00
Double-diffusive interfaces, their formation, extent and possible importance for the vertical heat flux.
Laurie Padman

14:00 – 15:00
Intrusions and interleaving.
Barry Ruddick

15:00-15:30 Coffee

15:30 – 16:15
Observation of mixing processes in the interior of the Arctic Ocean.
Luc Rainville

16:15 – 17:00
Meso-scale eddies and their role in property redistribution.
Wieslaw Maslowski

17:30 Bus to Falmouth

Tuesday 22/10

8:30 Bus from Falmouth to WHOI

9:00 – 12:30 Mixing at the boundaries and interaction with the interior *Chair: Sheldon Bacon*

9:00 – 9:45
Observations of mixing processes present at the continental slopes of the Arctic Ocean.
Yueng-Djern Lenn

9:45 – 10:30
Dynamics of and entrainment into thin, dense boundary currents descending from the shelves into the deep basins.
Lars Umlauf

10:30 – 11:00 Coffee

11:00 – 11:45 *Chair: Mary-Louise Timmermans*
Stability of the boundary current and eddy formation.
Mike Spall

11:45 – 12:30
Un-mixing and the creation of new temperature and density differences in the ocean.
Benoit Cushman-Roisin

12:30 – 13.30 Lunch

13:30 – 17:30 The large-scale picture *Chair: Sheldon Bacon*

13:30 – 14:15
Relation to large scale circulation, heat and freshwater transports & Relation to modeling: processes and parameterization.
Andrey Proshutinsky

14:15 – 14:30
The Arctic Ocean under ice: Ekman veering, internal waves, turbulence
Sylvia Cole

14:30 – 15:00 Coffee

15:00 – 16:00
The Arctic Climate – a balance between local radiation, advected heat and freshwater
Bert Rudels (Physical Oceanograhy Seminar)

16:00 – 16:30
What have we missed – input from the Norbert Untersteiner workshop in Fairbanks.
Laurie Padman & Barry Ruddick

16:30 – 17:30
General Discussion
Where do we go from here? What processes are important? How can knowledge be improved?
Which priorities should be set?

17:30 Workshop ends

18:00 Bus to Falmouth

A2: Participation list

Participants IASC mixing workshop at WHOI 21/10 - 22/10 2013.

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Observations of turbulence in the upper ocean.

Takashi Kikuchi, JAMSTEC

To collect observational data in the Arctic Ocean, we (all of the Arctic Ocean scientists) use icebreaker/research vessel, ice drifting buoy, mooring and other technologies. There are strengths and weaknesses to each approach. Regarding turbulent observation in the upper ocean, ship-based or ice-drifting buoy observation is more useful than others at this moment. Mooring observation are judged as less satisfactory since we could not collect data in upper 30m layer due to the presence of sea ice (to escape ice-risk).

As part of the North Pole Environmental Observatory (NPEO), JAMSTEC had been operated J-CAD (JAMSTEC Compact Arctic Drifter) or POPS (Polar Ocean Profiling System). Using these data since 2000, ocean-to-ice heat flux in the Atlantic side of the Arctic Ocean was estimated. The yearly averaged ocean-to-ice heat flux was greater in 2000 (3.10 W m^{-2}) and 2002 (2.89 W m^{-2}) than in 2004-2006 (~ 1.44 W m^{-2}). Surface mixed-layer temperatures above freezing point (δT) were higher in 2000 and 2002 than in 2003-2006. Although background oceanographic conditions in the buoy drift area were different for each year, we confirmed the hypothesis of Inoue and Kikuchi (2006) that sea ice drift speed in June and July (JJ) is the most important factor in determining total heat input from the atmosphere to beneath sea ice during the melting season. The mean ice drift in JJ was highly correlated with δT and the estimated ocean-to-ice heat flux and total basal melting in the Transpolar Drift. Based on this correlation between sea ice motion in JJ and ocean-to-ice heat flux, we suggest that ocean-to-ice heat flux displayed an increasing trend before the early 1990s, but a weakly decreasing trend after the mid-1990s to at least the mid-2000s. After impressive sea ice reduction in 2007, distribution of sea-ice age and thickness in the Arctic Ocean has changed. Kawaguchi et al. (2012, *Polar Sci.*) show that using POPS and ITP data at NPEO 2010, ocean-to-ice heat flux exceeded 60-70 W m^{-2} under first-year ice. It corresponds to about 1.5 m of ice melt over three months. In contrast, the multiyear ice region indicates nearly 40W m^{-2} at most and cumulatively produced 0.8 m ice melt, which was still much higher number than those before 2006. Kawaguchi et al. (2012, *Polar Sci.*) also suggested that wind-forced ice divergence led to enhanced absorption of incident solar energy in the expanded areas of open water and thus to increased ice melt.

Since late 1990s, JAMSTEC had been conducting observational cruise in the Pacific side of the Arctic Ocean by R/V Mirai which is ice-strengthen research vessel. Microstructure measurements were conducted in the recent R/V Mirai cruise using an ALEC Electronics Turbulence Ocean Microstructure Acquisition Profiler (TurboMAP). The TurboMAP collects profiles of micro-scale velocity shear; high- and low-resolution temperature; conductivity; pressure; turbidity; fluor-escence; and x, y, and z-acceleration between the surface and depths of approximately 500m as the device descended. From data collected during R/V Mirai 2010 cruise, a vigorous horizontal interleaving structure was identified in the vertical temperature and salinity profiles (see Kawaguchi et al., 2012 (*Deep-Sea Res.*)). The locations are in the vicinity of unusually big warm core eddy observed in the western Canada Basin. Several micro-scale measurements reveal that such interleaving is widespread and causes a rapid dissipation of temperature variance through double diffusion, which is likely to contribute to a significant delay of ice formation during late-fall or winter. Two weeks stationary observation in the northern Chukchi Sea was conducted by R/V Mirai between September 11 and 25, 2013. Interesting oceanic response to changes of atmospheric conditions were observed. Similar stationary observation for three weeks will be made in September 2014, depending upon ice conditions.

Regarding mooring observation in the upper ocean, we could collect interesting year-long data by Multi-frequency Acoustic Zoo-plankton Fish Profiler (MF-AZFP) manufactured by ASL Environmental Science. It can visualize both zoo-plankton activity and a change of physical oceanographic conditions. Although there are some difficulties to detect signal of turbulent motions, mixing, and internal waving from MF-AZFP data, I guess that the sensor has huge potential on our research purposes.

How ocean heat flux is melting sea ice?
Jari Haapala, FMI

Abstract still missing

Sea ice formation and brine rejection
Andrew Wells, Atmospheric, Oceanic & Planetary Physics, University of Oxford

The Arctic sea ice cover is undergoing a period of rapid change, one consequence of which is the increasing significance of first year ice processes. Sea ice is an evolving porous material consisting of an ice crystal matrix bathed in liquid brine, and fluid flow through the porous ice controls the desalination of sea ice and buoyancy forcing for the ocean. This talk reviews the thermodynamic processes contributing to sea ice growth, and the controls on brine rejection. Vertical salinity gradients within the ice drive convective gravity drainage as the dominant mechanism for desalination of first year ice in winter, whilst flushing by surface melt water is effective in summer. The convective gravity drainage results in dense saline plumes sinking through narrow brine channels, with a weak return flow from the ocean through the remainder of the ice. Field observations, laboratory experiments and theoretical modelling have provided valuable insight into many of the processes at hand. However, we have an incomplete quantitative understanding of certain factors such as granular sea ice formation from frazil ice, or the impact of time dependent forcing or ocean heat fluxes on brine rejection from sea ice.

Double-diffusive interfaces; formation, extent and possible importance for the vertical heat flux.
Laurie Padman, ERS, Corvallis

Abstract still missing.

Intrusions and Interleaving
Barry Ruddick, Dalhousie

Abstract still missing.

Observations of Mixing Processes in the interior of the Arctic Ocean
Luc Rainville, UW-APL

The interior of the Arctic Ocean is characterized by weak turbulence levels. Observations from ice camps and ice-based instruments have shown that the sea-ice cover effectively isolates the water column from direct wind forcing and damps existing motions, resulting in an internal wave field much weaker than at lower latitudes and relatively small upper ocean variability. Under the ice, direct and indirect estimates across the Arctic basins suggest that turbulent mixing does not play a significant role in the general distribution of oceanic properties and the evolution of Arctic water masses. However, during ice-free periods, the wind generates inertial motions and internal waves, and contributes to deepening of the mixed layer both on the shelves and over the deep basins - as at lower latitudes. Strong lateral gradients, generated by localized buoyancy or momentum forcing, may also lead to instabilities and diapycnal mixing. We are challenged to capture these episodic and spatially inhomogeneous mixing processes in both observational and numerical studies and understand their integrated role on the Arctic system.

Mesoscale eddies and their role in the Arctic System
Wieslaw Maslowski NPS

Abstract still missing.

Observation of mixing processes at the continental slopes and shelves of the Arctic Ocean
Yeung-Djern Lenn, Bangor

The deep Arctic basins are relatively quiet diapycnal mixing environments where eddies and intrusions carry warm salty Atlantic and Pacific water laterally from the boundaries into the interior basins and double diffusive convection slowly fluxes heat up through the halocline to the ice-covered polar mixed layer. Like much of the global ocean, the continental slope and shelf seas of the high Arctic are expected to be the more energetic environments characterised by high dissipation of turbulent kinetic energy (tke) that can drive vigorous diapycnal mixing. For instance, we know that Arctic internal tides generated at the critical continental slopes must be dissipated locally as they are prohibited from propagating. However, microstructure shear observations of tke dissipation along the Arctic continental slope show that there is large variability in diapycnal mixing along the Arctic boundary. High dissipation and diapycnal mixing are confined to regions of significant topography or tides such as the Yermak Plateau, Chukchi Cap and north of Svalbard. Along the Beaufort Sea margin where there is frequent generation of shelf-break jet eddies, there are also elevated tke dissipations observed. Elsewhere along the Arctic continental slope, slow double diffusion convection dominates heat fluxes of 1-2 W m ^-2 through the halocline as it does in the deep basins. North of Laptev Sea, the double diffusive convection is an order of magnitude too small to account for changes in heat content and salinity of the halocline, implicating lateral exchange with the basins and shelves as a more important process for water mass transformation. In contrast, observations prove the fresh Arctic shelf seas to be much more energetic environments. In addition to the many processes important for dispersing freshwater across the shelves, such as tidal straining, brine rejection, wind-driven mixing, we identify a shear-spiking diapycnal mixing mechanism driven by the interaction of the tide with the surface stress transmitted either from the winds or sea ice drift. Observations demonstrate that this is an important process that accounts for intermittent pycnocline mixing events of up to 50 W m^-2, 25 times as much as the background fluxes, that can dominate the overall mixing in the Laptev Sea. Further research applying the shear-spiking to the open ocean suggests that this intermittent mixing may be important here too, and highlights the need for proper time-series process studies to adequately resolve the intermittent turbulent mixing elsewhere in the Arctic. The contrasting environments of the Arctic basins, slope and shelf seas points us towards seeking a better understanding of the cross-slope exchange processes that together affect the water mass transformations of the high Arctic. Candidate processes for future research should include the role of eddies, the role of tides both in mixing at the margins and exporting high-salinity shelf water across the slope, Ekman transport both in terms of a barotropic response to on/off-shelf surface transport and bottom Ekman layers on the slope.

Dynamics of entrainment into thin, dense boundary current descending from the shelves into the deep basins
Lars Umlauf, Warnemünde

Abstract still missing.

Stability of the boundary current and eddy formation
Michael Spall, Woods Hole Oceanographic Institution

It has become increasingly apparent in recent years that mesoscale eddies are an integral part of the time dependent circulation in the Arctic Ocean. Eddies have been observed in the upper halocline, lower halocline, Atlantic layer, and deep Arctic, and are found in both the Canada and Eurasian Basins. Water mass properties of these eddies indicate that most originate from narrow boundary currents, which are

themselves formed from waters on the shelves or connected to the Atlantic Ocean. These eddies transport heat, freshwater, potential vorticity, and other tracers such as nutrients large distances across the Arctic basins. Linear theory, numerical models, and mooring data suggest that baroclinic instability of boundary currents is responsible for their formation. An idealized numerical model and a three-layer analytic model of the Arctic Ocean suggests that such eddies may play a central role in the maintenance of the Arctic halocline and drive the circulation of Atlantic Water into the Arctic Ocean. While current understanding suggests that eddies are an important component of Arctic oceanography and, by extension, Arctic climate, many questions remain regarding their formation mechanisms, propagation and mixing processes, and role in the general circulation.

Recreating density differences in the sea – The Adriatic case

Benoit Cushman-Roisin, Dartmouth

Abstract still missing.

Relation to large scale circulation, heat and freshwater transports & to modelling: processes and parameterisations.

Andrey Proshutinsky, WHOI

Abstract still missing.

The Arctic Ocean under sea ice: Ekman veering, internal waves, turbulence.

Sylvia Cole, WHOI

The ice-ocean system is investigated on inertial to monthly timescales using winter 2009- 2010 observations from the first Ice-Tethered Profiler (ITP) equipped with a velocity sensor (ITP-V). Fluctuations in surface winds, ice velocity, and ocean velocity at 7 m depth were correlated. Observed ocean velocity was primarily directed to the right of ice velocity and spiraled clockwise while decaying with depth through the mixed layer. Inertial and tidal motions of the ice and in the underlying ocean were observed throughout the record. Just below the ice-ocean interface, direct estimates of the turbulent vertical heat, salt, and momentum fluxes and the turbulent dissipation rate were obtained. Periods of elevated internal wave activity were associated with changes to turbulent heat and salt fluxes as well as stratification primarily within the mixed layer. Turbulent heat and salt fluxes were correlated particularly when the mixed layer was closest to the freezing temperature. An improved heat flux parameterization is suggested which accounts for this correlation. Momentum flux is adequately related to velocity shear using a constant ice-ocean drag coefficient, mixing length based on the planetary and geometric scales, or Rossby similarity theory. Ekman viscosity described velocity shear over the mixed layer. The ice-ocean drag coefficient was elevated for certain directions of the ice- ocean shear, implying an ice topography that was characterized by linear ridges. Mixing length was best estimated using the wavenumber of the beginning of the inertial subrange or a variable drag coefficient. Analyses of this and future ITP-V data sets will advance understanding of ice-ocean interactions and their parameterizations in numerical models.

The Arctic Ocean climate – a balance between local radiation, advective heat and freshwater

Bert Rudels, Finnish Meteorological Institute

The debate about the existence, or non-existence, of an ice cover in the Arctic Ocean has a long history, starting in the 18th century, before any vessel yet had penetrated into the Arctic Ocean. One reason for the belief that a northerly ocean might be ice free in spite of the severe high latitude climate was the northward transport of warm water by the ocean currents, especially the Gulf Stream that could prevent ice to form. Nansen’s drift with Fram 1893-1896 put an end to these speculations. The Arctic Ocean was ice covered. The warm water from the Atlantic was present in the Arctic Ocean but covered by a low salinity layer that could be cooled to freezing temperature without convecting into the Atlantic layer, thus allowing ice to

form. Laboratory experiments showed that cooling might generate a thermally driven meridional circulation (Sandström, 1908), but ice melting on warmer water would create a low salinity upper layer, preventing convection (Nansen, 1912). The buoyancy added by the melt water thus dominates over the buoyancy loss due to cooling and could act to break the meridional overturning circulation. The main processes determining the conditions in the Arctic Ocean and the Nordic Seas were then known 100 years ago. Cooling at high latitudes makes water denser and partly drives the ocean meridional circulation northward. However, the freshwater transported by the atmosphere from lower to higher latitudes causes a freshwater input to the Arctic Ocean that prevents deep convection, isolates the heat and allows ice to form. Can the presently observed changes in the Arctic Ocean ice cover be indications that this state might change, and if so, what would be the effects on the ice cover and on the ocean circulation and what is the role of the ocean in this process? To partly answer these questions the exploration and the research in the Arctic Ocean during the last 100 years are reviewed and then five important aspects of the Arctic Ocean circulation are discussed: (1) The radiation balance is presented. (2) The inflow of Atlantic water through Fram Strait and the Barents Sea and the circulation of the two inflows in the Arctic Ocean, and how heat is transferred from the Atlantic water to ice melt and the atmosphere are then discussed. (3) The freshwater balance of the Arctic Ocean is described and the possibility to determine the freshwater storage from the assumption of geostrophic upper layer flow in the passages is explored. (4) The fact that the Arctic Ocean is a double estuary, transforming the inflowing Atlantic water into both less dense water through ice melt and freshwater input, and to denser water by freezing and brine rejection on the shallow shelves that then sinks down the continental slopes as entraining boundary plumes ventilating the deeper layers is presented. The implications of these processes for the exchanges through Fram Strait are then briefly described. (5) Finally the Stommel (1961) box model of the thermohaline circulation is discussed. The different time constants or feedbacks of heat and freshwater (salt) allow for two different modes of thermohaline circulation, one direct mode where warm water flows north and loses heat at the surface, sinks and returns in the deep, and one, weaker mode where freshwater input at high latitudes makes the water less dense and it returns at the surface to be supplied from below by warm, saline water sinking in the tropics. This mode cannot lose heat directly to the atmosphere. Instead it has to be mixed into the surface layer from below, leading to a much smaller oceanic heat input to the high latitude atmosphere. Can such excessive freshwater input, e.g. by melting of the Greenland ice sheet, take place today? Although unlikely, it is a possibility and it points to the pivotal role of freshwater, freshwater transports and phase changes. In a cold climate freshwater resides as ice, the albedo is high and the heat supplied by the short-wave radiation is small. The heat balance is maintained by the export of ice that melts at lower latitudes. In a warmer climate, more freshwater is exported northward by the atmosphere, carrying latent heat, and when it reaches the Arctic it affects the radiation balance by increasing the long-wave back radiation to the sea surface. Less ice export is then required to close the Arctic heat balance and an Arctic Ocean with only a seasonal ice cover becomes a real possibility. In a cold climate the high latitude can influence the lower latitudes. In a warmer climate the heat and freshwater transports in the atmosphere and their effects on the radiation balance appear to dominate the processes taking place in the Arctic causing its temperature to rise.