# Arctic Ocean Water Mass Transformation in the Arctic Subpolar gyre sTate Estimate (ASTE): Budget Analysis in Temperature-Salinity Space


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## Introduction

The Arctic has warmed at a significantly higher rate than lower latitudes [9, 8, 4]. Atlantification, the process of increasing advection of Atlantic Water (AW) into high Northern latitudes is a source of heat for the Arctic Ocean (AO). Thus, identifying pathways by which AW reaches the AO and modifies heat content in the water column is fundamental to understanding the impact of climate warming on Arctic sea ice cover.

The Water Mass Transformation (WMT) framwork can be applied to the Arctic to study the pathways of AW inflow. Previous studies of AW pathways have included analysis in geographic space [6], or have performed WMT analysis without accounting for conservation relations [7]. Novel diagnostics in the Arctic Subpolar gyre sTate Estimate (ASTE) combine observational data with physical consistency, enabling comprehensive analysis of closed budgets at the grid scale assessment of the relative contributions of surface, advective, and diffusive fluxes in modifying water masses, particularly through analyses conducted in temperature salinity (T-S) space.

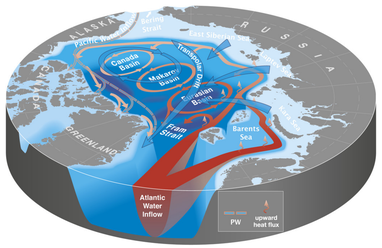


Figure 1. A schematic of circulation of the surface water, intermediate Pacific Water, and Atlantic Water of the Arctic Ocean [2]

## WMT Framework

By using conservation relations, flow across isothermal/isohaline surfaces is expressed in terms of diffusive and surface fluxes of heat/salt independently of any time changes in a volume $V$ [10, 3]:

$$G_S = S\frac{\partial E}{\partial S} - \frac{\partial F_S}{\partial S} \tag{1a}$$

$$G_T = -\frac{1}{c}\frac{\partial Q}{\partial T} - \frac{1}{c}\frac{\partial F_T}{\partial T} \tag{1b}$$

Above, $E$ is the net flux of freshwater, $Q$ is the net flux of heat, and $c$ is the heat capacity per unit volume. From these equations, we create a 2-dimensional vector that gives the strength and direction of transformations in the coordinates of temperature and salinity:

$$\mathbf{J} = (\frac{\partial G_S}{\partial T}, \frac{\partial G_T}{\partial S}) \tag{2a}$$

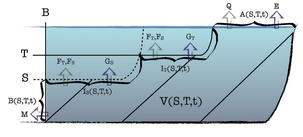


Figure 2. WMT can be quantified through discrete volumes in the ocean. Here, $G_S, G_T$ are volume flows across isohaline or isothermal surfaces, and $F_S, F_T$ are diffusive salt and heat fluxes. Using the output of ASTE, these can be calculated for analysis in T-S space.

## Initial Results

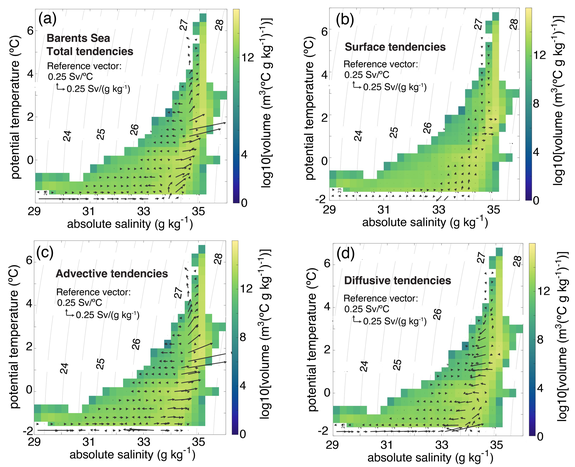


Figure 3. T-S diagrams from ASTE Release 1 for the year 2014 in the Barents Sea, showing the net transformation (a), which is broken down into components due to surface (b), advective (c) and diffusive (d) fluxes.

Figure 3 shows the volume distribution in T-S space in the Barents Sea using the WMT framework in ASTE. We can quantify the impact of each component of fluxes on WMT as follows:

- (a) The total tendencies show a transformation towards saltier water at high salinity as well as low temperature, and a warming of higher temperature waters. This reflects inflowing AW and surface forcing in this region. Slight transformation to fresher waters at low salinities reflects runoff and meltwater.
- (b) Surface fluxes (i.e. ocean-atmosphere exchange) lead to a transformation of Atlantic Water to cooler temperatures between 3–7°C, as well as transformation of cold and fresh surface water to higher temperatures between -1–3°C.
- (c) Diffusive fluxes have the impact of homogenizing Barents Sea Water. This is seen by the transformation of ending members of cold, fresh water and warm, salty water towards more central values of T and S.
- (d) Advective fluxes primarily make the Barents Sea saltier. In this region, this impact is due to the AW inflow through the Barents Sea Opening.

As Figure 3 demonstrates, the WMT diagnostic tools in ASTE provide substantially more verbose data and insights in T-S space than has previously been available in WMT analysis [3, 7]. These robust analyses can be used to evaluate ongoing changes to the Arctic Ocean due to Atlantification in the changing climate.

## Arctic Subpolar gyre sTate Estimate (ASTE)

ASTE [6] is a medium-resolution Arctic-North Atlantic model-data synthesis for the period 2002–2017. It utilizes non-linear the adjoint framework developed within the Estimating the Circulation and Climate of the Ocean consortium, and is based on the MITgcm [5]. Data constraints for ASTE comprises of $10^9$ satellite and in situ observations. The solution is obtained through least-square minimization of model-data misfits and non-linear inversion for input parameters. Through strict adherence to conservation laws, ASTE enables analysis of closed budgets of heat, salt, mass, and momentum at the grid scale. Recent developments to include water mass transformation diagnostics, updated from [1], further allows analyses of surface forcing, ocean transports, and mixing processes in both geographic and T-S space.

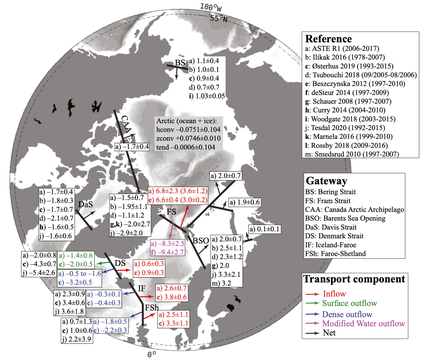


Figure 4. A comparison of volume transport records across key gateways in the Arctic. These volume transports can be further decomposed in T-S space using WMT diagnostics in ASTE.

## Research Objectives and Future Work

- Investigate WMT in Arctic sub-basins and across key gateways.
- Evaluate heat loss of Atlantic Water (AW) along its pathway as it circulates through the Arctic Ocean.
- Assess the mechanisms of ongoing Atlantification, focusing on the changing roles of surface forcing, lateral advection and internal mixing.
- Quantify effect of fluxes on WMT, assess influence of salinity or temperature.
- Investigate Arctic-Sub Arctic exchanges.
- Interrogate the processes which alter heat content in the mixed layer.

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