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Understanding the drift of Shackleton's *Endurance* during its last days before it sank in November 1915 using meteorological reanalysis data

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Abstract. On 5 December 1914, Sir Ernest Shackleton and his crew set sail from South Georgia aboard the wooden barquentine vessel *Endurance*, thus beginning the Imperial Trans-Antarctic Expedition to cross the Antarctic continent. However, Shackleton and his crew never reached land because the vessel became beset in the sea ice of the Weddell Sea in January 1915. *Endurance* then drifted in the pack for eleven months, was crushed by the ice and sank on 21 November 1915. Over many years, various predictions were made about the exact location of the wreck. These were based largely on navigational fixes taken by Captain Frank Worsley, the navigator of the Endurance, three days prior to, and one day after the sinking of *Endurance*. On 5 March 2022, the Endurance 22 expedition successfully located the wreck some 7.8 km southeast of Worsley's estimated sinking position. In this paper, we describe the use of meteorological reanalysis data to reconstruct the likely ice drift trajectory of *Endurance* for the period between Worsley's final two fixes, at some point along which she sank. This approach yields a mean 24-hour position error of 4 to 10 km, and a predicted location some 2 to 5.3 km from the position at which the wreck finally was found. In spite of numerous sources of uncertainty, these results show the potential for such methods in marine archaeology.

1 Introduction

The story of Sir Ernest Shackleton and the Imperial Trans-Antarctic Expedition has captivated historians and the public for more than 100 years. The Trans-Antarctic Expedition is well-documented, owing to various carefully written accounts produced by Shackleton and the crew (e.g. Shackleton, 1919; Worsley, 1931). Despite being a point of conjecture for decades,

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the precise location of the wreck of the *Endurance* was unknown until 5 March 2022, when the Endurance22 expedition located it at the bottom of the Weddell Sea.

Endurance 22 was an interdisciplinary maritime archaeological project aimed at locating and surveying the wreck of *Endurance*. It utilised the South African research icebreaker S.A. *Agulhas II* and Saab Sabretooth autonomous underwater vehicles (AUVs) to scan a predetermined search area of the seabed using low frequency side-scan sonar. The search area and strategy were developed by marine archaeologists, historians and a specialist sub-sea team who consulted archives and crew diaries (Bound, pers.comm, 14 May, 2022). Estimations of uncertainties in Captain Worsley's astronomical position fixes made using a sextant and the ship's chronometers, prior to and post sinking, formed a key determinant of the focus area (Bound, pers.comm, 14 May, 2022). The extent of the final search area was further constrained by the available bottom time and associated possible coverage of the seabed by the AUVs (Bound, pers.comm, 14 May, 2022). To assist the wreck search, the Endurance22 expedition team also comprised sea ice researchers and meteorological-oceanographic (met-ocean) specialists to support tactical ice navigation en-route to and within the search area. Specifically, predictions of short-term ice drift direction and speed were required to assist precise subsea survey operations at depths of 3000 m, beneath completely closed drifting sea ice cover. This necessitated the use of a wide range of data sources, including remote sensing data, numerical models and direct measurements. In particular, analysis of the ice pack and the timing and magnitude of wind and tidal shifts were important in guiding the safe navigation of the vessel and also the precise deployment of the AUVs for the subsea survey.

This aim of this study is to analyse the position uncertainties originating from the unknown sea ice drift between Worsley's celestial fixes on 18 and 22 November 1915. Further, it aims to reconstruct this unknown portion of *Endurance's* last days of drift using twentieth century meteorological reanalysis data and historical weather observations.

2 Data and methods

2.1 Navigational fixes

Throughout the voyage, Captain Frank Worsley obtained navigational fixes based on sun and star sightings to track the location and movement of *Endurance* through the ice pack. Endurance sank at around 19h00 hrs local time on 21 November 1915. However, bad weather around the time of the sinking only allowed for accurate navigational sights three days before on 18 November 1915 and again one day after on 22 November 1915. The ship's exact trajectory during the intervening approximately 4 days – referred to hereafter as the *target period* – remains unknown. However, Worsley estimated the position of Ocean Camp on 21 November, assuming the sea-ice drift to offset the position by about 1.5 nautical miles to the southeast, relative to the fix obtained on 22 November. We believe this estimate was based on local wind observations, as Worsley had no means by which to observe the sea ice drift directly. He then added a further offset of about 1 nautical mile to the south east, between Ocean Camp and the vessel before sinking. Dowdeswell et al. (2020) record that there are relatively small uncertainties in the positions of Ocean Camp and the Endurance due to factors including: the fact that Captain Worsley made no astronomical observations between 3 days before and nearly 16 h after the sinking because of bad weather; the drift of the

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chronometer used (primarily affecting longitude); the exact distance and bearing between Ocean Camp and the *Endurance*; and the speed and bearing of the ice drift assumed for dead reckoning of the position. In this work, we assume Worsley's fixes to be accurate, and concentrate our analyses on uncertainties introduced by the ice drift.

2.2 Meteorological observations

To estimate ice drift during this target period, we requested scans of the original log of the meteorological recordings and measurements made by the expedition meteorologist, Leonard Hussey, which are kept in the Archives of the Scott Polar Research Institute, University of Cambridge. Hussey recorded surface meteorological variables generally four times per day at 12:00, 16:00, 20:00 and 24:00 GMT. Among others, wind speed and direction were measured using an anemometer and reported in units of the Beaufort wind scale, and in cardinal and inter-cardinal directions, respectively. These data; specifically, the upper wind speed bounds of the reported Beaufort intervals and wind directions; were linearly interpolated to an hourly resolution and then utilised to produce a drift trajectory for the target period. It should be noted that no observations were taken during the local night hours, leaving significant data gaps and introducing large uncertainties in the reconstructed ice drift trajectory.

2.3 ERA-20C reanalysis data

The ERA-20C (Poli et al., 2016) is a global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). It provides a range of atmospheric and surface ocean variables with regular spatio-temporal resolution for the period 1900-2010. Data are produced by a modified version of an operational atmospheric general circulation model (AGCM) and a data assimilation scheme, which form the foundation of ECMWF's Integrated Forecast System (IFS). The IFS is normally used to produce short and medium term weather forecasts. Modifications to the AGCM configuration and details regarding boundary conditions and forcing have been described in detail by Hersbach et al. (2015), who showed that the model was successfully able to reproduce low frequency variability of large-scale atmospheric features. The purpose of data assimilation during production of the reanalysis is to enhance the performance of the model in simulating weather events. The meteorological observations of Hussey (see above) have not been assimilated into the ERA-20C (Poli et al., 2016) reanalysis dataset. As such, both datasets provide independent estimates of the actual synoptic situation during the time of *Endurance's* sinking. While the ERA-20C dataset comes with large uncertainties, it has been shown to be capable of describing the large-scale atmospheric circulation and by extension, should be able to describe the wind patterns in the western Weddell Sea. We extracted near-surface wind speeds and directions from the ERA-20C dataset (Poli et al., 2016) and used them as a proxy to reconstruct the ice drift trajectory.

2.4 Reconstructing ice drift trajectories

To construct the historical ice drift trajectories from both datasets, we assumed a free drift regime, where sea ice motion is purely described by wind forcing and internal dynamic forces and ocean forcing are neglected. This assumption has been

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shown be reasonable over short time scales (e.g. Holland and Kwok, 2012; Kottmeier et al., 1992; Kwok et al., 2017; Vihma et al., 1996). Ice drift speed is therefore prescribed as 2.5 % of the wind speed and ice drift direction is rotated 25° left of the wind direction for the Southern Hemisphere. This algorithm was also successfully used during the Endurance 22 expedition to predict short term ice drift trajectories from present day weather forecasts, and plan subsea survey work accordingly. Using historical wind data we have approximated *Endurance's* drift path for the target period (Figure 1). The candidate sinking locations can be revealed if we align, in time, the ice drift trajectory and the reported sinking time of the Endurance.

2.5 Trajectory alignment and nudging

None of the reconstructed trajectories is able to link Worsley's fix on 18 November to his 22 November fix. While this could be due to errors in Worsley's navigation, we assume that it is mainly caused by errors in the wind forcing datasets. To overcome this limitation we provide three versions of a corrected position track.

1. Our first approach is to nudge the path such that it leads from Worsley's 18 November fix to his 22 November fix. To achieve this, the predicted trajectory was co-located in the start point on 18 November and then we added for each time step the averaged position offset in such a way that the predicted position on 22 November matches Worsley's observation. (See dark orange and dark blue solid lines in Figure 1) This corresponds to a purely time dependent accumulating error.
2. The highest quality trajectory might, however, result from aligning the predicted trajectories at Worsley's fix closest in time on 22 November, without changing its general shape. (see light orange and light blue solid lines in Figure 1)
3. Doing the same alignment with his fix on 18 November (see dashed orange and blue lines in Figure 1) then allows us to roughly estimate the magnitude of position uncertainty associated with sea ice drift (see orange and blue ellipses in Figure 1).

3 Results and discussion

3.1 Validation

As described above, particularly the ERA-20C derived drift track comes with potentially larger uncertainty. However, we can count on some facts for validating Hussey's observations and the ERA-20C data against Worsley's position record. Both datasets (ERA-20 and Hussey-based ice drifts) agree on a southerly ice drift before 18 November and they all agree on a northerly ice drift after 22 November. Hence, a similar general atmospheric circulation seems to be represented in both datasets. They also agree on the transition from the southerly drift regime to a northerly drift regime during the target time. Thus, all sources point to a southerly excursion of *Endurance's* drift which is not described in Worsley's navigation data. A change in ice drift direction could also possibly have been related to the cause of the sinking of the *Endurance* by changing ice dynamics.

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However, the wind shift appears to have occurred prior to the recorded sinking time of *Endurance* in both the observations and ERA20-C reanalysis data.

3.2 Estimating ERA-20C drift prediction error

To assess the relative uncertainty of the ERA-20C drift predictions, we performed a basic assessment of mean predicted position error. Positions predicted by applying ERA-20C near-surface winds to virtual ice floes were reconstructed for the entire period during which *Endurance* was beset and drifting in the ice pack. The error is an average for the periods between daily positional fixes made by Worsley. The positions of virtual ice floes (defined by the navigational fixes) are forced according to the above mentioned forecast protocol by ERA-20C winds. Whenever a position update from Worsley's log becomes available, the end position is automatically corrected, such that the initial position for the next drift step is Worsley's most recent fix. Mean error is computed as the mean of the distances between the end position from the forecast and the corresponding end positions available in Worsley's log. Figure 2 shows the histogram of all position errors for the period during which *Endurance* was beset and drifting in the pack ice. In total, 316 position fixes were available, yielding a mean daily error of 9.7 km and 174 ° (i.e. Worsley's positions were generally south of the modelled positions). Typical errors for predicted drift positions were between 4 and 10 km for 24 hours lead times. This yields a total uncertainty of 16 to 40 km accumulated over the 4 day period during which Worsley was unable to obtain a fix.

3.3 Comparison of ERA-20C winds with Hussey observations

A comparison between the trajectories constructed from Hussey's wind observations with those derived from ERA-20C data highlights some interesting differences. Hussy's observations point to a slightly more south-westerly direction in the drift loop, while the ERA-20C prediction shows a larger spread and a more southerly direction (Figure 1). While the drift trajectories and projected sinking sites derived from Hussey's wind data are highly consistent with Worsley's estimation of the sinking location, the trajectories predicted from ERA-20C data are more consistent with the actual wreck location.
Two reasons could explain these differences: firstly, Hussey's observations were limited to half of the day only, which could mask significant sub-daily ice motion (whereas ERA20C provides 3-hourly information). Secondly, the assumption of a locally free-drifting ice pack might be very limited for the ice conditions in November 1915, where a thicker and hence stiffer ice pack would have reacted more likely to wind forcing on a larger scale. As such, the ERA-20C data, being likely more representative of the wind forcing in a broader area, could provide a better representation of the larger scale ice motion. This could cause the differences between observed local winds and larger scale non-free drift ice motion processes.

3.4 Reconstructed trajectories and sinking sites

The reconstructed trajectories indicate that the principal source of uncertainty in *Endurance's* sinking location was unknown sea ice drift. This uncertainty is on the order of tens of kilometres and particularly oriented in the meridional (north-south) direction. The confirmed location of the wreck at 68°44’21” S, 052°19’47” W is much closer to the sinking sites derived from the ERA20-C data than those derived from Hussy’s wind and Worsley’s astronomical observations. This provides strong evidence for our theory of a southern drift excursion which was unaccounted for in Worsley’s original navigational records. It also highlights the importance of considering sea ice drift for marine archaeological projects in the polar seas.

4 Conclusions

This study demonstrates the potential of modern reanalysis weather models to help reconstruct the ice drift trajectory of Shackleton’s Endurance, and for use in marine archaeological projects more generally. We showed that position uncertainties related to ice drift can be up to one order of magnitude larger than the uncertainties typically associated with celestial position fixes obtained by skilled navigators using traditional methods. In this case specifically, ice drift uncertainties cause larger uncertainty in latitude, while uncertainty estimates based purely on navigational error yields larger longitudinal uncertainty. We showed that between 18 and 22 November, *Endurance’s* drift track likely followed a southerly excursion which is not described in Worsley’s navigational data. We conclude that rigorous analysis of all available sea ice drift data is of significant importance to marine archaeological projects in sea ice covered oceans. This is not only true for proper positioning of the drifting survey vessel in the ice, but also for understanding the implications of sea ice drift on the position and trajectory of historic vessels locked in the ice.

Author Contribution

Conceptualization: MdV; Data curation: MdV, CK, PK; Formal analysis: PK, CK, MdV; Investigation: MdV, PK, CK, LR, JS; Methodology: MdV, CK, LR, PK; Project administration: MdV, CK, LR, JS; Resources: MdV, LR, PK; Software: MdV, CK, PK, MS; Supervision: MdV, JS, LR; Validation: CK, MdV; Visualization: MdV, CK, MS; Writing – original draft preparation: MdV, CK; Writing – review & editing: all authors.

Competing interests

The authors declare that they have no conflict of interest.

Data Availability

ERA-20C data is freely available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-20c. Leonard Hussey’s meteorological observations are available upon request of the Archives of the Scott Polar Research Institute,

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University of Cambridge, with reference: SPRI Archive MS 1605/2/1 Hussey, L.D.A. Meteorological returns: Endurance 1.1.1915-31.12.1915.

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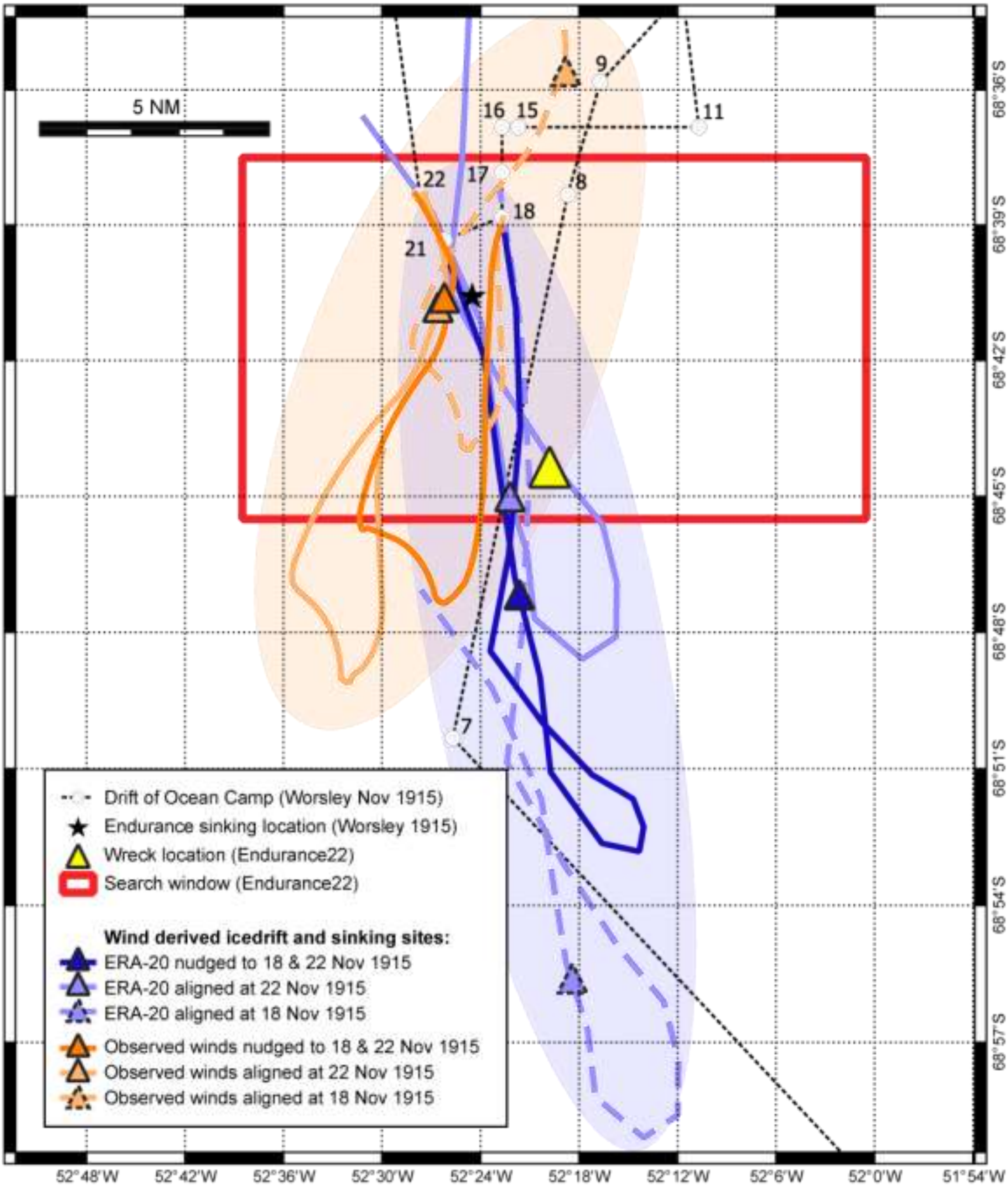

Figure 1. Reconstructed drift tracks and sinking sites using ERA-20C reanalysis (blue) and Hussy's meteorological observations (orange). Coloured ellipses show approximate uncertainty regions associated with the respective dataset.

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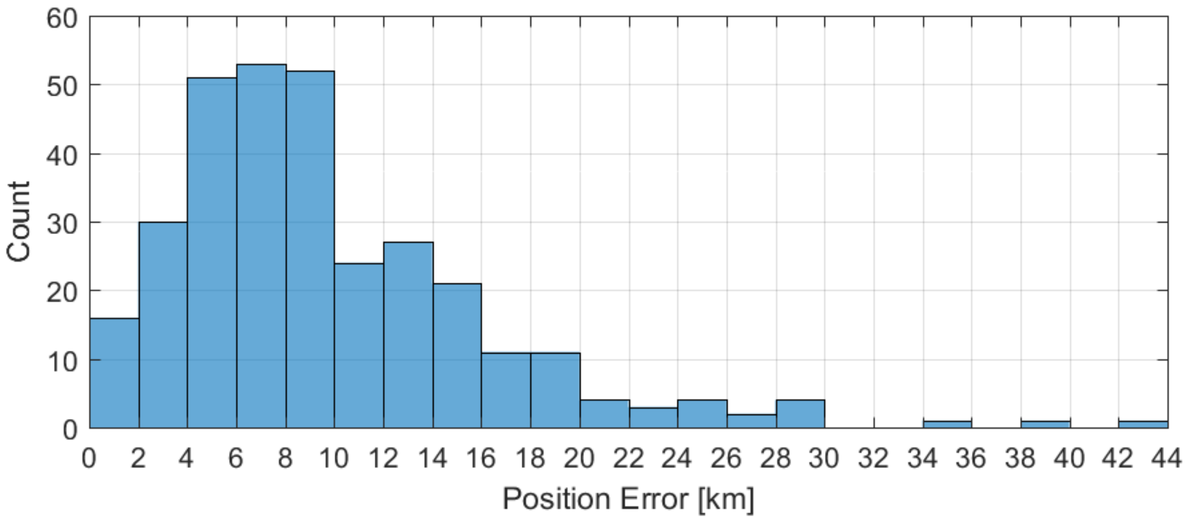

Figure 2. Distribution of errors for predicted end positions when forcing virtual ice floes from initial positions as defined in Worsley's navigational fixes, using ERA-20C surface winds.