An objective global climatology of polar lows based on reanalysis data

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Here we present an objective global climatology of polar lows. In order to obtain objective detection criteria, the efficacy of several parameters for separating polar lows from other cyclones has been compared. The comparison and the climatology are based on the ERA-Interim reanalysis from 1979 to 2016 and the high-resolution Arctic System Reanalysis from 2000 to 2012. The most effective parameters in separating polar lows from other extratropical cyclones were found to be the difference between the sea-level pressure at the centre of the low and its surroundings, the difference in the potential temperature between the sea surface and the 500 hPa level, and the tropopause wind speed poleward of the system. Other parameters often used to identify polar lows, such as the 10 m wind speed and the temperature difference between the sea surface and the 700 hPa level, were found to be less effective. The climatologies reveal that polar lows occur in all marine basins at high latitudes, but with high occurrence density in the vicinity of the sea-ice edge and coastal zones. The regions showing the highest degree of polar-low activity are the Denmark Strait and the Nordic Seas, especially for the most intense polar lows. In the North Atlantic and Pacific, the main polar-low season ranges from November to March. In the Southern Hemisphere, polar lows are mainly detected between 50 and 65°S from April to October, indicating that this hemisphere compared to its northern counterpart has a two months longer, but less intense, polar-low season. No significant hemispheric long-term trends are observed, although some regions, such as the Denmark Strait and the Nordic Seas, experience significant downward and upward trends in polar lows, respectively, over the last decades. For intense polar lows, a significant declining trend has been observed for the Northern Hemisphere.

KEYWORDS
Arctic hurricane, detection/identification criteria, long-term trend, mesoscale cyclone, marine cold-air outbreak, polar low, tracking algorithm

1 INTRODUCTION

Polar lows (PLs) are intense mesoscale cyclones occurring over the oceans at high latitudes. Due to their strong winds, they are a threat to fishing, maritime operations, and to life in coastal zones of the polar regions. They are often associated with high amounts of snowfall, so that at landfall they can cause increased avalanche danger and traffic chaos. Furthermore, PLs may lead to fast accumulation of ice on aircrafts and ships (Samuelsen et al., 2015). In particular, PLs can be dangerous since they often develop rapidly, so hazardous conditions occur suddenly.

Probably the most cited definition of a polar low was formulated by Rasmussen and Turner (2003):
“A polar low is a small, but fairly intense maritime cyclone that forms poleward of the main baroclinic zone (the polar front or other major baroclinic zone). The horizontal scale of the polar low is approximately between 200 and 1000 km and has surface winds near or above gale force.”
FIGURE 1  Map of the polar regions of the (a) Northern and (b) Southern Hemispheres. White denotes areas with an average sea ice cover above 20% during the main polar low season, being for (a) November–April and for (b) April–October, for the years 1979–2016 from ERA-I

Some PLs are referred to as Arctic hurricanes due to their clear central “eye” surrounded by deep convective cloud bands (e.g. Emanuel and Rotunno, 1989). However, in contrast to their tropical counterparts, the definition of a PL is vague, and the transition between a PL and the weaker form of a polar mesoscale cyclone is fluid. The scientific community does not agree on criteria for the classification of a cyclone as a PL. This study aims to develop a set of objective identification criteria for the detection of PLs in reanalyses by examining a broad range of previously suggested parameters and to investigate a global PL climatology based on these criteria.

Different PL climatologies have been developed by inspection of satellite images, starting from the late 1970s and early 1980s for the Nordic Seas (Figure 1; Wilhelmsen, 1985). For the same region, and for the years 2000–2012, Noer et al. (2011) developed the Sea Surface Temperature and Altimeter Synergy for Improved Forecasting of Polar Lows (STARS) database. Recently Smirnova et al. (2015) proposed a new PL climatology of this region based on satellite passive microwave data for 1995–2009 and referred to here as the Smirnova database. This database includes considerably more cases than does the STARS database. This reveals the key problem when investigating and comparing different climatologies: they are generally based on different criteria and methodologies. Two meteorologists might come to different conclusions on whether a system is classified as a PL or not, based on a vague notion of what a PL is.

The Nordic Seas are probably the region most often investigated with respect to PL activity, but some other studies have developed climatologies based on satellite images for other regions, such as the Gulf of Alaska for 1975–1983 (Businger, 1987), the North Pacific for 1976–1984 (Yarnal and Henderson, 1989), the Sea of Japan and Northwest Pacific for the winter 1995/96 (Fu et al., 1999), and in the Southern Hemisphere (SH) for 1977–1983 (Carleton and Carpenter, 1990). However, the subjective nature of PL identification makes comparisons between different climatologies difficult.

Global atmospheric reanalyses can be used to overcome this subjective identification problem. Laffineur et al. (2014) showed that global reanalyses include some PLs, but only a small fraction of the STARS PLs were identified as sea-level pressure (SLP) minima in reanalysis datasets. By using the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-I; Dee et al., 2011), only 13 out of 29 STARS PLs for the period December 1999 to May 2002 were found, although this analysis showed a considerable improvement compared to using the older ERA-40 reanalysis, where only six systems were identified. Laffineur et al. (2014) also showed that by downscaling ERA-I with a 12 km resolution model, 22 of the 29 STARS PLs were detected. Kolstad (2011) attempted to circumvent the issue of the under-representation of PLs in coarse-resolution global reanalysis datasets by compiling a climatology of conditions favourable for PL development. Two criteria were considered, one for the low-level static stability and the other for the upper-level forcing, to obtain the duration over which both criteria are satisfied simultaneously in a given region.

Although global reanalyses show deficits in representing mesoscale systems, Zappa et al. (2014) and Bromwich et al. (2016) showed that it is generally possible to identify a considerable number of PLs in ERA-I. They show that 55% (19 out of 34) of the STARS PLs of the period 2008–2011 could be automatically detected by objective criteria based
on the 850 hPa vorticity, the 10 m wind speed and a measure for the static stability, Michel et al. (2018) detected about 60% of all STARS PLs in ERA-I with an automatic tracking algorithm based on the Laplacian of the SLP. In the higher-resolution ECMWF operational analysis, Zappa et al. (2014) detected 70% (23 out of 34) of the events. Investigations by Smirnova and Golubkin (2017) estimate that ERA-I represents 48% (22 out of 46) of the PLs during the cold seasons 2000/2001–2003/2004 from the STARS database, but only 26% (41 out of 158) from the Smirnova database. Further, they show that the recently developed high-resolution Arctic System Reanalysis (ASR) version 1 (Bromwich et al., 2016) represents 89% (41 out of 46) of the PLs from the STARS dataset and 66% (104 out of 158) from the Smirnova dataset. The improvement is explained by the improved representation of mesoscale systems in this high-resolution reanalysis (Smirnova and Golubkin, 2017). The conclusion from this comparison of different reanalysis products indicates a considerable improvement of ASR over ERA-I in terms of PL representation; the ECMWF operational analysis used by Zappa et al. (2014) and ERA-I downscaled with a 12 km resolution mesoscale model as performed by Laffineur et al. (2014) are still missing a higher proportion of STARS PLs than ASR. Although the studies used different time periods and methodology, ASR could be regarded as one of the most reliable and consistent datasets for PL representation in the Arctic.


Objective PL climatologies depend crucially on criteria applied in order to detect PLs from the whole variety of cyclonic features that are present in the data. Commonly, a threshold for the strength of the SLP minima, or for the vorticity extrema, are imposed, to ensure a certain intensity of the system. Some other additional criteria which are often applied are presented in the following.

Because PLs develop only over sea areas and dissipate rapidly after making landfall, presence over open water is commonly set as a criterion. The PL definition of Rasmussen and Turner (2003) includes a condition for near or above gale force surface winds, which is generally considered as the maximum of the near-surface wind speed in a certain radius around the PL centre. Often, a threshold of 15 m s$^{-1}$ in a radius of 2.5° around the centre, is applied (e.g. Yanase et al., 2016). However, global reanalyses such as ERA-I have been shown to under-represent maximum wind speeds associated with PLs (e.g. Zappa et al., 2014), making a strict application of the wind criteria problematic. In ASR the near-surface wind were observed to be more realistic (Smirnova and Golubkin, 2017).

Even though the definition of Rasmussen and Turner (2003) does not mention the occurrence of PLs in marine cold-air outbreaks (MCAOs), there seems to be a general agreement within the scientific community that an MCAO is required for a cyclone to be classified as a PL. This is partly taken into account in the widely applied static-stability criterion, given by a difference between the sea-surface temperature (SST) and the overlying atmospheric temperature, either at 500 hPa (Zahn and von Storch, 2008; Zappa et al., 2014), at 700 hPa (Bracegirdle and Gray, 2008; Kolstad, 2011) or at 850 hPa (e.g. Papritz et al., 2015). Commonly, a threshold of $SST - T_{500} > 43$ K is used, although Terpstra et al. (2016) and Smirnova and Golubkin (2017) argue that this threshold excludes a considerable number of PL cases. Bracegirdle and Gray (2008) investigated different temperature parameters, and found the difference between the wet-bulb potential temperature at 700 hPa and the SST to be the most effective of their considered parameters to separate PLs from other cyclones. To our knowledge the study of Bracegirdle and Gray (2008) was the first to objectively compare the effectiveness of different parameters for PL detection. As indicated above, the research community does not agree on a set of parameters and thresholds for objective PL detection, and a comprehensive comparison of criteria is still lacking. In addition, an important part of the PL definition formulated by Rasmussen and Turner (2003) – the formation poleward of the main baroclinic zone – to our knowledge has previously not been used as a criterion for PL detection.

This study aims to objectively compare the efficacy of different parameters for the identification of PLs and to apply the derived criteria to the development of an objective, global PL climatology. The paper is structured as follows. After presenting the methods and data in section 2, the results are divided into two parts. In section 3, the efficacy of the different parameters for PL identification from reanalysis datasets based on the subjective STARS dataset is compared, and in section 4 the obtained global PL climatologies based on the application of the most effective derived criteria are analysed. The paper ends with a discussion and conclusion in section 5.

2 | DATA AND METHODS

2.1 | Reanalysis datasets

The ERA-I is a time-consistent and homogeneous global, atmospheric reanalysis product at a T255 horizontal spectral resolution, which corresponds to a grid spacing of about 80 km, and with 60 vertical sigma levels of which 12 are below 850 hPa (Dee et al., 2011). ERA-I is produced using four-dimensional variational data assimilation (4D-Var) with
a 12 h window. The analysis data are provided and retrieved with a 6-hourly time step and a horizontal spacing of 0.5°. To obtain a reasonable time resolution for the tracking of mesoscale cyclones, the time resolution of the vorticity fields is increased to become 3-hourly by using the 3 h and 9 h forecasts starting at 0000 and 1200 UTC every day. Other fields are not extended to 3-hourly resolution, since not all (compare Table 1) can be retrieved from the ERA-I forecast. For this study full-year data for 1979–2016 for both hemispheres are used.

The recently released Arctic System Reanalysis (ASR) version 2 is a regional reanalysis of the greater Arctic (north of ~40° N) based on the Weather Research and Forecasting Model (WRF) version 3.6.0 with adaptations relevant for polar regions (Bromwich et al., 2017). It has a horizontal grid resolution of 15 km, has 71 vertical eta levels, of which 25 are below 850 hPa, and is produced from 2000 to 2012. ERA-I is used for the lateral boundary condition and for spectral nudging above 100 hPa. ASR applies 3D-Var with a 3 h window to include additional in-situ measurements, GPS radio occultation and radiance data from numerous satellite platforms, including 10 m ocean wind speed information. The output fields from ASR are provided 3-hourly on a polar stereographic grid.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Type</th>
<th>r (° lat)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity criteria</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T40–T100 filtered relative vorticity at 850 hPa</td>
<td>(\xi_{850})</td>
<td>point</td>
<td>0</td>
</tr>
<tr>
<td>Maximum 10 m wind speed within radius r</td>
<td>(U_{\text{1m}})</td>
<td>max</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Sea level pressure</td>
<td>SLP</td>
<td>point</td>
<td>0</td>
</tr>
<tr>
<td>Difference of the mean SLP within radius r and the SLP of the cyclone centre</td>
<td>SLP – SLP</td>
<td>mean – point</td>
<td>1, 2, 3, 5</td>
</tr>
<tr>
<td><strong>Marine cold air outbreak criteria</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean temperature at 500 and 700 hPa within radius r</td>
<td>(T_{500}, T_{700})</td>
<td>mean</td>
<td>1</td>
</tr>
<tr>
<td>Mean sea-surface temperature within radius r</td>
<td>SST</td>
<td>mean</td>
<td>1</td>
</tr>
<tr>
<td>Mean equivalent potential temperature at 700 and 850 hPa within radius r</td>
<td>(\theta_e_{700}, \theta_e_{850})</td>
<td>mean</td>
<td>1</td>
</tr>
<tr>
<td>Mean and maximum difference between the SST and (T_{500}/T_{700}) within radius r</td>
<td>SST – (T_{500}/T_{700})</td>
<td>mean, max</td>
<td>1</td>
</tr>
<tr>
<td>Difference in the potential temperature at the sea surface and (p = 500/700/850) hPa</td>
<td>(\theta_{\text{SST}} – \theta_e)</td>
<td>mean, max</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Difference in the equivalent potential temperature at the same levels</td>
<td>(\theta_{\text{SST}} – \theta_e)</td>
<td>mean, max</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>MCAO criterion used by Kolstad and Bracegirdle (2008) with (p = 500/700) hPa</td>
<td>MCAO_{500}</td>
<td>mean, max</td>
<td>1</td>
</tr>
<tr>
<td>MCAO criterion used by Bracegirdle and Kolstad (2010) at 700 hPa</td>
<td>MCAO_{700}</td>
<td>mean, max</td>
<td>1</td>
</tr>
<tr>
<td>Mean and minimum potential temperature of the tropopause within radius r</td>
<td>(\theta_u)</td>
<td>mean, min</td>
<td>1, 3, 5</td>
</tr>
<tr>
<td>Difference in the potential temperature of the sea surface and the tropopause</td>
<td>(\theta_{\text{SST}} – \theta_u)</td>
<td>mean, max</td>
<td>1, 3</td>
</tr>
<tr>
<td>Maximum tropopause pressure within radius r</td>
<td>(p_u)</td>
<td>max</td>
<td>3, 4, 5</td>
</tr>
<tr>
<td>Mean planetary boundary layer height within radius r</td>
<td>PBH</td>
<td>mean</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Maximum gradient of the 850 hPa equivalent potential temperature within radius r</td>
<td>(\nabla \theta_e_{850})</td>
<td>max</td>
<td>3, 4, 5</td>
</tr>
<tr>
<td>Mean of the total column water within radius r</td>
<td>water</td>
<td>mean</td>
<td>1</td>
</tr>
<tr>
<td><strong>Polar-front criteria</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum tropopause wind speed poleward of the cyclone centre</td>
<td>(U_{\text{w850}})</td>
<td>max</td>
<td>Poleward</td>
</tr>
<tr>
<td>Maximum 500 hPa wind speed poleward of the cyclone centre</td>
<td>(U_{\text{w500}})</td>
<td>max</td>
<td>Poleward</td>
</tr>
<tr>
<td>Maximum of the gradient of the (\theta_e_{850}) poleward of the cyclone centre</td>
<td>(\nabla \theta_e_{850})</td>
<td>max</td>
<td>Poleward</td>
</tr>
</tbody>
</table>

Parameters are grouped after their type: the intensity criteria, the marine cold-air outbreak (MCAO) criteria, and the polar-front criteria. Generally the parameters are larger for PLs than for average cyclones, but parameters denoted with * are typically smaller. A radius (r) of 1° lat is equivalent to 110 km.

#### 2.2 | STARS polar low list

The STARS dataset version 2 provides a list of 185 PL tracks over the Nordic Seas from January 2001 to March 2011 (Noer et al., 2011). The PLs are subjectively identified by forecasters at the Norwegian Meteorological Institute by inspection of satellite infrared data, scatterometer winds and the operational weather forecasting model HIRLAM 4 (Rojo et al., 2015; Terpstra et al., 2016), for evaluation of PL occurrence in different datasets (e.g. Laffineur et al., 2014; Smirnova and Golubkin, 2017), and the evaluation of objective detection methods (e.g Zappa et al., 2014).

#### 2.3 | Tracking algorithm

Several methods are applied for the automatic detection and tracking of PLs in models and reanalyses. They are based on the detection of local minima in the SLP (e.g. Zahn and von Storch, 2008), of local maxima in the Laplacian of the SLP (e.g. Michel et al., 2018), or on local extrema in the relative vorticity (e.g. Zappa et al., 2014). To our knowledge no study has found particular evidence for the advantage of one method over another for the detection of PLs. For extratropical cyclones in general, Neu et al. (2013) found little evidence for differences in statistics between the detection algorithms based on vorticity and SLP.
2.4 | Representation of STARS PLs in TRACK cyclones

In section 3, PLs will be compared to all tracked cyclones. For this, the TRACK cyclones that correspond to a PL from the STARS dataset are identified. A STARS PL has a corresponding TRACK cyclone if it matches within a radius of less than 250 km at more than half of its time steps with the same TRACK cyclone. A STARS-matched PL is defined as the part of the corresponding TRACK cyclone where the matching is satisfied. These STARS-matched PL are investigated in the following.

The distance of 250 km was chosen from consideration that the $\zeta_{f,850}$ extrema in the reanalysis dataset can be displaced in comparison to the subjectively detected PL centre in the satellite images. Bracegirdle and Gray (2008) estimate that displacement errors between subjectively identified polar mesoscale cyclones and features from a model-based cyclone database in the order of 300 km can occur, but applied a radius of 200 km by arguing that the maximum displacement seldom occurs. The sensitivity of the matching was examined with a radius of 200 and 300 km and almost the same results were obtained as for a radius of 250 km.

It was also decided that a STARS PL has to match at more than half of its time steps with the same TRACK cyclone, in contrast to all time steps, since the initialization and decaying time can vary for cyclones between the datasets. Nevertheless, as presented below, most STARS PLs that match with one TRACK cyclone do so for all time steps.

2.4.1 | ERA-I

In ERA-I, only PLs from the STARS dataset with a duration of at least 6 h are considered, so that they are represented in at least one time step in the 6-hourly ERA-I analysis data. Note that only the vorticity is extended to 3-hourly time resolution, as described in section 2.1, to obtain a time resolution sufficient for tracking of mesoscale cyclones. As a result, 138 out of the 185 STARS PLs are of a duration of at least 6 h, out of which 109 are matched with a TRACK cyclone in ERA-I. Of these, 76 PLs matched for all the STARS time steps, and the remaining 33 for more than half of the STARS time steps. Three pairs out of the 109 STARS PLs are associated with the same TRACK cyclones within an overlapping time window. This is due to multiple PL events documented in the STARS dataset. These three pairs are merged, such that 106 STARS-matched PLs remain for ERA-I.

Occurrence over open water is commonly required as criterion for PLs. For example, Zappa et al. (2014) excludes in their detection algorithm TRACK cyclones with an ocean fraction smaller than 75% within a radius of 1°. For the comparison in section 3, only the time steps where the TRACK cyclone is located over open water are included. Open water is here defined as within a circle of radius of 220 km (equivalent to 2° latitude) with more than 75% of the grid cells having water, as opposed to both land and sea ice. Of the 106 STARS-matched PLs, 94 have at least one time step occurring over open water. These 94 STARS-matched PLs are used for the development of the PL criteria in section 3. The 12 excluded cases occur close to the coast or the ice edge in the matching time steps, and are represented closer to the land or ice in ERA-I than in the STARS dataset. Analyses using different radii and fractions of water cover compared to the chosen values show negligibly small differences in PL exclusion.

2.4.2 | ASR

Since all the ASR data are obtained at 3-hourly time resolution, PLs from the STARS dataset with a duration of at least 3 h are considered. Out of the 185 STARS PLs, 163 are of a duration of at least 3 hr, and of these, 139 match with a TRACK cyclone in ASR. Out of these, 115 PLs match for all STARS time steps, and the remaining 24 for more than half.

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1 STARS PL numbers: 7 and 8, 84 and 85 from the northern list, and 19 and 20 from the southern list.
of the STARS time steps. The same three pairs of PLs as in ERA-I are identified as multiple PLs and merged, so that 136 STARS-matched PLs remain from ASR. Out of these, 123 have at least one time step with occurrence over open water, and these remaining 123 STARS-matched PLs are used in section 3.

The comparison of the PL representation between the two reanalyses reveals that the matching is more often satisfied in ASR (139 out of 163 = 85%) than in ERA-I (109 out of 138 = 79%), that it is more often satisfied in all time steps in ASR (115 out of 139 = 83%) than in ERA-I (76 out of 109 = 70%), and that the STARS-matched PLs in ASR more often have at least one time step occurring over open water (123 out of 136 = 90%) than in ERA-I (94 out of 106 = 87%). This shows the improved PL representation in ASR in comparison to ERA-I, even though ASR includes 3–6 hourly events that are often less well represented in reanalysis than longer-lasting systems.

3 | DEVELOPMENT OF POLAR LOW IDENTIFICATION CRITERIA

In this section, different parameters are compared for the full set of extratropical cyclones and the subset of STARS-matched PLs, in order to find effective criteria to separate the PLs from other cyclones. These criteria will be applied in section 4 for the detection of PLs in the reanalysis datasets. Therefore, the distribution of different parameters of the STARS-matched PLs and the large set of all TRACK cyclones, where the latter represent the whole variety of cyclonic systems including PLs, are compared. In the following the prefix “TRACK” and “STARS-matched” are often skipped.

Table 1 summarizes the parameters considered in order to separate the PLs from other cyclones. Here, all parameters are compared that have been found in the literature relating to PL detection from model products. Some additional parameters that were considered as being possibly useful for PL detection, as for example the planetary boundary-layer height (PBH), the gradient in the equivalent potential temperature detection, as for example the planetary boundary-layer height parameters that were considered as being possibly useful for PL detection from model products. Some additional parameters that have been found in the literature relating to separate the PLs from other cyclones. Here, all parameters are compared that have been found in the literature relating to PL detection from model products. Some additional parameters that were considered as being possibly useful for PL detection, as for example the planetary boundary-layer height (PBH), the gradient in the equivalent potential temperature detection, as for example the planetary boundary-layer height parameters that were considered as being possibly useful for PL detection from model products. Some additional parameters that generally would not be considered as MCAO criteria are put into that category. Examples of these parameters are the maximum tropopause pressure \( p_w \), as suggested by Kolstad (2011), and the potential temperature at the tropopause \( \theta_{tr} \), as suggested by Terpstra et al. (2016). These are both applied to identify areas of upper-level forcing. Another example is \( \nabla \theta_{850} \), which is investigated for the efficacy to exclude systems close to the main baroclinic zone. However, the classification of the parameters into different types of criteria is done for clarity reasons only and does not influence the result of obtaining the most skilful PL identification parameters.

With the intensity criteria, the filtered vorticity \( \xi_{f,850} \) and the difference of the mean SLP within a circle of radius \( r \) and the SLP of the cyclone centre \( \text{SLP - SLP} \), both consider intensity within the mesoscale. The \( \xi_{f,850} \) is the spectrally filtered value, and \( \text{SLP - SLP} \) measures the depth of the low compared to the local surroundings.

The tropopause properties, such as the potential temperature \( \theta_{tr} \), the pressure \( p_w \) and the wind speed \( U_w \), are taken from the 2 PVU level. For ASR, only a selection of the parameters from Table 1 were investigated, since some, such as the tropopause properties and the PBH, were not directly available, and others, such as the equivalent potential temperature, were not expected to lead to improved criteria, based on the investigations with ERA-I.

The comparison includes two MCAO criteria suggested from recent studies:

\[
\text{MCAO}_1 = \frac{\theta_{SST} - \theta_p}{\text{SLP} - p},
\]

applied by Kolstad and Bracegirdle (2008) at the pressure level \( p = 700 \text{ hPa} \) and here also at \( p = 500 \text{ hPa} \), and

\[
\text{MCAO}_2 = \frac{L}{Z_{700}} (\ln \theta_{SST} - \ln \theta_{700})
\]

from Bracegirdle and Kolstad (2010), with \( Z_{700} \) being the geopotential height at 700 hPa and \( L = 7.5 \times 10^5 \text{ m} \), a scaling
FIGURE 2  Normalized distributions of (a) the difference between the mean SLP within a radius of 110 km and the SLP of the cyclone centre, (b) the maximum potential temperature difference between the sea surface and the 500 hPa level within a radius of 110 km, and (c) the tropopause wind speed poleward of the system, for all types of cyclone (blue) and the STARS-matched PLs of ERA-I (orange). Also shown are the mean (green dot) and in (a, b) the 10th percentile (red dot) and in (c) the 90th percentile (red dot) of the PL distributions. These criteria were found to be the most effective for discrimination between PLs and other cyclones in ERA-I.

height. The latter parameter is, together with $p_{tr}$, used by Kolstad (2011) to identify areas with favourable PL conditions.

In the following, the maximum value of these parameters during the lifetime of the STARS-matched PLs and all cyclones, including PLs, are computed, and their distributions are compared. The more the distributions differ from each other, the better the variable is for separating PLs from non-PL cyclones. Here, it is implicitly assumed that only a small number of the cyclones are PLs. Note that, for variables that are found to be smaller for PLs than for all cyclones, such as SLP, SST, $\theta_{500}$/$\theta_{700}$, $\theta_e$, $\theta_{850}$, water, $U_{tr,p}$ and $U_{500,p}$, the minimum values during the lifetime are compared.

3.1  |  ERA-I

It was chosen to compare the identified 94 STARS-matched PLs to all TRACK cyclones occurring in potentially PL active regions and seasons, since the aim is to find effective parameters to distinguish between the two. For ERA-I, all cyclones over open water north of 30° N in the time ranges January–April and October–December 2003, representing the PL active season, are taken for the comparison. This sample includes 8301 cyclones. Because of the large number of cyclonic events, it is assumed that one year of cyclones is representative of the distribution of all cyclones in the same season during the whole dataset. This assumption is supported by a comparisons of the cyclone distributions for a few parameters for the whole timespan of the dataset from 1979 to 2016 and for the year of 2003 only (not shown). The year 2003 is an arbitrary choice.

3.1.1  |  The measure for the efficacy of different parameters for PL detection

Examples of the comparison between the distributions of the parameters SLP – SLP, $\theta_{SST} - \theta_{500}$ and $U_{tr,p}$ for PLs and cyclones are shown in Figure 2. For these three parameters, the distributions for all cyclones and PLs differ considerably, with PLs showing deeper lows, lower static stability, and lower maximum tropopause wind poleward of the system.

A comparison of the efficacy of all included parameters to distinguish between PLs and cyclones is summarized in Table 2. For parameters where the mean and maximum values over different radii are tested, the table includes only the most effective set-up for distinguishing between PLs and cyclones. The efficacy of a parameter for PL detection is measured as follows. The 10th percentile of the parameters for the PLs (red dot in Figure 2 and fourth column in Table 2) are calculated. For parameters that are generally found to be lower for PLs than for cyclones, such as SLP, SST, $\theta_{500}$/$\theta_{700}$, $\theta_e$, $\theta_{850}$, water, $U_{tr,p}$ and $U_{500,p}$, the minimum values during the lifetime are compared.

3.1.2  |  Most effective criteria – the PL-IC

The three most effective parameters of each category are found to be

(a) intensity criteria: a difference of the mean SLP within a radius of 110 km and the SLP of the cyclone centre, SLP – SLP > 0.4 hPa;

(b) MCAO criteria: a maximum difference of the potential temperature at the sea surface and 500 hPa within a radius of 110 km, $\theta_{SST} - \theta_{500} > -9.4$ K; and
### TABLE 2  Comparison of the efficacy of different parameters for the selection of PLs from the large set of all cyclones in ERA-I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Radius (km)</th>
<th>10th percentile of polar lows</th>
<th>Excluded cyclones (%)</th>
<th>Excluded cyclones after two criteria (%)</th>
<th>Excluded cyclones after three criteria (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity criteria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varphi_{850}$ point</td>
<td>point</td>
<td>0</td>
<td>$&gt; 5.04 \times 10^{-5}$ s$^{-1}$</td>
<td>71.4</td>
<td>58.3</td>
<td>22.4</td>
</tr>
<tr>
<td>$U_{10m}$ max</td>
<td>max</td>
<td>220</td>
<td>$&gt; 13.3$ m s$^{-1}$</td>
<td>43.3</td>
<td>27.0</td>
<td>7.7</td>
</tr>
<tr>
<td>SLP * point</td>
<td>point</td>
<td>0</td>
<td>$&lt; 1000.7$ hPa</td>
<td>49.1</td>
<td>16.1</td>
<td>2.7</td>
</tr>
<tr>
<td>SLP – SLP †† mean – point</td>
<td>110</td>
<td>$&gt; 0.4$ hPa</td>
<td>77.9</td>
<td>63.7</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>SLP – SLP †† point</td>
<td>330</td>
<td>$&gt; 2.3$ hPa</td>
<td>74.9</td>
<td>53.3</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td><strong>Marine cold air outbreak criteria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{500}$ * mean</td>
<td>mean</td>
<td>110</td>
<td>$&lt; 241.4$ K</td>
<td>81.0</td>
<td>52.6</td>
<td>2.7</td>
</tr>
<tr>
<td>$T_{700}$ * mean</td>
<td>mean</td>
<td>110</td>
<td>$&lt; 260.3$ K</td>
<td>72.5</td>
<td>45.9</td>
<td>2.7</td>
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<tr>
<td>$\theta_{c_{700}}$ * mean</td>
<td>mean</td>
<td>110</td>
<td>$&lt; 292.5$ K</td>
<td>68.3</td>
<td>44.6</td>
<td>1.1</td>
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<tr>
<td>$\theta_{c_{500}}$ * mean</td>
<td>mean</td>
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<td>$&lt; 290.9$ K</td>
<td>61.6</td>
<td>41.5</td>
<td>3.3</td>
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<tr>
<td>SST * mean</td>
<td>mean</td>
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<td>$&lt; 281.8$ K</td>
<td>51.4</td>
<td>19.1</td>
<td>10.4</td>
</tr>
<tr>
<td>SST – $T_{500}$ max</td>
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<td>$&gt; 41.4$ K</td>
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<td>69.9</td>
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<tr>
<td>SST – $T_{700}$ max</td>
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<td>110</td>
<td>$&gt; 22.8$ K</td>
<td>73.6</td>
<td>67.7</td>
<td>13.7</td>
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<tr>
<td>$\theta_{500} - \theta_{c_{500}}$ † †</td>
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<td>$&gt; -9.4$ K</td>
<td>88.5</td>
<td>72.3</td>
<td>0</td>
</tr>
<tr>
<td>$\theta_{500} - \theta_{c_{700}}$ max</td>
<td>110</td>
<td>$&gt; -4.1$ K</td>
<td>79.5</td>
<td>66.0</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>$\theta_{500} - \theta_{c_{550}}$ mean</td>
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<td>64.0</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>$\theta_{c_{550}} - \theta_{c_{500}}$ mean</td>
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<td>$&gt; -3.1$ K</td>
<td>65.3</td>
<td>46.7</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>$\theta_{c_{550}} - \theta_{c_{700}}$ max</td>
<td>110</td>
<td>$&gt; 4.3$ K</td>
<td>63.0</td>
<td>62.5</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td>$\theta_{c_{550}} - \theta_{c_{350}}$ max</td>
<td>110</td>
<td>$&gt; 5.8$ K</td>
<td>55.3</td>
<td>63.4</td>
<td>24.6</td>
<td></td>
</tr>
<tr>
<td>MCAO1,500 max</td>
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<td>110</td>
<td>$&gt; -20.0 \times 10^{-5}$ K Pa$^{-1}$</td>
<td>86.9</td>
<td>70.4</td>
<td>0</td>
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<tr>
<td>MCAO1,700 max</td>
<td>max</td>
<td>110</td>
<td>$&gt; -14.1 \times 10^{-5}$ K Pa$^{-1}$</td>
<td>79.2</td>
<td>66.3</td>
<td>8.7</td>
</tr>
<tr>
<td>MCAO2 * mean</td>
<td>mean</td>
<td>110</td>
<td>$&gt; -4.0$</td>
<td>79.0</td>
<td>66.5</td>
<td>8.7</td>
</tr>
<tr>
<td>$\theta_{p}$ * mean</td>
<td>mean</td>
<td>330</td>
<td>$&lt; 300.7$ K</td>
<td>86.1</td>
<td>56.0</td>
<td>9.3</td>
</tr>
<tr>
<td>$\theta_{350} - \theta_{p}$ mean</td>
<td>mean</td>
<td>330</td>
<td>$&gt; -19.0$ K</td>
<td>88.5</td>
<td>65.3</td>
<td>11.5</td>
</tr>
<tr>
<td>$p_{tr}$ mean</td>
<td>max</td>
<td>330</td>
<td>$&gt; 382$ hPa</td>
<td>53.5</td>
<td>13.1</td>
<td>4.4</td>
</tr>
<tr>
<td>PBH</td>
<td>max</td>
<td>330</td>
<td>$&gt; 902$ m</td>
<td>53.7</td>
<td>45.9</td>
<td>16.4</td>
</tr>
<tr>
<td>$\varphi_{\theta_{350}}$ * max</td>
<td>max</td>
<td>550</td>
<td>$&lt; 7.9 \times 10^{-2}$ K km$^{-1}$</td>
<td>37.3</td>
<td>29.1</td>
<td>23.5</td>
</tr>
<tr>
<td>water * mean</td>
<td>mean</td>
<td>110</td>
<td>$&lt; 10.8$ kg m$^{-2}$</td>
<td>60.8</td>
<td>46.5</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Polar-front criteria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U_{10m}$ * † †</td>
<td>max</td>
<td>polew</td>
<td>$&lt; 31.3$ m s$^{-1}$</td>
<td>77.6</td>
<td>31.7</td>
<td>0</td>
</tr>
<tr>
<td>$U_{500,p}$ *</td>
<td>max</td>
<td>polew</td>
<td>$&lt; 24.8$ m s$^{-1}$</td>
<td>69.6</td>
<td>34.0</td>
<td>9.8</td>
</tr>
<tr>
<td>$\varphi_{\theta_{500,p}}$ * max</td>
<td>max</td>
<td>polew</td>
<td>$&lt; 7.2 \times 10^{-2}$ K km$^{-1}$</td>
<td>31.9</td>
<td>19.0</td>
<td>20.2</td>
</tr>
</tbody>
</table>

The first column expresses the used parameter. The second column indicates whether the value taken is at a point, or the maximum or mean value within the radius given by column 3. For $U_{10m}$, $U_{500,p}$ and $\varphi_{\theta_{500,p}}$, the maximum value poleward of the system is considered. The fourth column presents the value of the 10th percentile of the PLs, meaning that 90% of the PLs have a higher value. Parameters which are lower for PLs than for all cyclones are marked with *, and the 90th percentile is calculated instead. The fifth column shows the fraction of cyclones below the 10th (above the 90th) percentile. The higher the value, the more effective is the parameter. The most effective parameter of each category is denoted by † † in the first column. These are the PL identification criteria (PL-IC). The sixth column presents the fraction of cyclones that are excluded by the 10th (90th) percentile of PLs after the PL-IC from the other two categories have been applied. The seventh column gives the fraction of cyclones after application of all three PL-IC, which are below (above) the 10th (90th) percentile. Values around 10% or below show that this criterion would not contribute to an improved separation of PLs from all cyclones.

(c) polar-front criteria: a maximum tropopause wind poleward of the system, $U_{10m} < 31.3$ m s$^{-1}$.

In the following, these three parameters are referred to as the PL identification criteria (PL-IC). Column 6 in Table 2 depicts the fraction of cyclones that have not been excluded by the PL-IC of the other two categories, and that are excluded by applying the 10th percentile threshold of the parameter. It is found that SLP – SLP > 0.4 hPa and $\theta_{500} - \theta_{c_{500}} > -9.4$ K exclude about 63.7 and 72.3% of the cyclones that have not been excluded by the other two PL-IC. $U_{10m} < 30.7$ m s$^{-1}$ excludes about 31.7% of the cyclones satisfying the other two PL-IC. The high proportion of cyclones excluded by each of the PL-IC after application of the other two PL-IC shows that these criteria are non-redundant. However, each PL-IC excludes a lower fraction of cyclones after the other two PL-ICs have been applied (column 6) than if they would not have been applied (column 5), meaning that the PL-IC are not completely independent of each other.

These three PL-IC are found to be sufficient for PL detection. The last column of Table 2 shows the proportion of cyclones being excluded by the different parameters after application of all three PL-IC. Note that, for the PL-IC
themselves, no additional cyclones are excluded, since these parameters were already used for exclusion. The additional application of parameters with a value around or below 10% in the last column would exclude about as many PLs as cyclones, and those parameters therefore do not contribute to a better identification of PLs. This applies for most of the additional parameters. Some examples are presented in Figure 3 for the distributions of the 10 m wind speed ($U_{10m}$), the total column water, $\theta_{e,SST}-\theta_{e,700}$, $\xi_f$, $\psi \theta_{e,850}$, and $p_t$, which all show differences between PLs and cyclones (Figure 3a–c,g–i). After application of the PL-IC, the distributions of PLs and cyclones for most other parameters become similar (Figure 3d–f,j–l). For example, using $\theta_{e,SST}-\theta_{e,850}$ as an extra criterion to the PL-IC would exclude an additional 24.6% cyclones (value in last column of Table 2), but Figure 3f depicts that none of the additional excluded cyclones is far away from the exclusion threshold (red dot). This implies that $\theta_{e,SST}-\theta_{e,850}$ as an additional criterion would not exclude cyclones significantly different from the STARS-matched PLs. The same argument is valid for $\theta_{e,SST}-\theta_{e,700}$.

Two other parameters, $\xi_f$ and $\psi \theta_{e,850}$, exclude more than 20% of the remaining cyclones as additional criteria (see value in last column of Table 2. The comparison of the distributions of these two parameters with and without application of the PL-IC (Figure 3g,h and j,k) shows that the distributions of the remaining cyclones and PLs are more similar, but not identical. These two parameters were tested as additional PL-IC and, in order not to exclude too many of the matched PLs, the exclusion threshold was lowered from the 10th to the 5th percentile. The characteristics of the resulting climatology with the three PL-IC (presented in section 4), and the resulting climatology with $\xi_f$ and $\psi \theta_{e,850}$ as additional criteria are similar to each other (not shown). Since it is considered advantageous to use as few criteria as possible, it was decided to not include $\xi_f$ and $\psi \theta_{e,850}$ as PL-IC.

The fact that, after application of the three PL-IC, the identified cyclones show a similar distribution in almost all parameters to the 94 STARS-matched PLs gives confidence that the criteria perform well for PL detection and that the identified cyclones can be considered to be PLs (e.g. Figure 3e,f). A time step of a cyclone that satisfies all three PL-IC in the following discussion will be called a PL point. Most of the STARS PLs (72 out of 94 = 76.6%) include at least one PL point, while only a small proportion of the large set of cyclones (183 out of 8301 = 2.2%) include a PL point.

3.1.3 | Intensity criteria
In the following, the different parameters within each type of criteria are compared, starting with the intensity criteria. Within the intensity criteria, the filtered vorticity $\xi_f$ and a measure for the local depth of the low SLP–SLP (Figure 2a) are both effective parameters, with the latter being slightly better than the former. The SLP–SLP was found to be the most effective, if the mean was calculated within a radius of 110 km, probably since this best considers the mesoscale nature of PLs. Most of the cyclones excluded by the $\xi_f$ criterion are also excluded by the application of the SLP–SLP criterion (comparison of Figure 3g,j and the values in the last two columns of Table 2 for $\xi_f$). However, the distribution of $\xi_f$ for the identified cyclones is shifted slightly towards weaker systems compared with the PL distribution (Figure 3j). This shows that the two intensity criteria are strongly related, but not completely redundant.

The maximum 10 m wind speed ($U_{10m}$) was found considerably less effective in identifying PLs than SLP–SLP and $\xi_f$. The $U_{10m}$ distributions for PLs and cyclones are relatively similar to each other (Figure 3a). After application of the PL-IC, the distributions of the identified cyclones and STARS-matched PLs are similar (Figure 3d). The 10th percentile of $U_{10m}$ for PLs is found to be 13.3 m s$^{-1}$, lower than the threshold of 15 m s$^{-1}$, which represents gale force, commonly used for detecting PLs from low-resolution reanalyses (e.g. Zappa et al., 2014; Yanase et al., 2016).

It was noticed by e.g. Zappa et al. (2014) that the wind criterion of 15 m s$^{-1}$ excludes a relevant number of PLs (for their study region, 9 out of 34 = 26%), and for our analysis it was found to exclude a comparable fraction (26 out of 94 = 28%). This can partly be explained by an under-representation of strong winds associated with PLs in ERA-I, as for example found by Smirnova and Golubkin (2017). Another possible reason for the better performance of SLP–SLP and $\xi_f$ compared to $U_{10m}$ is the occurrence of PLs in synoptic-scale MCAOs, which are often associated with large-scale wind speeds in the order of 10 m s$^{-1}$. The first two parameters are considering the occurrence of PLs within a synoptic-scale phenomenon, while the $U_{10m}$ can almost be satisfied by the MCAO itself.

3.1.4 | Marine cold air outbreak criteria
In the following the parameters representing the MCAO criteria are compared. The $\theta_{SST}-\theta_{700}$ is the most effective parameter for PL identification within the MCAO criteria.

Static stability measures, such as SST $-T_p$, $\theta_{SST}-\theta_p$ and MCAO, perform in general better for discrimination between PLs and other cyclones when the upper-level value is obtained from the $p = 500$ hPa level instead of from the 700 or 850 hPa level. This result is not in contradiction with lower-level temperature differences, for instance $\theta_{SST}-\theta_{850}$ as applied by Papritz et al. (2015), being more effective for the identification of MCAOs, since the outbreaking air often stays below a strong inversion layer. However, for PLs, deep instability and convection are observed. The outbreaking air is warmed by the sea surface and lifted through the inversion layer until it reaches the upper troposphere (Noer et al., 2011).

MCAO1 and MCAO2, which are formulae dependent on the ratio of the $\theta$ differences to pressure/height difference
between the levels, do not show improvement compared with the difference in $\theta$ between the same two levels.

Bracegirdle and Gray (2008) did a similar study to investigate the efficacy of some MCAO criteria for PL detection on the basis of a subjective dataset. They found that the difference in temperature between the 700 hPa level and the sea surface is more effective than between the 500 hPa level and the sea surface. However, they investigated a different
temperature parameter and used only a small subjective database of 58 polar mesoscale cyclones (both PLs and weaker systems) during the three months December 2001 to February 2002.

The comparison reveals that potential temperature performs better at identifying the PLs than the temperature difference between two levels. The former includes the sea-level pressure, making it a more accurate measure of the static stability. Since PLs often coincide with lower SLP than other cyclones (Table 2), static stability based on $\theta$ rather than on $T$ becomes more distinct for PLs than cyclones. Interestingly, the equivalent potential temperature difference, an even more accurate parameter for the vertical stability since it includes moisture, is not as effective at identifying the PLs. This may be explained by the occurrence of PLs in cold environments where the atmosphere holds very little moisture and therefore considering $\theta_e$ instead of $\theta$ has only a small effect. In warmer environments, where midlatitude cyclones develop, and where the atmospheric water content is larger, moisture contributes more to the static instability.

The temperatures at 500 and 700 hPa also perform well at distinguishing between PLs and other cyclones, but slightly less well than the differences in potential temperature between the same level and the sea surface. The SST on its own does not seem to be a successful parameter for discrimination. This leads to the suggestion that the upper-level temperature is more important than the SST for identification of PLs.

A commonly used threshold for the static stability is \(T_{500} - T_{500} > 43\) K evaluated as a mean within a 1° radius (e.g. Zappa et al., 2014). Our methodology of calculating the 10th percentile from the PLs would suggest a weaker threshold of 39.7 K for this parameter (not shown). A threshold of 43 K for this parameter would exclude 30.9% of the PLs and therefore appears to be too high. Also, Terpstra et al. (2016) noted that this threshold excludes a considerable number of PLs in the North Atlantic.

Kolstad (2011) suggested the use of the maximum value of the tropopause pressure ($p_u$) within a radius of 400 km to identify areas of upper-level forcing, a mechanism that Kolstad (2011) argued to be necessary for PL development. By taking the 5th percentile of a subjective PL dataset, Kolstad (2011) suggests a threshold of $p_u > 470$ hPa for the detection of PL favourable regions. In our study, the threshold defined by the 10th percentile of the STARS-matched PLs is $p_u > 382$ hPa, which is considerably weaker than the threshold from Kolstad (2011). In our study $p_u$ is found to be less effective than other parameters for PL identification (also Figure 3i).

Terpstra et al. (2016) use the potential temperature at the tropopause ($\theta_u$) to indicate upper-level potential vorticity anomalies. This parameter appears effective to distinguish between PLs and other cyclones, but slightly weaker than $\theta_{SST} - \theta_{500}$ and redundant after application of the three PL-IC (Table 2). The difference in the potential temperature of the sea surface and the tropopause ($\theta_{SST} - \theta_u$) has the same score for cyclone exclusion as $\theta_{SST} - \theta_{300}$, and the only reason for choosing the latter is that it excludes more cyclones after the other two PL-IC have been applied (column 6 in Figure 2).

Whether the PBH could be an effective discriminator was also tested, since PLs are often found to be connected to a higher PBH than other cyclones (column 5 in Table 2). The high PBH is believed to be induced by the convection associated with the PLs. Another parameter, the total column water, in general shows lower values for PLs than for cyclones (Figure 3b), which can be explained by the occurrence of PLs in cold environments. However, both parameters appear to be less effective than most of the other stability measures.

Most of the static-stability parameters perform best for PL detection when the maximum value within a rather small radius (here 110 km) is utilized. However, the difference from using a calculated mean over a larger radius is small (not shown).

### 3.1.5 Polar-front criteria

Three parameters are compared as polar-front criteria. One parameter is the maximum gradient in the equivalent potential temperature at 850 hPa poleward of the system ($\nabla \theta_{e,850,p}$). Since the main baroclinic zone is generally in the vicinity of the jet stream by the thermal wind relation, the other two parameters are based on the maximum wind speed poleward of the cyclone in the tropopause ($U_{500,p}$) and at the 500 hPa level ($U_{500,p}$). The comparison reveals that the inspection of the strength of the jet stream is more effective than the temperature gradient in the lower troposphere. The tropopause wind speed is more effective as a single parameter, while the 500 hPa wind speed performs slightly better after the other two PL-IC are applied.

### 3.2 ASR

For ASR, 15018 cyclones for the months of January–April and October–December for 2003 in the ASR domain are considered for comparison to the 123 identified STARS-matched PLs. As discussed above, fewer parameters are included in the comparison for ASR than for ERA-I.

The same procedure as for ERA-I is applied to the parameters in ASR, to investigate their efficacy in distinguishing between PLs and other cyclones. Results are summarized in Table 3. The 10th percentile boundary from PLs for the same parameters in ERA-I and in ASR (column 4 in Tables 2 and 3) are in general reasonably close to each other. This gives confidence that the same criteria can be used independently of the underlying dataset. Differences in thresholds can be due to a larger number of the STARS PLs being recognized in ASR than in ERA-I (123 versus 94), and due to a difference in resolution of the two datasets. The precise comparison of the number of the excluded cyclones in ERA-I and ASR...
TABLE 3  As Table 2, but for ASR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Radius (km)</th>
<th>10th percentile of polar lows</th>
<th>Excluded cyclones (%)</th>
<th>Excluded cyclones after two criteria (%)</th>
<th>Excluded cyclones after three criteria (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity criteria</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>22.9</td>
</tr>
<tr>
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<td>220</td>
<td>&gt; 17.4 m s^{-1}</td>
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<td>53.1</td>
<td>19.8</td>
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<tr>
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<tr>
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<td>mean – point</td>
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<td>&gt; 2.38 hPa</td>
<td>83.3</td>
<td>69.0</td>
<td>0</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{500}$ *</td>
<td>mean</td>
<td>110</td>
<td>&lt; 240.4 K</td>
<td>84.8</td>
<td>67.2</td>
<td>6.8</td>
</tr>
<tr>
<td>$T_{700}$ *</td>
<td>mean</td>
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<td>&lt; 259.6 K</td>
<td>75.1</td>
<td>59.4</td>
<td>7.6</td>
</tr>
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<td>&gt; 42.0 K</td>
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<td>77.4</td>
<td>4.5</td>
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<tr>
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<td>&gt; 23.2 K</td>
<td>74.1</td>
<td>73.4</td>
<td>10.7</td>
</tr>
<tr>
<td>$\theta_{SST} – \theta_{500}$ ††</td>
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<td>&gt; −8.5 K</td>
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<td>80.5</td>
<td>0</td>
</tr>
<tr>
<td>$\theta_{SST} – \theta_{700}$</td>
<td>max</td>
<td>110</td>
<td>&gt; −3.4 K</td>
<td>80.9</td>
<td>75.7</td>
<td>6.8</td>
</tr>
<tr>
<td><strong>Polar-front criteria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U_{500,p}$ ††</td>
<td>max</td>
<td>polew</td>
<td>&lt; 29.6 m s^{-1}</td>
<td>61.6</td>
<td>26.4</td>
<td>0</td>
</tr>
</tbody>
</table>

FIGURE 4  Normalized distribution of the (a) difference between the mean SLP in a radius of 330 km and the SLP of the cyclone centre, (b) mean potential temperature difference between the sea surface and 500 hPa within a radius of 110 km, and (c) the 500 hPa wind speed poleward of the system for all types of cyclones and PLs of ASR. The green and red dots are as in Figure 2. These criteria were found to be most effective for discrimination between PLs and cyclones in ASR.

by the 10th percentile threshold of different parameters (column 5 in Tables 2 and 3) has to be done with caution due to at least two reasons. Firstly, ASR includes cyclones of shorter minimum duration than does ERA-I (3-hourly versus 6-hourly), and secondly, in ERA-I, all cyclones north of 30° N are included, while ASR includes cyclones in its whole domain, which is bounded by varying latitudes between 25 and 40° N (Figure 5c). Even though these limitations exist, the difference in the efficacy of the single parameters from ERA-I and ASR lies within 10%.

For ASR, the most effective of the investigated parameters for the exclusion of cyclones within each type of criteria are

(a) the difference in the mean SLP within a radius of 330 km and the SLP of the cyclone centre, SLP – SLP > 2.38 hPa;
(b) the maximum difference of the potential temperature at the sea surface and 500 hPa within a radius of 110 km, $\theta_{SST} – \theta_{500} > −8.5$ K; and
(c) the wind speed at 500 hPa poleward of the system, $U_{500,p} < 29.6$ m s^{-1}.

The distributions of these three parameters for all types of cyclones and PLs are shown in Figure 4. They are the PL-IC for ASR and are only slightly different from those for ERA-I.

The SLP – SLP is more effective in ASR than in ERA-I if the mean is calculated over a larger radius. However, differences in the efficacy of different radii are relatively small. The threshold of SLP – SLP is dependent on the radius over which the mean is calculated, and the thresholds are in general close to each other for ASR and for ERA-I for the same radius.

The main difference within the compared parameters between ERA-I and ASR is observed for $U_{10m}$, where the 10th percentile threshold for PLs in ASR is much higher (17.4 m s^{-1}) than in ERA-I (13.3 m s^{-1}). This can be explained by a better representation of the near-surface wind in ASR connected to PLs, as observed by Smirnova and Golubkin (2017). But even though the $U_{10m}$ is more realistically represented in ASR than in ERA-I, both SLP – SLP and $\xi_{f,850}$ are found to be more skillful for PL identification.
The $\theta_{SST} - \theta_{500}$ parameter is for both datasets more effective than the other MCAO criteria. The threshold of $\theta_{SST} - \theta_{500} > -8.5$ K is stricter than in ERA-I, where $-9.4$ K is applied. This might be explained by the smoothing of local maxima due to the coarser resolution in ERA-I than in ASR. For other considered parameters within the MCAO criteria, the same findings as for ERA-I are obtained. The efficacy of these compared parameters for PL identification do not seem to depend much on the resolution of the dataset. This may be due to the large-scale character of MCAOs.

In ASR, $U_{500,p}$ is the only parameter included as a polar-front criterion. The fraction of excluded PLs by $U_{500,p}$ as an additional criterion suggests that this parameter improves the PL identification. Since in ERA-I the efficacy of these compared parameters for PL identification do not seem to depend much on the resolution of the dataset. This may be due to the large-scale character of MCAOs.

As for ERA-I, the other parameters considered show distributions that are comparable for the STARS-matched PLs and the identified cyclones after the application of the three PL-IC (distributions are not shown, but see last column of Table 3), giving confidence that the PL-IC for ASR are sufficient for PL identification, and that the identified cyclones can be considered PLs. Most of the STARS-matched PLs (93 out of 123 = 75.6%) include at least one time step where the three PL-IC are satisfied, called PL points, while only a small proportion of the cyclones include a PL point (297 out of 15018 = 2.0%). Thus, in ASR, a slightly smaller proportion of subjective PLs are excluded by the PL-IC, and a slightly lower proportion of the cyclones are classified as PLs as compared to ERA-I. This is an indication that the identified cyclones in ASR include fewer falsely excluded and falsely included PLs than in ERA-I.

4 | ANALYSIS OF THE CLIMATOLOGIES

In order to detect PLs, the PL-IC derived in section 3 are applied to all cyclones which occur over open water poleward of 30° for ERA-I and in the complete domain of ASR for the whole time span of the two reanalyses. To the knowledge of the authors, no PL has been reported between 30° S and 30° N, and systems occurring within these latitudes would not be classified as being PLs, since the polar front is far poleward over open sea.

From the identified PLs, two climatologies are derived. One for the timespan 1979–2016 for ERA-I and one for 2000–2012 for ASR. In the following, these two climatologies are first briefly inspected and then analysed further in terms of their spatial and temporal distributions.

4.1 Inspection of the climatologies

One way to test the climatologies is to investigate for “false hits.” Inspection of some randomly picked PL cases from the climatologies reveals that most of these can be classified as being PLs or the weaker form of polar mesoscale cyclones. Since the transition between being a PL and a mesoscale cyclone is fluid, a decision for a system being a PL is subjective. The counting of “true hits” and “false hits” strongly depends on a subjective decision on whether a system is regarded as a PL or not, hence this type of analysis was not performed. However, only a small fraction of the cases in the climatologies are clear-cut PLs. The climatology also includes some cases of occluded synoptic-scale systems with convective signatures. These could possibly be excluded by applying a constraint on the size of the system. This is challenging for PLs, since automatic size calculation of cyclones is often based on closed isobars (e.g. Rudeva and Gulev, 2007). PLs, occurring in a pressure gradient that causes the MCAO, are not always local SLP minima, especially not in low-resolution reanalysis datasets such as ERA-I (Laffineur et al., 2014).

The number of PLs in the derived climatologies can be compared to the STARS and Smirnova datasets. The STARS dataset includes 185 PLs in the Nordic Seas for the years 2000–2011. The climatologies include 911 PLs for ERA-I and 1321 PLs for ASR for the same time period and approximately the same area as STARS. A possible explanation for
this difference is that the STARS dataset includes only clear PL cases, while the climatologies include a large number of cases whose status as PL would be debated among meteorologists. It is noted that other PL climatologies, such as the Smirnova database, find a considerably higher PL density. The Smirnova dataset includes 637 PLs for the time period of 1995/1996–2008/2009 in the Nordic Seas. The derived climatology for ERA-I shows 709 cases for the same time period and approximately the same area as the Smirnova dataset. This reveals that other studies have found a similar PL density as those derived here.

An objective study of the “false misses” is impossible, since no accepted global PL dataset exists. However, a comparison with some existing PL climatologies is performed. Of the vaguely described 27 PLs in the period 1979–1982 from Wilhelmsen (1985), 22 PLs are identified in the climatology based on ERA-I. A one-to-one comparison cannot be performed due to the inaccurate description of the PL tracks in Wilhelmsen (1985). Of the list presented in Yanase et al. (2016), eight of the 19 PLs can be recognized in ERA-I and, of the eight PLs in the years 2000–2012, four can be found in ASR and two in ERA-I. This reveals that the derived climatologies do not include all cases of other subjective PL datasets, but they recognize a relevant proportion of them. It also should be noted that observational studies are subjective in nature.

### 4.2 Spatial distribution of PLs

Another factor giving confidence in the climatologies is that the spatial and the temporal distributions are comparable to existing climatologies, as will be discussed in the following. The spatial annual-averaged distribution of PL duration is presented in Figure 5 for (a) the NH and (b) SH from ERA-I, and (c) from ASR. The PL duration is calculated by multiplying the number of detected PL points by application of the PL-IC derived in section 3 by the time resolution of the dataset, which is 6 h for ERA-I and 3 h for ASR. This presentation of the average annual PL duration per area was chosen rather than the number of PLs, since the PL duration is considered to be a better measure of the PL activity in a region. A long-lasting PL contributes more to the PL activity than a short-lasting one, which is taken into account in the PL duration.

The spatial distribution of the climatologies in the NH between the two reanalyses shows similar patterns. They are in good agreement with that presented for the North Atlantic by Zahn and von Storch (2008), and for the North Pacific by Chen and von Storch (2013), even though different methodologies are used.

High PL density is often found in areas where Kolstad (2011) and Fletcher et al. (2016) detected a high frequency of MCAOs, e.g. in the Barents Seas and the Sea of Okhotsk, although this is not always the case. For example, these two studies found a relatively low frequency of MCAOs in the Denmark Strait, which is here found as one of the major PL regions. Kolstad (2011) identified the Labrador Sea as the region with the most favourable PL conditions in the North Atlantic (section 1), while the Norwegian Sea south of 70° N shows rather unfavourable PL conditions, both in disagreement with our results. As opposed to the Kolstad (2011) approach, Zahn and von Storch (2008), Zappa et al. (2014), Yanase et al. (2016) and this study identify individual cyclones and apply criteria to determine whether they can be regarded as PLs.

Some regions of intense PL activity can be recognized. In ERA-I, the Denmark Strait, between the southern tip of Greenland and Iceland, is identified as the region with the highest, and the Nordic Seas as the region with the second highest PL density of both hemispheres. This finding agrees with Zahn and von Storch (2008), who found that the Denmark Strait had the highest activity within the North Atlantic. In ASR, the Nordic Seas are recognized as having slightly higher PL activity than the Denmark Strait. This indicates that these two areas have the highest PL activity of the entire globe. Within the Nordic Seas, the highest PL density is identified in an area around 72° N, 15° E, also known as “Tromsø flake,” which is in agreement with Noer et al. (2011).

The results suggest that more PLs occur in the North Atlantic (64%) than in the North Pacific (36%). On the Pacific side, the Gulf of Alaska, the Bering Sea, the Sea of Okhotsk and the Sea of Japan are found to be PL active regions. PLs in the North Pacific occur as far south as 40° N, while in the North Atlantic PLs are rarely identified south of 50° N. In general, increased PL density is observed close to land masses or sea-ice edges and the density decreases in the direction of open sea. Yarnal and Henderson (1989) presented comparable maps of observed comma-cloud and spiral-form systems for the North Pacific with comma-cloud systems being observed as far south as 40° N, and with the occurrence of spiral systems often present in the vicinity of land masses. The maps generally show high agreement with the density maps of the derived climatologies. Yanase et al. (2016) objectively identified PLs in the Sea of Japan and presented a spatial distribution of the PLs at their maximum intensity, similar to the results derived here from ERA-I and ASR. Kolstad (2011) identified the same area in the Sea of Japan and the Sea of Okhotsk as favourable for PL development in the North Pacific, but did not recognize the areas to the east of this as being PL active.

In the SH, most PL activity is found between 50 and 65° S, with three areas showing increased activity: (a) the Bellinghausen and Amundsen Sea, (b) the sea south of New Zealand and (c) the Mawson and Davis Sea southwest of Australia. (a) and (b) are the regions where Kolstad (2011) found PL favourable conditions in the SH, but the third region was not identified in that study. Carleton and Carpenter (1990) identified more PLs at lower latitudes up to 30° S, although their identification of PLs is based on satellite imagery and does not include criteria on intensity or the occurrence in an MCAO.
The density of PL occurrence is in general lower than in active regions in the NH. Nevertheless, due to a larger ocean area, the SH has only 17% less PL activity than the NH in ERA-I.

4.3 Temporal distribution of PLs

The average seasonal distributions of PL duration in ERA-I for the NH and SH and ASR are presented in Figure 6a–c. PLs occur in the extended winter seasons of both hemispheres. In the NH, this is five months from November to March, with the maximum activity in January, some cases in April and October, and a few cases in May and September.

The hemispheric seasonal PL distribution cannot be compared with the literature since, to our knowledge, no global PL climatology has yet been developed. However, seasonal distributions for different regions can be compared. This comparison has to be considered with caution, since the domains are often chosen differently. Also, other studies often count the PLs, whereas here the duration of PL activity is presented.

For the Nordic Sea (defined by box 1 in Figure 5a), our climatology reveals a similarly high PL activity from November to March, with some PLs occurring in October and April, and less activity of PLs in September and May. Noer et al. (2011) and Smirnova et al. (2016) present seasonal PL distributions for the Nordic Seas that in general show similar PL activity for the same time period as found here. However, they also find local extrema in PL frequency in the main season, such as a distinct and strong maximum in March. In agreement with our results, Zahn and von Storch (2008) observe the highest PL activity for the North Atlantic in December and January, without local maxima in other months. Months of extrema in PL frequency in climatologies of short duration are possibly explained by the high interannual variability of PL occurrence (Figure 5d).

The seasonal distribution of PLs in the North Pacific is in general in good agreement with the distribution presented by Chen and von Storch (2013). The PL season in the northwest Pacific and the North Atlantic are comparable, except for considerably fewer PL occurrences in the former region in March. In the Sea of Japan, PLs are mainly detected in December to February with few cases in autumn and spring, in good agreement with Yanase et al. (2016).

In the SH, the PL season is seven months long, ranging from April to October with some cases in March and November, and a few cases even in the SH summer (December to February). Since none of the months in the SH shows as high PL frequency as in the NH, it can be concluded that the PL season in the SH is longer and less intense than in the NH.

The trend in PL activity is negligible for the NH from ERA-I (0.42 PL hours per year with p-value of 0.95 by a two
sided $t$-test). ASR is regarded as being too short for an investigation of a trend. For the SH, ERA-I shows an increasing trend of 7.8 PL hours per year, which is not significant, with a $p$-value of 0.28. More interesting for the SH is the decade from 1992 to 2001 which shows strongly increased PL activity. The seven most PL active years between 1979 and 2016 fall into this 10-year period.

In Figure 7 the difference in PL occurrence in ERA-I in the last versus the first 15 years is compared, to identify regions of significant increase and decrease of PL activity. The strongest decline in PL activity is observed east of Greenland’s southern tip, and the highest increase on the Tromsø flake south of Svalbard, both with a change of up to 2 days of PL occurrence per year. In the Southern Ocean, increased PL activity is observed on the northern side of PL active areas, while partly reduced activity is recognized closer to Antarctica, leading to the suggestion that PL activity is propagating away from the continent. However, note that $p$-values smaller than 5% by the $t$-test can still be obtained by coincidence.

**4.4 Intense PLs**

A climatology of the most intense PLs was also derived. In order to detect these systems, the 10th percentile threshold used in section 3 is replaced by a threshold of the 50th percentile for both the intensity and the MCAO criteria, while the same polar-front criterion is used as before. Hereby the most intense PLs that develop in strong MCAOs are detected. For ERA-I (and ASR) this results in the detection criteria of $\text{SLP} - \text{SLP} > 0.71 \text{hPa}$ (5.07 hPa) and $\theta_{\text{SST}} - \theta_{500} > -4.4 \text{K}$ (−4.0 K). The set of these thresholds excludes 73 of 94 (89 of 123) STARS PLs and retains only 21 of 8301 (21 of 15018) cyclones in the NH of the year 2003 for ERA-I (and ASR). Hence only about 20% of the earlier identified PLs, now referred to as “all PLs,” of the NH, are detected with these stricter thresholds.

The spatial distributions of intense PLs, presented in Figure 8a–c, resemble the distributions of all PLs depicted in Figure 5, with the difference that regions of high activity, being the Nordic Seas and the Denmark Strait, stand out more clearly. About 4 times more intense PLs develop in the NH as compared to the SH. In the NH most (about 75%) of the intense PLs occur in the North Atlantic.

The seasonal distributions of intense PLs, shown in Figure 8d–f, are in general more restricted to the winter months December–March in the NH and June–August in the SH. The time series of the annual duration of intense PLs in the NH, depicted in Figure 8g, has a significant decaying trend of $−1.1$ PL hours per year ($p = 0.034$), which is equivalent to a reduction of approximately 10% between 1979 and 2016. This decaying trend is twice as strong in the central North Atlantic as in the Nordic Seas.

A possible explanation for the decrease in intense PLs is a decline in the strength of MCAOs. From climate model projections, Kolstad and Bracegirdle (2008) found a weakening of MCAOs for the end of the 21st century compared with the end of the 20th century. However, to the knowledge of the authors, no study has observed a decay in the strength of MCAOs over the past decades.

**5 DISCUSSION AND CONCLUSION**

For the first time, an objective global PL climatology has been developed. The climatology is based on ERA-I and ranges from 1979 to 2016. A second climatology is derived from the higher-resolution ASR reanalysis for the greater Arctic from 2000 to 2012. Both climatologies are developed by applying constraints on cyclone tracks identified by a tracking
algorithm based on spectrally filtered 850 hPa vorticity data (Hodges, 1995; 1999). The criteria were objectively developed by finding parameters that were most effective in distinguishing between PLs from the subjective STARS database (Noer et al., 2011) and all kinds of mid- and high-latitude cyclones.

For ERA-I (and ASR), the criteria were found to be

(a) a difference larger than 0.4 hPa (2.38 hPa) of the mean SLP within a radius of 110 km (330 km) and the SLP of the system; (as earlier)

(b) a maximum potential temperature difference above \(-9.4 \text{ K} (-8.5 \text{ K})\) within a radius of 110 km between the sea surface and 500 hPa level; and

(c) the absence of a tropopause (500 hPa) wind of magnitude higher than 31.3 m s\(^{-1}\) (29.6 m s\(^{-1}\)) poleward of the system.

Criterion (a) is applied to identify intense mesoscale systems, criterion (b) for the detection of MCAOs with connected deep convection, and criterion (c) to guarantee the occurrence of the systems poleward of the polar front. The result that the same parameters are found to be most effective for PL detection for both ERA-I and ASR, with thresholds only slightly stricter for ASR than for ERA-I, gives confidence that the criteria can be applied to other datasets as well.

Several other parameters (summarized in Table 1) were investigated for ERA-I and ASR, but none of them were found to improve the detection of PLs as additional criteria. Importantly, a constraint on the near-surface wind speed, a commonly applied intensity criterion, is found to be much less effective for PL detection than criterion (a), a measure for the depth of the low. This applies for ERA-I, where maximum winds connected to mesoscale systems are under-represented, but also for ASR, even though it was found to better represent near-surface wind speeds (e.g. Smirnova and Golubkin, 2017). It is therefore suggested to avoid the 10 m wind speed for the detection of PLs from reanalyses.

The application of an MCAO criterion for PL detection is generally agreed upon, and it may be included in the PL definition by Rasmussen and Turner (2003), presented in

FIGURE 8  Spatial and temporal distributions of the most intense PLs. (a)–(c) are as Figure 5, and (d)–(i) are as Figure 6.
section 1. Often, a temperature difference larger than 43 K between the sea surface and the 500 hPa level is utilized. Our analysis suggests that potential temperature performs better for PL detection than the actual temperature, and that the commonly used threshold of SST – $T_{500} > 43$ K is too strict, since it excludes a considerable proportion of PLs, which was also noted by Terpstra et al. (2016). A comparison of the temperature difference between the sea surface and three atmospheric pressure levels reveals that the 500 hPa is more useful for PL identification than the 700 and 850 hPa levels. This result is in disagreement with Bracegirdle and Gray (2008), although they used different temperature measures and a smaller set of polar mesoscale cyclones, which includes systems that are too weak to be considered as PLs. Here, a new criterion is suggested, ensuring that only systems poleward of the polar front are detected. This criterion excludes about one third of the otherwise falsely detected cyclones and is therefore regarded as being important.

The investigation of our obtained climatologies reveals that they detect a significant fraction of the subjectively identified PLs from STARS and other satellite-based PL datasets. Not all systems identified in our climatologies would be classified as definite PLs, but only a few could be excluded by experts as clearly non-PLs. This expresses the classical PL problem of not having an absolute objective definition. In this study, as in other studies where PLs are identified objectively, all conditions for a PL have to be satisfied at the same time step, without considering the evolution of the cyclone. A more sophisticated approach would be to include all time steps of the system, when deciding whether or not it should be classified as a PL. The use of cyclone-tracking algorithms, as done in this study, gives the opportunity to apply this approach.

Due to the higher resolution of the ASR data compared to ERA-I, the ASR climatology is regarded as better than that based on ERA-I, although ASR has the disadvantage of having a shorter temporal coverage and a domain only for the NH. The two climatologies show similar spatial and temporal PL distributions. The Denmark Strait and the Nordic Seas are found to be the two most active PL regions. Also, other regions in the North Atlantic, the North Pacific and the Southern Seas between 65° and 50° S were found to be PL active. It is observed that high PL activity occurs often in the vicinity of the sea-ice edge or the coast. The PL season generally ranges from November to March, with few cases in October and April for the NH. In the SH, the PL season is about two months longer, from April to October, with a few cases in March and November, but less active. The annual PL activity is about 17% lower in the SH than in the NH. The most intense PLs are mainly constrained to the two most active PL regions and the core winter season.

The total annual PL occurrence for both hemispheres shows high interannual variability, but no significant trend during the period of ERA-I. However, in the SH a decade (1992–2001) of increased intensity was identified, and some regions in both hemispheres show changes in PL occurrence. The strongest decreasing trend is observed in the Denmark Strait and the highest increasing trend in the Nordic Seas to the south of Svalbard. Also, for the most intense PLs in the NH, a significant decaying trend was observed.

The derived PL climatologies can be used for further investigation of different PL types and of typical synoptic-scale patterns associated with PL development in different regions. It will be of interest to investigate the PL representation in the recently produced high-resolution global reanalysis ERA-5 and to derive a PL climatology based on this reanalysis once it is fully released. Also of relevance would be to compare how the derived criteria depend on the underlying subjective PL list, such as the STARS or Smirnova datasets.

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