Supplementary material

Intra-seasonal and inter-annual variability

In order to examine the role of intra-seasonal and inter-annual variability in the evolution of the chlorophyll mean seasonal cycle, 8 boxes were extracted, spanning 5 degrees in latitude (from 30ºS to 80ºS) for three 10º longitude transects, one in each of the ocean basins. Each box displays the annual and mean chlorophyll concentrations, bloom initiation dates, mean MLD's and PAR. The corresponding figures for each of the three transects are presented according to the four seasonal cycle zones (STZ, TZ, ACZ and MIZ) in Figures S1, S2, S3 and S4 respectively.

The latitudinal progression in seasonal characteristics of the chlorophyll bloom is evident. In the northern most boxes of the STZ (Figure 1a, b, c, d), autumn (May-June) bloom initiation dates are tightly phased onto the same ~2 weeks of every year. Relatively low variability is also observed in inter-annual and intra-seasonal chlorophyll concentrations, consistent with earlier observations of the progression of chlorophyll being phase locked to the seasonal cycle of net heat fluxes and the deepening of the MLD. In the Pacific (Figure S1c, d), there is a southward progression of the subtropical zone of winter chlorophyll maxima to ~40ºS. In the subtropical zone, nutrient limitation is the dominant limiting factor to phytoplankton production and seasonal heat flux is the dominant forcing mechanism responsible for winter overturning and nutrient replenishment. The lack of other buoyancy forcing of the mixed layer on intra-seasonal time scales likely accounts for the low variability found here.

South of the STZ the TZ is marked by a high degree of inter-annual variability in bloom initiation dates (Figure S2), consistent with figure 3, and a large inter-annual and intra-seasonal variability in chlorophyll concentrations, consistent with figure 4. In the Atlantic and Indian basins of the Southern Ocean, the TZ is observed between 35ºS and 40ºS (Figure S2a and S2b respectively), whereas in the Pacific, the TZ of high variability extends from 40-50ºS (Figure S2c, d). Of particular interest is the extremely low chlorophyll concentrations for the entire TZ of the Pacific (< 0.18 mg

m^{-3}), compared to the Atlantic (< 0.35 mg m^{-3}) and Indian (<0.25 mg m^{-3}). Consistently low chlorophyll concentrations in the Pacific and the lack of any significant seasonality were similarly noted by Treguer and Jacques (1992) and Banse (1996). Treguer and Jacques (1992) cast their explanation entirely in terms of irradiance and MLD, whereas Banse (1996) invoked year-round control by grazing in an Fe-limited ecosystem. We propose that increased seasonally sustained positive buoyancy forcing in the Pacific, prevents the deepening of the winter mixed layer to below the ferricline thus failing to re-set the seasonal nutrient supply which in addition to the light limitations from high latitudes (South of 40ºS) and variable MLD's prevents a sustained summer phytoplankton bloom. Unlike the Pacific, the Atlantic and Indian Ocean basins have deep winter MLD's in the TZ (>200 and >300 m respectively) (Figure 6a), an array of subantarctic islands and shallow bathymetry that results in higher mesoscale activity. Increased mixing associated with such features likely increases the sub-surface flux of Fe into surface waters (Sokolov and Rintoul, 2007). These Fe sources moderate the factors simultaneously limiting production. When the time scales of sub-seasonal forcing of the MLD (through wind mixing and buoyancy forcing from mesoscale variability) is optimal, phytoplankton production and biomass accumulation can occur.

Both Treguer and Jacques (1992) and Banse (1996) infer that the lack of seasonality in the subantarctic Pacific extends to 65ºS. Our results however show that in the ACZ south of the TZ, there is a well defined bloom in summer that extends from 50 to 65ºS (Figure S3c, f, i). A similarly well defined and fairly short lived bloom is found in the ACZ of the Atlantic (45-55ºS) (Figure S3a, d, g) and Indian (45-60ºS) (Figure S3 b, e, h, j) which starts in October/November, peaks in December and ends in January/February. Light limitation through deep mixed layers limits phytoplankton growth in early spring (Veth et al., 1997; Lancelot et al., 2000; Smith et al., 2000; Boyd et al., 2001), whereas at the end of summer, light levels decline, mixed layers deepen and nutrients (particularly Fe and Si) are at their seasonally depleted minimum values (Moore and Abbott, 2002). Although the phasing of the chlorophyll blooms in the ACZ are coherent, with low variability in bloom initiation dates, there is high inter-annual variability in the amplitude of the bloom (consistent with Figure 1c) and in some years relatively high intra-seasonal variability (Figure S3). The high intra-seasonal variability is likely the result of the complex interaction between multiple limiting factors (nutrients and light) from multiple physical forcing mechanisms (e.g. buoyancy forcing from seasonal heat flux and mesoscale activity together with high wind stress). In this region of the Southern Ocean, surface Fe concentrations are likely to have a strong impact on the magnitude of the summer phytoplankton bloom (hence the high inter-annual variability) but not on the phasing of the seasonal cycle. The low variability in bloom initiation dates is likely the result of sufficient Fe reserves through winter overturning to initiate a bloom when the seasonal PAR threshold for increased primary production and biomass accumulation is met in spring.

South of the ACZ is the MIZ where chlorophyll concentrations are particularly high through elevated nutrients (Fe) associated with the Antarctic continental shelves and melting ice (Fitch and Moore, 2007). The additional Fe supply together with a favourable light environment through fresh water buoyancy forced stratification allows for the accumulation of unusually high concentrations of phytoplankton biomass. The larger latitudinal extent of the MIZ in the Atlantic (55-70ºS, Figure S4a, d, f) through the influence of the Weddell Gyre is evident when compared to the Indian (60-70ºS, Figure S4b, e)) and Pacific (65-70ºS, Figure S4c) transects. Although a small degree of variability in bloom initiation is apparent in the transition between the ACZ and MIZ, notably in the Atlantic (Figure S4a, see also Figure 3), bloom initiation dates are fairly consistent in the remaining MIZ zone where sufficient Fe reserves allow a summer bloom initiation when the PAR threshold (~15-20 Einstein m^{-2} d^{-1}) for increased specific growth rates and biomass accumulation is reached (Figure S4b, c, d, e, f). The variability in the seasonal progression and amplitude of chlorophyll concentrations is high both intra-seasonally and inter-annually (Figure S4). This high variability is forced by short term variability in the amount of open water area associated with the MIZ and as such, productivity is much more temporally variable in the MIZ than in the pelagic province (Arrigo et al., 2008). Moore and Doney (2006) suggest that variable Fe content and release from melting ice also plays a significant source of mesoscale variability in chlorophyll concentrations in the SW Pacific sector of the Southern Ocean. According to Fitch and Moore (2007), increased stratification due to melt water alone cannot account for the observed variability in the MIZ. Their strong inverse relationship between wind speeds and bloom occurrences suggest that wind forcing plays an important role in driving the spatial and temporal variations in MIZ bloom distributions through the deepening of MLD's and light limitation of phytoplankton production. The typically low PAR of the MIZ makes it more sensitive to small changes in the MLD. Again, buoyancy forcing of mixed layer dynamics through the combination of intra-seasonal and mesoscale/ sub-mesoscale physical forcing mechanisms plays an important role in determining inter-annual and intra-seasonal variability of phytoplankton distribution.

Accurately assessing bloom initiation dates in regions of poor data coverage

Significant problems are known to exist in ocean colour retrievals at high latitudes that are related to low solar angle, sea ice cover and clouds. If the effects of poor data coverage were significantly impacting the calculation of bloom initiation dates, one would expect a systematic delay in bloom initiation date with an increase in latitude. This however is not what we observe, south of Australia for example, regions of late bloom initiation (November/December) are found north (40-50°S) of early bloom initiation regions (August/September) further south (50-50°S) (Figure 2). The transition between late and earlier bloom initiation south of Australia appears to be delineated by the Polar Front (Figure 2), which implies that the differences in bloom initiation date are physically driven rather than a poor data-related artefact.

Although it is no possible to directly determine the effects of poor data coverage on the inter-annual variability in bloom initiation dates, one would similarly expect that the variability in bloom initiation date would systematically increase with latitude if it were dependant on the number of observations. This however was not the case and instead, the pattern of variability in bloom initiation date shows the highest degree of variability in the TZ between different seasonal regimes centred around ~40°S (Figure 3).

Furthermore, the bloom initiation date north of the MIZ and south of ~40°S and is found to occur mainly between September and November. The number of available SeaWiFS data observations (8-day composites) for September (Figure S5c) shows that outside the MIZ, at least half of the total number of potential observations are generally available during spring. Missing values are thus unlikely to bias the determination of the bloom initiation dates north of the MIZ. As we cannot detect a phytoplankton bloom in an ice-covered grid-point, one can expect that there will be a delay in the bloom initiation date related to the MIZ. This was found to be the case with bloom initiation dates in the MIZ occurring in summer (December to February) reflecting the time it takes for phytoplankton blooms to respond to the newly created ice-free waters. This was similarly shown to be the case in the Arctic where phytoplankton blooms took ~20 days to respond to sea-ice melt (Perrete et al., 2011).

Supplementary Figure Legends

Figure S1-4: 8 boxes were extracted, each spanning 5 degrees in latitude (from 30ºS to 70ºS) for a 10º longitude transect in the Atlantic (0 – 10ºE), the Indian (85 – 95ºE) and the Pacific (110 – 100ºW). The upper panel of each box presents the MLD (black curve, depth in meters, y-axis on right) and the mean annual cycle of PAR (red curve, Einstein m^{-2} day^{-1}, left-hand y-axis) with a minima / maxima envelope in yellow. The middle panel presents the mean annual cycle of chlorophyll (mg m^{-3}). The lower nine panels present the chlorophyll concentration for each year (y-axis) and the time of the year (x-axis). Years are defined from May 0 to April +1. Bloom initiation dates are marked by a black circle.

Figure S1: Subtropical Zone (STZ) boxes from longitudinal transects in the Atlantic (0 – 10ºE) a) 30-35ºS, the Indian (85–95ºE) b) 30-35ºS, and the Pacific (110–100ºW) c) 30-35ºS, d) 35-40ºS.

Figure S2: Transition Zone (STZ) boxes from longitudinal transects in the Atlantic (0–10ºE) a) 35-40ºS, the Indian (85–95ºE) b) 35-40ºS, and the Pacific (110–100ºW) c) 40-45ºS, d) 45-50ºS.

Figure S3: Antarctic Circumpolar Zone (ACZ) boxes from longitudinal transects in the Atlantic (0–10ºE) a) 40-45ºS, d) 45-50ºS, g) 50-55ºS, the Indian (85–95ºE) b) 40-45ºS, e) 45-50ºS, h) 50-55ºS, j) 55-60ºS, and the Pacific (110–100ºW) c) 50-55ºS, f) 55-60, i) 60-65ºS.

Figure S4: Marginal Ice Zone (MIZ) boxes from longitudinal transects in the Atlantic (0–10ºE) a) 55-60ºS, d) 60-65ºS, g) 65-70ºS, the Indian (85–95ºE) b) 60-65ºS, e) 65-70ºS, and the Pacific (110–100ºW) c) 65-70ºS.

Figure S5. Maps presenting the total number of available observations of SeaWiFS data (8-day composite periods) from 1998 to 2007 for a) July and b) January and c) September.

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Supplementary figures

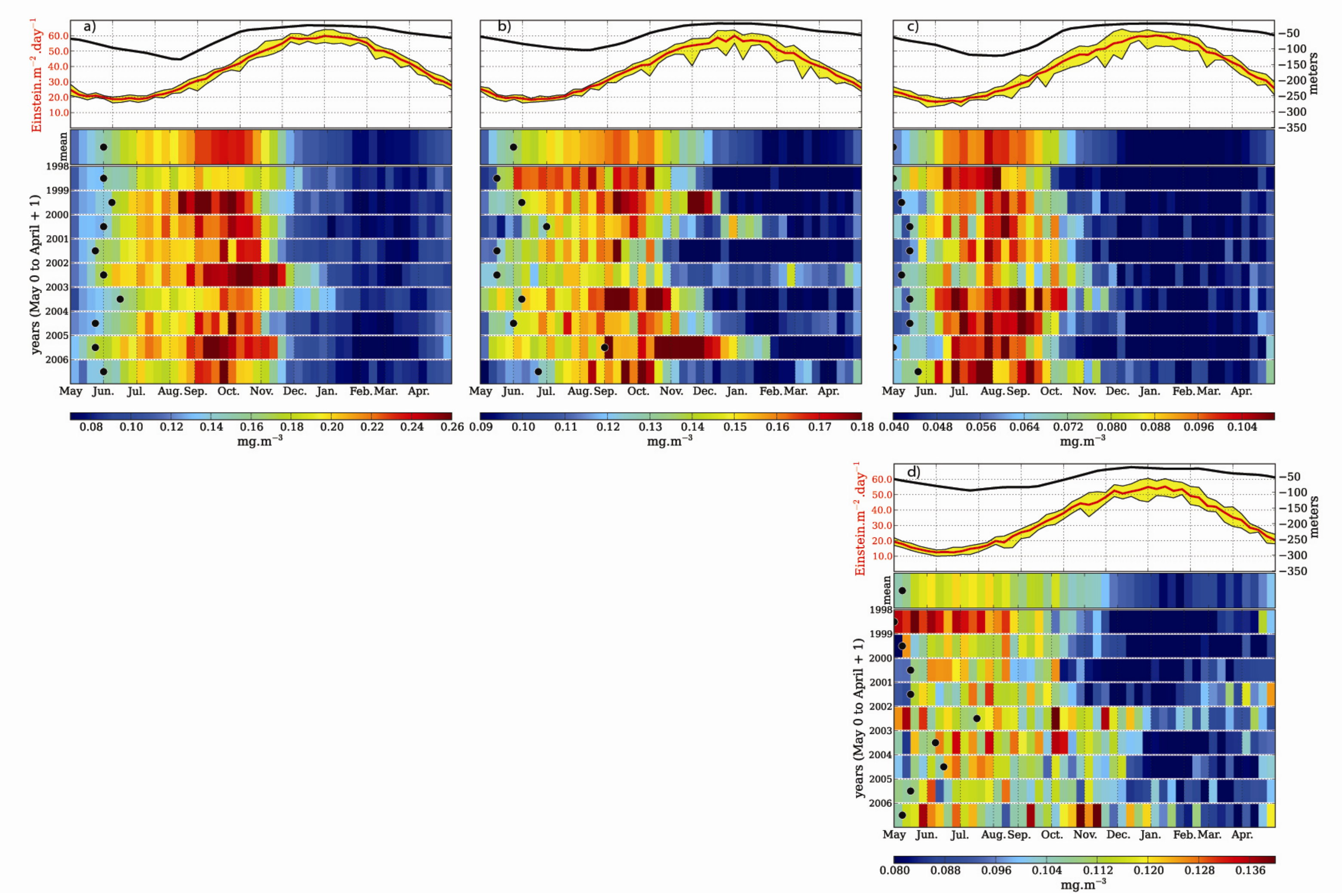
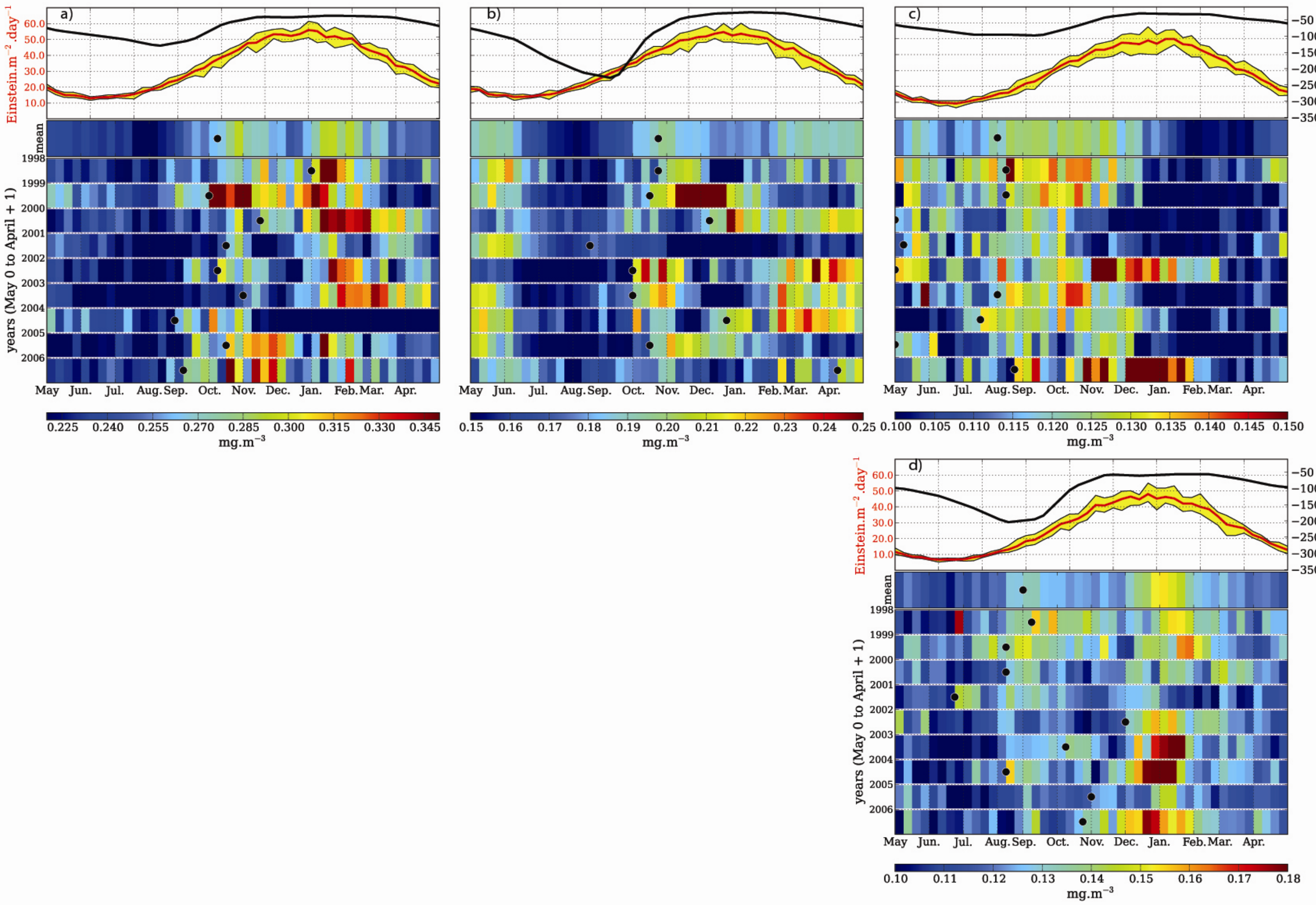
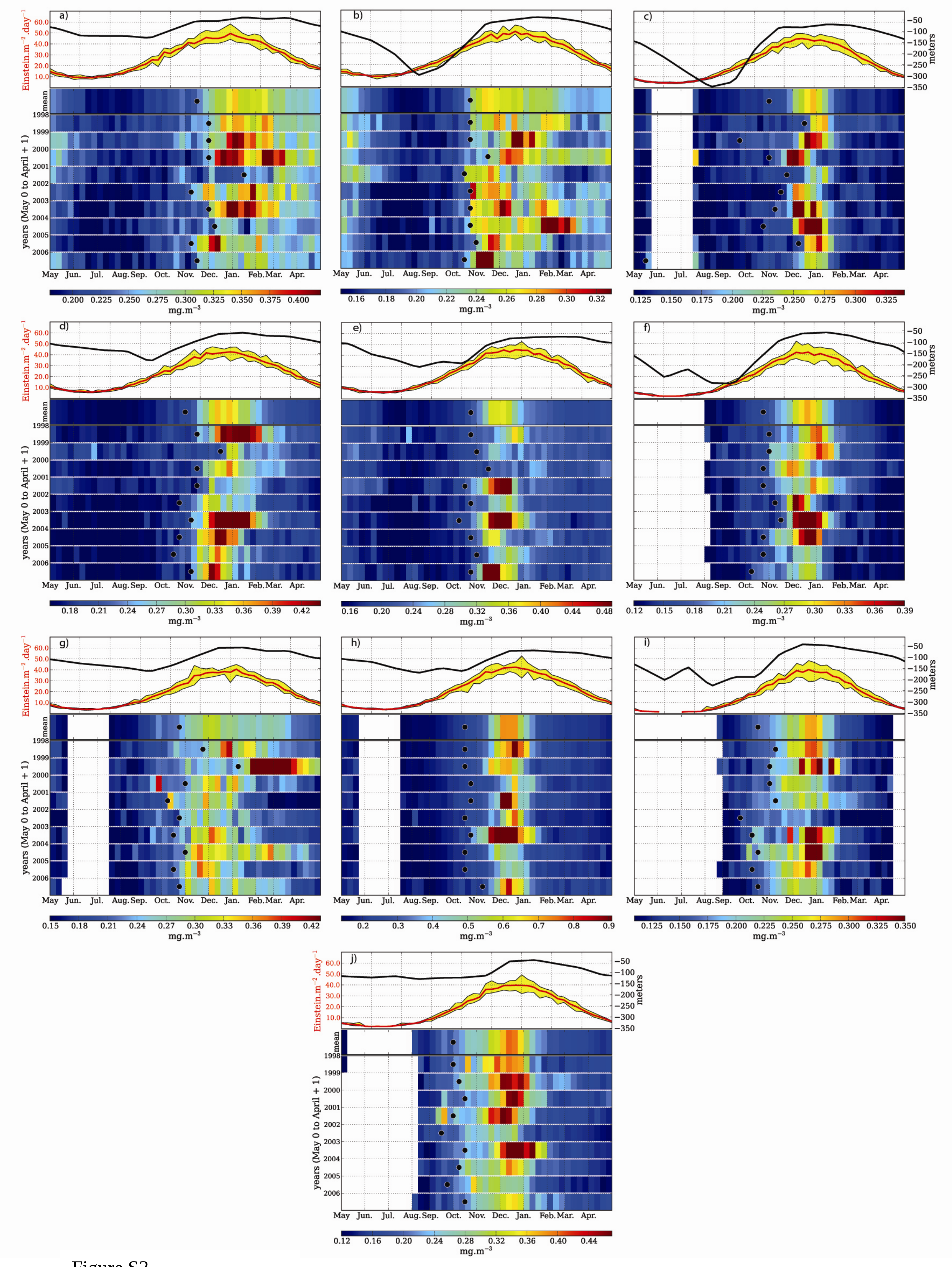


Figure S1



a)
b)
c)
d)
Einstein.m^{-2}.day^{-1}
meters
mean
years (May 0 to April + 1)
May Jun. Jul. Aug. Sep. Oct. Nov. Dec. Jan. Feb. Mar. Apr.
mg.m^{-3}

Figure S2


a)
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Einstein.m^{-2}.day^{-1}
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meters
-50 -100 -150 -200 -250 -300 -350
mean
years (May 0 to April + 1)
1998 1999 2000 2001 2002 2003 2004 2005 2006
May Jun. Jul. Aug. Sep. Oct. Nov. Dec. Jan. Feb. Mar. Apr.
mg.m^{-3}
0.200 0.225 0.250 0.275 0.300 0.325 0.350 0.375 0.400
0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30 0.32
0.125 0.150 0.175 0.200 0.225 0.250 0.275 0.300 0.325
0.18 0.21 0.24 0.27 0.30 0.33 0.36 0.39 0.42
0.16 0.20 0.24 0.28 0.32 0.36 0.40 0.44 0.48
0.12 0.15 0.18 0.21 0.24 0.27 0.30 0.33 0.36 0.39
0.15 0.18 0.21 0.24 0.27 0.30 0.33 0.36 0.39 0.42
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0.125 0.150 0.175 0.200 0.225 0.250 0.275 0.300 0.325 0.350
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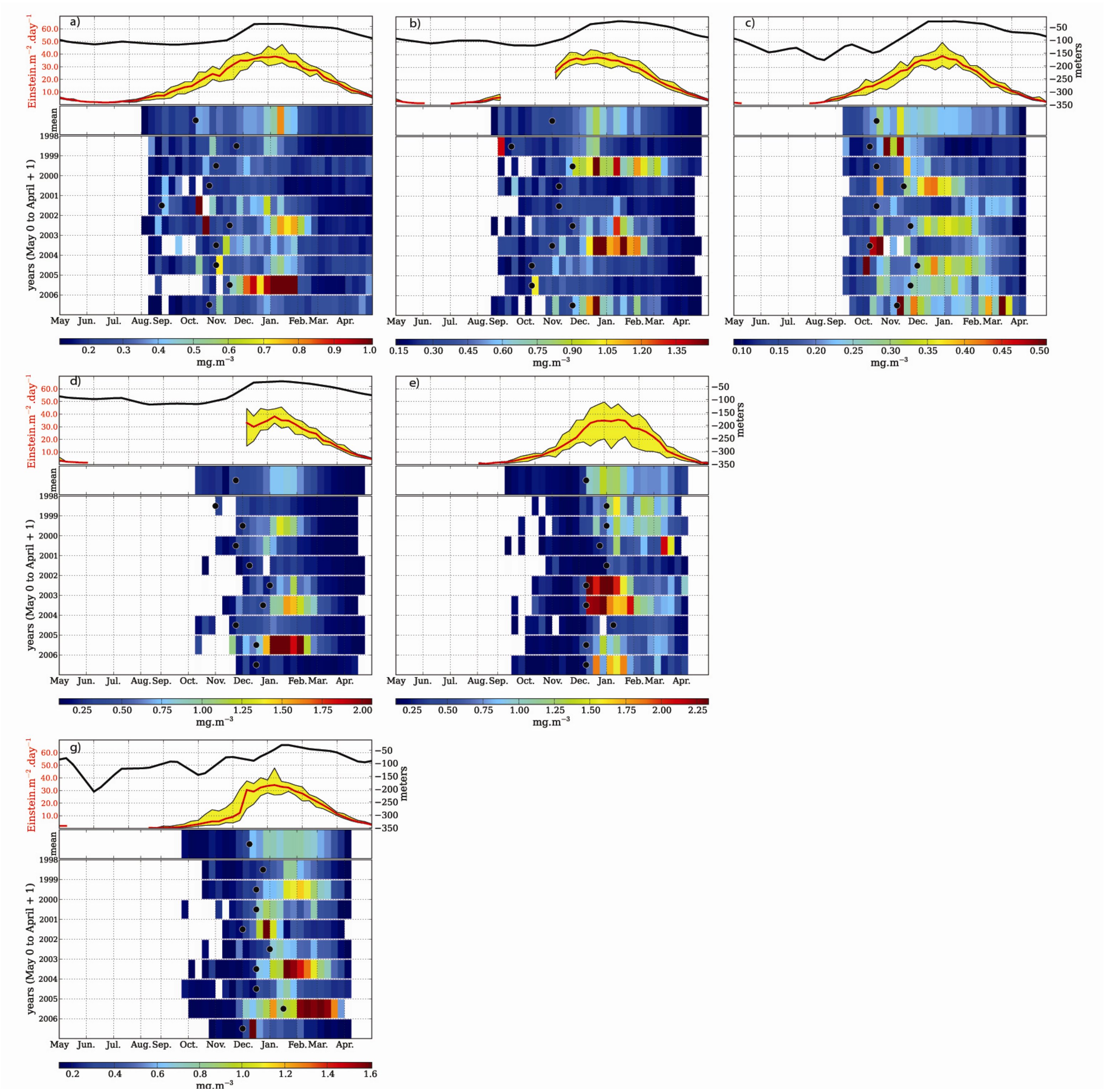
Figure S3



a)
b)
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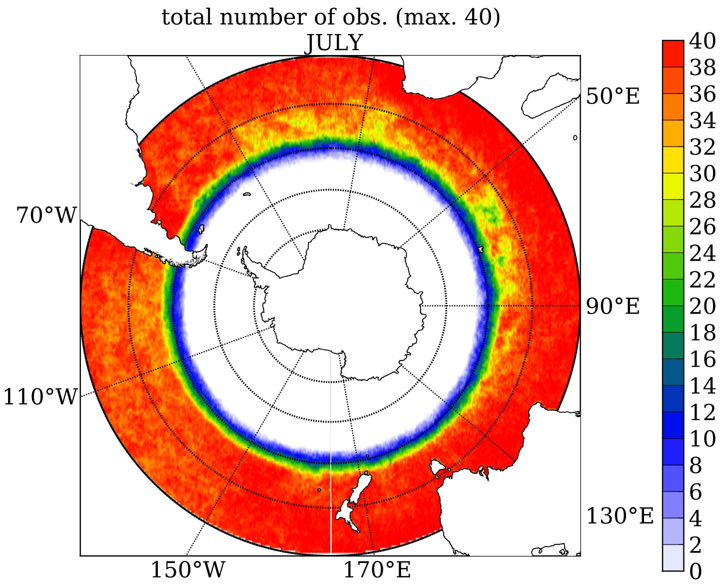
Einstein.m^{-2}.day^{-1}
meters
mean
years (May 0 to April + 1)
May Jun. Jul. Aug. Sep. Oct. Nov. Dec. Jan. Feb. Mar. Apr.
mg.m^{-3}

Figure S4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50°E
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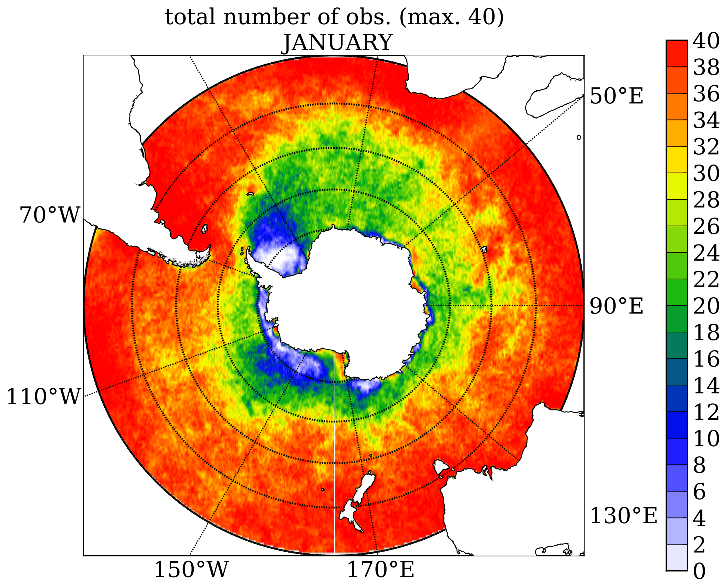
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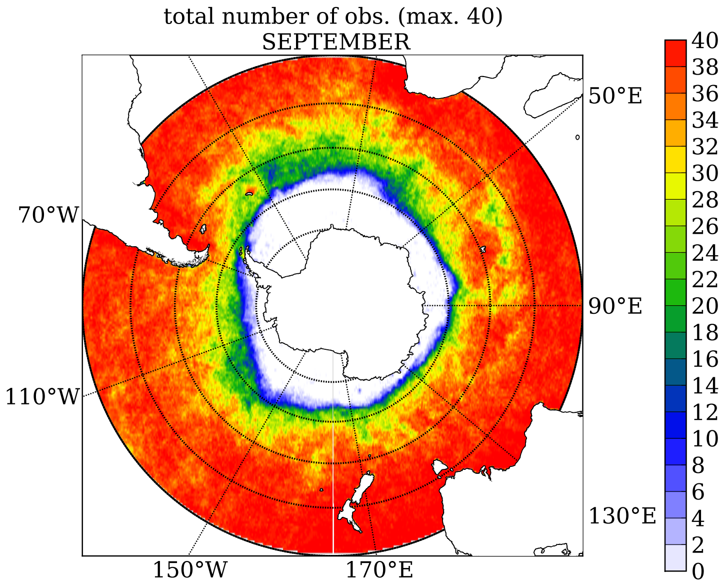
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SEPTEMBER
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