Near-Real Time Detection of the Re-Opening of the Weddell Polynya, Antarctica, from Spaceborne Infrared Imagery

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***Abstract*—A hole in the Antarctic sea ice cover, the Weddell Polynya, unexpectedly re-opened in winter 2017 for the first time since 1976. Models suggest that the polynya opened because warm oceanic water moved up to the surface, melting the ice from below. Here three temperature thresholds applied to near-hourly spaceborne infrared imagery (AVHRR) successfully detect the appearance of a warm spot up to five days before the polynya opened in June and September 2017. Traditional sea ice concentration and thickness criteria could only detect the polynya once it was open. An automatised warning system, using near-real time passive monitoring of warm spots, would allow researchers to reroute vessels or autonomous sensors in order to finally study the polynya as a whole when it opens again, from its preconditioning to its impacts on the climate system.**

I. Introduction

At the beginning of the satellite era, over the winters 1974-1976, a 300 000 km^2 hole was observed in the Antarctic sea ice cover in the Weddell Sea [1]. This so-called Weddell Polynya, by exposing the comparatively warm ocean to the austral winter atmosphere, had a large impact on the full 4000 m water column [2] and its effect can still be felt nowadays [3]. Although models suggest that such a polynya should open often in the Weddell Sea [4], it had not happened since 1976... until the Weddell Polynya unexpectedly re-opened this year.

Open ocean polynyas occur as sea ice is melted from below by relatively warm water moving up to the surface, and according to climate models the Weddell Polynya is no exception [5]. The hypothesis driving this work is that the arrival of such warm water at the surface must be visible on infrared satellite imagery. Monitoring the appearance of a warm spot could be an efficient advance warning system. Moreover, infrared imagery from Advanced Very High Resolution Radiometer (AVHRR) aboard several satellites would provide near-real time information about the upcoming opening of the polynya and allow for a faster response from the observation community than traditional passive monitoring by microwave radiometres [6].

II. Data and Methods

We concentrate on the area of the Weddell Sea, Antarctica, where the polynya opened in the 1970s [1] and where modelled polynyas always start [4]: 55 to 75°S, 15°W to 20°E. Within this area we isolate the "polynya-prone" region of 60 to 68°S, 6°W to 12°E for our calculations (purple box, Fig. 1).

We use the daily sea ice maps produced by the University of Bremen: concentration from Advanced Microwave Scanning Radiometer 2 (AMSR2) data at 3.125 km resolution over the so-called Neumayer region [6], and thin ice thickness from the L-band microwave Soil Moisture and Ocean Salinity (SMOS) sensor [7] at 12 km resolution around Antarctica. From the sea ice concentration maps we visually detected two polynya openings on 10 June and 2 September 2017, i.e. two occasions where a hole formed in the Weddell sea ice cover and resulted in an area of open water (sea ice concentration lower than 15%, e.g. [8]) entirely encircled by sea ice. We obtained all AVHRR images by the National Oceanic and Atmospheric Administration (NOAA) available for the week preceding each of these two detected openings and which included the entire polynya-prone region and the majority of our study area. In order to compute false alarm rates, we also randomly picked one AVHRR image per week from 1 May to 30 September 2017, limited to 10:00 - 13:59 UTC to minimise the impact of diurnal SST variations on our results. We selected the 4 km resolution product, more directly comparable to the sea ice products than the 1 km option.

We analysed 186 images of black body temperature at 10800 nm (hereafter referred to as sea surface temperature or SST) between 5 - 12 June and 27 August - 3 September 2017. Those were reprojected using the SNAP software onto the WGS 84 / SCAR IMW ST29-32 standard projection, centered on 90°S and 0°E. We applied a very basic cloud filtering and removed from our calculations any point whose SST was colder by two standard deviations than the mean of the non-land points of the image.

The aim of this paper is to investigate the potential of the AVHRR infrared images for automatic detection of an upcoming polynya opening. We determine whether an area with comparatively warm SSTs forms several days before the openings and is large enough to be automatically detected.

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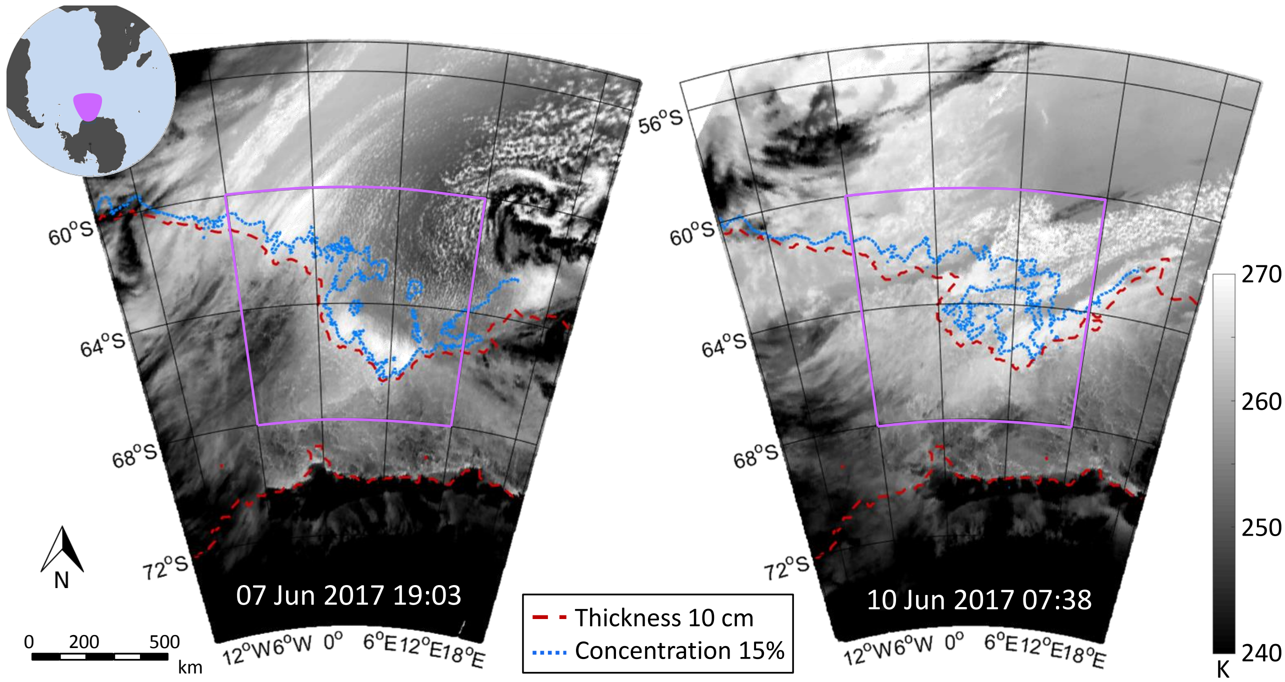

Fig. 1. First opening of the Weddell Polynya in June 2017 as seen by spaceborne AVHRR imagery (gray shading), sea ice thickness (red contour at 10 cm) and sea ice concentration (blue contour at 15%). Purple box indicates the area for the calculations of Fig. 3.

For comparison, we also compute the areas corresponding to traditional criteria of sea ice concentration lower than 15% and thickness lower than 10 cm [9].

III. Results and Discussion

We want to determine some criteria from the 2017 events that could be applied to spaceborne-retrieved sea surface temperature to automatically detect in the coming years that the Weddell Polynya is about to re-open. We observe a first hole in the sea ice cover with a concentration lower than 15% on 10 June 2017 (blue contours on Fig. 1). A comparison with the sea ice concentration of several days before (e.g. 7 June on Fig. 1) reveals that the hole did not open in an ice-covered area but rather that an ice arch formed. The sea ice thickness (red contours) there is lower than 10 cm and cannot be used to detect the polynya. On June 7 however the SST seems warmer than 270 K at the sea ice edge, in the area that will become the polynya (shading on Fig. 1). It may also be the case on 10 June, but this day was very cloudy.

The polynya closed late June (not shown) and re-opened on 2 September 2017 (Fig. 2). This was an actual polynya event: in a fully ice covered area (e.g. 28 August 2017, Fig. 2), a hole with sea ice concentration lower than 15% opens around 64°S and 4°E. As in Alaskan polynyas [9], the 10 cm sea ice thickness contour matches that of the concentration (red and blue contours). Similar to the June opening the SST exceeds 270 K at the polynya location. This hole grew and stayed open until December, when the polynya disappeared as the sea ice edge retreated beyond its limits.

Visually, the region where the polynya will open thus seems associated with warm SSTs. We test whether the appearance of a warm spot in the polynya-prone region (purple box on Figs 1 and 2) can be used more effectively than sea ice concentration and thickness to detect the upcoming opening of the polynya. To do so, we determine whether a polynya opening is associated with an increase in the percentage of the polynya-prone area with:

- SSTs larger than 260, 265 and 270 K (coloured dots on Fig. 3);
- sea ice concentration lower than 15% (gray downward triangles);
- sea ice thinner than 10 cm (black upward triangles).

For the first opening (Fig. 3a), the sea ice criteria are ineffective. The areas of low sea ice increase only once the polynya is open (green vertical line). This is probably because the whole sea ice cover is increasing in June: any decrease in concentration in the polynya area is masked by the advance of the sea ice edge. Variations in the area of the warm spot are clearer: all three criteria return non zero areas on 5 and 8 June (Fig. 3a). The lower the SST threshold, the larger the increase (25% of the polynya-prone area is warmer than 260 K three days before the polynya opens). All the thresholds exhibit a 3 day cycle, with peaks on 5, 8 and 11 June. This cycle is also present if we consider the area itself rather than the percentage of the cloudless area of the image (not shown) and hence is not an artefact of the varying cloud cover. Although we lack in-situ measurements to determine its origin, we can assume that this cycle is caused by vertical motions in the ocean induced by the polynya, similar to what happens in models [5]. That is, wind and/or sea ice formation causes a cooling of the ocean surface whose waters thus become denser and sink, which in

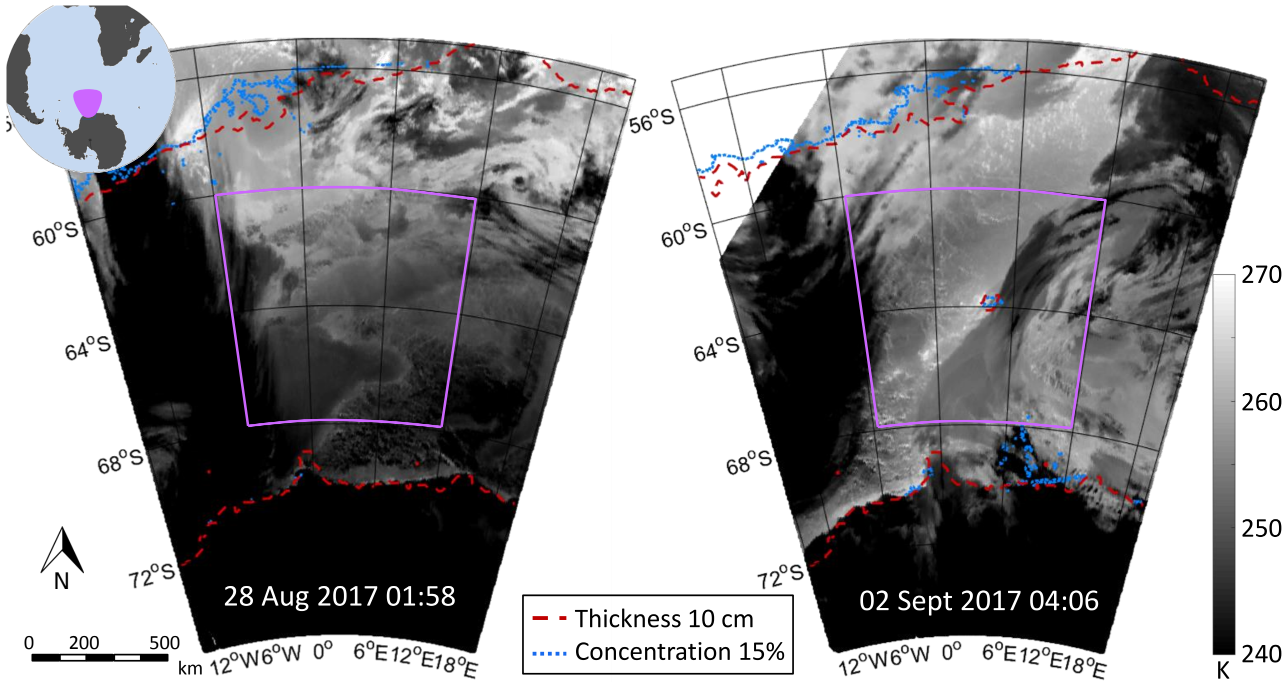

Fig. 2. Same as Fig. 1 for the second opening in September 2017.

turn induces an upward motion of warmer waters.

A similar cycle is also seen ahead of the second polynya opening (Fig. 3b), albeit with smaller amplitudes. The 270 K threshold hardly detects anything. The patch warmer than 265 K covers a mere 2% of the polynya-prone region on 30 August, that is three days before the polynya opens. The most sensitive threshold is 260 K, which detects an area covering 6% of the cloudless polynya-prone region on 28 August, 6 days before the opening, or over 40 000 km^2. The sea ice criteria detect smaller areas than the SST; the thickness threshold fails at detecting the polynya opening ahead of the sea ice concentration and the human eye (gray triangles, Fig. 3b).

For both openings, the smaller the SST threshold the easier the detection, but also the larger rate of false alarms in between events. The median area of the polynya-prone region detected as potentially preparing a polynya when there is in fact no event (as visually detected by the authors) is 0.0 $\pm$ 0.4 % for the 270 K threshold, 0.1 $\pm$ 3.8 % for 265 K, and 8.8 $\pm$ 14.7 % for 260 K. One possibility is that our cloud mask is too rudimentary and that we occasionally detect clouds and/or fog instead of a warming of the ocean when using the 260 K threshold. This risk could be minimised for example by using several bands [10] or by filtering out clouds and aerosols based on their texture [11]. We must also bear in mind that we are using data from only one year. Future reopenings of the polynya would help us refine our criteria.

We could also think of other methods. AVHRR images are strongly impacted by clouds and aerosols, but modelling work has shown that the Weddell Polynya itself locally impacts the atmosphere [12]; maybe clouds and fog could be used as a proxy for polynya detection. For sea ice concentration and SSTs, shape recognition algorithms could help distinguish polynya opening from tortuous sea ice formation, especially during sea ice growth season. And of course, now that the polynya has occurred again, active finer monitoring by Synthethic Aperture Radars can be envisaged.

IV. Conclusion

The re-opening of the Weddell Polynya in June and September 2017 could be predicted five days in advance by monitoring on AVHRR images the appearance of a warm spot, probably caused by the upwelling of comparatively warm water that will melt the sea ice from below. Five days would be enough to reroute autonomous sensors that are already monitoring the region, or even for a ship from South Africa, in order to be on site and ready to measure as the polynya opens. Future polynya openings, hopefully as early as winter 2018, will help refine this method for an improved early warning system but also as a near-real time complement of other methods.

Acknowledgment

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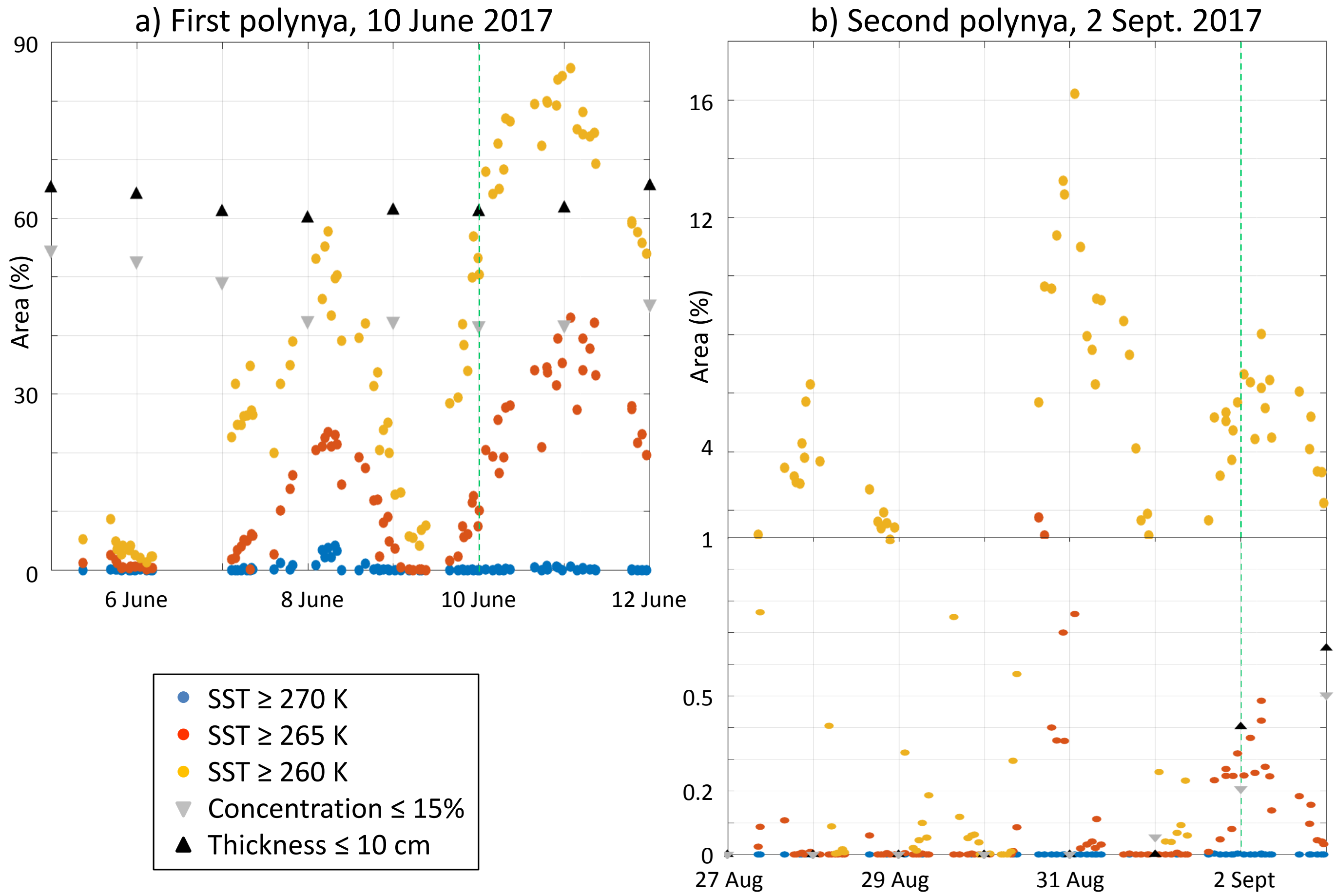

Fig. 3. Percentage of the area defined by the purple box on Figs 1 and 2 that matches the five different criteria for polynya opening detection as detailed in the text for the a) June and b) September 2017 events. Note the different y-axes on the panels, in particular the 0-1% zoom for b. Green vertical lines indicate visual detection of the polynya on sea ice concentration maps by the operator.

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