

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 30°S to 80°S) for three 10° 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 ~40°S. 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 35°S and 40°S (Figure S2a and S2b respectively), whereas in the Pacific, the TZ of high variability extends from 40-50°S (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 ($< 0.35 \text{ mg m}^{-3}$) and Indian ($< 0.25 \text{ mg m}^{-3}$). 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 40°S) 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, 2007a). 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 65°S . 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 65°S (Figure S3c, f, i). A similarly well defined and fairly short lived bloom is found in the ACZ of the Atlantic (45 - 55°S) (Figure S3a, d, g) and Indian (45 - 60°S) (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 (55-70°S, Figure S4a, d, f) through the influence of the Weddell Gyre is evident when compared to the Indian (60-70°S, Figure S4b, e) and Pacific (65-70°S, 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 ($\sim 15\text{-}20$ Einstein $\text{m}^{-2} \text{d}^{-1}$) 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.

Supplementary figure legends

Figure S1: Subtropical Zone (STZ) boxes (5° of latitude each) for Atlantic ($0 - 10^\circ\text{E}$), Indian ($85 - 95^\circ\text{E}$) and Pacific ($110 - 100^\circ\text{W}$) transects. The upper panel presents the MLD (black curve, depth in meters, y-axis on right) and the mean annual cycle of PAR (red curve, Einstein $\text{m}^{-2} \text{day}^{-1}$, 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 S2: Same as figure S1 but for the Transition Zone (TZ).

Figure S3: Same as figure S2 but for the Antarctic Circumpolar Zone (ACZ).

Figure S4: Same as figure S3 but for the Marginal Ice Zone (MIZ)

Supplementary figures

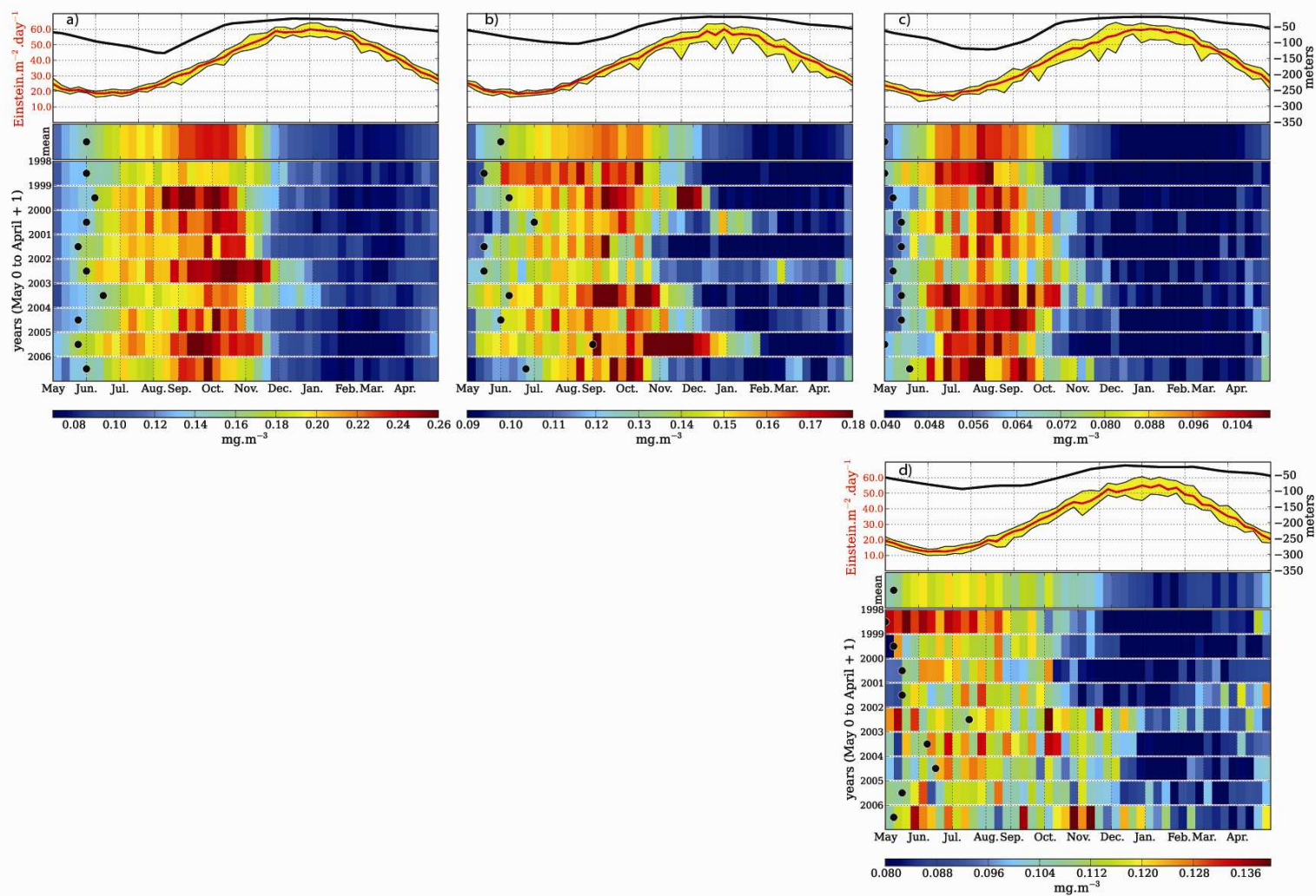


Figure S1

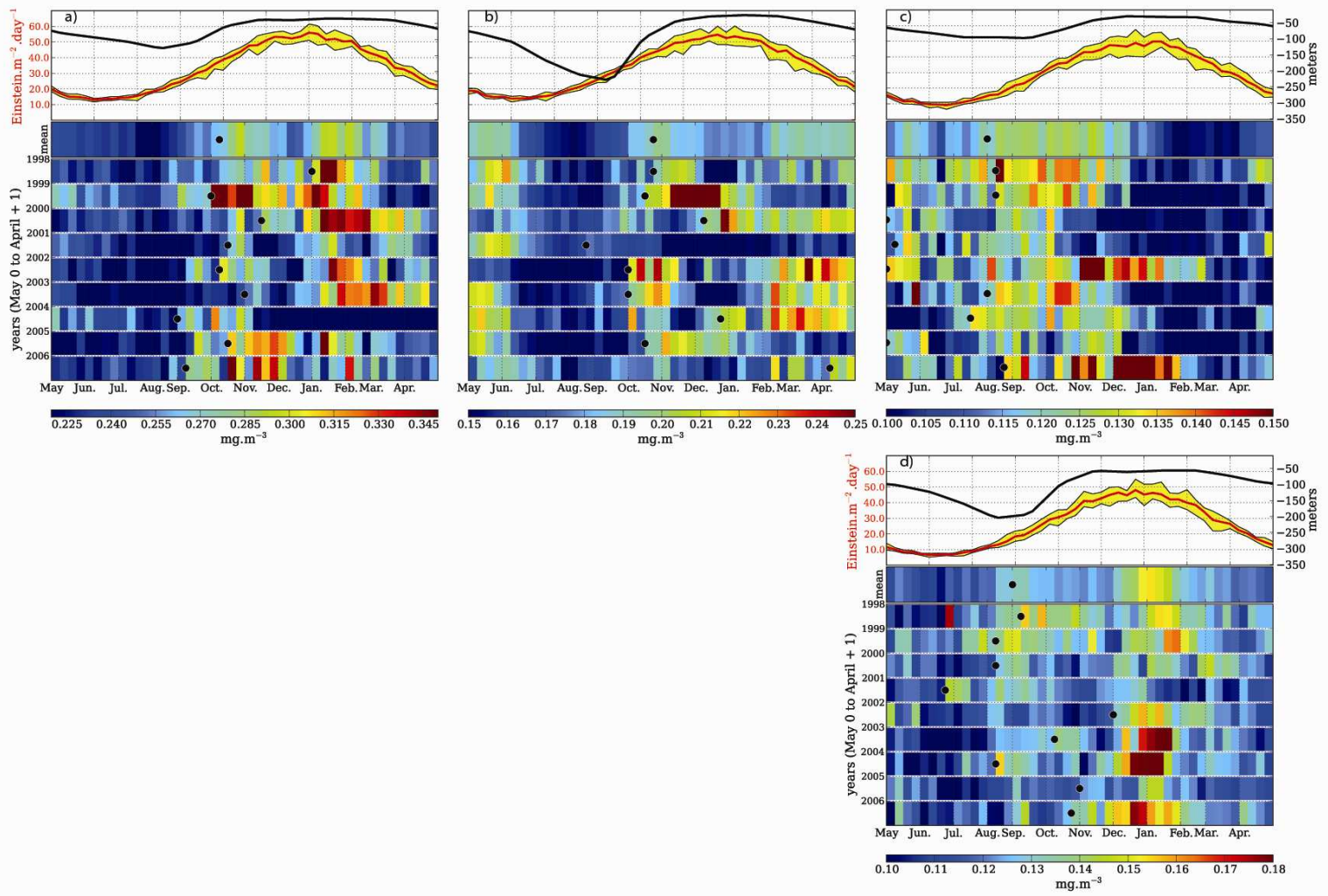


Figure S2

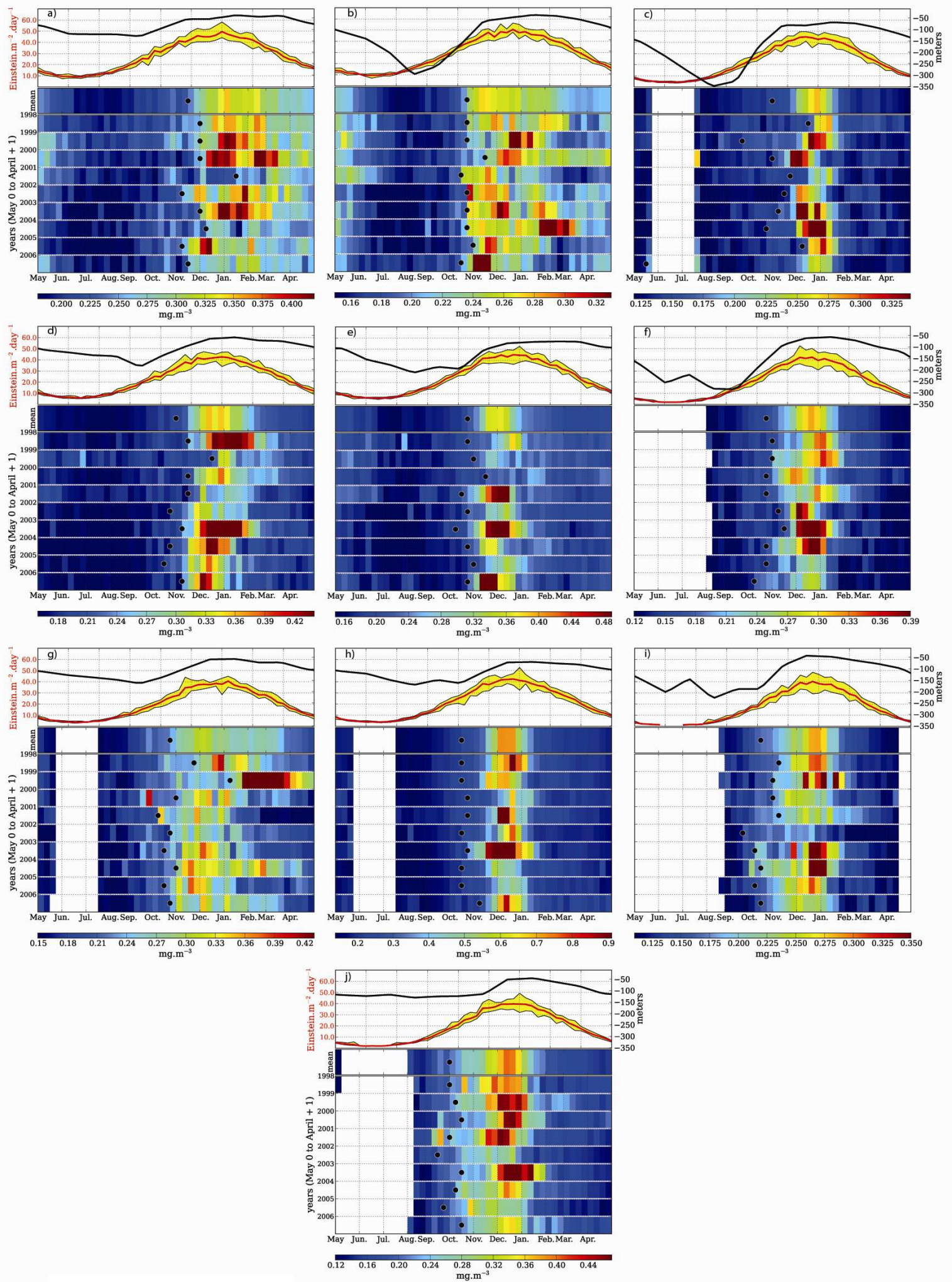


Figure S3

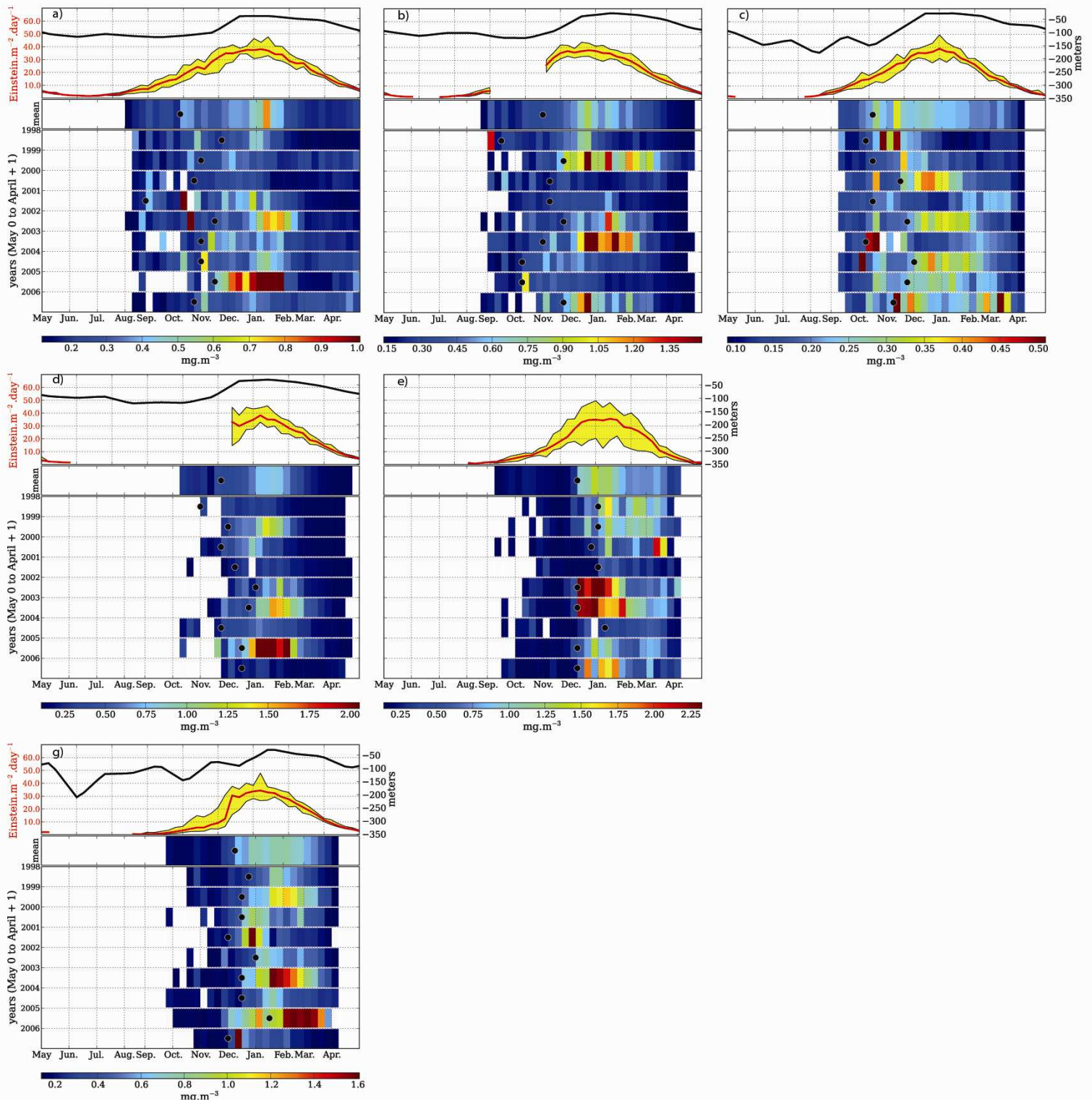


Figure S4