Iceberg Severity off the East Coast of North America in relation to Upstream Sea Ice Variability: An Update

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***Abstract*— Earlier examination of strong correlations between mid-winter spatial extents in Davis Strait and large annual variations in the estimated numbers of icebergs passing south of 48°N motivated detailed studies of the origins of variability in iceberg numbers was conducted over twenty years ago [1].**

This work established the critical role played by the processes that control the cyclonic movement of the icebergs from their primary West Greenland calving ground to the northern perimeter of Baffin Bay and, subsequently past the coastal shelves of North America. It was demonstrated that the effectiveness of these processes and year to year variations in their timing tended to overwhelm interannual variations in Greenland iceberg calving rates. A major connection between such fluxes and upstream ice extent was established through the effectiveness of extensive pack ice in lowering deterioration and melt rates of freely drifting icebergs during the last, late winter through early summer, segments of their drift trajectories. This role is exercised through the effectiveness of sea ice in lowering the local water temperature and reducing sea state parameters which essentially determine iceberg lifetime in these segments. Comparisons between historical International Ice Patrol (IIP) records of annual south of 48N iceberg numbers and a shorter record (post-1960's) of sea ice extents indicated strong correlations between the former and the January spatial extent of ice in Baffin Bay and Davis Strait north of 67N. Measures of this extent, designated as the Davis Strait ice index (DSII) were subsequently used on their own or with modifications as a basis for early season assessments and apportionments of resources by the IIP and others with interests in East Coast navigation.

The iceberg severity off Newfoundland is revisited in the light of several major efforts to document and reorganize East Coast iceberg data-taking and analyses as well as the availability of, roughly, 20 more years of higher quality sea ice and iceberg data. The updated and extended analysis includes assessing impacts of suspected over-counting in early iceberg surveys and access to improved Canadian Ice Service (CIS) digital ice chart data, available from 1971 to the present, which allows better resolution of the sea ice data in marine areas upstream of 48N both in terms of areas of interest and in time. Examination of the 1971-2014 sea ice concentrations in Davis Strait for mid-January reveal that the post 2000 ice extents are consistent with the iceberg numbers being lower than those observed and inferred from the 1980-1999 sea ice concentrations. This extended analysis also discriminates between sea ice types, in particular first year ice vs. the thinner new to young ice categories for regions with three-tenths or more in ice concentration in the DSSII area of interest.

I. Ice Introduction and Background

In the mid- and later-1980's, the imminence of offshore development off eastern Canada created needs for anticipating the severities of individual annual iceberg seasons, with emphasis of on the late spring and early summer period when icebergs occur most frequently. In historical and practical terms, such severities were defined as the annual (October through September) number of icebergs crossing 48°N. These icebergs represent the longest surviving portions of the cyclonic flow of freshwater linking the glacier fronts of West Greenland (and, possibly, East Greenland) to the Northwest Atlantic (Fig.1).

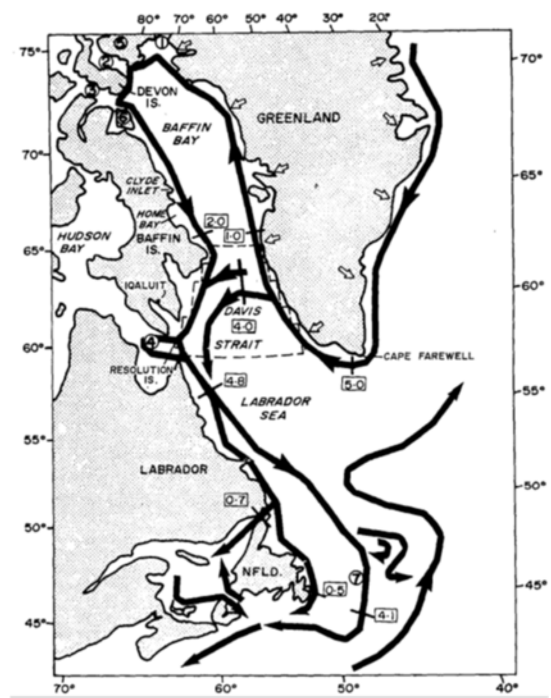

Fig. 1. A map of the pathways of iceberg circulation off eastern North America. The numbers appended at various points along the circulation are representative of ocean current volume transports (units of million m3/s) for the indicated regional circulation features [1].

Several approaches to improved seasonal forecasts (i.e. 4-6 months) of the upcoming iceberg season severity were examined [2] [3], including statistical correlations with temperature and pressure trends as well as with broader modes of atmospheric variation, such as the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO index).

Arguably, the simplest and most effective of the various potential predictors was the spatial extent of sea ice in January in a defined central portion of Davis Strait. The resulting "Davis Strait Index" (DSI), defined by the spatial extent of this region occupied by concentrations $\geq$ 3/10 normalized to 180,000 km^2, was tested on historical data from the period 1953-1985.

Comparisons between the DSI values and annual iceberg numbers were classified into three categories of severity: low ($\leq$200), intermediate (200 < and $\leq$ 600), and high (> 600) showed encouraging correspondences. Specifically, 6 prediction errors were noted over the 33-year hindcast period. Of these, five were errors by one severity category, four of these were associated with years prior to 1960 characterized by highly uncertain sea ice data, and only one (1975) was a two-category error. Although the identified relationship was subsequently refined and briefly employed for seasonal planning purposes by the International Ice Patrol, interest in sea ice and other iceberg predictors later languished in the face of improved iceberg surveillance efficiency and effectiveness.

Nevertheless, rising concerns over global climate change eventually refocused attention back onto the East Coast iceberg circulation and its environmental determinants. In particular, there have been ongoing concerns over the past 30 years [4] [5] that regional warming would accelerate Greenland iceberg calving and greatly increase southward iceberg fluxes. This possibility was examined in [1], which intensively examined the empirical connections between upstream ice and icebergs surviving to southern latitudes. This work drew on recently acquired ocean circulation data, a body of satellite-beacon-tracked iceberg data [6], and extensions of the earlier empirical correlation studies. Key findings were that the population of icebergs crossing 48°N were clearly in the "near-extinction regime" identified earlier by [7] as shown in Fig. 2 where the probability of occurrence is much lower and skewed towards zero, by contrast to the calving or near-production areas off West Greenland.

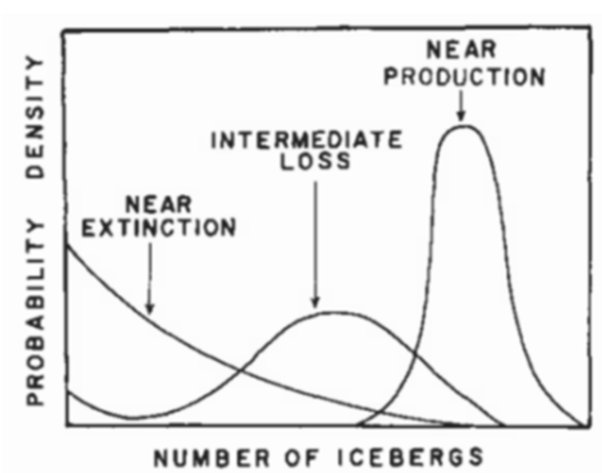

Fig. 2. Probability density of iceberg numbers at locations near Greenland production areas, en route (intermediate) to the Grand Banks and in the severity measurment areas south of 48°N [7].

Within this framework, the annual 48°N iceberg numbers, corresponding to total ice volumes equivalent to a small fraction of 1% of typical annual calving volumes [1], are relatively insensitive to iceberg calving rates. Instead, severity is controlled by a complex interplay of dissipative mechanisms that divert and destroy glacial ice fragments in regions north of the surveyed regions

The empirically-deduced role of sea ice in the dissipation process was attributed to two different mechanisms. In the first case, this role was based upon the capabilities of pack ice for minimizing iceberg fragmentation and melt through suppression of wave activity and surface water temperatures. A less obvious, but comparably potent role of sea ice is to prevent icebergs from being diverted into shallow continental waters, where serial groundings can lead to large losses of iceberg volume over periods as long as several months. Once the motion of the iceberg is resumed, its volume may be too small to either survive the remaining portions of the southward drift or to even justify designation as an iceberg. Evidence for the potency of this depletion mechanism lay in the observations that only 1 of 21 icebergs fitted with satellite beacons in NW Baffin Bay in during the summers of 1978 and 1979 reached the 67°N northern boundary of Davis Strait, with most of these icebergs undergoing grounding events of extended durations of up to 13 months [6].

A simple model, based upon the two identified protective functions of sea ice [1], was shown to reproduce the seasonal character of the observed 48°N iceberg fluxes (i.e. seasonal peaking in the April-June period) and statistically correct coarse relationships between iceberg numbers and corresponding annual January Davis Strait ice extents. The importance of the Davis Strait ice extent resulted from its tendency to increase following earlier growth of fast ice on the continental shelves, thus, enhancing iceberg numerical densities. Also, the observed high (r^2 =0.82) correlations (Fig. 3) of January Davis Strait ice extents with Labrador Sea spring ice extents, in effect, made it a determinant of the durations of ice-free iceberg travel.

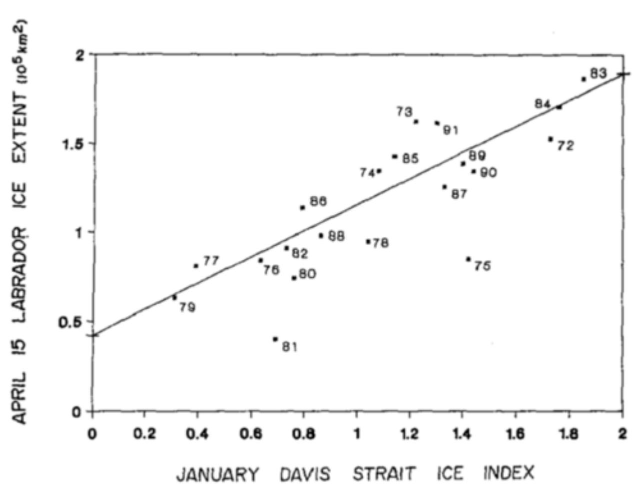

Fig. 3. Annual April 15 extents of sea ice $\geq$ 30 cm in thickness in three 2° latitude strips between 47° and 55° N [1] plotted as a function of the January Davis Strait Ice Index [2] for the years 1972 to 1991. Labels indicate year.

On the other hand, a body of glaciologically-oriented research [9] [10] arrived at quite different conclusions. This work utilized applications of a widely-used non-linear auto-regressive model in conjunction with: more than century-long record of annual iceberg severity; a coupled iceberg – ocean trajectory- iceberg trajectory and melting model; and a surface mass balance model of the Greenland ice sheet to draw very broad conclusions. These analyses concluded that the apparent effectiveness of sea ice as an iceberg-severity predictor was tied to its correlations with one or more of the variables used in the autoregressive model. The confidence of the authors in the utilized methodology was such that it was suggested that iceberg severity could provide a proxy measure of Greenland iceberg calving rates. It would appear that much of this confidence was derived from prior widespread use of the utilized auto-regression model on a variety of other applications. However, it is notable that the inputs for such earlier applications tended to be characteristically high in both data quality and quantity. In our view, such claims seem out of place for the near-extinction zone, given that the icebergs are subjected, over vast differences, to highly variable environmental which ultimately determine the fate of the icebergs. More specifically, questions can be raised on the accuracies of the assumptions made during the iceberg transport process. In particular, melt rate assumptions, and the treatment of the ocean current flow field in, at least, Baffin Bay were greatly over-simplified. The assumed greater relative importance of southern West Greenland iceberg sources relative to central and northern West Greenland needs verification.

In the absence of additional, systematic data it is difficult to assess the relative merits of these two basically different approaches if, as [10] suggest, model relationships are not stationary and/or the regions of interest are currently being significantly impacted by climate change. The present work is directed at examining this situation by looking for evidence of change in the much simpler and, possibly, more transparent regional sea ice extent severity predictors.

II. Methodology

Data on the numbers of icebergs that passed south of 48 degree north latitude are available from the published values provided by the International Ice Patrol at monthly intervals from 1900 to 2011 [11] and updated for annual totals to 2014 (Murphy, 2014, pers. comm.). There is a pronounced seasonal variability in the frequency of icebergs crossing 48°N, as shown in Fig. 4, for the years 1964 to 2011. Icebergs are most frequently present in the late winter and spring (March to June) with much reduced numbers in the months of February, July and August, and very few icebergs appear from September to January.

Over this 46-year long period, there appears to be a change in seasonal patterns towards a greater proportion of the icebergs being present in the March to June period in 1996-2011 (16 years), with relatively few iceberg occurrences in July and August as well as in January to February, i.e. the duration of the presence of substantial numbers of icebergs has been reduced to a shorter, March to June portion of the year relative to the two earlier 16 year-study periods.

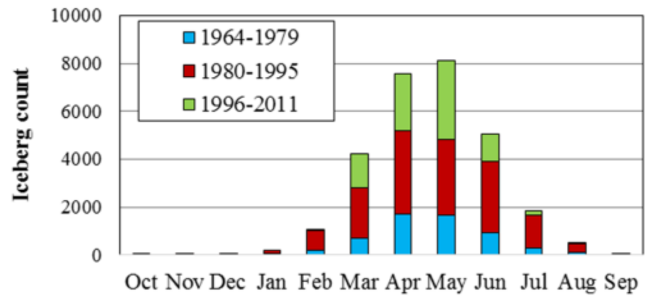

Fig. 4. Monthly iceberg count totals for three 16-year periods: 1964-1979, 1980-1995 and 1996-2011 (derived from the [11] data source).

The sea ice areal extent data is derived from the online Canadian Ice Service Digital Archive database [12, 13], based on satellite and airborne remote sensing data as well as ship-based reports. From this online database, weekly CISDA ice charts since 1971 were digitized for this study for the Hudson Bay regional ice charts, which include most of Davis Strait and the northern to central portions of the Labrador shelf area. The digital weekly ice charts were ingested into a GIS-based analysis system in which various sea ice parameters can be extracted and analysed over specified regions of interest to a resolution of 4 km^2. However, gaps in the availability of weekly ice charts in the winter months for the period 1971-1979 led to restriction of our investigation of iceberg vs. sea ice extent to the 35 years spanning 1980-2014.

Analyses focused on the fractional coverages of the 4 identified Davis Strait ice surveillance zones and the two Labrador Sea zones (Fig. 5), which were used to calculate equivalent fractional coverages for the full Davis Strait and Labrador Sea regions at key seasonal times. These coverages were calculated both for ice of all thicknesses and for ice restricted to thicknesses > 30 cm.

Fig. 5. Map showing the areas of interest (AOIs) used for the sea ice analyses. AOIs 1 to 4 represent portions of Davis Strait; AOIs 5 and 6 represent the northern and central Labrador shelf and slope regions. Map by M. Henley, ASL.

The resulting coverages (in tenths) were divided by 10 and multiplied by the subzone area to obtain estimates of subzone ice extents. Summations over all subzones yielded corresponding Davis Strait and Labrador Sea estimates.

III. COMPARISON RESULTS

Two fundamental issues of interest are whether observed changes in the global and sub-Arctic and Arctic Regional climates have impacted upon: the basic characteristics of the iceberg populations reaching 48°N, and the relationships (causative or correlative) that have been observed to tie these populations to the regional sea ice environment.

Realistically, the "natural" variability of the annual iceberg severity (Fig. 6) has, historically, been large enough to preclude definite conclusions based upon even a 34-year long record of very good data. Nevertheless, on the basis of a 5-year running average plot (Fig. 7), the severity has been trending downward since the early 1990's. In more graphic terms, for the 1980-2014 interval of relatively uniform surveillance efforts, annual iceberg counts fewer than 100 were only recorded 9 times during this period: 7 of these low counts occurred in the 16 years subsequent to 1998. This apparent downward trend has coincided with a period in which total Greenland calving rates were estimated [14] to have increased by 40%: posing a possible conflict with the autoregressive modelling approach [10] or, at least, signalling yet another shift in the underlying statistical relationships.

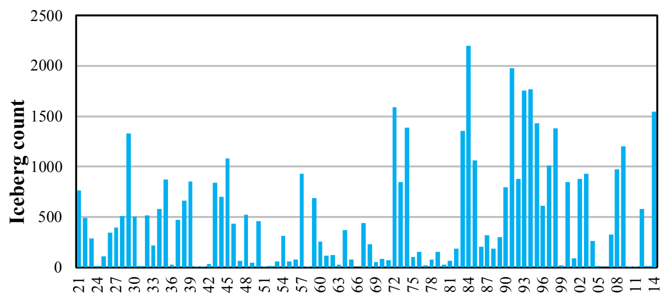

Fig. 6. Annual iceberg count south of 48° N latitude (derived from the data sources: [12] and Murphy pers..comm., 2014).

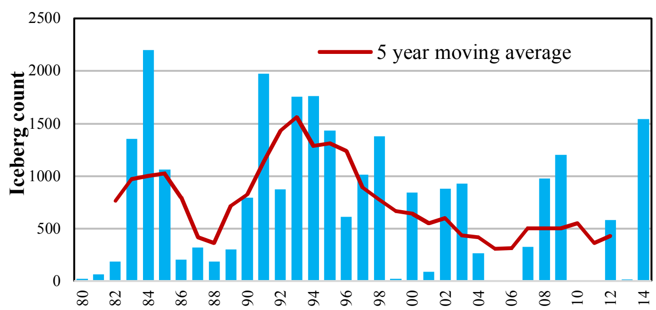

Fig. 7. Annual iceberg count south of 48° N latitude from 1980 onwards. The five-year moving average is shown in red. (derived from data sources: [12] and Murphy pers..comm., 2014).

Our explorations of iceberg severity relationships to Davis Strait ice extents showed equivalent levels of correspondence with both ice extents of all thicknesses and of those > 30 cm. Consequently, our comparisons to iceberg severity were based on the areal extent of the thicker Davis Strait sea ice as in the initial severity treatments [1] Slightly better comparisons, in terms of empirical r^2 values were also achieved with respect to the Jan. 1 Davis Strait ice coverages, as opposed to their Jan. 31 counterparts. These earlier measures of Davis Strait ice extent will be used in seeking relationships to downstream ice and iceberg changes. The ratio of iceberg severity to Jan. 1 Davis Strait ice coverage comparisons are plotted in Fig. 8 with the use of separate coding for data corresponding, alternatively to the 1980-1997 and 1998-2014 portions of the full 1980-2014 study interval. A similar comparison of iceberg severity counts with Labrador sea ice extent is presented in Fig. 9. When viewed as a whole these data show a broad scatter of points with severities roughly rising with ice coverage: a result which is generally consistent with the earlier results [1] which were based on iceberg severity comparisons with sea ice extents for the years 1963-1991.

On the other hand, our updated Davis Strait results for the 1980-2014 period do not easily lend themselves to being broken into categories of iceberg severity defining potential boundaries of the three reasonably distinct severity classes based on comparisons with the Labrador sea ice extents, as in the earlier work [2]. In this case, the plot shows obvious differences in the intrinsic extent of scatter in the data as indicated by the r^2 values listed separately for 1980-2014, 1980-1997 and 1998-2014 time intervals. These values suggest that the apparent degradation of the 1980-2014 severity/ice coverage relationship relative to our expectations from earlier work was largely confined to data acquired in the post-1997 period. Specifically, the fraction of variance explained by a tested linear proportionality relationship decreased from 0.64 to 0.1 between the first and second halves of the studied period.

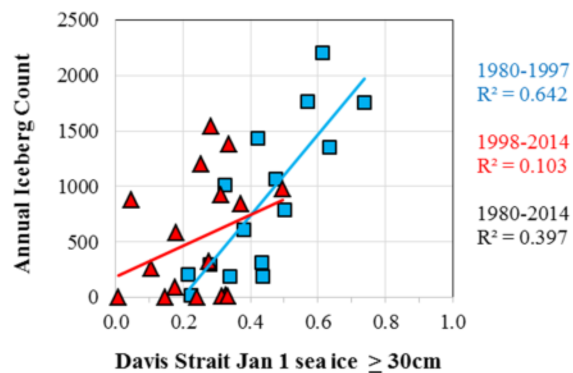

Fig. 8. Annual Iceberg counts as a function of January 1 Davis Strait coverage by sea ice of thicknesses ≥30 cm for the first and second halves of the 1980-2014 study interval.

The Labrador Sea spring ≥ 30 cm ice coverage data provided further insights into this rather dramatic change through comparisons with the contemporary annual Davis Strait coverages and iceberg severities. Interestingly, if we use the April 1 Labrador Sea ice coverage as an iceberg severity predictor (Fig. 9), we actually find values of r^2 for the full study period to have been comparable to those attained with the January Davis Strait ice coverage but, in this case, no degradation of correlations was noted in the 1998-2014 period. In fact, correlations with severity in this period were somewhat better than those deduced from data acquired during the previous 18-year time interval.

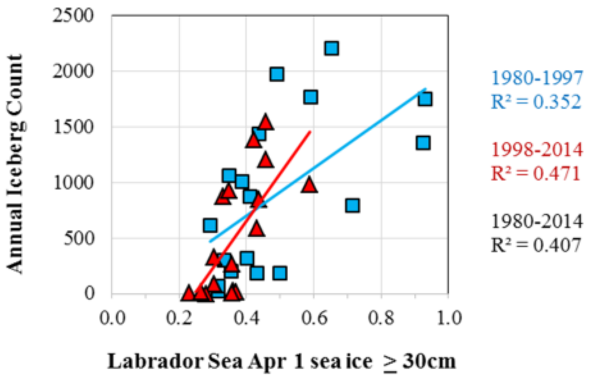

Fig. 9. Annual Iceberg counts as a function of April 1 Labrador Sea coverage by sea ice of thicknesses ≥30 cm for the first and second halves of the 1980-2014 study interval.

Some insights into these results may be gained from Table 1 in the form of r^2 values linking the Labrador Sea coverages on March 1, April 1, and May 1 to the preceding January 1 Davis Strait coverage. It can be seen that both overall, and in the first half of the study period, the attained correlations for the Labrador Sea Apr. 1 sea ice are comparable to those derived for the 1972-1991 period (Fig. 3), and the correlations decrease only slowly over the March1 through the May 1 period, as expected with the increasing separation in time from the Jan.1 Davis Strait coverage estimates. In the previous study [1], January Davis Strait sea ice coverage was identified as the likely major statistical determinant of spring Labrador ice. This role, in part, probably reflects some similarities in regional air temperature trends, but also, almost certainly, was a simple consequence of the fact that ice in Davis Strait in January moves southward and usually appears off Labrador in the spring months. The 1998-2014 data strongly suggest that since, at least, 1998, this statistical connection has been greatly weakened.

TABLE I. R^2 VALUES FOR COMPARISONS OF LABRADOR SEA ICE COVERAGES WITH JAN. 1 DAVIS STRAIT COVERAGE (ALL FOR ICE THICKNESSES ≥ 30 CM

Labrador Sea Coverage	R^2 (1980-1997)	R^2 (1998-2014)	R^2 (1980-2014)
March1	0.86	0.31	0.69
April 1	0.74	0.40	0.65
May 1	0.60	0.10	0.52

IV. SUMMARY AND DISCUSSION

Although the 35 year duration of the data included in this study is only marginally longer than the 30 year ballpark figure traditionally used to identify sustained climate trends, it is hard to offer interpretations which do not include major changes in the inter-relationships connecting major cryosphere parameters off Eastern Canada. The observed continuity in the relationship between iceberg severity and the Labrador Sea ice coverage would appear to imply that the post-1997 degradation of an equivalent relationship between severity and the Jan. 1 Davis Strait ice coverage has its direct origins in the observed contemporary breakdown in correlations between the latter quantity and Labrador Sea coverages during all 3 spring months. The Davis Strait pack ice extent is no longer as dominant as previously reported [1] for the years 1972-1991 in establishing the travelling environment for icebergs off Labrador.

The data in Figs. 8 and 9 are consistent with recently reported [15] trends in ice area which corresponded to decadal decreases of -4% and -8% for Davis Strait and the Northern Labrador Sea, respectively, over the years, 1980-2011. In the results of this study, no Jan. 1 Davis Strait coverages ≥ 0.5 and no Labrador Sea coverages ≥ 0.6 were observed since 1990, although such coverages were fairly common in earlier years (see Figs. 8 and 9). These trends are reasonably compatible with December-February warming air temperature trends deduced [15] for Davis Strait land stations (Iqaluit, +1.06°C/decade) and Labrador (Cartwright, (+1.33°C/decade) over the slightly longer 1980-2012 period.

The Labrador Sea spring ≥ 30 cm ice coverage data provided additional data on this rather dramatic change through its apparent recent decoupling from the corresponding annual January Davis Strait ice extents.

In short, the observed recent changes in iceberg severities and East Coast ice extents, since the 1990's, are consistent with observed changes in regional climate. Our results would appear to indicate that such changes have been sufficiently extensive that they appear to be impacting upon previously existing relationships between important components of the regional cryosphere.

Going forward, the results of this preliminary analysis indicate that further studies are warranted with an emphasis on investigating in more detail the physical linkages between the Labrador Sea ice extents with upstream Davis Strait ice during the January to May periods of the past two decades. In particular, possible changes in patterns relative to earlier decades should be documented. Such a study would go beyond statistical relationships to address causal connections between the two adjoining areas in terms of downstream advection of sea along with the effects of both air temperatures in melting pack ice and wind forcing in controlling offshore displacements of the sea ice into and out of warmer water. The availability of winter to spring remote sensing data on icebergs in the Davis Strait and Labrador Sea region from all weather radar-based satellite data sets, as well as airborne reconnaissance surveys, should also be considered in future research studies on this topic.

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