Comparison of primary productivity models in the Southern Ocean-preliminary results

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ABSTRCT

Three models were used to estimate primary productivity (PP) in the Southern Ocean for the summer of 2003-2007. They are the widely accepted model VGPM, a carbon-based model CbPM and a new type of model which uses phytoplankton absorption coefficient as input variable in stead of chlorophyll concentration. It was found that the degree of agreement among the results from three models was low, but the difference appeared relatively small with regard to previous reports. Nevertheless, the results were comparable to that from a PP model parameterized specifically for use in Southern Ocean waters. Among the three models, the output from CbPM differed the most from that estimated by the other two models. The different PP estimates were primarily attributed to the different ways these models treat phytoplankton physiology, along with the difference in input variables.

Keywords: Primary productivity, model, chlorophyll, carbon, absorption, the Southern Ocean

1. INTRODUCTION

Concerns on addressing eco-responses to climate change advocate making improvements on models to estimate ocean primary productivity (PP) based on satellite observations. A range of PP modeling approaches existed[1, 2], and a series of round-robin experiments have been conducted to compare and evaluate these models[3, 4, 5]. It was found that model results diverged the most for the Southern Ocean[4]. Models involved in the comparative studies all used chlorophyll concentration (Chl) in the surface water as a primary input variable, and none of them used phytoplankton absorption as an input variable. Recent studies suggest that phytoplankton absorption is a strong predictor of primary productivity in the surface ocean[6], and this variable can be analytically derived from satellite ocean color[7, 8] without the involvement of chlorophyll-specific coefficient. It is thus important to characterize the difference of basin scale PP estimated using phytoplankton absorption-based models from that estimated using biomass-based models.

Here in this study, we focus on the Southern Ocean (Fig.1) and try to compare PP from a new type of model[6, 9], that uses phytoplankton absorption rather than chlorophyll, with PP from the most widely accepted model VGPM[2] and PP from a recently developed carbon-based model CbPM[10]. Our target is to determine where, how and why the model results may differ. The efforts and results may help to further improve PP models in the Southern Ocean.

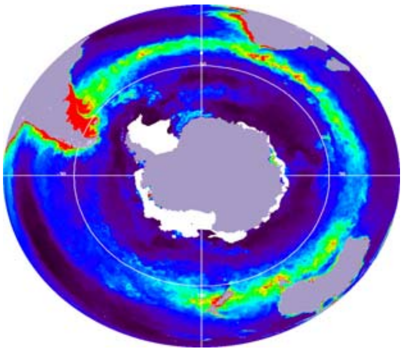


Figure 1. The study region (south of 50° S)

2. MODELS

Three models were used to calculate PP for the Southern Ocean. All symbols used were summarized in Table 1.

(1) VGPM[2]

$$PP = 0.66125 * P_B^{opt} * (E_0 /(E_0 + 4.1)) * Z_{eu} * Chl * DL \tag{1}$$

Where P_B^{opt} depends on satellite sea surface temperature, and E_0, Z_{eu} and Chl are satellite products.

(2) CbPM[10]

$$PP(z) = \mu(z) * C(z) \tag{2}$$

Phytoplankton growth rates (μ) were calculated from the growth irradiance and the ratio of chlorophyll to phytoplankton carbon (Chl:C). The Chl:C was estimated from ocean-color satellite Chl and backscattering coefficient (b_{bp}). PP at each depth (PP(z)) was then vertically integrated within the euphotic zone to get PP.

(3) A simplified absorption-based model (SAM)

Based on Lee et al. (1996)[9] and Marra et al.(2007)[6], a simplified spectrally integrated absorption-based model can be expressed as:

$$PP(z) = \frac{K_\phi \exp(-\nu * E(z))}{K_\phi + E(z)} [\phi_m * a_{ph} * E_0 \exp(-K_{PAR}(z) * z)] \tag{3}$$

Where ν =0.01 (Ein/m^2/day)$^{-1}$ and K_Φ=10 Ein/m^2/d[9], and Φ_m=0.01 mol C/(Ein absorbed)[11]. a_{ph} and K_{PAR} can be derived from remote sensing reflectance. Similar to the CbPM, PP at each depth (PP(z)) is vertically integrated within the euphotic zone to get water-column PP.

3. INPUT DATA AND METHODS

Most of the data we used were downloaded from NASA (http:// oceancolor.gsfc.nasa.gov). They are MODIS chlorophyll (Chl) retrieved using OC3 algorithm (hereafter OC3_Chl), sea surface temperature (4 micron, SST4), normalized water leaving radiances (nLw), and SeaWiFS diffuse attenuation coefficient at 490 nm (K_d(490)) and PAR (Version r2009.1). The 8-day composite data were used, with a spatial resolution of 9 km.

Table 1 Symbols and units

Symbol	Units	Description
P^B_{opt}	mgC/mgChl/h	Maximum C fixation rate within a water column
E_o	Ein/m^2/day	surface photosynthetically available radiation (PAR)
Z_{eu}	M	euphotic zone depth
Chl	mg/m^3	surface chlorophyll concentration
DL	Hour	length of day time
μ	d^{-1}	Phytoplankton growth rate
C	mg C	Phytoplankton carbon
K_{Φ}	Ein/m^2/day	Value of E when $\Phi = \Phi_m/2$
v	(Ein/m^2/day)$^{-1}$	Photoinhibition factor
Φ_m	mol C/(Ein absorbed)	Maximum quantum yield
a_{ph}	m^{-1}	Phytoplankton absorption coefficient
K_{PAR}	m^{-1}	Diffuse attenuation coefficient for downwelling irradiance

For VGPM, the input data are OC3_Chl, SST and PAR.

For CbPM, two of the input variables are Chl and $b_{bp}(443)$, which were retrieved from MODIS nLw with GSM Version 4[12] and were obtained from U. California, Santa Barbara. The others were $K_d(490)$, PAR, mixed layer depth (MLD) and nitracline depths (Z_{NO3}). MLD was obtained from the Ocean Productivity website at Oregon State University (OSU, http://www.science.oregonstate.edu/ocean.productivity/mld.html), and Z_{NO3} were calculated from monthly climatological nutrient fields reported in the World Ocean Atlas (Westberry et al., 2008).

For SAM, $a(490)$, $b_b(490)$ and $a_{ph}(412, 443, 488, 531, 551)$ were retrieved from nLw with QAA Version 5[8] and then K_{PAR} was calculated based on $a(490)$ and $b_b(490)$[13]. Finally the average of $a_{ph}(412, 443, 488, 531, 551)$ and K_{PAR} were input into SAM to get PP at each depth interval, which were vertically integrated to get PP. The euphotic zone depth (Z_{eu}) was calculated based on K_{PAR}[14].

All the input fields were interpolated to a 2160x1080 grid (18 km spacing) to drive the models.

In addition, in order to examine the differences in PP induced by using different Z_{eu} products, we chose VGPM to conduct a test. VGPM was run with Z_{eu} derived using an empirical Z_{eu} algorithm[15], as well as an IOP-centered Z_{eu} algorithm[14]. Hereafter we used VGPM_{z1} to annotate the former and VGPM_{z2} for the latter.

Finally we output austral summer (December-February) mean PP over 2003-2007. We chose to focus on summer data because it is the time when daily rates of production are highest and interannual variability in primary production is greatest[16].

To compare models, we calculated a correlation coefficient (r) and a percentage difference map for each pair of models.

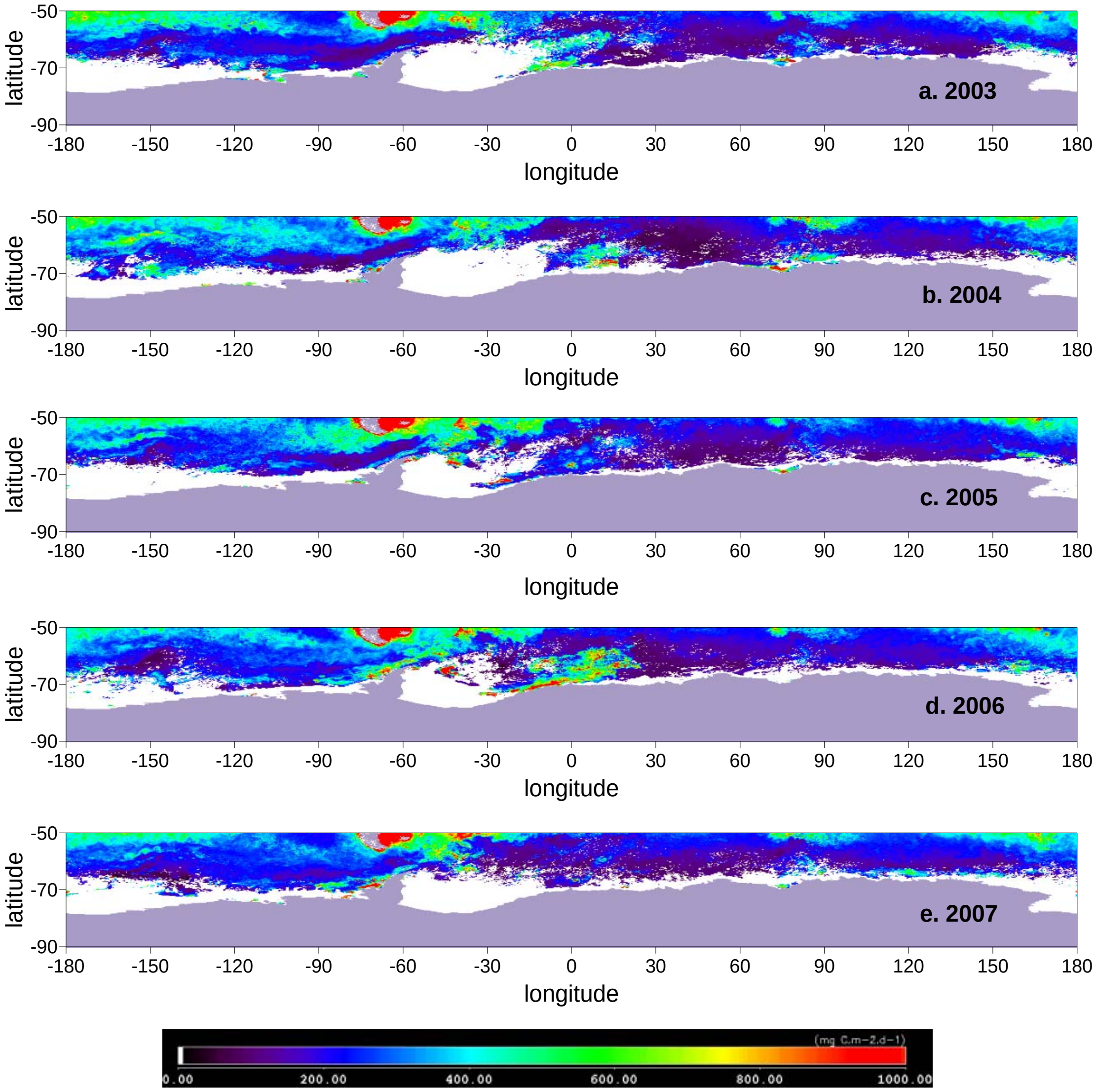
$$\text{Percentage difference} = [(\log(\text{PP2}) - \log(\text{PP1}))/\log(\text{PP1})] \times 100\% \qquad (4)$$

PP2 and PP1 represent outputs from different models, for example, PP2 for CbPM and PP1 for VGPM.

4. RESULTS AND DISCUSSION

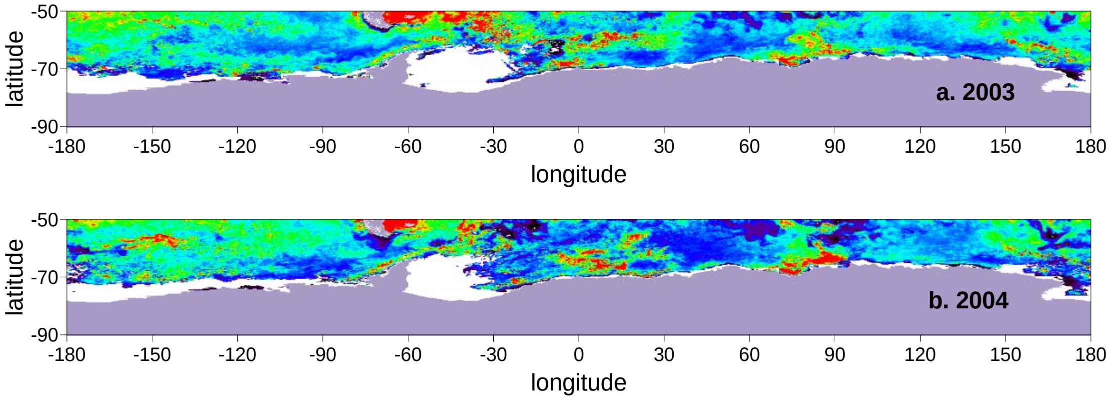
4.1 Comparison among VGPM, CbPM and SAM

Results produced from three models are shown in Figs. 2-5, and the summary of statistic analysis for PP products is listed in Table 2.



(e) 2007

Figure 2. PP output from VGPM; the same color bar was applied to Figs. 2-5.



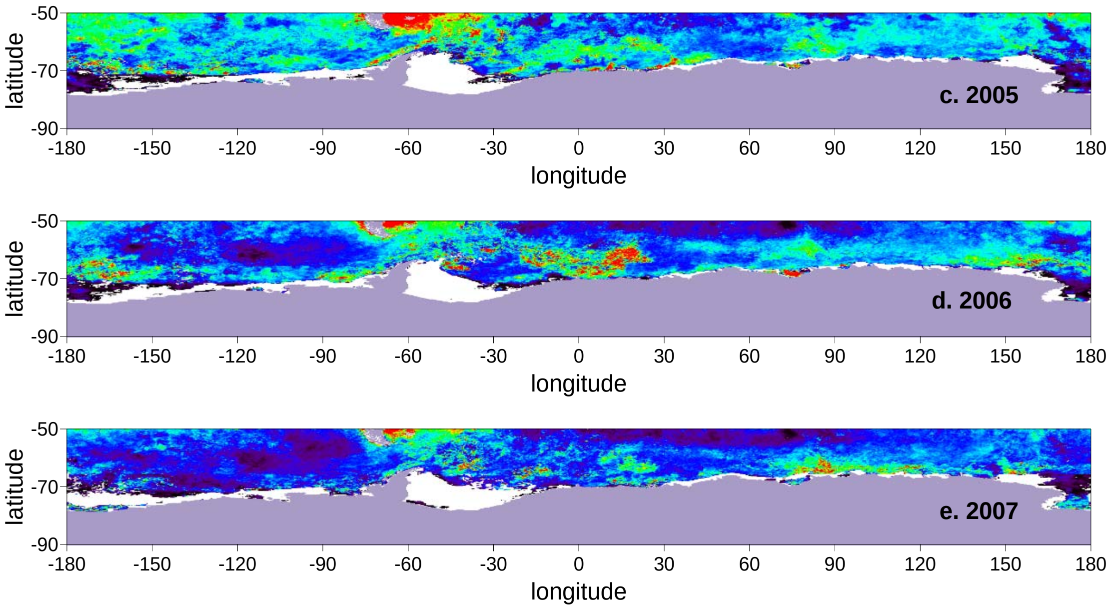
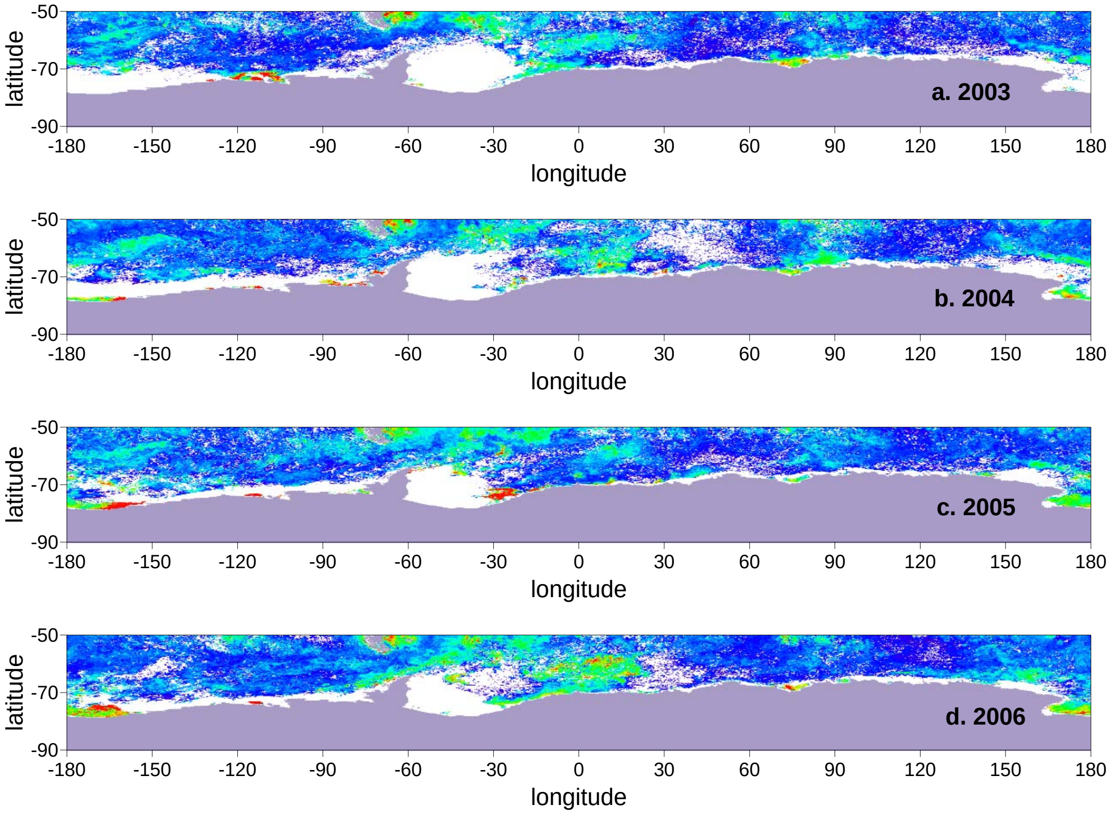


Figure 3. PP output from CbPM



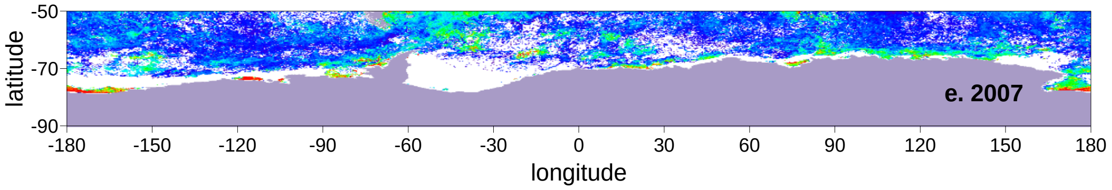


Figure 4. PP output from SAM

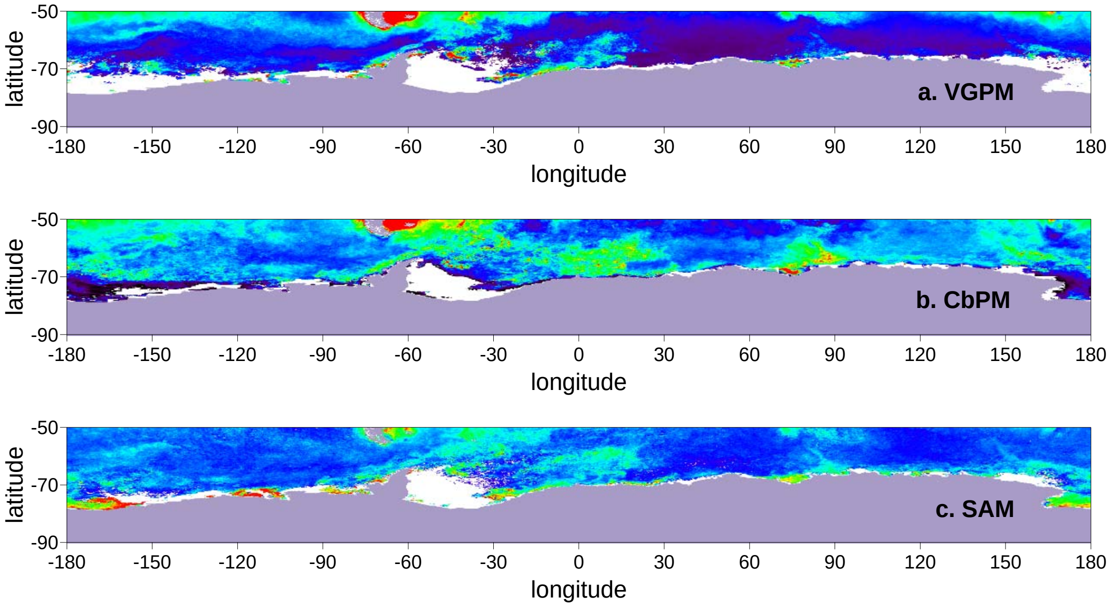


Figure 5. PP of 2003-2007 mean

The 2003-2007 mean value of PP produced from CbPM was the highest (354±159 mgC/m^2/d), while the PP from VGPM was the lowest (278±187 mgC/m^2/d), and that of SAM was in the middle (330±121 mgC/m^2/d). Nevertheless, these numbers are comparable to the result of a recent PP model that was parameterized specifically for the Southern Ocean[16], where PP ranged 200-400 mgC/m^2/d in December-February for the year of 2002-2005. The result of Moore and Abbott (2000)[17] using Chl from SeaWiFS and the VGPM appeared 46% higher than that of Arrigo et al. (2008)[16], however Moore and Abbott (2000)[17] calculated PP for the period of 1998-1999 while Arrigo et al. (2008)[16] provided an average of 1997-2006.

Table 2 Descriptive statistics for PP measurements (mgC/m^2/d)

	VGPM		CbPM		SAM	
	Mean	Std	mean	Std	Mean	Std
2003	277	205	437	238	309	113
2004	282	211	408	235	324	116
2005	282	204	380	212	325	130
2006	289	220	326	213	331	134
2007	262	183	266	162	312	128
2003-2007 mean	278	187	354	159	330	121

Low correlation between each pair of models was found. The correlation coefficient (r) was 0.55 between VGPM and SAM, and 0.28 between VGPM and CbPM (log-transformed PP). And it dropped to -0.11 between CbPM and SAM, suggesting very low degree of agreement between CbPM and SAM. This is quite different from the results of comparisons of 12 algorithms at 89 stations that revealed high correlations (>0.9) in many cases[3]. The high correlation may be partially that the 12 algorithms all used Chl as the primary input variable.

The spatial patterns of the differences between each pair of models are shown in Fig.6. CbPM and SAM generated higher estimates of PP than VGPM in almost the same areas.

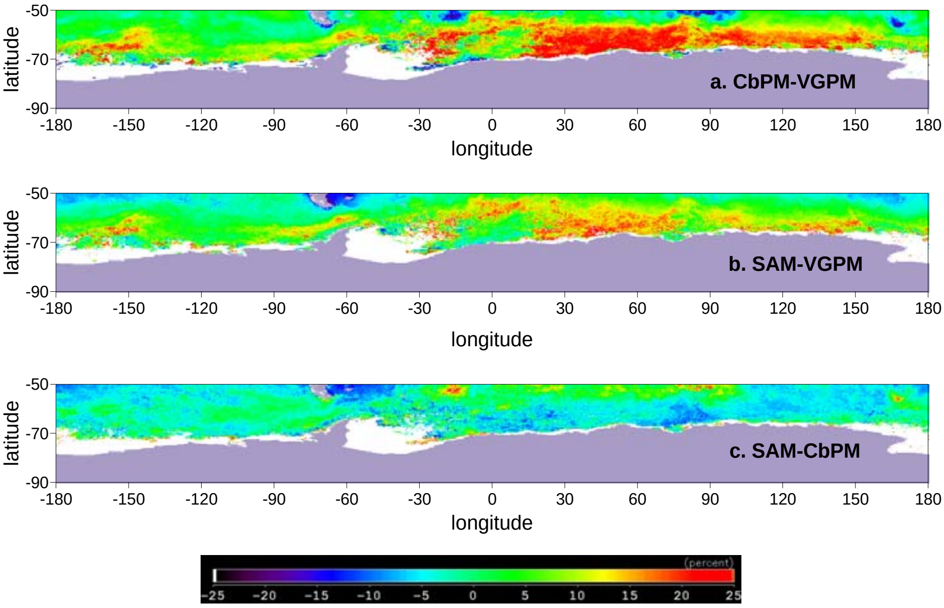


Figure 6. Map of percentage difference for 2003-2007 mean

The three models also generated different interannual variations of PP (Fig.7). The VGPM and SAM PP showed very weak variation between years, while CbPM PP showed a distinct and strong decreasing trend over 2003-2007. Arrigo et al. (2008)[16] reported similar results as those from VGPM and SAM. They concluded that interannual variability in total production in the Southern Ocean was relatively small, with all years falling within 6% of the mean for the 1997–2006 period. The VGPM and SAM estimated PP here was within 7-10% of the mean for the summer of 2003-2007.

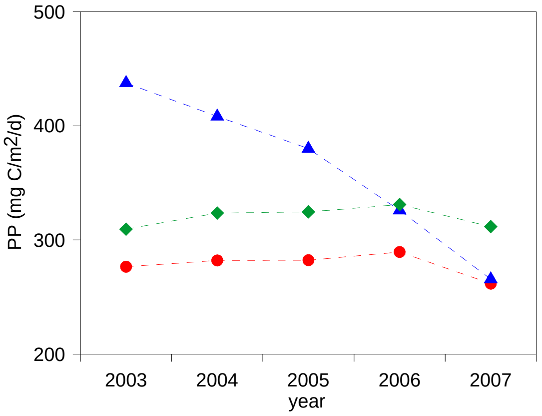


Figure 7. Interannual variation of PP; Red-VGPM，blue-CbPM，green-SAM.

A comparison of global output from 24 satellite-based primary production algorithms showed that agreement between algorithms was especially poor for the Southern Ocean[4]. The large divergence between algorithms was attributed primarily to the differences in the way they formulate primary production as a function of temperature. The extremely low temperature in many Southern Ocean waters (<0ºC) resulted in estimated PP by the 24 algorithms varying over a range of 372%. If we consider the mean PP (Table 2), the results from the three models compared here are not that highly different from what is reported in Carr et al.(2006)[4]. The difference range of the mean PP is ~8% (the maximum minus the minimum expressed as a percentage of the mean daily rate). The correlation of 0.55 between VGPM and SAM, and the relatively high similarity of spatial and temporal patterns between VGPM and SAM (Figs.6-7), suggested that these two models agreed with each other to some extent. However, in SAM, there is no application of temperature as an input, while in VGPM temperature exerted a strong influence on productivity. Thus the divergence between model results was more likely due to the differences in the input variables.

4.2 Comparison with *in situ* measured data

Several studies have measured primary production on the Ross Sea shelf at rates> 1000 mg C/m^2/d[18, 19]. This could be observed in the results of SAM, but not in the results of other two models (Figs.2-4). And the *in situ* measured daily PP of 571 mgC/m^2/d for the Weddell Sea and 962 mgC/m^2/d for the Ross Sea were reported in January[20]. VGPM and CbPM produced large patches of high PP (> 1000 mgC/m2/d) in Weddell Sea (Figs.2-3). For these two models, either the maximum or the mean value of PP was higher in the Wedell Sea than in the Ross Sea. The SAM also produced higher mean value of PP in the Wedell Sea, but it produced higher maximum value of PP in the Ross Sea rather than in the Wedell Sea. Without performing a statistically valid comparison by using coincident satellite derived and in situ measured PP, it is hard to tell which one of these three models produce PP closer to *in situ* observations.

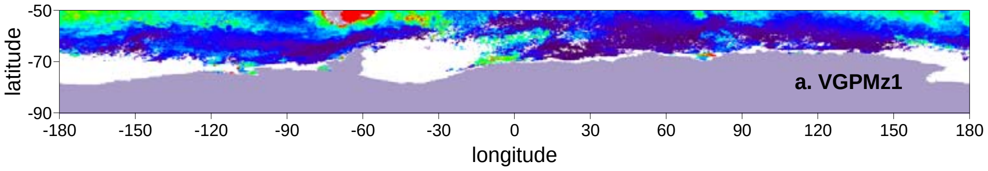
4.3 VGPM with different Z_{eu} input data

The test of different Z_{eu} product as input showed relatively small difference in PP (Fig.8). The PP of $VGPM_{Z2}$ was ~9% higher on average than that of $VGPM_{z1}$. The most significant difference was likely occurred in the water of low Chl (~<0.1 mg/m3). Z_{eu} derived based the IOP approach could be ~30% deeper than that based on Chl in these waters (Fig.9).

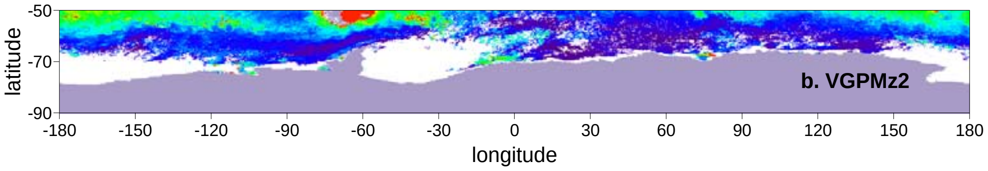
5. SUMMARY

For waters in the Southern Ocean, we found that the degree of agreement among PP from three models was low, but the difference also appeared low compared to that reported in Carr et al.(2006)[4]. And, among the three models we studied, PP from CbPM differed the most from the PP of the other two models.

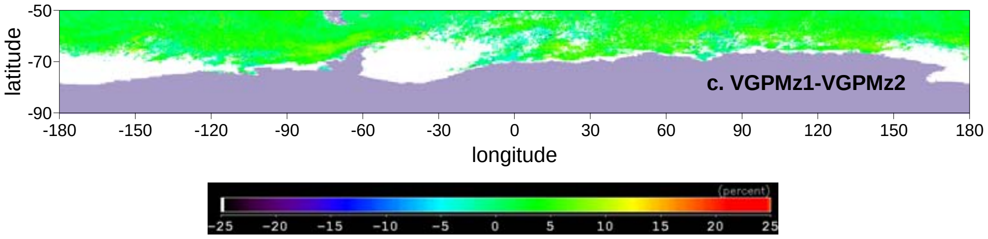
The information of ice cover was not taken into the model calculation. It might introduce extra uncertainties in the vicinity of the ice edge. And the uncertainty of modeled mixed layer depth might be large in high latitudes, which might affect the output of CbPM to a great extent. Further research is required.



(a) VGPMz1



(b) VGPMz2



(c) percentage difference between $VGPM_{z1}$ and $VGPM_{z2}$

Figure 8. PP outputs with different Zeu inputs and their percentage difference in 2003

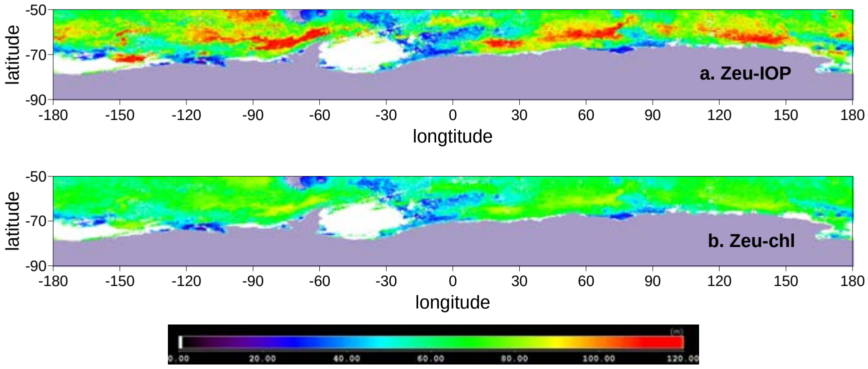


Figure 9. IOP-based Zeu and Chl-based Zeu in 2003

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