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Supplement of

A global climatology of polar lows investigated for local differences and wind-shear environments

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Supplemental material

1 Match statistics

A track from a PL list has a match, if a cyclone track is located within 150 km for at least half of the time steps of the PL track. This ensures a reasonable good spatio-temporal agreement in the tracks, which respects for some inaccuracies in the subjective PL lists, the reanalysis product and the cyclone tracking algorithm to detect or produce the PL centre. Different merging distances were tested and compared in Table S1. A distance of 250 km results in only slightly higher detection rates than 150 km, but is more prone to false positive matches. A distance of 100 km significantly reduces the detection rate as compared to 150 km distance, especially for the PL lists from Rojo and Smirnova. Hence, the choice for a 150 km distance in the track matching.

PL list	cases > 3 steps	detect 250km	%	detect 150km	%	detect 100km	%
Noer	162	138	85	131	81	119	73
Rojo	391	285	73	255	65	214	55
Smirnova	251	181	72	153	61	116	44
Golubkin	123	85	69	80	65	74	60
Yanase	(19)	13	68	13	68	11	58
Verezemskaya	1139	542	48	361	32	202	18

Table S1: Match statistics of the derived tracks in the different PL lists. A match is obtained if the track is in the vicinity of the PL for at least half of the time steps of the PL. Distances of 250, 150 and 100 km are compared.

2 Parameter correlation

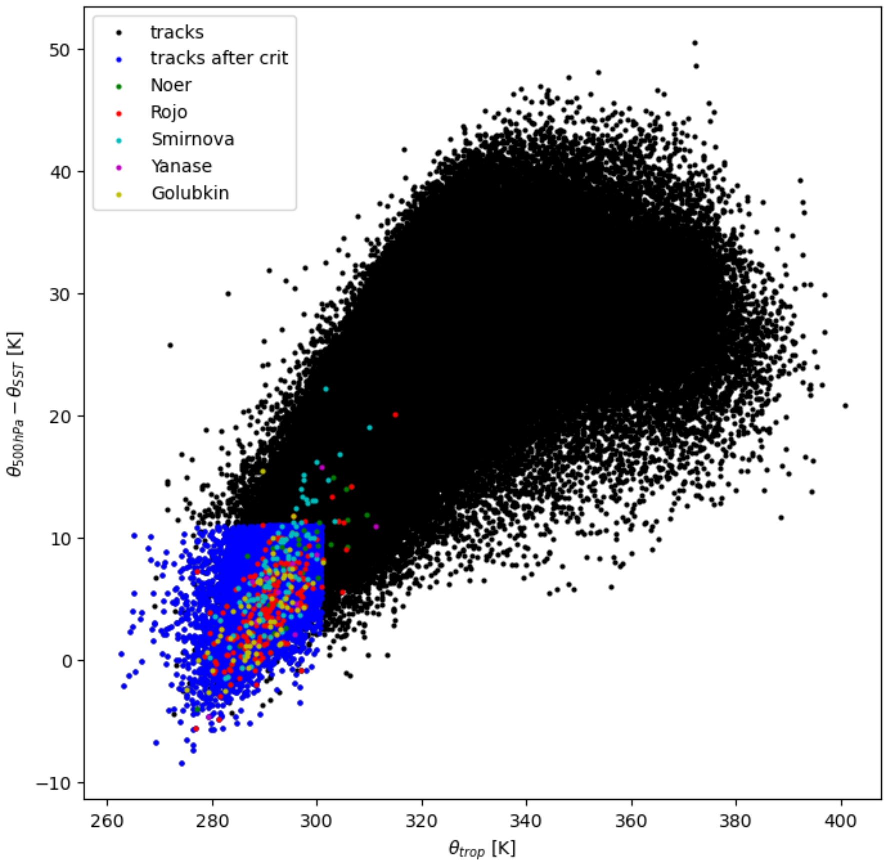

Figure S1: The potential temperature at the tropopause plotted against the static stability, $\theta_{500hPa} - \theta_{SST}$, for all tracks of the NH (black), the tracks satisfying all polar-low (blue), and the PLs from the different lists (other colors).

3 Comparison to the Verezemskaya list

The Verezemskaya list collects 1735 mesoscale cyclones in the Southern Ocean in June - September 2004 detected from satellite infra-red imagery [Verezemskaya et al., 2017]. Mesocyclones are a more general class of cyclones than PLs since they are not necessarily intense enough for being considered PLs and are not necessarily occurring in the polar air masses. Verezemskaya et al. [2017] state that 69% of the mesocyclones satisfy the near-surface wind threshold of $15\,\mathrm{m\,s^{-1}}$ included in the PL definition by Rasmussen and Turner [2003], however the available list does not include this information. These 69% of systems are considered PLs by Verezemskaya et al. [2017], however, the interpretation of the author is the fraction of PLs within the list is considerably smaller due to following reasons:
(i) The satisfaction of the near-surface wind threshold can be aided by a strong environmental flow, whereas the mesocyclone itself may be rather weak. (ii) The tracking algorithm applied to ERA-5 is developed and tuned for detecting cyclones with an intensity expected for PLs. However, only 32% of the tracks match a cyclone track from ERA-5 (Tab. S2). Hence, most systems in the Verezemskaya list do not exceed the vorticity threshold used in the tracking algorithm.

Table S2: As Table 1 from the article, but including the Verezemskaya list of mesocyclones. The second column provides the number of PLs in each list, the third column the number of PL tracks with more than three time steps, considered necessary for a trustworthy matching. The Yanase list is treated differently since it provides only one track point per PL. The number and fraction of PLs matched by a ERA-5 cyclone track is presented in column 4 and 5, respectively. A match is obtained if the cyclone track is within a distance of 150 km of the PL for at least half of the track points of the PL. Column 6 displays the amount of matched cases that are excluded since they start or end more than 24 h earlier or later than the PL from the list. Column 7 shows the number of tracks that are excluded since the ERA-5 track matches two PLs from the list. The last column provides the amount of matched PLs included in the parameter derivation.

Polar-low list	area	time period	number cases	cases > 3 steps	ERA-5 matched	%	excl. >24h	excl. 2x	remaining matches
Noer	N-E Atlantic	2002 - 2011	185	162	131	81	32	1	98
Rojo	N-E Atlantic	1999 - 2019	420	391	255	65	38	4	213
Smirnova	Nordic Seas	1995 - 2009	637	251	153	61	54	0	99
Golubkin	North Atlantic	2015 - 2017	131	123	80	65	15	0	65
Yanase	Sea of Japan	case studies	19	(none)	13	68	0	0	13
Verezemskaya	Southern Ocean	Jun - Sep 2004	1735	1139	363	32	93	13	257

(iii) The derivation of the list does not ensure the development of the mesocyclones in the polar air masses. (iv) The Southern Ocean is not known for especially vigorous PL activity [Rasmussen and Turner, 2003]. However, the list includes a large number of cases in a short time period of four months as compared to the PL lists presented in Section 2.2 of the article that span multiple years (Tab. S2, Col. 3,4).
(v) The PL lists of the Northern Hemisphere largely agree in the distributions of the parameters utilised as PL criteria (Section 3 of the article). This points towards

Table S3: Statistics for the satisfaction of the polar-low criteria from the five polar low lists and the mesocyclone list from Verezemskaya.

Polar-low list	Number of tracks	Satisfying all criteria	%
Noer	98	80	82
Rojo	213	184	86
Smirnova	99	68	69
Golubkin	65	58	89
Yanase	13	9	69
Verezemskaya	257	50	20

a generality of the parameters used as PL criteria independent of the region or developer of the list. PLs may be different in the Southern Hemisphere (which according to the comparison in Section 5.1 of the article is rather not the case), still they are PLs and therefore need to satisfy some general characteristics. The four PL criteria are connected to general characteristics associated to PLs by the scientific community (Section 1 of the article). Most systems from the five PL lists satisfy the PL criteria (Tab S3, 69 - 89%), however, only a few from the Verezemskaya list do (20%).

Since the Verezemskaya list of mesocyclones contains too many non-PL, it is not included for the derivation of the thresholds of the PL criteria. However, as a superclass to PLs, the mesocyclones lay at the same end of the broad spectrum of cyclones. Therefore, in the following the parameter distributions are compared between the mesocyclones from the Southern Ocean, the PLs from the Northern Hemisphere and general cyclone tracks from both hemispheres (Figure S2, S3). Note, that as in the manuscript the ERA-5 matched tracks of the systems are compared.

Many mesocyclones from the Southern Hemisphere (Verezemskaya) have a lower potential temperature at the tropopause than general cyclones but have higher values than the Northern Hemisphere PLs (Fig. S2a). Also, a considerable fraction of mesocyclones are on the equator side of the jet stream, however considerably less than for general cyclones (Fig. S3a). Both point towards, that some mesocyclones are not located in the polar air masses, however that many of them do, hence supporting argument (iii) on why some of the systems may be non-PLs in the Verezemskaya list. The agreement in distributions of PLs and mesocyclones is better in the potential temperature at the tropopause than in the maximum wind speed poleward at the tropopause, pointing towards a better applicability as a general PL criteria of the former, which is also used in this study.

Also for the static stability parameters (Fig. S2b, S3b,c), the distributions of mesocyclones are close to the PL distributions as compared to the cyclone tracks, however, with many mesocyclones featuring higher stability than the PLs. The reason for the latter may be that some mesocyclones are not located in the polar air masses. However, the former points towards the applicability of the static stability criteria for the Southern Hemisphere. Also distributions in $\theta_{500hPa} - \theta_{SST}$ are in better agreement for PLs and mesocyclones than the distributions in SST - T_500hPa,

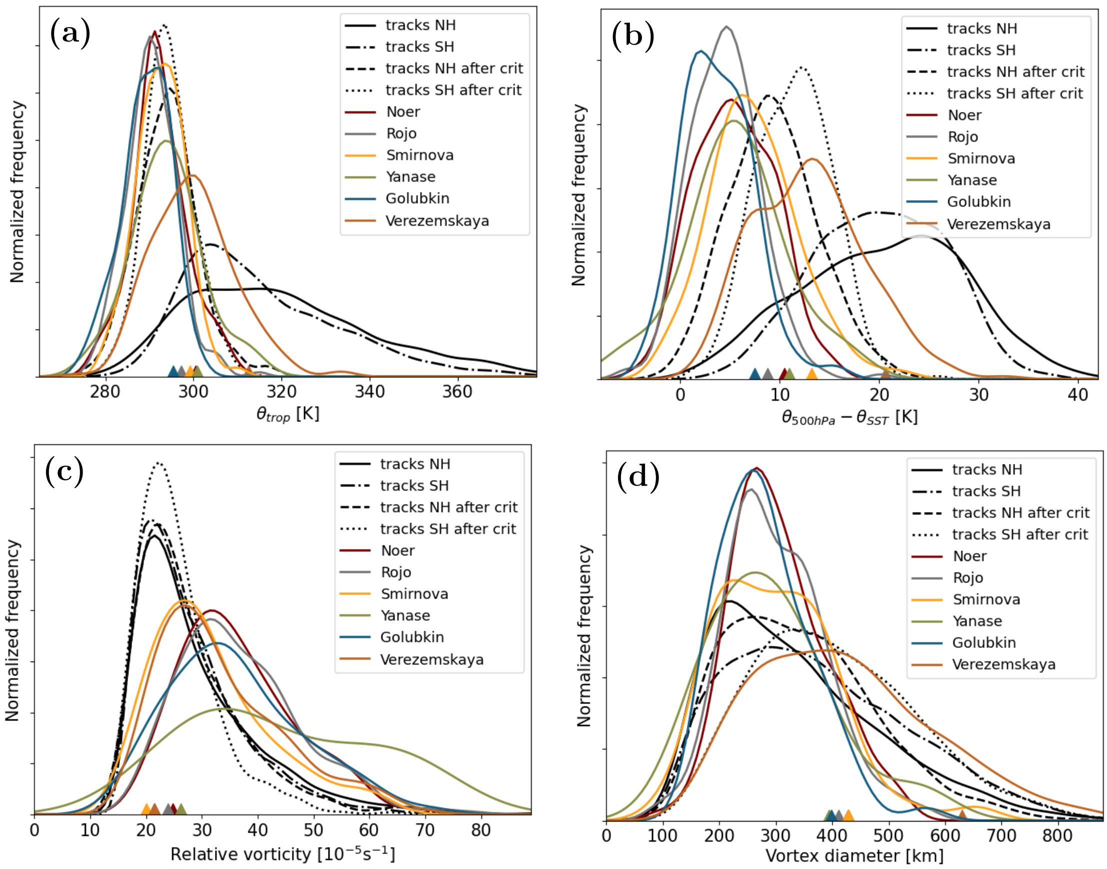

Figure S2: As Table 1 from the article, but including the Verezemskaya list of mesocyclones. Distribution in the parameters used to identify polar lows, these are the polar-low criteria which are successful in distinguishing between all tracks of both hemispheres (black) and polar low from the different lists (colours). The tracks that remain after application of the other three polar-low criteria are presented (black dashed-dotted and dotted) to express the additional value of the parameter to the other three criteria. (a) The potential temperature at the tropopause, θ_{trop}, is computed as lifetime-mean of the track, (b) the potential static stability, $\theta_{500hPa} - \theta_{SST}$, as lifetime-minimum. (c) The relative vorticity and (d) the vortex diameter expresses the lifetime-maximum. The coloured triangle along the x-axis denotes the threshold satisfied by 90% of the polar lows of each list.

indicating that the former is a more general criteria.

The mesocyclones share the near-surface wind distribution with the PLs (Fig. S3d), however have often a lower vortex strength which is comparable to the PLs from the Smirnova list (Fig. S2c). This supports argument (i) from the beginning of this section. However, the mesocyclones are as the PLs on the intense side of the cyclone spectrum, and an intensity criteria depending on the relative vorticity is applicable independent on the hemisphere.

The mesocyclones from the Verezemskaya list include multiple large systems, which appear to be non-PLs (Fig. S2d). This provides another argument for not using

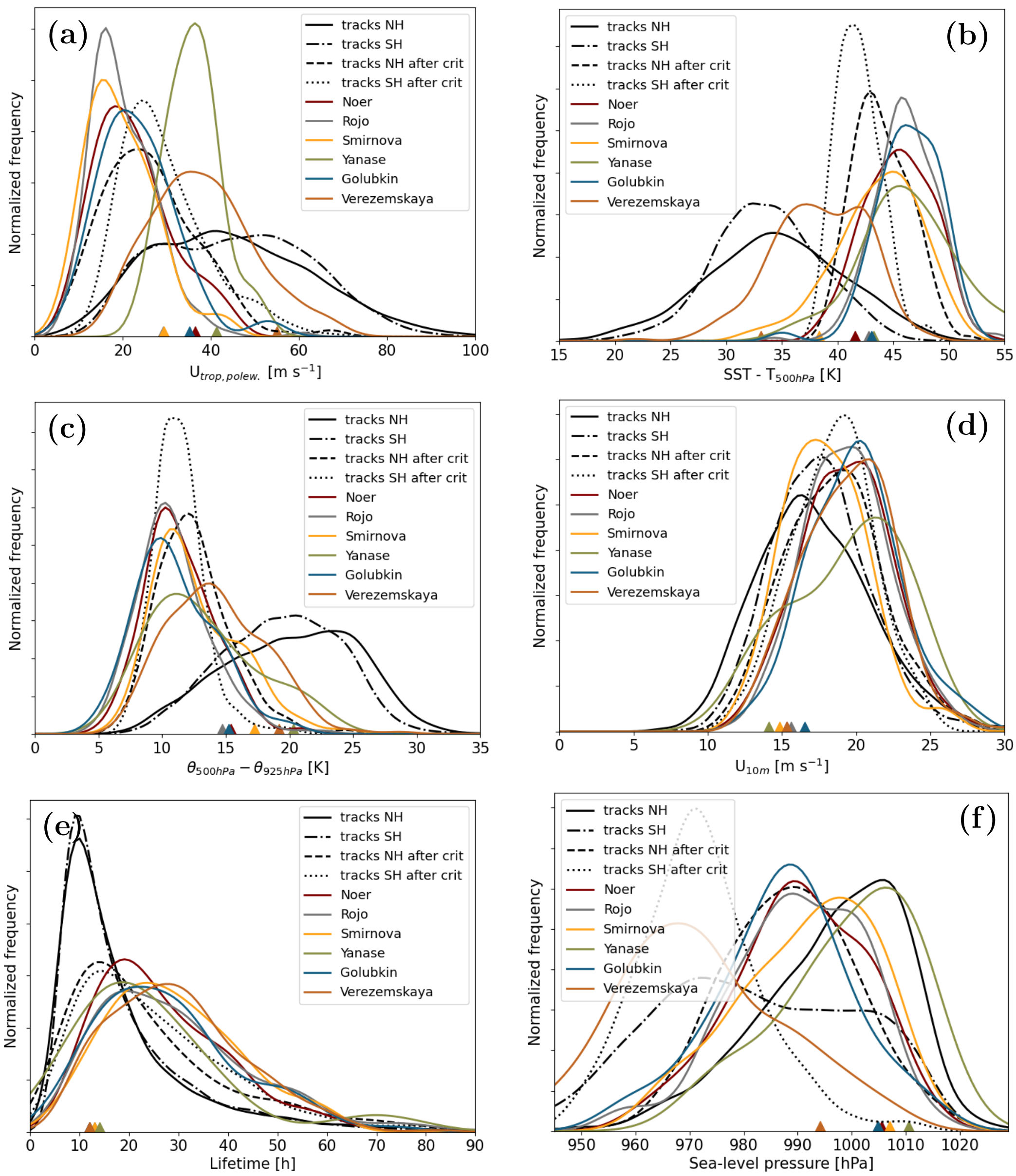

Figure S3: As Figure 2 from the article, but including the Verezemskaya list of mesocyclones. The distribution in different parameters for all tracks of the Northern and Southern Hemisphere (black), different polar low lists (colors) and in the tracks that remain after application of the polar-low criteria for the two hemispheres (black dotted and dash-dotted). (a) The maximum wind speed at the tropopause poleward of the system, $U_{trop,polew}$, is computed as the lifetime mean of the track. (b) The temperature difference between the 500 hPa level and the sea surface, SST$-T_{500hPa}$, and (d) the maximum near-surface wind speed, U_{10m}, as lifetime maximum. (c) The potential temperature difference between 500 hPa and 925 hPa, $\theta_{500hPa} - \theta_{925hPa}$, and the sea-level pressure, as lifetime minimum.

this list for the derivation of the PL parameters. However, it is generally agreed on that PLs are of mesoscale size and measuring the size of the cyclone with the

vortex diameter is not dependent on the hemisphere or environment (beside possible distortion by land masses). Hence, the size criterion derived from the PL lists of the Northern Hemisphere is not doubted.
To summarize, the mesocyclones and PLs mainly share qualitatively similar characteristics. Generally, the Verezemskaya list supports the PL criteria, a further argument for their general applicability.

4 Sensitivity climatologies

4.1 Near land

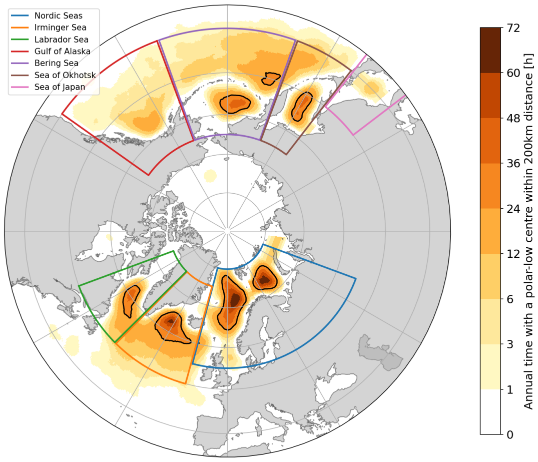

Figure S4: As Figure 3 from the article, but only including PL time steps with a distance more than 200 km from land.

4.2 Strong criteria

Table S4: As Table 3 from the article. Statistics of the strict thresholds for the sensitivity climatologies as compared to the polar-low criteria. The first row within each criterion repeats the polar-low criteria, the second row depicts the stricter threshold, that excludes 20 - 30% of the PLs from the Noer, Rojo, Yanase and Golubkin lists.

Parameter	Threshold	excluded polar lows [%] N/R/S/Y/G	excluded cyclones NH/SH [%]	excl. cyclones after other crit. NH/SH [%]
Polar-front criterion				
θ_{trop}	$< 300.8\,\mathrm{K}$	9/4/5/8/2	76/ 65	14/ 14
	$< 295\,\mathrm{K}$	30/21/33/54/12	86/ 75	43/ 43
Static-stability criterion				
$\theta_{500hPa} - \theta_{SST}$	$< 11.0\,\mathrm{K}$	7/4/17/8/3	80/ 74	34/ 55
	$< 7.0\,\mathrm{K}$	35/22/49/31/14	89/ 80	70/ 87
Intensity criterion				
$\xi_{smth,850}$	$> 20.0 \times 10^{-5}\mathrm{s}^{-1}$	0/1/9/8/5	19/ 19	20/ 20
	$> 30.0 \times 10^{-5}\mathrm{s}^{-1}$	30/28/55/23/34	64/ 67	65/ 79
Meso-scale size criterion				
vortex diameter	$< 430\,\mathrm{km}$	9/8/9/8/5	25/ 34	22/ 32
	$< 350\,\mathrm{km}$	28/28/31/23/20	40/ 51	43/ 55

Intense PLs need to exceed an intensity criteria of $\xi_{smth,850} > 30.0 \times 10^{-5}\mathrm{s}^{-1}$ instead of $20.0 \times 10^{-5}\mathrm{s}^{-1}$. This criteria excludes additional 56% of the PL time steps from the Northern Hemisphere and 74% from the Southern Hemisphere. Hence, considerably less intense PLs occur in the Southern Hemisphere (Fig. S5). In the Northern Hemisphere, the intense PLs develop in the same regions as general PLs, however, more constraint to regions in the vicinity of land masses.
Small PLs are defined by a threshold on the vortex diameter of below 350 km, instead of 430 km. This excludes additional 27% and 34% of the PLs from the Northern and Southern Hemisphere, respectively. The spatial distribution of small PLs is quite similar to the one of all PLs (Fig. S5).

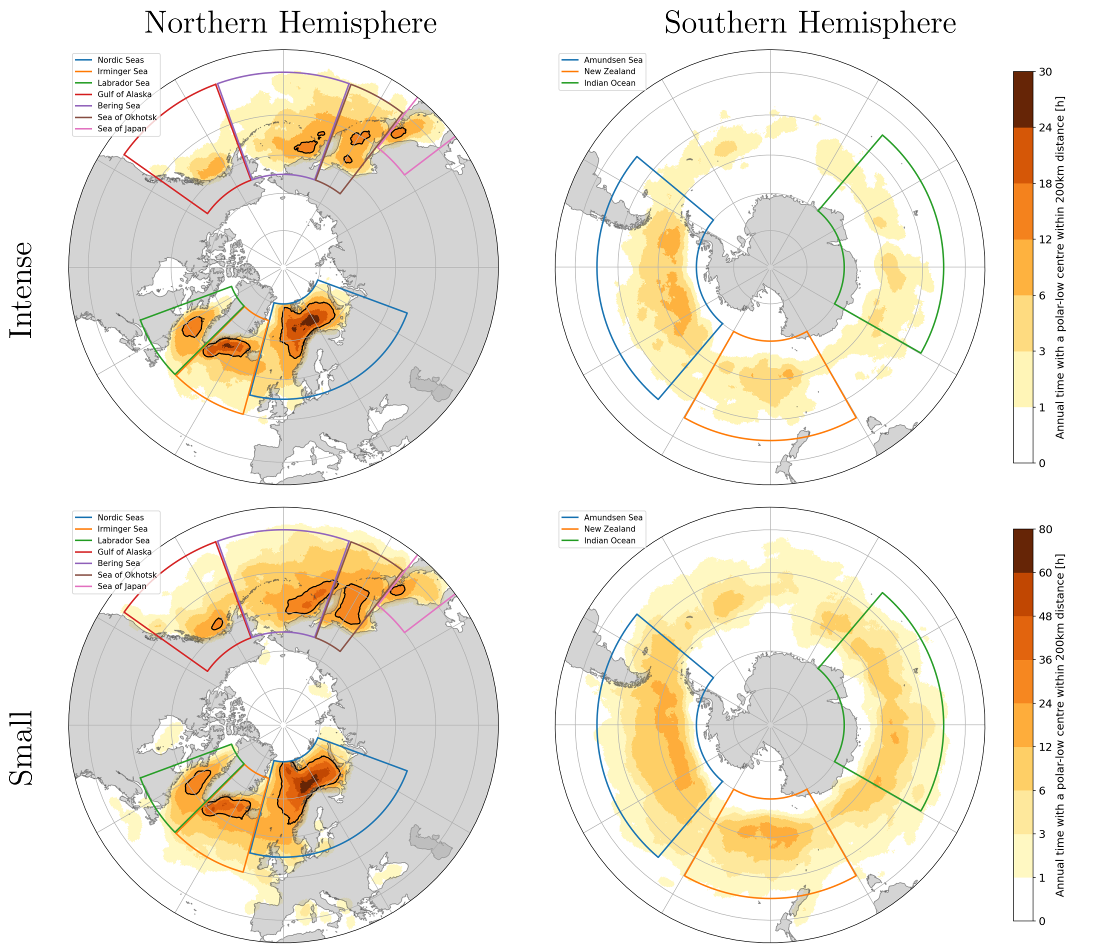

Figure S5: As Figure 3 from the article, but for sensitivity climatologies with stricter criteria. Top panels for the intense PLs, satisfying $\xi_{smth,850} > 30.0 \times 10^{-5}\mathrm{s}^{-1}$. Bottom panels for the small PLs with a vortex diameter$<$ $350\,km$.

PLs occurring at a low static stability are found by a threshold of $\theta_{500hPa} - \theta_{SST} <$ 7.0 K, instead of 11.0 K. A low static stability is reached by strong heating from the sea surface and favors a fast growth rate of PLs. The stricter criteria excludes additional 55% and 71% of the PLs from the Northern and Southern Hemisphere, respectively. Hence, the spatial distribution of PLs occurring at a low static stability features considerably less PLs in the Southern Hemisphere and the North Pacific (Fig. S6). The North Atlantic is less influenced by the stricter static stability criterion.

Polar lows with a low potential temperature at the tropopause are identified by a threshold of $\theta_{trop} < 295\,\mathrm{K}$, instead of 300.8 K. This criteria excludes additional 34% of the PL time steps from both hemispheres. The PLs satisfying the stricter criteria are developing deeper in the polar air masses. Hence, the spatial distributions feature less PLs at lower latitudes, whereas the higher latitudes are less effected (Fig. S6).

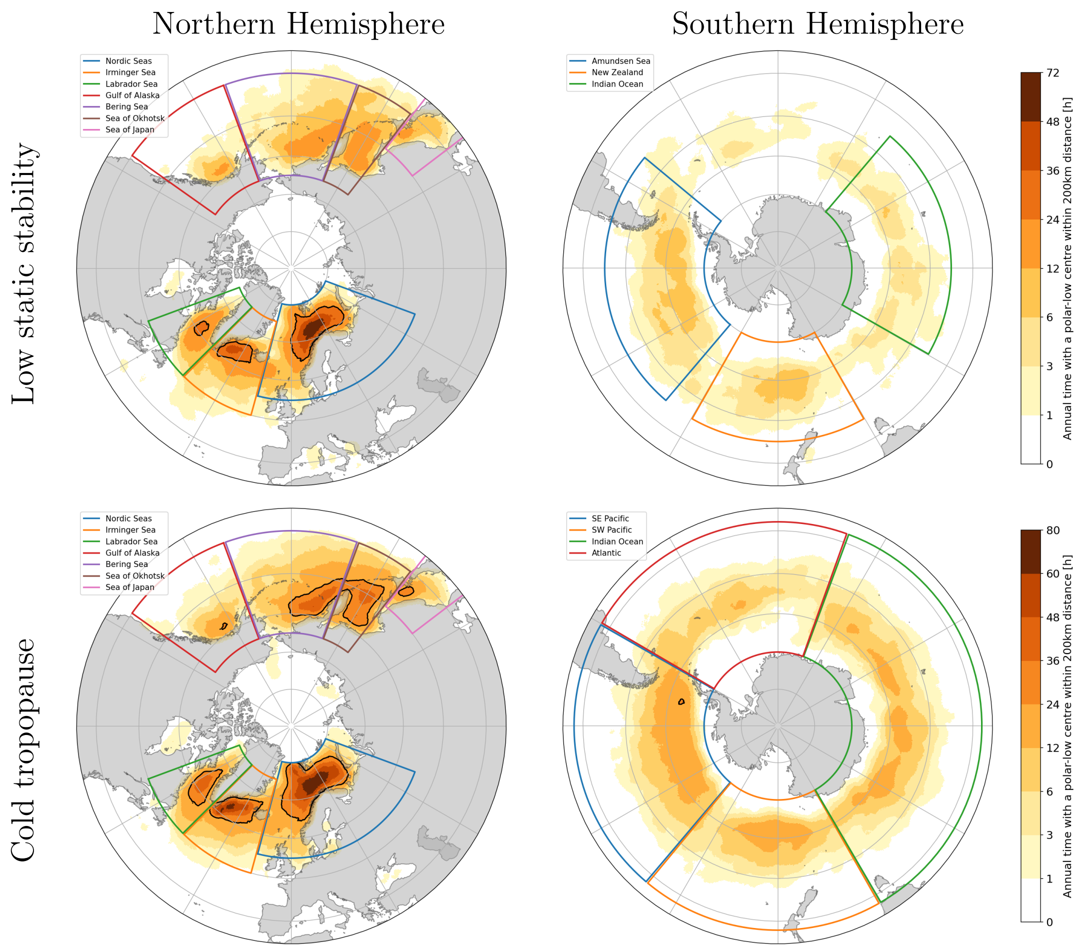

Figure S6: As Figure 3 from the article, but for sensitivity climatologies with stricter criteria. Top panels for the PLs developing at low static stability, $\theta_{500hPa} - \theta_{SST} < 7.0\,\mathrm{K}$. Bottom panels for PLs occuring within air masses of low potential temperature at the tropopause, $\theta_{trop} < 295\,\mathrm{K}$.

5 Similarities across the shear categories

PLs of the different shear categories are rather similar in the parameters displayed in Figure S7.

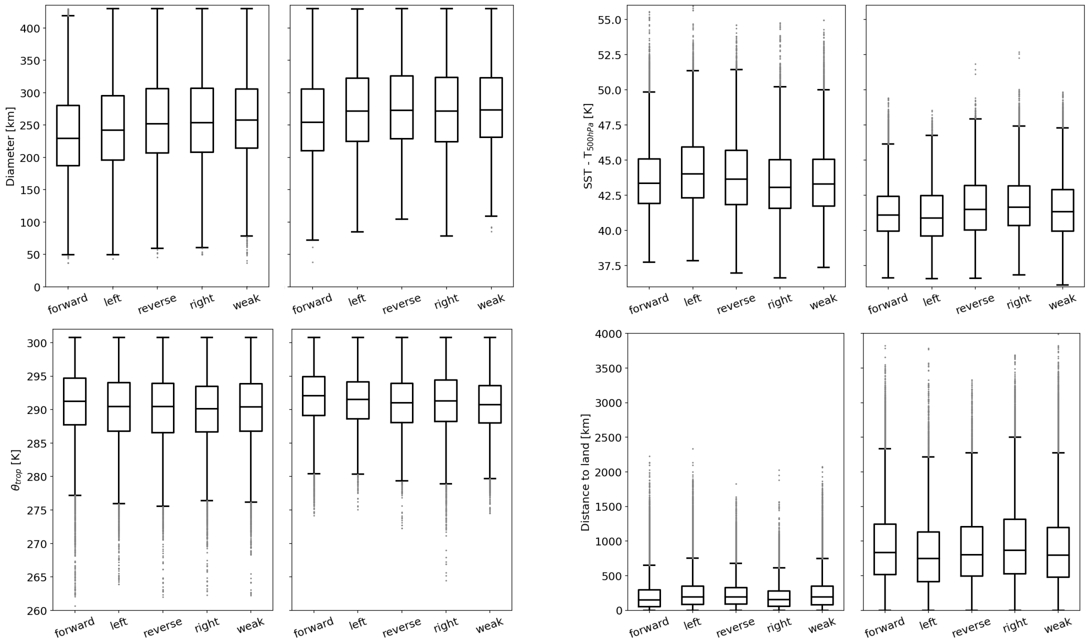

Figure S7: As Figure 10 of the article. Distributions for the different shear categories for the Northern (left) and Southern Hemisphere (right).

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