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Key Points:
- Ocean models suggest that net DOC production contributes significantly to NCP, O_2 outgassing, and carbon export in the Southern Ocean
- The observed APO_{NCP} cycle supports the model results and suggests that satellite-based estimates underestimate the seasonal amplitude of NCP
- The underestimate is due in part to early spring NCP, which is not well represented by in situ and satellite-based approaches

Supporting Information:
- Supporting Information S1

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Net Community Production in the Southern Ocean: Insights From Comparing Atmospheric Potential Oxygen to Satellite Ocean Color Algorithms and Ocean Models

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Abstract The contribution of oceanic net community production (NCP) to the observed seasonal cycle in atmospheric potential oxygen (APO) is estimated at Cape Grim, Tasmania. The resulting APO_{NCP} signal is compared to satellite and ocean model-based estimates of POC export and NCP across the Southern Ocean. The satellite products underestimate the amplitude of the observed APO_{NCP} seasonal cycle by more than a factor of 2. Ocean models suggest two reasons for this underestimate: (1) Current satellite products substantially underestimate the magnitude of NCP in early spring. (2) Seasonal O_2 outgassing is supported in large part by storage of carbon in DOC and living biomass. More DOC observations are needed to help evaluate this latter model prediction. Satellite products could be improved by developing seasonally dependent relationships between remote sensing chlorophyll data and in situ NCP, recognizing that the former is a measure of mass, the latter of flux.

Plain Language Summary Phytoplankton in the surface ocean transform carbon dioxide into organic carbon while also producing oxygen. A fraction of the carbon is exported into the deep ocean, while the oxygen is emitted to the atmosphere. The carbon export rate influences how much carbon dioxide the ocean can absorb. The rate is commonly estimated using satellite-based phytoplankton color measured in the surface ocean, but such estimates involve many uncertain steps and assumptions. Small but detectible seasonal cycles in atmospheric oxygen have been used as an independent method for evaluating satellite-based estimates of organic carbon export. In this study, we evaluate eight satellite-derived carbon export estimates based on their ability to reproduce the observed seasonal cycle of atmospheric oxygen measured at a southeastern Australia site. All underpredict the seasonal oxygen cycle by at least a factor of 2, in part because they fail to capture the carbon and oxygen produced in early springtime and also because they focus on large particles of carbon that are heavy enough to sink while neglecting the dissolved fraction of organic carbon. Our study suggests that satellite estimates could be improved by a better understanding of seasonal variations in the relationship between phytoplankton productivity and carbon export.

1. Introduction

The ocean's biological carbon pump is an important regulator of atmospheric CO_2 concentration. Together, the soft tissue (i.e., organic carbon) and hard tissue (i.e., plankton skeletal compounds) carbon pumps maintain approximately 70% and 20%, respectively, of the surface-to-deep vertical gradient in ocean dissolved inorganic carbon (DIC; Gruber & Sarmiento, 2002). This gradient reduces the CO_2 saturation in the surface ocean compared to what would occur in the absence of life (Lee, 2001; McKinley et al., 2017; Volk & Hoffert, 1985). The soft tissue pump is driven by phytoplankton that draw down and fix DIC into organic carbon in surface waters. A fraction of the total fixed organic carbon is exported out of the surface ocean and below the seasonal thermocline as both particulate and dissolved organic carbon (POC and DOC).

Current estimates of biological carbon export involve substantial uncertainty. Direct observational estimates are sparse despite broad coverage in space and time (Dunne et al., 2005; Laws et al., 2000). Satellite ocean color products, calibrated against available observations, are commonly used to provide more

comprehensive coverage. However, these products are based on models of vertically integrated net primary production (NPP) and ef-ratio (i.e., the ratio of export or new production to NPP), both of which are several steps removed from the water leaving radiances actually measured by the satellite (Behrenfeld & Falkowski, 1997; Dunne et al., 2007; Henson et al., 2011, 2015; Siegel et al., 2014). An additional uncertainty is that some ef-ratio formulae used in satellite-algorithms are calibrated strictly based on POC export, as estimated by sediment traps and ^{234}Th methods, while others are calibrated using nitrate-based estimates of new production either alone or in combination with sediment trap and ^{234}Th data (Dunne et al., 2005; Laws, 2004; Laws et al., 2011). New production is commonly defined based on uptake of nitrate considered new to the surface ocean, while the closely related term net community production (NCP) is defined as the net amount of organic carbon fixed by the community (accounting for heterotrophic respiration) over the depth of the mixed layer or another vertical reference depth representative of the surface ocean (e.g., 100 m). NCP encompasses the production of living biomass and subsequent production of DOC and POC. At steady state and when averaged over appropriate spatial and temporal scales, NCP is essentially equal to carbon export.

NCP in organic carbon flux units can be converted interchangeably to O_2 flux units using the O_2:C photosynthetic quotient for the coproduction of O_2 and phytoplankton biomass (Anderson, 1995; Laws, 1991). This quotient is about 1.4 and varies on the order of 10 to 20% based on phytoplankton species and metabolism (Smith et al., 2012). Recently, Li and Cassar (2016) used satellite data calibrated against observed surface ocean measurements of O_2/Ar to develop two new satellite-based NCP products. O_2/Ar data are used to estimate the air-sea bioflux of O_2, referred to here as $FO_{2,NCP}$, which is based on a steady state mixed layer budget that assumes that air-sea exchange of biological O_2 is entirely balanced by NCP (e.g., Cassar et al., 2011; Li & Cassar, 2016; Reuer et al., 2007). One of the main uncertainties associated with the O_2/Ar NCP method involves vertical mixing of O_2 undersaturated waters, which can negatively bias the NCP estimate, particularly in early spring within the Southern Ocean (Cassar et al., 2014; Jonsson et al., 2013).

Observed seasonal changes in atmospheric potential oxygen (APO) provide an alternative, independent way to evaluate NCP (Nevison et al., 2012). APO is a unique atmospheric tracer of ocean biogeochemistry that is calculated by combining high-precision atmospheric O_2 and CO_2 data (Manning & Keeling, 2006; Stephens et al., 1998). By design, APO is insensitive to land-atmosphere exchanges associated with terrestrial photosynthesis and respiration but highly sensitive to exchanges across the air-sea interface, because of the contrasting chemistries of CO_2 and O_2 in surface waters. Carbonate chemistry in seawater strongly damps variability in dissolved CO_2 but has no influence on dissolved O_2. As a result, the largest contribution to seasonal cycles in APO arises from air-sea exchange of O_2 due to seasonal variations in surface cooling and heating, deep ventilation, and upper ocean NCP.

Nevison et al. (2012) partitioned the seasonal cycle of APO at several Southern Hemisphere monitoring sites into contributions from three ocean processes: (1) mixed layer NCP, (2) deep water ventilation, and (3) thermal in and outgassing:

$$APO_{obs} = APO_{NCP} + APO_{vent} + APO_{therm} \quad (1)$$

The partitioning relied on measurements of the additional atmospheric trace gases N_2O and CFC-12. The isolation of the NCP signal in APO allowed for the first time a direct comparison of APO data to estimates of carbon export production based on satellite ocean color data, given the assumption that carbon export, NCP, and $FO_{2,NCP}$ are essentially equivalent.

In this paper we reexamine the relationship among carbon export, NCP, and the corresponding air-sea oxygen flux $FO_{2,NCP}$. We begin with an updated estimate of APO_{NCP}, as calculated based on observed APO and other atmospheric trace gases at Cape Grim, Tasmania. We demonstrate that O_2 outgassing estimated by current satellite NCP products accounts for less than half of the observed seasonal amplitude in APO_{NCP}. We proceed with a detailed examination of the other missing components of NCP, based on analysis of Community Earth System Model (CESM) ocean general circulation biogeochemistry model output. We show supporting results from several CMIP5 models in which the export of DOC and live plankton make important contributions to NCP and total carbon export on a seasonal and annual mean basis. Finally, we describe why satellite ocean color algorithms, even those calibrated against O_2/Ar-based estimates of NCP, may

underestimate the seasonal amplitude of APO_{NCP} and we discuss the implications of our analysis for development of new algorithms.

2. Methods

2.1. APO_{NCP}

APO_{NCP} was calculated at Cape Grim, Tasmania (40.7°S, 144.7°E) based on the method of Nevison et al. (2012), with updated inputs and uncertainty propagation as described in section S1 in the supporting information. Our presentation of APO_{NCP} focuses on Cape Grim because this site has the most reliable high-precision in situ data for the three auxiliary species, N_2O, CFC-11, and CFC-12, used in the calculation. The final product is presented as a window of uncertainty, reflecting a range of realizations resulting from a spread of parameter choices.

2.2. Concepts and Terminology

We compare APO_{NCP} to a variety of ocean model and satellite products with the guiding framework that

$$NCP = \Sigma J_{Ci} = J_{POC} + J_{DOC} + J_{phyto} + J_{zoo}, \quad (2)$$

where J_{Ci} is the net biological source/sink term for each of $i = 4$ types of organic carbon, C_i = POC, DOC, phytoplankton, and zooplankton. We consider the two latter types to be living biomass and define POC and DOC as nonliving byproducts of plankton mortality, grazing, and (for POC only) aggregation, where POC is heavy enough to sink while DOC remains suspended in the water column. Here it is notable that ocean models can distinguish between living biomass and POC, whereas in situ ocean measurements of POC concentration typically include both living and dead organic material.

We assume that each C_i type obeys

$$J_{Ci} = EXP_{Ci} + STOR_{Ci}, \quad (3)$$

where EXP_{Ci} is the export of C_i across the base of a defined surface layer and $STOR_{Ci}$ is the rate of accumulation (i.e., the storage term) and J_{Ci} is the net biological source/sink term within that layer. $STOR_{Ci}$ can be positive or negative depending on season. We focus in this paper on the J_{Ci} terms but also discuss the export and storage terms in the supporting information (S2).

Many ocean models do not explicitly carry POC as a tracer but rather assume that a fraction of total POC production at any given depth level is exported instantly following a decaying Martin-type curve (Martin et al., 1987) with another fraction instantly routed to DIC. Thus, in the framework of equation (3), these models calculate EXP_{POC} as a function of depth and assume that $STOR_{POC} = 0$. We assume therefore throughout this paper that $J_{POC} = EXP_{POC}$ and that the two terms are interchangeable.

NCP and its component J_{Ci} terms can be converted readily from carbon production into O_2 production units by multiplying by the stoichimetric O_2:C ratio ($R_{O2:C} \sim 1.4$). If C_i is exported from or stored within the surface layer for longer than the O_2 air-sea exchange time scale of 2–3 weeks, we assume as per Eddebbar et al. (2017) that

$$FO_{2,NCP} = R_{O2:C} NCP, \quad (4)$$

where $FO_{2,NCP}$ is the net air-sea O_2 flux associated with NCP. Eddebar et al. assumed this equivalence when NCP was integrated over the top 100 m, but the most appropriate depth integral over which equation (4) applies is unclear, hence our exploration below of several integrals. We necessarily use equation (4) to estimate $FO_{2,NCP}$, since ocean models can calculate NCP exactly but generally only calculate the total net FO_2 flux, which is influenced also by thermal and deep ventilation components (Nevison et al., 2012).

2.3. CESM Forced Run: NCP Budget Terms

We analyzed output from an ocean-sea ice *hindcast* simulation of the CESM forced with observed and reanalyzed momentum, heat, and freshwater fluxes from 1948 to 2007 (Long et al., 2013; Lovenduski et al., 2013). The model uses 1° horizontal and 10-m vertical resolution in the upper 160 m with 60 total vertical levels. NCP

and all component J_{Ci} terms from equation (2) are available from this simulation (although see note above about J_{POC}). We assessed these terms over two fixed depths, 100 and 150 m, as well as over the monthly varying mixed layer depth. We also inferred corresponding EXP_{Ci} terms as described in section S2 in the supporting information. Finally, we estimated an alternative NCP field by scaling CESM NPP with the Laws et al. (2011) equation (2) ef-ratio, calculated using CESM Chl and SST as inputs. All calculations focused on the Southern Ocean and were integrated zonally from 40 to 60°S and averaged over hindcast years 2001 to 2005.

2.4. CMIP5 Models

We used archived NCP output from three CMIP5 historical coupled carbon climate simulations for 2001–2005, including the Geophysical Fluid Dynamics Laboratory (GFDL) Earth System Models (depth-based ESM 2 M and density-based ESM 2G vertical oceans; Dunne et al., 2012, 2013) and the Norwegian Earth System Model-ME (NorESM1-ME; Tjiputra et al., 2013). NCP is not a standard CMIP5 output variable but can be estimated based on the dissolved inorganic nitrogen biological source/sink variable (fbddtdin) integrated over the top 100 m and scaled by the appropriate C:N Redfield ratio. EXP_{POC} at 100 m and thus J_{POC} (see section 2.2) were also available for all three models. In addition, for NorESM1-ME, J_{DOC}, J_{phy}, and J_{zoo} were computed online and provided specifically for this study.

2.5. Satellite Ocean Color Data

We tested eight different satellite-based NCP products. Two of these, genetic programming and support vector regression, were calibrated based on optimizing the relationship between observed O_2/Ar-NCP and multiple satellite observations and products (Li & Cassar, 2016). The remaining six were computed from three different satellite-based NPP models, each paired with two commonly used export efficiency (ef-ratio) algorithms, one calibrated from N-based new production only (Laws equation (2)) and the other calibrated based on a combination of POC export and new production measurements (Laws equation (3); Laws et al., 2011). The NPP products included the Carbon-based Productivity Model (CbPM; Westberry et al., 2008) and the chlorophyll-based Vertically Generalized Productivity Model (VGPM; Behrenfeld & Falkowski, 1997; Oregon State University, 2018). The third NPP product also was based on VGPM but used a factor-of-2-increased Chl relative to Oregon State University (Johnson et al., 2013; Li & Cassar, 2016). In principle, all the satellite products represent NCP, but in practice, they may neglect some component J_{Ci} terms in equation (2) such as J_{DOC}.

2.6. Atmospheric Transport Model Simulations of APO_{NCP}

The $FO_{2,NCP}$ fluxes from the ocean models and satellite ocean color products were translated into APO_{NCP} using forward simulations with the GEOS-Chem atmospheric transport model (Nassar et al., 2010; Suntharalingam et al., 2004), where GEOS-Chem was run from 2001 to 2005 at 2 × 2.5° horizontal resolution, with 47 sigma levels, driven by MERRA (Modern Era Retrospective Analysis) forcing. The resulting atmospheric O_2 fields in ppm were converted to per meg units using equation (5), where X_{O2} = 0.2094.

$$APO_{NCP} = \frac{1}{X_{O2}}(O_2) \tag{5}$$

3. Results

3.1. APO_{NCP}

The updated climatological-mean annual seasonal cycle in APO_{NCP} observed at Cape Grim, Tasmania (Figure 1), is consistent with the results of Nevison et al. (2012) in showing that the NCP component signal is closely associated with the springtime rise in observed APO. Figure 1 shows observed APO_{NCP} as a green band that allows for several uncertain parameters (as described in section S1 in the supporting information) and compares it to a variety of satellite and model products.

All satellite NCP products and most ocean model EXP_{POC} products underestimate the amplitude of the observed APO_{NCP} seasonal cycle by a factor of 2 or more (Figures 1a and 1b). The satellite NCP products also tend to predict a delayed phasing of observed APO_{NCP} by 1 month or more. In contrast, most ocean model NCP products reproduce the observed amplitude and phasing of APO_{NCP} relatively well (Figures 1c and 1d). NorESM1-ME is an outlier in that its EXP_{POC} captures observed APO_{NCP} well while its NCP overestimates

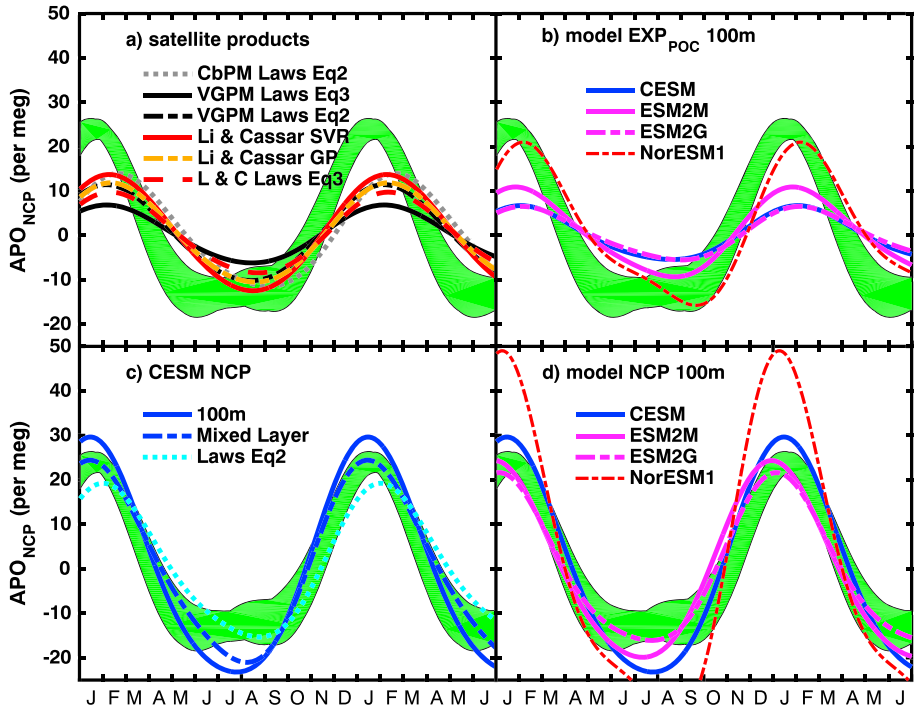

Figure 1. Mean seasonal cycle of APO_{NCP} observed at Cape Grim (green envelope from Figure S1) compared to various satellite and ocean model-based estimates of EXP_{POC} and NCP, which have been converted to air-sea $F_{O2,NCP}$ fluxes and then to APO_{NCP} using GEOS-Chem and equation (5).

APO_{NCP} by a factor of 2. The Laws et al. (2011) equation (2) product using CESM NPP and SST inputs is reduced in amplitude and delayed in phasing relative to the prognostic CESM NCP tracers (Figure 1c) but captures observed APO_{NCP} more closely than the satellite-based products (Figure 1a).

3.2. Components of Model NCP

Figure 2 shows that the sum of J_{POC}, J_{DOC}, J_{phyto}, and J_{zoo} equals NCP more or less exactly in CESM and NorESM1-ME. The components of NCP have not been defined explicitly in previous documentation of these models, so this equivalence confirms the conceptual framework in equation (2). In both models, J_{POC} alone accounts for less than half of total NCP over a seasonal cycle during the peak growing season months (Figure 2). For all models other than NorESM-1, the J_{POC} component correspondingly falls short in explaining observed APO_{NCP} (Figure 1b). For the GFDL models, only NCP and J_{POC} (actually EXP_{POC}) are available, but the large residual of those two terms suggests that DOC and/or plankton also make important contributions to NCP.

Integrated over the entire annual cycle, the J_{DOC}, J_{phyto}, and J_{zoo} terms are less important to NCP than they are on a seasonal basis but still contribute substantially. Together, these terms account for up to half of annual mean NCP and hence also total organic carbon export, depending on ocean model and vertical depth integral (Figure 3). EXP_{POC} accounts for an increasingly large portion of total export as one moves from the mixed layer to the 100 m to the 150-m depth integral in CESM. These results indicate that DOC and plankton are not completely respired back to DIC in the surface ocean over an annual cycle but rather that a fraction of each is exported to deeper waters. The mechanisms of export include deep winter mixing and detrainment with shoaling mixed layer depth and are discussed in detail in S2.

4. Discussion

4.1. Previous Work Relating APO to NCP and POC Export

One of the original goals of long-term atmospheric oxygen monitoring was the use of observed seasonal cycles to constrain oceanic NCP and to evaluate model or satellite-based estimates of NCP (Keeling et al.,

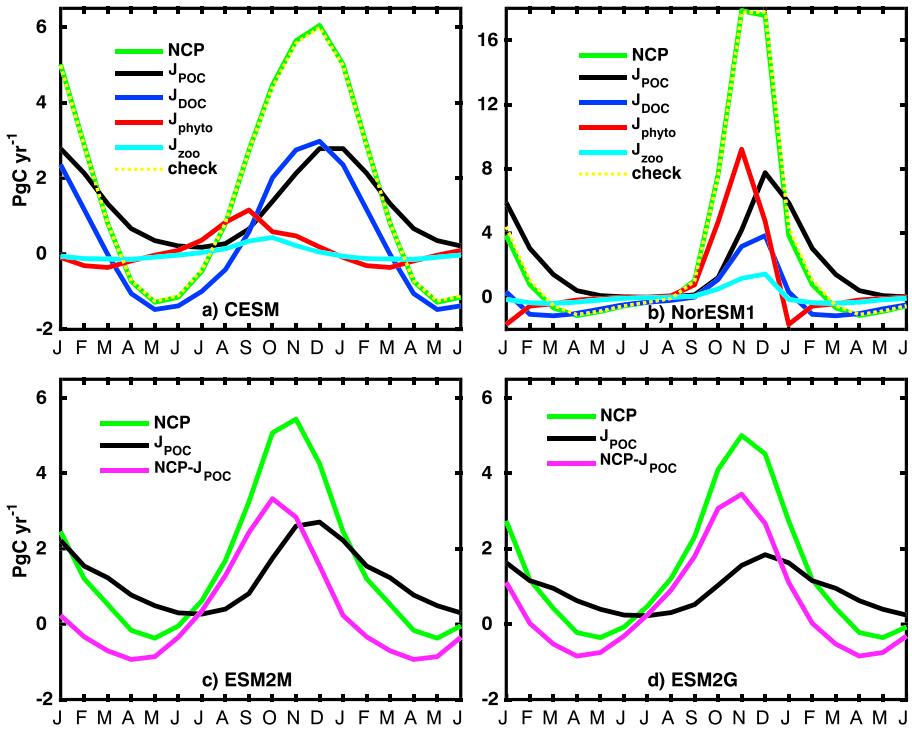

Figure 2. Net community production (NCP) over a mean seasonal cycle integrated from the surface to 100-m depth over 40–60°S in the Southern Ocean. For (a) CESM and (b) NorESM1-ME, the complete set of component contributions to NCP is shown. Note the different *Y* axis scale for NorESM1-ME in panel b. The yellow dotted line checks that the sum of $J_{POC} + J_{DOC} + J_{phyto} + J_{zoo}$ reproduces NCP. For (c) ESM 2 M and (d) ESM 2G, only NCP and J_{POC} are available. The difference between those terms (magenta) is inferred to be the sum of $J_{DOC} + J_{phyto} + J_{zoo}$. For all models, we assume as per section 2.2 that $J_{POC} = EXP_{POC}$, where the latter is the actual model output variable.

1993). In practice, this application has been challenging due to a number of complexities, including the fact that observed APO is influenced not just by NCP but also by thermal and ventilation components (Bender et al., 1996; Keeling et al., 1998; Keeling & Shertz, 1992; Najjar & Keeling, 2000; Nevison et al., 2012). Uncertainty also exists in the relationship between NCP (or POC export) and the associated air-sea O_2 flux. A further complexity is the need for an atmospheric transport model to translate ocean model or satellite-based oceanic air-sea O_2 fluxes into an atmospheric signal (Naegler et al., 2007; Stephens et al., 1998, 2007).

In previous work, Nevison et al. (2012) used the APO_{NCP} signal isolated from observed APO data to evaluate satellite POC export flux products. They made the simple assumption that when POC is exported from the mixed layer, it leaves behind a stoichiometric amount of O_2 that outgasses quickly to the atmosphere; that is, in the framework of (2–4) they assumed $FO_{2,NCP} = NCP = EXP_{POC}$. That assumption gave reasonable agreement between observed APO_{NCP} in the Southern Ocean and satellite EXP_{POC} products. However, those products were likely biased high for several reasons. First, they were based on the Southern Ocean-specific SPGANT algorithm for Chl, which yields substantially (factor ~2.5) higher Chl in the Southern Ocean than most conventional NASA algorithms (Kahru & Mitchell, 2010). Second, SPGANT Chl was input to a modified version of VGPM and the computed NPP product was input to the Laws (2004) ef-ratio algorithm, yielding ef-ratios that frequently exceeded 0.5 in the Southern Ocean and were scaled down to agree with the inverse model results of Schlitzer (2002). However, the magnitude of satellite Chl remains a subject of debate with work by Johnson et al. (2013) supporting higher Chl in the Southern Ocean similar to SPGANT and recent work by Haentjens et al. (2017) supporting the lower Chl from conventional NASA algorithms. Here we present a wider range of satellite NCP products, which use low and high Chl inputs to both the standard VGPM and CbPM NPP algorithms, which in turn are converted to NCP using revised Laws et al. (2011) ef-ratio algorithms calibrated based on a mix of new production and POC_{exp} data; all products yield atmospheric signals that substantially underestimate the observed APO_{NCP} amplitude (Figure 1a).

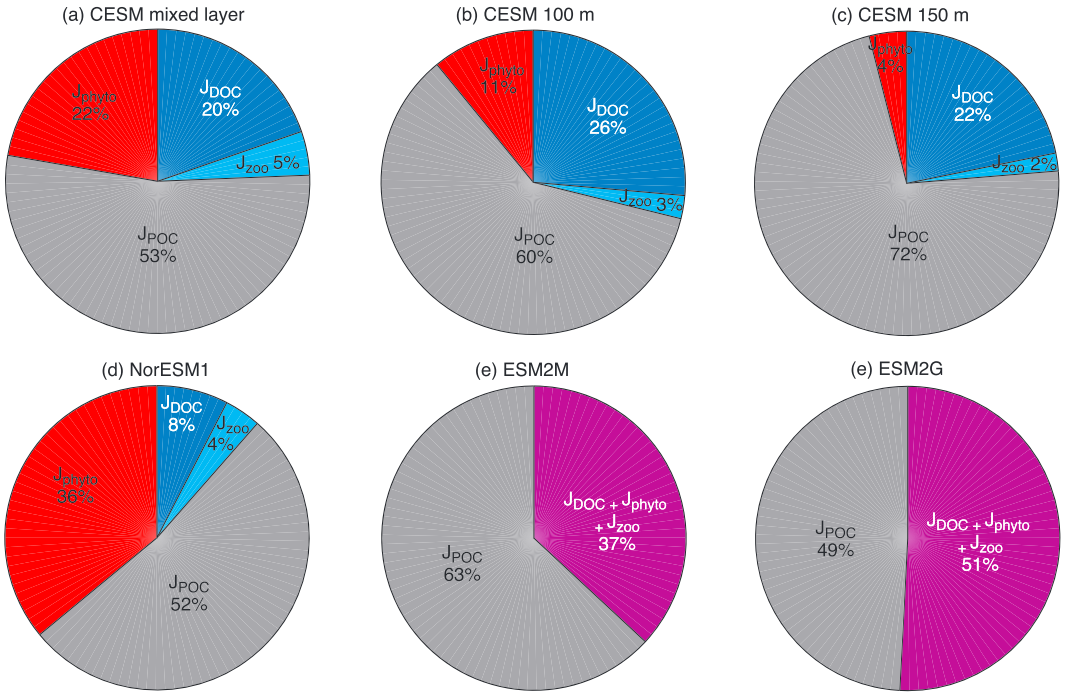

Figure 3. Annual mean NCP, partitioned into J_{POC}, J_{DOC}, J_{phyto}, and J_{zoo}. Results are integrated over 40–60°S in the Southern Ocean for the CESM forced run at three different depth integrals (mixed layer, 100 m, and 150 m) and three CMIP models (NorESM1-ME, ESM 2 M, and ESM 2G) integrated over the top 100 m. Note that for the GFDL models, only NCP, J_{POC}, and the residual of the two (magenta wedge) are available.

4.2. An Important Role for DOC in Seasonal and Annual NCP and Carbon Export

Ocean models offer a simple explanation for the discrepancy between observed APO_{NCP} and atmospheric tracers derived from model EXP_{POC}. This explanation extends to atmospheric tracers derived from satellite products that nominally reflect NCP but in practice are calibrated largely with observed EXP_{POC} data. All four of the ocean models presented here suggest that organic carbon is seasonally exported or stored in DOC and live plankton long enough to support release to the atmosphere of the associated net O_2 production (Figure 2). Indeed, all four models predict that some combination of DOC and plankton accounts for more than half of the seasonal O_2 outgassing, contradicting the assumption that EXP_{POC} is the dominant component of the APO seasonal cycle (Figure 2). A detailed partitioning of NCP is only possible for two out of the four ocean models. Of these, CESM predicts that EXP_{DOC} + $STOR_{DOC}$ (i.e., export and/or storage of carbon in DOC) outweighs EXP_{phyto} + $STOR_{phyto}$ in its contribution to seasonal O_2 outgassing, while NorESM1-ME predicts the reverse. The disparate partitioning occurs because models differ in their parameterizations of phytoplankton and zooplankton production and losses due to mortality, aggregation and grazing, and the associated production of DOC and POC. These pathways are complex, often ill-constrained by observations, and are highly variable among models (Laufkotter et al., 2016).

All four ocean models predict that the export of DOC and living biomass is also important on an annual mean basis. Together, EXP_{DOC}, EXP_{phyto}, and EXP_{zoo} account for some 28%–51% of annual organic carbon export out of the surface layer of the Southern Ocean, depending on model and vertical depth integral (Figures 3 and S2). DOC export is difficult to quantify, and the few available observational studies have measured highly variable fractions of DOC export relative to total export in different seasons and ocean ecosystems (Hansell et al., 2012; Stukel & Ducklow, 2017). Studies that extrapolate these limited data or assimilate them into global biogeochemistry models suggest that DOC production accounts for less than 20% of annual NCP globally (DeVries & Weber, 2017; Hansell & Carlson, 1998; Roshan & DeVries, 2017). An alternative approach based on inverse modeling found best agreement with dissolved nutrient data in the Southern Ocean when annual DOC export was prescribed to equal 40% of POC export (i.e., 28% of total organic C export) at 133 m (Schlitzer,

2002) close to the model results presented in this study. Roshan and DeVries (2017) find a much smaller (<20%) fraction in the high-latitude Southern Ocean using a data-constrained global circulation model.

Our study using APO_{NCP} provides indirect evidence that J_{DOC}, J_{phyto}, and J_{zoo} are important seasonally to oceanic O_2 outgassing, given that both ocean model and satellite EXP_{POC} fluxes alone in most cases are not able to reproduce observed APO_{NCP}. In other words, our results suggest that NCP and EXP_{POC} can be decoupled on seasonal time frames. However, the contribution of DOC to this decoupling in CESM becomes less important the deeper the depth horizon, and the contribution of living biomass becomes very small. Ultimately, only deep carbon export below the seasonal mixed layer may matter for maintaining the surface to deep DIC gradient that is critical to the biological pump (Palevsky et al., 2016).

4.3. Satellite Products and Biogeochemical Budget-Based NCP Observations

In view of the ocean model results, the underestimate of APO_{NCP} is not surprising for satellite ocean color products that use ef-ratios calibrated largely by sediment trap data and other measurements of POC export (e.g., Dunne et al., 2005; Laws et al., 2011). Somewhat more surprising is that the Li and Cassar (2016) satellite products, which are derived from O_2/Ar-based NCP, also fail to capture the magnitude of APO_{NCP} and furthermore predict a delayed phasing of APO_{NCP}. One possible explanation is that O_2/Ar-based NCP is biased negatively by vertical mixing of O_2-depleted water in early spring (i.e., October–November in the Southern Ocean; Cassar et al., 2014), precisely the time when the ocean models predict the greatest relative contribution of DOC and living biomass to NCP (Figure 2). This early spring bias in O_2/Ar-based NCP may be compounded by a coincidental bias in the satellite NPP products, since much of NPP in early spring may occur in deep mixed layers that are not accessible to satellite measurements (Schlitzer, 2002). Thus, when O_2/Ar-based NCP and satellite NPP were combined to develop the Li and Cassar (2016) algorithms, both variables may have been biased low in early spring.

In support of the spring bias in satellite products, several studies have noted discrepancies between NCP (or export production) estimated from in situ geochemical measurements versus derived from satellite ocean color data. Palevsky et al. (2016) found that primary production estimates across the North Pacific based on in situ triple oxygen isotope measurements were generally higher than satellite-based estimates, with largest discrepancies during winter and spring. Both Weeding and Trull (2014) and Munro et al. (2015) analyzed in situ biogeochemical observations at different time series sites within the Southern Ocean and determined that the large majority of seasonal NCP occurs in austral spring prior to 1 January. In contrast, satellite products predict positive NCP well into austral summer (Munro et al., 2015).

Our study indicates that current satellite products provide a poor representation of seasonality in NCP, due in part to algorithms that directly relate a measurement of mass (i.e., chlorophyll) to a flux (i.e., NCP or POC export; Figure S5a). In contrast, ocean model results indicate that surface concentrations of chlorophyll and DOC are out of phase with NCP, with NCP peaking earlier than both chlorophyll and DOC (Figure S5b). Other factors contributing to poor representation of seasonality in NCP by satellites include the lack of in situ NCP estimates throughout an entire annual cycle and the complexity of the seasonal evolution of biomass relative to NPP, NCP, and export flux (Figure S5). A related issue is that current satellite-based products cannot predict net heterotrophy in winter, which contributes to the lower amplitude of satellite-derived APO_{NCP} relative to observed (Figure 1c). A recent analysis of satellite NCP/export products in the Southern Ocean used updated chlorophyll fields that predicted increased wintertime NPP, which resulted in even less seasonality relative to the products used in this analysis (Arteaga et al., 2018). However, heterotrophy is suggested during austral winter by CESM and other models (Figure 2) and observational studies (Briggs et al., 2018). Recently deployed biogeochemical floats (Briggs et al., 2018; Johnson et al., 2017) and moorings (Weeding & Trull, 2014) will improve understanding of seasonality in NCP throughout the Southern Ocean including the degree of heterotrophy during austral winter. A better seasonal distribution of in situ observations should allow a new generation of algorithms based on seasonally dependent relationships between remote observations and NCP.

5. Conclusions

To date, estimates of vertical organic carbon transport have focused on POC export, but four ocean biogeochemistry models presented here indicate that export of DOC and living biomass are also important in the

Southern Ocean, a view that is supported indirectly by APO observations. Ocean color satellite data might be better suited for estimating NCP, which encompasses all forms of organic carbon production, rather than POC export alone, especially since satellites realistically cannot resolve process occurring at depth. However, satellite data also appear to miss a substantial fraction of NCP in early spring, when the mass of surface Chl is still accumulating and may not provide a direct gauge of the strength of the NCP flux. Overall, there is a need for observational estimates of DOC and NCP throughout the year both to capture the importance of DOC and living biomass signals and to develop seasonally varying relationships between satellite observations, biological productivity, and export flux.

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