2.3. MODEL SENSITIVITY

2.3.1. Coastal ocean scenarios

The sensitivity study of the model was carried out for six coastal ocean scenarios – each a combination of different concentrations of water-colouring substances and different water depths (Table 2.2). These scenarios represent realistic situations expected in Lucinda waters under various environmental conditions.

Low values of suspended sediments, chlorophyll and dissolved organics are unlikely to be found in nearshore waters where resuspension and river proximity affect the concentrations. Therefore, the oligotrophic ocean scenario is assumed to occur in waters deeper than 30 m. The mesotrophic concentrations reproduce typical levels of optically significant substances in coastal ocean at Lucinda during the dry season (Appendix 4, Figures A6, A7, A9). For these scenarios, water-leaving radiance spectra are insensitive to depth changes below 6 m, while the representative depth of shallow waters is 4 meters. Three of the naturalistic scenarios describe the eutrophic, or concentration-rich, ocean. The first (scenario 4) simulates a river flood event and is characterised by high concentrations of terrigeneously derived TSS and CDOM and mesotrophic levels of CHL. The second eutrophic case, a phytoplankton bloom (scenario 5), reflects a situation which usually occurs several days after the peak river discharge: proliferation of phytoplankton due to (i) consumption of terrestrially-derived nutrients and (ii) increased light availability as TSS have already settled out; hence, relatively low concentrations of both constituents exist for this scenario. Finally, a combination of high concentrations of all three water-colouring constituents can potentially occur (scenario 6) in a sequence of events such as an initial input of terrestrial nutrients with a river flood triggering phytoplankton bloom, followed by a second pulse of flood waters from the river. The bio-optical model is insensitive to sea floor reflection for the last three scenarios because at such concentrations euphotic depth is less than a meter.

Scenarios	CHL, mg/m^3	TSS, g/m^3	CDOM, m^{-1}	Depth, m
1. Oligotrophic ocean	0.1	0.5	0.03	> 30
2. Mezotrophic deep ocean	2	4	0.4	> 6
3. Mezotrophic shallow ocean	2	4	0.4	4
4. River flood	2	20	1	> 1
5. Phytoplankton bloom	20	4	0.4	> 1
6. Combined flood and phytoplankton bloom	20	20	1	> 1

Table 2.2. Scenarios for the model sensitivity study.

2.3.2. Forward model sensitivity to water colouring constituents

The sensitivity of the forward bio-optical model to variations in input concentrations of optically significant substances was assessed by studying the changes in water-leaving radiance nLw resulting from ignoring one of the substances in the model, i.e. setting its concentration to zero, while other concentrations were unchanged:

$$\Delta nLw = nLw(X,Y,Z) - nLw(0,Y,Z). \qquad (2.21)$$

X, Y and Z represent optically significant substances, namely, chlorophyll, total suspended sediments and coloured dissolved organic matter. The procedure was repeated for each of the water-colouring constituents (i.e. variable X was sequentially set to CHL, TSS and CDOM) and for all the ranges of concentrations used in the model (Table 2.1). Results are presented as 2-dimensional distributions of changes in water-leaving radiance ΔnLw (expressed in percentages) due to neglecting a particular substance (its concentration X before setting to zero is displayed on the X-axis) (Figure 2.3). The Y-axis shows the concentration Y, while three discrete values of the third variable (substance Z) are used to produce three panels of X-Y distributions. Isolines show 5 % and 10 % changes in water-leaving radiance. A critical level of ΔnLw, below which the water property was considered unresolvable by the model, was set to 10 % – the estimated accuracy of SeaWiFS water-leaving radiance (Gross et al 2000). At ΔnLw greater than 10 % (densely coloured regions on Figure 2.3), the present model was assumed to be sensitive to the ignored water property and thus its retrieval is expected to be robust.

The change in water-leaving radiance due to neglecting TSS in the model is over 20 % for all CHL-CDOM combinations for the whole domain of TSS variations (distributions are not shown). Therefore, TSS retrievals are robust regardless of underwater environmental and optical conditions.

The modelled water-leaving radiance spectra are very sensitive to neglecting CDOM in the model. At the same time, some regions on the CDOM-induced sensitivity maps exhibit smaller than 10 % changes in water-leaving radiance due to ignoring CDOM in the model. At extremely low CDOM (< 0.06 m^{-1}) and flood TSS (20 g/m^3) levels, dissolved organic matter cannot be determined (ΔnLw < 10 %) at any CHL value. Moreover, the bio-optical model is insensitive to CDOM values below 0.1 m^{-1} with concurrent CHL concentrations above 20 mg/m^3, regardless of TSS levels. However, this is a highly improbable scenario, as CHL and CDOM tend to co-vary in Lucinda waters (see section 3.1.3).

At CHL values < 3 mg/m^3, water-leaving radiance is insensitive to ignoring this substance in the model at concomitant high levels of TSS (20 g/m^3) and CDOM (> 3 m^{-1}) (i.e. river flood scenario). At lower concentrations of these constituents, the critical level of unresolvable CHL decreases so that for the mesotrophic scenario (TSS = 4 g/m^3, CDOM = 0.4 m^{-1}) CHL retrieval cannot be robust at < 1 mg/m^3, while for the oligotrophic case (TSS = 0.5 g/m^3, CDOM = 0.03 m^{-1}) ΔnLw is greater than the critical level of 10 %, indicating strong retrieval potential of CHL for such combinations of concentrations. At higher CHL concentrations (> 3 mg/m^3) the model is sensitive enough to the presence of this substance to derive it confidently over the entire CDOM and TSS domains.

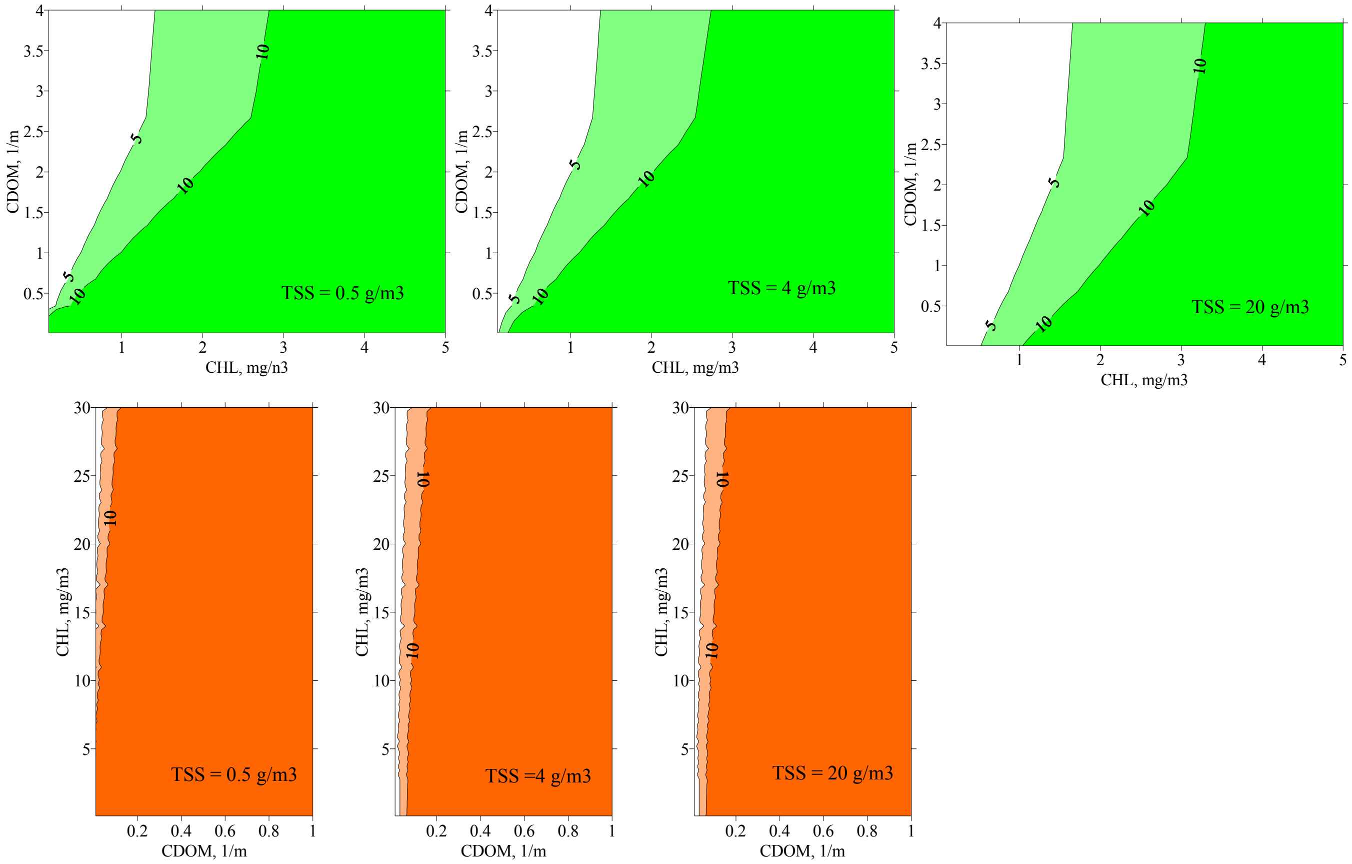

Figure 2.3. Changes in water-leaving radiance in percentage due to ignoring CDOM (a-c) and CHL (b-f) in the bio-optical model. Distributions at CDOM absorption > 1 m^{-1} and CHL concentration < 5 mg/m^3 are not shown as ΔnLw > 10 % for these regions.

2.3.3. Forward model sensitivity to model parameters

Model optical parameters, namely, specific absorption coefficients of phytoplankton and non-chlorophyll particles, specific backscatter coefficient of particulates, exponential slopes of CDOM and non-CHL particles and slope of particular backscatter, were subjected to sensitivity analysis where each of the parameters varied between its maximum/minimum and average values (Table 2.1), while other parameters stayed fixed. The resultant changes in water-leaving radiance ΔnLw due to parameter variations between average and high/low values for coastal ocean scenarios (Table 2.2) are shown in Figure 2.4.

Of all the optical parameters studied, water-leaving radiance is most sensitive to specific backscatter of particulates bb^*_{TSS} for all studied scenarios except for the phytoplankton bloom situation. At its maximum value (0.036 m^2/g), bb^*_{TSS} produces changes in water-leaving radiance of 100 % on average relative to radiance computed with the average parameter value (0.02 m^2/g), except for oligotrophic and phytoplankton bloom cases where these changes are around 90 % and 60 % respectively. The effect of setting bb^*_{TSS} to its low value in the model is not as pronounced in the resultant radiance spectra for all the scenarios studied, with ΔnLw about 20 % less than for a corresponding increase in the parameter value.

Not surprisingly, specific absorption of phytoplankton a^*_{ph} becomes a significant player in the model at high CHL concentrations. For phytoplankton blooms and combined flood and bloom conditions, changes in water-leaving radiance at shorter wavelengths are above 100 % and 50 %, respectively, relative to corresponding average-parameter-value case. At non-bloom chlorophyll levels, sensitivity of the model to changes in a^*_{ph} is within 20 % on average, with the green spectral domain (443 and 490 nm) affected the most.

Except for cases with high chlorophyll concentration, specific absorption of non-chlorophyllous particles a^*_{np} is the next most important parameter affecting the water-leaving radiance spectra after specific backscatter of particulates. If an incorrect value of a^*_{np} is assigned, the model generates errors in water-leaving radiance up to 40 % below 550 nm. At longer wavelengths, the bio-optical model sensitivity to the parameter becomes negligible due to exponential decrease of non-CHL particulates absorption with increasing wavelength.

Variations in exponential slopes of CDOM and non-CHL particulates S_{np} and S_{CDOM} do not affect water-leaving radiance at their reference wavelength of 440 nm. Changes in nLw due to variations in these parameters increase when moving away from these wavelengths and decrease further in near infrared due to insignificant absorption of dissolved and non-living particulate matter in this spectral region. S_{np} or S_{CDOM} variations trigger changes in modelled water-leaving radiance by 15-25 % and 5-25 %, respectively. Taking into account the accuracy limits of SeaWiFS water-leaving radiance (10 %, (Gross et al 2000)) the model can be considered insensitive to changes in S_{np} for oligotrophic and phytoplankton bloom scenarios.

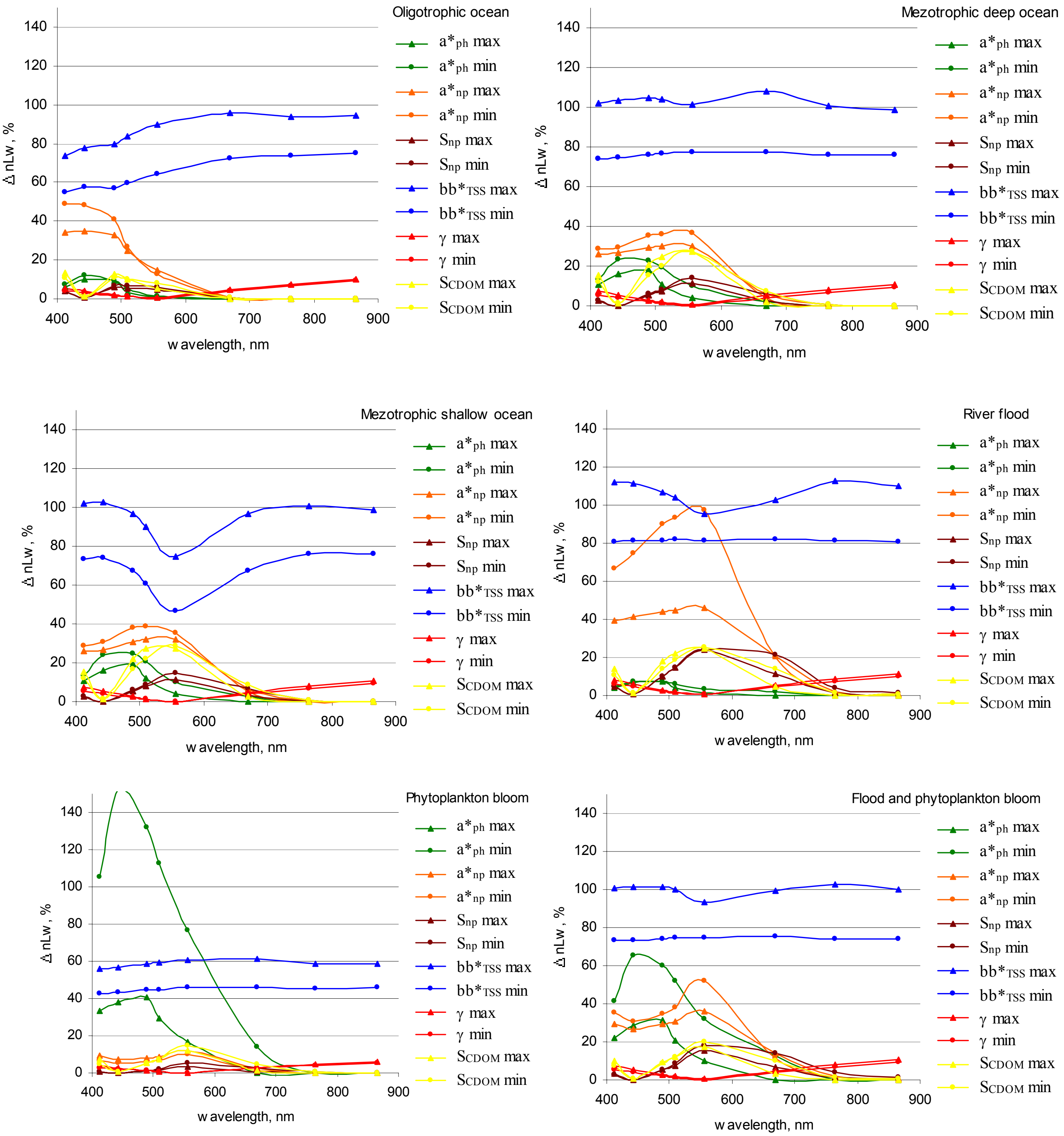

Figure 2.4. Changes in water-leaving radiance ΔnLw due to variations in optical parameters from average values in Table 2.1 for coastal ocean scenarios (Table 2.2).

Variations in the spectral slope of particulate backscatter γ generate changes in water-leaving radiance below 10.5 % for all scenarios studied. These changes are insignificant in the context of the accuracy of SeaWiFS water-leaving radiance (Gross et al 2000). Therefore, for the purposes of the present study this parameter can be eliminated as an unknown and safely fixed at its average value of 1.

In summary, specific backscatter of particulates is the most influential parameter in the present bio-optical model followed by specific absorption of non-CHL particulates, with the exception of high chlorophyll concentration scenarios where variations in specific absorption of phytoplankton become more important for modelled water-leaving spectra. The parameter describing the spectral shape of particulate backscatter (backscatter slope γ) is the least significant parameter in the model. Changes in water-leaving radiance produced by variations in γ are within the SeaWiFS accuracy limits, thus justifying its setting as a constant in the model.

2.3.4. Inverse model sensitivity to input water-leaving radiance

The inverse bio-optical model determines concentrations of CHL, TSS and CDOM that would generate water-leaving radiances most closely resembling the input spectra. If the forward model computes an input spectrum of radiances from the known concentrations of water-colouring constituents, the inverse model retrieves exactly the same concentrations as those, which generated its input (provided these known concentrations are within the ranges used for creating the water-leaving spectra database (Table 2.1)). This exact retrieval is expected due to the inversion procedure used in the present work, which iterates through the whole set of precomputed spectra. Accordingly, in case of perfect remotely sensed data, exact retrievals are envisaged. However, satellite-derived water-leaving radiances, for which the inverse model is designed, inevitably possess noise as a result of radiometric uncertainty of the sensor as well as imperfections of atmospheric correction algorithms. Therefore, in order to understand the accuracy of water property retrievals from remote sensing data, an assessment of the sensitivity of the inverse bio-optical model to expected noise levels in the input data is highly desirable.

The initial SeaWiFS Project objective was to achieve accuracy of *"water-leaving radiances to within 5 % absolute, and chlorophyll_a concentration to within 35 % over the range of 0.05-50.0* mg/m^3*"* (Hooker et al 1992). The validation efforts of the ocean colour community suggest that actual retrievals of water-leaving radiance did not achieve this objective (http://seabass.gsfc.nasa.gov/cgi-bin/matchup_results.cgi?sensor=s). However, deviations of observed values from the satellite-derived ones can mostly be attributed to spatial inhomogeneities between point in situ and 1 km^2 averaged remote sensing data (Bryan Franz, on-line communication at Ocean Color Forum, http://ocforum.gsfc.nasa.gov/). Gross, Thiria et al. (2000) attempted to assess the actual accuracy of SeaWiFS-derived marine reflectances, and their estimates amounted to just above 10 %. With the above considerations, two levels of accuracy of water-leaving radiance were adopted for the sensitivity study of the inverse bio-optical model to input radiances: 5 % representing intended and 10 % representing realistic accuracies of water-leaving radiances as supplied by the SeaWiFS sensor. Similarly to the original SeaWiFS Project objective, the retrieval of an optically significant substance from noisy input data is considered satisfactory if the retrieved value is within 35 % of its no-noise counterpart.

The inverse bio-optical model sensitivity to noise in water-leaving radiances was assessed for the coastal ocean scenarios shown in Table 2.2. Normally distributed spectrally uncorrelated noise with zero mean and 5 % or 10 % standard deviation was added at each wavelength to input water-leaving radiances generated by the forward model for a particular coastal ocean scenario with fixed average optical parameters (Table 2.1). Water-colouring constituents derived by the inverse model with noisy input data were then compared to original concentrations. For each scenario and noise level the procedure was repeated 50 times, and the sensitivity of the inverse model to noise in input data was analysed in terms of standard deviations of noise-affected water-colouring constituents from their no-noise values. Results for each scenario are presented in Figure 2.5. Each error bar shows an absolute value of standard deviation for a particular scenario at one of the noise levels, while a number above the bar provides the same information in percentages relative to no-noise retrievals.

The objective of 35 % accuracy of CHL retrieval is met only for phytoplankton bloom and combined flood and bloom conditions. In other words, CHL is reasonably well retrieved at high concentrations. At mesotrophic concentrations, standard deviations of noise-induced retrievals are between 60 and 150 % for both noise levels (i.e. 2 ± 1.2 mg/m^3 and 2 ± 3 mg/m^3, respectively). At oligotrophic concentrations CHL retrievals vary by as much as 200 % for both 5 % and 10 % noise levels. From the present sensitivity analysis it can be concluded that although noise-affected CHL estimates are of the same order of magnitude as original values (below 0.3 mg/m^3 for oligotrophic case, below 5 mg/m^3 for mesotrophic cases and between 15 and 25 mg/m^3 for eutrophic cases), the potential for CHL retrieval is unsatisfactory at non-bloom concentrations. This is consistent with the sensitivity study of the forward bio-optical model (section 2.3.2), which revealed that the model was sometimes insensitive to neglecting chlorophyll concentration at levels below 3 mg/m^3. Other researchers have arrived at similar conclusions and reported low accuracy in chlorophyll retrievals using similar inverse reflectance models (Roesler et al 1995; Lahet et al 2000).

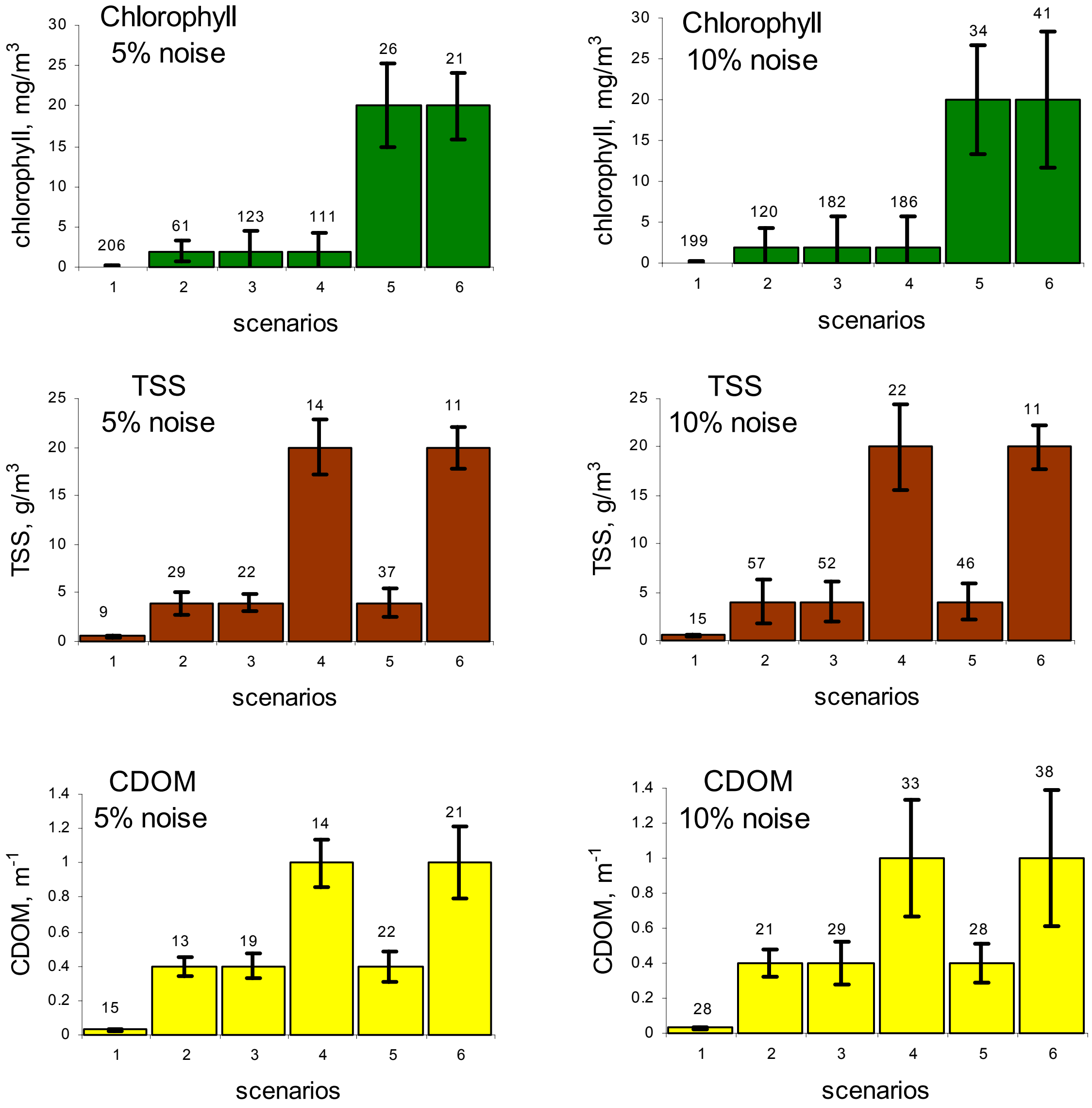

Figure 2.5. Standard deviations of noise-affected retrievals of CHL, TSS and CDOM relative to original concentrations for normally distributed uncorrelated noise levels of 5 % and 10 %. Each error bar shows an absolute value of standard deviation for a particular scenario at one of the noise levels, while a number above the bar provides the same information in percentages relative to no-noise retrievals. For description of scenarios, see Table 2.2.

At 5 % normally distributed noise introduced to input water-leaving radiance, TSS meets the objective of 35 % accuracy for all studied scenarios, while at 10 % noise it meets the objective at high and low concentrations. At medium concentrations and 10 % noise, TSS is retrieved with an accuracy of about 50 % (i.e. 4 ± 2 g/m^3). Such accuracy is in agreement with recent studies which have derived distributions of surface turbidity and suspended particulate matter concentrations from satellite data (Doxaran et al 2002; Ouillon et al 2004).

CDOM meets the objectives of accuracy of less than 35 % for all scenarios at noise levels up to 10 %. This result is consistent with similar inversion studies done elsewhere, which were able to retrieve CDOM absorption at 440 nm with accuracy of 20-25 % (Lee et al 1999; Pozdnyakov et al 2003). Overall, CDOM is retrieved the most accurately, followed by TSS and CHL. This conclusion is substantiated by the sensitivity study of the forward bio-optical model (section 2.3.2) where CDOM affected water-leaving radiance the most relative to other constituents (average change in water-leaving radiance due to neglecting CDOM was 246 % as opposed to 97 % for TSS and 67 % for CHL).

In summary, at the expected noise levels in the input remote sensing data, the water-colouring constituents studied can be retrieved within the 35 % accuracy criterion at high concentrations, such as are usually encountered during bloom and/or flood conditions. During the dry season and in the clear open ocean, CHL retrieval is questionable, while CDOM and TSS can be accurately mapped (within 35 % uncertainty) using the proposed technique. Results of this sensitivity study are summarized in Table 2.3.

Scenarios	CHL, mg/m^3	TSS, g/m^3	CDOM, m^{-1}
1. Oligotrophic ocean	0.1 ± 0.2(0.2)	0.5 ± 0.05(0.08)	0.03 ± 0.005(0.008)
2. Mezotrophic deep ocean	2 ± 1.2(2.4)	4 ± 1.2(2.3)	0.4 ± 0.05(0.08)
3. Mezotrophic shallow ocean	2 ± 2.5(3.6)	4 ± 0.9(2.1)	0.4 ± 0.07(0.12)
4. River flood	2 ± 2.2(3.7)	20 ± 2.9(4.4)	1 ± 0.14(0.33)
5. Phytoplankton bloom	20 ± 5.2(6.7)	4 ± 1.5(1.9)	0.4 ± 0.09(0.11)
6. Combined flood and phytoplankton bloom	20 ± 4.1(8.2)	20 ± 2.1(2.3)	1 ± 0.21(0.38)

Table 2.3. Accuracy of retrieval of water colouring constituents at 5 % (10 %) normally distributed noise in water-leaving radiance for coastal ocean scenario.