13.2 ARCTIC OCEAN CHANGE: WHAT CHANGES AND WHAT DOESN'T

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1. INTRODUCTION

Against paucity of observations and unanswered challenges to modeling, it is difficult to see which changes in the Arctic ocean reflect larger complexes of change. We seek to understand causal relations, in part to help monitor change and in part (perhaps?) to anticipate change.

The purpose in this paper is to try to conceptualize the Arctic ocean/cryo system as simply as possible, aiming to recognize what changes and what (relatively) may not change. Three layers are considered:

1) the snow/ ice/ near surface ocean,
2) a halocline layer,
3) the sub-halocline ocean,

with the main focus of this paper upon the sub-halocline. Conceptual aspects are tested and elaborated from modeling.

2. SNOW, ICE & NEAR SURFACE

This is the realm of hugely rich physics, well represented by abstracts at this meeting. Responses to changes in radiant and thermal energy forcing, affected by snowfall and snow blow, along with lateral ice motion under varying windstress, can be rapid -- occuring over timescales from hours to seasons. It is a subject area of intense, ongoing research, and there is nothing to add from this talk.

3. HALOCLINE LAYER

Physics may get a little simpler (but not simple!) in a salinity stratified, cold layer from tens to O(100) m deep. While subject to surface buoyancy forcing, especially during sea ice formation, the principal control over changing halocline thickness and transport results from changes in larger scale windstress. These are processes amenable to numerical modeling. Although observation of halocline circulation has proven difficult, model results suggest that wind-forced halocline flows participate with the observed sea ice motion in shifts between more anticyclonic and more cyclonic flow. Timescales for change are seasonal to interannual.

4. SUB-HALOCLINE

The main thrust for this paper is change occuring below the main halocline, and its interaction with halocline flow. Large changes have been observed, such as shifting Atlantic/ Pacific boundaries during the mid-1990s (Jones et al., 1996; McLaughlin et al., 1996; Swift et al., 1997). Do these changes reflect major reorganization of sub-halocline flow?

Numerical model results across nine major models collected within the Arctic Ocean Model Intercomparison Project (AOMIP) reveal markedly different versions of sub-halocline flow. Under as nearly as possible the same forcing, and evaluated for the same time period, even the *sense* of circulation (more cyclonic or more anticyclonic) is *ambiguous* across the suite of models.

So far as models express our best knowledge of physics (limited by finite computation), are we learning something about actual physics of the sub-halocline Arctic? Is it the case that that a balance of physics for the sub-halocline is really so delicately poised, easily reversing sense under modest external change? Or is the physics represented by ocean models systematically deficient?

5. PHYSICS RECONSIDERED?

I suggest it is mistaken physics that leads us to ideas of easily reorganised sub-halocline circulation. Traditional notions of ocean dynamics (hence ocean models) come from classical mechanics applied to geophysical fluids ("GFD"). In part these are valid, as reflected in partial successes of models. However, classical mechanics remains incomplete, missing the role of statistical physics. In the case of the sub-halocline Arctic, I believe the "missing physics" (from traditional modeling) accounts for a highly persistent circulation. The problem instead will be how to account for change! But first the missing physics --

Because variability within the Arctic far exceeds ability to observe or to model (in entire detail), we instead consider probabilities of possible Arctics and moments (expectations) from those probabilities. Equations of motion of moments of probable Arctics resemble traditional modeling, but there is more.

Gradients of the entropy (- <logP>), where P is the probability function, act as forcing upon the moment fields. One can complete the physics of traditional models, as was done in Arctic context by Nazarenko et al. (1998) or Polyakov (2001) employing different methods. In both cases, inclusion of statistical physics resulted in stunning differences for sub-halocline flow as persistent, narrow, cylonic rim currents appeared which were absent or ambiguous under traditional modeling.

A new challenge emerges. With statistical physics, sub-halocline transport pathways are dominated by strong, persistent cylonic rim currents which are not directly related to external forcing by wind or buoyancy. While the ice, near surface and halocline layers are forced to shift between cyclonic and anti-cyclonic regimes, the sub-halocline circulation seems little affected. Then how can water properties change markedly?

6. A SIMPLIFYING SCHEME

Learning Arctic dynamics from numerical model outputs can be slow and hazardous. However, dominance of statistical physics in the sub-halocline simplifies matters. Although full models *(statistically completed!)* remain necessary for testing and quantifying myriad details, we can schematize. Because classical forcing is relatively weak below the halocline, the entropy gradient (with respect to circulation) must be also weak. Then we can characterize the deeper circulation as being near a locus of vanishing entropy gradient, i.e. near the maximum entropy or minimum information ("unprejudiced", as Holloway and Ramsden, 1990) flow. This has been further simplified to a transport streamfunction $Y^*=-fL^2H$ from which the velocity map in Fig 1 was drawn, where f is Coriolis, L a length scale (a few km) from eddy vorticity spectra, and H is total depth.

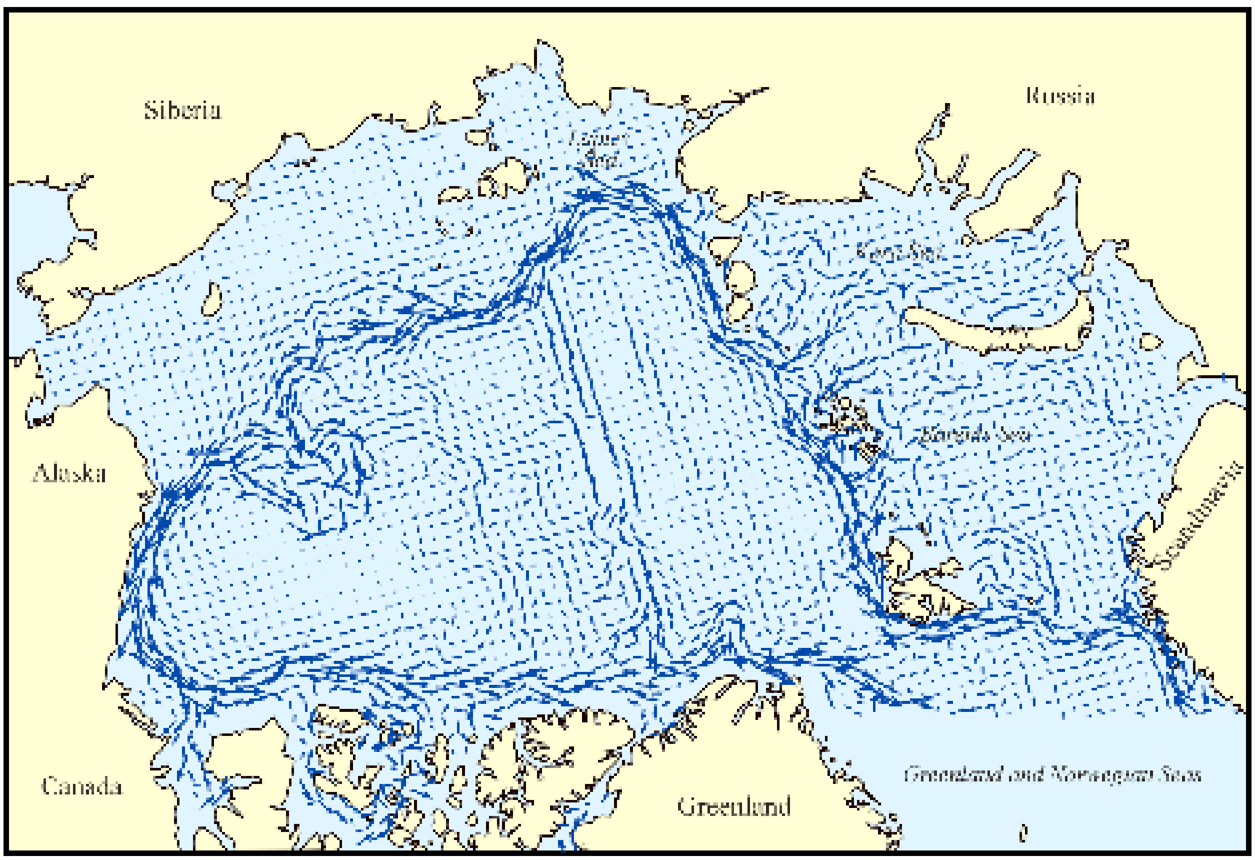

Figure 1. Unprejudiced flow.

A point should be made clear. Fig. 1 is not a "theory" of Arctic circulation but only a simplifying *(no numerical model)* starting point for discussion.

Notably, $Y^*=-fL^2H$ offers little prospect for change on contemporary timescales! What I do believe is that changes of external forcing, affecting the near surface and halocline layers, drive the Arctic away from Y*. Displacements from Y* then induce the entropy gradients which complete the force balance (Holloway, 1999,2002).

We may imagine -- schematically -- the Arctic under more cyclonic or anticyclonic forcing, seen in Figures 2 and 3. Light arrows indicate upper ocean flow while red arrows indicate the sub-halocline flow after Y*.

The key question remains: if flows shown by red arrows are remarkably unchanging, how do sub-halocline propety boundaries change? The answer, I think, comes at only a very few key diffluence (branching) points where even subtle displacements from Y* feed large changes to property boundaries.

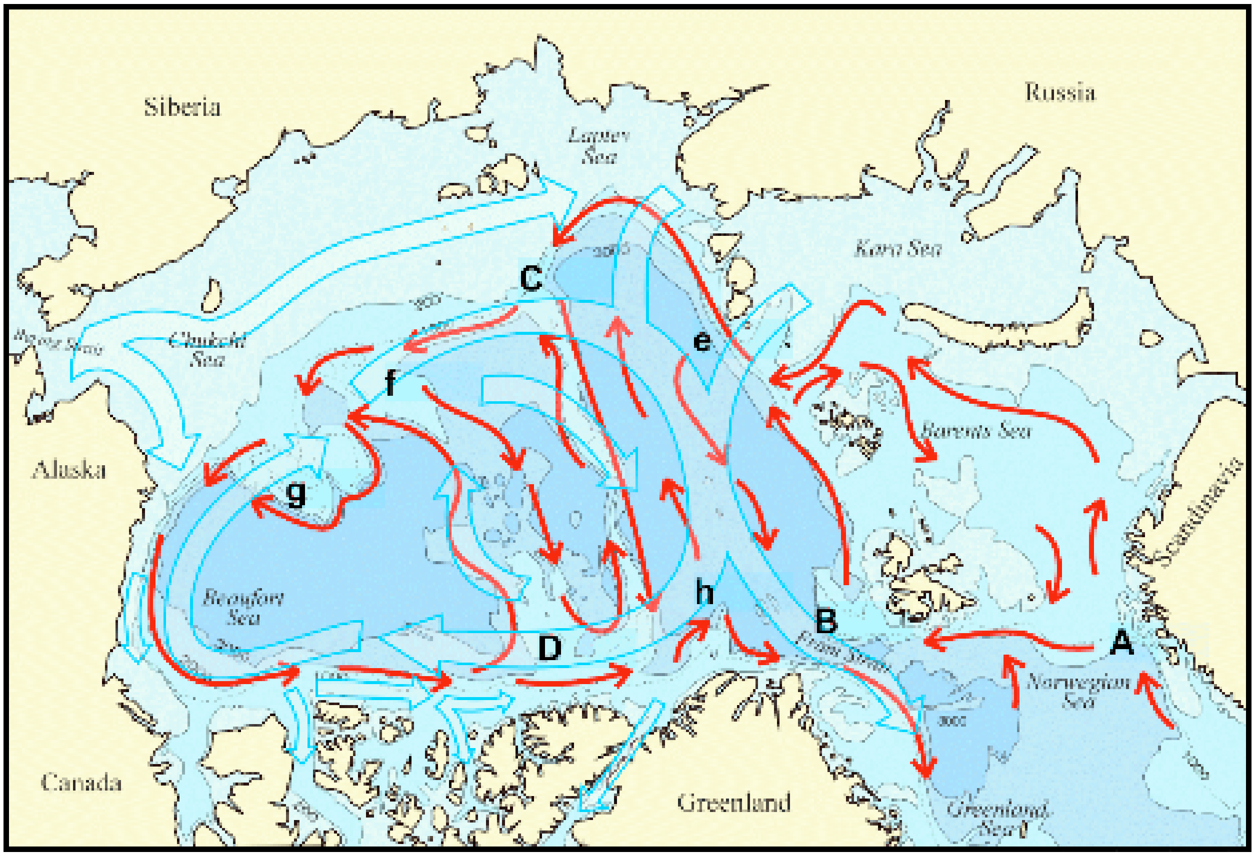

Figure 2. The anticyclonic scheme.

On Fig 2 letters mark diffluent points, with the more important in capitals. These points will be well recognized by Arctic researchers. To “tour” briefly --

The first important diffluence is at “A” where fractions of Atlantic water turn more into the Barents Sea or more along the Norway-Spitzbergen slope as affected by regonal wind.

The next major diffluence, “B” is at Fram Strait, denoting a region where changing fractions of Atlantic water may be caught up in recirculation into the Greenland Sea. (I make a worried confession about giving too little attention to diffluences associated with the Bear Island trough.)

Then there is a puzzle how important may be diffluences “e” both at St Anna Trough where some Atlantic water from the Arctic Ocean is turned back onto the Barents Sea and east of Vorigin Trough where a variable portion of Atlantic water is captured within the Nansen Basin. The region exhibits high variability due to confluence of the Barents and Fram Strait branches, with varying strengths (after “A” and “B”) and upstream properties. Although the region is marked by high property variability, I am only guessing that the role of diffluence at “e” is less. This region (should “e” be “E”?!) invites and requires far more thorough investigation from observation and modeling.

We come next to what I nominate as the single most critical diffluence within the Arctic: “C” at the juncture of the Lomonosov Ridge and Siberian Slope (Woodgate et al., 2001). Here, subject to subtle regional forcing transmitted through the halocline, differing fractions of Atlantic water are retained in the Amundsen-Nansen Basins or spill over into the Makarov-Canada Basins. It is at "C" that I would look for the cause of most property boundary changes.

Diffluence "f" at the Mendeleyev-Siberian juncture affects retention of Atlantic properties within the Makarov Basin.

Then "g" is a little different. In part I only denote the complex Chukchi Borderland region with special interest from strong encounters of Pacific-source and Atlantic-source waters. Of further interest near "g" is the oppostion of imposed forcing that tends anticyclonically and the statistical forcing that would sustain cyclonic rim currents. "g" is not so much a diffluence as a region of instability where Atlantic properties carried by the boundary current may readily shed to the basin interior.

"D" is another mystery region (in caps because it's my pen) denoting the complex Alpha-Lomonosov-Canadian Slope juncture where a variable fraction of Canada Basin water mmay be retained or "lost" to the Atlantic.

Finally "h" denotes a diffluence within the Eurasian basins which plays roles both closing a deeper Amundsen gyre and also feeding Canada basin properties into the Eurasian basins interior.

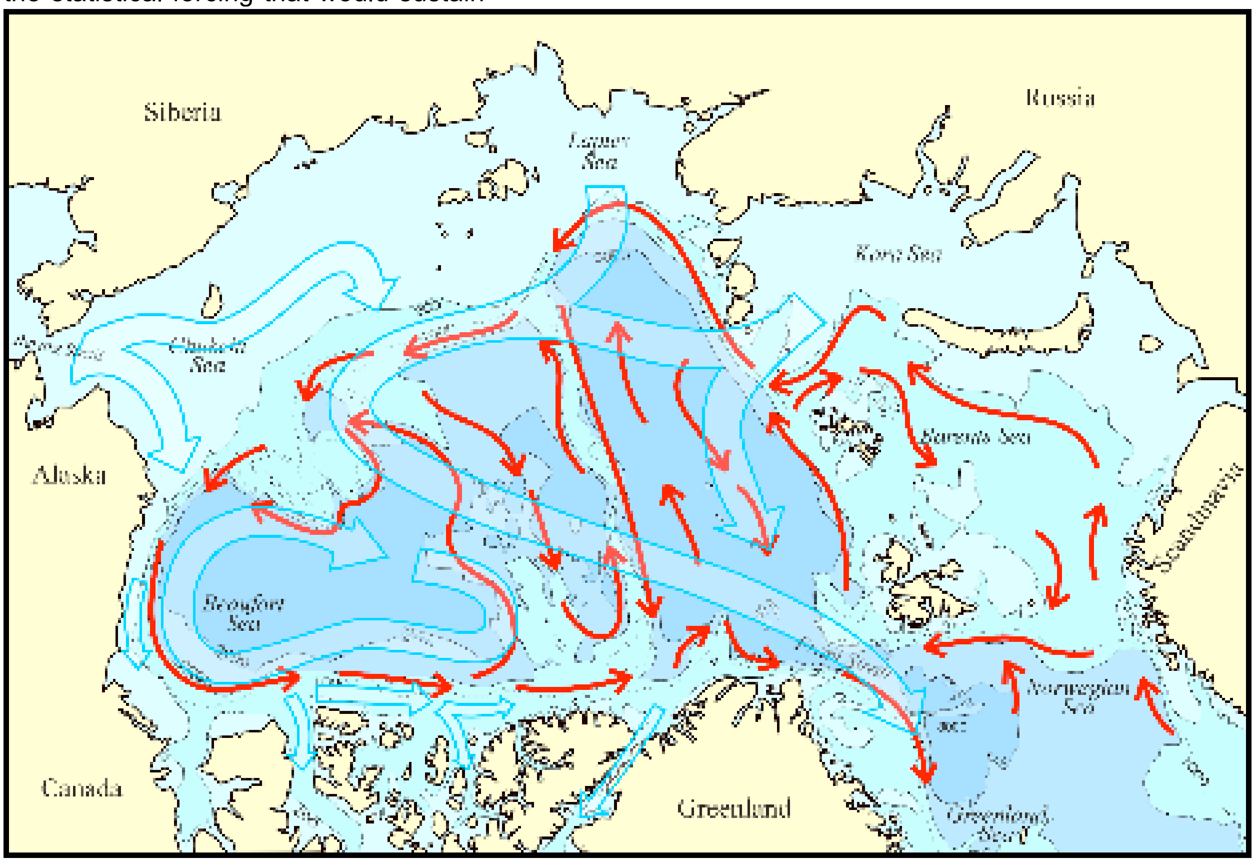

Figure 3. The cyclonic scheme.

7. OUTLOOK

The goal above is simplicity. More detail can and surely will be added. Relative significances of the indicated diffluences will be reconsidered. Quantification (indeed testing) of these ideas perforce rests with numerical models. There is a vital caution though. Models merely do the bookeeping after we persons provide the physics (and chemistry and biology in some cases). The main concept here presented is that applied forcing displaces Arctic circulations in ways that set up gradients of entropy which, in turn, act to force the circulations (understood as moments of probable circulations). Traditional models, grounded in classical mechanics (GFD) recognize applied external forces but not the induced entropy gradient forcing. I believe this omission leads to a sense of ambiguous sub-halocline circulation, readily subject to change. I believe that is mistaken. Physics didn't end with classical mechanics and neither should we.

8. ***References***

Holloway, G. and D. Ramsden, 1990: Unprejudiced ocean circulation. Eos, **71**, 174.

Holloway, G., 1999: Moments of probable seas: statistical dynamics of Planet Ocean. *Physica D*, **133**, 199-214.

Holloway, G., 2002: Toward a statistical ocean dynamics. p277-288, in Statistical Theories and Computational Approaches to Turbulence. Y.Kaneda and T.Gotoh, eds. Springer, 409 pp.

Jones, E. P., K. Aagaard, E. C. Carmack, R. W. Macdonald, F. A. McLaughlin, R. G. Perkin and J. H. Swift, 1996: Recent changes in Arctic Ocean thermohaline structure: Results from Canada/U.S. 1994 Arctic Ocean Section. *Mem. Natl Inst. Polar Res.*, Special Issue **51**, 307-315.

McLaughlin, F. A., E. C. Carmack, R. W. Macdonald and J. K. B. Bishop, 1996: Physical and geochemical properties across the Atlantic/Pacific water mass front in the southern Canadian Basin. *J. Geophys. Res*., **101**, 1183-1197.

Nazarenko, L., G. Holloway and N. Tausnev, 1998: Dynamics of transport of 'Atlantic signature' in the Arctic Ocean. *J. Geophys. Res*., **103**, 31003-31015.

Polyakov, I., 2001: An eddy parameterization based on maximum entropy production with application to modeling of the Arctic Oceancirculation. *J. Phys. Oceanogr*., **31**, 2255-2270.

Swift, J. H., E. P. Jones, K. Aagaard, E. C. Carmack, M. Hingston, R. W. Macdonald, F. A. McLaughlin and R. G. Perkins, 1997: Waters of the Makarov and Canada basins. *Deep Sea Res. II*, **44**, 1503-1529.