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Remote-sensing observations relevant to ocean acidification

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Ocean acidification, a consequence of the ocean absorbing about a third of the anthropogenic carbon dioxide (CO₂) emitted into the atmosphere, is poised to affect biogeochemical cycles and the seawater chemical system. Traditional research methods, such as field and *in situ* sampling, are precise and reliable, but are inherently limited in spatial and temporal coverage and resolution. This article summarizes remotely sensed products, including air-sea CO₂ fluxes, total alkalinity, suspended calcite (particulate inorganic carbon), particulate organic carbon and calcification rates, which can be used to observe ocean acidification indirectly. Confounding factors and limitations of algorithms are major sources of errors. This article also discusses remote-sensing algorithms and satellite technology developments. Remote sensing, considering its great advantages and successful applications in climate change, will be an important tool in future studies of ocean acidification.

1. Introduction

1.1 Background

Increased fossil fuel burning caused by general industrialization, including power generation, transport and cement production and the land-use changes caused by agricultural activities have made atmospheric CO₂ concentrations increase from approximately 280 parts per million (ppm) to 387 ppm. This is about a 40% increase since the beginning of the industrial revolution (Raven *et al.* 2005, Solomon 2007, Doney *et al.* 2009). The atmospheric concentration of CO₂ is now higher than that at any time in the last 800 000 years (Luthi *et al.* 2008) and will exceed 800 ppm by the end of the century, according to the ‘business-as-usual’ emission scenario of the Intergovernmental Panel on Climate Change (IPCC). The oceans, which absorb about one-third of all anthropogenic carbon emissions from the atmosphere, play an important buffering role in slowing the rate of increase in atmospheric CO₂ concentration. However, the increasing CO₂ partial pressure (*p*CO₂) in seawater profoundly affects the marine carbonate system. While atmospheric CO₂ has increased from 280 to

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387 ppm, the average pH of the ocean surface has decreased from approximately 8.21 to 8.10 units. The concentration of carbonic acid (H_2CO_3) has increased by about 44.4%, bicarbonate anions (HCO_3^-) by 5% and H^+ by about 28.9%, while the concentration of carbonate (CO_3^{2-}) has decreased by about 16.2% (Raven *et al.* 2005). With the 0.3–0.4 pH drop expected for the twenty-first century, there will be an increase equivalent to approximately 150% in H^+ and a decrease of 50% in CO_3^{2-} concentrations (Kleypas *et al.* 2006) (figure 1). Studies under laboratory and field experimental conditions (table 1) show that ocean acidification is poised to cause major effects on marine organisms and biological systems. Calcifying organisms are predicted to be most seriously affected, due to the decreasing calcification caused by elevated CO_2 . However, the responses to ocean acidification are expected to differ from one species to another and even between organisms in different life stages.

So far, most of our understanding of the effects of ocean acidification on the marine chemical system is derived from field-sampling data. Ship surveys and a growing number of autonomous moored and underway platforms directly provide accurate long-term time series for studies and modelling. The first observation of basin-wide ocean acidification was in the North Pacific Ocean through in situ shipboard sampling. Comparing pH readings from 1991 to 2006 in Pacific seawater between Oahu, Hawaii and Kodiak, Alaska, the upper-ocean (depth to 100 m) pH decreased by approximately 0.026 units over the one-and-half decades, equivalent to an average annual pH change of -0.0017 (Byrne *et al.* 2010). Significant upper ocean acidification was concluded to be mostly caused by rising anthropogenic emissions of CO_2 (figure 2). From historical atmospheric CO_2 data, ocean surface pH and $p\text{CO}_2$ data of the Hawaii Ocean Time-Series (HOT) station Aloha, the increasing rates from 1990 to 2007 of oceanic and atmospheric CO_2 are seen to be consistent, which indicates that the uptake of anthropogenic CO_2 is a major cause for changes in the marine carbon system

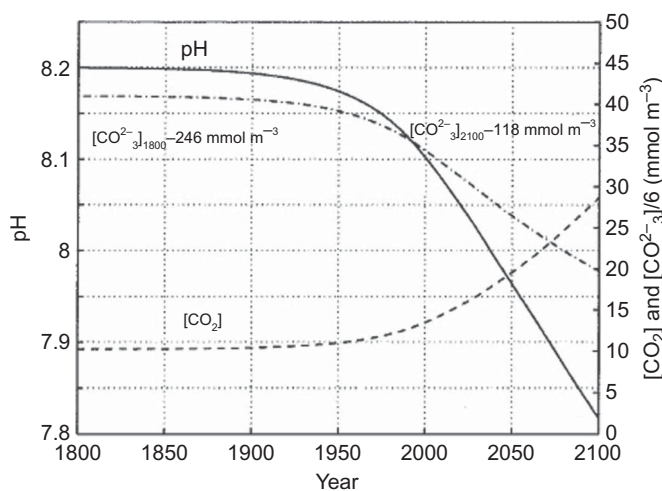


Figure 1. Changes in the ocean surface carbonate system in response to elevated atmospheric CO_2 . Models based on the IS92a scenario of the IPCC report 1995: pH (solid line), CO_2 concentration (dashed line) and CO_3^{2-} concentration (dash dotted line) (Wolf-Gladrow *et al.* 1999).

Table 1. Effects of ocean acidification on some major biological processes under different experimental conditions.

Biological process	Research organisms	Conditions	Exposure period	Result	References
Positive effects Photosynthesis	Diatoms and coccolithophores	CO ₂ at 700 and 1050 ppm	24 days	27% and 39% of CO ₂ uptake increase	Riebesell <i>et al.</i> (2007)
	<i>Synechococcus</i>	CO ₂ at 750 ppm	At least 14 days	Great evident elevated photosynthesis rate	Fu <i>et al.</i> (2007)
	<i>Emiliania huleyi</i>	CO ₂ at 750 ppm	1.5–3 days	100% to 150% increase of photosynthesis rates over a CO ₂ range from 280 to 750 μ atm	Iglesias-Rodriguez <i>et al.</i> (2008)
Fe-bioavailability	Coastal mesocosms	CO ₂ at 1050, 700 and 350 ppm	25 days	Higher Fe values in high CO ₂ mesocosms	Breitbarth <i>et al.</i> (2009)
Nitrogen fixation	<i>Trichodesmium</i>	CO ₂ at 750 ppm	2 days	35%–100% increase in N ₂ fixation rates	Hutchins <i>et al.</i> (2007)
Negative effects Calcification	Crustose coralline alga	CO ₂ at 765 ppm	7 weeks	78% decrease in crustose coralline algae recruitment rate	Kuffner <i>et al.</i> (2008)
	<i>Emiliania huxleyi</i>	CO ₂ at 700 ppm	20 days	25% decrease in net calcification rate	Sciandra <i>et al.</i> (2003)
	Coccolithophorid	CO ₂ at 700 ppm	25 days	40% decrease in net community calcification	Delille <i>et al.</i> (2005)
	<i>Mytilus edulis</i>	CO ₂ at 740 and 1800 ppm	2 months	25% decrease in calcification rates at 740 ppm and a dissolution of mussels at 1800 ppm <i>p</i> CO ₂ values	Gazeau <i>et al.</i> (2007)

(Continued)

Table 1. (Continued.)

Biological process	Research organisms	Conditions	Exposure period	Result	References
Growth rate	<i>Echinometra mathaei</i>	CO ₂ at 560 ppm	6 month	Growth stop after the sixteenth week and 8% reduction of the mean wet weight at last	Shirayama and Thornton (2005)
	<i>Emiliana huxleyi</i>	CO ₂ at 750 ppm	1.5 to 3 days	Lower growth rates	Iglesias-Rodriguez <i>et al.</i> (2008)
	<i>Mytilus galloprovincialis</i>	pH at 7.3	90 days	Slower shell growth at 7.3 pH than that at pH 8.05; obvious less shell length at last	Michaelidis <i>et al.</i> (2005)
	<i>Ophiothrix fragilis</i>	pH at 8.10, 7.9, 7.7	25 days	Longer time for larvae to reach the same development stage under pH 7.7 and 7.9 compared to pH 8.10.	Dupont <i>et al.</i> (2008)
Survival	<i>Psammochinus militaris</i>	pH at 6.16	8 days	100% urchin mortality at pH 6.16 after 7 days	Miles <i>et al.</i> (2007)
	<i>Sipunculus nudus</i>	pH at 8.10, 7.05, 6.55	Long term	A significant decrease of time to 100% mortality	Langenbuch and Portner (2004)
	<i>Ophiothrix fragilis</i>	pH at 8.10, 7.9, 7.7	26 days	Significant increase of mortality; 9.1% d ⁻¹ of the average mortality in 25 days	Dupont <i>et al.</i> (2008)

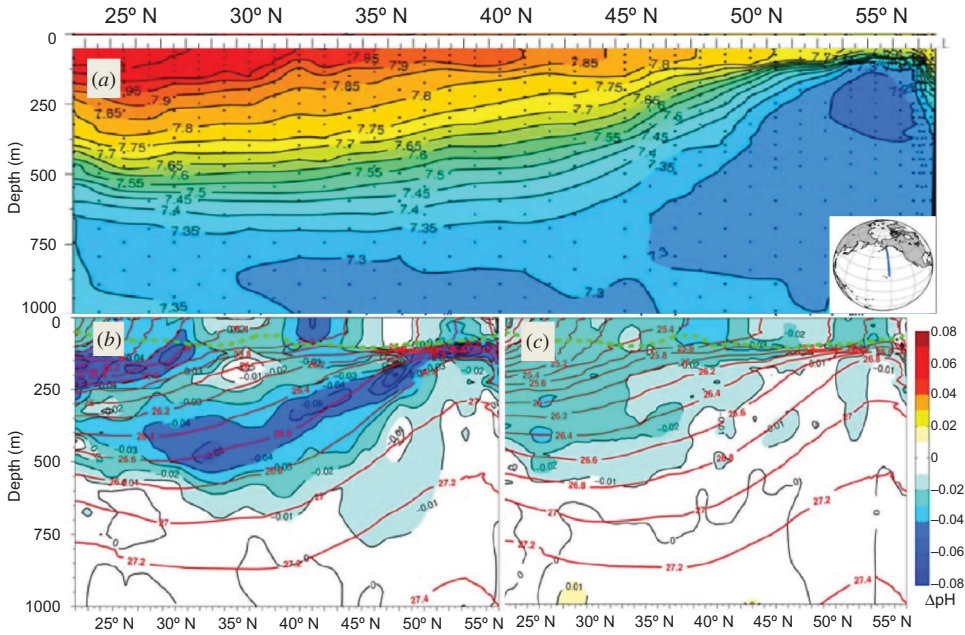


Figure 2. Changes of pH between 1991 and 2006 in the North Pacific Ocean. (a) Vertical pH of modern North Pacific seawater, at 25°C; (b) total pH changes; (c) pH change attributed to the uptake of anthropogenic carbon. $\Delta\text{pH} = \text{pH}_{2006} - \text{pH}_{1991}$). Red contours show isopycnal surfaces. The dashed green line marks the estimated 152° W late-winter mixed layer depth and is roughly equivalent to the average mixed layer depth between the two March cruises (Redraw after Byrne *et al.* (2010)).

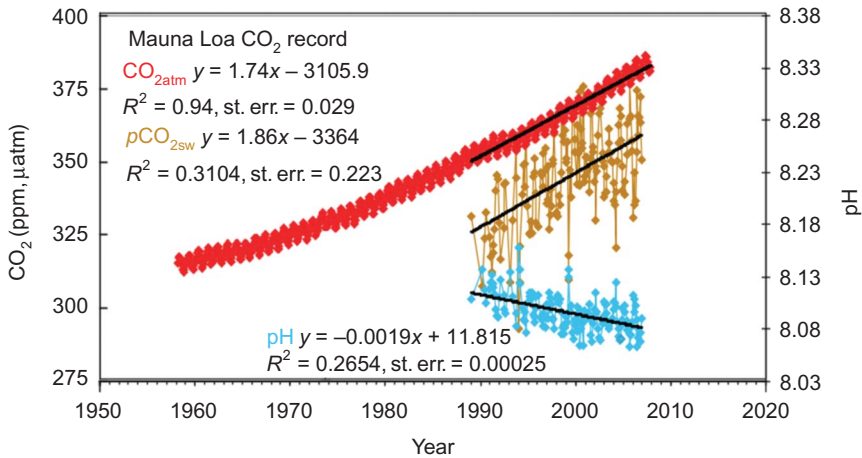


Figure 3. Time series of changing atmospheric CO₂, ocean surface pH and pCO₂ in the subtropical North Pacific Ocean. Atmospheric CO₂ (in ppm) is acquired from Mauna Loa, and pCO₂ (μ.atm) is from Ocean Station ALOHA (Redraw after Doney *et al.* (2009)).

(Doney *et al.* 2009) (figure 3(c)). These field-sampling observations provide direct and detailed knowledge of ocean-acidification processes and promise to be a powerful tool in future studies.

1.2 Remote sensing

Ocean acidification occurs on a large scale and is influenced by many environmental parameters. Direct field measurements are inherently limited in spatial (time series, moored stations) and/or temporal resolution (ship surveys). Laboratory experimental measurements cover short time scales, usually ranging from hours to weeks. Besides, most observations are made on single-species cultures. Under more-natural conditions, the consequences would be different, due to the higher complexity in the 'real world'. Remote sensing is a relatively new technology, developing rapidly in recent decades. It offers an avenue for expanding observations and analysing the temporal and spatial variability of the global ocean. This article describes observations related to ocean acidification derived from satellite remote sensing and discusses their applications. It also surveys the possibilities of the remote sensing on ocean acidification in the future.

2. Methods

The ocean is one of the major global reservoirs of carbon and a major sink of anthropogenic CO₂. The seawater carbonate system is governed by a series of chemical reactions:



Under typical ocean surface conditions, about 90% of the total CO₂ is formed as HCO₃⁻, 9% as LCO₃²⁻ and only 1% as undissociated CO_{2(aq)} and H₂CO₃ (Feely *et al.* 2009). In the ocean carbonic acid system, pH, total alkalinity (*A_T*), total dissolved inorganic carbon (DIC) and the partial pressure of CO₂ in surface seawater (*p*CO_{2,sw}) are the four essential parameters for determining changes in seawater properties. In addition to sea surface temperature (SST) and salinity, at least two, and preferably three of these carbonate parameters need to be observed to fully describe the seawater carbonic system at any given depth. Thus, knowing the thermodynamic dissolution constants and the composition of seawater as a function of salinity, the pH value can be calculated.

3. Results

3.1 Remotely sensed ocean-acidification-related products

Using remote sensing to monitor and detect seawater pH changes and their impacts on marine organisms is not feasible at present. However, a host of satellite-derived products, such as air-sea CO₂ fluxes calculated based on *p*CO_{2,sw}, particulate inorganic carbon (PIC), particulate organic carbon (POC), *A_T* and calcification rates, can contribute valuable information (table 2). Some of these measurements measure the ocean carbon cycle directly (e.g. air-sea CO₂ fluxes, POC and PIC); others measure geobiochemical responses to ocean acidification (e.g. *A_T* and calcification rates). Air-sea exchange is the first step of oceanic CO₂ uptake from the atmosphere and activates the biological pump. The ratio of PIC to POC is thought to be shifted by increasing CO₂. A change in this ratio could affect the ability of the ocean to act as a CO₂ sink, forming important feedback in the carbon cycle. The geobiochemical responses are good

Table 2. Carbonate parameters derived from satellite products.

Carbonate elements	Data for algorithm			Precision	Concluding remarks	Reference
	Analytical approach	Satellite data	<i>In situ</i> data			
$p\text{CO}_{2,\text{sw}}$	Least squares fit	SST	T, S, total inorganic CO_2 , PO_4	RSME of $p\text{CO}_2$ was $\pm 17 \mu\text{atm}$ and $\pm 40 \mu\text{atm}$ in subtropical North Pacific and northwestern subpolar region An error bar of $\pm 21 \mu\text{atm}$ between the generated and shipboard data	SST well used in regions where $p\text{CO}_{2,\text{sw}}$ is controlled primarily by temperature	Stephens <i>et al.</i> (1995)
	Multiple regression	SST, chl- <i>a</i>	$p\text{CO}_2$		SST and chl- <i>a</i> used in $p\text{CO}_2$ deriving	Ono <i>et al.</i> (2004);
		SST, chl- <i>a</i>	$p\text{CO}_2$, T, MLD	RMSE of $p\text{CO}_2$ in period with observed Chl- <i>a</i> data and period without Chl- <i>a</i> data were ± 10.8 , $\pm 5.6 \mu\text{atm}$, respectively	Net annual CO_2 sink was estimated (0.0058 Gt C yr^{-1} or 0.6mol C $\text{m}^{-2} \text{yr}^{-1}$)	Chierici <i>et al.</i> , (2009)
	Self-organizing neural network	SST, chl- <i>a</i>	$p\text{CO}_2$, SST, chl- <i>a</i>	Basin-wide RMS errors were 19.0 μatm and 21.1 μatm for remote-sensing data gaps and filled SST, chl- <i>a</i> areas	Neural network with SST and chl- <i>a</i> was used to derive $p\text{CO}_2$	Friedrich and Oeschies (2009)

(Continued)

Table 2. (Continued.)

Carbonate elements	Data for algorithm			Precision	Concluding remarks	Reference
	Analytical approach	Satellite data	<i>In situ</i> data			
Total alkalinity	Principal component analysis and multiple regression	SST, chl- <i>a</i>	SST, A_T , chl- <i>a</i> , DIC	RSME was 50.2 μatm between observed and predicted $p\text{CO}_2$	Air-sea fluxes of CO_2 derived in river-dominated coastal margin	Lohrenz and Cai (2006)
	Empirical algorithm	SST	S	Mean computed A_T was $2375 \pm 36 \text{ mmol kg}^{-1}$ compared to the mean shipboard $2366 \pm 77 \text{ mmol kg}^{-1}$	Derived A_T algorithms for five oceanographic regimes	Gledhill <i>et al.</i> (2008)
Particulate Inorganic Carbon	Three-band algorithm	$L_{\text{wn}}(670)$, $L_{\text{wn}}(765)$, $L_{\text{wn}}(865)$	–	A 10% error between estimated and measured coccolith counts in blooms of coccolithophorid <i>E. huxleyi</i> examination	Especially for blooms of coccolithophorid <i>E. huxleyi</i>	Gordon <i>et al.</i> (2001)
	Two-band algorithm	$L_{\text{wn}}(440)$, $L_{\text{wn}}(550)$	PIC, acid-labile backscattering (b_b)	RSME of global PIC $< 0.08 \text{ mg PIC L}^{-1}$ after binning into 36 km^2 and 90 day averages compared to the averaged 2 mg PIC L^{-1}	Seasonal, global maps of the standing stock of pelagic PIC	Balch <i>et al.</i> (2005)

(Continued)

Table 2. (Continued.)

Carbonate elements	Analytical approach	Data for algorithm		Precision	Concluding remarks	Reference
		Satellite data	<i>In situ</i> data			
Particulate organic carbon	Empirical regression	$R_{rs}(555)$	POC, $b_{bp}(510)$	In situ POC values agreed to $\sim 8\%$ and 12% with satellite values	b_{bp} first used in POC algorithm	Stramski <i>et al.</i> (1999)
	Least squares fit	$R_{rs}(412)$, $R_{rs}(443)$, $R_{rs}(490)$, $R_{rs}(510)$, $R_{rs}(555)$, $R_{rs}(670)$	$c_p(660)$, POC, PM	RMSE of POC was 4.1 mg m^{-3} compared to 100 mg m^{-3} in the surface waters	Maximum normalized difference carbon index (MNDCI) algorithm	Son <i>et al.</i> , (2009)
Calcification rates	Semi-analytical approach	$R_{rs}(443)/R_{rs}(555)$, $L_{wn}(443)/L_{wn}(555)$ chl- a ,	POC, chl- a , $c_p(660)$, $b_b(589)$	The best RSME was 6.5%	Blue-to-green ratio of R_{rs} as parameters in the POC algorithm	Stramska and Stramski (2005)
	Least-squares multiple-linear regression	SST, D_{eu} , chl- a	T, D , PIC, chl- a	RMS = 0.6 Pg PIC compared to the total global annual value 1.61 Pg y^{-1}	The first satellite calcification algorithm	Balch <i>et al.</i> (2007)

Notes: c_p , the beam attenuation coefficient of particles; T, temperature; D , sample depth; L_{wn} , normalized water-leaving radiance; b_{bp} , particulate backscattering coefficient; R_{rs} , remote-sensing reflectance; $K(\lambda)$, diffuse attenuation coefficient; D_{eu} , depth of the euphotic zone; $b_b(\lambda)$, total backscattering coefficient of seawater; RMSE, root mean square error; PM, particulate matter.

reflections of ocean acidification. Total alkalinity, one of the four essential parameters for determining changes in seawater, could be used as an important element to calculate the state of the carbonate system. Calcification rates, which are expected to be affected most severely by ocean acidification, will also be an efficient monitoring factor in ocean-acidification studies.

Since derived values agree well with the field-sampling data at the surface, concentration and distribution from depth have been calculated as well. Integrated POC reservoirs over certain depth ranges were calculated with empirical algorithms, both on regional and global scales (Balch *et al.* 2005, Stramska 2009). Global patterns of near-surface POC concentration (POC_{sur}) and POC over the euphotic layer (POC_{zeu}) are found to follow the major gyre systems and other large-scale circulation features. The mean global value of POC_{zeu} over the global ocean is 3742 mg m^{-2} . The standing stocks of POC are $3.92 \times 10^{14} \text{ g}$ and $1.19 \times 10^{15} \text{ g}$ over the first penetration and euphotic depths, respectively (Duforet-Gaurier *et al.* 2010). Global total and monthly calcification rates were generated using MODIS data with an empirical calcification algorithm based on day length, sample depth, SST, chlorophyll-*a* (*chl-a*) concentration and suspended calcite concentration. The annual calcification rate over the euphotic depth was estimated at 1.61 Pg C (Balch *et al.* 2007).

3.2 The experimental Ocean Acidification Product Suite

Satellite products provide us with an indirect way to derive the pH of seawater. The National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch and Atlantic Oceanographic and Meteorological Laboratory have developed the Experimental Ocean Acidification Product Suite (OAPS) to provide synoptic estimates of sea surface carbonate chemistry in the Greater Caribbean Region (online at: <http://coralreefwatch.noaa.gov/satellite/oa/>). The product offers a monthly, 0.25×0.25 synthesis of satellite and modelled environmental data sets, including aragonite saturation state (Ω_{ar}), $p\text{CO}_{2,\text{sw}}$, A_{T} , carbonate ions and bicarbonate ions (figure 4). The $p\text{CO}_{2,\text{sw}}$ is estimated using an empirical model relating the difference between sea surface and atmospheric CO_2 partial pressures to changes in CO_2 gas solubility (K_0). Sea surface A_{T} is derived using the empirical relationships describing subtropical surface A_{T} as a function of sea surface salinity (SSS) and SST. Monthly composites of these A_{T} and $p\text{CO}_{2,\text{sw}}$ fields are then coupled to derive the carbonic acid system using the Carbon Dioxide Information Analysis Center (CDIAC) Program for CO_2 System Calculations. The model estimates an increase in dissolved inorganic carbon (DIC) at a rate of $1.2 \mu\text{mol kg}^{-1} \text{ y}^{-1}$ and a decline in the annual mean Ω_{arg} from 4.05 to $3.9 (\pm 0.08)$, at a rate of $0.012 \Omega_{\text{arg}} \text{ y}^{-1}$, from 1996 to 2006 as a consequence of rising atmospheric CO_2 (Gledhill *et al.* 2008).

3.3 Errors for remote sensing of ocean acidification

Several important input variables, such as *chl-a* and SST, have been derived from satellite data for many years, and SSS is also now available. The SSS products derived from the Soil Moisture and Ocean Salinity Satellite (SMOS), which was launched by the European Space Agency in 2009, could reach a precision of 0.1–0.2 psu (Font *et al.* 2004). Remote-sensing algorithms giving ocean-acidification-related products are still being developed. The precision of these indirect observations are not as high as direct field measurements (table 2) but could meet analysis needs in regions where the algorithms are well developed. The OAPS programme is a useful attempt to observe ocean

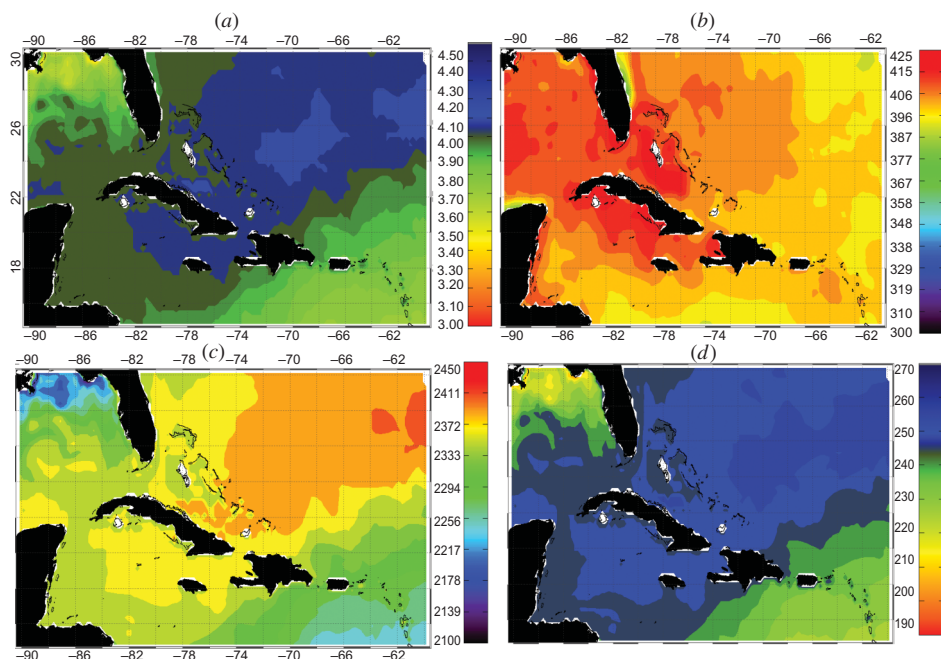


Figure 4. Distribution of OAPS products for August, 2010. (a) Aragonite saturation state, (b) $p\text{CO}_{2,\text{sw}}$ (μatm), (c) total alkalinity ($\mu\text{mol kg}^{-1}$) and (d) carbonate ion ($\mu\text{mol kg}^{-1}$). NOAA Coral Reef Watch Ocean Acidification Product Suite Version 0.2 preliminary across the Greater Caribbean Region (from <http://coralreefwatch.noaa.gov/satellite/oa>).

acidification with remotely sensed data. Sea surface carbonate chemistry parameters were evaluated against the averaged collected measurements from geochemical cruises from 1997 to 2006. The mean sea surface $p\text{CO}_{2,\text{sw}}$, modelled with an empirical relationship using in situ $p\text{CO}_{2,\text{sw}}$, SST, SSS and sea-level barometric pressure, was $374 \pm 15 \mu\text{atm}$ compared to the mean ship-measured $p\text{CO}_{2,\text{sw}}$ of $372 \pm 18 \mu\text{atm}$ ($n = 20\ 141$). The mean modelled A_{T} value was $2735 \pm 36 \mu\text{mol kg}^{-1}$ compared to the mean ship-measured value of $2366 \pm 77 \mu\text{mol kg}^{-1}$. The mean-modelled sea surface Ω_{ar} , calculated from monthly composites of the daily $p\text{CO}_{2,\text{sw}}$, A_{T} , SST and SSS fields using the CO2SYS programme, was 4.00 ± 0.10 compared to the mean ship-measured value of 4.01 ± 0.17 (Gledhill *et al.* 2008) (figure 5).

4. Discussion

4.1 Sources of errors

Confounding factors may strongly affect the precision of the remotely sensed observations. In particulate inorganic carbon (PIC) algorithms, differences in water mass and particle types and mean changes in the background backscattering may affect the satellite-derived results. In coccolithophore blooms, examined by a three-band algorithm, agreement between the backscattering coefficient at 546 nm and the detached coccolith concentration would increase by 5% after assuming the chl-*a* concentration in the blooms to be 1 mg m^{-3} rather than zero (Gordon *et al.* 2001). Background chl-*a* concentration should also be considered in POC algorithms and should be developed

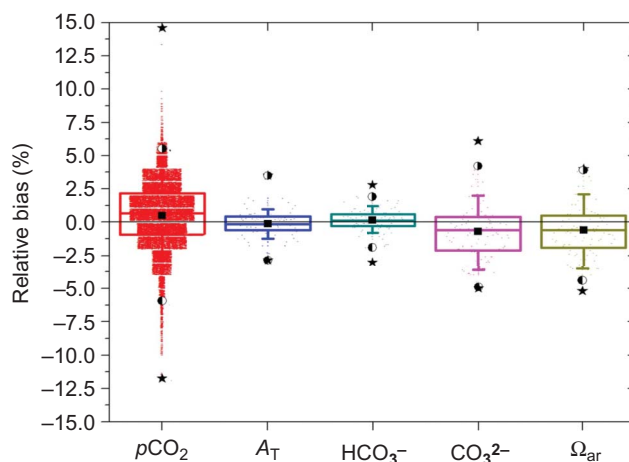


Figure 5. Bias between the OAPS modelled values and co-located ship-measured values. ★ stands for the maximum and minimum values, ■ stands for the mean value and ● stands for values ranging from 1% to 99% of the total values (modified from <http://coralreefwatch.noaa.gov/satellite/oa>).

separately according to water trophic status (oligotrophic, mesotrophic or eutrophic conditions).

As most of the remotely sensed products are derived using empirical algorithms and are, thus, inherently limited by the input data set, the validity of these algorithms outside their data domain is not well known. For example, results from an algorithm developed from SST agree well (root mean square (RMS) deviation of $\pm 17 \mu\text{atm}$) with that in the subtropical North Pacific, since the $p\text{CO}_2$ there is controlled primarily by temperature. However, in the northwestern subpolar region, $p\text{CO}_2$ is controlled by temperature and also shows significant seasonal change, and this algorithm gives poorer results (RMS deviation of $\pm 40 \mu\text{atm}$) (Stephens *et al.* 1995). In the future, the analysis approach and models should be developed to overcome these shortcomings.

4.2 Future developments for remote sensing of ocean acidification

Remotely sensed products and the OAPS programme provide an indirect way to monitor chemical changes in seawater and offer a first significant step to observe ocean acidification. However, problems (e.g. immaturity of the algorithms in the OAPS system and the low spatial resolution of the products) still exist. Future work needs to focus on three issues:

4.2.1 Algorithm development. Present marine carbonate algorithms are too immature to be used widely and accurately. The basic chemistry of seawater is still not fully understood, so the impact factors in an algorithm may be only partly considered. Besides, as empirical regression algorithms are inherently limited in accuracy, derived results may not agree well with observed data and may give major errors outside specified conditions. More analytical or semi-analytical approaches should be developed to improve precision and to extend the application of satellite products.

4.2.2 Remote-sensing algorithms. Considering that $p\text{CO}_2$, A_T , DIC and pH are four essential parameters to understand marine carbon chemistry and that algorithms exist for only two ($p\text{CO}_2$ and A_T), remote-sensing algorithms for the other two parameters (DIC and pH) should also be derived to verify results. Such work has been started. An empirical relationship between salinity (S)-normalized total inorganic carbon C_T ($\text{NC}_T = C_T \times 35/S$), SST and nitrate (NO_3^-) in the form of $\text{NC}_T = a + b \times \text{SST} + c \times \text{SST}^2 + d \times \text{NO}_3^-$ was determined from C_T measurements made in major ocean basins (Lee *et al.* 2000). Input parameters are SST and nitrate, of which SST could be obtained accurately, and nitrate algorithms are being developed (Goes *et al.* 2000, Silio-Calzada *et al.* 2008). Since C_T is made up of PIC and DIC and satellite PIC algorithms are available, it is possible to obtain DIC contribution in surface water. A direct pH algorithm was derived using measured surface seawater pH, SST and chl-*a* data sets over the North Pacific: $\text{pH} (\text{total hydrogen scale at } 25^\circ\text{C}) = 0.01325 \times \text{SST} - 0.0253 \times \text{chl-}a + 4.150$ ($R^2 = 0.95$, $p < 0.0001$, $n = 483$) (Nakano and Watanabe 2005). The mean difference between measured and predicted pH was 0.006 ± 0.022 pH; thus, the spatiotemporal distribution of pH over the North Pacific could be determined using this algorithm.

4.2.3 New satellite technology. This refers to two aspects.

1. Techniques for measuring the inorganic carbon system in seawater (e.g. A_T , DIC and $p\text{CO}_2$) could improve sensitivity, accuracy and precision. Balch and Fabry (2008) noted two recent optical advances. The first is the lidar technique, which can be used to measure the vertical distribution of optically scattering particulate matter over the euphotic zone. The second is the Multiangle Imaging Spectroradiometer (MISR) instrument on the NASA Terra satellite. This measures reflectances at incidence angles ranging from -70° to 70° , which could help improve atmospheric correction and better determine the anisotropic properties of light reflectance from the sea.
2. Seawater pH affects ultrasonic wave transmission in the water column. This provides a possible direct way to derive pH. As direct measurements from a satellite sensor should be the most accurate means to monitor ocean acidification, efforts should focus on possible sensor design. Some developed countries, such as the USA, intend to develop new satellite technologies to monitor and detect ocean-acidification-related ecological changes, and it is reported that new instruments will be put into use over the next 5–10 years (Ocean Carbon and Biogeochemistry Program Subcommunity 2009).

5. Concluding remarks

Oceans absorb one third of anthropogenic carbon emissions from the atmosphere. This will cause great change, both in the seawater chemical system and in the marine ecosystem. Growing efforts are being made in ocean-acidification research, mostly on *in situ* measurements, laboratory experiments and model simulations. These measurements provide us with the most-accurate means to observe and understand ocean acidification, but inherent limitations exist. Some remotely sensed products, including air-sea flux, PIC, POC, A_T and calcification rate, could be indirectly observed for ocean-acidification study. These products are not so accurate compared to direct field measurements, and the validities of the algorithms used needs to be improved.

Considering these defects, developments on both algorithms and satellite technology are needed.

Ocean acidification is a large spatio-temporal scale phenomenon and needs to be observed globally. As ocean acidification becomes more and more serious, an integrated programme, including experimental measurements, modelling approaches, field monitoring and satellite observation, is required to provide policymakers with sufficient information for management strategies in the future.

Generally, remote sensing, with its real-time and large-scale advantages compared to traditional measurements, is certain to play a tremendous part in studies of ocean acidification, which will help humans better mitigate and adapt to the expected long-term changes.

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