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Supplement of

Stratospheric ozone trends for 1985–2018: sensitivity to recent large variability

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The following figures provide supporting evidence and information for the main journal article.

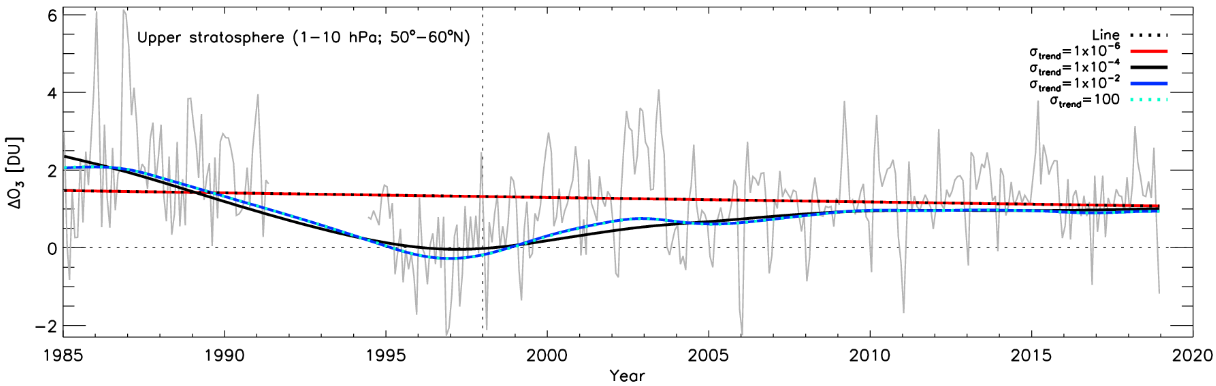

Figure S1: Upper stratosphere deseasonalised partial column ozone timeseries for 1-10 hPa and 50-60N (grey line). Thick colour lines are DLM non-linear trends using different sigma_trend parameters (see legend). A straight line is plotted over the red DLM non-linear trend to demonstrate this line is essentially almost perfectly straight.

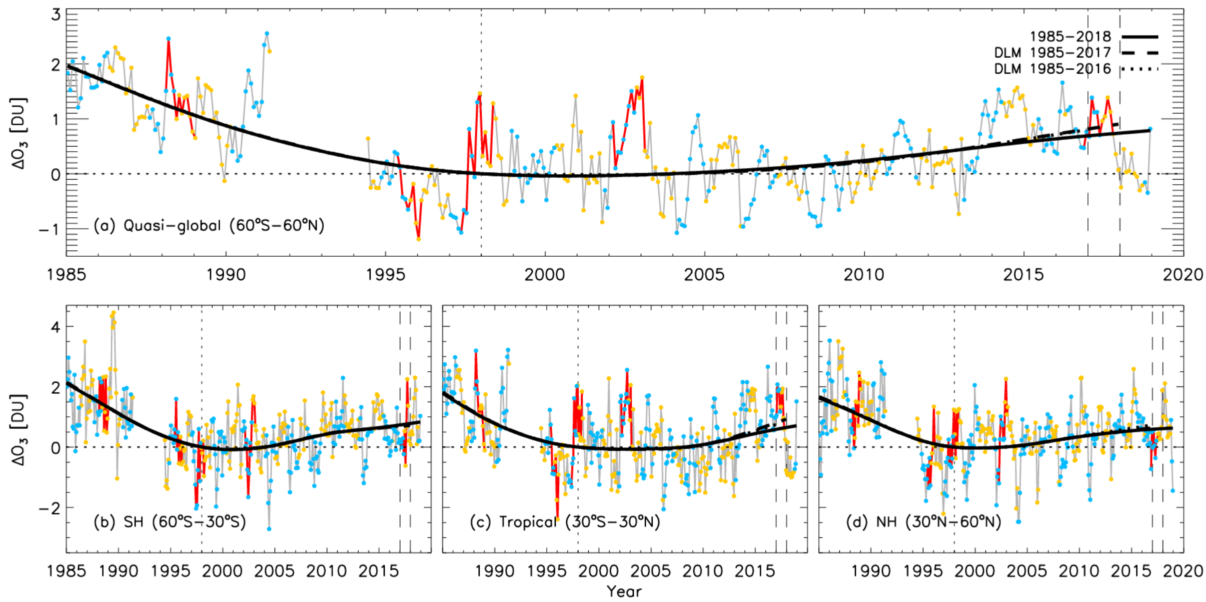

Figure S2: As for Fig. 2 of the main article, but for the upper stratosphere (1-10 hPa).

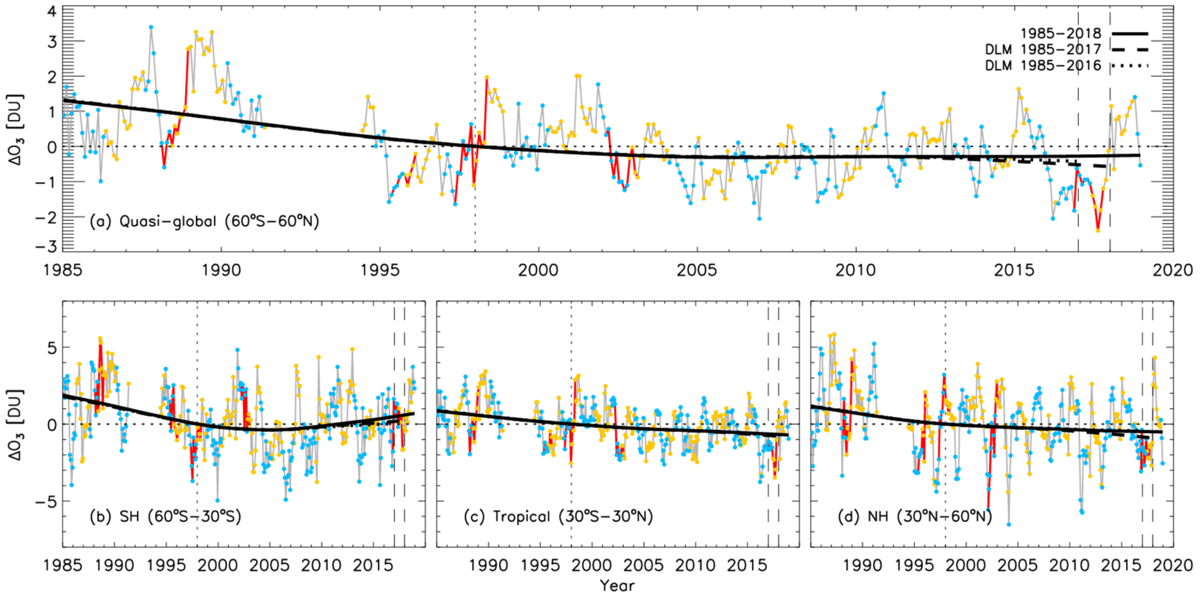

Figure S3: As for Fig. 2 of the main article, but for the middle stratosphere (10-50 hPa).

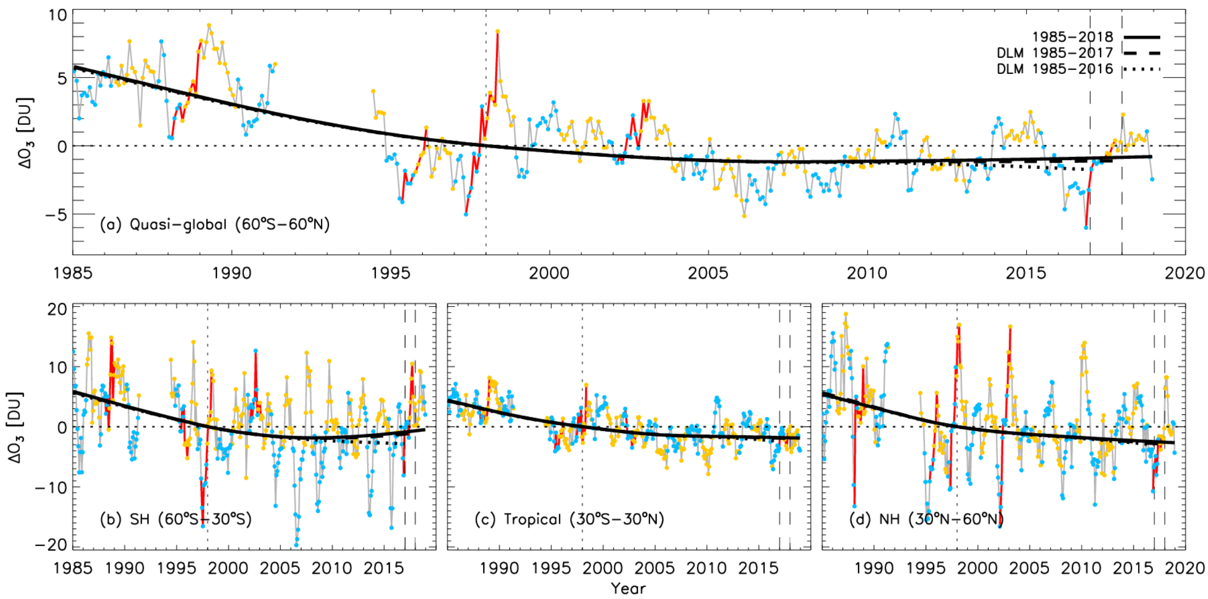

Figure S4: As for Fig. 2 of the main article, but for the whole stratosphere (1-147 hPa at 60-30^o and 1-100 hPa over 30^{o}S-30^{o}N).

Spatial inference of minima year

We can expand the idea of inferring the likely earliest minimum using the DLM with spatially-resolved data. In Fig. S5, we present a spatial map indicating the earliest occurrence after 1995 that ozone reached a minimum. Since the minimum is sensitive to the end year of the timeseries, we consider the earliest occurrence from the set of DLM analyses with end dates ranging from 2013 to 2018. Doing this accounts for the end year sensitivity, so that a large upswing in, e.g., 2017 in the SH lower stratosphere can push back the minimum date from 2016 (for end year in 2016) to ~2013 (Figs. 2 and 5 of the main paper). The actual DLM curve for which the first minimum is found in Fig. S5a, is shown in Fig. S5b, i.e. if a minimum date of 2013 is found from an analysis of the period 1985-2013, the location is assigned '2013'; if a later minimum or end point is lower in DU than the 2013 estimate, e.g. in 2017, it will instead be assigned to '2017'. We do not consider the significance of the minimum date, but point out that an earlier year in Fig. S5b indicates that the minimum is more robust to the subsequent addition of data, which is why we consider Fig. S5b as the `stability' of the minimum year in Fig. S5.

The minimum of ozone in the stratosphere is canonically assumed to be around 1998-2000 [Harris et al., 2015, WMO 2014, WMO 2018). Fig. S5a indicates that this is indeed the case in the upper stratosphere. But, below ~7 hPa in the tropics, and 10 hPa at mid-latitudes, a minimum is not reached until after 2010, and generally later than 2013. A large fraction of the tropical and NH stratosphere below 10 hPa (32 km) displays no halt in ozone decreases as late as 2018. The upsurge in 2017 on a spatial scale leaves 2013-2017 as minima years in the SH lower stratosphere.

In some regions of Fig. S5a, there are features that indicate sharp gradients in the minima, e.g. 50-40ºS near 1 hPa where the minimum is late compared to surrounding regions; in this case data exhibit an early rise, and we have not yet ascertained the reason. Fig. S5a provides further evidence that the decline up to ~2013 or later is consistent, widespread, and overall relatively insensitive to the end year. A key question then remains as to why the minimum in ozone below 10 hPa is much later than in the upper stratosphere. Natural variability may well play a part [Chipperfield et al., 2018, Stone et al., 2018], but the sensitivity analysis performed here covering six end years includes major stratospheric modes of variability such as the QBO (~2 years) and ENSO (~5-7 years). However, it should be clarified that we do not consider the non-linear seasonal dependence of the QBO in the regression analysis that was demonstrated to be important in Section 3.3 of the main paper.

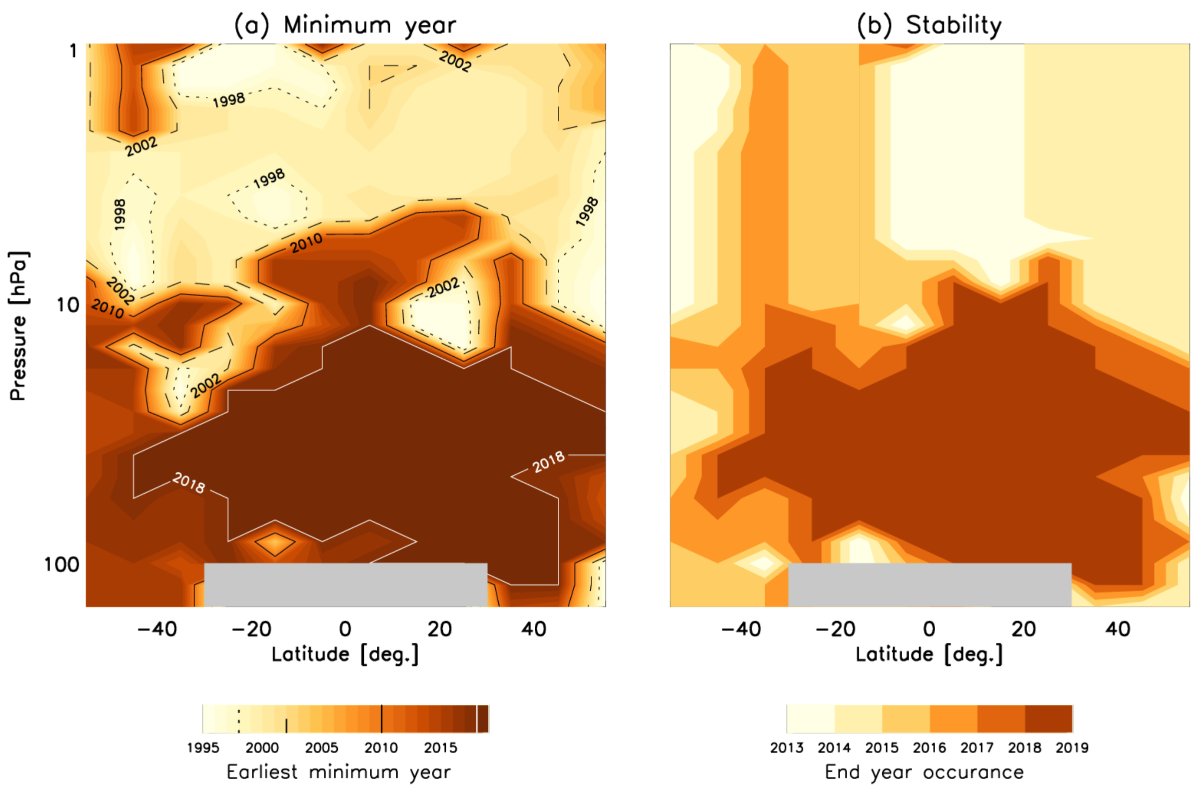

Figure S5: (a) Indicator of the year after 1994 that the non-linear ozone trend reaches a minimum and (b) the stability of that year, i.e. the earliest and deepest occurrence of this minimum, i.e. earlier implies the minimum is more stable to the end year. The set of ending years ranges from 2013 to 2018. Contours for January 1998 (dotted), 2002 (dashed), 2010 (solid) and 2018 (solid, white) are presented in (a). The non-linear trends for 1985-2018 for each panel are presented in the supplementary figure Fig. S6.

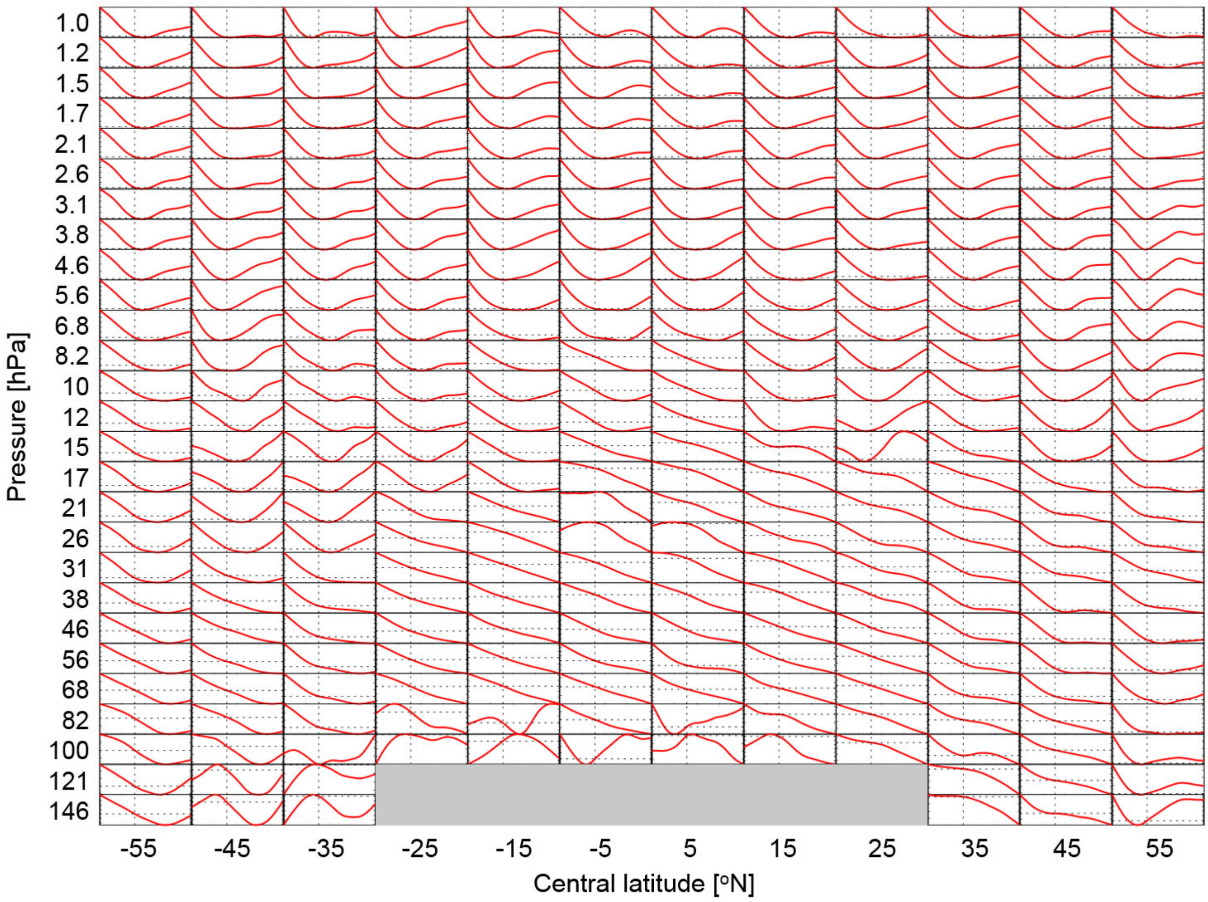

Figure S6: All DLM non-linear ozone trends estimated for 1985-2018. The x-axis of each panel ranges from January 1985 to December 2018. All trend lines are relative to January 1998 (vertical dotted line), with the zero level represented by the dotted horizontal line. The y-axis of each panel is fitted to the range of the DLM non-linear trends, i.e. is different for each panel and cannot be compared.

	60°-30°S	50°-30°S	30°S-30°N	20°S-20°N	30°-50°N	30°-60°N	50°S-50°N	60°S-60°N
1998 Absolute level [DU]								
Whole	260.2	257.9	231.0	229.8	265.7	270.8	241.4	246.5
Upper	47.2	49.1	56.0	57.1	49.3	48.0	53.6	52.9
Middle	96.8	100.4	115.1	117.4	102.0	98.9	110.2	107.6
Lower	116.0	108.2	59.9	55.2	114.0	123.5	77.7	86.1
1998-2018 ΔO_3 [DU]								
Whole	-0.5	-0.4	-1.9	-2.5	-3.2	-2.6	-1.1	-1.1
Upper	0.8	0.8	0.7	0.6	0.6	0.6	0.8	0.8
Middle	0.7	0.8	-0.7	-0.9	-0.5	-0.5	-0.4	-0.2
Lower	-1.6	-1.7	-2.1	-2.1	-1.9	-1.5	-1.8	-1.7
1998-2018 ΔO_3 [%]								
Whole	-0.2	-0.2	-0.8	-1.1	-1.2	-1.0	-0.5	-0.4
Upper	1.7	1.6	1.3	1.1	1.2	1.3	1.5	1.5
Middle	0.7	0.8	-0.6	-0.8	-0.5	-0.5	-0.4	-0.2
Lower	-1.4	-1.6	-3.5	-3.8	-1.7	-1.2	-2.3	-2.0
1998-2018 ΔO_3 [%/decade]								
Whole	-0.1	-0.1	-0.4	-0.5	-0.6	-0.5	-0.2	-0.2
Upper	0.8	0.8	0.6	0.5	0.6	0.6	0.7	0.7
Middle	0.3	0.4	-0.3	-0.4	-0.2	-0.2	-0.2	-0.1
Lower	-0.7	-0.7	-1.7	-1.8	-0.8	-0.6	-1.1	-0.9
1985 Absolute level [DU]								
Whole	266.0	262.6	235.3	233.7	270.8	276.2	246.7	251.2
Upper	49.4	50.9	57.7	58.7	50.8	49.6	55.5	54.4
Middle	98.6	101.6	115.9	118.1	103.0	100.0	111.3	109.1
Lower	118.3	110.3	61.6	57.0	117.1	126.9	79.7	87.8
1985-1997 ΔO_3 [DU]								
Whole	-5.8	-4.8	-4.4	-3.9	-5.1	-5.4	-5.3	-4.7
Upper	-2.1	-1.8	-1.8	-1.6	-1.5	-1.6	-1.9	-1.5
Middle	-1.9	-1.2	-0.9	-0.7	-1.0	-1.1	-1.1	-1.5
Lower	-2.3	-2.1	-1.7	-1.8	-3.2	-3.4	-2.1	-1.7
1985-1997 ΔO_3 [%]								
Whole	-2.2	-1.8	-1.9	-1.7	-1.9	-2.0	-2.1	-1.9
Upper	-4.3	-3.5	-3.1	-2.7	-3.0	-3.2	-3.4	-2.8
Middle	-1.9	-1.2	-0.8	-0.6	-1.0	-1.1	-1.0	-1.4
Lower	-1.9	-1.9	-2.8	-3.2	-2.7	-2.7	-2.6	-1.9
1985-1997 ΔO_3 [%/decade]								
Whole	-1.6	-1.3	-1.3	-1.2	-1.3	-1.4	-1.5	-1.3
Upper	-3.0	-2.5	-2.2	-1.9	-2.1	-2.3	-2.4	-2.0
Middle	-1.4	-0.8	-0.6	-0.4	-0.7	-0.8	-0.7	-1.0
Lower	-1.4	-1.4	-2.0	-2.3	-2.0	-1.9	-1.9	-1.3
1985-2018 ΔO_3 [DU]								
Whole	-6.3	-5.2	-6.3	-6.4	-8.3	-8.0	-6.4	-5.8
Upper	-1.3	-1.0	-1.1	-1.0	-0.9	-1.0	-1.1	-0.7
Middle	-1.2	-0.4	-1.6	-1.6	-1.5	-1.6	-1.5	-1.7
Lower	-3.9	-3.8	-3.8	-3.9	-5.1	-4.9	-3.9	-3.4
1985-2018 ΔO_3 [%]								
Whole	-2.4	-2.0	-2.7	-2.7	-3.1	-2.9	-2.6	-2.3
Upper	-2.6	-2.0	-1.9	-1.7	-1.8	-2.0	-2.0	-1.3
Middle	-1.2	-0.4	-1.4	-1.4	-1.5	-1.6	-1.3	-1.6
Lower	-3.3	-3.4	-6.2	-6.8	-4.4	-3.9	-4.9	-3.8
1985-2018 ΔO_3 [%/decade]								
Whole	-0.7	-0.6	-0.8	-0.8	-0.9	-0.9	-0.8	-0.7
Upper	-0.8	-0.6	-0.6	-0.5	-0.5	-0.6	-0.6	-0.4
Middle	-0.4	-0.1	-0.4	-0.4	-0.4	-0.5	-0.4	-0.5
Lower	-1.0	-1.0	-1.8	-2.0	-1.3	-1.1	-1.4	-1.1

Table S1: Absolute ozone levels, in Dobson Units (DU) in 1985 and 1998, and ozone changes over 1985-1998, 1998-2018, and 1985-2018 in DU and %. Values for 1985-2018 are calculated using 1985 absolute values and from the table for 1998-2018 and 1985-1997. Changes for 1985-1997 are from January 1985 to January 1998, and 1998-2018 for January 1998 to December 2018. All numbers rounded to 1 decimal place.