Sea ice dynamics and the role of wind forcing over the Beaufort Sea

Alek Petty[1,2], Jennifer Hutchings[3], Sinead Farrell[1,2], Jacqueline Richter-Menge[4], Mark Tschudi[5]

1. Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland, USA. 2. NOAA Center for Weather and Climate Prediction, College Park, Maryland, USA. 3. College of Earth, Ocean and Atmosphere, Oregon State University, Burt 304, Corvallis, Oregon 07331, USA. 4. Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, USA. 5. Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, USA.

ABSTRACT: Sea ice drift estimates from feature tracking of satellite passive microwave data are used to investigate the seasonal trends in ice circulation around the Beaufort Sea, over the period 1980-2013. A flux-gate analysis demonstrates consistency across a suite of drift products, revealing the inter-annual and seasonal variability in ice circulation. We find increasing anti-cyclonic ice drift across all seasons with the strongest trend in autumn, associated with an increase in ice export out of the southern Beaufort Sea (into the Chukchi Sea). Despite the seasonal trends in anti-cyclonic ice drift, a significant anti-cyclonic wind trend occurs in summer only. Seasonal correlations between the wind and ice drift curl indicate a strong correlation in summer, when the ice is close to a state of free ice drift, and winter, when the ice is consolidated. A strong deviation from a linear relationship between the wind and ice drift curl occurs in the mid-late 2000s, suggesting an increased role of the ocean and/or non-linear ice interaction feedbacks. The results also demonstrate a weakening of the ice circulation since 2010, recovering to a pre-2007 ice circulation; highlighting the potential for a continued release of freshwater from the region over the coming years.

Sea ice and the Beaufort Gyre

The Beaufort Gyre is an anti-cyclonic circulation feature of the Arctic Ocean (see Figure 1), which stores a large volume of freshwater through Ekman convergence, and thus provides a significant control on the Arctic Ocean freshwater budget [Aagaard and Carmack, 1989; Proshutinsky et al., 2002, 2009]. The overlying sea ice cover modulates the transfer of heat, salt, momentum, solar radiation and various gasses between the atmosphere and ocean, while the circulation of ice within the gyre contributes to the fate of the thicker, multi-year (MY) ice that is imported in from the central Arctic (see e.g. Hutchings and Rigor, 2012].

The Beaufort Gyre has experienced an increase in its liquid freshwater content over recent decades, based on in-situ measurements of the sea surface salinity and satellite altimeter estimates of the sea surface height [Proshutinsky et al., 2009; McPhee et al., 2009, Giles et al., 2012]. Krishfield et al. [2014], however, estimate that around 300 km^3 of fresh water has been released from the BG between 2010 and 2012 (through a combination of solid and liquid freshwater export), suggesting a potential weakening of the anti-cyclonic circulation in recent years.

In this study we present new insight into the changing response of the sea ice circulation in relation to the wind forcing on a regional and seasonal scale; complimenting on-going work investigating the changing ocean circulation and sea ice characteristics. We hope to further understand how the changing sea ice cover may be influencing the transfer of momentum between the atmosphere and ocean in this region.

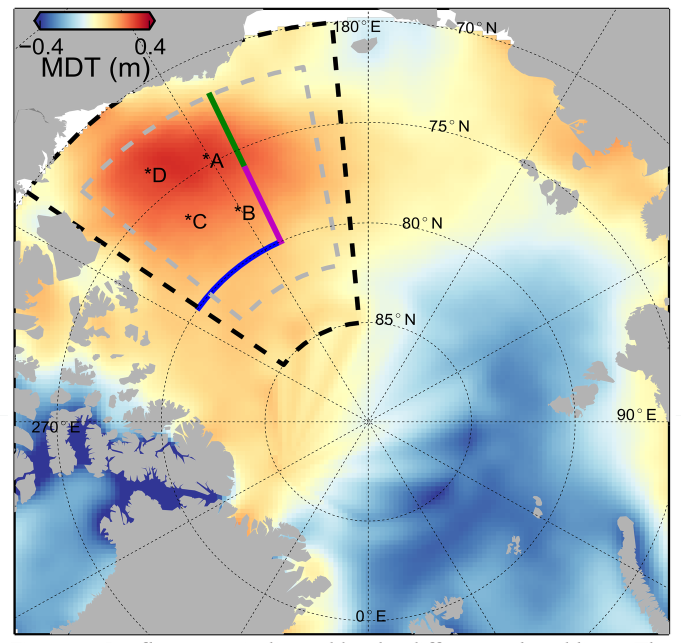


Figure 1: Ice flux gates indicated by the different colored lines. The grey dashed box (72-82°N/130-170°W) indicates the ice drift curl calculation region and the black dashed box (70-85°N/125-175°W) indicates the wind field curl calculation region. The backgroud image shows the mean (2003-2009) dynamic topography (MDT) of the Arctic Ocean derived from satellite altimetry [Farrell et al., 2012]. The letters (A–D) indicate the locations of the moorings used to calculate ice draft (Fig 6), from Krishfield et al. [2014]

Wind field and ice drift curl analysis

The Beaufort Gyre accumulates freshwater through Ekman convergence (a wind driven 'spin-up' of the ocean). Ekman convergence is a function of the curl of the oceanic stress (the ice-ocean stress given a fully concentrated ice cover). Neglecting the near-surface ocean currents and ice interaction force, and assuming the atmosphere/ocean drag coefficients to be constant in space and time, the curl of the ice-ocean stress should be well approximated by a linear relationship with the curl of the atmosphere-ice stress. Any deviations from this linear relationship therefore suggest an influence from ocean currents or changing sea ice characteristics. We therefore analyze the curl of the square of the wind and ice drift, which represent the atmosphere/ocean drag excluding the variable atmosphere/ocean drag coefficients.

Figure 2 (time series also shown in the top panels of Figure 3) shows the seasonal wind field curl over the Beaufort Sea. We use wind data from three separate reanalyses: the NCEP/NCAR Reanalysis 2 (NCEP-R2), the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim) and the Japanese 55-yr Reanalysis Project (JRA-55). The only significant trend in the wind curl is in summer, with all three reanalyses showing a significant (>97%) anti-cyclonic trend, mainly driven by the lows experienced throughout the 2000s.

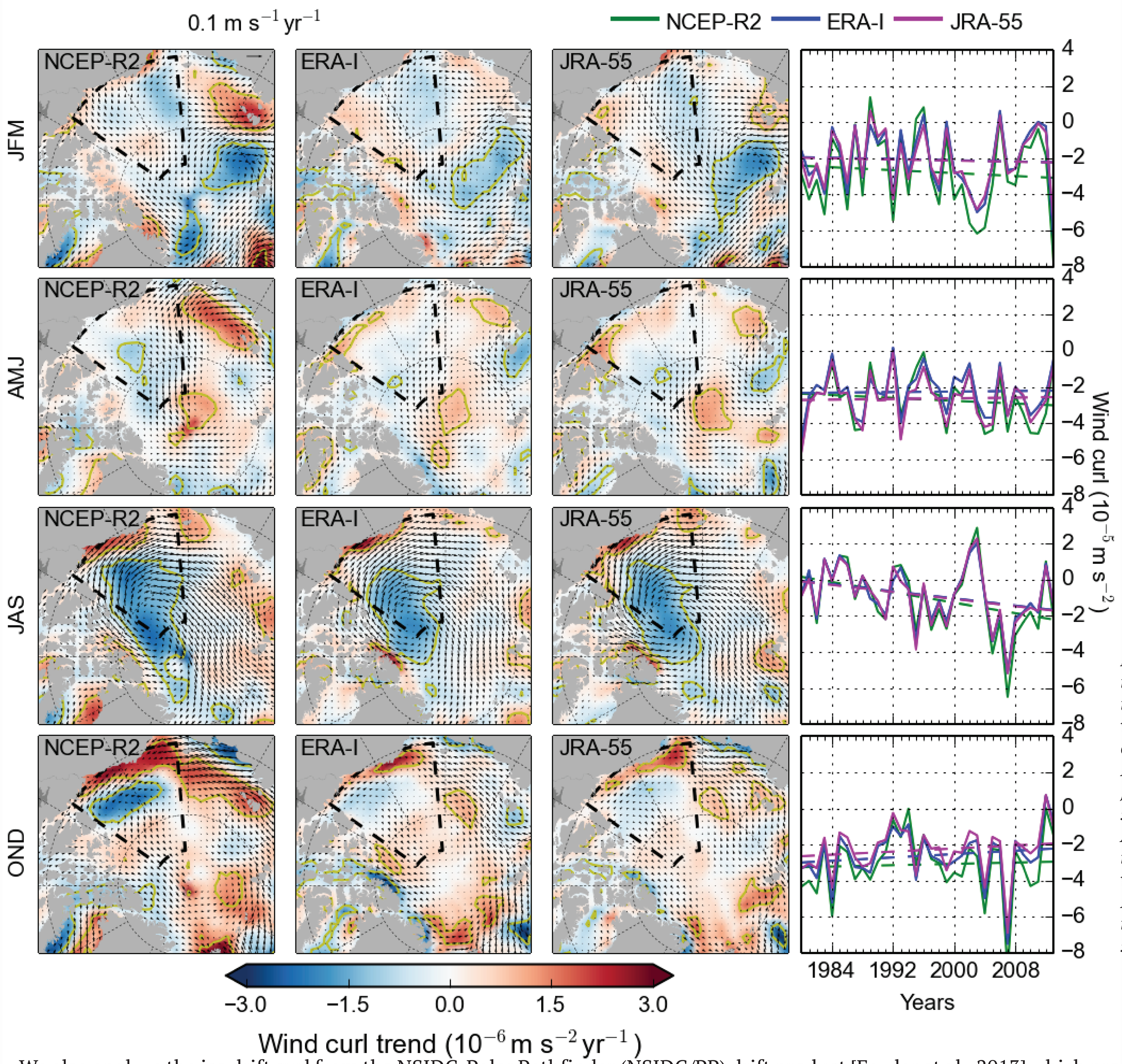
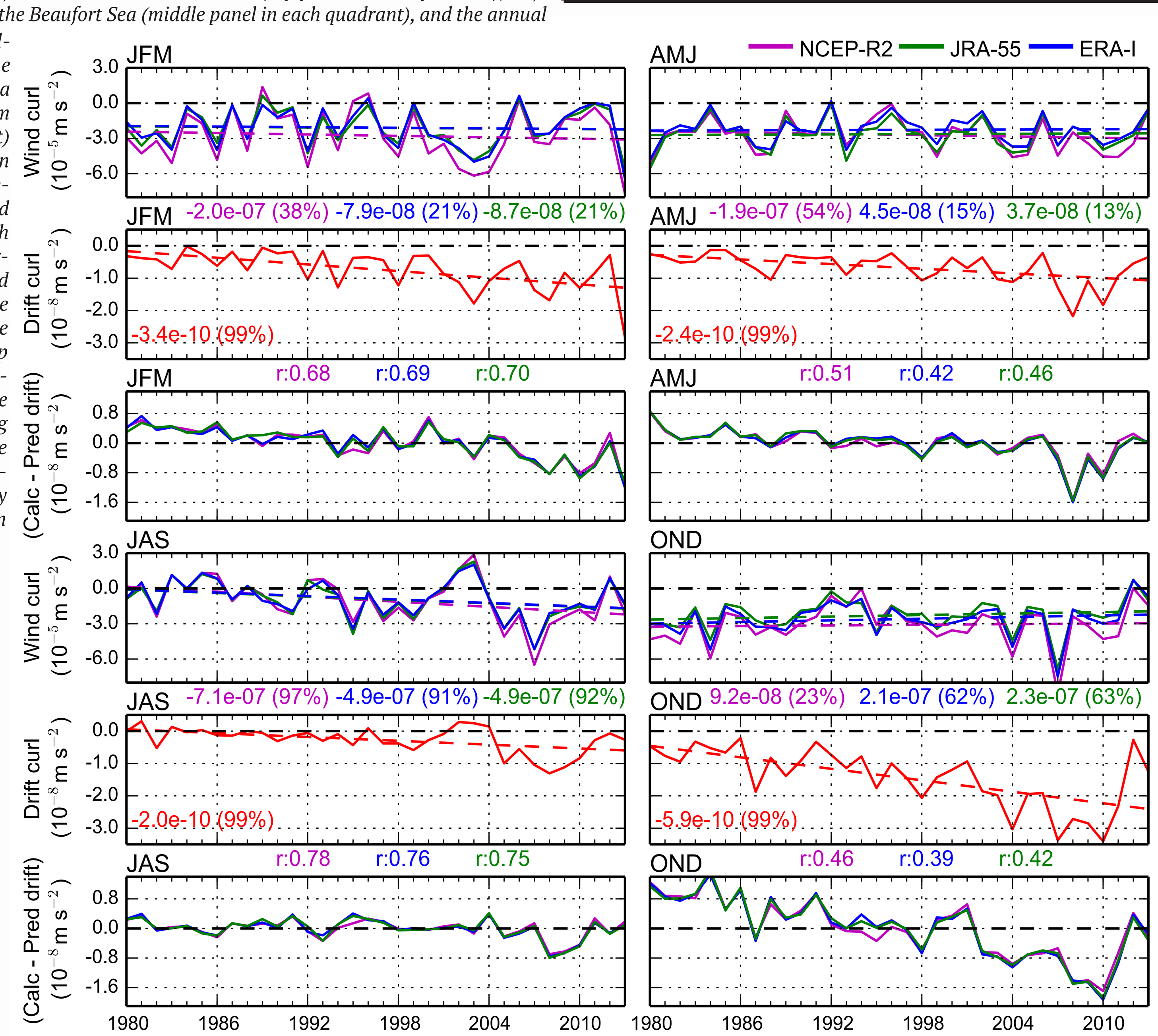


Figure 2 (left): Annual trend (1980-2013) in the seasonal mean wind field curl, based on the NCEP-R2 (left), ERA-I (middle) and JRA-55 (right) reanalysis data. (right panels) Annual time series of the seasonal mean wind curl over the Beaufort Sea (within the black dashed boxes, same as in Figure 1).

Figure 3 (below, right): Seasonal mean 1980-2013 wind curl over the Beaufort Sea from ERA-I/NCEP-R2/JRA-55 (top panel in each quadrant), drift curl from NSIDC/PP over the Beaufort Sea (middle panel in each quadrant), and the annual anomaly between the calculated drift curl and the predicted drift curl from a linear regression (bottom panel in each quadrant) as shown graphically in Figure 4. The r-values between the middle and and bottom panels in each quadrant show the correlation between the wind and drift curl (from the three reanalyses), while the numbers below the top panels indicate the magnitude and direction of the linear trends (including their significance). The wind curl (drift curl) is calculated within the grey (black) box shown in Figure 1.



We also analyze the ice drift curl from the NSIDC Polar Pathfinder (NSIDC/PP) drift product [Fowler et al., 2013] which provides drift data from1980-2013. We compare this with several drift products produced by CERSAT/IFREMER, which combine passive microwave drift data with scatterometry (a flux gate comparison is dicussed on the right. A drift curl comparison is not shown but is available on request). The middle (red line) panels of each quadrant in Figure 3 show that the ice drift curl (from NSIDC/PP data) exhibits significant (>99%) anti-cyclonic drift trends across all seasons, with the strongest trend in autumn despite the recent recovery (less anti-cyclonic) after 2010. The correlation (r values shown in Figure 3) between the wind and ice drift curl is strongest in summer (when the ice is close to free drift) and winter (when the ice is consolidated). The correlations are significantly lower in spring and autumn, when the ice condtiions are more variable (see section in the bottom right).

Investigating the non-linearity between the wind and ice drift curl

To assess the potentially non-linear relationship between the wind and drift curl, Figure 3 also shows the temporally evolving difference between the calculated drift curl and the drift curl expected from a linear fit to the wind curl (demonstrated graphically in Figure 4). This shows that across all seasons, the drift curl is less anti-cyclonic (positive value) or similar (near zero) to that expected from the wind curl during the 1980s, transitioning to a more anti-cyclonic drift curl than expected (negative value) in the 2000s including a large anti-cyclonic deviation from the linear fit in the mid-late 2000s.

The strong non-linear deviation in the late 2000s is most pronounced in spring and summer, while autumn shows a more continuous anti-cyclonic deviation from 1980-2010. Spring, summer and autumn show a recovery (similar ice drift curl to that expected from the winds) after 2010, with all seasons showing a dampened ice circulation in 2012, driven by a more neutral wind forcing. The winter results show enhanced anti-cyclonic drift in 2013 coinciding with anomalously anti-cyclonic winds. The impact, however, is still much greater (more anti-cyclonic) than predicted from the winds, implying the continued potential for highly anti-cyclonic ice drift curl than in previous decades.

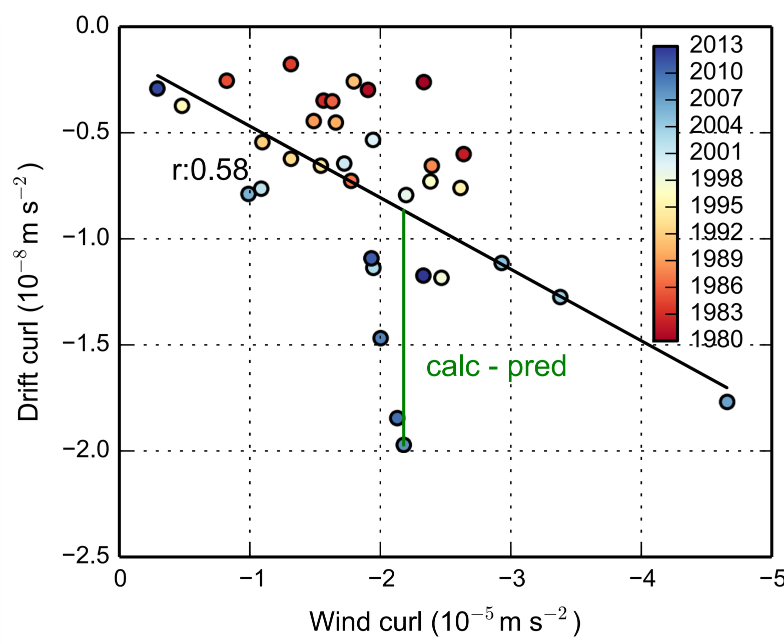


Figure 4 (left): Annual mean 1980-2013 wind curl (NCEP-R2) and drift curl (NSIDC/PP) over the Beaufort Sea for the black (wind) and grey (drift) boxes shown in Figure 1. The black line is the linear regression and the green line indicates an example of the calculated minus predicted (calc - pred) drift curl metric, as used in Figure 3. Note that each colored circle represents a different year in the regression analysis.

Flux gate analysis

Two zonal flux gates (along 155°W) are used to highlight the export of ice from the northern and southern Beaufort Sea into the neighboring Chukchi Sea and the recirculation of ice back into the Beaufort Sea. One meridional flux gate is used to highlight the import of ice into the Beaufort Sea from the central Arctic (see colored lines in Figure 1). Monthly sea ice drift vectors from NSIDC and CERSAT together with monthly sea ice concentration estimates from the NASA Team processing of passive microwave satellite data are interpolated onto the flux gates (every 20 km) to produce estimates of the total ice flux through the zonal and meridional gates. The different products show strong agreement, increasing confidence in the estimated ice circulation around the Beaufort Sea. The strongest trend is in autumn, wheere the ice flux doubles from ~1x10^5 km^2 in the 1980s to ~2x10^5 km^2 in the 2000s (bottom/middle plot in Figure 5).

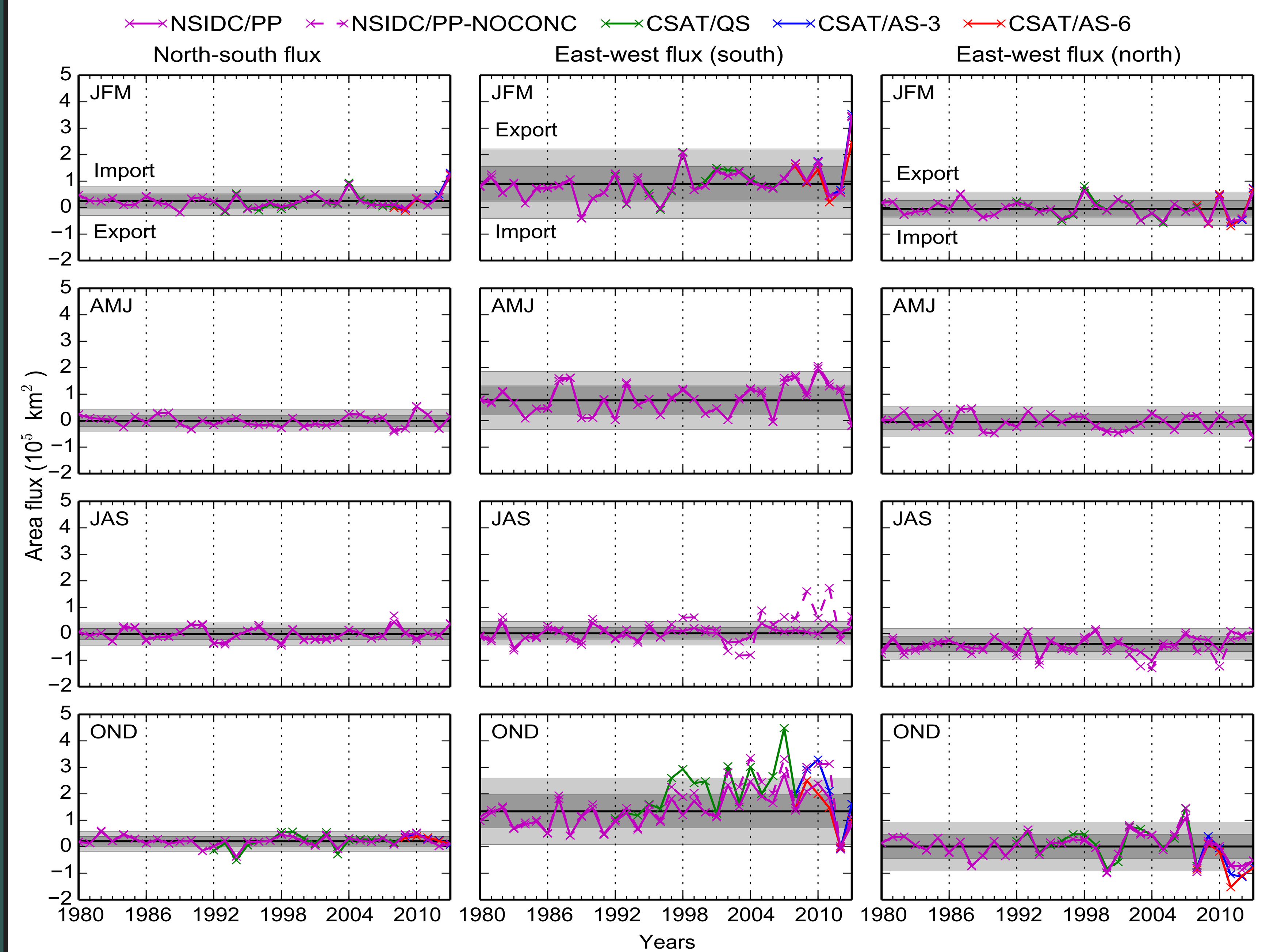


Figure 5: Seasonal mean (top to bottom) ice area flux through the three flux gates shown in Figure 1 (left to right) calculated from the NSIDC/PP (1980-2013, magenta), CSAT/QS (1992- 2008, green), CSAT/AS-6 (2008-2013, red) and CSAT/AS-3 (2008-2013, blue) drift datasets combined with NASA Team ice concentration data. The dark (light) grey shading represents ±1(2) standard deviations from the mean of the NSIDC/PP results (black line). The dashed ma- genta line shows the area flux from the NSIDC/PP product excluding ice concentration weighting (NSIDC/PP-NOCONC).

Changing sea ice conditions in the Beaufort Sea

Here we assess the potential role of the changing sea ice state in the non-linear behaviour between the wind and ice drfit curl (Figures 3 and 4). We expect the Beaufort Sea ice to be close to a state of free drift in summer, when the ice concentration has consistently remained below ~70-80% (Figure 7), meaning the strong decline in concentration may not have resulted in much change in the pack ice strength. The concentration declines in spring and autumn, however, may have pushed the ice towards free-drift in these seasons.

In winter, however, changes in ice thickness are likely to be crucial, as the ice remains consolidated. Recent ULS mooring and IceBridge thickness data (Figure 6) suggest a decline in thickness throughout all seasons which could also help explain the non-linear behaviour shown in the 2000s (Figures 3 and 4).

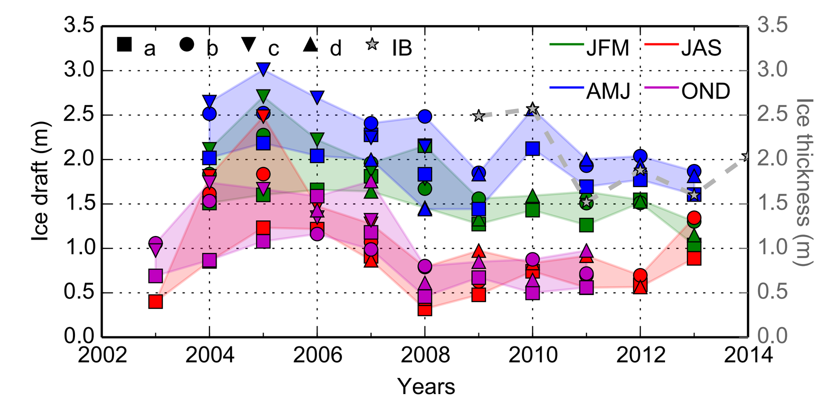


Figure 6: Seasonal mean 2003-2013 ice draft in the Beaufort Sea from Upward Looking Sonar measurements[Krishfield et al., 2014]. The shading represents the regional variability from the different four moorings (a, b, c, d). The gray stars (and gray dashed lines) indicate the mean ice thickness within the Beaufort Sea calculated from IceBridge observations in spring 2009-2014.

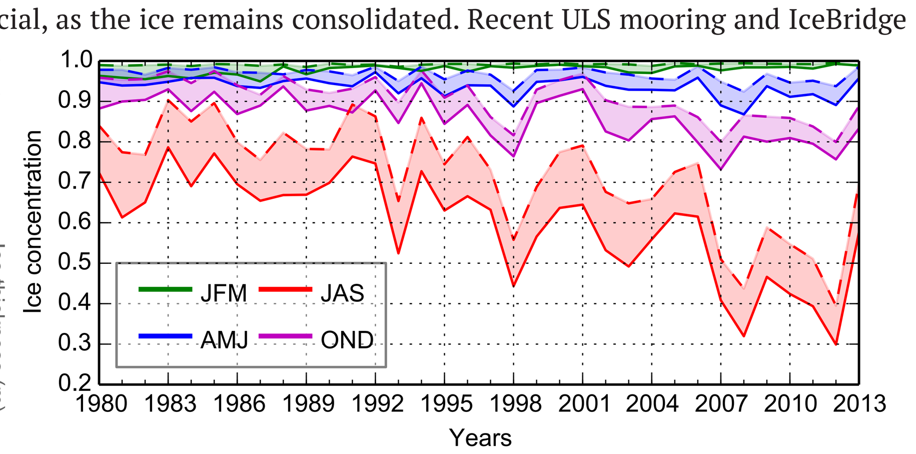


Figure 7: Seasonal mean 1980-2013 ice concentration within the Beaufort Sea black box in Figure 1). The solid (dashed) line either side of the color shading is the ice concentration calculated using the NASA Team (Bootstrap) algorithm.