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

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ABSTRACT: Sea ice drift estimates from satellite feature tracking are used to investigate the seasonal trends in ice circulation over the Beaufort Sea (BS). A flux-gate analysis demonstrates strong agreement across the different products, revealing interannual variability in the BS ice circulation. We find an increase in ice export out of the southern BS (into the Chukchi Sea) across all seasons, although the mean and trend is strongest in autumn. We find increasing anti-cyclonic ice drift across all seasons with the strongest trend in autumn, similar to the southern BS flux-gate results. Despite these seasonal trends in ice drift curl, three separate atmospheric reanalysis products indicate a significant anti-cyclonic wind trend occurs over the BS in summer only. The 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 drift; and winter, when the ice is fully concentrated. A strong deviation from a linear fit occurs in the mid-late 2000s, suggesting non-linearity in the atmosphere-ice coupling.

The Beaufort Gyre - the importance of sea ice

The Beaufort Gyre (BG) is an anti-cyclonic circulation feature of the Arctic Ocean, storing a large volume of fresh water through Ekman convergence and thus providing a significant control on the Arctic Ocean freshwater budget. The freshening of the BG has been associated with a wind-driven spin-up of the gyre [Proshutinsky et al., 2009; Giles et al., 2012], and increased transport of Eurasian river runoff into the BG [Morison et al., 2012]. Krishfield et al. [2014] estimate that around 320 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.

The effective transfer of momentum between the atmosphere and ocean over the ice covered ocean is influenced by the concentration of ice, the internal strength of the ice pack and variability in the ice surface morphology, along with the more direct influence of atmospheric and ocean forcing. In this study we choose to present new insight into the changing response of the sea ice 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 carry out a seasonal analysis of the wind forcing and ice circulation due to the seasonality in the sea ice behavior demonstrated in previous studies.

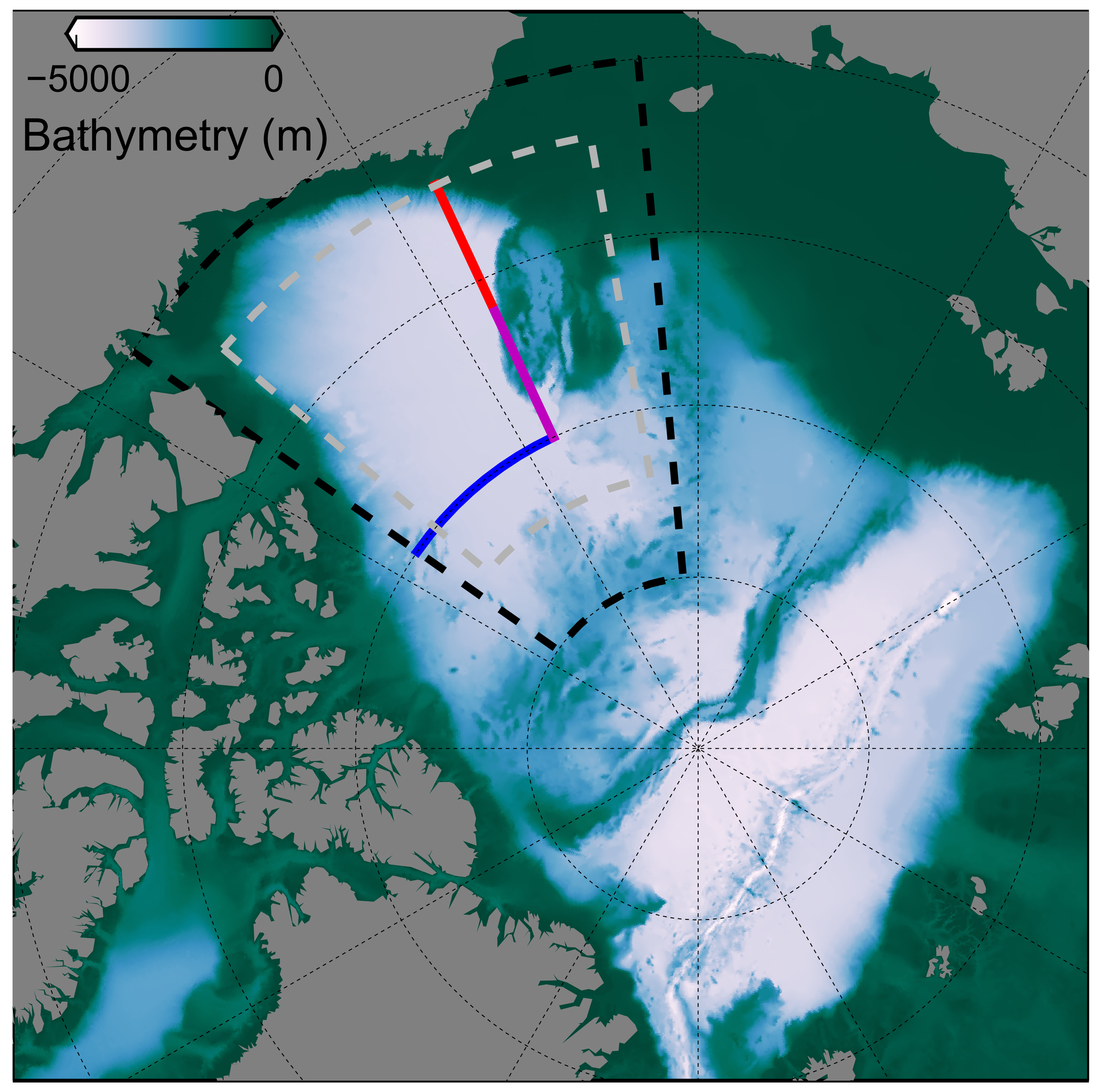


Figure 1: Beaufort Sea schematic. Ice flux gates at (155W/72N-76N, red), (155W/76N-80N, magenta), and (125-155W/80N, blue). The dashed grey box (72-82N/130-170W) indicates the ice drift curl region of interest and the black box (70-85N/125-175W) indicates the wind curl region of interest. Also plotted is the IBCAOv3 batthymetry of the Arctic Ocean.

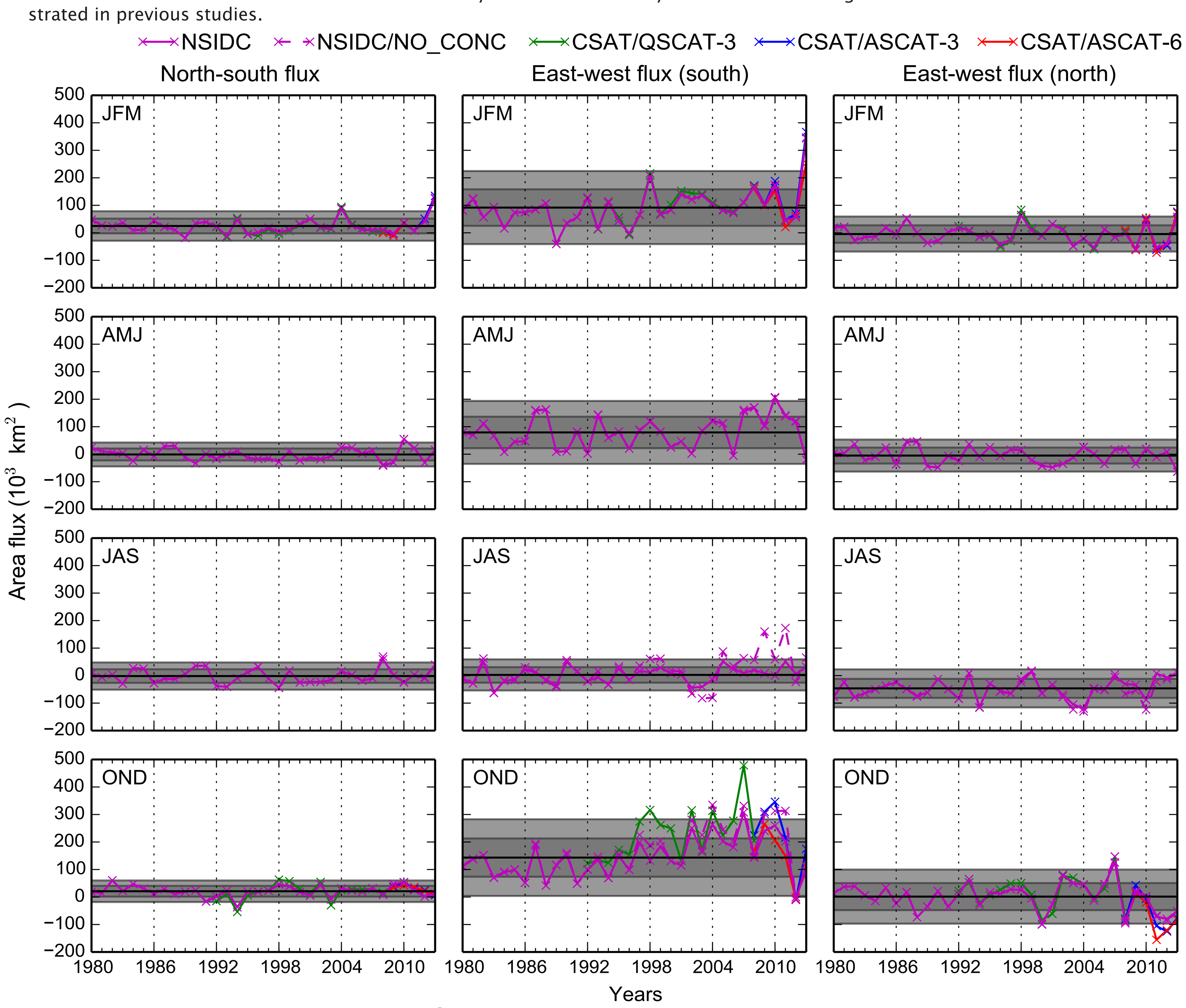


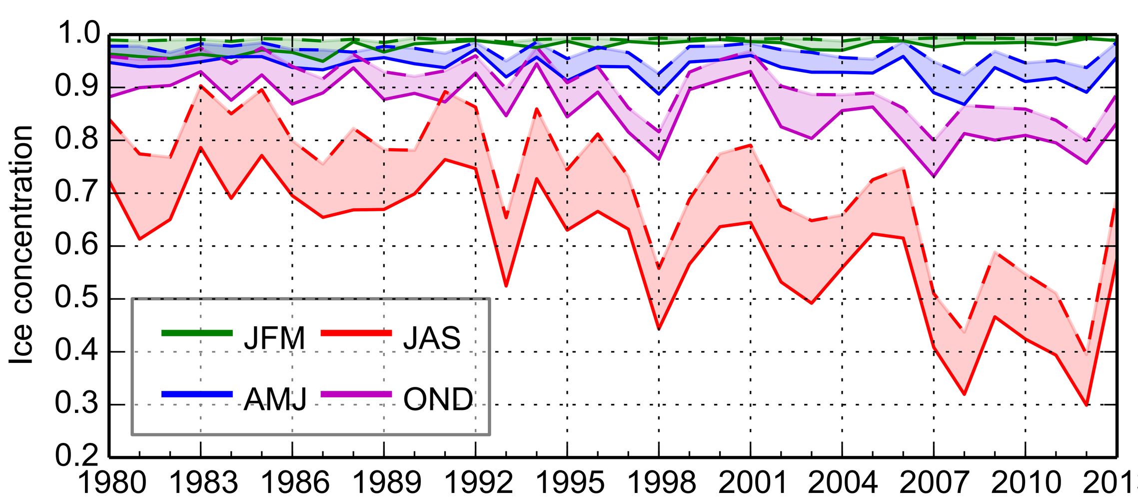
Figure 2: Seasonal mean (top to bottom) ice area flux through the three flux gates shown in Figure 1 (left to right) calculated from the NSIDC (1980-2013, magenta), CSAT/QSCAT (1992-2008, green), CSAT/ASCAT-6 (2007-2013, red) and CSAT/ASCAT-3 (2007-2013, blue) drift datasets combined with NASA Team ice concentration data. The dark (light) grey shading represents ±1(2) standard deviations from the mean of the NSIDC results (black line). The dashed magenta line shows the area flux from the NSIDC data excluding ice concentration weighting.

FLUX GATE ANALYSIS (above)

Two zonal flux gates (along 155W) 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 the Beaufort Sea from the central Arctic (see colored lines in Figure 1). The monthly drift vectors together with monthly sea ice concentration estimates from the NASA Team processing of passive microwave satellite data are interpolated onto the flux gates (20km) to produce estimates of the total ice flux through the zonal and meridional gates.

The export through the southern zonal flux gate in autumn shows the strongest trend of all seasons/flux gates. Here the estimated ice flux becomes anomalously high in the 2000s (~2×10^{5}km2) compared to the 1980s/1990s (~1×10^{5}km2), peaking in 2007, before reducing to an anomalously low flux with no clear import or export in 2012 (~2 s.d. below the mean). The flux returns to a value more representative of the climatological mean in 2013.

No clear trends are apparent in the import of ice through the meridional flux gate into the Beaufort Sea, although the results do indicate anomalously high imports in winter 2004 and 2013, spring 2010, and summer 2008.



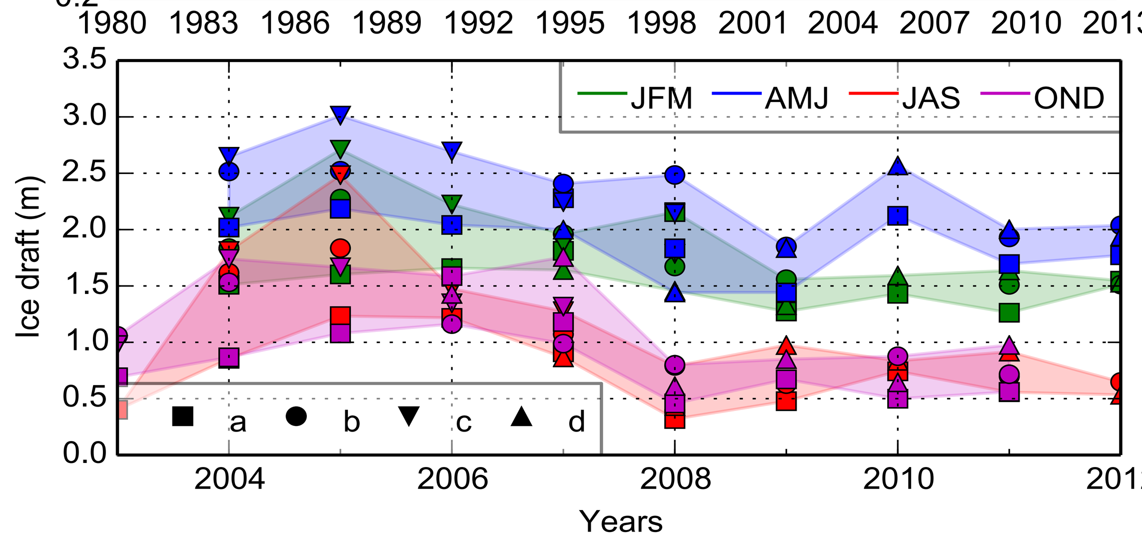


Figure 5 (top): Seasonal mean 1980-2013 ice concentration within the Beaufort Sea (black box in Figure 1). The solid (dashed) line either side of the color shading is the ice concentration calculated using the NASA Team (Bootstrap) algorithm.

Figure 4 (left): Seasonal mean 2003-2012 ice draft in the Beaufort Sea from Upward Looking Sonar measurements, as described in Krishfield et al., [2014]. The mean ice drafts are a combination of four separate moorings (a-d) that have been deployed for varying annual periods, as indictaed in the figure.

WIND/ICE DRIFT CURL ANALYSIS (below)

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 drag coefficients to be constant in space and time, the curl of the ice-ocean stress should be linearly related to 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.

Figure 3 shows the seasonal wind and drift curl over the Beaufort Sea. We use wind data from three separate reanalyses: NCEP/NCAR Reanalysis 2 (NCEP-R2), European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim) and Japanese 55-yr Reanalysis Project (JRA-55), together with the NSIDC drift product shown in Figure 2.

The only significant trend in the wind curl is in summer, with all three reanalyses showing a significant (97-99%) anti-cyclonic trend, mainly driven by the lows experienced throughout the 2000s. In contrast, the ice drift curl shows significant (>99%) anti-cyclonic trends across all seasons, with the strongest trend in autumn despite the recent recovery (less anti-cyclonic) after 2010.

This shows that across all seasons, the drift curl is less anticyclonic or similar to that expected from the wind curl during the 1980s, transitioning to a more anticyclonic drift curl than expected in the 2000s including a large anticyclonic deviation from the linear fit in the mid-late 2000s. This anomalous behavior in the late 2000s is most pronounced in spring and summer.

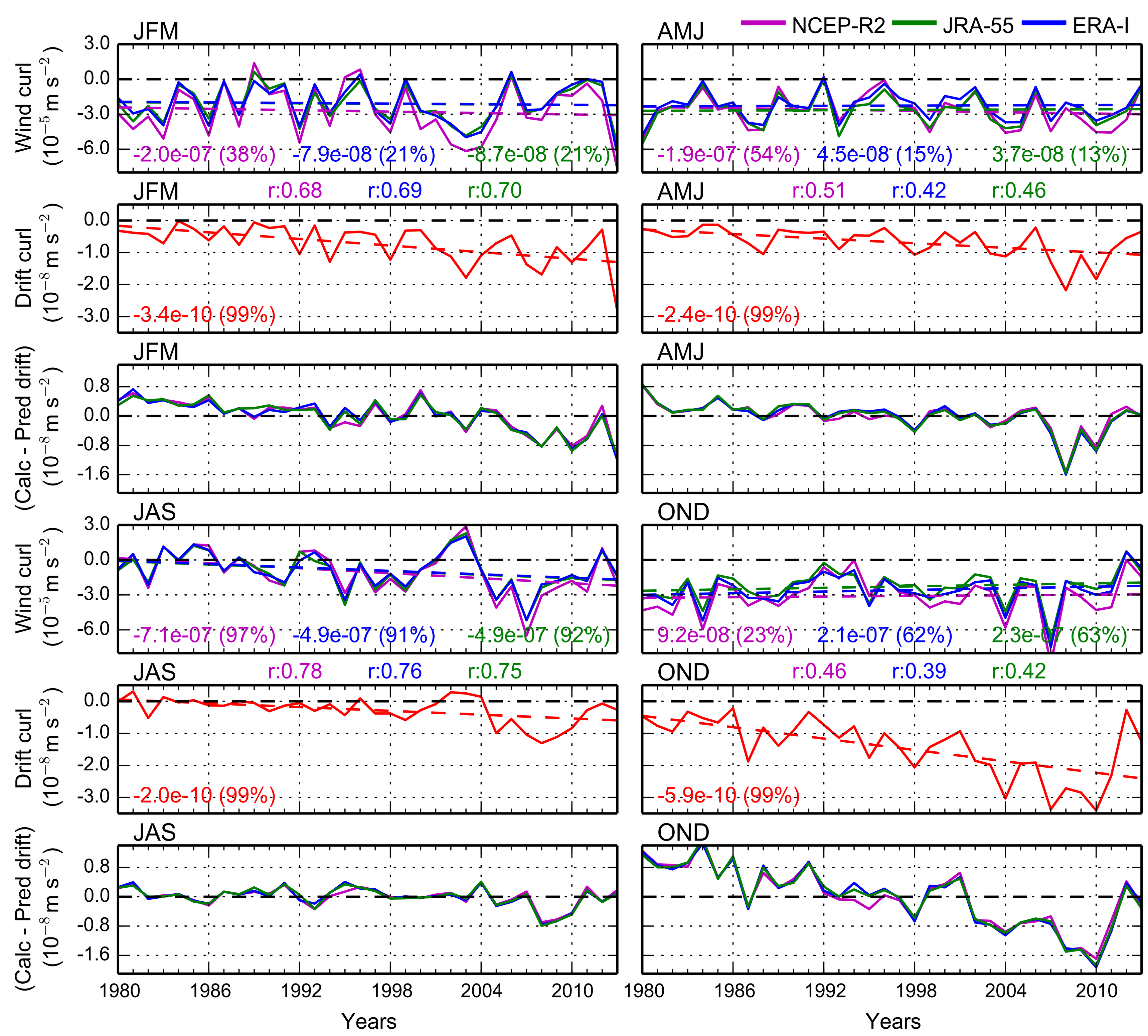


Figure 3 (right): Seasonal mean 1980-2013 wind curl over the Beaufort Sea from ERA-I/NCEP-R2/JRA-55 (top panel in each quadrant), drift curl from NSIDC over the Beaufort Sea (middle panel in each quadrant), and the annual anomaly between the calculated drift curl and the predicted drift curl from a linear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

CONCLUSIONS

In summary, we find increasing anti-cyclonic ice drift across all seasons with the strongest trend in autumn, likely driven by the strong export out of the southern Beaufort Sea. Despite these seasonal trends in ice drift curl, a significant anti-cyclonic wind trend occurs in summer only.

The 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 drift, and winter, when the ice is fully concentrated.

A strong deviation from a linear fit occurs in the mid-late 2000s, suggesting non-linear feedbacks between the atmosphere-ice-ocean circulation. The results suggest a weakening of the ice circulation and potential return to a previous state since 2010.

Several mechanisms have been proposed to describe these seasonal changes, however more extensive modelling and observational analysis is needed before we can hope to quantify their relative contributions to the long-term (1980-2010) spin-up and recent (2010-2013) spin-down of the Beaufort Sea.

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