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Variability of Lagrangian pathways and coherent structures in the Arctic and its effect on the predictability of MOSAiC drift and material transport

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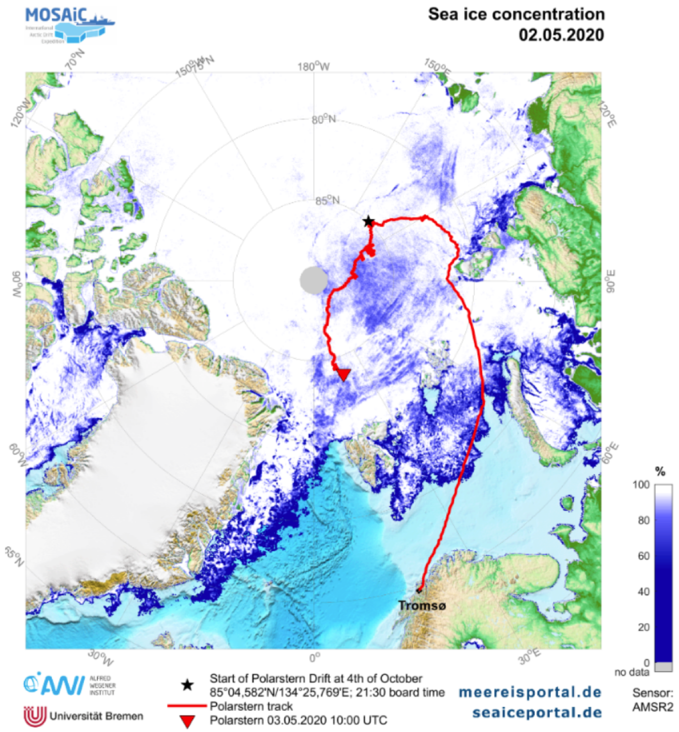
Highlights: A. Significant interannual variability in ensemble-mean drift track associated with movement of "saddle" fixed points. B. Spatiotemporal variability at mesoscale and smaller important for track bifurcation and predictability (link to tracer dispersion).

Fig. 1

MOSAiC drift observations

Latest drift track of R/V Polarstern (03.05.20)

(seeiceportal.de)



Motivation

i. Huge, international, freely-drifting expeditions like MOSAiC (Multidisciplinary Observatory for the Study of Arctic Climate) are vital for observing the changing Arctic, but there remains uncertainty in predicting their likely drift track (actual drift for first 7 months is shown in Fig. 1, red)

ii. Although high-resolution models of the Arctic exist, they are typically not used predictively for the annual time scales, appropriate for MOSAiC

iii. It is not yet clear whether mesoscale variability in surface ice-ocean dynamics might play a significant role in drift predictability, for example due to the potential to capture stronger rates of strain or stronger nonlinear variability

iv. Insights through Lagrangian particle statistics may also provide a way to understand advective pathways and diffusive processes relevant to tracers, such as nutrients and carbon, as well as pollutants.

Methods

- We use a 2005-2015 hindcast of the realistic, eddy-resolving, global NEMO ocean+ice model, forced by the Drakkar Forcing Set, which is based on the ERA-40 atmospheric reanalysis (Marzocchi et al., 2015).

- Surface velocity from NEMO (its standard 5-day mean output at 1/12 deg. lateral resolution), for both sea ice and ice-free conditions, is then used drive many offline, large-ensemble, Lagrangian experiments with ARIANE (Blanke and Raynaud, 1997; Kelly et al., 2019).

- Each year of simulation is treated as an independent estimate of typical future state, under a 'perfect model' assumption. We use the hindcast to dynamically generate a range of one-year states, each beginning at the same time of year. ARIANE permits us to efficiently simulate advection offline using a huge number of particles, to explore the range of drift behaviour.

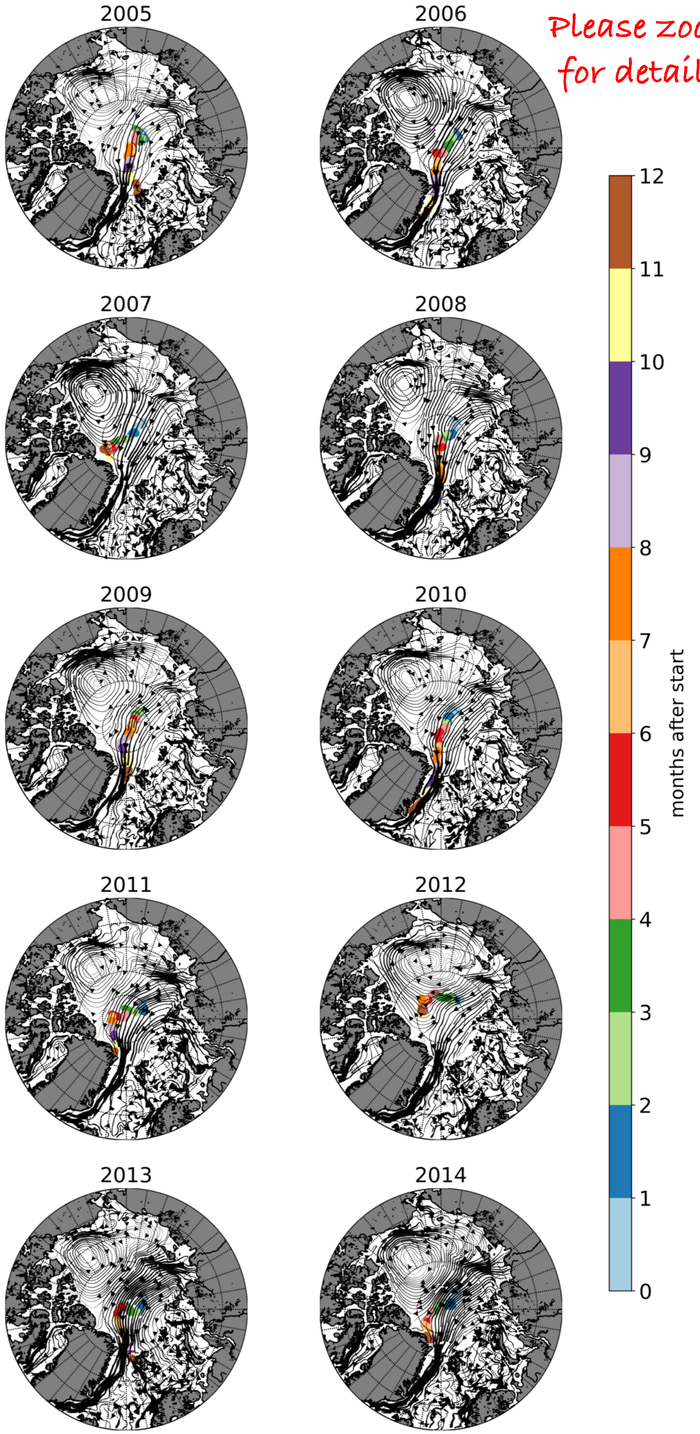
- ARIANE experiments involve the seeding of a patch of particles, centred on the best estimate of start time and location for the MOSAiC expedition, which we obtained from the MOSAiC team a couple of weeks before it began: t0=1200 hrs, 6 October; (lon0, lat0)=(135 E, 85 N). In reality, the initial conditions (134.43 E, 85.08 N, 2130 hrs, 4 October 2019) depended on the logistics of reaching the site after setting off from Tromsø and also the choice of a suitable ice floe.

- Patch contains 25 x 25 = 625 particles equally dividing the lon, lat box (134-136 E, 84-86 N) (~6 km spacing), and 21 temporal increments (t0-10 day, …, t0, t0+10 day), equating to 13,125 particles for each of the 10 years, starting 2005-2014. Each particle is advected for 1 year and its position is stored daily.

- Lagrangian particle statistics are used to analyse the huge amount of data. The ensemble mean position, for a given initial condition, indicates the most likely drift track. Root-mean-square particle pair separation (RPPS) is a measure of the spread of the particles about the mean (see LaCasce, 2008) and is related to the ‘cloud dispersion’ measure of a continuous tracer.

Fig. 2

Evolution of ensemble-mean particle position across a 25 x 25 patch of particles, initialised at t=t0=6 October in each of 2005-14 and advected for one year. Daily positions shown by colours as a function of time. Streamlines of the 1-year-mean surface flow from 6 October each year until 5 October the following year is overlaid. Streamline thickness is proportional to flow speed (max. 0.2 m/s).



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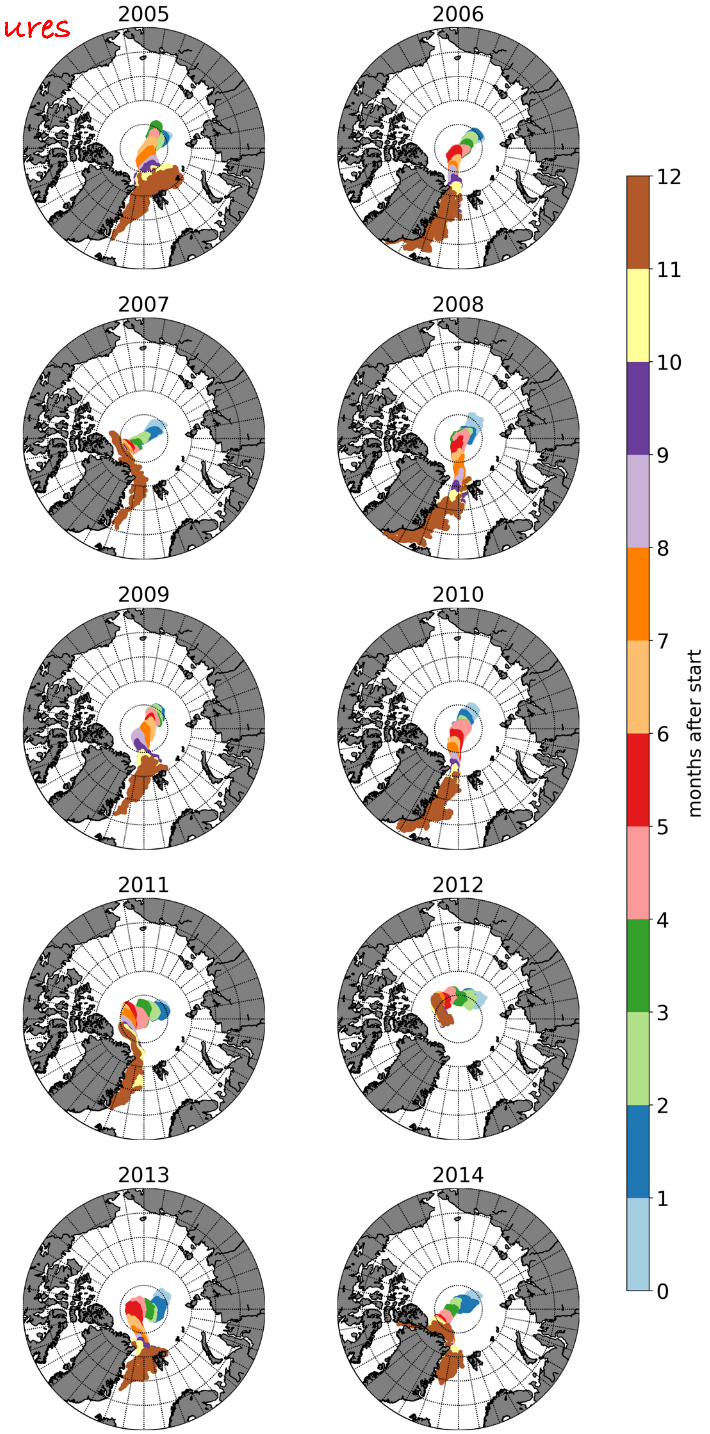
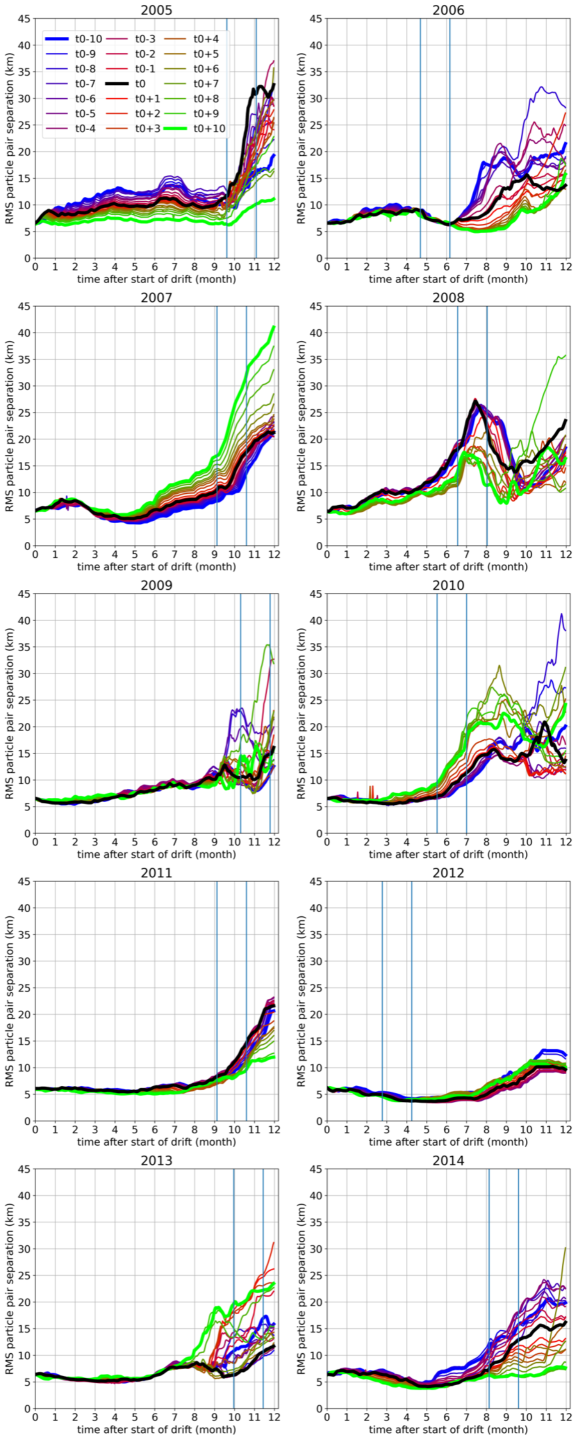


Fig. 3

As for Fig. 2, but showing all 625 particles in the patch, initialised at t=t0, as they advect and the patch deforms. For greater clarity, the streamlines are not overlaid here. Note that some of the particles are unavoidably obscured by plotting of later times over earlier times. The spreading about the ensemble mean is most striking at month 12 (brown).

Fig. 4

Root-mean-squared particle pair separation (km) for the 25 x 25 particle patch as a function of time after the start of drift. Each of the 21 coloured lines shown each year represents one-day increment time offsets from t0=6 October in that year. Thick lines represent the extreme and central times. The instantaneous statistics are based on 195,000 particle pairs for each line plotted. Divergence in the temporal evolution indicates sensitive dependence on initial conditions and is a measure of reduced local potential predictability. Vertical blue lines correspond to the pair of snapshots of the particles shown in Fig. 5.



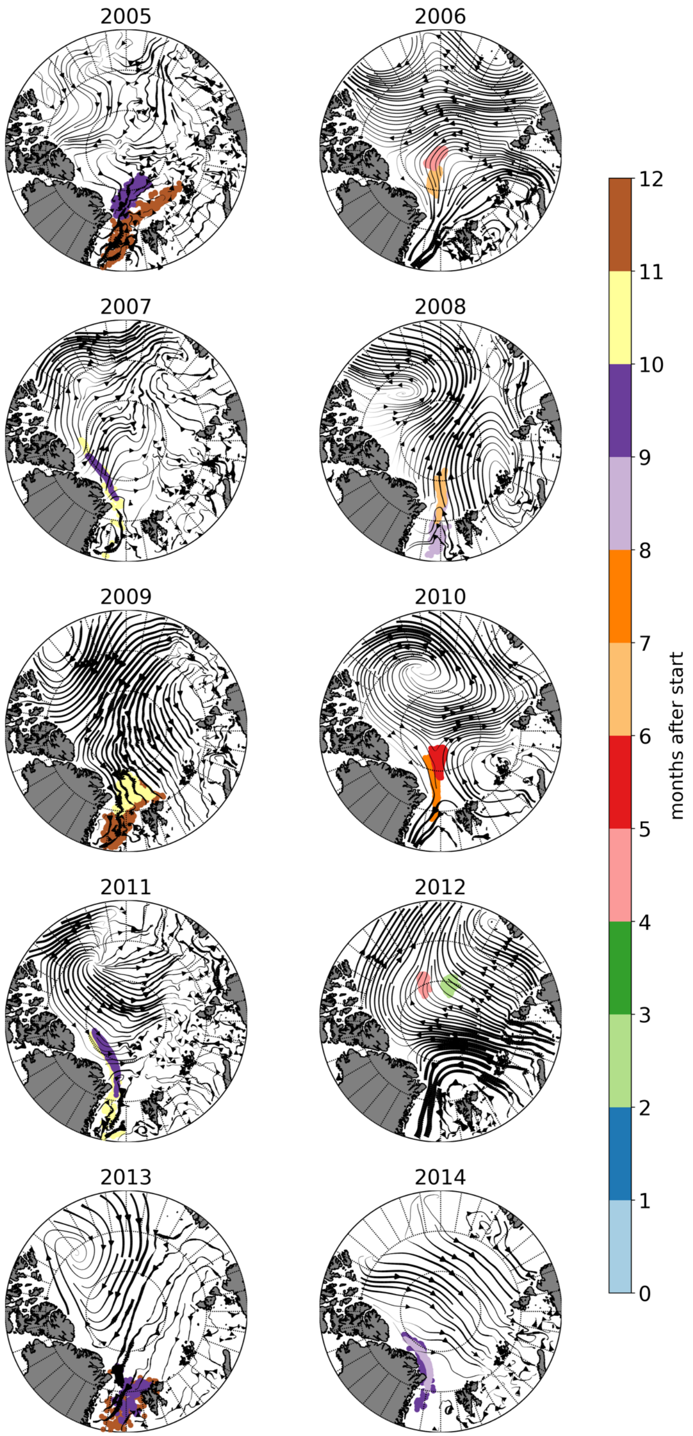


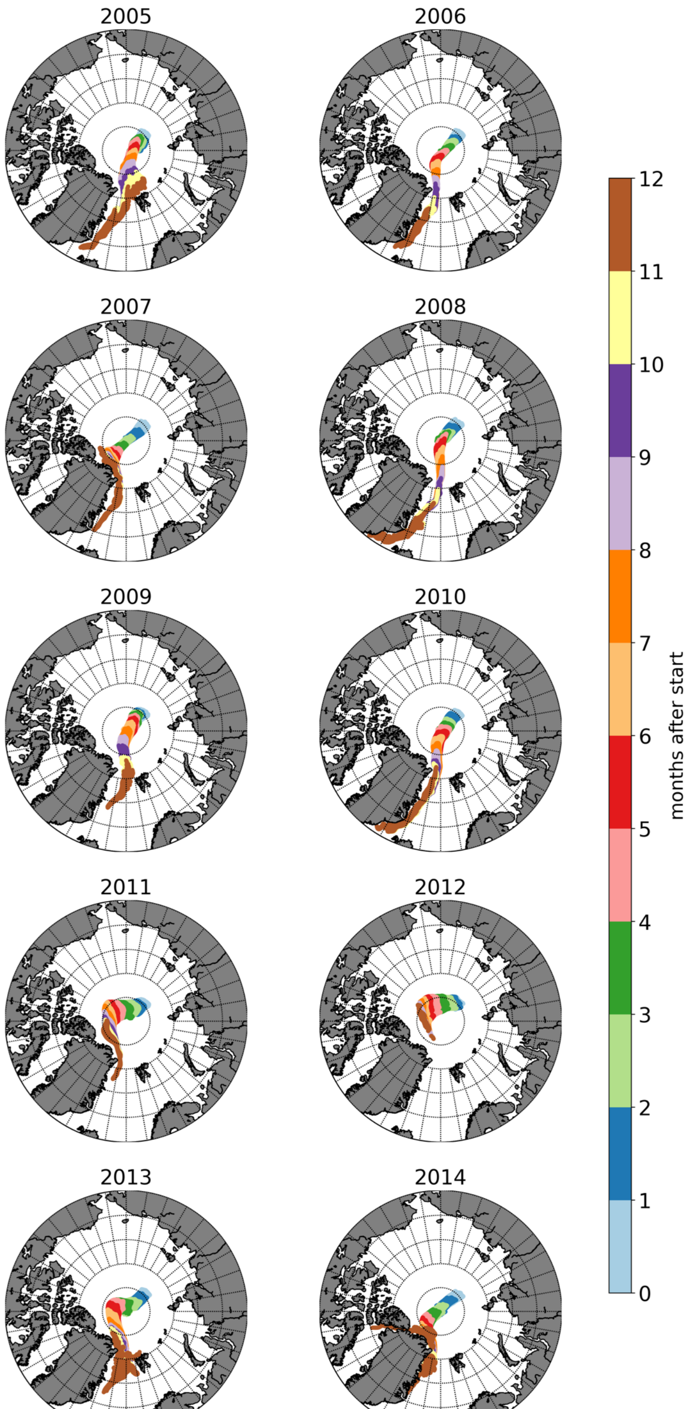
Fig. 5

Individual examples of mean flow structure and particle patch deformation in each year. Colours show the particle positions for particular times after the start for the t0 release (black line, Fig. 4) given by the pairs of blue lines in Fig. 4. Streamlines of the 5-day-mean 'snapshot' surface flow at the mid-time are overlaid, with streamline thickness proportional to flow speed (max. 0.2 m/s). Note that the region shown here is a zoom, north of 75 deg. N, and that here, particles are plotted with earlier times overlaying later times.

Please zoom into figures for details

Fig. 6

As for Fig. 3, but using a surface velocity, which was filtered to suppress the mesoscale (90 day moving boxcar), as input to ARIANE for particle advection. Note that the particle dispersion is generally reduced, compared to Fig. 3 (which is shown again on the right for comparison).



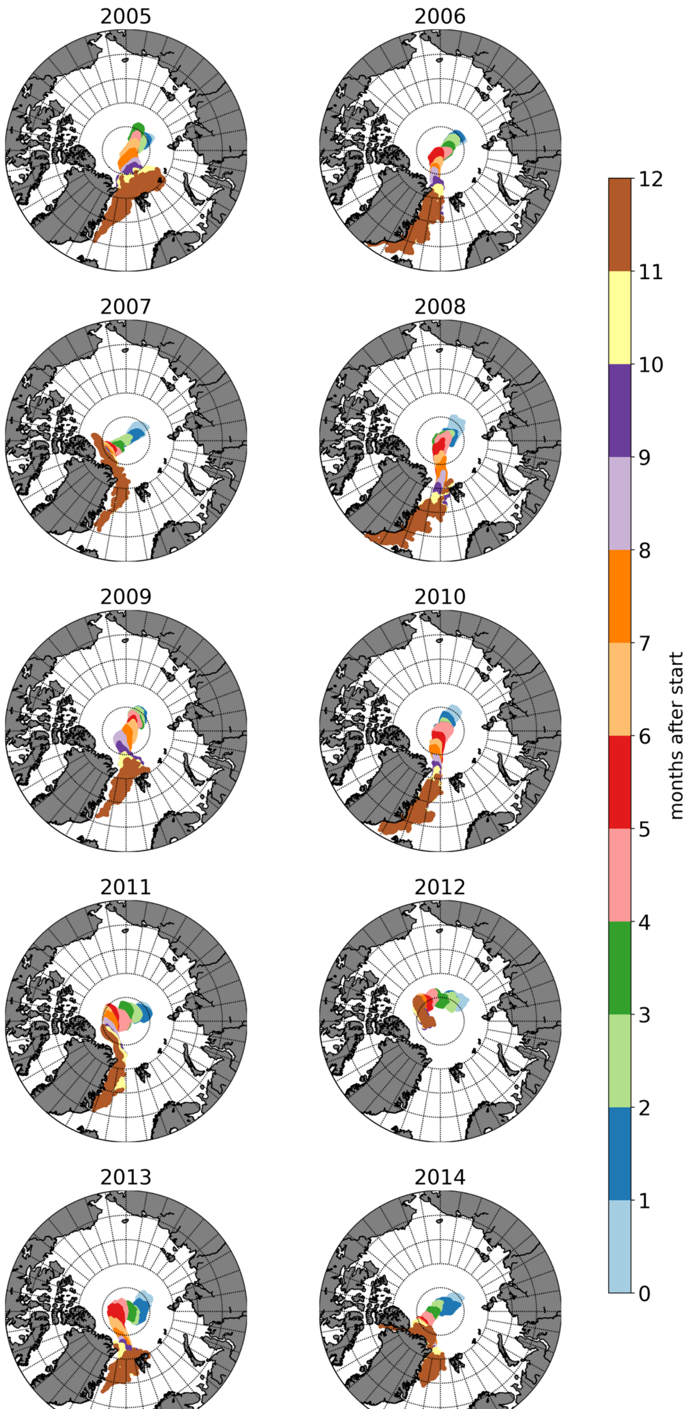


Fig. 3 (repeated)

As for Fig. 2, but showing all 625 particles in the patch, initialised at t=t0, as they advect and the patch deforms. For greater clarity, the streamlines are not overlaid here. Note that some of the particles are unavoidably obscured by plotting of later times over earlier times. The spreading about the ensemble mean is most striking at month 12 (brown).

Results

- The ensemble-mean drift has large interannual variability and broadly follows the annual mean streamlines (Fig. 2), although there is also evidence of Stokes' drift, where the Lagrangian flow crosses Eulerian mean streamlines, pointing to a role for eddy-driven advection.

- The interannual shifting of a saddle point in the mean streamlines, in the vicinity of Nares Strait, at the junction of the Beaufort Gyre and Trans-Polar Drift (Fig. 2) governs both the ensemble-mean drift (Fig. 2) as well as particle dispersion due to saddle bifurcation in the flow (Fig. 3, 2007, 2014).

There is a further bifurcation near Svalbard (Fig. 3, 2005, 2008, 2009, 2013).

- In some years RMS particle pair separation (and ensemble mean drift track, not shown) is more sensitive to time of initial release (Fig. 4). RPPS changes may occur on timescales of a few months or less, associated with the mesoscale. Typically, RPPS remains small until after 6-9 months, when the patch has crossed the basin and reached the boundary currents. Intermittent, wind-driven changes involving the mesoscale and its embedded coherent flow structures control patch deformation local to its time of evolution (Fig. 5), which is often in striking contrast to the annual mean flow (Fig. 2).

- When the surface flow is filtered to suppress the mesoscale, using a 90-day moving boxcar filter, the spreading of particles in the patch is also suppressed (Fig. 6).

Conclusions

- Interannual variability in the Beaufort Gyre, Trans-Polar Drift and circulation in the vicinity of Svalbard is associated with existence and movement of ***saddle points*** in the annual mean surface flow streamlines.

- One persistent saddle point links BG and TPD to the boundary current near Nares Strait and extends into the basin interior.
- Another, intermittent saddle point emerges for some years near Svalbard.

- These coherent flow structures appear to:

    a) govern the ensemble-mean path of advected particles or tracer;

    b) be associated with bifurcation of the particle patch in certain years.

- Patch deformation and bifurcation equates to reduced potential predictability of drift track.

- RMS particle pair separation shows that the patch generally deforms after crossing the basin, after 6-9 months. Additional coherent structures in the local mesoscale flow provide high strain rate on small spatiotemporal scales and are responsible for rapid patch deformation seen particle snapshot sequences and statistics.

- Information about the likely interannual variability in the wind-forced ocean+ice surface circulation and also the representation of mesoscale flow structures are needed to predict surface drift and tracer dispersion.

- The mesoscale may be impossible to predict more than weeks-months ahead, but it might be possible to include mesoscale effects in estimates of the range of possible predictions. This study has shown that it may be important to do so, especially in order make the optimal use of coarse resolution climate projections.

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