

The authors would like to thank the referees for their constructive reviews. In response, we have added text to the Introduction and Discussion sections to address Referee #2's comments and clarifying our Methodology to address Referee #1's concerns. The Results section has been revised in order to better weight the text and figures as suggested by Referee #3. We believe the manuscript is much improved after addressing the comments of the three referees.

Our responses (black) follow each specific comment of the reviewers (blue) with any large changes to the text italicized and in quotations. Unless otherwise stated, the page and line numbers are in reference to the updated manuscript.

## Referee #1

This study investigates the influence of springtime cyclones on surface ozone concentrations of two surface measurement sites in Ireland (Mace Head) and Portugal (Monte Velho). After a statistical evaluation of reanalysis data, the authors present four case studies – two for each measurement site – of cyclones leading to high ozone values at the surface. The results show that cyclones passing the measurement sites within a certain range can have a recognizable effect on the surface ozone concentration – either by transporting ozone-rich air directly from the stratosphere or by lower aged stratospheric air.

This manuscript is interesting and very carefully written and therefore in the scope of ACP.

## Major comments

My only major comment deals with the cyclone intensity. Why did you choose the most intense cyclones?

**Authors' comments:** We choose the most intense cyclones for two reasons: a) so that the cyclones would be an exact match in both the ERA-Interim and the MACC data sets and moreover b) to ensure the airstreams controlling the ascent and descent were evident. Another benefit of selecting the most intense cyclones would be for storm compositing, as was done in Knowland et al. (2015). The most intense cyclones tend to follow similar storm track pathways within the main North Atlantic or North Pacific storm track region. Moderate to weak cyclones are not located solely in the major storm track pathways and tend to be shorter-lived (Knowland et al., 2015, ACP), resulting in a less coherent composite. The N1 cyclone was one of the cyclones in the NA composite in Knowland et al. (2015).

We have added the following text to Sect. 3.2.1 (Page 9, lines 19-21) to clarify this approach:

*“This ensures that the cyclones will be within the top 20 % of the cyclones in the NA and that the cyclone is an exact match identified in both the ERA-Interim and the MACC reanalysis data sets (not shown). Moreover, the airstreams within strong cyclones will be more evident than in the weaker cyclones (Catto et al., 2010).”*

Would it be better to investigate in addition also “normal” or “weaker” cyclones to get a broader picture of the influence of cyclones on surface ozone? Do only strong cyclones have this impact on the ground stations? Is there a clear relationship of high ozone and intense cyclones? Can weaker cyclones have a stronger impact on the measured ozone by advecting aged low-level ozone-rich air to the measurement sites?

**Authors’ comments:** The statistics presented in Sect. 4.1 were performed on all tracks, not just the most intense cyclones. For the reasons described above, we selected the most intense cyclones for the case studies. As we learned from the case studies, the mean intensity of the cyclone is not the only factor determining the strength of the dry intrusion: the S2 cyclone, which was weaker than the S1 and N2 cyclones based on the relative vorticity, was characterized by very strong descent. We also note that the position of the cyclone and both upstream and downstream pressure systems as much as the intensity of the cyclone that determines the impact on ground stations.

We tested the suggestion on the case study criteria made by the referee and found that if instead we select the cyclones for case studies based on the highest O3 for tracks which had at least two time steps of >75th pc O3, then moderate to weak cyclones are selected. Hence, weaker cyclones can also impact surface O3 at ground stations .

The following text has been added to the Discussion (Page 31, Lines 3-12):

*“The case study analysis focused on the strongest cyclones associated with high O3 at Mace Head and Monte Velho such that 1) the cyclone tracks would be exact matches in the MACC and ERA-Interim reanalyses (Knowland et al., 2015) and 2) airstreams would be most evident (Catto et al., 2010). An alternative method to select case study cyclones would be to start by selecting the tracks associated with the highest (or lowest) O3. This leads to the selection of moderate to weak cyclones (which are generally not located solely in the major storm track pathways and which tend to be shorter-lived (Knowland et al., 2015)). While the case study analysis presented here highlights the regional differences in the strongest springtime mid-latitude cyclones associated with high surface O3, the relationship between cyclones and surface O3 likely depends on a number of complex factors including cyclone location relative to the measurement station and upstream and downstream pressure systems, cyclone intensity, stratosphere-to-troposphere transport, and long-range transport of trace gases within the free troposphere and the boundary layer.”*

### Technical corrections

Page 4, line 31: Do not use italics for units. Use  $\text{m}^2 \text{kg}^{-1} \text{s}^{-1}$  instead of  $\text{m}^2 \text{kg}^{-1} \text{s}^{-1}$

**Authors’ comments:** Changed (Page 5, Line 19).

Section 2.2.2 Please indicate already here the spatial resolution of the MACC data (it follows in Sec 3.1, but for completeness it would be nice to have it already in the data description part)

**Authors' comments:** The details of the spatial resolution are now included in the sentence in Section 2.2.2 (Page 5, Lines 30-31):

*“The MACC reanalysis has the same spatial (TL255) and temporal (6-hourly) resolution as the ERA-Interim reanalysis.”*

Page 9, line 14: Are two time steps enough to justify the term “persistent”?

**Authors' comments:** The US national air quality standard for O<sub>3</sub> is based on the daily maximum 8-hour average O<sub>3</sub> concentration. Therefore, two or more 6-hourly time steps where high O<sub>3</sub> was present in the area could result in a daily maximum 8-hour average of O<sub>3</sub> exceeding an air quality standard.

Text was added to justify the criteria that the cyclones must have two or more 6-hourly time steps associated with high O<sub>3</sub> (Page 9, lines 23-25):

*“This selects the cyclones that are associated with elevated levels of O<sub>3</sub> at the monitoring station for a prolonged period of time which can be related to averaging periods typically used for policy metrics such as the daily maximum 8-hour average O<sub>3</sub>.”*

Figure 4: something went completely wrong with the labelling (see screenshot) -> please check Figure 11: a,b,c,d labels are missing.

**Authors' comments:** Thank you for bringing this to our attention. We will check the on-line proofs carefully. Figures 4 and 11 have been corrected.

## Referee #2

### General Remarks

The topic of an elevated stratospheric ozone contribution at the surface has been in the focus of numerous recent studies driven by air-quality considerations. In particular, it has been a mystery to me why Mace Head is reached by descending air masses, which has not been observed that frequently elsewhere. The paper is well written and deserves publication, but I recommend considering a few amendments.

### Details

- 1) Introduction: Consider mentioning the role of STT in some of the recent air-quality studies, such as:

Lefohn et al., Atmos. Environ. 45 (2011), 4845-4857

Langford et al., JGR 117, D00V06 (2012)

M. Lin et al., JGR 117, D00V22 (2012)

Lefohn et al., Atmos. Environ. 62 (2012), 646-656

Ma et al., ACP 14 (2014), 5311-5325

Dempsey, Atmos. Environ. 98 (2014), 111-122

M. Lin et al., Nature Communications 2015

Itoh and Narazaki, ACP 16 (2016), 6241-6261

Langford et al., JGR 122 (2017), 1312-1337

High-lying sites are ore affected by STT (western US, Alps (Zugspitze, Jungfraujoeh), Tibet).

**Authors' comments:** We thank the referee for these additional references. We have used these references in the following text and in the responses below. The following text was added to the Introduction (Page 2, Lines 26-28):

*“This can result in surface O<sub>3</sub> exceeding air quality standards, especially at high elevations such as in the western USA (Langford et al., 2009, 2015; Lefohn et al., 2009; Lin et al., 2012, 2014). In particular, Lin et al. (2012) found that in spring 2010 up to 60 % of total modeled surface O<sub>3</sub> in the western USA during air quality exceedances could be attributed to stratospheric intrusions of O<sub>3</sub>...”*

- 2) Introduction/Discussion: The penetration of STT air into the PBL has been rarely observed (you cite Davis and Schuepbach (1994); some more words can be found in Eisele et al., J. Atmos. Sci. 56 (1999), 319-330). The probability of entrainment into the PBL seems to be low, which suggests subsidence during night-time followed by day-time turbulent mixing (Eisele et al., 1999; Ott et al., JGR 121 (2016), 3687-3706; Langford et al., 2017) to be a more reasonable mechanism. Is there anything different at the seaside (Cooper et al., JGR 100 (2005), D23310; Itoh and Narazaki (2016))? You mention a fraction around 50 %. Could this be related to the chance of night-time subsidence?



**Authors' comments:** This is a very good point. The following text regarding the ability for O<sub>3</sub>-rich air to be entrained into the PBL has been added (Page 2, Lines 33 – Page 3, Line 4):

*“Air from the free troposphere is largely limited to daytime entrainment into the lowest layer of the atmosphere as the planetary boundary layer (PBL) height increases (e.g., Itoh and Narazaki 2016; Ott et al., 2016); however, the ability for O<sub>3</sub>-rich air to reach the surface depends on a complex array of factors including the diurnal cycle (Itoh and Narazaki 2016; Langford et al., 2009, 2012; Ott et al., 2016) and the seasonal cycle of the PBL height (Langford et al., 2015, 2017), the presence of convective mixing (Eisele et al., 1999, Langford et al., 2017), and the elevation of the monitoring station, which if located within the free troposphere, especially with the night-time collapse of the PBL, can experience direct STT (Langford et al., 2015, 2017).”*

We have also added to the sentence describing why there is a springtime peak in the seasonal O<sub>3</sub> cycle at marine, background stations (Page 3, Lines 21-28):

*“Also in springtime, there is a peak in the seasonal O<sub>3</sub> cycle at marine, background stations including Mace Head (Simmonds et al., 1997, Wilson et al., 2012, Derwent et al., 2016); at such stations there is often a minimum in O<sub>3</sub> in summer, as a result of enhanced O<sub>3</sub> loss by increased water vapor within the stable marine boundary layer (MBL) (Ayer et al., 1992; Oltmans and Levy, 1994), in contrast to urban environments with the peak in O<sub>3</sub> in summer associated with photochemical production. Parrish et al. (2016) and Derwent et al. (2016) demonstrate that the seasonal cycle of O<sub>3</sub> at MBL stations, including Mace Head, can be reasonably represented by two harmonics of the seasonal cycle with the first explaining most of the seasonal variation, capturing the summertime O<sub>3</sub> loss (and therefore a late winter/early spring maxima) and the spring maxima in O<sub>3</sub> within the free troposphere which is entrained into the MBL.”*

3) Also constituents from originally lofted Canadian fire plumes were observed at Mace Head (Forster et al., JGR 106 (2001), 22887-22906

**Authors' comments:** We thank the referee for this comment. According to Forster et al. (2001), carbon monoxide (CO) can be transported from the regions of biomass burning in Canada to Europe, which can lead to enhanced CO at Mace Head (58% above background for August 1998 fire season) as the plume passes over. The following text has been added to the Discussion section (Page 30, Lines 33—Page 31 Line 2):

*“Biomass burning plumes from as far away as Canada have reached Europe, leading to enhanced CO at Mace Head as the plume passes over (Forster et al., 2001). Within a fire plume, O<sub>3</sub> can be produced associated with the increased precursors and this has the potential to enhance European O<sub>3</sub>, including at Mace Head.”*

P. 4, line 28: The spatial resolution seems to be sufficient to resolve STT layers. This is an important issue (e.g., Roelofs et al., J. Geophys. Res. **108** (2003), 8529; Eastham and Jacob, ACP **17** (2017), 2543-2553). However, there is, still, the issue of mixing even in high-resolution

models that can lead to a loss of information (two rather bad comparisons between measurements and a high-resolution ECMWF model results: Trickl et al., ACP 16 (2016), 8791-8815). This topic should be addressed somewhere in the paper.

**Authors' comments:** This is a very important distinction to make. We have added the following text to the end of Sect. 2.2 (Page 5, Lines 4-8):

*“While models and reanalyses with coarse horizontal resolution (> 100km) are able to identify stratospheric intrusions (Roelofs et al., 2003; Lin et al., 2015; Ott et al., 2016), the fine-scale nature of the O<sub>3</sub> filaments is best identified at higher horizontal resolutions (Buker et al., 2005; Lin et al., 2012; Ott et al., 2016), such as the MACC and MERRA-2 reanalyses and by the stratospheric tracer. However, even high-resolution reanalyses may struggle to represent the complex structure of stratospheric intrusions (e.g., Trickl et al., 2016).”*

## Referee #3

### General Remarks

This manuscript investigates how passing mid-latitude cyclones influence the surface ozone levels at two stations in Western Europe (Mace Head and Monte Velho) by comparing ozone observations and reanalysis data from ERA-Interim, MACC and MERRA-2. Four case studies were presented to support the main results. The strong impact of the downward transport of O<sub>3</sub>-rich air masses from the stratosphere on the surface ozone levels was pointed out.

The topic and the general length of the paper are relevant for publication in ACP. Generally the paper is compact and well-written, however Sec. 4.2.1-4.2.3 should be improved as suggested below. The structure of the paper is logical. The introductory discussion is adequate and the referencing is sufficient. In a few cases more details on the methods are needed. Some of the figures need improvement.

For the reasons mentioned above and below the paper is appropriate for publication in ACP after a major revision.

### Specific comments:

**Authors' comments:** We want to thank the referee for the many constructive comments regarding the results section of this manuscript. We have made modifications to the text and figures in Sect. 4.2.1-4.2.4 to improve the readability of the figures and the discussion.

-Shorten Sect. 4.2.1 and improve the text of this section (write more compact and structured). Perhaps add a table to shorten the text.

**Authors' comments:** Section 4.2.1 describes the first case study, the N1 cyclone. We have reduced the text in this section by modifying the text describing Fig. 6 to focus on the airstreams; instead of adding a table to shorten the text, we have removed details already discussed in relation to Figs. 3 and 4 in the geographical coordinate system. Now the paragraphs describing Fig. 6 have been reduced to one paragraph instead of three (Page 17 Line 26—Page 18, Line 5).

This section does include necessary text as to how to read the cyclone-centered figures, especially the TFP figures. We believe it would make it more difficult to read these figures without this text unless the reader was familiar with them from previous literature.

-Section 4.2.2 should be better weighted (better incorporate the amount of text compared to the number of figures).

**Authors' comments:** To better weight text and figures in Sect. 4.2.2, Fig. 8 has been reduced from four panels to two panels for the initial description of the S1 cyclone using the geographical coordinates (Pages 21-22).

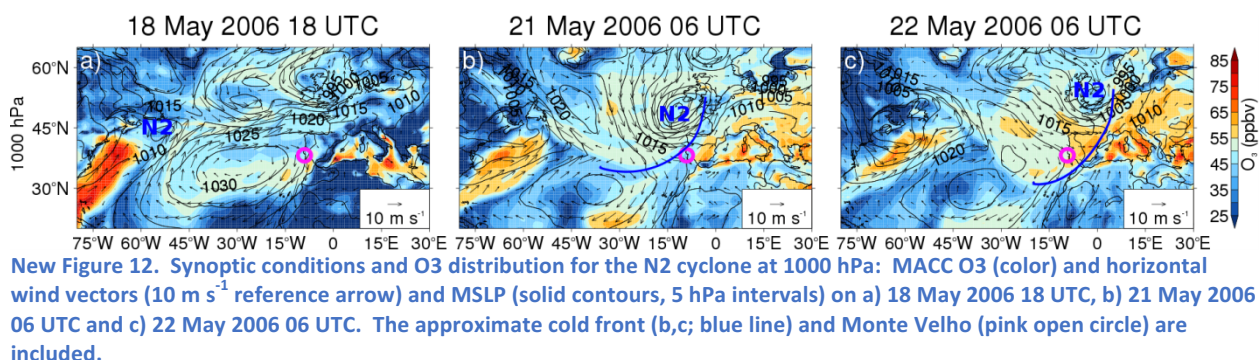
Also, the text in Sect. 4.2.2 has been modified to focus on the residual O3 that becomes entrained into the cyclone, which was not seen in the N1 cyclone in the same way, and the differences in the S1 cyclone using the two reanalyses.

-In comparison Section 4.2.3 is extremely brief and all information is shifted to the Supplement.  
-> I get the general impression that Sect. 4.2.1-4.2.3 must be better weighted and the text must be improved and more compact written. Sometimes hard to follow for the reader.

**Authors' comments:**

We appreciate this feedback and in the Sect. 4.2.2-4.2.4 the emphasis in the text is now on how the remaining case studies are different to the N1 cyclone and therefore provide insight on how strong cyclones can bring high levels of O3 to Mace Head and Monte Velho.

Specifically for Sect. 4.2.3, we have added a new figure and text (inserted below; Pages 26 Line 13 – Page 27 Line 3). The new Fig. 12 highlights the synoptic conditions and O3 distribution at the surface over the North Atlantic sector during the life time of the N2 cyclone (based on the bottom panel of the N2 figures in the supplemental).



The text in Section 4.2.3 provides an overview of the N2 cyclone, however the main discussion for the N2 cyclone is still in the supplemental material since the N2 cyclone is similar to the N1 and S1 cyclones discussed in Sects. 4.2.2 and 4.2.3, respectively. The following text is Section 4.2.3 on Page 26 (new text in italics):

“The N2 cyclone is a strong cyclone which passed north of Monte Velho and advected high O3 to the observation site. Cyclogenesis of the N2 cyclone occurs off the east coast of Florida on 17 May 2006 at 12 UTC (not shown) and then tracks northeastward (Fig. 2b). *The synoptic conditions at the time of the N2 cyclone are similar to the N1 cyclone: About a day after cyclogenesis, the N2 cyclone is located just south of Newfoundland and downwind of the N2 cyclone are a series of low pressure systems across the NA region as well as a strong Azores High stretching over most of the NA (Figs. 12a and S7c). The large pressure gradient results in strong westerly winds at near 45° N (Fig. 12a) throughout the troposphere (Fig. S7). Similar to the N1 cyclone, stratospheric O3 descends into the troposphere within the low pressure systems in the NA ahead of the N2 cyclone (Figs. 12a and S7). Similar to the S1 cyclone, a high pressure system develops to the west of the N2 cyclone (Fig. 12b-c), supporting upper-level descent*

*behind the N2 cyclone's cold front and negating transport across the NA from North America (Figs. 12b-c, S8 and S9).*

*As was seen for the N1 cyclone, the N2 cyclone is also associated with low O3 before high O3 is observed at the monitoring station due to the passage of a cold front (Fig. 12b-c). Since the N2 cyclone is similar to the N1 and S1 cyclones discussed in Sects 4.2.2 and 4.2.3, respectively, full details for this case can be found in the Supplemental material (Sect. S2.3)."*

-Sometimes the numbers for statistics are rather low (number of strong cyclones, see minor comments). Comment on this!

**Authors' comments:** All cyclones, not only the strong cyclones, were used in the statistics presented in Sects. 4.1. To clarify, we have added the following (italics, Page 11, Lines 7-8):

*"Here, tracks were not filtered for intensity. For springtime during the period of observations from 1988—2010 at Mace Head, the average number of the total cyclone tracks associated with O3 > 75<sup>th</sup> pc ...as a percentage of the total tracks in each region."*

The intensity of the cyclone was only a factor in selecting the case study cyclones to ensure that 1) the cyclones are an exact match in ERA-Interim and the MACC reanalysis and 2) the airstreams within strong cyclones will be more evident than in weaker cyclones. This additional information regarding the case study cyclone identification methodology has been added to the manuscript (Page 9, Lines 18-20) following Referee #1's comment.

-Perhaps it would also be useful to show observed ozone time series for the whole months of your case studies?

**Authors' comments:** We do not believe a time series of the observed O3 alone would add further value to the manuscript. For example, the Figure 1 below is the Mace Head hourly O3 observed (dashed blue contour) and the 6-hourly averaged O3 (thick black contour) for March 2007 when the N1 cyclone occurred. While the observed change from low to high O3 can be seen in the time series at the time of the N1 cyclone, it is hard to pick out the impact of the cyclone on the O3 variability in the time series without prior knowledge of the cyclone. The ozone time series shows strong variability especially from the diurnal and seasonal cycles.

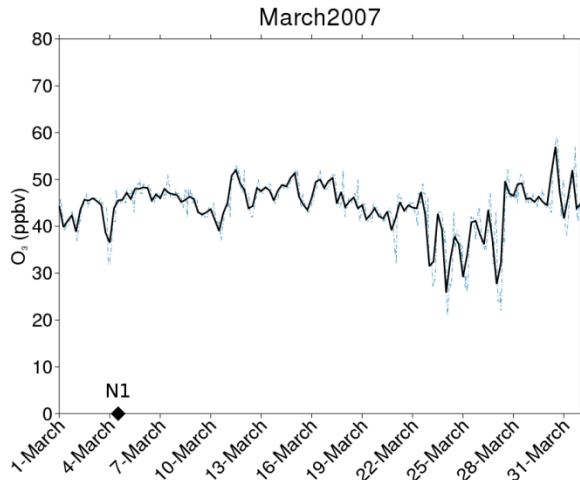


Figure 1 - Time series of 6-hourly averaged O<sub>3</sub> (thick black contour) calculated from the 1-hour observed O<sub>3</sub> (blue dashed contour) for Mace Head for March 2007. The N1 cyclone reached maximum vorticity on 4 March 2007 12 UTC (black diamond).

However, figures showing the O<sub>3</sub> time series with additional information such as departure from the seasonal mean, variability explained by the diurnal cycle, possible outside influences on surface O<sub>3</sub> such as long-range transport of emissions precursors (i.e., biomass burning events as suggested by Referee #2), long-range transport of O<sub>3</sub>, stratospheric O<sub>3</sub>, and frequency of storms in the area could be enlightening, although difficult to do without extensive further analysis and model simulations.

Your results must be very sensitive to the vertical distribution of ozone in the tropopause layer (reanalysis data). Have you investigated this in detail? How accurate are the reanalysis data at these altitudes?

**Authors' comments:** The distribution of O<sub>3</sub> in the upper troposphere and lower stratosphere is sensitive to the representation in the reanalyses. According to Innes et al. (2008), the MACC reanalysis biases compared to ozonesondes are within  $\pm 5$  to 10% in the Northern Hemisphere between 200 and 1000 hPa, and less than 10% over Europe and North America when compared to MOZAIC flight data. Wargan et al. (2017) recommends that studies of mid-latitude stratosphere-troposphere exchange using the MERRA-2 reanalysis should limit the time period to when the EOS Aura data was assimilated (October 2004 until present). Specifically, over Europe (45°-60°N, 0°-60°E), the springtime MERRA-2 ozone profiles in 2005 resemble the vertical structure of the ozonesondes, although biased low, with  $r^2 > 0.6$  down to 5km below the tropopause (Wargan et al., 2017). In MERRA-2, a low bias in the UT is expected as the production of O<sub>3</sub> from lightning-NO<sub>x</sub> and pollution (including surface emission sources of O<sub>3</sub> precursors) is not included (Wargan et al., 2015). The GEOS-5 model has a higher vertical grid spacing of about 1 km in the UTLS compared to the MLS data (2.5 – 3 km) (Wargan et al., 2015).

We have added discussion of the representation of UTLS O<sub>3</sub> in reanalyses to Sect. 4.2.2 (Page 22, Line 13 – Page 23 Line 6):

*“The vertical transport of O<sub>3</sub> will be sensitive to the strong gradients of O<sub>3</sub> near the tropopause...Both the MACC and MERRA-2 O<sub>3</sub> have good agreement to independent*

*observations in the upper troposphere/lower stratosphere (UTLS) region (Inness et al., 2013; Wargan et al., 2015, 2017). In the Northern Hemisphere (NH) extra-tropics, MACC O3 between 500 and 100 hPa has a bias of -10--0% when compared to ozonesondes profiles (Inness et al., 2013) and Wargan et al. (2017) found that the average MERRA-2 O3 profile over Europe (45°-60°N, 0°-60°E) in the spring of 2005 (after the assimilation of MLS and OMI satellite retrievals) captures the vertical structure of the ozonesondes in that region ( $r^2 > 0.6$ ), although biased low (up to -20 %) in the UTLS."*

#### Minor comments and technical corrections:

Page 2, line 7: Add also the mean latitude for the Icelandic low, since you also give this for the Azores High (line 9).

**Authors comment:** The mean latitude added (Page 2, Line 7)

Page 2: Add this reference to your discussion: Trickl, T., O.R. Cooper, H. Eisele, P. James, R. Mucke, and A. Stohl (2003), Intercontinental transport and its influence on the ozone concentrations over central Europe: Three case studies, *J. Geophys. Res.*, 108, 8530, doi: 10.1029/2002JD002735, D12.

**Authors' comments:** Reference added to Introduction (Page 2, Lines 17-21)

Page 3, line 25-30: What kind of instrument was used for the ozone measurements?

**Authors' comments:** Details on the instruments has been added to Sect. 2.1 (Page 4, Line 7 and 12-14)

Page 3, line 29: Replace "pink" by "orange"

**Authors' comment:** Text modified as suggested.

Page 4, line 5: More clearly point out the difference between the present paper and Knowland et al., 2015.

**Authors' comment:** Knowland et al., 2015 identified and composited together the most intense cyclones over the North Pacific and North Atlantic sectors. In this paper, we are looking at a few individual cyclone cases over the North Atlantic/European sector.

We have added to the text (italics; Page 4, Lines 21-22):

*"Through a composite cyclone analysis, it was clearly shown that intense cyclones over the North Pacific (NP) and NA regions redistribute O3 and CO horizontally and vertically within the WCB and DI airstreams (Knowland et al., 2015)."*

Page 4, line 12-13: Add webpages for ERA-Interim, MACC, and MERRA-2 reanalysis.

**Authors' comment:** Webpages added to the "Data availability" at end of paper (Page 33).

Page 4, line 25: What does "cycle 31r2" mean?



**Authors' comment:** Added following text to clarifying that “cycle” refers to the IFS model version (Page 5, Lines 11-13):

“...with the ECMWF's Integrated Forecast System (IFS) cycle 31r2 (*a full history of changes made to the ECMWF IFS, as indicated by the cycle number, is available at <https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model>*), with a sequential...”

Page 5, line 2: What does “cycle 36r1” mean?

**Authors' comments:** Added text to clarify the IFS model version used in MACC is more recent version compared to ERA-Interim (Page 5, Lines 23-24).

Page 5, line 13: What is the explanation for the underestimate?

**Authors' comments:** It is not known why there is an underestimation in the MACC reanalysis O<sub>3</sub> during spring over central and northern Europe (Innes et al., 2013). We have added the following text to provide possible explanations based on Innes et al. (2013) (Page 6, Line 3-8):

*“The reason(s) for the biases in the seasonal O<sub>3</sub> is not known although Innes et al. (2013) hypothesize that the biases in the MACC surface O<sub>3</sub> are related to the diurnal cycle possibly due to 1) there is no diurnal cycle in the NO<sub>x</sub> emissions used in the CTM resulting in negative O<sub>3</sub> biases during the day-time and positive O<sub>3</sub> biases during the night-time, 2) misrepresentation of vertical mixing between the boundary layer and free troposphere, and/or 3) less observations are available (and therefore not assimilated) at night.”*

Page 6, line 2-5: Reorder the references in chronological order (and for same years in alphabetical order).

**Authors' comments:** Thank you for bringing this to our attention. Reference order changed.

Page 6, line 11: Write out STFR.

**Authors' comments:** Acronym now defined.

Page 6, line 19: Reorder the references in chronological order.

**Authors' comments:** Reference order changed.

Page 6, line 27: “< 1000 km” in what time?

**Authors' comments:** This distance would be for the life cycle of the cyclone. Sentence now reads (Page 7, Lines 20-21):

*“On completion of the tracking process, the stationary cyclones (travel < 1000 km during the cyclone's life cycle) and short-lived cyclones (cyclone's life cycle lasts < two days)....”*

Page 8, Figure 1: The letter size of lat and lon numbers is too large compared to the track density numbers.

**Authors' comments:** The font size in Fig. 1 has been improved as per suggestion (Page 8).



Page 9, Table 1: The number of strong cyclones used in the study is very low. Is this number high enough for your statistics?

**Authors' comments:** All cyclones, not only the strong cyclones, were used in the statistics presented in Sects. 4.1. The number of strong cyclones presented in Table 1 was used in the selection of the case study cyclones to ensure the airstreams within the case study cyclones were identifiable.

Page 10, line 23: What does "SGF" mean?

**Authors' comments:** Abbreviation now defined in main text (Page 11, Line 12).

Page 11, Table 2: Last column (right): "percent" -> "Percent"

**Authors' comments:** Text has been changed.

Page 11, Table 2: The number of years given in the brackets (SGF) is very low. Can you comment on this low number for your statistics?

**Authors' comments:** Nearly all the years with more tracks associated with high O3 for the North region associated with Mace Head are significant (15 of the 18 years) and half of the years with more tracks associated with low O3 for the South region associated with Mace Head are significant (8 of the 16). It is true there are a small number of years which had significant differences for tracks passing in the other regions near Mace Head and in the regions near Monte Velho. The low number of significantly different years is likely because as we move away from the NA storm track region more tracks are associated with both high and low O3 so it is expected the number of years with more tracks associated with high O3 or with low O3 would be less and therefore have less significant differences. This provided the motivation to look at the case study cyclones.

We have modified the text to read (Page 13, line 7-10):

"The number of these years having more tracks in the North, Center, and South regions associated with high O3 is almost equal to the number of years which had more tracks associated with low O3. Very few of the years have a significant  $\chi^2$  difference, possibly due to the percent of tracks associated with both high and low O3 increases (up to 31 % of tracks) the further away from the main NA storm track (Table 2)."

Page 14, Figure 3 legend: Always mention latitude first and longitude. Check this through the paper.

**Authors' comments:** The order of the coordinates has been corrected in the figure captions for Figs. 3, 4, 8, 9, 12, and 13 as well as in the text in Sect. 4.2.2.

Page 15, Figure 4: It is very hard to recognize Ireland in the maps (especially in b and c).

**Authors' comments:** In order to improve the readability of Fig. 4, the spacing between wind bars has been increased, the reference arrow in Fig. 4d has been increased from 10 to 20 m s<sup>-1</sup>,

and the ascent contour interval has increased from 10 to 15 hPa h<sup>-1</sup>. By reducing the amount of information, the country borders are now more visible.

Page 16, line 34: Not common to mention Fig. 6c before Fig. 6a.

**Authors' comments:** To be consistent with the other figures, the 500 hPa (Fig. 6a) is above the 1000 hPa (Fig. 6c), however in the manuscript it is more logical to describe the surface front features prior to the upper-level features in Fig. 6. We have added the following sentence to the start of the paragraph, prior to discussing Fig. 6c as the cold frontal boundary is a feature throughout all four panels in Fig. 6 (Page 17, Lines 26-27):

*“The main feature at 4 March 2007 00UTC in both the meteorological fields and O3 distribution is the cold frontal boundary which separates the WCB and DI airstreams (Fig. 6). The strong cold frontal boundary features as the sharp gradient in the 1000 hPa O3 distribution and the curve in the isobars in the southwest quadrant of Fig. 6c (similar to Fig. 3). The front is identified .....Fig. 6b). ”*

Page 18, Figure 6: the letters “a)” and so on are too big in comparison to the numbers along the axes. Reduce this for all figures throughout the paper.

**Authors' comments:** The font size of the panel lettering has been reduced in all figures (including the figures in the supplemental material).

Page 18, Figure 6: In a) the white lines are very hard to see.

**Authors' comments:** The thickness of the white lines in Fig. 6a has been increased (Page 19). We have increased the thickness of the white lines in Figs. 7a, 10a, and 11a.

Page 19, line 27-29: This is a good example of the sentences that should be improved in this section (as mentioned in “Specific comments”).

**Authors' comments:** This sentence has been shortened to focus on the main point of the sentence, that the MERRA-2 O3 shows elevated O3 within the dry airstream in same location as seen in the MACC reanalysis O3 (Page 21, Lines 7-9) and now reads:

*“In the troposphere, MERRA-2 O3 is expected to be biased low (Sect. 2.2.3), and while the MERRA-2 troposphere O3 mixing ratios are lower in the N1 cyclone compared to the MACC reanalysis, there is still relatively higher O3 within the DI airstream reaching the surface (Figs. S1b,d and S3b-d) as seen in Figs. 6 and 7.”*

Page 21, line 22: White contours are hard to recognize.

**Authors' comments:** Changing the thickness of the contours or changing the style of the contours did not improve the readability of Fig. 9. Instead, we decided to add an inset of the 15° by 15° region over Ireland and the UK, without the wind arrows, in order to improve the readability of the white contours over Mace Head (Page 23).

Page 21-26: In this section you present many figures, however very little text to the figures. Weight figures and text better.

**Authors' comments:** Changes made to Section 4.2.2 have been addressed in the Specific Comments above. Specifically, the number of panels in Fig. 8 has been reduced to two, having removed the panels that are not necessary for the text. The text has also been modified to focus on the differences in the S1 cyclone compared to the N1 cyclone.

Page 31, line 15-16: This sentence is somehow stand-alone. What is the message?

**Authors' comments:** The message is that the presence of high O3 in the mid-troposphere in the composite cyclone of Knowland et al. (2015) is related to a parent low or downstream cyclone. We have modified the text to make a clearer connection between the composite analysis of Knowland et al. (2015) and the case study cyclones. The final sentence has been modified to read (Page 31, Line 35 – Page 32, Line 5):

*“In addition, the case studies depict elevated O3 from either a parent low pressure system (e.g., the N1 cyclone case study) or an upstream decaying cyclone (e.g., the S1 and N2 cyclones) can become entrained within the cyclone; this is a strong feature in mid-latitude cyclones as there is elevated O3 (up to 5 ppbv greater than the background composite) similarly to the north of the NA composite cyclone center, not within the main DJ airstream and separated from the O3-poor WCB, that wraps cyclonically around the composite cyclone (Knowland et al., 2015).”*

Page 31, line 18: “We have shown passing cyclones have” -> “We have shown that passing cyclones have”

**Authors' comments:** Text changed as per suggestion.

Page 31, line 26: For a better structure after “Specifically:” Add a “-“ to all small paragraphs that follow and use an insertion slide-in.

**Authors' comments:** Text changed as per suggestion.

Supplement: Figs. S2c, S4c, and S6c are not very useful, since they are too dark.

**Authors' comments:** The STFR color bar has been changed to use blue color scale, with low STFR as light blue and increasing to a dark blue, but never as dark as the original blues in the Figs. S2, S4, and S6.

# The influence of mid-latitude cyclones on European background surface ozone

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**Abstract.** The relationship between springtime mid-latitude cyclones and background ozone ( $O_3$ ) is explored using a combination of observational and reanalysis data sets. First, the relationship between surface  $O_3$  observations at two rural monitoring sites on the west coast of Europe – Mace Head, Ireland and Monte Velho, Portugal – and cyclone track frequency in the surrounding regions is examined. Second, detailed case study examination of four individual mid-latitude cyclones and the influence of the associated frontal passage on surface  $O_3$  is performed. Cyclone tracks have a greater influence on the  $O_3$  measurements at the more northern coastal European station, Mace Head, located within the main North Atlantic (NA) storm track. In particular, when cyclones track north of  $53^\circ$  N, there is a significant relationship with high levels of surface  $O_3$  (> 75th percentile). The further away a cyclone is from the NA storm track, the more likely it will be associated with both high and low (< 25th percentile) levels of  $O_3$  at the observation site during the cyclone’s life cycle. The results of the four case studies demonstrate a) the importance of the passage of a cyclone’s cold front in relation to surface  $O_3$  measurements, b) the ability of mid-latitude cyclones to bring down high levels of  $O_3$  from the stratosphere and c) that accompanying surface high pressure systems and their associated transport pathways play an important role in the temporal variability of surface  $O_3$ . The main source of high  $O_3$  to these two sites [in springtime](#) is from the stratosphere, either from direct injection into the cyclone or associated with aged airstreams from decaying downstream cyclones that can become entrained and descend toward the surface within new cyclones over the NA region.

## 1 Introduction

Tropospheric ozone ( $O_3$ ), which is harmful to human health and vegetation (Scherrer et al., 2006; Krzyzanowski and Cohen, 2008), has both natural and man-made sources. In the free troposphere,  $O_3$  can be transported over large distances as it has a lifetime on the order of a few weeks (Akimoto, 2003; Monks et al., 2009). Rural monitoring ground stations, which are not influenced by local emission sources, are used to monitor the “clean” hemispheric baseline, or background, levels of pollutants such as  $O_3$  (e.g., Parrish et al., 2012; Torseth et al., 2012; Wilson et al., 2012). The measurements from these remote stations in Europe previously have been used to study the concentrations of  $O_3$  in polluted air arriving from different source regions

separate from the background O<sub>3</sub> levels (e.g., Li et al., 2002; Wilson et al., 2012). A large number of observations (about 70 %) taken at the Mace Head station on the west coast of Ireland have been found to be associated with maritime air from over the North Atlantic (NA) and the remainder are associated with continental European air (Jennings et al., 1991; Simmonds et al., 1997).

5 The meteorological factors – wind speed and direction, humidity and temperature – that impact the variability of pollutant concentrations are determined by the large-scale nearby atmospheric pressure centers. For Western Europe, this is mainly the location of two climatological features: 1) the semi-permanent Icelandic Low ~~– a climatological feature between 60°–65° N,~~ due in part to the NA storm track (the region known for frequent, strong cyclones) ~~– and~~ and 2) the semi-permanent Azores High ~~– a climatological feature~~ over the Atlantic Ocean near 40° N. Studies of airflow relative to cyclones' frontal zones have led  
10 to three-dimensional (3D) conceptual models of cyclones with generally three main airstreams: a warm conveyor belt (WCB; Harrold, 1973), a cold conveyor belt (CCB; Carlson, 1980) and the dry intrusion (DI; Browning, 1997). The horizontal and vertical transport of air within these airstreams can play an important role in the redistribution not only of moisture, heat, and momentum, but also chemical properties of the air from different source regions (Bethan et al., 1998). The frequent cyclones associated with the Icelandic Low can entrain polluted air from different source regions, primarily, Europe and North America  
15 (Merrill, 1994; Parrish et al., 2012). During stagnant conditions, there is pollution build-up which can be dispersed by passing cyclones (Mickley et al., 2004; Hegarty et al., 2007; Leibensperger et al., 2008; Barnes and Fiore, 2013). Within the cyclones, the polluted air at the surface is lofted up into the free troposphere by the WCB (e.g., Bethan et al., 1998; Cooper et al., 2002b; Hannan et al., 2003; Trickl et al., 2003). Once in the free troposphere, pollutants can be transported rapidly in the stronger westerly winds and eventually become mixed with the background composition (e.g., Trickl et al., 2003; Cooper et al., 2004b).  
20 The pollutant-enriched air can descend in downwind systems as part of the DI airstream behind the cold front of a mid-latitude cyclone (hereafter, referred to as cyclone) or as part of a nearby anticyclone (Danielsen, 1980; Bader et al., 1995; Trickl et al., 2003).

In addition to the transport of anthropogenic O<sub>3</sub>, cyclones enable the vertical transport of O<sub>3</sub> from the lower stratosphere into the troposphere (stratosphere-to-troposphere transport (STT)) (e.g., Danielsen, 1968, 1980; Sprenger and Wernli, 2003;  
25 Škerlak et al., 2014). Several studies have shown that STT events which reach the surface can lead to higher surface O<sub>3</sub>, of the order of 20-50 ppbv higher than the background levels for the hourly mean, leading to peak surface O<sub>3</sub> concentrations of up to 100 ppbv (e.g., Derwent et al., 1978; Davies and Schuepbach, 1994; Lin et al., 2012a). This can result in surface O<sub>3</sub> exceeding air quality standards, especially at high elevations such as in the western USA (e.g., Langford et al., 2009, 2015; Lefohn et al., 2012; Lin et al., 2012a, 2014). In particular, Lin et al. (2012a) found that in spring 2010 up to 60 % of total modelled  
30 surface O<sub>3</sub> in the western USA during air quality exceedances ~~in spring 2010~~ could be attributed to stratospheric intrusions of O<sub>3</sub>, whilst at Mace Head, using a tagged tracer approach, Derwent et al. (2004) diagnosed stratospheric O<sub>3</sub> to contribute to at least 25 % of the observed annual mean O<sub>3</sub>. However, the direct connection between STT and peaks in ground-level O<sub>3</sub> observations are generally infrequent, with only a small fraction of STT trajectories descending below the mid-troposphere ~~–~~  
(Viezee et al., 1983; Derwent et al., 1998; Eisele et al., 1999; Stohl, 2001; Škerlak et al., 2014). Air from the free troposphere is largely limited to daytime entrainment into the lowest layer of the atmosphere as the planetary boundary layer (PBL) height  
35

increases (e.g., Itoh and Narazaki, 2016; Ott et al., 2016); however, the ability for O<sub>3</sub>-rich air to reach the surface depends on a complex array of factors including the diurnal cycle (Itoh and Narazaki, 2016; Langford et al., 2009, 2012; Ott et al., 2016) and the seasonal cycle of the PBL height (Langford et al., 2015, 2017), the presence of convective mixing (Thompson et al., 1994; Eisele et al., 1999; Langford et al., 2017), and the elevation of the monitoring station, which if located within the free  
5 troposphere, especially with the night-time collapse of the PBL, can experience direct STT (Langford et al., 2015, 2017). The influence of the stratospheric air, although weaker by the time the air reaches the surface (Monks, 2000), can last longer in the mid- to lower troposphere if the O<sub>3</sub>-rich air becomes entrained in high pressure systems behind the surface cold front and continues to subside (Danielsen, 1980; Davies and Schuepbach, 1994; Cooper et al., 2004b).

Previous studies of O<sub>3</sub> measurements at these stations have not focused on the specific role of the cyclones on the temporal  
10 variability of O<sub>3</sub> (e.g., Simmonds et al., 1997; Derwent et al., 2004, 2008). The aim of this study is to quantify the influence synoptic-scale extra-tropical cyclones have on the temporal variability of surface O<sub>3</sub> on the west coast of Europe when cyclones are nearby. In particular, we address the following questions:

- Do passing cyclones have a detectable impact on surface O<sub>3</sub> observations?
- What are the key synoptic features associated with cyclones that impact surface O<sub>3</sub> concentrations?

15 To address these questions, the sensitivity of O<sub>3</sub> measurements at two coastal observation sites – one within the main NA storm track region (Mace Head) and the other south of the main NA storm track region (Monte Velho, Portugal) – will be tested in relation to the frequency and passage of cyclones. This will be followed by detailed analysis of the dynamical processes within four individual cyclones and their possible impact on tropospheric O<sub>3</sub> distributions. The focus of this study will be on surface O<sub>3</sub> in the spring (MAM) since this is the principal season for intercontinental transport of O<sub>3</sub> across the NA (Monks,  
20 2000; Stohl et al., 2002; Dentener et al., 2010). Furthermore, STT events exhibit a springtime maximum due to the build-up of O<sub>3</sub> in the lower stratosphere over the winter and spring (Danielsen and Mohnen, 1977; Holton et al., 1995; Monks, 2000; Pausata et al., 2012). Also in springtime, there is a peak in the seasonal O<sub>3</sub> cycle at marine, background stations including Mace Head. ~~Furthermore, STT events exhibit a springtime maximum due to the build-up of~~ (Simmonds et al., 1997; Wilson  
25 at such stations there is often a minimum in O<sub>3</sub> in summer as a result of enhanced O<sub>3</sub> loss by increased water vapor within the stable marine boundary layer (MBL) (Ayers et al., 1992; Oltmans and Levy, 1994), in contrast to urban environments with the peak in O<sub>3</sub> in the lower stratosphere over the winter ~~summer associated with photochemical production~~. Parrish et al. (2016) and ~~spring~~-Derwent et al. (2016) demonstrate that the seasonal cycle of O<sub>3</sub> at MBL stations, including Mace Head, can be reasonably represented by two harmonics of the seasonal cycle with the first explaining most of the seasonal variation, capturing the summertime O<sub>3</sub> loss (and therefore a late winter/early spring maxima) and the spring  
30 maxima in O<sub>3</sub> within the free troposphere which is entrained into the MBL.

The article continues with a description of the data used, including the O<sub>3</sub> observations and the reanalysis variables (Sect. 2). The methodology is presented in Sect. 3. The relationship between cyclones and O<sub>3</sub> observations is quantified in Sect. 4. Section 4 also provides a detailed analysis of the airstreams and O<sub>3</sub> distributions within the cyclone case studies. Discussion of

how cyclones may influence the temporal variability of the surface O<sub>3</sub> observations is given in Sect. 5, with final conclusions in Sect. 6.

## 2 Data

Three different types of data are used in this study. The ground-based observation data is first presented followed by descriptions of the reanalyses and a modelled stratospheric tracer.

### 2.1 Surface O<sub>3</sub> data

Mace Head (MH: 53.3° N, 9.9° W; location indicated by the blue dot on Fig. 1) is located on the west coast of Ireland. Surface O<sub>3</sub> measurements, supported by the European Monitoring and Evaluation Programme (EMEP; www.emep.int), are hourly averages of O<sub>3</sub> taken every 10 seconds [using a commercial UV spectrometer \(Model 8810, Monitor Labs, USA\)](#) (Derwent et al., 1998; Simmonds et al., 2004) for the period 1 April 1988 – 31 December 2012 (<http://actris.nilu.no>, last retrieved 6 February 2015).

Monte Velho (MV: 38.08° N, 8.8° W; location indicated by the [pink-orange](#) dot on Fig. 1) is a rural observation site on the west coast of Portugal, also supported by EMEP, which began hourly surface O<sub>3</sub> observations on 1 January 1988 and continued for 21 years, ending on 31 December 2009 (<http://actris.nilu.no>, last retrieved 6 February 2015). [Observations were made using Dasibi analyzer instruments: the original instrument was replaced in 1999 which again failed in 2010 and was not replaced until 2014 \(Lourdes Bugalho, pers. comm.\)](#). The total number of years in this study for Monte Velho is 19 years, from 1989–2009, exclusive of 1999 and 2005 when data are missing.

### 2.2 Modelled data

Numerous previous studies of long-range transport of trace gases have used chemistry-transport models (CTMs) nudged by reanalysis meteorological fields and are validated against observations. Knowland et al. (2015) was the first study to use the Monitoring Atmospheric Composition and Climate (MACC) project's reanalysis data set (Inness et al., 2013), a combined 3D meteorological and composition data set, to explore the relationship between cyclones and air pollution transport of O<sub>3</sub> and carbon monoxide (CO). ~~It~~ [Through a composite cyclone analysis, it](#) was clearly shown that ~~eyelones~~ [intense cyclones over the North Pacific \(NP\) and NA regions](#) redistribute O<sub>3</sub> and CO horizontally and vertically within the WCB and DI airstreams (Knowland et al., 2015). Therefore, this reanalysis [data set](#) can be used to both establish the location and intensity of the cyclones and link the detailed meteorological fields with tropospheric and lower stratospheric composition.

In this study, four different model data sets are used which includes three reanalyses – the European Centre for Medium-Range Weather Forecasts' (ECMWF) ERA-Interim reanalysis (Dee et al., 2011), the MACC reanalysis, and NASA's Modern-Era Retrospective Analysis for Research and Applications Version-2 (MERRA-2) reanalysis (Bosilovich et al., 2015) – and a stratospheric tracer data set (Ott et al., 2016). The ERA-Interim cyclone tracks are used here to establish the long-term relationship between cyclones and O<sub>3</sub> observations. Since the MACC reanalysis uses a similar atmospheric model to ERA-



Interim, MACC is used to explore the mechanisms within the case study cyclones that can influence surface O<sub>3</sub> concentrations at Mace Head and Monte Velho. The MERRA-2 reanalysis also provides 3D distributions of O<sub>3</sub>, although less ideal for analysis of surface O<sub>3</sub> concentrations since MERRA-2 O<sub>3</sub> ~~is biased low outside the stratosphere as it~~ does not have a detailed chemistry scheme or emission sources for the troposphere (Wargan et al., 2015, 2017). The MERRA-2 reanalysis, which has the potential to identify more features within the cyclones as the resolution is higher than the MACC reanalysis, is used in conjunction with the MACC reanalysis to provide a measure of uncertainty to the case study analysis. The stratospheric tracer, which uses a similar atmospheric model to the MERRA-2 reanalysis, provides additional information on air mass origin. While models and reanalyses with coarse horizontal resolution (> 100 km) are able to identify stratospheric intrusions (Roelofs et al., 2003; Lin et al., 2015; Ott et al., 2016), the fine-scale nature of the O<sub>3</sub> filaments is best identified at higher horizontal resolutions (Büker et al., 2005; Lin et al., 2012a; Ott et al., 2016), such as the MACC and MERRA-2 reanalyses and by the stratospheric tracer. However, even high-resolution reanalyses may struggle to represent the complex structure of stratospheric intrusions (e.g. Trickl et al., 2016).

### 2.2.1 The ERA-Interim reanalysis data set

The ERA-Interim reanalysis data set is available from 1 January 1979 to three months prior to present-day at 6-hourly resolution (Dee et al., 2011). It is produced with the ECMWF's Integrated Forecast System (IFS; cycle 31r2) model of the ECMWF, (a full history of changes made to the ECMWF IFS, as indicated by the cycle number, is available at <https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model>), with a sequential four-dimensional variational data assimilation (4D-Var) scheme using 12-hourly analysis cycles (Dee et al., 2011). ERA-Interim has a spectral spatial resolution of TL255 (nominally 0.7° longitude and latitude) with 60 vertical levels from the surface to 0.1 hPa.

This study uses the ERA-Interim 6-hourly 850 hPa relative vorticity ( $\zeta_{850}$ ) field for cyclone tracking. It also uses the potential vorticity (PV) field for diagnosing the dynamical tropopause whereby the dynamical tropopause is determined as the 2 PVU (1 PV unit (PVU) =  $10^{-6} \frac{m^2 kg^{-1} s^{-1}}{K m^2 kg^{-1} s^{-1}}$  (Holton et al., 1995)) isosurface.

### 2.2.2 The MACC reanalysis data set

The MACC reanalysis data set, which covers the period 2003–2012, is produced with the ECMWF IFS ~~(cycle 36r1)~~ model two-way coupled to a CTM. The IFS assimilates the same conventional meteorological observations as ERA-Interim as well as satellite observations of three reactive gas species: CO, O<sub>3</sub>, and nitrogen oxides (NO<sub>x</sub>) (Flemming et al., 2009; Inness et al., 2013). Although the IFS cycle (cycle 36r1) is a more recent cycle than used for ERA-Interim, the meteorology in the two reanalyses is similar. The CTM is a modified version (Stein, 2009; Stein et al., 2012) of the Model for OZone And Related chemical Tracers (MOZART-3; Kinnison et al., 2007) with the chemical reactions of 115 species in the troposphere and stratosphere (Stein, 2009; Stein et al., 2012; Inness et al., 2013). The two models are run in parallel and, every hour, the IFS provides the CTM with the updated mixing ratios after the horizontal and vertical advection of the assimilated chemical species (Flemming et al., 2009; Stein, 2009; Stein et al., 2012). In turn the CTM provides the IFS system with updated chemical



tendencies which are used to constrain the assimilated species. The MACC model-reanalysis has the same spatial and-temporal (TL255) and temporal (6-hourly) resolution as the ERA-Interim reanalysis.

In the model evaluation, Inness et al. (2013) compared EMEP O<sub>3</sub> observations from all available EMEP monitoring stations at low altitudes (< 600 m) to the MACC reanalysis O<sub>3</sub> and found that the O<sub>3</sub> was underestimated in the reanalysis during  
5 spring over central and northern Europe (based on 27 stations within 40°–50° N and 72 stations within 50°–70° N, respectively, absolute monthly biases in spring ranged between about -2 to -9 ppbv for both regions) and agreed well (small overestimation)  
for southern Europe (based on 5 stations within 30°–40° N, absolute monthly biases in spring ranged between about 1 to 2 ppbv). The reason(s) for the biases in the seasonal O<sub>3</sub> is not known although Inness et al. (2013) hypothesize that the biases  
10 in the MACC surface O<sub>3</sub> are related to the diurnal cycle possibly due to 1) there is no diurnal cycle in the NO<sub>x</sub> emissions used in  
the CTM resulting in negative O<sub>3</sub> biases during the day-time and positive O<sub>3</sub> biases during the night-time, 2) misrepresentation  
of vertical mixing between the boundary layer and free troposphere, and/or 3) less observations are available (and therefore not  
assimilated) at night. For full details on the input emission data sets and model validation see Inness et al. (2013) and references  
therein.

In order to evaluate the horizontal and vertical distributions of O<sub>3</sub> within cyclones, several parameters from the MACC  
15 reanalysis are used following Knowland et al. (2015). These variables include  $\zeta_{850}$ , mean sea level pressure (MSLP), zonal  
and meridional wind components ( $u$  and  $v$ , respectively), vertical velocities ( $\omega$ ), temperature ( $T$ ), specific humidity ( $q$ ) and  
O<sub>3</sub> mixing ratios. Variables required on pressure levels were extracted on twelve pressure levels from 1000 to 200 hPa. The  
equivalent potential temperature,  $\theta_e$ , is obtained using  $T$  and  $q$ . In this study,  $\omega$  in pressure coordinates (hPa h<sup>-1</sup>) is multiplied  
by -1 in order to have the sign be positive to indicate ascent and negative to indicate descent. Since the MACC reanalysis  
20 did not archive PV data, instead the ERA-Interim PV data is used to determine the dynamical tropopause as the MACC and  
ERA-Interim reanalyses are similar in terms of the IFS and data assimilation.

### 2.2.3 The MERRA-2 reanalysis data set

NASA's MERRA-2 reanalysis is the most recent reanalysis product from NASA's Global Modeling and Assimilation Office  
(Bosilovich et al., 2015). It is a high-resolution data set (0.5° latitude x 0.625° longitude, 72 vertical levels from surface to  
25 0.01 hPa; Bosilovich et al. (2015, 2016); Gelaro et al. (2017)) for the period from 1 January 1980 to within a couple weeks  
of real time. The MERRA-2 reanalysis is a product of the Goddard Earth Observing Systems Model, Version 5 (GEOS-5)  
data assimilation system (DAS) version 5.12.4 atmospheric general circulation model (AGCM), with 3D-Var assimilation with  
the Gridpoint Statistical Interpolation scheme (GSI; Wu et al. (2002); Derber et al. (2003); Purser et al. (2003a, b)) using  
6-hourly analysis cycles. The GEOS-5 model includes a simplified ozone chemistry scheme for both the stratosphere and the  
30 troposphere based on monthly-dependent ozone production and loss rates derived from a two-dimensional chemistry model  
(Stajner et al., 2008; Bosilovich et al., 2015; Wargan et al., 2015). For the period since October 2004, the high-resolution  
stratospheric O<sub>3</sub> profiles from the Microwave Limb Sounder (MLS; Waters et al. (2006)) and total column ozone from the  
Ozone Mapping Instrument (OMI, Levelt et al. (2006)), both aboard NASA's Aura satellite, are assimilated (Bosilovich et al.,  
2015; Wargan et al., 2015; McCarty et al., 2016). Since the assimilated O<sub>3</sub> observations are mainly stratospheric, it is expected

that the MERRA-2 analysis O<sub>3</sub> will realistically represent the direct influence of stratospheric O<sub>3</sub> into the troposphere, such as STT events, however O<sub>3</sub> concentrations will be biased low elsewhere in the troposphere (Ott et al., 2016).

The MERRA-2 variables used in this study include 6-hourly SLP,  $u$ ,  $v$ ,  $\omega$ , Ertel's PV (EPV), T, q, and O<sub>3</sub> mixing ratios (GMAO, 2015a, b).

## 5 2.2.4 GEOS-5 stratospheric tracer

To provide more information on air mass origins, a simple stratospheric tracer has also been implemented in GEOS-5 (~~STFR~~[stratospheric fraction \(STFR\)](#); Ott et al. (2016)). At every model time step (7.5 minutes), the tracer is set to 1 above the tropopause (defined as the higher height of the thermal or dynamical tropopause) and reset to 0 at the surface. Values of this tracer quantify the fraction of air that has recently been in the stratosphere. For this study, STFR was computed by running the GEOS-5 AGCM constrained by the MERRA-2 meteorological reanalysis to ensure physical consistency with the ozone and meteorological reanalysis fields.

## 3 Methods of analysis of high and low O<sub>3</sub> observations and their relationship to cyclone tracks

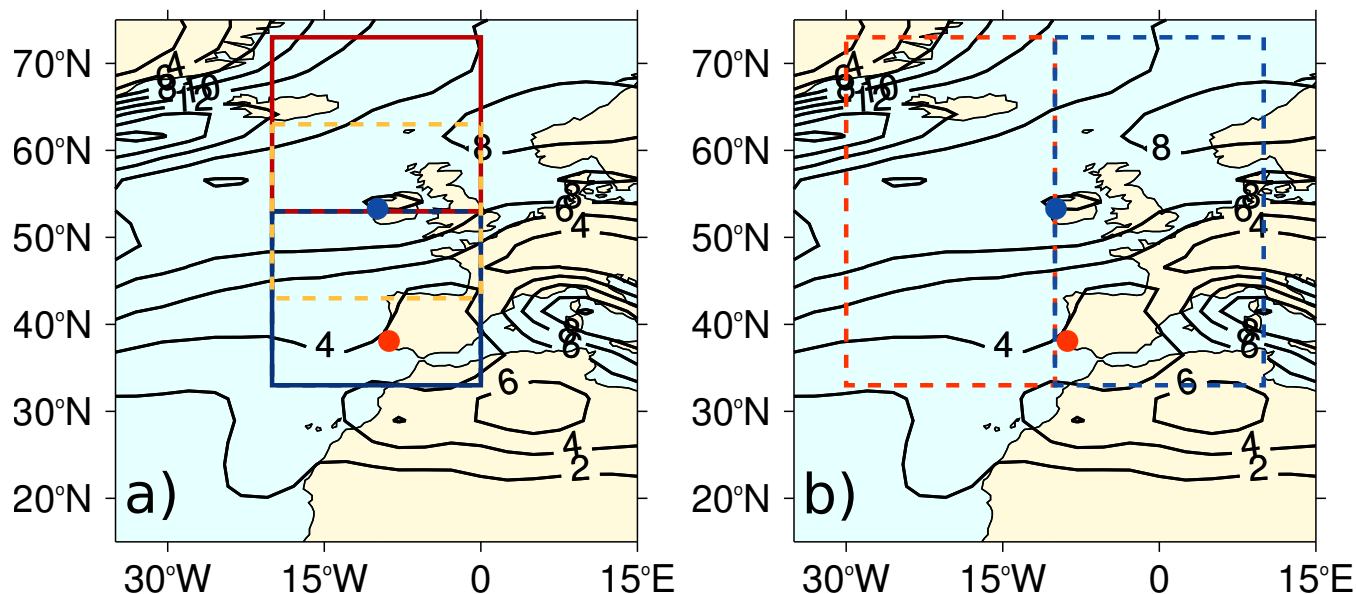
### 3.1 Cyclone identification

The objective feature tracking algorithm, TRACK (Hodges, 1994, 1995, 1999), can be used to track synoptic-scale features such as minima in MSLP or maxima in relative vorticity (e.g., Hoskins and Hodges, 2002; Bengtsson et al., 2006, 2009; Catto et al., 2010; Knowland et al., 2015). Here, TRACK is used to identify cyclones as maxima in  $\zeta_{850}$  in the ERA-Interim and MACC reanalyses. To be consistent with previous studies using TRACK, a spectral analysis, based on a spherical harmonic expansion, is performed which allows the large-scale background field to be removed (planetary-scale waves with total wave number,  $n$ ,  $\leq 5$ ). At the TL255 resolution of the ERA-Interim and MACC reanalyses, vorticity contains many small-scale features such as frontal regions, shear zones, and mesoscale features; therefore, to focus on the synoptic scales, the resolution is reduced to T42 using triangular truncation and spectral tapering of the coefficients (Hoskins and Hodges, 2002). The tracking is performed on the unit sphere and the tracks are constructed by minimizing a track smoothness cost function subject to adaptive constraints (Hodges, 1995, 1999). On completion of the tracking process, the stationary cyclones (travel  $< 1000$  km) ~~or during the cyclone's life cycle~~ and short-lived cyclones (~~last cyclone's life cycle lasts~~  $< 2$  days) are removed to focus on those cyclones which are likely to be mobile (Hodges, 1999) and hence contribute to O<sub>3</sub> transport.

#### 3.1.1 O<sub>3</sub> observations associated with cyclone tracks

In order to relate the EMEP hourly O<sub>3</sub> observations to the cyclone frequencies, the hourly O<sub>3</sub> observations were averaged together every six hours, with the first of the six hours corresponding to the reanalysis time step. The 6-hourly averaged O<sub>3</sub> data are then matched to the cyclone tracks based on the reanalysis time step. The cyclone tracks, with the accompanying O<sub>3</sub> data, are then sorted by different regions relative to the observation site. A cyclone is considered as passing near Mace Head if

one 6-hourly cyclone track point occurs within a 20° latitude by 20° longitude region, approximately  $3 \times 10^6$  km<sup>2</sup>, centered on Mace Head (hereafter referred to as the Center region, 43°–63° N, 20° W–0°, yellow box, Fig. 1a). The size of the region was defined in order to capture the large spatial coverage of each cyclone, and in particular to capture the trailing cold fronts which can be on the order of 100 to 1000 km (Shapiro and Keyser, 1990). Four additional regions (North, South, East, and West) in the vicinity of Mace Head were defined to test the influence of the location of the cyclones and their associated fronts in relation to surface O<sub>3</sub> at Mace Head (see Fig. 1 caption). The equivalent five regions around Monte Velho (orange dot, Fig. 1) are defined such that the Center region is the 20° by 20° region centered around Monte Velho (28°–48° N, 19° W–1° E), with the other regions defined in the same fashion as around Mace Head (not shown). The larger East and West domains in Fig. 1b are defined to examine the influence of the cyclones potentially interacting with relatively clean maritime air to the west of sites and relatively polluted continental air to the east of sites.



**Figure 1.** Maps showing the five regions where cyclones pass near Mace Head (blue dot) which are associated with O<sub>3</sub> measurements from Mace Head: (a) North region 53°–73° N, 20° W–0° (red box), Center: 43°–63° N, 20° W–0° (yellow box) and South: 33°–53° N, 20° W–0° (blue box) and (b) West: 33°–73° N, 30°–10° W (orange box) and East: 33°–73° N, 10° W–10° E (blue box). In addition, track density distribution for cyclones from ERA-Interim for MAM 1979–2011 (black contour lines; interval of 2 cyclones per month per 5° spherical cap) and Monte Velho (orange dot) are indicated.

For each cyclone track point which occurred within the specified region, the accompanying 6-hourly averaged O<sub>3</sub> observation was classified as high, average or low. To perform this analysis, the 6-hourly averaged O<sub>3</sub> data are first sorted by magnitude, and the percentile (pc) values were calculated in order to identify high O<sub>3</sub> (> 75<sup>th</sup> pc values) and low O<sub>3</sub> (< 25<sup>th</sup> pc values) for each spring at the two stations. The extreme high and extreme low O<sub>3</sub> values (95<sup>th</sup> and 5<sup>th</sup> pc, respectively), to represent the peak and baseline concentration levels, respectively, based on Wilson et al. (2012), are included in the Supplemental material.

The percentile values were calculated for each spring separately to avoid capturing the increasing trend in background O<sub>3</sub> over the observation period. If the accompanying 6-hourly averaged O<sub>3</sub> observation was classified as either high or low O<sub>3</sub> at Mace Head then the entire cyclone track is classified as associated with high or low O<sub>3</sub>, respectively. However, with this methodology, it is noted that a single cyclone-track can be associated with both O<sub>3</sub> criteria.

- 5 To test if there is a significant difference in the levels of O<sub>3</sub> observed at Mace Head or Monte Velho associated with the passing of a cyclone, the  $\chi^2$  contingency test was used (Press et al., 1992). By calculating the  $\chi^2$  value for each season over the period of available observations, the  $\chi^2$  contingency test shows the number of years where there is a significant relationship between the high and low O<sub>3</sub> observations at the surface and the number of cyclone tracks in the area.

### 3.1.2 Case study cyclone identification

- 10 To investigate the temporal variability of O<sub>3</sub> at the surface with the passing of the cyclones and their associated fronts, several individual cyclones were identified in the MACC reanalysis with the specific objective of determining how high O<sub>3</sub> is associated with cyclone passage and dynamics. Over the NA region for the period 2003–2012, there is an exact match of about 90 % of the cyclone tracks between the MACC reanalysis and the ERA-Interim reanalysis (matching criteria similar to Hodges et al. (2011) of a minimum mean separation distance of 5° (geodesic) and at least 10 % of the track points overlap in time),
- 15 with discrepancies generally occurring for weaker cyclones (Knowland, 2016). This is expected since the MACC reanalysis and the ERA-Interim reanalysis use similar systems in terms of data assimilation and IFS model, and assimilate the same meteorological observations.

The following criteria were used to select cyclones for the case studies:

- 20 – Cyclones passing through the North and South regions of the two sites associated with high 6-hourly averaged O<sub>3</sub> (> 75<sup>th</sup> pc) were identified.
- Of all the cyclones identified, the strongest cyclones (where maximum  $\zeta_{850} > 80^{th}$  pc of springtime NA  $\zeta_{850}$  ( $8.0 \times 10^{-5} \text{ s}^{-1}$ ) within the region) were selected. This ensures that the cyclones will be within the top 20 % of the cyclones in the NA and that the cyclone is an exact match identified in both the ERA-Interim and the MACC reanalysis data sets (not shown). Moreover, the airstreams within strong cyclones will be more evident than in the weaker cyclones (Catto et al., 2010).

- 25 The strongest storms then have to satisfy the following additional criteria:

- The cyclones must have two or more 6-hourly time steps associated with high O<sub>3</sub>. This selects the cyclones that are associated with elevated levels of O<sub>3</sub> at the monitoring station which can be related to averaging periods typically used for policy metrics such as the daily maximum 8-hour average O<sub>3</sub>.
- 30 – The difference between the high 6-hourly averaged O<sub>3</sub> observations and the MACC O<sub>3</sub> at 1000 hPa within the grid box of the observation site is  $\leq 20$  %.

If the additional criteria are not satisfied for the strongest cyclone, the criteria are then examined for the next strongest storm and so on until a cyclone is found which satisfies the criteria.

Number of cyclones (by strength) associated with high O <sub>3</sub> (O <sub>3</sub> > 75 <sup>th</sup> pc)					
	All cyclones	Strong cyclones	Moderate cyclones	Total tracks	Percent of all cyclones associated with high O <sub>3</sub>
<b>Mace Head</b>					
North	171	20 ( <b>N1</b> )	78	319	54 %
South	121	6 ( <b>S1</b> )	32	253	48 %
<b>Monte Velho</b>					
North	95	3 ( <b>N2</b> )	28	213	45 %
South	69	0	4 ( <b>S2</b> )	117	59 %

**Table 1.** The number of cyclones by strength (where strong cyclones and moderate cyclones are a subset of all cyclones) from the MACC reanalysis associated with high 6-hourly averaged O<sub>3</sub> observations at Mace Head for the period 2003–2012 and at Monte Velho for the period 2003–2009 (exclusive of 2005) using the 6-hourly averaged O<sub>3</sub> pc values. The case study cyclones are included in the respective category.

From the total MACC reanalysis cyclone tracks in the North and South regions, there were 171 and 121 cyclones in each region, respectively, that satisfied the requirement of high O<sub>3</sub> at Mace Head (Table 1). Of the 171 cyclones associated with high O<sub>3</sub> at Mace Head while in the North region, 20 of the cyclones are classified as strong (Table 1). The strongest of the 20 cyclones in the North region is selected for further study and hereafter referred to as the N1 cyclone (Table 1; see Fig. 2a). The N1 cyclone is one of the 58 intense cyclones used in the NA composite analysis of Knowland et al. (2015). In the South region, there are fewer strong cyclones associated with high O<sub>3</sub> at Mace Head (6 of the 121 cyclones, Table 1). The strongest cyclone in the South region will be referred to as the S1 cyclone (Table 1; see Fig. 2a). The N1 and S1 cyclones, with 4 and 5 high O<sub>3</sub> time steps whilst in the region, respectively, both satisfied the two additional criteria.

The same procedure was performed to select the case study cyclones for the regions near Monte Velho (95 and 69 cyclones in the North and South regions, respectively, Table 1). In the region to the north of Monte Velho, only 3 of the 95 cyclones which are associated with high O<sub>3</sub> observed at Monte Velho are classified as strong cyclones (Table 1). The third strongest cyclone was selected for further study as out of the three cyclones it was the only system with persistent high O<sub>3</sub> (2 time steps). This cyclone will be referred to as the N2 cyclone (Table 1; see Fig. 2b).

In the South region, there are no “strong” cyclones associated with high O<sub>3</sub> at Monte Velho (Table 1). Here, the  $\zeta_{850}$  threshold value was reduced to select moderate cyclones, where the maximum  $\zeta_{850} > 50^{th}$  pc of springtime NA  $\zeta_{850}$  ( $5.83 \times 10^{-5} \text{ s}^{-1}$ ), which identified 4 moderate cyclones in the South region associated with high O<sub>3</sub> (Table 1). The strongest of these four cyclones, the S2 cyclone (Table 1; see Fig. 2b), satisfies the additional criteria, in particular, during the S2 life cycle within the South region, there were 7 time steps associated with high O<sub>3</sub> at Monte Velho.

### 3.1.3 The Thermal Front Parameter function

The distribution of O<sub>3</sub> within the airstreams of the case study cyclones is examined using both the geographical coordinate system and the cyclone-centered coordinate system (See Appendix Bengtsson et al., 2007). In the geographical coordinates, archived MSLP analysis charts can be used to identify the fronts. In the cyclone-centered coordinate system, the cyclone fronts

can be identified using an objective frontal location parameter. The thermal front parameter (TFP) function, given by Eq. 1, is the frontal location parameter calculated using  $\theta_e$  on a given pressure surface (Clarke and Renard, 1966). With knowledge of the front locations, the airstreams within the strongest cyclones can then be identified and the vertical transport pathways for  $O_3$  can be examined.

$$TFP \equiv -\nabla|\nabla\theta_e| \cdot \frac{\nabla\theta_e}{|\nabla\theta_e|} \quad (1)$$

## 4 Results

### 4.1 Overview of the relationship between cyclone frequency and surface $O_3$

The observed  $O_3$  levels at the two sites are first examined in relation to the ERA-Interim reanalysis cyclone tracks due to its longer time period to match the  $O_3$  observations. Here, tracks were not filtered for intensity. For springtime during the period of observations from 1988–2010 at Mace Head, the average number of the total cyclone tracks associated with  $O_3 > 75^{th}$  pc (hereafter, high  $O_3$ ),  $O_3 < 25^{th}$  pc (hereafter, low  $O_3$ ) or both high and low  $O_3$  is shown in Table 2 as a percentage of the total tracks in each region. In addition, the number of years during 1988–2010 which have more tracks associated with high  $O_3$  than with low  $O_3$  and the number of years which have more tracks associated with low  $O_3$  than with high  $O_3$  are shown in Table 2, including the number of years where this difference is significant (“SGF”) based on the  $\chi^2$  statistic.

There are higher mean percentages of tracks passing through the North and Center regions associated with high  $O_3$  at Mace Head, 52 and 51 %, respectively, than with low  $O_3$  at Mace Head, 37 and 41 %, respectively (Table 2). The North region has the greatest number of years (18 out of 23 years, Table 2) where the percentage of tracks associated with high  $O_3$  is greater than the percentage of tracks associated with low  $O_3$ , where 15 of these years have a significant  $\chi^2$  difference (North region (SGF), Table 2). The Center region also has a large number of years (17 years) where the percentage of tracks associated with high  $O_3$  is greater than the percentage of tracks associated with low  $O_3$ , although only about a third of those years have a significant difference (Table 2). In the South region, in contrast to the North and Center regions, there are more cyclones passing south of Mace Head (Table 2) which are associated with low  $O_3$  at Mace Head (53 %) than with high  $O_3$  (45 %). In the South region, there are 16 years which have more tracks associated with low  $O_3$  than with high  $O_3$ , of which half of these years have significant differences (Table 2). The transition from significantly more cyclones in the North and Center regions (located within the main storm track region, Fig. 1) associated with high  $O_3$  at Mace Head to significantly more cyclones in the South region (generally south of the main storm track region, Fig. 1) associated with low  $O_3$  at Mace Head illustrates how  $O_3$  levels are sensitive to the passage of cyclones and their frontal zones. The percent of tracks which have both high and low  $O_3$  increased from 12 % in the North region to 20 % in the South region (Table 2).

The region east of Mace Head shows a slightly higher mean percentage of tracks associated with high  $O_3$  compared to low  $O_3$  (48 compared to 45 %, Table 2) with 15 out of 23 years marked by more tracks associated with high  $O_3$  than low  $O_3$  (6 of which were significant, Table 2) and 15 % of the tracks associated with both high and low  $O_3$  observations. The West region

Region	Mean percent of tracks per season associated with $O_3 > 75^{th}$ pc	Number of years with more tracks associated with $O_3 > 75^{th}$ pc ( <i>SGF</i> )	Mean percent of tracks per season associated with $O_3 < 25^{th}$ pc	Number of years with more tracks associated with $O_3 < 25^{th}$ pc ( <i>SGF</i> )	Mean number of tracks per season (MAM)	Percent of tracks associated with both high and low $O_3$
<b>Mace Head</b>						
North	52 %	18 (15)	37 %	5 (0)	32	12 %
Center	51 %	17 (6)	41 %	6 (1)	30	14 %
South	45 %	7 (2)	53 %	16 (8)	25	20 %
West	51 %	11 (0)	52 %	12 (2)	50	20 %
East	48 %	15 (6)	45 %	8 (2)	52	15 %
<b>Monte Velho</b>						
North	51 %	8 (1)	52 %	11 (3)	29	18 %
Center	55 %	11 (1)	50 %	8 (2)	24	23 %
South	61 %	10 (2)	61 %	9 (3)	17	31 %
West	60 %	7 (4)	61 %	12 (2)	39	29 %
East	58 %	12 (4)	56 %	7 (0)	45	26 %

**Table 2.** The mean percent of cyclone tracks associated with high  $O_3 (> 75^{th}$  pc) and low  $O_3 (< 25^{th}$  pc) measured at the surface at **(top)** Mace Head based on each MAM season in the period 1988–2010 and **(bottom)** Monte Velho based on each MAM season in the period 1989–2009 (excluding 1999 and 2005 which had insufficient data). The total number of years in the **(top)** 23-year period (1988–2010) and **(bottom)** 19-year period (1989–2009, excluding 1999 and 2005) which have a greater number of tracks associated with  $O_3 > 75^{th}$  pc and  $O_3 < 25^{th}$  pc are also given. The total number of those years which have a significant  $\chi^2$  difference at  $p < 0.05$  confidence interval are given in the brackets (*SGF*). See Sect. 3.1.1 for definition of regions.

has only a slightly higher mean percentage of tracks associated with low O<sub>3</sub> compared to high O<sub>3</sub> (52 compared to 51 %), with about half of the years (12 out of 23 years) with more tracks associated with low O<sub>3</sub> than high O<sub>3</sub> (Table 2) and 20 % of the tracks associated with both high and low O<sub>3</sub> observations. ~~Though~~ ~~Although~~ the differences are small and ~~that~~ this method did not test which direction the cyclone tracks passed through the region, these results suggest that the cyclones in the East region  
5 are associated with more polluted air than cyclone tracks in the West region.

The relationship between cyclone location and surface O<sub>3</sub> is also examined for the southern site, Monte Velho (Table 2). The Center region has a greater mean percentage of cyclone tracks associated with high O<sub>3</sub> (55 %) compared to those associated with low O<sub>3</sub> (50 %), whilst in the remaining regions the difference between the mean percent of tracks associated with high O<sub>3</sub> and with low O<sub>3</sub> is small (Table 2). ~~In addition, the~~ ~~The~~ number of these years having more tracks in the North, Center, and  
10 South regions associated with high O<sub>3</sub> ~~are is~~ almost equal to the number of years which had more tracks associated with low O<sub>3</sub>, ~~with very~~. ~~Very~~ few years having a significant  $\chi^2$  difference, ~~possibly due to the percent of tracks associated with both high and low O<sub>3</sub> increases (up to 31 % of tracks) the further away from the main NA storm track (Table 2)~~. However, there are a greater number of years (12 out of 19 years) where the cyclone tracks are associated with low O<sub>3</sub> to the west of Monte Velho, and also 12 years where the cyclone tracks are associated with high O<sub>3</sub> when tracks are to the east of Monte Velho (Table 2).  
15 Despite the small differences in the mean percent of tracks (~~and the small number of significant years~~) associated with high and low O<sub>3</sub> at Monte Velho, ~~the percent of tracks associated with both high and low O<sub>3</sub> increases (up to 31 of tracks) the further away from the main NA storm track (Table 2)~~. ~~This~~ ~~this~~ indicates that the cyclone tracks still play a role in affecting surface O<sub>3</sub> measurements at Monte Velho associated with ~~an increase in temporal~~ ~~the temporal variability of O<sub>3</sub> variability~~.

In summary, the O<sub>3</sub> measurements at Mace Head and Monte Velho are influenced by cyclone tracks passing in the vicinity  
20 of the observation sites. The relationship between the O<sub>3</sub> observed and the cyclone tracks varies at the two observation sites. In the following sections, several individual cyclone tracks are selected using the MACC reanalysis and examined using the MACC and MERRA-2 reanalyses and the STFR tracer to identify the possible sources of high O<sub>3</sub> as well as the transport pathways of O<sub>3</sub> within the cyclones which can affect the surface O<sub>3</sub> observations at Mace Head and Monte Velho.

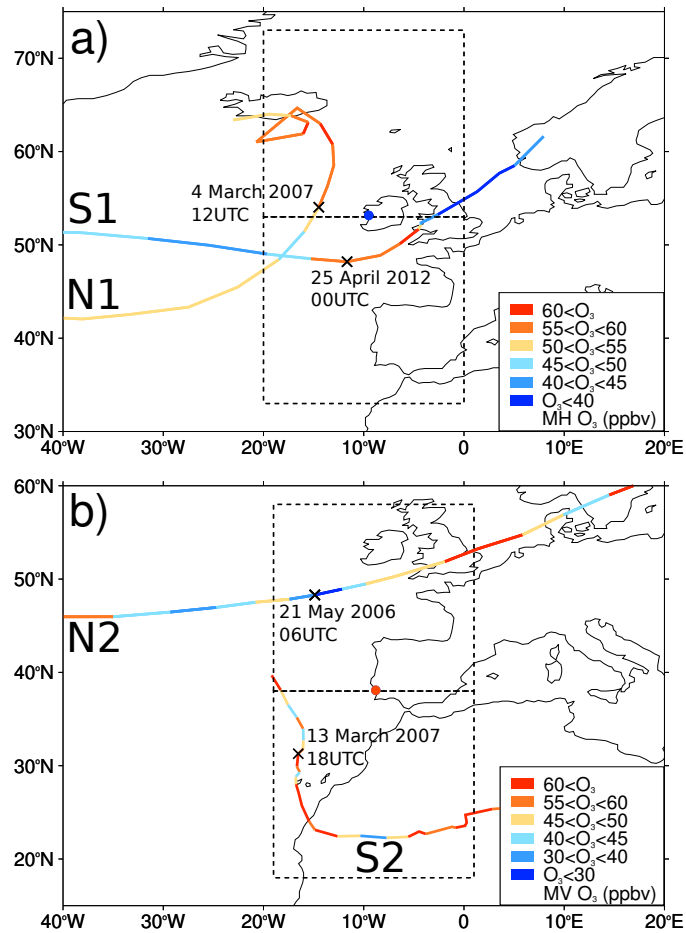
#### 4.2 Cyclone case studies associated with high O<sub>3</sub> at Mace Head

25 The four case study cyclones, selected in Sect. 3.1.2, are shown in Fig. 2 with the tracks colored by the corresponding MACC reanalysis O<sub>3</sub> at Mace Head (N1 and S1 tracks, Fig. 2a) and Monte Velho (N2 and S2 tracks, Fig. 2b).

The N1 cyclone occurred during March 2007. The N1 cyclone track across the NA is further south than the S1 cyclone track before it turns northward, remaining to the west of Mace Head. During the time the N1 cyclone is in the North region (4–7 March 2007), high O<sub>3</sub> (> 55 ppbv) occurs for about a day and a half at Mace Head. The S1 cyclone occurred at the end of  
30 April 2012. As the S1 cyclone passes to the south of Mace Head, there is an increase in O<sub>3</sub> until it leaves the South region.

In May 2006, the N2 cyclone moves through the North region about 10° (approximately 1000 km) to the north of Monte Velho (Fig. 2b), so that Monte Velho was likely impacted by the trailing cold front. The N2 cyclone is a good example of how surface O<sub>3</sub> levels can vary during the life cycle of a passing cyclone. At the time of maximum vorticity, the surface O<sub>3</sub> at Monte Velho is < 30 ppbv, while just before the N2 cyclone leaves the North region the O<sub>3</sub> concentration at Monte Velho has nearly doubled





**Figure 2.** (a) Springtime strong cyclone tracks, N1 and S1, associated with high O<sub>3</sub> (O<sub>3</sub> > 75<sup>th</sup> pc) at Mace Head (blue dot) while in the North and South regions, respectively. Tracks colored by MACC O<sub>3</sub> interpolated to the Mace Head location. (b) Springtime strong cyclone track, N2, in the North region and moderate cyclone track, S2, in the South region which are associated with high O<sub>3</sub> at Monte Velho (orange dot). Tracks colored by MACC O<sub>3</sub> interpolated to the Monte Velho location. The time of maximum vorticity of each track is given at the location along the track, indicated by the cross.

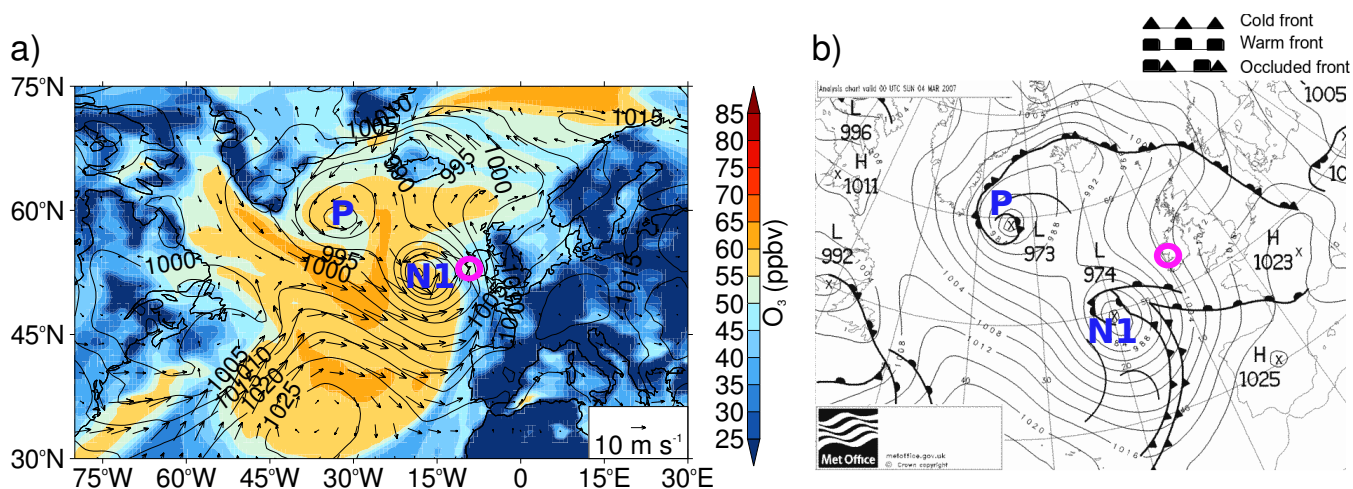
(Fig. 2b). The S2 cyclone also occurred in March 2007, shortly after the N1 cyclone. The S2 cyclone originates about 10° to the west of Monte Velho and slowly tracks to the southeast toward and across North Africa (Fig. 2b). There is high O<sub>3</sub> (> 45 ppbv) at Monte Velho during the majority of [the](#) S2 cyclone's life cycle in the South region.

The following sections will explore in more detail how the dynamics of the case study cyclones influenced the surface O<sub>3</sub> at Mace Head and Monte Velho. The synoptic conditions during different stages in the life cycle of the case study cyclones are described using the MACC reanalysis data set, and where stated, also using the MERRA-2 reanalysis data set and the STFR

tracer, in order to investigate the importance of time and location of the cyclone relative to the high and low O<sub>3</sub> observations at the monitoring stations.

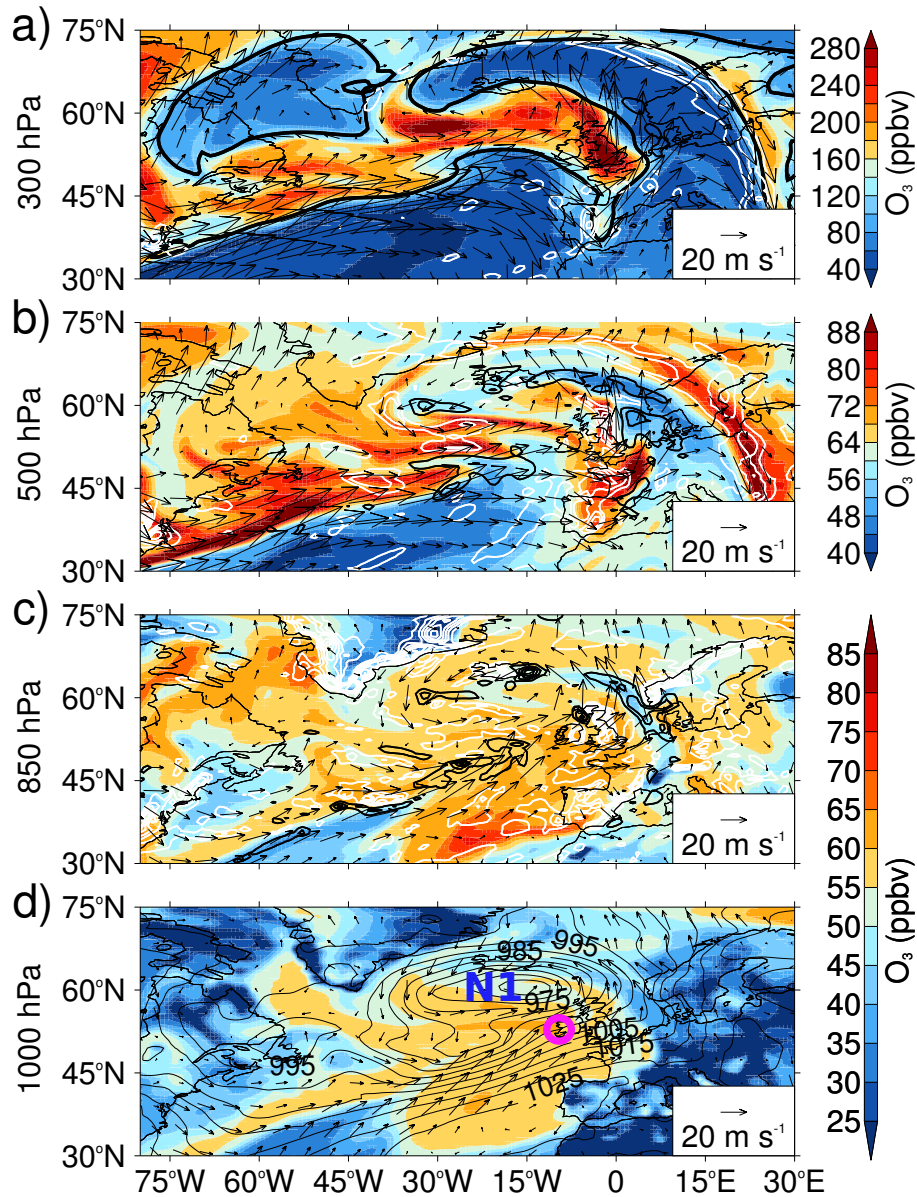
#### 4.2.1 N1 cyclone: synoptic conditions associated with high O<sub>3</sub> at Mace Head

The N1 cyclone is a secondary frontal cyclone which formed over the western NA (42.6° N, 50.6° W) on 2 March 2007  
 5 06 UTC from the parent low located between Greenland and Iceland. Analysis of the N1's life cycle indicates there is high O<sub>3</sub>  
 already in the lower troposphere over the Labrador Sea (up to 70 ppbv at 1000 hPa) which had descended from the stratosphere  
 as part of the DI airstream of the parent low (not shown). This O<sub>3</sub>-rich air appears to be advected toward Mace Head by the  
 N1 cyclone (Figs. 3a and 4). Nearly two days after the N1 cyclone formed, high levels of O<sub>3</sub> (> 55 ppbv, Fig. 3a) at 1000 hPa  
 are then advected southeastward into the NA behind the cold front of the N1 cyclone (see Fig. 3b for location of fronts) and  
 10 northward around the parent low (Fig. 3a). The high O<sub>3</sub> eventually reaches Mace Head on 5 March 2007 at midnight, after the  
 cold front has passed over Mace Head (Fig. 4d), and persists until 6 March 2007 at 12 UTC.



**Figure 3.** (a) 1000 hPa MACC O<sub>3</sub> (color) and horizontal wind vectors (10 m s<sup>-1</sup> reference arrow) and MSLP (solid contours, 5 hPa intervals) on the 4 March 2007 at 00 UTC, 12 hours prior to maximum  $\zeta_{850}$  for N1 cyclone (N1: 52° N, 19° W). Parent low (P: 34.59° W, 59.34° NW) is located between Greenland and Iceland. Mace Head indicated by pink open circle. (b) Analysis chart for 4 March 2007 at 00 UTC from UK Met office (available from archive at <http://www.wetterzentrale.de/topkarten/tkfaxbraar.htm>, retrieved 19 May 2015) shows the complex fronts associated with the N1 cyclone and the parent low. Mace Head (pink circle) is located to the north of the N1 warm front.

At the time of maximum vorticity ( $\zeta_{850} = 11.56 \times 10^{-5} \text{ s}^{-1}$ , 4 March 2007 12 UTC, not shown), the N1 cyclone and its  
 decaying parent low merged at the surface, intensifying the N1 cyclone. Strong westerly winds developed throughout the  
 troposphere across the NA region as a result of the large pressure difference between the low pressure systems in the NA (the  
 15 N1 cyclone and an upstream low over Newfoundland) and the Azores High (Fig. 4d). In addition to the descent (white contour



**Figure 4.** Synoptic conditions and  $O_3$  distribution for the N1 cyclone (**d**;  $1359^\circ$  W,  $5913^\circ$  NW) on 5 March 2007 at 00 UTC, 24 hours after Fig. 3. High  $O_3$  was reported at Mace Head.  $O_3$  (color; note different scales used for different levels) and horizontal winds (note magnitude of  $20 \text{ m s}^{-1}$  reference arrow changes) are shown on four levels: (a) 300 hPa, (b) 500 hPa, (c) 850 hPa, and (d) 1000 hPa. In addition, MSLP (d; solid contours, 5 hPa intervals),  $\omega$  (a, b, and c; black contours for positive values indicating ascent,  $1015 \text{ hPa h}^{-1}$  contour intervals, and white contours for descent,  $-5 \text{ hPa h}^{-1}$  contour intervals), and 2 PVU isosurface (a; thick contour) are shown.

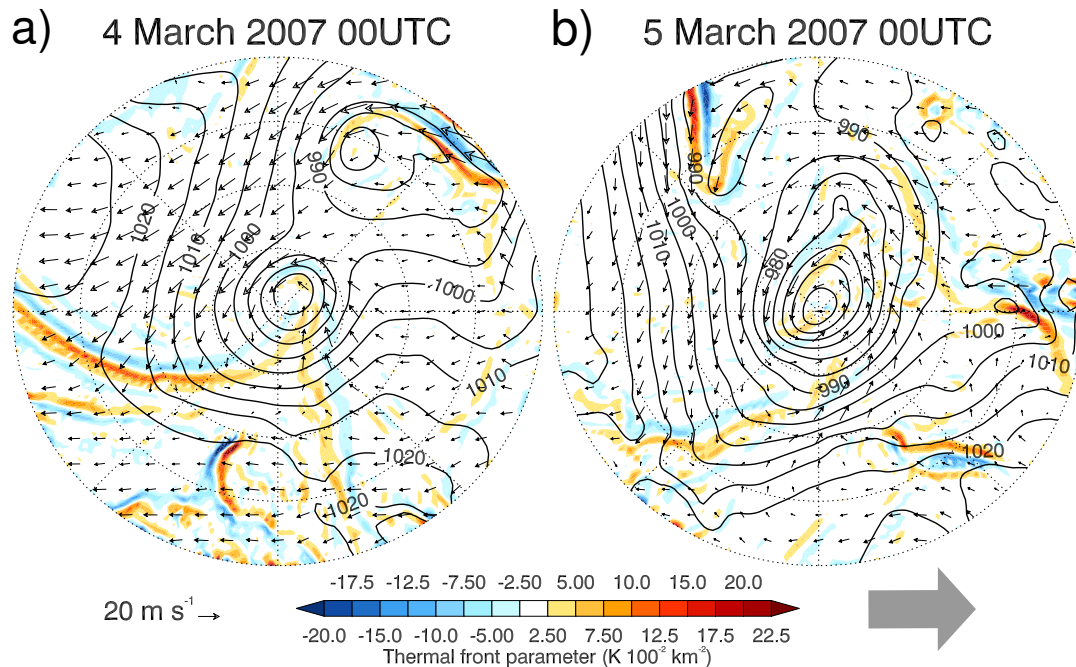
lines indicate  $\omega$ , Fig. 4a-c) of stratospheric O<sub>3</sub>-rich air within the DI of the N1 cyclone, O<sub>3</sub>-rich air from aloft (300 and 500 hPa) has descended toward the surface from the stratosphere as part of DI in the upstream low (e.g., Fig. 4a-d). The strong westerly winds appear to transport this O<sub>3</sub>-rich air across the western NA (Fig. 4a-d). This results in persistent high O<sub>3</sub> observed at Mace Head in the days following the maximum vorticity of the N1 cyclone (e.g., Fig. 4d), and even after the cyclone has left the North region (Fig. 2a).

The N1 cyclone is a good example of how one cyclone can bring both ~~high and low~~ low and high O<sub>3</sub> to Mace Head. Prior to maximum vorticity, low O<sub>3</sub>, defined to be less than the MAM 2007 6-hourly averaged O<sub>3</sub> 25<sup>th</sup> pc value of 39.1 ppbv, is reported at Mace Head on 4 March 2007 00 UTC (Fig. 3a). Figure 3a shows there is a sharp contrast in O<sub>3</sub> (> 10 ppbv) at the cold frontal boundary, with higher O<sub>3</sub> levels behind the cold front and lower O<sub>3</sub> levels ahead of the cold front in the warm sector between 30°–50° N. This low O<sub>3</sub> is advected from the subtropics northward towards Mace Head parallel to the cold front within the ~~WCB airstream~~ warm sector (Fig. 3a).

The distribution of O<sub>3</sub> within the airstreams of the N1 cyclone can be examined by using a cyclone-centered coordinate system (Figs. 5–7 and S1–S4). Here, the reanalyses are sampled onto a radial grid centered on the cyclone track points within a 20° (approximately 2000 km) radius with the cyclones rotated to be moving from left to right in the figures following Bengtsson et al. (2007). For discussion of the cyclone-centered maps, the unit circle with cardinal points are used instead of using geographical coordinates ~~, i.e., such that~~ the direction of cyclone propagation is from “west” to “east” (Knowland et al., 2015).

In the cyclone-centered coordinate system, the fronts are identified using the TFP function (Fig. 5). In Fig. 5a, the TFP values on the 925 hPa surface on the 4 March 2007 00 UTC show there is a baroclinic zone (strong horizontal temperature gradient on a constant pressure surface) or front from the N1 cyclone center toward the west/southwest (relative to the direction of cyclone propagation) as well as another one to the south/southeast. However, this does not indicate whether the fronts are warm fronts or cold fronts. Using the synoptic chart in Fig. 3b, in combination with the system-relative winds (where the speed of the cyclone propagation has been subtracted from the winds about each cyclone ~~;~~ (Catto et al., 2010; Dacre et al., 2012; Knowland et al., 2015)) and the MSLP contours on Fig. 5, the front trailing from the center of the N1 cyclone toward the west is diagnosed as a cold front and the weaker baroclinic zone in the bottom right quadrant is a warm front (Fig. 5a). There is an additional baroclinic zone associated with the parent low in the top right quadrant as well as other baroclinic zones within the warm sector of the cyclone that are not seen in the analysis chart (Fig. 3b). A day later, the N1 cyclone has become occluded and the baroclinic zones are weak around the cyclone center and along the trailing cold front which is now further to the south (Fig. 5b).

The ~~strong main feature at 4 March 2007 00UTC in both the meteorological fields and O<sub>3</sub> distribution is the~~ cold frontal boundary ~~can also be seen at 1000 hPa featured which separates the WCB and DI airstreams (Fig. 6). The strong cold frontal boundary features~~ as the sharp gradient in the 1000 hPa O<sub>3</sub> distribution and the curve in the isobars in the southwest quadrant of Fig. 6c (similar to Fig. 3). ~~As stated above, there is generally high O<sub>3</sub> (> 55 ppbv) throughout the troposphere in the region of the N1 cyclone on the 4 March 2007 at 00 UTC (Fig. 6), except within the warm sector of the N1 cyclone. This high O<sub>3</sub>~~

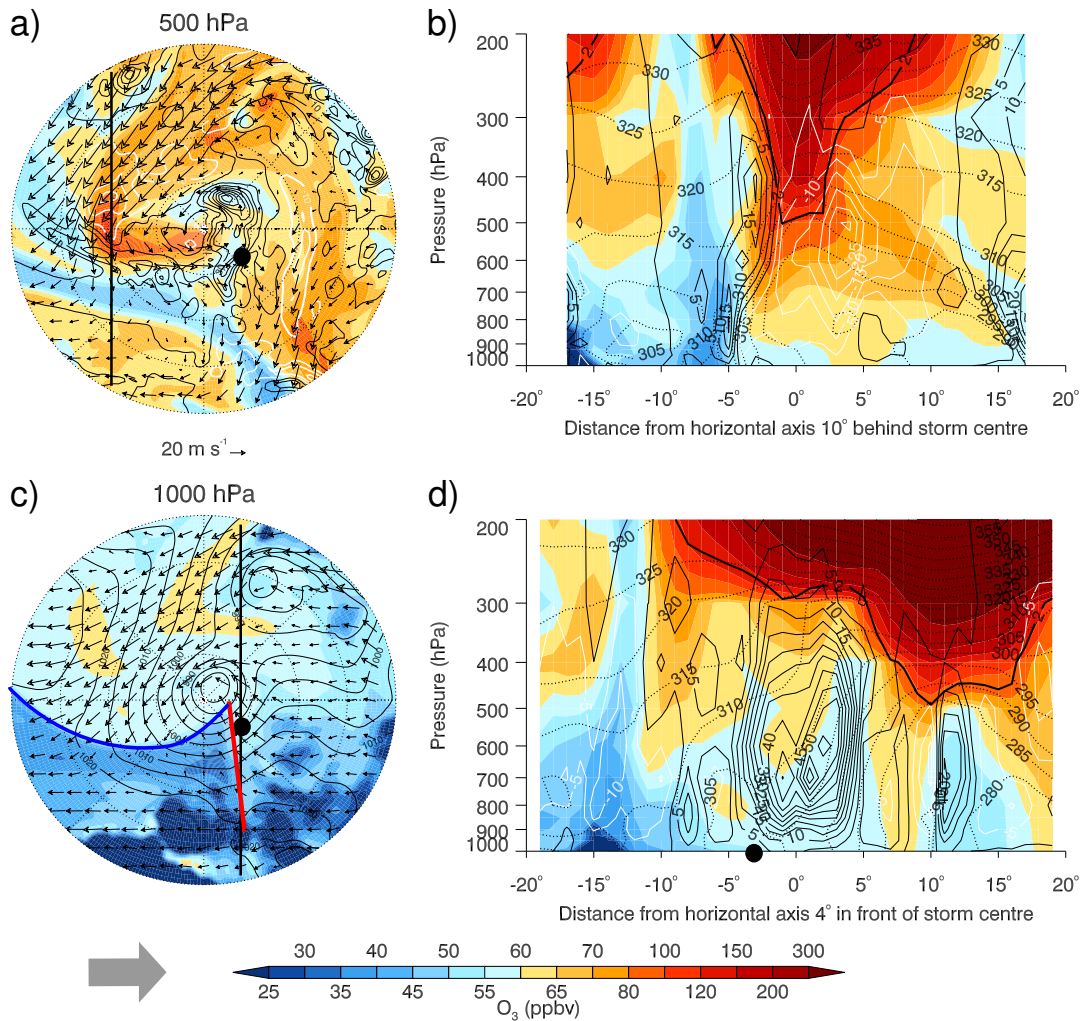


**Figure 5.** N1 cyclone-centered MSLP (solid black contours, 5 hPa contour intervals), 925 hPa system relative horizontal winds ( $20 \text{ m s}^{-1}$ , reference arrow), and 925 hPa thermal front parameter (color,  $2.5 \text{ K } 100^{-2} \text{ km}^{-2}$  intervals) on (a) 4 March 2007 00 UTC and (b) 5 March 2007 00 UTC. Radial dotted lines are plotted every  $45^\circ$  and dotted circles represent  $5^\circ$ ,  $10^\circ$ ,  $15^\circ$ , and  $20^\circ$  radii from cyclone center. The cyclone has been rotated in order that the direction of cyclone propagation is toward the right, indicated by the large grey arrow. N.b., geographical north for (a) and (b) is toward the right of the page.

is also a strong feature at 500 hPa, with only a narrow band of lower  $\text{O}_3$  to the southwest of the cyclone center (Fig. 6a). The high  $\text{O}_3$  front is  $\geq 30$  stratospheric origin (Figure S2a).

The vertical cross-section in Fig. 6b is taken along the north-south line  $10^\circ$  behind the cyclone center shown in Fig. 6a in order to capture the maximum descent of air within the DI airstream. The cross-sections are up to  $40^\circ$  diameter, with positive axis values in the direction to the North. In Fig. 6b, a narrow band of lower  $\text{O}_3$  levels to the southwest of the cyclone center can be identified as part of the warm sector ahead of the cold front (between  $-10^\circ$  to  $-5^\circ$ ). The front is identified between  $-5^\circ$  to  $-2^\circ$  throughout the troposphere by a strong gradient in equivalent potential temperature,  $\theta_e$ , from 1000 to 400 hPa, located between the high values of  $\theta_e$  (warm and moist) to the south of the cyclone center ( $-15^\circ$  to  $-5^\circ$ ) compared to the lower values of  $\theta_e$  (cool and dry) to the north ( $-2^\circ$  to  $15^\circ$ , Fig. 6b). The cold front is also ahead of the cold front, the WCB airstream transports  $\text{O}_3$ -poor air into the N1 cyclone (Fig. 6). The WCB airstream can be identified by the region of strong ascent ( $\omega$ , thin black contours) in the warm sector and strong descent (white contours, Fig. 6a) throughout the troposphere ( $-5^\circ$ , 1000–400 hPa; Fig. 6b) behind the cold front.





**Figure 6.** N1 cyclone-centered O<sub>3</sub> (color) and system relative winds ( $20 \text{ m s}^{-1}$ , reference arrow) on 4 March 2007 00 UTC: **(a)** 500 hPa with  $\omega$  ( $10 \text{ hPa h}^{-1}$  contour intervals, with black contours for positive values indicating ascent and white contours for negative values indicating descent) and **(c)** 1000 hPa with MSLP (solid black contours, 5 hPa contour intervals) and approximate location of the warm (red line) and cold (blue line) fronts based on Figs. 3b and 5a. The cyclone has been rotated in order that the direction of cyclone propagation is toward the right, indicated by grey arrow. The additional thick vertical lines in **(a)** and **(c)** indicate the location of the vertical transects **(b)** and **(d)** of O<sub>3</sub> (color),  $\omega$  ( $5 \text{ hPa h}^{-1}$  contour intervals, with black contours for positive values indicating ascent and white contours for negative values indicating descent),  $\theta_e$  (dotted contour lines, 5 K intervals), and the 2 PVU isosurface for the dynamical tropopause (thick solid contour): **(b)**  $10^\circ$  behind the cyclone center; and **(d)**  $4^\circ$  ahead of cyclone center, respectively. The cross sections are  $<40^\circ$  diameter with positive axis values to the north. The approximate location of Mace Head is indicated by the large black dot **(a, c, d)**.

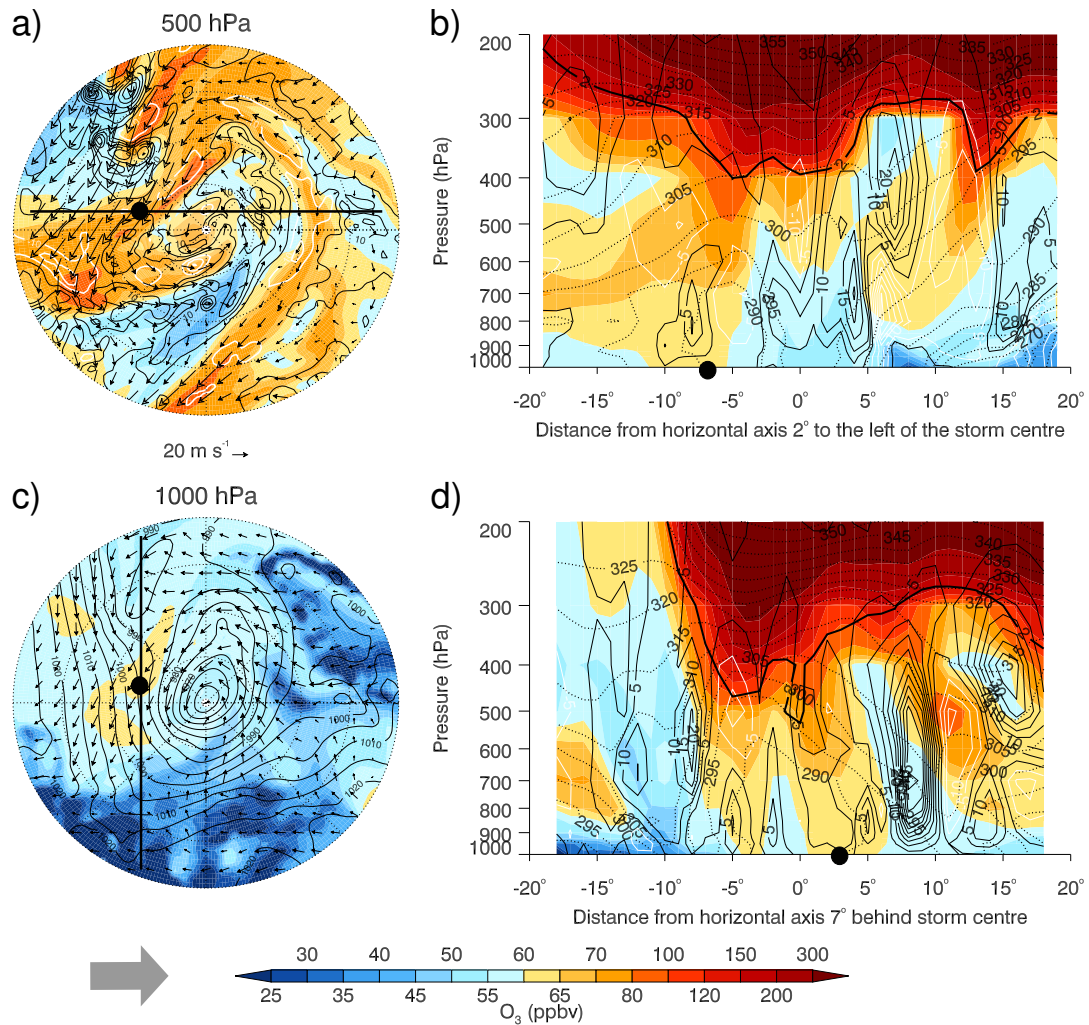
5 The vertical cross-section in Fig. 6b through a.d. Within the N1 cyclone is far from Mace Head (about 1400 km) and shows how  $O_3$ -rich air descended toward the surface within the DI airstream of the N1 cyclone, however this is far from Mace Head (about 1400 km) at this time (Fig. 6a,b). Stratospheric  $O_3$ -rich air, identified here by high levels of  $O_3$  ( $> 100$  ppbv) above the dynamical tropopause (thick solid black contour), reaches down to nearly 500 hPa, behind the cold front, between  $-2^\circ$  and  $3^\circ$  (Fig. 6b). There is further isentropic descent (along constant  $\theta_e$  contours) of the relatively high levels of  $O_3$  behind the cold front over a large area between  $-5^\circ$  to  $15^\circ$ , with strong descent of  $\omega \leq -30$  hPa  $h^{-1}$ . This results in high  $O_3$  ( $> 55$  ppbv) at 1000 hPa behind the surface cold front ( $-5^\circ$  to  $17^\circ$ , Fig. 6b and c). The stratospheric fraction of air behind the cold front is  $\geq 30\%$  down to 700 hPa and  $\geq 10\%$  down to 850 hPa (Fig. S2b).

10 At this time, the warm front is approaching Mace Head and low  $O_3$  was reported (37 ppbv). The vertical cross-section in Fig. 6d, taken  $4^\circ$  ahead of the cyclone center (Fig. 6c), highlights the ascent of low  $O_3$  from low levels over Mace Head into the free troposphere along the WCB. The passage of the associated WCB, identified in Fig. 6d by the strong ascent near the cyclone center (between  $-5^\circ$  to  $5^\circ$ , maximum  $\omega > 60$  hPa  $h^{-1}$  at 700 hPa), lofts  $O_3$  from the surface ( $O_3 < 60$  ppbv, Fig. 6d) towards upper levels (400 hPa, also seen over Mace Head in Fig. 6a).

15 A day later, the cold front associated with the N1 cyclone has passed over Mace Head and high  $O_3$  (55 ppbv) is reported at the surface with high  $O_3$ . There are elevated levels of  $O_3$  from in both reanalyses: the MACC reanalysis at the 1000 hPa also near Mace Head ( $> 60$  ppbv, Fig. 7c; also relatively high in ) and the MERRA-2  $O_3$ , 45–50 ppbv at 950 hPa, is 45–50 ppbv (Fig. S3c). Since the cyclone has started to decay, it is more difficult to identify the fronts and airstreams within the cyclone (Fig. 5b). The maximum WCB ascent ahead of the N1 cyclone at 500 hPa ( $\omega > 30$  hPa  $h^{-1}$ , Fig. 7a) is approximately half the value compared to the day before ( $\omega > 60$  hPa  $h^{-1}$ , Fig. 6a). There However, there are strong values of positive  $\omega$  at 500 hPa (Fig. 7a,d) associated with the upstream cyclones (closest cyclone is identified as a closed low contour to the northwest of the N1 cyclone in Fig. 7c).

25 The vertical cross-sections in Fig. 7b,  $2^\circ$  to the north of the cyclone center (Fig. 7a), and in Fig. 7d,  $7^\circ$  behind the cyclone center (Fig. 7c), highlight the vertical  $O_3$  distribution within the troposphere that has led to the high  $O_3$  at Mace Head. The DI airstream has also weakened, yet the tropopause is still visibly depressed at 400 and 500 hPa and (Fig. 7b and d, respectively) and high levels of  $O_3$  ( $> 55$  ppbv) are present throughout the mid- to lower troposphere (Fig. 7b and d). The  $O_3$  originally from the stratosphere has descended isentropically toward the surface near the location of Mace Head (black dot, near  $-7^\circ$  in Fig. 7b and  $3^\circ$  in Fig. 7d). This is also portrayed in the MERRA-2  $O_3$  in Fig. S3b,d, with a tongue of large STFR over Mace Head (at 700 hPa, STFR  $> 40\%$  and  $> 30\%$ , Fig. S4b and d, respectively). The strong vertical velocities associated with the upstream low pressure systems can be identified in Fig. 7d to the north of Mace Head between  $6^\circ$  and  $18^\circ$ . The high  $O_3$  associated with the upstream cyclone descends into the mid-troposphere ( $10^\circ$ , Fig. 7d) and is associated with high  $O_3$  at Mace Head later in the life cycle of the N1 cyclone.

35 The MACC and MERRA-2 representations of the N1 storm (Figs. 6–7 and Figs. S1–S4, respectively), especially including the stratospheric  $O_3$  mixing ratios, are similar. Although the tropospheric  $O_3$  in the troposphere, MERRA-2  $O_3$  is expected to be biased low (Sect. 2.2.3), and while the MERRA-2 are biased low, there is troposphere  $O_3$  mixing ratios are lower in the N1



**Figure 7.** N1 cyclone on 5 March 2007 00 UTC, similar to Fig. 6, except 24 hours later. The additional thick vertical lines (**a**, **c**) indicate the location of the vertical transects (**b**) 2° to the north of the cyclone center and (**d**) 7° behind the cyclone center, respectively. The cross sections have positive axis values to the east (**a**, **b**) and to the north (**c**, **d**). The approximate location of Mace Head is indicated by the large black dot. The cyclone has been rotated in order that the direction of cyclone propagation is toward the right, indicated by grey arrow.

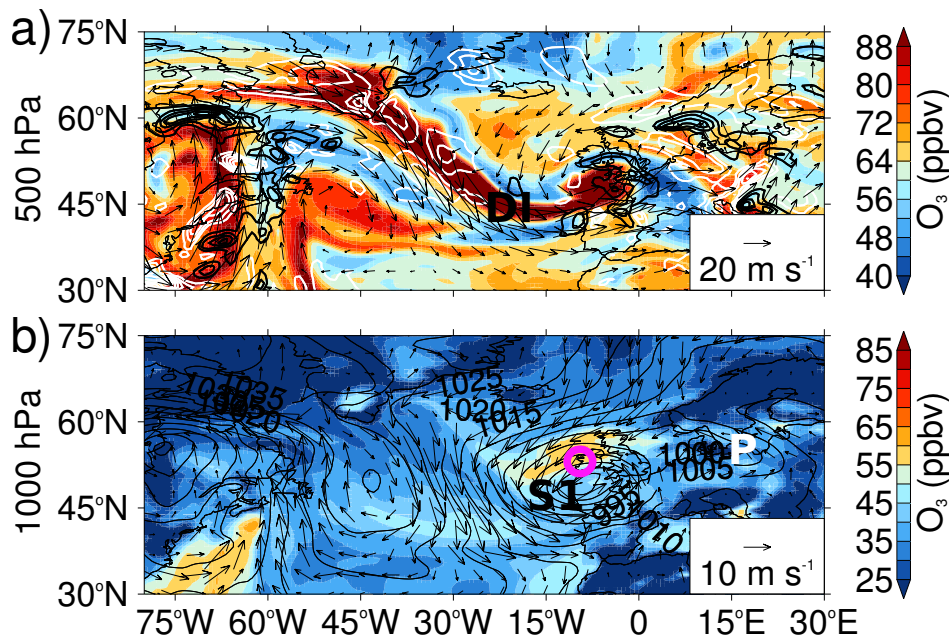


cyclone compared to the MACC reanalysis, there is still relatively higher  $O_3$  within the DI airstream reaching the surface at  $5^\circ$  in Fig(Figs. S1b and between  $5^\circ$  and  $10^\circ$  in Fig. S1d, d and S3b-d) as seen in FigFigs. 6, and reaching Mace Head, between  $-10^\circ$  and  $-5^\circ$  in Fig. S3a and between  $0^\circ$  and  $5^\circ$  in Fig. S3d, as seen in Fig. 7. The higher vertical resolution of MERRA-2 shows the tropopause fold reaches just below 600 hPa at ( $-3^\circ$  in Fig. S1b,) which is 100 hPa closer to the surface than shown in the MACC reanalysis (Fig. 6b). Since both reanalyses show similar  $O_3$  spatial patterns, although not quantitatively the same, we are confident the  $O_3$  reaching Mace Head has stratospheric origin.

Since the N1 cyclone was described in great detail, in the following case studies we will highlight differences compared to the N1 cyclone.

#### 4.2.2 S1 cyclone: synoptic conditions associated with high $O_3$ at Mace Head

10 The S1 cyclone originated over New York, USA ( $74.43^\circ$  W,  $43^\circ$  N,  $74^\circ$  NW) on 22 April 2012 and tracked past Mace Head through the South region between 24 April and 26 April 2012. High  $75^{th}$  pc 6-hourly averaged  $O_3$  ( $> 45$  ppbv) was generally observed at Mace Head while the S1 cyclone was in the South region on 24 April at 12 UTC to 26 April 2012 at 06 UTC (Fig. 2a).



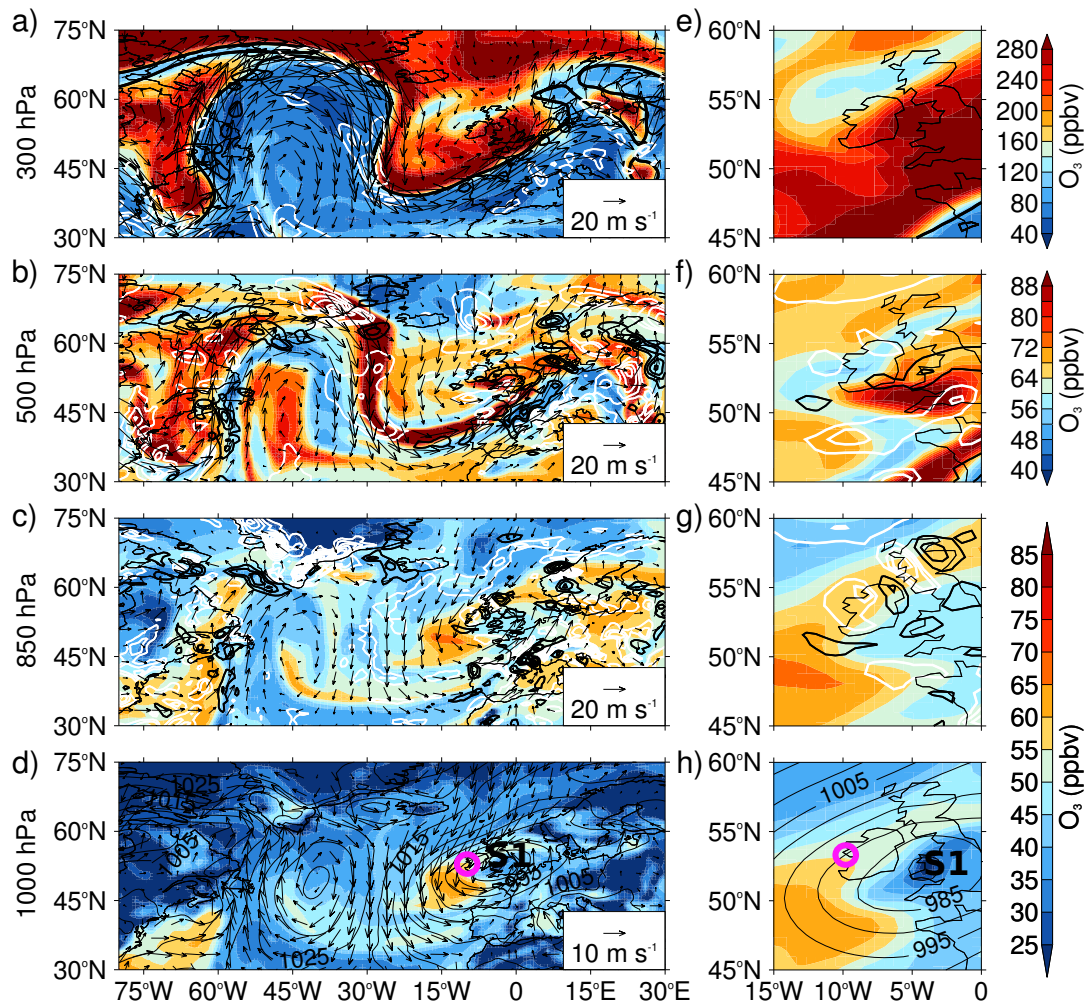
**Figure 8.** Synoptic conditions and  $O_3$  distribution for the S1 cyclone (**db**;  $48.12^\circ$  W,  $42.48^\circ$  N) on the 25 April 2012 at 00 UTC, at the time of maximum  $\zeta_{850}$ . Two levels are shown: (a) 500 hPa and (b) 1000 hPa. Additional features are labelled including the DI airstream (**ba**), the downstream decaying parent low to the S1 cyclone (white "P", **db**) and Mace Head is indicated (**db**).

The center of the S1 cyclone at the time of maximum vorticity (25 April 2012 at 00 UTC), is located almost directly to the south of Mace Head (50° N, 10° W, Figs. 2a and 8db) having merged with a downstream decaying cyclone (“P”, Fig. 8d-b). At this time, Mace Head reported median O<sub>3</sub> levels. There is a high pressure system located directly to the west, centered at approximately 50° N, 45° W, which appears to block transport from upwind North American sources (Figs. 8d-b and 9d). The atmospheric circulation pattern of high pressure to the west and the S1 cyclone south of Mace Head is very different to the pattern seen during the life cycle of the N1 cyclone, where there were several cyclones in the NA sector and strong westerly winds due to the pressure gradient between the cyclones and the Azores High (Figs. 3 and 4).

The source of high-elevated surface O<sub>3</sub> (> 55 ppbv) at Mace Head is not associated with descent of air directly from the lower stratosphere within the DI airstream. ~~Instead it comes from of the S1 cyclone, as seen in the N1 cyclone. Instead there is~~ “residual” high O<sub>3</sub> in the mid- to lower troposphere (50°–60° N, 20° W–30° E, Fig. 8b-ea). This O<sub>3</sub> is referred to as residual O<sub>3</sub> as it descended several days prior to the S1 cyclone passing near Mace Head (not shown) within the DI of the downstream cyclone (“P”, Fig. 8db) prior to its decay. ~~There is also descent of this high O<sub>3</sub> (> 50 ppbv) to the northeast of S1 (white contours in Fig. 8b and c over the North Sea and Germany) associated with the merging downstream cyclone.~~ This high O<sub>3</sub> appears to become entrained on the north side of the S1 cyclone ~~throughout the troposphere (Fig. 8b-d) and advected cyclonically around the S1 cyclone~~ in the lower and mid-troposphere over northern UK and Eastern Europe/Scandinavia (Fig. 8e and d).

Eighteen hours after the S1 cyclone reached maximum vorticity (25 April 2012 at 18 UTC), high levels of O<sub>3</sub> were reported at Mace Head. The MSLP field is still characterized by a blocking high in the western NA and the S1 cyclone is to the southeast of Ireland (Fig. 9d,h). Above Mace Head, there is descent (closed white contour, Fig. 9c,g) in the region of high O<sub>3</sub> (> 55 ppbv) which can facilitate the transport of O<sub>3</sub> from the mid-troposphere toward the surface. A large ridge has formed over the NA, identified at 300 hPa by the anticyclonic wind flow aloft as well as the 2 PVU contour (Fig. 9a). On either side of the ridge at 300 hPa, the troughs bring stratospheric air towards lower latitudes than Mace Head (Fig. 9a). This allows for O<sub>3</sub>-rich air to be transported towards the surface at lower latitudes as part of the DI airstream within such strong cyclones as the S1 cyclone. ~~As shown in Fig. 9b-d, descent of stratospheric O<sub>3</sub> at 30° W from upper levels (300 and 500 hPa) toward the surface occurs within the DI of the S1 cyclone; however, it reaches more southerly latitudes ((between 35° and 45° N) than Mace Head, Fig. 9b-d).~~

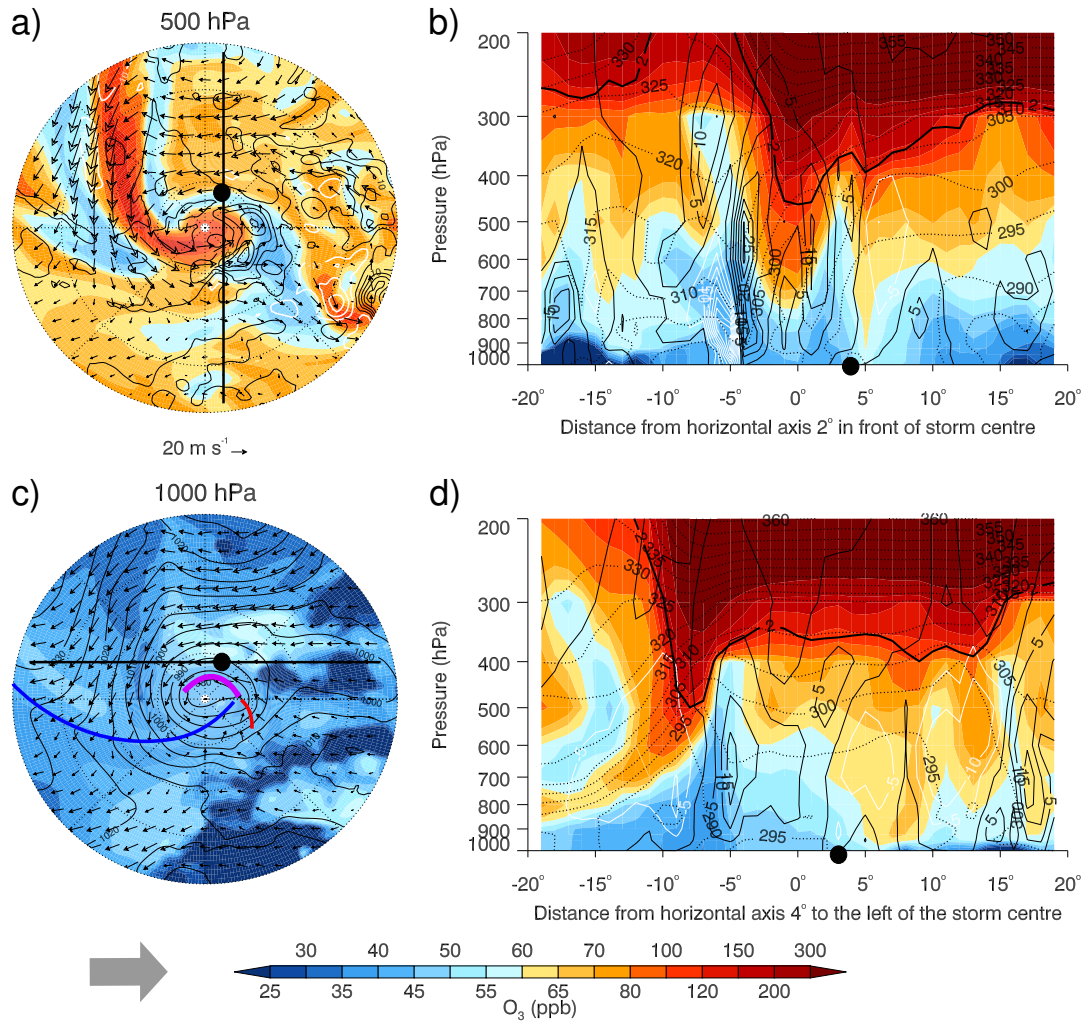
~~The influence of the~~ To investigate the residual O<sub>3</sub> in more detail, we compare the S1 cyclone airstream on the vertical and horizontal distribution of O<sub>3</sub> ~~within the S1 cyclone are examined~~ at the time of maximum  $\zeta_{850}$  (25 April 2012 00 UTC) using the cyclone-centered coordinate system in both the MACC and MERRA-2 reanalyses (Figs. 10, 11 and S6). ~~On 25 April 2012 00 UTC, most of the~~ In Figs. 10a and 11a, the stratospheric O<sub>3</sub> within the DI airstream arrives into the center of the cyclone from the northwest quadrant and is bounded by the WCB ascent to the right of the cyclone’s center (black contours with maximum at 5° radius). Most of the northeast quadrant of the S1 cyclone at 500 hPa, shown in Figs. 10a and 11a, is dominated by the residual high levels of O<sub>3</sub> (> 55 ppbv; STFR is > 20 %, Fig. S6a) identified above as coming from the downstream decaying cyclone. The MACC and MERRA-2 O<sub>3</sub> mixing ratios throughout the ~~troposphere-mid-troposphere~~ (above 600 hPa) ~~and lower stratosphere to lower stratosphere (200 hPa)~~ are comparable during the S1 cyclone (Figs. 10 and 11). ~~In the lower troposphere (below 600 hPa) in the region to the northeast of Mace Head, MERRA-2 underestimates~~ The vertical transport of O<sub>3</sub> will be sensitive to the strong gradients of O<sub>3</sub> by up to 15 ppbv compared to the near the tropopause. The MACC O<sub>3</sub> ;



**Figure 9.** Similar to Fig. 8 (a-d) but also includes an inset over Ireland and the UK (45°–60° N, 15° W–0°; e-h, winds not included) for the S1 cyclone (d; 51° W N, 15° NW) 18 hours later, on the 25 April 2012 at 18 UTC for four pressure levels: (a,e) 300 hPa, (b,f) 500 hPa, (c,g) 850 hPa, and (d,h) 1000 hPa. High O<sub>3</sub> reported at Mace Head.

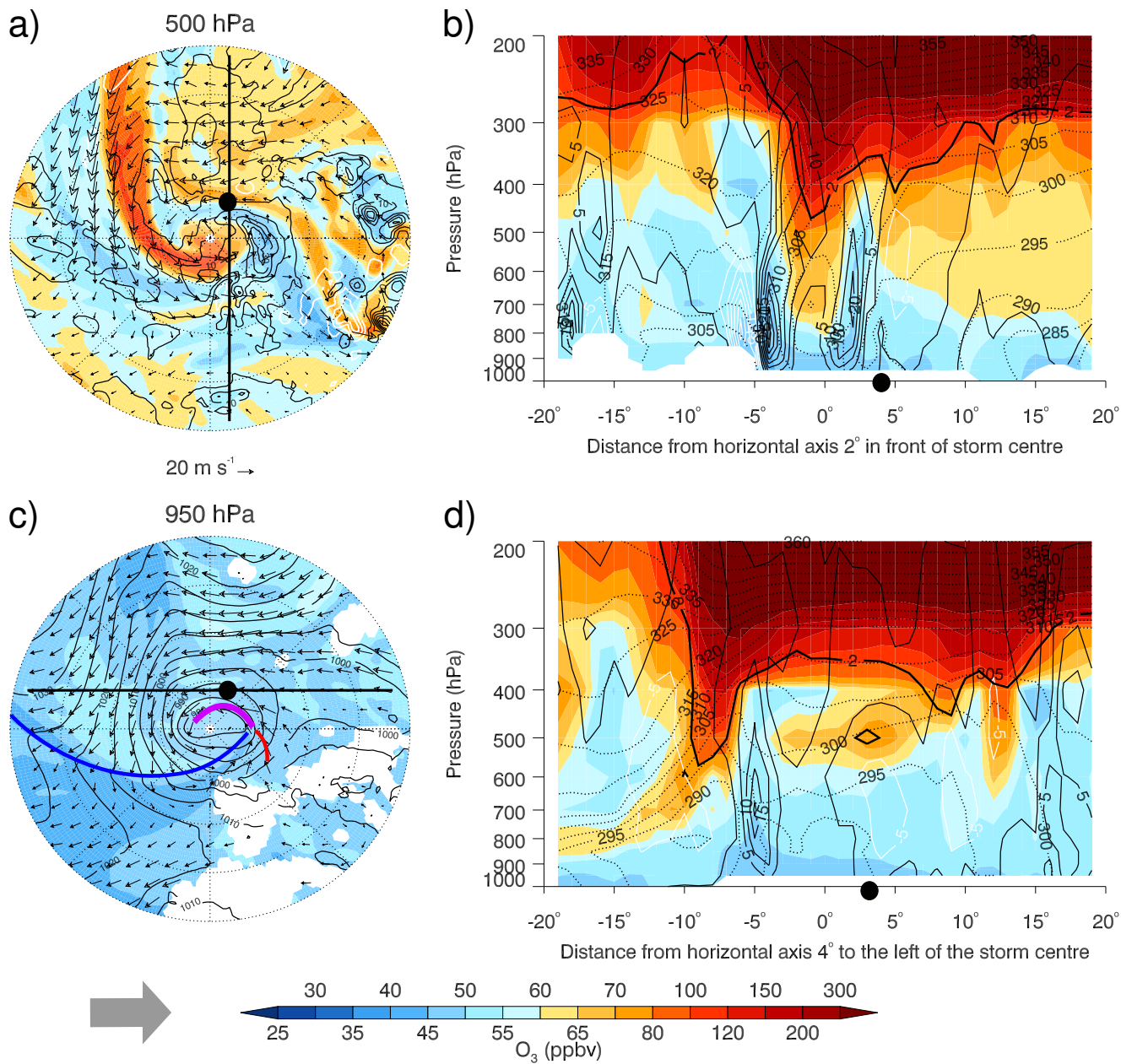
however, within the S1 cyclone most of the lower tropospheric within the DI airstream can be as much as 75 ppbv higher than the MERRA-2 O<sub>3</sub> is greater than the MACC, as the MERRA-2 reanalysis O<sub>3</sub> by up to 15 ppbv since there is less variability associated with the values decrease closer to the dynamical tropopause compared to the MACC O<sub>3</sub> climatologies used in the production of MERRA-2 (Figs. 10 and 11).

- 5 At this time, Mace Head, which reported median distribution. Both the MACC and MERRA-2 O<sub>3</sub> levels, lies between this residual high O<sub>3</sub> and the low have good agreement to independent observations in the upper troposphere/lower stratosphere (UTLS) region (Inness et al., 2013; Wargan et al., 2015, 2017). In the Northern Hemisphere (NH) extra-tropics, MACC O<sub>3</sub> from within the warm sector of the S1 cyclone which is wrapped around the cyclone center (Figs. 10c and 11e). In Figs. 10a



**Figure 10.** Similar to N1 cyclone Figs. 6 and 7 except for the S1 cyclone on 25 April 2012 00 UTC (see Fig. 8). The approximate location of the occluded (purple line), warm (red line) and cold (blue line) fronts in **c** are based on the fronts in Fig. S5a and the synoptic analysis chart (not shown). The additional thick vertical lines in **(a)** and **(c)** indicate the location of the vertical transects **(b)** 2° in front of the cyclone center and **(d)** 4° to the north of cyclone center, respectively. The cross sections have positive axis values to the north (**a**, **b**) and to the east (**c**, **d**). The approximate location of Mace Head has been indicated by large black dot. The cyclone has been rotated in order that the direction of cyclone propagation is toward the right, indicated by grey arrow.





**Figure 11.** S1 cyclone on 25 April 2012 00 UTC, similar to Figs. 10 except using MERRA-2 reanalysis data. Note, panel c is 950 hPa instead of 1000 hPa to minimize the missing data plotted. This occurs since the GEOS-5 model masks orography.

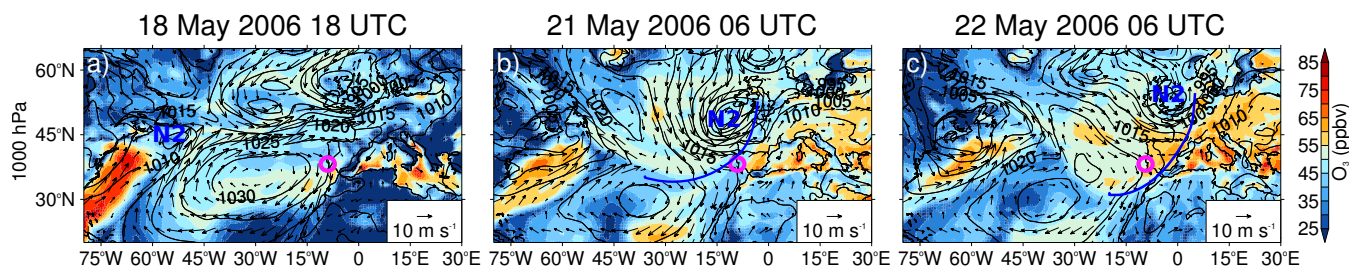
and 11a, the stratospheric O<sub>3</sub> between 500 and 100 hPa has a bias of -10-0% when compared to ozonesondes profiles (Inness et al., 2013) and Wargan et al. (2017) found that the average MERRA-2 O<sub>3</sub> within the DI airstream arrives into the center of the cyclone from the northwest quadrant and is bounded by the WCB ascent to the right of the cyclone's center (black contours with maximum at 5° radius). The STFR is large (> 30 profile over Europe (45°-60°N, 0°-60°E) in the spring of 2005 (after the assimilation of MLS and OMI satellite retrievals) captures the vertical structure of the ozonesondes in that region ( $r^2 > 0.6$ ), although biased low (up to -20 %) within the S1 cyclone's DI airstream (Fig. S6a and b) in the UTLS.

The two vertical cross-sections in Figs. 10b,d and 11b,d intersect the approximate location of Mace Head and the residual high O<sub>3</sub> in the mid-troposphere that is not associated with the S1 cyclone's DI airstream. The tropopause is depressed to about 500 hPa throughout the DI, shown close to the cyclone center (0°) in Figs. 10b and 11b and behind the S1 cyclone (-8°) in Fig. 10d and 11d. High levels of O<sub>3</sub> (> 55 ppbv) are found down to 800 hPa associated with the DI at the cyclone center (Fig. 10b and 11b) and within the isentropic descent behind S1 between -19° to -5° (Fig. 10d and 11d). There is no injection of stratospheric air into the troposphere occurring near Mace Head from the S1 cyclone, as the tropopause remains almost parallel with the isentropes in the transects between 5° to 15° in Figs. 10b and 11b and between -4° to 15° in Figs. 10d and 11d. The MERRA-2 reanalysis shows the DI of the upstream parent low is directly related to the high O<sub>3</sub> in the mid-troposphere as a small closed 2 PVU contour circle – the dynamical tropopause – is above Mace Head at 500 hPa (Fig. 11d) which is not seen in the coarser MACC reanalysis (Fig. 10d). At 500 hPa, the STFR is > 40 % within the remnant O<sub>3</sub> associated with the decaying cyclone to the east of the S1 center (Fig. S6d). At about 5° in both Fig. 10b and d transects, there is descent (-5 hPa h<sup>-1</sup> contour) of this residual high O<sub>3</sub> from the mid-troposphere toward the surface over Mace Head in the MACC reanalysis. Despite the negative vertical velocity above Mace Head in Fig. 11b and d, the simulated MERRA-2 O<sub>3</sub> does not descend fully to the surface, however the simulated O<sub>3</sub> at the surface at Mace Head in both reanalyses is approximately 45 ppbv.

#### 4.2.3 N2 cyclone: synoptic conditions associated with high O<sub>3</sub> at Monte Velho

The N2 cyclone is a strong cyclone which passed north of Monte Velho and advected high O<sub>3</sub> to the observation site. ~~It is also an example of a cyclone associated with low O<sub>3</sub> before high O<sub>3</sub> is observed at Monte Velho.~~ Cyclogenesis of the N2 cyclone occurs off the east coast of Florida on 17 May 2006 at 12 UTC (not shown) and then tracks northeastward. ~~Downwind~~ (Fig. 2b). The synoptic conditions at the time of the N2 cyclone are a similar to the N1 cyclone: About a day after cyclogenesis, the N2 cyclone is located just south of Newfoundland and downwind of the N2 cyclone are a series of low pressure systems across the NA region as well as a strong Azores High stretching over most of the NA (Fig. Figs. 12a and S7c, ~~about a day after cyclogenesis, the N2 cyclone is located just south of Newfoundland~~). The large pressure gradient results in strong westerly winds at near 45° N (Fig. 12a) throughout the troposphere (Fig. S7a-e). S7). Similar to the N1 cyclone, stratospheric O<sub>3</sub> descends into the troposphere within the low pressure systems in the NA ahead of the N2 cyclone (Figs. 12a and S7). Similar to the S1 cyclone, a high pressure system develops to the west of the N2 cyclone (Fig. 12b-c), supporting upper-level descent behind the N2 cyclone's cold front and negating transport across the NA from North America (Figs. 12b-c, S8 and S9).

As was seen for the N1 cyclone, the N2 cyclone is also associated with low O<sub>3</sub> before high O<sub>3</sub> is observed at the monitoring station due to the passage of a cold front (Fig. 12b-c). Since the N2 cyclone is similar in behaviour to the N1 cyclone, further



**Figure 12.** Synoptic conditions and O<sub>3</sub> distribution for the N2 cyclone at 1000 hPa: MACC O<sub>3</sub> (color) and horizontal wind vectors (10 m s<sup>-1</sup> reference arrow) and MSLP (solid contours, 5 hPa intervals) on a) 18 May 2006 18 UTC, b) 21 May 2006 06 UTC, and c) 22 May 2006 06 UTC. The approximate cold front (b,c): blue line) and Monte Velho (pink open circle) are included.

details and results and S1 cyclones discussed in Sects. 4.2.1 and 4.2.2, full details for this case can be found in the Supplemental material (Sect. S4.2.3S2.3).

### **4.3 S2 cyclone: synoptic conditions associated with high O<sub>3</sub> at Monte Velho**

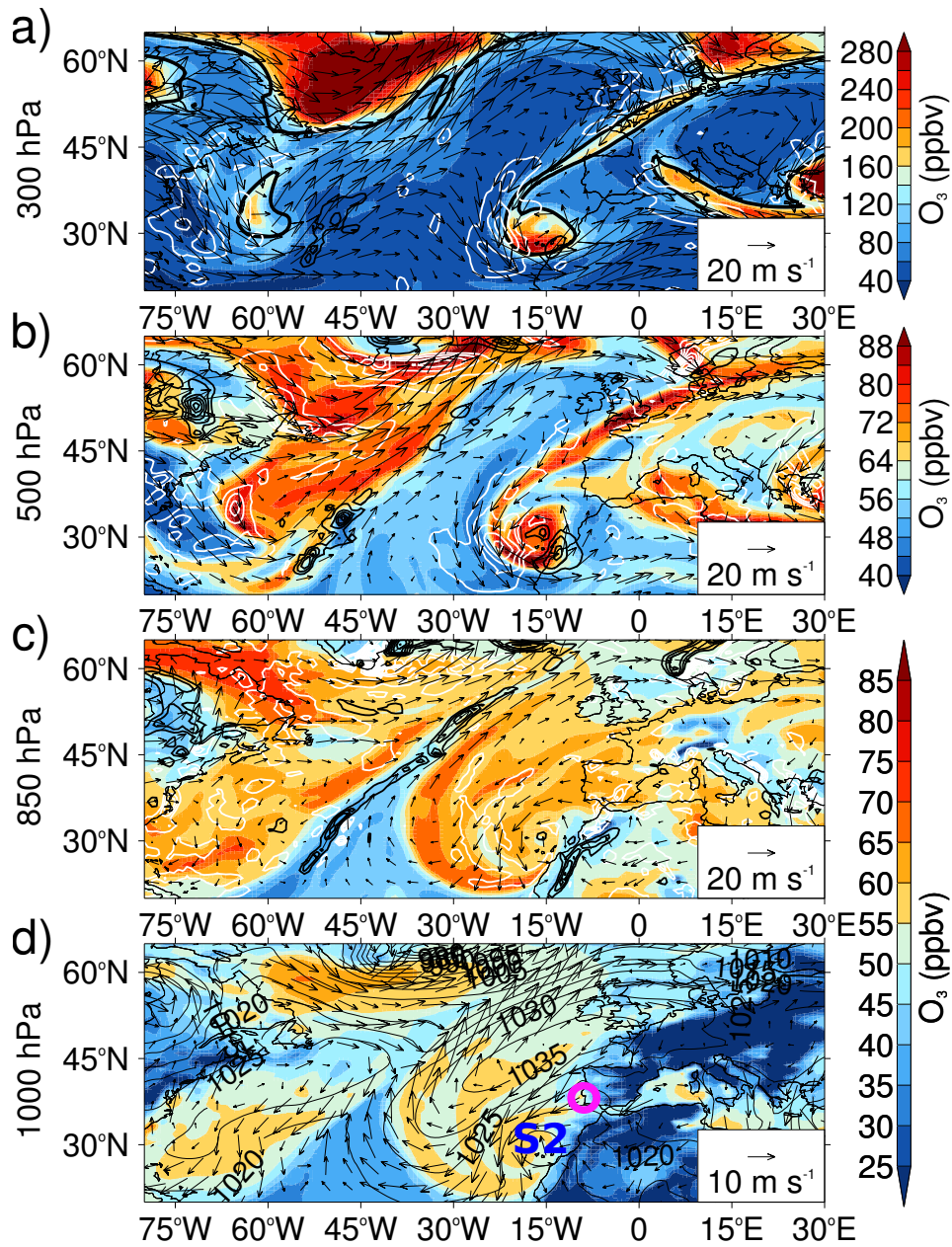
#### **4.2.1 S2 cyclone: synoptic conditions associated with high O<sub>3</sub> at Monte Velho**

- 5 The S2 cyclone is a moderate cyclone that formed on 12 March 2007 00 UTC to the south of a large high pressure system which extended over the eastern NA and Europe (not shown). On 13 March 2007 18 UTC, 42 hours later, the S2 cyclone reaches maximum vorticity ( $\zeta_{850} = 7.3 \times 10^{-5} \text{ s}^{-1}$ , 31.3° N, 16.5° W) and is still located to the south of the high pressure system over the eastern NA (Fig. 13d). At this time, there are additional strong weather systems in the NA region: a deep Icelandic low, a low over Hudson Bay and a high pressure system over the western NA. Within the S2 cyclone, there is strong descent within the DI airstream between 300 and 850 hPa (Fig. 13a-c), with maximum descent at 500 hPa ( $\omega < -25 \text{ hPa h}^{-1}$ , Fig. 13b) nearly as strong as the N1 cyclone (Fig. 6b). High values of O<sub>3</sub> (> 80 ppbv) descend from upper levels toward the surface within the DI airstream and advect cyclonically around the S2 cyclone and anticyclonically within the high pressure system at lower levels, behind the low-level cold front (850 and 1000 hPa, Fig. 13c and d). Over the Iberian Peninsula at 850 hPa, there is descent of O<sub>3</sub>-rich air likely associated with the large region of descent throughout the troposphere over the Mediterranean
- 10
- 15 Sea associated with a downstream cyclone (Fig. 13a-c).

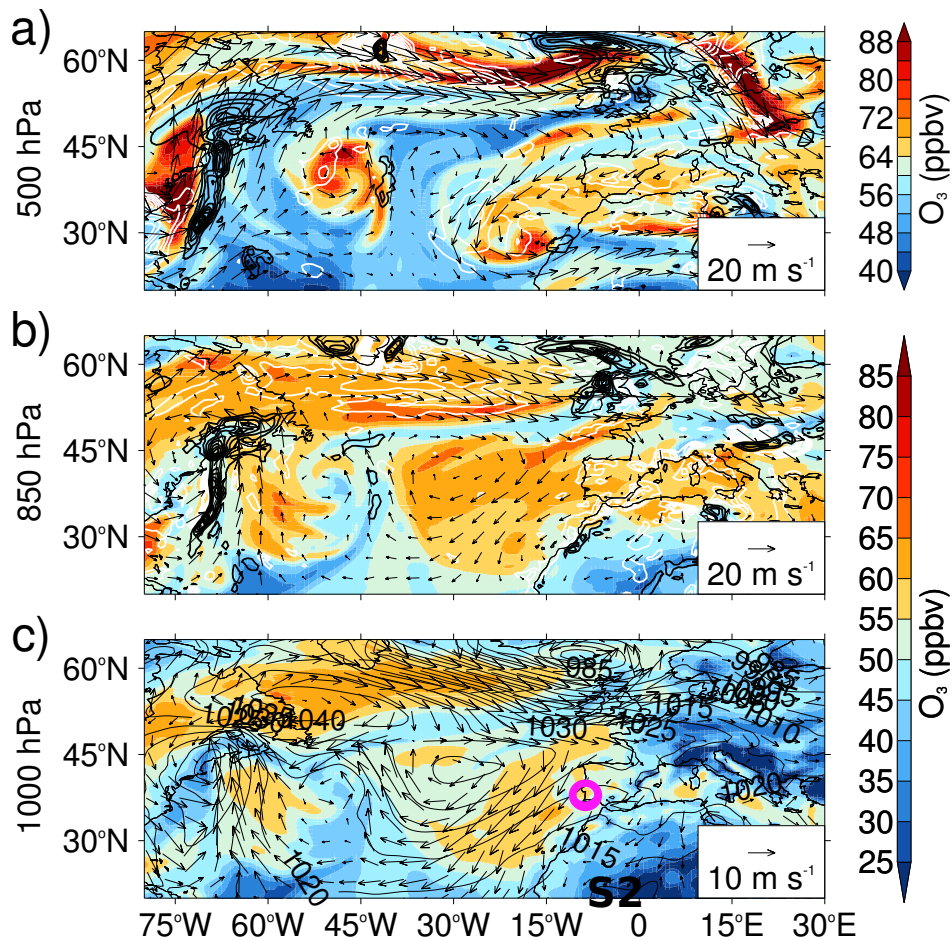
Over the following four days, the high O<sub>3</sub> at Monte Velho associated with the S2 cyclone persists while the S2 cyclone tracks southeastward (see Fig. 2b). At upper-levels, a closed low detaches from the stratosphere (not shown). In Fig. 14a, the descent within the DI of the S2 cyclone can be identified at 500 hPa, however the S2 cyclone can no longer be identified by a closed low pressure system over Northern Africa in Fig. 14c. The high pressure system over the eastern NA moves southwestward with the O<sub>3</sub>-rich air which has accumulated within it (Fig. 14c). There is still descent occurring over the Iberian Peninsula in the mid-troposphere, which continues to transport relatively high levels of O<sub>3</sub> to the surface at Monte Velho (Fig. 14a and b).

20





**Figure 13.** Synoptic conditions for the S2 cyclone (**d**;  $4731^{\circ}$   $WN$ ,  $3417^{\circ}$   $NW$ ) on the 13 March 2007 18 UTC, at the time of maximum  $\zeta_{850}$ . O<sub>3</sub> (color; note different scales used for different levels) and horizontal winds (note magnitude of reference arrow changes) are shown on four levels: (a) 300 hPa, (b) 500 hPa, (c) 850 hPa, and (d) 1000 hPa. In addition, MSLP (**d**; solid contours, 5 hPa intervals),  $\omega$  (**a**, **b**, and **c**; 5 hPa h<sup>-1</sup> contour intervals, black contours for positive values indicating ascent (n.b., different interval to previous cyclones) and white contours for descent), and 2 PVU isosurface (**a**; thick contour) are shown. Monte Velho indicated by pink open circle.



**Figure 14.** Similar to Fig. 13 except for the S2 cyclone (c;  $\pm 23^\circ$  W,  $\pm 231^\circ$  NW) nearly 4 days later on the 17 March 2007 12 UTC. High O<sub>3</sub> recorded at Monte Velho. O<sub>3</sub> (color; note different scales used for different levels) and horizontal winds (note magnitude of reference arrow changes) is shown on three levels: (a) 500 hPa, (b) 850 hPa, and (c) 1000 hPa. In addition, MSLP (c; solid contours, 5 hPa intervals) and  $\omega$  (a and b; 5 hPa h<sup>-1</sup> contour intervals, black contours for positive values indicating ascent and white contours for descent) are shown.

The cyclone-centered analysis was not performed for the S2 cyclone since 1) the high O<sub>3</sub> at Monte Velho prior to maximum vorticity is associated with a downstream cyclone's DI airstream (as seen in the S1 cyclone) and 2) after the S2 cyclone started to decay the high O<sub>3</sub> is associated with subsidence in the high pressure system behind the S2 cold front.

## 5 Discussion

- The influence of springtime mid-latitude NA cyclones on O<sub>3</sub> observations at two marine background sites – Mace Head, Ireland and Monte Velho, Portugal – has been quantified using a frequency analysis test and explored through cyclone case studies. About 50 % of the cyclones which track to the north or close to Mace Head show a relationship with high levels of

O<sub>3</sub> (> 75<sup>th</sup> pc) observed at Mace Head, while 53 % of the tracks to the south of Mace Head are associated with low levels of observed O<sub>3</sub> (< 25<sup>th</sup> pc). The N1 case study cyclone to the north of Mace Head illustrates how O<sub>3</sub>-rich air, which originated in the stratosphere, reaches the surface within the DI airstream as the cyclone passes Mace Head. In contrast, at the southern measurement station, Monte Velho, the levels of O<sub>3</sub> are not strongly influenced by the passing cyclones to the north or to  
5 the south. If the tracks pass close to Monte Velho, 55 % of tracks are associated with high levels of O<sub>3</sub>. The location of the Monte Velho site relative to the Azores High is the determining meteorological factor for the temporal variability of O<sub>3</sub> at this site since Monte Velho is located south of the NA storm track. Within the Azores High, neighboring the cyclone, there is build-up of high concentrations of O<sub>3</sub> related to the anticyclonic descent within the DI airstream behind the cold front.

In this study, up to 30 % of springtime cyclones are associated with both high O<sub>3</sub> and low O<sub>3</sub> observations at Mace Head or  
10 Monte Velho associated with frontal passage relative to the measurement sites. For example, the difference in modelled MACC O<sub>3</sub> across the N1 cyclone's cold front is > 10 ppbv, with high O<sub>3</sub> behind the cold front and low O<sub>3</sub> ahead of the cold front. Prior to the N1 cyclone reaching maximum intensity, Mace Head is located in the warm sector of the cyclone with moderate levels of O<sub>3</sub> (< 45 ppbv) arriving from the southwest possibly south of 30° N. Previous studies have associated air arriving at Mace Head from the NA with relatively clean maritime air masses (e.g. Jennings et al., 1991; Simmonds and Derwent,  
15 1991; Simmonds et al., 1997; Derwent et al., 1998). Simmonds et al. (1997) noted O<sub>3</sub>-poor air, around -5 ppbv relative to the background levels, arrives at Mace Head in April and May from the southwest with subtropical signatures (Simmonds et al., 1997).

It is shown here that high levels of O<sub>3</sub> can be associated with the natural sources of O<sub>3</sub> transported from the stratosphere and can arrive at Mace Head from the west. The stratospheric O<sub>3</sub>-rich air descends toward the lower levels within the DI  
20 airstream following direct STT, such as in the N1 intense cyclone and the S2 moderate cyclone. However, the S1 and N2 strong cyclones show that O<sub>3</sub>-rich air in the mid-troposphere can be older, undiluted ("residual") O<sub>3</sub>-rich air due to STT occurring in a previous downstream cyclone which then becomes entrained in the new cyclone and descends. In the S1 cyclone near Mace Head, O<sub>3</sub>-rich air from the DI of a downwind cyclone is found in the mid-troposphere (700 to 400 hPa) and is advected cyclonically around the cyclone subsequently descending toward the surface in the DI airstream. As a result, high levels of  
25 O<sub>3</sub> (> 55 ppbv) at Mace Head persists for about a day and a half. This feature of older O<sub>3</sub>-rich air descending toward the surface in the DI airstream in combination with subsidence in the anticyclone behind the cyclone was found in the N2 and S2 case studies. Cooper et al. (2004a) also found that O<sub>3</sub>-rich air that had descended in the DI of single cyclone was advected westward within a high pressure system behind the cyclone and then became entrained within an upstream cyclone's WCB. A number of studies suggest it can take many days for O<sub>3</sub>-rich air to be diluted into the free troposphere, in which time there  
30 are several transport pathways before the air eventually reaches the surface (Johnson and Viezee, 1981; Colbeck and Harrison, 1985; Davies and Schuepbach, 1994; Cooper et al., 2004a). In the case study cyclones examined here, the main pathways are direct entrainment into the cyclone or an upstream cyclone and subsidence within a neighboring anticyclone.

In all four case studies, stratospheric intrusions do occur within the DI airstream regardless of the cyclone intensity. In particular, the moderate S2 cyclone, to the south of Monte Velho, exhibits strong descent from upper levels ( $\omega < -25$  hPa h<sup>-1</sup>)  
35 comparable to the N1 cyclone and greater than the descent within the N2 and S1 cyclones. Based on stratospheric intrusions

targeted by 10 flights over Central USA in the spring and fall of 1978, Johnson and Viezee (1981) conclude that all low pressure troughs may be associated with STT, however the amount would be proportional to the strength of the trough. Cooper et al. (1998) used ozonesondes to sample pre- and post-frontal vertical profiles at Bermuda and two US sites and found that the mean tropospheric O<sub>3</sub> always increased with height after the cold front had passed, with back trajectories indicating the source was ~~upper-tropospheric/lower-stratosphere~~ the UTLS to the northwest. The stratospheric “influence” tracer from Ott et al. (2016) was used to represent the fraction of stratospheric air within the case study cyclones; however, in order to diagnose the amount of O<sub>3</sub> from the stratosphere that is irreversibly transferred into the troposphere a chemistry transport model or a chemistry climate model – such as GEOS-5 Chemistry-Climate model – should be run in order to evaluate the fluxes of O<sub>3</sub> or tagged-tracers of O<sub>3</sub>, neither of which are archived in the MACC or MERRA-2 reanalyses. In addition, other sources of both natural and man-made pollutants could become entrained into the DI airstream (e.g., Brown-Steiner and Hess, 2011; Lin et al., 2012b; Langford et al., 2017). Biomass burning plumes from as far away as Canada have reached Europe, leading to enhanced CO at Mace Head as the plume passes over (Forster et al., 2001). Within a fire plume, O<sub>3</sub> can be produced associated with increased precursors and this has the potential to enhance European O<sub>3</sub>, including at Mace Head. This work is ongoing.

~~Since the cyclone case studies all originated to the west of the monitoring sites the influence of anthropogenic~~  
15 The case study analysis focused on the strongest cyclones associated with high O<sub>3</sub> at Mace Head and Monte Velho such that 1) the cyclone tracks would be exact matches in the MACC and ERA-Interim reanalyses (Knowland et al., 2015) and 2) airstreams would be most evident (Catto et al., 2010). An alternative method to select case study cyclones would be to start by selecting the tracks associated with the highest (or lowest) O<sub>3</sub>. This leads to the selection of moderate to weak cyclones (which are generally not located solely in the major storm track pathways and which tend to be shorter-lived (Knowland et al., 2015)). While the case study analysis presented here highlights the regional differences in the strongest springtime mid-latitude cyclones associated with high surface O<sub>3</sub> ~~from sources further east in Europe on~~, the relationship between cyclones and surface O<sub>3</sub> ~~at Mace Head and Monte Velho was not examined here, however should also be considered for future studies~~ likely depends on a number of complex factors, including the cyclone location relative to the measurement station and upstream and downstream pressure systems, cyclone intensity, stratosphere-to-troposphere transport, and long-range transport of trace gases  
20 within the free troposphere and the boundary layer.  
25

For the case studies, it is difficult to identify anthropogenic O<sub>3</sub> from surface emission sources arriving at Mace Head or Monte Velho from the west across the NA since anthropogenic O<sub>3</sub> can be an order of magnitude smaller than the levels of stratospheric O<sub>3</sub> from STT. Regardless, Li et al. (2002) show North American major transatlantic pollution events are infrequent, identifying only 2 such events during the spring of 1997. For pollution from North American emission sources  
30 to reach western Europe, the perfect set up of sequential low pressure systems and a strong Azores-Bermuda high, as seen during the life cycles of the N1 and S2 cyclones, are required to rapidly transport the pollutants in the resultant strong westerly winds (Li et al., 2002; Creilson et al., 2003). Li et al. (2002) found in their study that such events are more likely to occur during positive phases of the North Atlantic Oscillation (NAO; Walker and Bliss, 1932). The month of March 2007 which included the N1 and S2 cyclones was characterized by a positive NAO index (1.44, Climate Prediction Center (Last retrieved  
35 19 September 2014)). The synoptic set-up during the S1 and N2 cyclones had a blocking high directly to the west, representative

of the negative NAO phase; the NAO index was weakly positive (0.47) and negative (-1.28) during the months of April 2012 and March 2006, respectively. The relationship between the NAO, STT and pollution transport has been explored previously (e.g. Creilson et al., 2003; Sprenger and Wernli, 2003; Pausata et al., 2012), however the direct impact of the cyclones and their associated airstreams on the distributions of trace gases such as O<sub>3</sub> during the different NAO phases will be addressed in a further study.

This analysis has built upon the findings of earlier studies of airstream analysis and chemical composition (e.g. Bethan et al., 1998; Cooper et al., 2001, 2002a, b; Owen et al., 2006; Knowland et al., 2015) to identify consistent pathways in which relatively high levels of O<sub>3</sub> are transported through cyclones in the NA during spring. From a composite of intense springtime cyclones which included the N1 cyclone, Knowland et al. (2015) characterized the main mechanisms which advect O<sub>3</sub> horizontally and vertically within cyclones and hence the extent to which the airstreams can influence O<sub>3</sub> concentrations throughout the troposphere. The case studies corroborate with the findings of the composite study that a typical NA cyclone WCB is often associated with relatively lower levels of O<sub>3</sub> while the DI is associated with relatively higher levels of O<sub>3</sub> connecting the stratospheric reservoir with the surface (a Type 3 intrusion as defined by Johnson and Viezee (1981)). ~~The In addition, the case studies depict elevated O<sub>3</sub> rich air at 500 hPa north of the WCB from either a parent low pressure system (e.g., the N1 cyclone case study) or an upstream decaying cyclone (e.g., the S1 and N2 cyclones) which can become entrained within the cyclone; this is a strong feature in the NA composite of is now identified as aged stratospheric cyclones as there is elevated O<sub>3</sub> entrained from downwind cyclones as seen in the S1 and N2 cyclone life cycles. (up to 5 ppbv greater than the background composite) similarly to the north of the NA composite cyclone center, not within the main DI airstream and separated from the O<sub>3</sub>-poor WCB, that wraps cyclonically around the composite cyclone~~ (Knowland et al., 2015).

## 6 Conclusions

We have shown that passing cyclones have a discernible influence on surface O<sub>3</sub> concentrations; especially when cyclones track north of 53° N, there is a significant probability that the surface O<sub>3</sub> at Mace Head will be high (> 75<sup>th</sup> pc). Cyclones are more likely to be associated with both low O<sub>3</sub> (< 25<sup>th</sup> pc) and high O<sub>3</sub> if the cyclones track to the south of the observation site or if the cyclones are to the west of the observation site.

The four case studies demonstrate the main drivers associated with cyclones that impact surface O<sub>3</sub> concentrations: a) the importance of the passage of a cyclone's cold front to influence surface O<sub>3</sub> measurements, b) the ability of cyclones to bring down high levels of O<sub>3</sub> from the stratosphere and c) that accompanying surface high pressure systems play an important role in the temporal variability of surface O<sub>3</sub>. From these four case studies we have seen that the location of the different fronts at different stages in the cyclone life cycle influence the surface O<sub>3</sub> reported at these two observation sites. Specifically:

- Prior to the passing of the N1 and N2 cold fronts, low-level, O<sub>3</sub>-poor subtropical air within the WCB arrived from the southwest to Mace Head and Monte Velho, respectively. After the cold fronts had passed over the respective observation site, high surface O<sub>3</sub> was reported.



- The N1 cyclone showed a direct connection with stratospheric O<sub>3</sub>-rich air descending within the DI airstream which reaches Mace Head after the cold front passes. Within the S1 and N2 cyclones, there is aged stratospheric O<sub>3</sub>-rich air entrained from previous downwind cyclones. This O<sub>3</sub>-rich air subsequently descends within the strong cyclone and impacts the surface O<sub>3</sub> observations after the cold front has passed over the site. Strong descent of stratospheric O<sub>3</sub> within the DI airstream occurs within moderately strong cyclones outside the main storm track as demonstrated during the lifetime of the moderately strong S2 cyclone to the south of Monte Velho.
- During the life cycles of the S1 and N2 cyclones, there are blocking high pressure systems in the western NA which cut off any transport of O<sub>3</sub>-rich air from upstream sources. An important descent mechanism was identified during the life cycle of the S2 cyclone, whereby subsidence and accumulation of O<sub>3</sub>-rich air within the neighboring Azores High pressure system impacted O<sub>3</sub> measurements at Monte Velho while the S2 cyclone tracked over northwest Africa.

This study has shown that there are diverse cyclone-related dynamical processes which influence the variability of surface O<sub>3</sub> levels at two remote European coastal measurement sites on short time scales of hours to days. In addition, the spatial variability in the low and high pressure systems over the North Atlantic can distinctly influence the O<sub>3</sub> values observed at near sea level.

- 15 *Data availability.* This study used publicly available O<sub>3</sub> observations supported by EMEP (<http://actris.nilu.no>). The ERA-Interim reanalysis and the MACC reanalysis are available for download from ECMWF (<http://apps.ecmwf.int/datasets/>). The MERRA-2 reanalysis data is available through the NASA GES DISC online archive (<https://disc.gsfc.nasa.gov/uuui/datasets>). The GEOS-5 STFR data will be provided upon request by Lesley Ott.

*Competing interests.* There are no competing interests.

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