Sea ice and oxygen

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Research Article

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Abstract

1) Atmospheric oxygen cycles on a seasonal basis, as does carbon dioxide.  2) Photosynthesis is likely contributing
to these cycles, but the dominant spatial regions are unknown and the contribution of marine plankton has been
assumed to be small.  3) I test and confirm the prediction that seasonal sea ice and oxygen rates are highly coherent
at high latitudes, with peak oxygen emission in months of peak rates of sea ice loss within each Hemisphere.  4) The
similarity of oxygen dynamics in Northern and Southern Hemispheres is consistent with the dominant seasonal
fluxes of oxygen and carbon dioxide being marine.  5) The similar dynamics of oxygen and argon are also consistent
with the dominant seasonal fluxes of oxygen being marine.  6) No stronger similarity has yet been found between
seasonal changes in oxygen and terrestrial productivity (NDVI), but much more detailed comparison is required.  7)
Air temperature near the Poles is very closely synchronized with the seasonal rate of change of oxygen at high
latitudes.  8) These results are consistent with a hypothesised major influence of Arctic plankton in the seasonality of
‘global’ oxygen levels.  9) Determining causality requires far more observations and experimentation.  10) These
results provide further evidence that polar phenomena have been neglected in studies of the oxygen and carbon
cycles and are consistent with a proposed major role of high latitudes in these cycles.

Keywords  Argon • Carbon dioxide • Cycles • Plankton • Polar • Phenology • Productivity • Seasonal • Ventilation

Introduction

Atmospheric oxygen has seasonal cycles (Keeling & Shertz 1992; Bushinsky et al 2017; Scripps O2 Program 2022).
Since most free oxygen is of biological origin these cycles are assumed to be driven by photosynthesis and thus to
some extent mirror the seasonal cycle of carbon dioxide (Keeling & Manning 2014). Understanding the oxygen
cycle will require understanding the carbon cycle and involve disentangling biotic and abiotic fluxes. Potential
abiotic fluxes of oxygen may also be explored by comparisons with seasonal cycles of argon which are widely
accepted to be caused by abiotic marine fluxes (Cassar et al 2008; Hambler 2023).

It is widely assumed that seasonal cycles of oxygen in the Southern Hemisphere are of largely marine origin (Keeling
& Shertz 1992; Keeling & Manning 2014; Bushinsky et al 2017) because the Southern Hemisphere has relatively
little seasonal terrestrial vegetation. If the Northern Hemisphere cycles of oxygen are similar to (but in antiphase
with) the Southern Hemisphere cycles then I propose oxygen fluxes in the Northern Hemisphere may also be
dominated by marine processes and by plankton.

Oxygen flux is partly decoupled from photosynthetic carbon dioxide flux through processes such as abiotic and
biotic calcium carbonate production (Rysgaard et al 2007, 2011, 2013; Fransson et al 2011; Geilfus et al 2013,
2015; Papakyriakou & Miller 2011; Keeling & Manning 2014; Hambler & Henderson 2020a; Keeling & Graven
2021). Carbon dioxide availability may limit some phytoplankton in some regions (Rivero-Calle et al 2015).
Solubility of oxygen in sea water varies with temperature (Keeling & Manning 2014; Manning & Keeling 2006;
Bushinsky et al 2017) as does carbon dioxide (Wiesenburg & Guinasso 1979) and argon (Cassar et al 2008;

Volcanoes release carbon dioxide and argon. Gas bubbles of varying compositions can form and move in sea ice (Crabeck et al 2014, 2016, 2019; Zhou et al 2013). Carbon dioxide flux (inverted) is thus insufficient to monitor oxygen flux. Flux rates of these gases would not be expected to co-vary precisely, but drivers of carbon dioxide flux will probably have some effect on oxygen flux.

Globally representative carbon dioxide levels at Mauna Loa, Hawaii, cycle in a famous 'sawtooth' curve (Keeling et al 2005; IPCC 2013). These cycles have been presumed to be driven by cycles of terrestrial productivity, particularly in the large land masses of the Northern Hemisphere (Keeling 1960, 2008; Keeling et al 2005; Peterson et al 1987; Denning et al 1995; Dettinger and Ghil 1998; Keeling et al 2001, 2005; Schaefer et al 2005; Buermann et al 2007; Ciais et al 2013; Graven et al 2013; Zhao & Zeng 2014; Keeling & Manning 2014; Barlow et al 2015; Yin et al 2018; Franey et al 2019; Haverd et al 2020; Keeling & Graven 2021; IPCC 2021). Marine plankton have been assumed to have low or negligible effect on the 'global' seasonal cycle of atmospheric carbon dioxide as measured at Mauna Loa (Keeling et al 2001; Gruber et al 2009; Monroe 2013; Haverd et al 2020. High-latitude fluxes of carbon dioxide have been identified (e.g. Semiletov et al 2004, 2007; Geilfus et al 2012; Brown et al 2015; Bushinsky et al 2017) and it has been argued that plankton are largely responsible (Takahashi et al 1993, 2009) although in some regions and timescales inorganic processes dominate (e.g. Semiletov et al 2007; Nomura et al 2010; Rysgaard et al 2011; Søgaard et al 2013; Brown et al 2015). The Arctic flux has been suggested to contribute little to the overall atmospheric flux of carbon dioxide (e.g. Brown et al 2015) and thus might be presumed of little importance to global oxygen flux.

However, there is evidence that the role of sea ice may have been neglected and indeed may dominate the cycles of atmospheric carbon dioxide (Nelson & Nelson 2016; Hambler & Henderson 2020a, 2022), of methane (Hambler & Henderson 2020b, 2022) and of argon (Hambler 2023). I therefore predict that sea ice extent changes will be strongly inversely correlated with oxygen flux within a year, at least at high latitudes. I predict oxygen dynamics will have some similarity in seasonal timing (phenology) to argon dynamics since argon is released in the spring melt of ice (Moreau et al 2014; Zhou et al 2014; Tison et al 2016) and when the ocean warms (Cassar et al 2008). Gas dynamics in sea ice regions are very hard to sample, contributing to a serious deficit of data and a very urgent need for further research (Rysgaard et al 2011; Søgaard et al 2013; Vancoppenolle et al 2013; Crabeck et al 2014; Moreau et al 2016; Vancoppenolle & Tedesco 2016; Tison et al 2016; Bushinsky et al 2017, 2019; MOSAiC 2019; Angelopoulos et al 2022).

In this study I examine data on atmospheric oxygen from a global monitoring program (Scripps O2 Program, 2022). I address five main questions:

1) Do seasonal cycles of atmospheric oxygen rates of change vary inversely with those of carbon dioxide?
2) Do seasonal cycles of atmospheric oxygen rates of change vary inversely with those of sea ice extent?
3) Do seasonal cycles of atmospheric oxygen rates of change vary with those of terrestrial productivity?
4) Do seasonal cycles of atmospheric oxygen rates of change vary with those of argon?
5) Do seasonal cycles of atmospheric oxygen rates of change vary with polar air temperatures?
## Methods

### Datasets

I use the datasets in Table 1.

### Table 1 Data sources

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source</th>
</tr>
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<tr>
<td>Atmospheric O$_2$/N$_2$</td>
<td><a href="https://scrippso2.ucsd.edu/data.html">https://scrippso2.ucsd.edu/data.html</a></td>
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<tr>
<td>Atmospheric CO$_2$</td>
<td>'per meg' = delta O2/N2 from interferometer; corrected for CO$_2$ interference</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ concentration (ppm) as measured on Siemens; corrected for non-linearity and primary drift</td>
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<tr>
<td></td>
<td>Scripps O$_2$ Program <a href="https://scrippso2.ucsd.edu/index.html">https://scrippso2.ucsd.edu/index.html</a></td>
</tr>
<tr>
<td></td>
<td>'Monthly' data accessed 17 September 2022 (or 1 February 2023 if so indicated in Appendix 1)</td>
</tr>
<tr>
<td></td>
<td>'Bimonthly' data accessed 24 August 2022</td>
</tr>
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<td>ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/</td>
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<tr>
<td></td>
<td>(Fetterer et al 2017)</td>
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<td>'North' (= 'Arctic'):</td>
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<tr>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>Accessed 19 February 2022</td>
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<tr>
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<td>MASIE NSIDC/NIC Sea Ice Product G02186 - Daily Ice Extent by Region in Square Kilometers</td>
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<tr>
<td></td>
<td>Accessed 5 February 2020</td>
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<tr>
<td>NDVI (Normalized Difference Vegetation Index)</td>
<td>MDOIS satellite imagery MOD13C2 product as 5 kilometre monthly mean global imagery</td>
</tr>
<tr>
<td>Monthly mean</td>
<td>Accessed July 2019</td>
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<tr>
<td>Alert air temperature</td>
<td>NCEP Reanalysis Dataset</td>
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<tr>
<td>Monthly mean</td>
<td>Produced at NOAA Physical Sciences laboratory</td>
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<tr>
<td></td>
<td>Accessed 6 January 2021</td>
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<tr>
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<td>Monthly mean</td>
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<td>Accessed 1 February 2023</td>
</tr>
</tbody>
</table>
Atmospheric sampling locations

Atmospheric oxygen levels are routinely monitored at ten recording stations, simultaneously with those of carbon dioxide, as part of a study of global oxygen dynamics (Scripps O₂ Program 2022).

I predict seasonal cycles of oxygen will be pronounced where those of carbon dioxide are pronounced, particularly the Northern Hemisphere high-latitude recording sites. I therefore examine Alert, Canada, and Point Barrow, Alaska ('Barrow') where gas dynamics have been considered in detail and compared to other sites (Peterson et al 1987; Semiletov et al 2004, 2007; Keeling et al 2005; Graven et al 2013; Barlow et al 2015; Hambler & Henderson 2020a,b, 2022).

I predict the oxygen cycle in the southern high latitudes will be in antiphase with the Northern Hemisphere, and select Cape Grim (Tasmania), Palmer Station (Antarctica) and the South Pole as the most suitable sites from those available in the Scripps data.

Other recording sites in the Scripps O₂ Program are considered here in less detail, and those with no data after 2006 (when the sea ice data start) are not included.

In the data sets used, oxygen is measured in flasks as 'per meg', technically $\delta$($O_2/N_2$) multiplied by $10^6$ (Keeling & Manning 2014; Scripps O₂ Program 2022). Changes in this ratio are assumed largely due to changes in $O_2$ because $N_2$ sources and sinks are much lower than for $O_2$ (Scripps O₂ Program 2023). Carbon dioxide is measured in flasks in parts per million (ppm).

I consider rates of change of atmospheric gases more informative for the purposes of identifying flux locations than are the raw data on the levels of these gases (Hambler & Henderson 2020a, 2022). Two data sets are available from the Scripps O₂ Program: a) The 'bimonthly' set, where intervals between samples of oxygen and carbon dioxide at the Scripps sites are nominally 'bimonthly' (approximately twice per month) but approximately weekly at Mauna Loa. These intervals vary slightly, with some missing dates in either time-series. For these data I calculate the rate of change of each gas 'per sample interval', i.e. between sample dates: the value in date two minus the value in date one, plotted for date two. b) The 'monthly' set, where data of unspecified frequency are given as a monthly average adjusted to a fixed date (mid-month) and are smoothed relative to the 'bimonthly' set. 'Monthly' rates of change of gas are derived from extent in month two minus extent in month one, plotted in month two.

Sea ice

Sea ice extent data were chosen to be directly comparable with previous work on carbon dioxide and methane dynamics (Hambler & Henderson 2020a,b, 2022). For 'Arctic' and 'Antarctic' sea ice extents I use data from National Snow and Ice Data Center (NSIDC) for the 'North' and 'South'. For a 'global' sea ice monthly extent I sum Arctic and Antarctic monthly extents, as per Hambler & Henderson (2022).

I also use sea ice extent for the 'Greenland Sea', a sub-region for the Arctic previously found to have particularly high correlation with carbon dioxide flux (Hambler & Henderson 2020a). These data were obtained from MASIE at 4 km resolution for the Greenland Sea (mapped at ftp://sidads.colorado.edu/DATASETS/NOAA/G02186/). Sea ice extent
rate is measured in square kilometres per month. Rates of change of ice are derived from extent in month two minus extent in month one, plotted in month two.

**NDVI and terrestrial productivity**

Some aspects of terrestrial primary productivity are monitored using NDVI (e.g. Buermann et al 2007; IPCC 2021). High net emission of oxygen on land might be expected in seasons when plants are greening fast or are most green (i.e. the monthly NDVI rate or the NDVI value is high). As described in previous work (Hambler & Henderson 2020a), data for Normalized Difference Vegetation Index (NDVI) were obtained for the Northern Hemisphere from the MODIS satellite imagery MOD13C2 product as 5 kilometre resolution monthly mean global imagery (Didan 2015) for January 2001 to May 2019. Mean values (provided with a scale factor of 10,000) for the defined areas were extracted using the Zonal Statistics function of ESRI's ArcMap 10.4. Rates of change of NDVI are derived from extent in month two minus extent in month one, plotted in month two. Previous work has shown peak rates of change of NDVI have similar phenology in a range of regions of the Northern Hemisphere (Figure 12 in Hambler & Henderson 2020a) and I focus here on two areas: 'North America and Eurasia, 35 - 70 degrees North' (denoted NAEUAS3570) and 'Northern Hemisphere, 0-70 degrees North' for ease of comparison with that work.

**Temperature**

I use monthly average air temperature data for the South Pole and for Alert, Canada to enable direct comparison with similar studies on carbon dioxide and methane (Hambler & Henderson 2022). These are two long-term recording stations at very high latitudes.

**Time-series durations and gaps**

For ease of comparison I choose time-series durations similar to those used in previous research on carbon dioxide and sea ice (Hambler & Henderson 2020a, 2022). Sea ice extent data with consistent methodology are readily available for the Arctic and Antarctic from November 1978 but for regions of the Arctic only from early 2006, which is therefore used as the start date in many comparisons presented here. Examinations of sea ice, temperature and gas rates (Hambler & Henderson 2020a,b, 2022) suggest the length of the time-series makes little difference to the clarity of strong relationships between variables and that plots of long time-series compress the detail of the curves making comparisons less easy. For the South Pole, monthly oxygen rate data are continuous from July 2001, enabling full annual cycles to be compared from 2002 to 2022 inclusive.

Alignment of time-series of 'bimonthly' gas data with monthly sea ice data in graphs is complicated by different sample dates and intervals, but is done here as an approximation by using a secondary horizontal axis in Excel of the same date span as the primary horizontal axis. When a date has missing data from either oxygen or carbon dioxide series, I delete the rates for both gases: this reduces artefactual differences between curves for the gases but leaves a gap in the graph for each gas at that date and the next. Simultaneous gaps in recording for both gases are treated as any other sample interval. Since the sample dates of oxygen and carbon dioxide in flasks are generally the same, the rates of change per interval in 'bimonthly' data will be partially an artefact of sample interval; an example is noted in some of the Figures. However, the general pattern and the strongest peaks are likely to be evident with sampling that was fairly consistently spaced. Measures of oxygen are assumed otherwise independent of those of carbon dioxide and argon.

No formal statistical analyses are performed: these would be complicated due to missing data points, differing sample dates and other issues. However, I suggest patterns evident on visual inspection would merit detailed subsequent analysis and invite others to attempt this. Strong visual similarity of seasonal phenologies of sea ice and
carbon dioxide rates invariably have very high statistical correlations (Hambler & Henderson 2020a,b, 2022). I do not compare all variables at all sites, but select examples which illustrate the desirability of more detailed and systematic work.

Moving averages of variables were plotted using Microsoft Excel (version 2210) to smooth the noisy oxygen and argon data for some graphs (Appendix 1); the average for the preceding 6 months is plotted in month 6. When data were missing from one time-series, data in the other time-series were deleted for the same dates. This generates artefacts in the curves; years for which the 6 month average includes gaps are indicated in the Figures so that amplitudes in those years can be ignored.

Results

Seasonal cycles of the oxygen level at Mauna Loa are shown in Fig. 1.

**Fig. 1** Level of atmospheric oxygen at Mauna Loa, Hawaii (monthly average data from Scripps O2 Program).
Oxygen rates at Alert are compared with those of carbon dioxide in 'bimonthly' data in Figs. 2 and 3. Equivalent graphs for other recording sites are given in version 1 of this paper: https://doi.org/10.21203/rs.3.rs-2045347/v1

**Fig. 2** Rates of change of oxygen and carbon dioxide per sample interval, Alert, Canada. 'Bimonthly' data. Note a gap in recording of over 2 months at the end of 2009 creates an artefact.

**Fig. 3** Rates of change of oxygen and carbon dioxide (inverted axis) per sample interval, Alert, Canada. 'Bimonthly' data. Note a gap in recording of over 2 months at the end of 2009 creates an artefact.
'Global' oxygen rate and carbon dioxide rate, as measured at Mauna Loa, are compared using monthly data in Fig. 4.

Fig. 4 Rates of change of oxygen and carbon dioxide (inverted axis), Mauna Loa, Hawaii. 'Monthly' data. Outlier values cut off; zeros on y axes not aligned. Note overlapping linear trendlines for oxygen (green dots) and carbon dioxide (black dots).

Rates of change of oxygen, carbon dioxide, sea ice and temperature are most easily compared visually, as in Figs. 5 - 23. Sites are listed from north to south, and the latitude and longitude of the recording station is given in the captions.

Fig. 5 Comparison of Arctic sea ice extent rate (inverted axis) and oxygen rate, Alert, Canada (82N, 62W).
Fig. 6 Comparison of Greenland Sea sea ice extent rate (inverted axis) and oxygen rate, Alert, Canada (82N, 62W).

Fig. 7 Comparison of NDVI rate for North America and Eurasia, 35-70 degrees North and oxygen rate, Alert, Canada (82N, 62W).
Fig. 8 Comparison of air temperature and oxygen rate, Alert, Canada (82N, 62W).

Fig. 9 Comparison of Greenland Sea sea ice extent rate (inverted axis) and oxygen rate, Point Barrow, Alaska (71N, 157W).
**Fig. 10** Comparison of NDVI rate for North America and Eurasia, 35-70 degrees North and oxygen rate, Barrow, Alaska (71N, 157W).

**Fig. 11** Comparison of Greenland Sea sea ice extent rate (inverted axis) and oxygen rate, Cold Bay, Alaska (55N, 163W).
Fig. 12 Comparison of Greenland Sea ice extent rate (inverted axis) and oxygen rate, La Jolla Pier, California (33N, 117W).

Fig. 13 Comparison of Greenland Sea sea ice extent rate (inverted axis) and oxygen rate, Cape Kumukahi, Hawaii (19.5N, 155W).
Fig. 14 Comparison of Greenland Sea sea ice extent rate (inverted axis) and oxygen rate, Mauna Loa, Hawaii (19.5N, 156W). Outlier values cut off; zeros on y axes not aligned. Note trendline for oxygen (green dots).

Fig. 15 Comparison of NDVI rate for North America and Eurasia, 35-70 degrees North and oxygen rate, Mauna Loa, Hawaii (19.5N, 156W). Outlier values cut off.
Fig. 16 Comparison of NDVI rate for Northern Hemisphere, 0-70 degrees North and oxygen rate, Mauna Loa, Hawaii (19.5N, 156W). Outlier values cut off.

Fig. 17 Comparison of NDVI level for Northern Hemisphere, 0-70 degrees North and oxygen rate, Mauna Loa, Hawaii (19.5N, 156W). Outlier values cut off.
Fig. 18 Comparison of 'Arctic plus Antarctic' sea ice extent rate (inverted axis) and oxygen rate, Mauna Loa, Hawaii (19.5N, 156W). Outlier values cut off; zeros on y axes not aligned.

Fig. 19 Comparison of Antarctic sea ice extent rate (inverted axis) and oxygen rate, American Samoa, Pacific Ocean (14.5S, 170W). Outlier values cut off.
Fig. 20 Comparison of Antarctic sea ice extent rate (inverted axis) and oxygen rate, Cape Grim, Tasmania (41S, 150E).

Fig. 21 Comparison of Antarctic sea ice extent rate (inverted axis) and oxygen rate, Palmer Station, Antarctic Peninsula (65S, 64W).
Fig. 22 Comparison of Antarctic sea ice extent rate (inverted axis) and oxygen rate, South Pole (90S, 0E).

Fig. 23 Comparison of air temperature and oxygen rate, South Pole (90S, 0E)

Supplementary figures selected as examples of strong patterns are given in Appendix 1 (Figs. A1 - A14). Comparisons between oxygen and argon rates (6 month running means) are given in Figs. A1 - A11. Scatter plots are given for Alert oxygen rate against Arctic sea ice extent rate against (Fig. A11) and for Palmer oxygen rate against Antarctic sea ice extent rate (Fig. A12). Long time-series are illustrated for the South Pole oxygen rate against Antarctic sea ice extent rate (Fig. A13) and South Pole oxygen rate against South Pole air temperature (Fig. A14); the South Pole has the longest uninterrupted oxygen record, enabling amplitudes of running means to be examined more easily.
Discussion

The seasonal variation of oxygen and carbon dioxide is generally inversely and strongly coherent (Figs. 2 - 4). This suggests either photosynthesis drives both rates, or that other variables which are highly correlated with one or both of these gases drive them. For the high-latitude sites, the timings of the greatest positive and negative rates in the seasonal cycle of carbon dioxide from the ‘bimonthly’ data are visually similar to those of monthly flask data from other data sets (Dlugokencky et al 2019; Hambler & Henderson 2020a, 2022), suggesting the peak rates are not merely an artefact of uneven sample intervals. Nevertheless, the coincidence of peaks and troughs in oxygen and carbon dioxide rates needs to be interpreted with caution, given that longer intervals for both could lead to larger apparent flux rates for both. An example of such an artefact is given in Figs. 2 and 3. Given the irregularity evident in some tropical time-series (Figs. 14 and 19) it would be valuable to have many more long-term monitoring sites for oxygen if subtle patterns and regional fluxes are to be detected.

A proposed dominant marine flux of oxygen is supported by the similarities between the Hemispheres. The very closely similar relationship between sea ice and oxygen evident in both Hemispheres (e.g. Figs. 5 and 22) also implies that further consideration should be given to the possibility of a largely marine origin of the Northern Hemisphere oxygen cycle.

At high latitudes, atmospheric oxygen rates of increase tend to be highest when sea ice is decreasing fastest within a year, and vice versa (Figs. 5 - 23; Fig. A13, Appendix 1). On visual inspection, it appears there may be a similar relationship between years, with very high peak ice melt rates often simultaneous with very high oxygen emission in at least in some sites - but confirmation would require complex statistical testing. Some similarities of carbon dioxide rate amplitudes and sea ice rate amplitudes have already been illustrated (Hambler & Henderson 2020a, 2022). At times when sea ice extent is not changing, regional rates of change of oxygen are also very near zero (e.g. Figs. A11 and A12, Appendix 1).

Oxygen levels might rise as sea ice declines seasonally because photosynthesis can increase. Sea ice and snow melt supports plankton in the photic zone (Ji et al 2013; Tremblay et al 2012, 2015; Vancoppenolle et al 2013; Leu et al 2015). Marine productivity in some high-latitude regions has narrow peaks after ice melt (Leu et al 2015). Ice-edge and under-ice algae have strong synchrony with ice melt (Semiletov et al 2004, 2007; Vancoppenolle et al 2013; Barber et al 2015; Tremblay et al 2012; Bai et al 2019). Seasonal drawdown of carbon dioxide has been ascribed at least in part to phytoplankton and to autotrophs in sea ice (e.g. Ishii et al 2002; Semiletov et al 2004, 2007; Bakker et al 2008; Nomura et al 2014; Legge et al 2015; Roden et al 2016; Bushinsky et al 2017; Fransson et al 2011, 2017; Ouyang et al 2020). However, overall Arctic productivity is estimated to be much larger than ice-edge algal productivity (Barber et al 2015; Vancoppenolle et al 2013).

Changes in ice cover may influence oxygen through other processes: for example it may enable or reduce upwelling and ventilation of deep water rich in nutrients and methane but also depleted of oxygen (Verdy et al 2007; Rysgaard et al 2011; Annett et al 2015; Bushinsky et al 2017, 2019; Zhang et al 2017; Ouyang et al 2020; Hambler & Henderson 2020b). Sea ice may, however, be a proxy for some other seasonal process such as light availability, temperature of air or sea, wind direction or even terrestrial productivity. Many biological and abiotic processes have sharp seasonal peaks which could be unrelated or interactive. An inverse relationship between oxygen and carbon dioxide (Figs. 2 - 4) could arise if abiotic factors influence these gases in different ways, although this is less parsimonious than a link through photosynthesis. Ventilation of deep water undersaturated in oxygen likely drives a high-latitude seasonal Southern Ocean oxygen sink, corresponding with a carbon dioxide source (Bushinsky et al 2017; Gray et al 2018). Some abiotic drawdown of carbon dioxide as sea ice melts (Hambler & Henderson 2020a, 2022) is not incompatible with a rise in plankton activity at this time.
Links between oxygen, sea ice and other variables may have escaped detection in part because marine productivity can be highly variable between years (McGowan et al 1998; Goes et al 2004; Corbière et al 2007; Semiletov et al 2007; Mundy et al 2009; Wang et al 2009; Sejrr et al 2011; Tremblay et al 2011, 2012; Kim 2012; Rosso et al 2017; Bushinsky et al 2017; Del Castillo et al 2019). Regional data deficiencies make isolation of the potential drivers very difficult (Mathis et al 2010; Gregg et al 2014; Roden et al 2016; Bushinsky et al 2017; Hammond et al 2017; Rosso et al 2017; Frey et al 2018; Bai et al 2019). Satellite, aircraft and float observations of some key variables (such as plankton density, sea ice algal productivity, oxygen and carbon dioxide fluxes) are as yet very sparse in high latitudes (Rysgaard et al 2011; Liang et al 2017; Gray et al 2018; Bushinsky et al 2017, 2019; Pinkerton & Hayward 2021; Stephens et al 2021) and remote sensing may not quantify under-ice productivity (Tremblay et al 2012).

The sea ice extent rate in the Arctic as a whole has visually closely synchronous major peaks and troughs to those of oxygen rate at high latitudes such as Alert (Fig. 5 and Fig. A13, Appendix 1). However, Greenland Sea ice extent by itself shows very similar phenology to oxygen rates at Alert, Barrow and even the much more remote La Jolla Pier (Figs. 6, 9, 12). This may result from the substantive fluxes of nutrients in this Sea as well as to its dramatic temperature variations (Shuchman et al 1998; Miller et al 1999; Beszcynska-Möller et al 2012; Kawasaki & Hasumi 2016; Hambler & Henderson 2020a; Selyuzhenok et al 2020). Features such as the Greenland Odden (sea ice tongue) are very dynamic and reflect particularly air temperature, with weaker correlations with wind speed and wind direction (Shuchman et al 1998; Rogers & Hung, 2008). I hypothesise such local and transient transient sea ice features are causing variation in oxygen, carbon dioxide and methane fluxes in the Arctic winter despite little change in light or primary productivity in those months. At Barrow, whilst carbon dioxide has very tight synchrony with Greenland Sea ice (Hambler & Henderson 2020a), oxygen rate leads Greenland Sea ice rates very slightly (Fig. 9) as with methane (Hambler & Henderson 2020b); this suggests various biological and abiotic processes may proceed at different rates as the ice melts, or different Arctic regions are most important for different gases (or that there are different monthly averaging methods). Remote sensing of ice extent may not be detecting some relevant changes in or beneath the sea ice. Other Arctic sea ice regions might have tighter or weaker synchrony with oxygen, as they do with carbon dioxide (Hambler & Henderson 2020a) and methane (Hambler & Henderson 2020b).

Similarities of fine detail in the gas and sea ice rate curves may help identify key regions despite many variables being strongly correlated at high latitudes (Hambler & Henderson 2022).

The monthly rates of change of oxygen are less well synchronized with monthly rates of change of terrestrial productivity as measured imperfectly by NDVI, lagging them by a month or two in the Northern Hemisphere (Figs. 10, 15, 16). Much closer synchrony is obtained with peak absolute levels of NDVI and oxygen rate (Fig. 17), as with carbon dioxide rate (Figure 18 in Hambler & Henderson 2020a). I suggest the fine detail of the negative and growth phase of oxygen rate does not have such a good visual match with NDVI rate (e.g. Figs. 10, 16) as it does with sea ice rate (e.g. Figs. 9, 18). It is rare for both the peak positive and peak negative rates of the oxygen and NDVI to coincide within a cycle - unlike for sea ice rates. This could reflect the measure of productivity used, the geographical areas selected for NDVI, or other factors - so better fits might be possible with other variables. Systematic comparison of gas rates (at many recording sites) with NDVI in numerous latitudinal and longitudinal zones (building on Buermann et al 2007) might reveal stronger correlations, as might satellite observations of gas rates.

The similarities between oxygen and argon and sea ice suggest the drivers of the dynamics of these gases are at high latitudes (whether sea ice is involved or not). The strong similarities between the annual cycles of oxygen rates and argon rates also suggest a dominant marine source of oxygen since argon cycles are marine in origin. The similar dynamics of oxygen dynamics and argon, a biologically inert gas, might indicate shared abiotic drivers. Both oxygen and argon have ‘noisy’ seasonal curves but when smoothed with 6 month moving averages the very strong similarity in phase of the two gases is apparent (Figs. A1- A10, Appendix 1). Any similarities in amplitude would be complex
to test at most sites due to missing data. Oxygen dynamics in southern high-latitude sites are also very tightly in
phase with the South Pole air temperature (Fig. 23, and smoothed in Fig. A14, Appendix 1), consistent with the
hypothesis that high-latitude temperature is a fundamental driver with predictive power for the global oxygen cycle.

Mauna Loa is often considered a good site to measure 'global' levels of atmospheric gases such as carbon dioxide and
methane - both of which have strong correlations with sea ice rates (Hambler & Henderson 2020a,b, 2022). It is
therefore used in this study as arguably the best available measure of 'global' oxygen levels. Peak positive oxygen
rates tend to occur around mid-year (Fig. 14), coincident with peak negative rates of carbon dioxide at about August
at this site (Fig. 4 and Hambler & Henderson 2020a). There are also often highly negative oxygen rates near
January. Enlarging the axis for oxygen rate to remove an outlier (Figs. 1 and 14), the detailed pattern of rate of
change of oxygen is visually similar to the Greenland Sea ice rate, but also often has the twin peak similar to the twin
peaks of global sea ice rate ('Arctic plus Antarctic', Fig. 18), with the putative Antarctic-induced peak being lower.

The Mauna Loa oxygen rate is lagged about 7 months behind the 'global' sea ice rate, as with carbon dioxide
(Hambler & Henderson 2020a, 2022), which I propose reflects lags in gas molecules reaching this low-latitude and
high-altitude site from polar regions. A revision of the putative locations of major oxygen fluxes would have
relevance to identifying the regions involved in determining and predicting 'global' oxygen levels and trends.

All other atmospheric recording stations in the Scripps O2 Program have been briefly examined (Figs. 1 - 23 and
Hambler, unpublished). In general, high-latitude sites in the north resemble Alert (Fig. 5), whilst high-latitude sites
in the south are more similar to Palmer (Fig. 21). Northern high-latitude sites have relatively high amplitudes in
oxygen rates, as with amplitudes in oxygen levels (Keeling & Manning 2014). Southern high-latitude sites appear
dominated by net absorption of oxygen punctuated by brief seasonal emission, consistent with data from floats
(Bushinsky et al 2017). Low-latitude sites have less clear seasonal patterns, consistent with the dominant drivers of
cycles being at high latitudes as proposed with carbon dioxide (Hambler & Henderson 2020a): any seasonal signal
from near the poles has perhaps been attenuated and merged with signals from other sources and sinks of oxygen.

American Samoa shows a complex pattern due to multiple regional influences (Manning et al 2003), but with
possibly a weak Antarctic imprint (Fig. 19). Despite the limited number of sites with long time-series for oxygen,
the similarity of the high-latitude sites to each other (within a Hemisphere) suggests that there are large air masses
with similar chemical properties near each Pole, as also suggested for carbon dioxide and methane (Hambler &
Henderson 2020a, 2022) and argon (Hambler 2023). All recording sites merit more detailed attention.

The annual rate of change of oxygen is very stable over recent decades, with a trend near zero (Figs. 1, 4, 14). This
steady decline in oxygen level is consistent with a large-scale driver of the trend having high inertia despite the inter-
annual variation in regional source and sink rates. Typically the decline has been linked to fossil fuel combustion
(Keeling et al 2014). However, as with a similarly stable carbon dioxide rate (Fig. 4; Hambler & Henderson 2022),
I suggest this may involve very large-scale ocean processes including upwelling and ventilation of water low in
oxygen and high in carbon dioxide (as in regions of the Southern Ocean, Bushinsky et al 2017; IPCC 2021). As a
provocative thought experiment, these results would be consistent with a highly controversial paradigm of general
oceanic absorption of oxygen over recent decades (driven by ocean ventilation), punctuated by sharp seasonal
emission (dominated by planktonic productivity, especially in the Arctic). This would be the converse of the pattern
for carbon dioxide, for which marine thermal outgassing may also contribute to a decadal trend (Hambler &
Henderson 2022). Better quantification is required for many parameters in the oxygen cycle to exclude some
potential drivers.

Conclusions

The similarities of Northern and Southern Hemispheres, and of seasonal oxygen and argon dynamics, are most
simply explained if the dominant seasonal fluxes of oxygen are marine in both Hemispheres - contrary to prevailing
models. The lower similarity of oxygen seasonality to terrestrial vegetation dynamics strengthens this conclusion.
Similarities with sea ice dynamics and polar temperature cycles suggest the dominant seasonal fluxes of oxygen are from relatively high-latitudes. The particularly clear seasonal cycles at high latitudes further support a high-latitude and likely temperature-dependent driver or drivers of oxygen and carbon dioxide dynamics within years. Areas near Greenland may be particularly important. If sea ice is found to be a major driver of oxygen flux - rather than a strong proxy for it - then seasonal carbon dioxide fluxes may also be strongly influenced by the marine biota (as well as by abiotic processes such as temperature-dependent degassing and calcium carbonate crystallization).

Marine plankton merit much greater attention in quantification of the oxygen and carbon cycles. A number of biotic and abiotic processes may interact positively or negatively to deliver the net seasonal oxygen flux in polar regions and globally. Much more detailed observation and analysis is required to quantify the individual contributions of several tightly synchronized high-latitude phenomena including sea ice, marine productivity and terrestrial productivity. Understanding the relatively erratic ‘global’ cycle of oxygen as measured at Mauna Loa will require many more regional measures of flux rates, and improved remote sensing.

An implication of plankton dominating the seasonal cycles of oxygen and carbon dioxide would be that increased terrestrial photosynthesis in the spring and summer is largely offset by increased terrestrial respiration at those times. In contrast, in the marine environment sinking detritus may decompose at any time. Earth system and climate models assuming large terrestrial fluxes of carbon dioxide need to be re-evaluated.

In addition to helping elucidate the carbon cycle and the regional sources and sinks of carbon dioxide, changes to seasonal fluxes of oxygen in the high-latitude oceans might have implications for longer term trends in the oxygen level.

Whilst the patterns I identify help suggest some potential drivers, other variables must be considered and substantive experimental work is required to test causality.

**Declarations**

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**Conflict of interest / Competing interest** The author declares he has no conflict of interest / competing interests.

**Availability of data and material** Data are available online from the providers indicated in the Methods.

**Code availability** Not applicable.

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Appendix 1.

**Fig. A1** Amplitudes for 2008, 2009 and 2010 are artefacts due to missing data. Note lag due to 6 month moving averages.

**Fig. A2** Amplitudes for 2010 and 2011 are artefacts due to missing data. Note lag due to 6 month moving averages.

Fig. A4 Amplitudes for 2006 - 2020 (inclusive) are artefacts due to missing data. Note lag due to 6 month moving averages.
Fig. A5 Amplitudes for 2018 and 2021 are artefacts due to missing data. Note lag due to 6 month moving averages.

Fig. A6 Amplitudes for 2006, 2015 and 2016 are artefacts due to missing data. Note lag due to 6 month moving averages.
Fig. A7 Amplitudes for 2010, 2017, 2018 and 2021 are artefacts due to missing data. Note lag due to 6 month moving averages.

Fig. A9 Amplitudes for 2021 are artefacts due to missing data. Note lag due to 6 month moving averages.

Fig. A10 Note lag due to 6 month moving averages.
**Fig. A11** Oxygen rate, Alert, Arctic Canada vs. Arctic sea ice extent rate. Oxygen rate data available from December 1989 to June 2022 inclusive (with some gaps). Oxygen data downloaded 10 October 2022.

**Fig. A12** Oxygen rate, Palmer Station, Antarctica vs. Antarctic sea ice extent rate. Oxygen rate data available from October 1996 to June 2022 inclusive (with some gaps). Oxygen data downloaded 10 October 2022.
Fig. A13 Note lag due to 6 month running means. Oxygen data downloaded 1 February 2023. Zeros on axes not aligned.

Fig. A14 Note lag due to 6 month running means. Oxygen data downloaded 1 February 2023.