Modelling spectrally-resolved light attenuation in a coupled physical-biological ocean model

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Submitted in partial fulfillment of the requirements for the degree of Bachelor of Environmental Sciences, School of Biological, Earth and Environmental Sciences, Faculty of science, The University of New South Wales

November 2006
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<td>$aA$</td>
<td>Absorption cross section of phytoplankton cells</td>
</tr>
<tr>
<td>$b_T$</td>
<td>Total scattering coefficient</td>
</tr>
<tr>
<td>$b_w$</td>
<td>Scattering coefficient of the water</td>
</tr>
<tr>
<td>$b_{phy}$</td>
<td>Scattering coefficient of phytoplankton</td>
</tr>
<tr>
<td>$C$</td>
<td>Pigment concentration</td>
</tr>
<tr>
<td>$C_P$</td>
<td>The specific heat capacity</td>
</tr>
<tr>
<td>$C_i$</td>
<td>The concentration of $i$th pigment</td>
</tr>
<tr>
<td>$f$</td>
<td>The Coriolis parameter</td>
</tr>
<tr>
<td>$g$</td>
<td>The gravitational acceleration</td>
</tr>
<tr>
<td>$g_1$</td>
<td>First numerical constant of scattering.</td>
</tr>
<tr>
<td>$g_2$</td>
<td>Second numerical constant of scattering.</td>
</tr>
<tr>
<td>$I$</td>
<td>Intensity of light</td>
</tr>
<tr>
<td>$K_d$</td>
<td>Total attenuation coefficient</td>
</tr>
<tr>
<td>$K_w$</td>
<td>Attenuation coefficient of water</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of phytoplankton cells</td>
</tr>
<tr>
<td>$n_a$</td>
<td>Refraction index of air</td>
</tr>
<tr>
<td>$n_w$</td>
<td>Refraction index of water</td>
</tr>
<tr>
<td>$r$</td>
<td>Radius of spherical cells</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>Distance in EW, NS and vertical directions</td>
</tr>
<tr>
<td>$u, v, w$</td>
<td>Velocity in EW, NS and vertical directions</td>
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<tr>
<td>$u_p$</td>
<td>Velocity in EW direction in the particle case</td>
</tr>
<tr>
<td>$u_{chl}$</td>
<td>Velocity in EW direction in the dissolved chlorophyll case (the non-particle case)</td>
</tr>
<tr>
<td>$v_p$</td>
<td>Velocity in NS direction in the particle case</td>
</tr>
<tr>
<td>$v_{chl}$</td>
<td>Velocity in NS direction in the dissolved chlorophyll case (the non-particle case)</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume of chlorophyll in one phytoplankton cell</td>
</tr>
<tr>
<td>$W_i$</td>
<td>The wavelength halfwidth of the Gaussian band</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$\lambda_i$</td>
<td>The wavelength of absorption $i$th pigment</td>
</tr>
<tr>
<td>$\gamma C$</td>
<td>Specific absorption coefficient at discrete wavelength with chl a, chl b, chl c, cart</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of light beam across the air-water interface</td>
</tr>
<tr>
<td>$\theta_a$</td>
<td>The zenith angle of the incident light in air</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>The angle between the downward vertical and the transmitted beam in water.</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Elevation of the sea surface</td>
</tr>
<tr>
<td>$\eta_p$</td>
<td>Elevation of the sea surface in the particle case</td>
</tr>
<tr>
<td>$\eta_{chl}$</td>
<td>Elevation of the sea surface in the dissolved chlorophyll case (the non-particle case)</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Radiation flux</td>
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*Table 1: The symbols are using in the equations*
Acknowledgements

I would like to thank my supervisor Dr. Mark Baird, who has been helping me to understand the biological concept, teaching me to use the Matlab program, and his review, guideline and suggestions on this work are sincerely appreciated. A huge thanks to Andrea Taschetto who enthusiastically correct my grammar, offer me great advice and help me use the latex program, to Agus Santoso who always helps me solve my Matlab programming problems, and to everyone in the Oceanography and Meteorology lab for their metal and physical support in many ways. Special thanks to my friends Wen-fei Yuan, Chee-sun Choung, I know that they are also in the final semester and busy with preparing their thesis, but they still took a lot of time to go through my work and help me to correct my grammar.
Abstract

Light attenuation in the ocean is investigated using spectrally-resolved solar radiation to force a coupled physical-biological model. Three descriptions of light attenuation are studied: 1) absorption by dissolved chlorophyll in the water column, 2) absorption by chlorophyll contained in particles, 3) a combination of absorption and scattering of particles. The particle effect is defined as the differences between particle and non-particle cases. The scattering effect is defined as the difference between particle and scattering cases. In order to analyse the light attenuation in the coastal ocean, the coupled model was forced with a northerly wind are configured for the East Australian Current (EAC). Results show that the particle effect decreases the attenuation of light by 40%-50% at the surface, increase to 60%-70% at depths, which in turn increases by 60% the phytoplankton biomass along the coastline between 60m to 90m depths. The scattering effect increases the attenuation; leading to a decrease of about 40% in light field at depths, resulting in a 20% reduction of phytoplankton biomass. The results also reveal that the light-absorption particle created a biological heating effect which reduces the velocity of the EAC. The reduced velocity of the EAC due to the particle effect is up to 15 cm s$^{-1}$ and reducing to 13 cm s$^{-1}$ when the scattering effect is included. Moreover, the coupling physical and biological models present a feedback process between physical and biological variables, which could result in about 20% of changes in the magnitude of the particle and scattering effects. This study improves the prediction of light attenuation in the coastal waters, and gives a better understanding of the effect of light attenuation on the biological production.
Chapter 1

Introduction

Light is one of the most important factors for the growth of organisms. Pelagic plants rely on the sun’s energy for their growth as an essential part of photosynthesis (Thurman and Trujillo, 2004). Therefore, it is important for scientists to understand and predict light fields in both physical and ecological analysis of ocean.

Investigation of ocean light fields has been conducted in many studies. In general, light is attenuated in the aquatic environment by the combination of absorption and scattering. According to Kirk (1977), three major light-attenuation components include water, yellow suspensions (gelbtiff) and phytoplankton species (such as diatoms, dinoflagellates, or blue-green algae). These components absorb different ranges of wavelengths (Kirk, 1977; Fujiki and Taguchi, 2002). For example, water more effectively absorbs wavelengths higher than 1000nm (Kirk, 1977, 1979), while phytoplankton absorbs most strongly in the 300nm to 760nm waveband, i.e. the visible light (Nybakken, 2001; Kirk, 1975a; Maske and Haardt, 1987; Staehr et al., 2004).
Earlier observational and modelling studies have looked at the influence of attenuation by discrete particles on the light field (the particle in this case is considered as phytoplankton cells) or the so-called the package effect (Duysens, 1956; Kirk, 1975a,b, 1976; Morel and Bricaud, 1981; Osborne and Geider, 1987, 1989; Nelson et al., 1993). Duysens (1956) was the first marine biologist who initiated the research on the light absorption by particles. He constructed a simple model to estimate the magnitude of the particle effect by using different sized and shaped phytoplankton species and assuming a light beam passing through the particles without scattering. He found that the larger the size of the particle for the same total volume, the less the light is attenuated. Kirk extended Duysnes’ work to different shapes of phytoplankton cell and showed they exhibited a different absorption rate (Kirk, 1975a).

Kirk (1975b, 1976) continued to work on the measurement of particle effect magnitude. He used a different structure of colonies of phytoplankton to determine the attenuation of light field. For instance, the spheroid cells have less attenuation rate than the large spherical cells because spheroids have lower absorption cross-section per colony (Kirk, 1975b, 1976). According to Kirk (1977, 1979), if this theory was applied in reality the scattering needs to be reconsidered when light beam passes through the particles. Kirk (1991) introduced the average pathlength of a traversing photon to approximate the process of scattering. He used an increased pathlength to represent the process of scattering.

Recently, the calculation of specific attenuation coefficients of the in vivo spectrum of phytoplankton (Maske and Haardt, 1987; Osborne and Geider, 1987, 1989; Sathyendranath and Hoepffner, 1991) have become more accurate for determining light fields in the ocean.
In order to include auxiliary pigment distributions within absorption coefficient equations, Sathyendranath and Hoepfner (1991) used a Gaussian curve to estimate the absorption properties of the major and auxiliary light-harvesting pigments depending on the individual absorption spectral waveband.

The relative sophisticated understanding of light attenuation is not routinely used in ocean models such as Baird et al. (2006a,b). Some previous studies had already tried to set up simple models of light field by using certain amount of phytoplankton biomass (Stramska and Dickey, 1993; Edwards et al., 2001; Edwards and Brindley, 1999; Edwards et al., 2004).

Biologically-induced velocity was first described by Edwards et al. (2001, 2004). In order to calculate the velocities induced by high phytoplankton biomass, the authors used a model based on the steady-state momentum equation, which includes the Coriolis force, pressure gradient and viscous effects. The light penetrates deeper into the water column at the low-phytoplankton-biomass side when compared to the high-phytoplankton-biomass side, causing an imbalance of temperature which induces the horizontal and vertical water movement in these experiments (Edwards et al., 2001). Edwards et al. (2004) set up a new model to examine the vertical circulation motion produced by biologically induced heating. The vertical upwelling water movement also brings nutrient from deep water, which in turn increases the biological production. However, biologically-induced transport is relatively small when compared to the ocean current movement, which makes it hard to measure the effect in the open-ocean waters. Edwards et al. (2004), also suggested that the biological heating needs to be determined in coupled biological-physical models. Nonetheless, the authors did not include the particle effect in their study, thus there is a gap between the
particle effect and biological heating modelling.

The aim of this study is to use a coupled physical-biological ocean model to investigate the behaviour of light field undergoing the combined processes of absorption by particles and scattering in water. The model will be run over 32-days with a northerly wind driving upwelling event off the NSW coast. By taking the differences of the physical and biological variables, we can investigate the influences of particle and scattering effect, respectively. Finally, we will determine how the light field is affected under different simulations. This improved representation of the light attenuation process should be a step toward a better physical and ecological understanding of the ocean.
Chapter 2

The coupled physical-biological model

The NSW coastal region was simulated by the coupled physical-biological ocean model developed by Baird et al. (2006a,b). This model is a combination of biomechanical pelagic ecosystem model and a physical coastal model.

2.1 The physical model

The Princeton Ocean Model (POM)

The physical model is the Princeton Ocean Model (POM). The POM has free surface and solves the nonlinear primitive equations on a horizontal orthogonal curvilinear grid and a vertical sigma coordinate system (Blumberg and Mellor, 1987). The grid is configured along the NSW coast from 28.4°S to 37.5°S in a distance of 1025km, extending offshore between 395km (at 28.4°S) and 500 km (at 37.5°S). Fig. 2.1 shows the model grid base on Baird et al. (2006a). There are 130 grid points in the offshore direction, with a
resolution varying between 1 to 6km. In the alongshore direction, there are 82 grid points with a resolution between 6.5 to 24 km. The boundary grid points are 1 to 6 and 77 to 81 in east-west direction and in the north-south direction is from 125 to 130. To avoid the boundary condition affects, we will use the interior grid with points ranging between 1 to 124 in the east-west direction, and 7 to 76 in the north-south direction. The vertical coordinates has 31 sigma-layer, containing the smoothed topographies at the bottom in a depth of 50 to 2000m (Baird et al., 2006a).

The light model

The light model contains 57 wavelengths chosen from 340 to 5000nm wavelengths as seen in Fig. 2.2. These 57 wavelengths depend on the absorption rate of phytoplankton variability of absorption with wavelength, and the total energy. There are 43 wavelengths between 300-760nm with a high resolution for every 10 wavelengths. Above the 1000nm waveband, the light is only absorbed by water and it vanishes within a few metres (as shown in Fig. 2.3). This is considered as the low penetration ability. In this case, resolution is taken in every 100 or 1000 wavelength.

2.2 The biological model

The biological model was developed by Baird and Emsley (1999). This model contains five state variables: dissolved inorganic nitrogen(N), phytoplankton(P), zooplankton(Z), and phytoplankton reserves of nitrogen(R_N) and energy(R_I). This biological model includes the following pelagic biological processes: nutrient uptake and light capture by
Figure 2.1: The model grid base on Baird et al. (2006a). The first grid line and then every 2nd grid line in the north-south and east-west direction are shown. Depth contours are shown in bold (200m, 1000m and 2000m), and the intermediate contours are 500m and 1500m. The dash-dot line is the cross-shelf section used for Figs. 3.1, Fig. 3.3, 3.5, and 3.6.
Figure 2.2: The spectral energy distribution of solar radiation at sea-level [W m$^{-2}$ nm$^{-1}$]. The 57 wavelengths shown (*) are those used in the light model.
Figure 2.3: The wavelength resolved light field in the dissolved chlorophyll case (the control case) on days 12.5, 20.5 and 28.5 at the grid points 30 in offshore direction and 40 in alongshore direction. The waveband between 340-760nm has enough energy to penetrate into 80m depth. The long wavelengths (inferred above 1000nm) only reach few meter depth. Light nearly vanishes below 100m depth. And the colourbar in \( \text{W m}^{-2} \)

phytoplankton, phytoplankton growth from internal reserves, zooplankton grazing on phytoplankton, and the mortality and sinking of both phytoplankton and zooplankton (Baird et al., 2004).
2.3 Theory of light absorption and scattering in the ocean

2.3.1 Light at the sea surface

Solar beams passing through the atmosphere undergoes the processes of scattering and absorption. These processes reduce the intensity and also change the spectral distribution of direct solar beams (Kirk, 1994), resulting in light at sea-level as depicted in Fig. 2.2.

Solar energy can be quantified by the units quanta s\(^{-1}\) and photons, for example 1 m\(^2\) of horizontal surface receives about \(10^{21}\) quanta s\(^{-1}\) of visible light in summer (Kirk, 1994). The solar energy of one quantum is dependent on the wavelength, decreasing with larger wavelengths. We use the following expression to convert the light energy in quanta s\(^{-1}\) to J s\(^{-1}\) (ie. Watt [W]) at a wavelength \(\lambda\):

\[
1 \text{ quanta m}^{-2}\text{s}^{-1} = 5.03 \times 10^{15} \Phi \lambda
\]

(2.1)

where \(\Phi\) is the light energy expressed in W m\(^{-2}\) or quanta s\(^{-1}\), and \(\lambda\) is the wavelength in nm.

When a light beam enters the waters surface, parts of it are reflected back to the atmosphere. The unreflected part is refracted as it passes across the air-water interface, changing its direction. The angle direction between two different media (air and water in this case) is governed by the Snells Law (Kirk, 1994):
\[
\frac{\sin \theta_a}{\sin \theta_w} = \frac{n_w}{n_a}
\]  \hspace{1cm} (2.2)

where \( n_a \) and \( n_w \) are the reflective indices of air and water, respectively, \( \theta_a \) is the zenith angle of the incident light in air, and \( \theta_w \) is the angle of the transmitted beam in water.

The attenuation of downward light field within an oceanic layer \( I \) [W m\(^2\)] with depth is given by:

\[
I_{\text{bot}} = I_{\text{top}} e^{-K_d dz}
\]  \hspace{1cm} (2.3)

where \( I_{\text{top}} \) and \( I_{\text{bot}} \) are light fields measured at the top and at the bottom of a layer within a changing \( dz \) depth, respectively, and \( K_d \) is the absorption coefficient.

The average light within each layer \( I_{av} \) is given by:

\[
I_{av} = \frac{I_{\text{top}} - I_{\text{bot}}}{K_d dz}
\]  \hspace{1cm} (2.4)

### 2.4 Attenuation due to absorption and scattering

In this study, we used three methods to calculate the attenuation of light field in the water: attenuation due to the absorption of water, attenuation due to the absorption of chlorophyll, and attenuation due to the combining process of absorption and scattering of particles.
2.4.1 Attenuation due to the absorption of chlorophyll

To consider the attenuation of light due to the absorption of chlorophyll, we ignored the auxiliary pigments and took into account, only the major pigment chlorophyll (Chl a) in the calculations. The absorption coefficient $K_d$ must be calculated first, as per the equation below:

$$K_d = K_w + \gamma C \cdot N \cdot V$$  \hspace{1cm} (2.5)

where $V$ is the volume of one phytoplankton cell, $N$ is the number of particles, $\gamma C \, [m^{-1}]$ is the specific absorption coefficient (see Fig, 2.4) and $K_w$ is the absorption coefficient of water. Sathyendranath and Hoepffner (1991) determined the spectrally-resolved $\gamma C$ using:

$$\gamma C = \sum_{i=1}^{n} \gamma C_i' \left(\lambda_i \right) \cdot C_i \cdot \epsilon \left(\frac{(\lambda - \lambda_m)^2}{2W_i^2}\right)$$  \hspace{1cm} (2.6)

where $C_i \, [mg(chl) \, m^{-3}]$ is the concentration of the $i$th pigment ($i = 1, \ldots, n$); $\lambda_i \,[nm]$ is the wavelength of maximum absorption for $i$th pigment and $W_i$ is the halfwidth of the $i$th Gaussian band [nm].

2.4.2 Attenuation due to absorption by particles

The absorption of particles is a function of shape, size and pigment concentrations. The larger the particles, the less light they absorb per unit volume. The flatter the shape, the more light the particles absorb (Baird, 2003). In order to avoid the complexity calculations of different shaped particles, we assume that they are spherical, with a projection of a circle area, $\pi r^2$. Therefore, the absorption cross-section coefficient $aA$ can be estimated by:
Figure 2.4: Absorption coefficient, $\gamma C$ [m$^{-1}$] of $1 \times 10^6$ mg(chl) m$^{-3}$ as approximated by a Gaussian curve.
where $r$ is the radius of the spherical particle.

Reformulating the Equ. 2.5, the attenuation coefficient $K_d$ becomes:

$$K_d = K_w + aA \cdot N$$  \hspace{1cm} (2.8)

### 2.4.3 Attenuation due to absorption and scattering

To take the scattering into account, we need to introduce a total scattering coefficient $b_T$, which is the sum of the scattering coefficients of water and phytoplankton cells:

$$b_T = b_w + 4210 \cdot b_{phy}N$$  \hspace{1cm} (2.9)

where $b_w$ is the scattering coefficient of water, $b_{phy}$ is the scattering coefficient of $N$ phytoplankton cell.

To approximate the scattering effect, we come up with an effective vertical attenuation coefficient (absorption and scattering) $K_d$, given by:

$$K_d = (K_w + aA \cdot N) \sqrt{\frac{b_T}{K_w + aA \cdot N}} \left(1 + g_1 \cos \theta - g_2\right)$$  \hspace{1cm} (2.10)

where $\theta$ is the angle of the light beam in water, $g_1 = 0.3$ is the 1st scattering coefficient and $g_2 = 0.14$ is the 2nd scattering coefficient for clear waters (Kirk, 1991).

However, due to the large range of light waveband, each wavelength results in different
absorption rate within a different absorbance. Therefore, the previous equations are only for calculating one particular wavelength.

### 2.4.4 Effect of light attenuation on water temperature

Particles absorb light energy and turn it into heat energy, which warms up the water, in a process known as the biologically-induced-heat effect (Edwards et al., 2004).

The relationship of change in temperature with time $\frac{\partial T}{\partial t}$ and the change in downward irradiance with depth $\frac{\partial I}{\partial z}$ is:

$$\frac{\partial T}{\partial t} = \frac{1}{C_P} \frac{\partial I}{\partial z} \quad (2.11)$$

where $C_P$ is the specific heat capacity. This relationship can be reversed to find out the change in downward light if the changes in temperature are known.
Chapter 3

Experimental design

The simulations are run under a Northerly Wind (NW) forcing which is upwelling favourable off the NSW coast. In this model, we set up six cases running under heating and non-heating separately.

- **Non-heating condition**
  - **Control**: chlorophyll fully dissolved into water (non-particle case)
  - **Particle case**: particles containing chlorophyll in the water, without scattering.
  - **Scattering case**: particle case including the scattering

- **Heating condition**
  - **Control**: chlorophyll fully dissolved into water (non-particle case)
  - **Particle case**: particles containing chlorophyll in the water, without scattering
  - **Scattering case**: particle case including the scattering.

To investigate how the particle and scattering effects influence the physical and biological properties in the ocean, we extracted 4 physical variables and 2 biological variables
from each case. By taking the differences of each variable between particle and non-particle cases, we can estimate the particle effect. The difference between scattering and particle is called the scattering effect. Both simulations are done under non-heating and heating conditions. However, under the non-heating conditions, both particle and scattering effect, do no have the physical variables changed under this condition, and thus only the biological variables are needed.

3.1 Physical and biological variables

Four physical variables are analysed in this study: temperature, velocities, tracer of the East Australian Current (EAC) and the age of water. Figs. 3.1, 3.3, 3.5 and 3.6, show how the variables are influenced by the EAC when time increases in the model. Fig. 3.1, indicates the current passing along the coast above 200m to 300m, which can influences the temperature below 1000m depth. The age represents the average time that parcels of water in a particular grid box (Baird et al., 2006a), which is used to distinguish the upwelled, cold and nutrient rich water from the nutrient poor water. In general, the younger water is deeper water (cold and nutrient rich), and the older water is top layer water (warm and poor nutrients). For example, Fig. 3.3 shows that the younger water (presented in lighter colour) moves up continuously from depths. This means that the cold and nutrient rich water upwells at the coast. Therefore, the age of water is also an important indicator for investigating biological changes. The conservative tracer (Baird et al., 2006a) is useful to show the flow paths of EAC. Fig. 3.4, depicts the as areas that would not be influenced by the current. The surface geostrophic balance shows the speed and direction of EAC with time, as exhibited in Fig. 3.2.
Figure 3.1: The vertical section of temperature [°C] in the dissolved chlorophyll case (the control case) under the heating condition. Depths down to 1000m along eastward offshore from 150°E to 157°E on days 8.5 (A), 20.5(B) and 28.5(C).

The two biological variables are the biomass distributions of phytoplankton and zooplankton. Fig. 3.3 shows the largest concentrations of phytoplankton and zooplankton distributed at the top of coastal water, and some concentrations distributed at deeper water covering the whole offshore areas (Fig. 3.5 and Fig. 3.6).

The determination of the light field is also needed to investigate the influence of particle effect. This can be done by taking the difference in light field between the particle and
Figure 3.2: The surface of geostrophic velocity of the dissolved chlorophyll (control case) under the heating condition on days 8.5(A), 20.5(B) and 28.5(C). The smallest speed is 0.0001 m s$^{-1}$ and the largest is 1.1200 m s$^{-1}$.
Figure 3.3: The vertical section of age of water [days] in the dissolved chlorophyll case (the control case) under the heating condition with depths down to 200m along eastward offshore from 150°E to 157°E at on days 8.5 (A), 20.5(B) and 28.5(C).
Figure 3.4: The conservative tracer of EAC interpolated onto 10m, 30m, 60m, and 90m depths at days 8.5, 12.5, 20.5 and 28.5. We set the original concentration of conservation tracer is contour 1. This figure here is using contour 0.9, which is the most clearly expresses the flow path of EAC in the model.
Figure 3.5: The vertical section of phytoplankton (mg(chl) m$^{-3}$) distribution in the dissolved chlorophyll case (the control case) under the heating condition with depths down to 200m along eastward offshore from 150°E to 157°E at days 8.5 (A), 20.5(B) and 28.5(C).
Figure 3.6: The vertical section of zooplankton (mg(chl) m$^{-3}$) distribution in the dissolved chlorophyll case (the control case) under the heating condition with depths down to 200m along eastward offshore from 150° E to 157° E at days 8.5 (A), 20.5(B) and 28.5(C).
non-particle cases. The scattering effect will be analysed by the difference between the scattering and particle cases. The results of physical and biological properties may explain the behaviour of the light in depths over 32.5 simulation days.

3.2 The structure of results

Once we have the particle and scattering cases, both run under non-heating and heating conditions, we will extract the temperature, water ages, and concentrations of phytoplankton and zooplankton as indicators to estimate the relative influence of particle and scattering effects. The light field will be shown at the end of each section; and it will be described by the physical and biological variables at each depth for every simulation. Results are structured as the following diagram:
Result structure

Non-heating

- Particle effect
  - Phytoplankton
  - Zooplankton

- Scattering effect
  - Phytoplankton
  - Zooplankton

Heating

- Particle effect
  - Physical variables
    - Temperature
    - Geostrophic velocity
    - Age of water
  - Biological variables
    - Phytoplankton
    - Zooplankton

- Scattering effect
  - Physical variables
    - Temperature
    - Age of water
  - Biological variables
    - Phytoplankton
    - Zooplankton
Chapter 4

Results

The model is investigated under a northerly wind (NW) condition which is upwelling favourable for an east coast in the Southern Hemisphere. The particle effect and scattering effect run under the heating and non-heating conditions, respectively, and give four experiments and six variables to be examined. Model outputs are averaged over the inertial period ($\omega = \left| \frac{2\pi}{f} \right| = 0.9022$ d) at midday on days 4, 8, 12 and 28, where $f = -8.06 \times 10^{-5}$ s$^{-1}$ is the Coriolis parameter in the centre of the model domain.

In the model depths vary from 50m to 2000m, but the light field is nearly vanished below 100m depth and the concentration distributions of phytoplankton and zooplankton varies strongest above 100m depth. Therefore, we will only focus on depth above 100m. Depths examined are: 10m, 30m, 60m and 90m.

Model time begins when the physical variables start to run, and the biological model begins 4 days later. The model runs for 32 days, and days 8.5, 12.5, 20.5 and 28.5 will be investigated. The 32 days time scale allows the biological variables to be fully evolved,
and gives enough time for the physical variable stabilise. We start to investigate from day 8.5 when the biological variables have been already computed for 4.5 days. The 12.5 and 20.5 days allow evaluating the physical and biological changes during 12 days. Eventually, on day 28.5 is the time for the model is fully matured.

4.1 Non-heating condition

The comparison of particle and non-particle cases during the NW simulation under non-heating conditions allows us to investigate the difference between the concentration of phytoplankton and zooplankton, and hence determine the light field in the water. Again, the physical variables stay the same; therefore we only compare the differences in biological variables and the light field within this simulation.

4.1.1 Particle effect

The particle effect resulted in significant differences of the variables, when compared to the scattering case. This is because the non-particle case absorbs light more effectively than the particle case, which has a different light attenuation. The different attenuation of light in these two cases eventually will result the different values for each variable after 32 days model simulation.

Phytoplankton

Including the particle effect results in an increase in phytoplankton of 10%-20% in the whole NSW coastal region, (represented by red colour) at day 8.5 with depths in Fig. 4.1A-D. At the depth of 90m (Fig. 4.1H, L and P), the particle effect increases the
phytoplankton concentration by 30% to 40% at day 12.5 and 20.5. On the surface, the concentration of phytoplankton is continuously decreased after day 8.5 (represented by blue colour), the greatest reduction are up to 80% in coastal areas (Fig. 4.1E,I, and M). By days 12.5 and 20.5, the distributed concentration of phytoplankton is also reduced by 30% to 40% in the southern of NSW coast at depth 30m, but it is increased in the northern of coasts (Fig. 4.1F, J). At 60m depth, the particle effect remains to increase phytoplankton concentration and extends the concentration increasing areas toward south (Fig. 4.1G, J). By day 28.5, the current forms in to two main eddies. The distribution of the percentage in phytoplankton follows the eddies dividing into north and south (Fig. 4.1M-P). At this time, the particle effect increases the amount of phytoplankton by 30% to 40% at depth 60m and 90m along the coastline (Fig. 4.1O,P). In general, the particle effect in non-heating case leads to decrease the phytoplankton biomass at 10m surface by 50% to 60% at coastal areas, but it also generates a high phytoplankton biomass (up to 60%) at depth below 60m, and the concentration of phytoplankton is increasing with the increase of depths and times.

Zooplankton

Due to the inclusion of the particle effect, the distribution of percentage in zooplankton is increasing with the depths and the times. By day 8.5, the concentration of zooplankton is increased by 5% at depth below 60m (Fig. 4.2A-D), and also increased up to 80% on day 20.5 and 28.5 at 10m surface. In 90m depth (Fig. 4.2H,L,and P), the particle effect enhances the number of zooplankton by 40% to 80% within the next 20 days (Days 12.5, 20.5 and 28.5). By day 12.5, zooplankton biomass is raised up to 20% in the coast off Sydney at 10m surface, and also increased by 40% to 50% at 30m -60m depth (Fig. 4.2E-
Figure 4.1: The percentage [%] change in phytoplankton biomass due to the inclusion of the particle effect during northerly wind simulation under the no-heating condition at depths of 10m, 30m, 60m and 90m on days 8.5, 12.5 20.5 and 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
Figure 4.2: The percentage [%] change in zooplankton biomass due to the inclusion of the particle effect during northerly wind simulation under the no-heating condition at depths of 10m, 30m, 60m and 90m on days 8.5, 12.5, 20.5 and 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.

H). In the NW simulation, the upwelling water constantly flows up zooplankton from the depth. As a consequence, the concentration of zooplankton at 10m surface has been enhanced by 50% to 60% for the next 16 days along the coastline (Fig. 4.2I, M). Below 10m depth, the concentration of zooplankton is increased by 50% to 60% (Fig. 4.2J-K,N-O), especially at coastal areas where the population of zooplankton is up to 80% (Fig. 4.2N,O and 4.2P). Moreover, the death rate of zooplankton is relatively small. As the remaining zooplankton accumulates from previous days, therefore the particle effect is able to increase the concentration of zooplankton as high as 80%-90% at day 28.5 (Fig. 4.2M-P).
**Light field**

In general, the inclusion of particle effect results in more light at depth (Fig. 4.3 areas in reddish). By day 4.5, the biological variables have not been changed. The phytoplankton is uniformly distributed, therefore the observation of the light field is nearly constant (Fig. 4.3A-D). From day 8.5, the biological variables start to evolve and redistribute, which makes the analysis of light field to become more complicated by changing of phytoplankton biomass as time proceeds.

At the surface, the particle effect enhances the light field by 60% to 80% near coast (in Fig. 4.3A,E, I and M). As the population of phytoplankton grows along the coast of NSW in a NW simulation, the particle effect increases the light field by 60% at the depth 60m, and at approximately 80% to 100% at 90m depth (Fig. 4.3K-L, O-P and S-T).

**4.1.2 Scattering**

The scattering effect results in relatively small changes in variables. The calculation of scattering used an extended pathlength which is used to approximate the total scattering of the light field in the water column. The coastal waters produce relatively low phytoplankton biomass. The low phytoplankton biomass resulted in the less scattering occurred in the water column.

**Phytoplankton**

On day 8.5, Fig. 4.4A-D presents a small decrease in the number of phytoplankton by 1% to 5%. After day 12.5, the distribution of phytoplankton concentration is increased on the top water layers (from 10m to 30m), but the concentration is constantly decreased below
Figure 4.3: The percentage [%] change in the 420nm light field due to the inclusion of the particle effect during northerly wind simulations under the non-heating condition at depths of 10m, 30m, 60m and 90m on days 4.5, 8.5, 12.5 20.5 and day 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
Figure 4.4: The percentage [%] change in phytoplankton biomass due to the inclusion of the scattering effect during northerly wind simulation under the no-heating condition at depths of 10m, 30m, 60m and 90m on days 8.5, 12.5, 20.5 and 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.

30m depth. As shown on day 12.5, the concentration of phytoplankton is increased by 5% at depths 10m and 30m, and decreased by 10% to 15% at depths 60m and 90m (Fig. 4.4E-H). By day 20.5 and 28.5, the scattering effect increases the number of phytoplankton by 10% to 20% at depth 30m along the southern coastline (Fig. 4.4J, M), and also increases by 10% along the coastal areas, decreases by 5% at Tasman front and 10% at southern regions at depth 60m (Fig. 4.4K, O). At a depth of 90m, the number of phytoplankton is decreased by 5% in the offshore areas, and 10% to 20% in coastal regions (Fig. 4.4H, L and P).
Zooplankton

Generally, the scattering effect leads to a more than 5% reduction of zooplankton biomass (Fig. 4.5). By day 8.5, there is a slightly decrease in percentage of zooplankton, it is only decreased by 5% in all depths (Fig. 4.5A-D). The reduction becomes faster after 12.5, the zooplankton population is decreased by 10% at centre of coastal area at 10m surface and 15% -20% at depths below 30m (Fig. 4.5F-H). By days 20.5 and 28.5, the concentration of zooplankton is continously decreased by 15% along the NSW coastal areas at depth 10m to 30m. Due to the greatest reduction of concentration of phytoplankton at depths, the concentraion of zooplankton is decreased by 20% along the coastline at depth 60m and the Tasman water at depth 90m on days 20.5 and 28.5 (Fig. 4.5K-L, O-P).

Light field

Light is determined by the distribution of phytoplankton. The highly concentrated phytoplankton biomass results in high scattering, and high attenuation of light. In Fig. 4.6, there are no changes in the light field due to the scattering effect on days 4.5 and 8.5 at depths 10m to 60m (Fig. 4.6A-C and E-G). At 90m depth, the light field is reduced by only 10% (Fig. 4.6D). After day 8.5, the inclusion of scattering effect reduces by 10% of light at 10m (Fig. 4.6M and Q) and by 30% at 30m (Fig. 4.6N and 4.6R) on days 20.5 and 28.5 along the coastline. At 60m depth, the light field is reduced from 10% to 70% within time period of days 12.5 to 28.5 at NSW coasts (Fig. 4.6K, O and K). The reduction intensity of the light field is raising from 40% to 80% over 16 days, (from days 12.5 to 28.5) in 90m depth (Fig. 4.6L, P and T).
Figure 4.5: The percentage [%] change in zooplankton biomass due to the inclusion of the scattering effect during the northerly wind simulation under the no-heating condition at depths of 10m, 30m, 60m and 90m on days 8.5, 12.5, 20.5 and 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
Figure 4.6: The percentage [%] change in light field due to the inclusion of the scattering effect during northerly wind simulations under the no heating condition at depths of 10m, 30m, 60m and 90m on days 4.5, 8.5, 12.5 20.5 and day 28.5. The latitude (30\degree S, 32\degree S, 34\degree S and 36\degree S) and longitude (150\degree E, 152\degree E, 154\degree E and 156\degree E) grid lines correspond to those in Fig. 2.1.
4.1.3 Conclusion of non-heating condition

The inclusion of particles under a non-heating condition decreases the concentration of phytoplankton, which could reduce the attenuation of light field at the surface, and increases it in depths. As a consequence, the growth rate of phytoplankton is enhanced at depths. Conversely, the inclusion of the scattering effect under the non-heating condition decreases the concentration of phytoplankton, and increases the attenuation of light at the surface. As a result, the concentration of phytoplankton is decreased at depths. In the NSW coastal water, which is considered the low productivity regions, the particle effect generates much larger results (percentage from -100% to 100%) than the scattering effect (percentage is only up to -20% to 20%). Therefore, the particle effect is much more important than the scattering effect.

4.2 Heating condition

Under the heating condition, the physical variables such as temperature and velocity will be changed. The physical variables will change the biological variables at the first few days in the model. After model running over 20 days, the biological variables will alter back to the physical variables such as biologically-induced heating. This biologically-induced heating in turn could have a impact back on the biological variables. Therefore, the results in the heating condition present the feedback between the physical and biological models.
4.2.1 Particle effect

Temperature

The inclusion of the particle effect under the heating condition leads to small differences in temperature, velocities and age of water. On day 8.5, there is only a tiny change in temperature at depth (Fig. 4.7A-D). In day 12.5, the particle effect brings down the temperature by 0.1°C on northern coastal surface. (Fig. 4.7E-H). After 12 days, temperature is raised by 0.3-0.4°C at northern coast (presented in red), and is brought down to 0.3°C north of the raising temperature at depths (presented in blue colour in Fig. 4.7I-L). This occurs because the north coast of NSW is an area strongly influenced by EAC. It is

the largest changes are presented in Fig. 4.7. By day 28.5, the particle effect cools down about 0.1-0.2°C at Tasman Front regions, warms up 0.2°C in the coastal areas at depths 30m-90m (Fig. 4.7N-P). The surface is cooled down 0.2°C covering most of EAC regions, except for Sydney coastal areas which presents warmer at 0.2°C (Fig. 4.7M).

Fig. 4.9 shows that the cooling observation on the surface is due to a shallow mixed layer (the curves of change of temperature show that the mixed layer occurs at 10m), which forces the cool water to replace the warm water from depths. The warmer coastal areas near Sydney, has the phytoplankton bloom. Therefore, a large amount of energy heat has been absorbed by the high concentration of chlorophyll, this process makes the areas warm up 0.2° (Fig. 4.8).
Figure 4.7: The temperature [°C] difference due to the inclusion of particle effect during northerly wind simulations under a heating condition at depths of 10m, 30m, 60m and 90m on days 8.5, 12.5, 20.5 and day 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
Figure 4.8: Difference in temperature [°C] due to the inclusion of the particle effect during northerly wind simulations under a heating condition at depth of 10m on day 28.5. A black cross is a point we taken for plotting Fig, 4.9.
Figure 4.9: Left: The concentration of phytoplankton [mg(chl) m$^{-3}$] of particle case (red) and the dissolved chlorophyll case (blue); Right: Change of temperature [°C] per day of particle case (red) and dissolved chlorophyll case (blue) on the grid point 42 (north-south direction) and 12 (east-west direction)
Age of water

This simulation does not significantly effect the age of the water. At days 8.5 and 12.5, the changes of age are very small (Fig. 4.10A-D and E-G). The particle effect increases age of water on days 20.5 and 28.5 with the increase of depths at Tasman Front (Fig. 4.10I-L and M-P), but it deceases the age of water next to the increasing areas. This indicates the EAC influences the age of water at the northern of the EAC areas. The deeper young water is mixed up with the surface older water. Along the coastline of Sydney, the difference of age is small enough to ignore. This illustrates the changes of phytoplankton biomass and temperature are not influenced by EAC along the Sydney coastline. Therefore, we can conclude that the physical and biological variables will not be influenced by EAC at the south of Sydney coastal areas.

Phytoplankton

The particle effect under the heating condition generates more phytoplankton biomass reduction areas at the depths within the last 20 days (Fig. 4.11). By day 8.5, the particle effect increases the concentration of phytoplankton up to 10% with depths. From days 12.5 to 20.5, in depths 10m and 30m, the concentration of phytoplankton is reduced by 10% to 20% due to the particle effect in the south of NSW coast, Tasman Front and some offshore places (Fig. 4.11E, F and 4.11I, J). At the depths of 60m and 90m, phytoplankton biomass is increased 20%-40% by the particle effect from days 12.5 to 20.5 along the coastline (Fig. 4.11G, H and K, L). By day 28.5, the particle effect results a 40% to 60% reduction of phytoplankton concentration on the surface, but enhances by 20%-40% in concentration of phytoplankton at depth from 30m to 90m in north NSW coast and Tasman Front regions (Fig. 4.11M-P).
Figure 4.10: Differences in age of water [days] due to the inclusion of particle effect during northerly wind simulations in a heating condition at depths of 10m, 30m, 60m and 90m on days 8.5, 12.5, 20.5 and day 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
Zooplankton

In general, due to the increase of phytoplankton, the concentration of zooplankton has been enhanced from 20% to 40% (Fig. 4.12). At depths 10m and 30m, the particle effect increases the zooplankton concentration from 10% to 60% along the coastal areas as time increases from days 8.5 to 28.5 (Fig. 4.12A-B, 4.12E-F, 4.11I-J, and 4.12M-N). At depths 60m to 90m, there are increases in the concentration of zooplankton of up to 80% due to the particle effect at coastal areas and the southern EAC regions after day 20.5 (Fig. 4.12C-D, 4.12G-H, and 4.12K-L). By day 28.5, the concentration of zooplankton is decreased by 20% by the influence of particle effect at depths 60m and 90m in north Tasman Front (Fig. 4.12O-P).

Light field

Under the heating condition, the light field (Fig. 4.13) seems similar to the non-heating condition (Fig. 4.3). This demonstrates that regardless of whether the particle effect is under heating or non-heating conditions, it always increases the intensity of the light field in the water column. In general, the light intensity increases as time passes and depth increases. In 10m surface (Fig. 4.13E, I, M and Q), show that the accumulated light field is increased by the particle effect up to 60% at the coastal areas from days 8.5 to 28.5, and the light field is also increased with depths. By day 28.5 in the coastal areas, the light field has been accumulated as high as 90% at the depth 90m (Fig. 4.13T). However, due to the increase in phytoplankton biomass at the Tasman Front, the attenuation of light due to the particle effect grows faster (the percentage shows in nearly 0%) at depth 10m, which
Figure 4.11: The percentage [%] change in phytoplankton biomass due to the inclusion of particle effect during northerly wind simulation under a heating condition at depths of 10m, 30m, 60m and 90m on days 8.5, 12.5, 20.5 and 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
Figure 4.12: The percentage [%] change in zooplankton biomass due to the inclusion of particle effect during the northerly wind simulation under heating condition at depths of 10m, 30m, 60m and 90m on days 8.5, 12.5, 20.5 and 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
Figure 4.13: The percentage [%] change in light field due to the inclusion of particle effect during northerly wind simulation under heating condition at depths of 10m, 30m, 60m and 90m on days 4.5, 8.5, 12.5, 20.5, and 28.5. The latitude (30°S, 32°S, 34°S, and 36°S) and longitude (150°E, 152°E, 154°E, and 156°E) grid lines correspond to those in Fig. 2.1.

extends to the depths down to 90m (Fig. 4.13Q-T).

4.2.2 Scattering

Temperature changes

The temperature changes are small when compared to the particle effect (Fig. 4.7 vs Fig. 4.14). The influence of the EAC causes a reduction in temperature due to the scattering effect at north coast of NSW. The scattering effect cools down the temperature with depth on days 8.5 and 12.5. By day 20.5, temperature is raised up to 0.2°C at the centre near coastal areas due to the influence of the EAC (Fig. 4.14I-L). By day 28.5 (Fig. 4.14M-P),
the scattering effect increases 0.2°C at south coast, but decreases 0.1°C at the centre of coastline. The increases of temperature due to the increasing of phytoplankton populations shown in Fig. 4.16 and Fig. 4.15.

Phytoplankton

Due to the scattering effect, light is more effectively attenuated. This results in a 10% reduction of phytoplankton biomass in most of the EAC regions (Fig. 4.17), and hence decreases the growth of zooplankton (Fig. 4.18). The concentration of phytoplankton has a constant decrease by 5% on day 8.5. Due to the greater attenuation of light, the scattering
Figure 4.15: Difference in temperature [°C] due to the inclusion of scattering effect during northerly wind simulations under heating condition at depths of 10m on days 28.5. A red cross is the point we taken for plotting Fig. 4.16.
Figure 4.16: Left: The concentration of phytoplankton [mg N m\(^{-3}\)] due to the scattering effect (red) and particle case (blue); Right: Change of temperature per day in the scattering case and particle case (blue) on the grid point 47 (north-south direction) and 12 (east-west direction)
effect decreases by 20% at the centre of coastline at depth 60-90m on days 12.5 and 20.5 (Fig. 4.17G-H and K-L). By day 28.5, the scattering effect increases about 10%-20% of the phytoplankton concentration at the centre of NSW coast above 50m depths, but it decreases the phytoplankton biomass about 20% at north and south coastline, and some of reduction distributed in Tasman Front (Fig. 4.17M-N). At depth 60-90m, the reduction of phytoplankton biomass due to the scattering effect dominates the whole EAC regions, along the NSW coastal area, the reduction is up to 20%.
Zooplankton

The decreases of phytoplankton biomass results in a decrease of zooplankton concentration (Fig. 4.18). The decreasing concentration of zooplankton becomes greater along the coast at the surface after 12.5 days, but on day 12.5 it is only reduced by 10% at 90m depth in centre of coast (Fig. 4.18H). By days 20.5 and 28.5, the significant reduction area is presented in coastal areas. The concentration of zooplankton is reduced to 60% by the scattering effect at 10m on day 28.5, and the reduction of zooplankton biomass is getting larger with the increase of depth (Fig. 4.18N-P).
Figure 4.19: The percentage [%] change under 420nm light field due inclusion of particle effect during northerly wind simulation under heating condition at depths of 10m, 30m, 60m and 90m on days 4.5, 8.5, 12.5, 20.5 and 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.

Light field

The scattering effect increases the attenuation of light field at all depths (Fig. 4.19). The difference in light intensity becomes larger at greater depths due to the scattering effect. As time passes, this difference increases, and can be up to 50% to 70%. However, due to the reduction of phytoplankton by the scattering effect occurs in some coastal areas, which causes the intensity of light increases. At depth of 60m to 90m, the light field is reduced up to 50% on day 28.5 (Fig. 4.19 O, S and P, T).
4.2.3 The influencing of geostrophic velocity

In general, the terms in the geostrophic velocity dominate, and model velocity is close to calculated geostrophic velocity (Fig. 4.21B). This geostrophic velocity can be calculated from the elevation gradient. The equations of geostrophic velocity are:

\[
g \frac{\partial \eta}{\partial x} = f v \quad (4.1)
\]

\[
g \frac{\partial \eta}{\partial y} = -f u \quad (4.2)
\]

where \( g \) is the gravity force, \( f \) is the Coriolis parameter, \( \eta \) is the elevation of sea surface and \( x \) and \( y \) stand for the distances in east-west and north-south directions, respectively.

Particle effect

For the calculation of the geostrophic velocities influenced by the particle effect, we took the differences in elevation and the velocities between the particle case and the non-particle case. Therefore, Eq. 4.1 and Eq. 4.2 become:

\[
g \frac{\partial (\eta_p - \eta_{chl})}{\partial x} = f (v_p - v_{chl}) \quad (4.3)
\]

\[
g \frac{\partial (\eta_p - \eta_{chl})}{\partial y} = -f (u_p - u_{chl}) \quad (4.4)
\]

The inclusion of particle effect results in an increase of temperature by 0 to 0.1°C in the north offshore areas on the surface which presents in a warm core. A decrease about 0.1 to
0.2°C in temperature can be seen in the centre of NSW coastline, this can be considered as a cold core in Fig. 4.20. The particle effect also leads to create a 0.02m to 0.04m high elevation at 30.5°S and 155°C, and drives down 0.04m low elevation at 32.5°S and 153°E in Fig. 4.21A. This sea-level gradient can be used to calculate the geostrophic velocity (Fig. 4.21A). However, the high elevation areas can correspond to the warm core with higher temperature, and the low elevation areas correspond to the cold core. Therefore, we can say that the elevation gradient is related with the temperature gradient.

The geostrophic velocity is calculated by using the Eqs. 4.3-4.4, which corresponds to the model surface velocity (Fig. 4.21B). The direction of the calculated geostrophic velocity is moving backward of EAC near coastal areas where is the flow path of EAC see Fig. 3.4. Therefore, it presents that the inclusion of particle effect reduces about 15 cm s⁻¹ of the EAC velocity in the model. The reduction in speed is due to the surface elevation gradient; and this elevation gradient is created differentiated heating. Finally, we can conclude that the decelerated speed is a result of a temperature gradient created by the light-absorption particles.

**Scattering effect**

Similarly, in order to work out the geostrophic velocity influenced by the scattering effect, we took the differences in elevation and velocities between the scattering case and particle case. Therefore, the Eqs. 4.1-.4.2 is become:

\[
g \frac{\partial (\eta_s - \eta_p)}{\partial x} = f(v_s - v_p) \tag{4.5}
\]
Figure 4.20: The surface temperature [°C] difference distribution with inclusion of particle effect under heating condition on day 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
Figure 4.21: The surface elevation [m] and the surface calculated geostrophic velocity [m s$^{-1}$] due to the particle effect (A); the surface geostrophic velocity [m s$^{-1}$] in the model due to the particle effect (B).
The inclusion of the scattering effect also decelerated EAC (Fig. 4.22), but the rate of the deceleration is about 2cm s⁻¹ slower than the particle effect. Fig. 4.22A shows that due to the scattering effect, there is an increase 0.01m high elevation area is located at 32°S and 154° and an other high elevation area is increased about 0.02m near the southern coastal areas 35°S and 152°E. These high elevation areas are corresponding to the raising temperature in 0.1°C and 0.2°C warm cores by the scattering effect (Fig. 4.23), respectively. The scattering effect also generates two cold cores with the decreasing temperature in 0 to 0.1°C, which correspond the two lower elevation areas (the smaller one is located at 32.5°S and 153°E and the larger one is at 34°S and 152°E).

The calculated geostrophic velocities are generated by this elevation gradient (Eqs. 4.5-4.6), which are showing that the scattering effect reduces about 13cm s⁻¹ of EAC velocity (Fig. 4.22A) at the centre of coastal areas, but increases the velocity in the offshore areas. We also can conclude that the decelerated and the accelerated EAC is a result of a temperature gradient created by the light-absorption particles.

4.2.4 Conclusion of heating condition

Under the heating condition, particle effect decreases the temperature and concentrations of phytoplankton and zooplankton at surface. As a result, the attenuation of light could be reduced. The inclusion of the scattering effect always increases the attenuation of light field, but it also increases 10% of phytoplankton biomass at the centre of coast on
Calculated geostrophic velocity & elevation

A

Figure 4.22: The surface elevation [m] and the surface calculated geostrophic velocity [m s\(^{-1}\)] due to the scattering (A); the surface geostrophic velocity [m s\(^{-1}\)] in the model due to the scattering effect (B).
Figure 4.23: The surface temperature [°C] difference distribution due to inclusion of scattering effect on day 28.5. The latitude (30°S, 32°S, 34°S and 36°S) and longitude (150°E, 152°E, 154°E and 156°E) grid lines correspond to those in Fig. 2.1.
day 28.5. In additional, the calculated geostrophic velocities demonstrate that the particle and scattering effects decelerate the EAC in 15 cm s\(^{-1}\) and 13 cm s\(^{-1}\), respectively. We can conclude that the reduction of speed is induced by the temperature gradient which is considered as the biological heating.
Chapter 5

Discussions and conclusions

This study is intended to use the theory of the particle effect (Kirk, 1975b, 1976, 1977) to extend the existing work on the biologically-induced heating model (Edwards et al., 2001, 2004). The effect of biologically-induced heating was described by Edwards et al. (2004) in detail. They exhibited a measurable upwelling water movement in 0.05 m s\(^{-1}\), induced by differential heating. However, the model they set up was limited in a controlled environment, which would not include any physical circulation background. To extend their work and further understanding and determining the biologically induced velocity, we employed a new light model which included 57 wavelengths spectral-resolved light attenuation and implement with a coupled physical-biological model. The coupled model is simulated the physical and biological circulations in coastal water, investigate the particle and scattering under the heating and non-heating conditions, respectively, hence detect the biologically-induced velocity.
5.1 The assumptions

In our model, we made several assumptions to leave some factors out of consideration. The phytoplankton also contains the auxiliary pigments (Chl b, c and carotenoids), the full description would include them in the calculation. However, the auxiliary pigments have only a slightly different rate of absorption compared to Chl a, and a slightly different absorption spectral waveband. Therefore, taking the auxiliary pigments in calculation would not significantly change the results presented in this study.

A particle absorbs incident light as a function of wavelength, pigment concentration and the particle geometry (Kirk, 1994). Here we considered the particles are spherical only. In open-ocean waters, particles have a wide range of shapes such as cone, rectangular prism, double cone and cylinder etc., and their projection areas are in many different shapes, resulting in different absorption coefficient in each shapes of particles (Baird, 2003). A spherical cell gives light capture surface as in a circle, which could avoided the complex calculations in different shapes and orientation. Moreover, the calculations of the other different shapes in phytoplankton cells would not have significantly different results in the particle and scattering effect and also it would not be the major reason to influence the EAC.

As light passes through a cell, part of the light beam is absorbed in the cell and another unabsorbed part is reflected back by the cell wall. For the absorbed part, light undergoes to reflection inside the cell, but it is also absorbed by the major and auxiliary pigments. The reflected part, the light will be absorbed or reflected by other cell, which is bouncing
between the cells. For the attenuation of light, the more-sophisticated calculations should include the scattering inside the cells. However, the calculation of scattering inside cells and scattering between the cells are too difficult and complicated at this stage. Therefore, it allows us to use the pathlength scattering coefficients to approximate the real scattering in the ocean (Kirk, 1977, 1979).

Our model runs under NW forcing only during summer time. If the model can run under Southerly Wind (SW) forcing during the winter, which is downwelling favourable (Baird et al., 2006a), the variables in the results will have differences when comparing the results in NW. Moreover, if the model runs through the whole year, it will give the interesting results for investigation of light field in different seasons. We choose the NW simulation because it is under upwelling favourable wind force, where a large amount of phytoplankton cells would be brought up to the surface. If there is in SW simulation, the phytoplankton bloom will not be seen on the surface, it usually occurs at 30m to 60m depths (Baird et al., 2006a,b).

5.2 The comparison of heating and non-heating conditions

The particle effect leads to a reduction of phytoplankton at 10m and 30m depths of water under both heating and non-heating conditions, which allows more light penetrating into the depths. The inclusion of scattering effect also reduces the phytoplankton biomass in the first 20.5 days. It increases by 10% of concentration of phytoplankton at centre of coast
only on day 28.5. This results in an increase of light attenuation at the top layer water. Therefore, the scattering effect is always decreases the light field at the depth. However, the results of scattering effect are much less than the particle effect, (the differences due to scattering are only up to 20% to 30%, but the differences due to particle effect can be up to as high as 80% or more). For example, including both the particle and scattering effects reduces the speed of the EAC by 13 cm$^{-1}$, while the particle effect is 15 cm s$^{-1}$ shown.

In the results, both heating and non-heating conditions gave similar results in particle and scattering effect. The difference between heating and non-heating is the feedback of the physical and biological models. The non-heating condition only changes the biological variables, but the heating condition can alter the physical and biological variables. Therefore, the differences between these two conditions appear after days 20.5 when the physical and biological components start to influence each other. The largest difference is showed in the percentage change of phytoplankton biomass due to the particle effect. Under the heating condition, there is a feature which presents the concentration of phytoplankton decreased about 40%-60% at the offshore areas, forms in two curves, starts from north Tasman area 30.5°S and 55°E and extents toward south-west down to 36°S and 151°E. This feature is also present under non-heating condition, and it appears at 10m and 30m depths (see Fig. 4.1I-L). Under the heating condition, the phytoplankton reduction feature is extended to depth 90m , but it also absents at the 10m surface (Fig. 4.1I-L ). The comparison of the light field under heating and non-heating conditions (see Fig. 4.3 and Fig. 4.13), there is a only difference appear on day 28.5 at the north of Tasman Front. Some small spots show that the light field is near 0% (Fig. 4.13)Q-T), but the light field due to the particle effect under non-heating condition is always increased at the depth on day
28.5 (Fig. 4.3Q-T). From those differences we found between the heating and non-heating conditions, we can conclude that the heating condition actually is causing a reduction of phytoplankton and zooplankton biomass growth at the depth and it is also decreasing the light intensity at depths when comparing to the non-heating condition.

In conclusion, this study improves the representation of light attenuated in coastal water, determined by the particle and scattering effects in a coupled physical-biological model of EAC region. In generally, we found that particle effect decreases by 30%-40% the biomass of phytoplankton and zooplankton at the surface of NSW coast. The decreasing of phytoplankton results a 20%-40% reduction of light attenuation at surface, but increases up to 80% of light penetration at depths, which in turn could increase by 20%-30% in phytoplankton productivity at depths. The scattering effect decreases about 10% of concentration of phytoplankton on the surface, but it also decreases the light field up to 40% at the depths along the coastline. In addition, the particle effect slowed the EAC by 15 cm s\(^{-1}\) by using the calculation of the sea-level gradient. The scattering decelerates the EAC near the NSW coast, but also leads to increased speed of the EAC at the offshore areas.
Bibliography


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