Photos taken at the CATS / ASOF-WEST meeting at IOS in Sydney Canada. See article on the right (see report at page 21).

Is the Oceanic Heat Transport in the North Atlantic Irrelevant to the Climate in Europe?

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It has long been believed that the transport of heat northward by the Atlantic Ocean circulation is of importance to mean/seasonal atmosphere-ocean climate, and with less certainty, to decadal climate variability. Indeed, ASOF is founded on the idea that oceanic fresh-water and heat transports are both crucial to climate. The importance of ocean circulation has been challenged by Seager, Battisti, Yin, Gordon, Naik, Clement and Cane (2002), hereinafter 'SBYGNCC', in their paper, 'Is the Gulf Stream responsible for Europe's mild winters?' While centering attention on the mild climate of Europe, their work, if correct would have greater consequences. Their argument is based on belief in following: that:

(i) only a small portion of the total northward heat transport north of 40°N, is accomplished by the ocean in comparison with the atmospheric heat transport

(ii) oceanic heat storage is *local*, with the summer's heating of the mixed layer being the dominant source of wintertime oceanic heat release to the atmosphere, with little contribution from oceanic heat transport

(iii) fresh-water transport coupled with heat transport can be neglected.

Here we argue that while (i) is true it is misleading, (ii) is based on a simple logical fallacy in their paper, and is incorrect for much of the northern Atlantic, and by neglecting (iii) they have missed the most important climate interaction of all.

One could hardly argue against the persuasive reasoning provided by SBYGNCC that the maritime climate maintains the temperature contrast between the North America and Europe. However, their conclusions regarding removal of the oceanic heat transport could be taken to mean that oceanic heat transport has no significant consequence for the climate in Europe and elsewhere, beyond a minor warming of 0°C-3°C.

We address points (i) to (iii) in order. (i): Satellite radiation measurements combined with atmospheric observations assimilated into models give estimates of total, atmospheric and oceanic meridional heat flux. Recent analyses elevate the atmospheric contribution somewhat, the atmospheric transport peaking between 4 and 5 PW (5×10^{15} watt), while the ocean transport peaks at about 2 PW (Trenberth and Caron, 2001). However, as Bryden and Imawaki (2001) emphasize [using transport estimates of Keith (1995)], the atmospheric flux is comprised of nearly equal contributions from latent- and sensible heat. Latent heat is fresh water (2.5 PW per Sverdrup), and its transport is an intrinsically coupled ocean/atmosphere mode. Keith's transports plotted against latitude show the dominance of subtropical ocean evaporation in driving the global system. The moisture/latent heat pump of the Atlantic storm track is a crucial part of maritime climate. It is ignored in the thermodynamic discussion of SBYGNCC. [This satellite and atmospheric assimilation method of inferring transports needs improvement, a symptom of error being the large flux divergence over land areas, which cannot be correct.]

(ii): If the ocean (here, the Atlantic Ocean) participated in climate only through local, seasonal heat storage and release in the shallow mixed layer, then calculations of ocean circulation would be unnecessary for climate models. Indeed, SBYGNCC state in their abstract that " ..the majority of heat released during winter from the ocean to the atmosphere is accounted for by the seasonal release of heat previously absorbed and not by ocean heat flux convergence." This conclusion follows from their comparison of the annual mean oceanic heat transport convergence with the wintertime release of heat at the sea surface, the latter being much larger. Both are inferred from reanalyzed surface heat flux observations of the northern Atlantic, by da Silva, *et al.* 1994. Values they estimate (averages north of 35°N) are 37 W m^{-2} heat convergence by the ocean circulation, vs. 135 W m^{-2} wintertime heat release from surface observations. This is based on the estimate of 0.8 PW northward oceanic heat transport at 35°N.

Let us assume all these numbers are accurate. A model of the annual cycle would then involve year-round northward heat flux by the Atlantic circulation, *together with its release to the atmosphere in a few winter months*. We thus should be comparing the time-averaged heat-flux convergence by the ocean circulation, *multiplied by the ratio 12/(number months of wintertime convection),* with the upward heat flux at the sea surface observed during those winter months. The details depend upon the vertical distribution of the north-south heat advection (referenced to the late winter mixed-layer temperature). Using an estimate that ½ of the transport lies deeper than 100m (above which depth most of the local, seasonal heating is trapped), suppose we release that heat in 3 winter months and release the other ½ from the upper 100m during 6 months of the year. The surface heat flux during winter becomes concentrated by a factor 12/6 x ½ + 12/3 x ½ = 3. Multiplying 37 W m^{-2} from above by 3 gives 111 W m^{-2}, enough to account for much of the observed winter upward heat flux at the sea surface (135 W m^{-2}). This argument shows that oceanic heat advection is plausibly important in warming the atmosphere in winter. The same, or even more dramatic, result follows of we take the da Silva *et al.* monthly surface heat fluxes and integrate them with respect to time, Figure 1. Start in spring, when the net surface flux changes sign and integrate forward. In regions with annual average heat flux that is upward, the integral will eventually come back to zero, indicating that the locally stored summer's heating has been removed by cooling from above. After this date, continuing upward heat flux must have been imported by the ocean circulation. Averaging north of 25°N latitude (keeping north of the zero-mean air-sea heat flux line) in the Atlantic we see that by early to mid-December, the locally stored

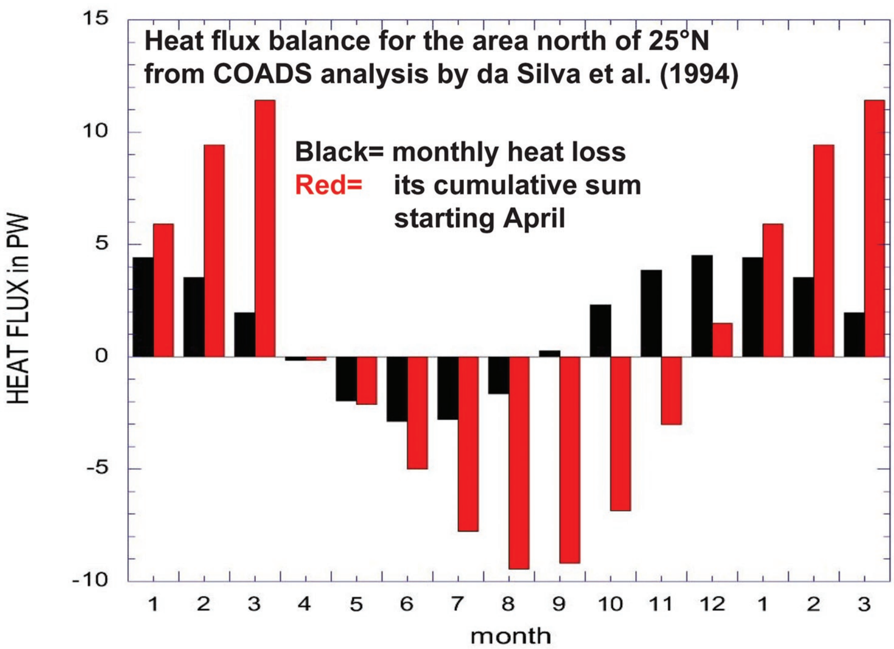

Figure 1. Using COADS air-sea heat flux reanalyzed by da Silva et al. 1994, (black bars) we integrate forward in time (red bars). When the integral returns to zero, the local, seasonal heating has been removed by autumnal cooling. On average, by early December the local heat source is exhausted and for the remainder of the winter oceanic warming of the atmosphere relies on heat imported by the ocean circulation.

heat is exhausted, and excavation of imported heat dominates the rest of the winter. These ideas are all subject to accuracy of the consensus oceanic heat transports, and analysis of air-sea heat-flux feedbacks due to the ocean circulation-induced SST. Improvement will occur when water-column heat storage observations become numerous enough. Indeed, wherever winter mixed layers exceed 50 to 100m in depth, we infer that ocean circulation is important, because seasonal surface heating cannot mix down deeper than this, even with the aid of the winds. This is a strong argument for sustained time-series observations of temperature and salinity as can be provided by floats, gliders and moorings. Several parallel arguments given in the SBYGNCC paper, and a similar one given by Wang and Carton (2002) suffer from the same logical error pointed out here, for example when geographical distribution of winter air-sea heat flux is compared with heat convergence by the ocean circulation.

Finally there are subjective elements here. The model simulations with suppressed ocean circulation show surface winter temperature changes of 6°C to 12°C over much of northern Eurasia, reaching 21°C in Scandanavia. The average temperature change north of 35°N is 6°C in their GISS-model. We would call these changes 'large'; yet SBYGNCC argue that they have "little impact". The great differences apparent between their two simulations (one with a non-dynamical ice model, the other without any ice model) remind us of the complexity and uncertainty of coarsely resolved climate model results, when so many critical high-latitude and upper ocean physical processes are under-represented. And, more to the point, surgical removal of oceanic heat transport has other implications (iii, below).

While this has been a discussion of mean wintertime heat balance, some aspects apply also to decadal and secular variability. The warming of northern Asia associated with greenhouse forcing, yet partially associated with strong positive phase of the North Atlantic Oscillation, is shown by Thompson and Wallace (2001) to involve zonal heat advection: we take this to be a sign of Atlantic oceanic heating penetrating farther eastward over Asia.

(iii) The SBYGNCC model experiments use oceanic mixed layer models which are only governed by heat exchange with the atmosphere and by (diagnosed) heat transport. This type of model ignores fresh-water flux and fresh-water transport which are known to play an important role in inhibiting heat release from the ocean and determining sinking regions of the meridional overturning circulation (MOC) at subpolar and polar latitudes: Too much fresh water at the surface stabilizes the water column and sea ice can form, changing fundamentally the seasonal cycle of heat exchange between the ocean and atmosphere. On spatial scales beyond the convective regions, the fresh water cycle and heat transport are coupled globally through the thermohaline circulation as was first discussed by Stommel and Csanady (1980). This coupling is played out on the θ-S plane, which is the fundamental 'phase plane' of physical oceanography (Bailey *et al.* 2003).

The global hydrologic cycle has a familiar pattern of high precipitation and runoff at high northern latitudes, evaporation in subtropical oceans, and narrow bands of evaporation and precipitation associated with the ICTZ. A net flux of fresh water from high northern latitudes to the low latitude evaporation sites is needed, even after river pathways are accounted for. The thermohaline MOC provides the return circuit for atmospheric vapor transport. In the North Pacific, low salinity stabilizes the surface layer of the subpolar gyre and there are no truly deep sinking regions. A shallow salinity minimum guided and subducted by the wind-driven Ekman transport, reaches toward the tropics. Yet most of the excess precipitation seems to escape through the Arctic. The robust MOC in the Atlantic illustrates how the θ-S diagram couples the heat- and fresh-water transports, and involves both subpolar and Arctic water-mass transformations. The pioneering study of Stommel and Csanady (1980) gave simple two-degree of freedom illustrations of the nature of these coupled transports. They estimated the northward mass transport of salty waters and the compensating mass transport of less salty deep water using the observational estimates of heat and fresh water transport and water mass properties for the latitudes 40-45°N.

We wish to reiterate the conclusions of Stommel and Csanady and to show that heat transport and fresh water transport are intimately coupled, removal of only one of them renders the problem meaningless. We consider a two-layer box model of the polar and subpolar oceans bounded by the Bering Strait and 45°N, using information of the 'known' mass fluxes at the surface, river runoff and at the Bering Strait. It is shown that from the conservation of salt and fresh water we can diagnose the overturning to satisfy the equilibrium conditions and at the same time diagnose the heat transport when the upper-lower layer temperature difference is given. The following computation is done using the definitions of Wijffels et al. (1992) for fresh water and salt transports. For simplicity we assume densities to be 1000kg m^{-3} for the ocean and river and P-E fluxes. The inflow (Vbe) of the Bering Strait is 0.8 Sv with salinity (Sbe) 32.5ppt. P-E flux over the area from the Bering Strait to 45°N is about 0.1Sv and the runoff (R) from land in the same region amounts to about 0.19Sv. At 45°N we want to solve the average flow (Vo) and the baroclinic transport V (all velocities are defined positive southward). The upper layer Atlantic salinity (Sa) is 35.3ppt and the bottom layer salinity (Sb) is 34.9ppt. Now we can set the conservation equations for salt and fresh water as follows:

Salt:
Vbe Sbe = (-V + Vo/2) Sa + (V + Vo/2) Sb
Fresh water:
Vbe (1-Sbe) + R + P-E = (-V + Vo/2) (1-Sa) + (V + Vo/2) (1-Sb)

Substituting the above given values in the conservation equation gives, for Vo and V, 1.09 Sv and 30.65 Sv respectively. This simple scheme illustrates the thermohaline nature of the fresh water redistribution where the northward mass transport in the upper layer is 29.04 Sv and the southward transport in the bottom layer is 30.11Sv. If the temperature difference between the upper and lower layer is 8C, the northward heat transport would be about 0.9PW at 45°N, which is close to the value quoted in SBYGNCC for the ocean heat transport at 40°N representative of the present climate. Thus based solely on conservation of salt and fresh water, with hydrographic data we can diagnose the overturning and the associated heat transport to satisfy the equilibrium conditions when the different fresh water fluxes of the present climate are given.

We have arrived at the crux of the problem not considered in the numerical experiments of SBYGNCC. Removal of the oceanic heat transport due to the thermohaline circulation means also that the redistribution of the fresh water is blocked which in the real world would lead to accumulation of fresh water at the high latitudes. The lack of the thermohaline circulation intensifies freshening because no salt is transported northwards. The fresh water accumulation will eventually build an extensive sea ice cover north of 40°N and influence the seasonal uptake of heat in the ocean. This is consistent with the paleo-records showing that periods of extensive ice cover over the high latitude ocean, and over the European and North American continents, were associated with weak production of North Atlantic deep water (Boyle and Keigwin, 1982; 1987) and thus a weak thermohaline circulation. So in fact during the height of the last ice age, the maritime effect was reduced to a minimum, and the temperature gradient across the Atlantic vanished.

In summary, accounting for the fresh water accumulation at the high latitudes alters significantly the picture suggested by SBYGNCC: It is the existence of the oceanic heat transport that allows the maritime effect to operate in the northern North Atlantic and to create a milder European climate than in the North America; without the heat transport, ice would likely extend over much greater areas of ocean and land. Since the northward heat transport and southward fresh water transport in the Atlantic are strongly tied together, removing oceanic heat transport influences the climate and atmospheric circulation in ways that are not possible to simulate with a simple mixed layer model coupled to an atmospheric model. This also suggests that use of this type of model with a fixed oceanic heat transport (today's climate) is not suitable to describe climatic states where the thermohaline circulation is expected to change significantly from the present, as might happen for instance in doubled CO_2 scenarios where the fresh-water input at high latitudes can increase by 40% or more (Manabe and Stouffer 1994).

Removal of one piece of a complex machine (here, the oceanic heat transport) can have unforeseen consequences. We have pointed out some, and there may be others, such as effects on cloudiness, atmospheric standing waves and storm tracks. The conclusion of SBYGNCC that the particular climate feature of interest, the warming of western Europe, is 'fundamentally caused by the atmospheric circulation interacting with the oceanic mixed layer', and thus 'does not require a dynamical ocean' is flawed in the three aspects described above. This abbreviated discussion will be expanded in a succeeding paper.

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ASOF in the Subpolar Gyre: Recent Results and Future Plans

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The subpolar North Atlantic is one of the best-studied oceans we know. Careful measurements over decades reveal intense water-mass transformation by both vigorous air-sea interaction and interior diabatic mixing. Through this reservoir pass the North Atlantic Current, yielding its heat to moderate Europe's climate, and North Atlantic Deep Water (NADW), a critical, but perhaps fragile, part of the global deep circulation. It also contains one antinode of the Atlantic-wide sea-surface temperature (SST) tripole pattern associated with the North Atlantic Oscillation (NAO) and has undergone large and sustained changes since 1950. Perhaps, nowhere else does such a small part of the ocean play such a large part in climate and its variability. Moreover, it continues to surprise us.

Most oceanographers believe that the central Labrador Sea is the formation site of the ubiquitous weakly-stratified waters of the mid-depth subpolar gyre - hence the name Labrador Sea Water (LSW). But recent work challenges this orthodoxy (Pickart et al. 2003a,b; see also the commentary by Dickson 2003). High-resolution, high-frequency meteorological data point to the southern Irminger Sea as another, maybe intermittent, region of LSW formation. Steered by the southern Greenland topography, frigid air