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Remote sensing tools to study ocean biogeochemistry: the state of the art

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Remote sensing of the world ocean presently provides measurements of sea-surface tmperature, sea surface height, wind speed and direction, and ocean color, from which chlorophyll concentration and aerosol optical thickness are obtained. It is well known that satellites enable excellent spatio-temporal coverage and consistency of methodology, but they are limited by what they can measure and their resolution, and depth of penetration. Conversely, the sampling coverage that is only possible from satellite-borne sensors provides a powerful capability for extrapolating, integrating, and constraining other observations and model results.

Biogeochemical variables that can be measured or inferred from satellite-borne sensors

The following compartments of the carbon cycle and accompanying oceanographic processes can be addressed with remote sensing observations.

Air-sea exchange of CO_2: Estimates of two major components relating to the exchange of CO_2 between ocean and atmosphere can be improved upon by using remote sensing: the air-sea gas exchange and the oceanic pCO_2. The air-sea exchange coefficient is usually parameterized using wind speed. Scatterometers provide global observations of wind speed and direction on a daily basis. Likewise improved parameterizations which use measurements of the surface roughness (from which capillary wave height is estimated) may give a more direct value of the exchange rate than wind-based parameterizations.

Much research has gone into parameterizing the partial pressure of CO_2 in ocean water (pCO_2) with SST or salinity (Boutin et al. 1999, Loukos et al 2000). The general consensus is that the relationships between SST and pCO2 are not globally applicable and that they change in space and time (Lee et al, 1998). Although chlorophyll concentration (obtained from ocean color) is often invoked as a factor determining pCO_2, the algorithms which would incorporate it are still under development.

Primary production: The rate of carbon uptake or photosynthesis is a process of major importance by drawing down carbon and changing the total inorganic carbon concentration of ocean water. The advent of ocean color measurements, from which chlorophyll concentration can be derived, has fueled the development of a suite of primary production (PP) models which use chlorophyll concentration, irradiance, and SST (all measured remotely). There are several types of PP models with varying degrees of complexity (Behrenfeld and Falkowski, 1997). At present, they provide estimates within a factor of two when compared with in situ measurements of carbon uptake made with ^{14}C (Campbell et al., submitted). Research is ongoing to improve their performance.

New or export production: Although models exist to estimate primary production, a further level of uncertainty is related to our estimations of new or export production. Most estimates utilize a relationship between f-ratio and SST or primary production, nitrate or chlorophyll concentration (Sathyendranath et al. 1991, Laws et al., in press). Other potential approaches directly address the supply of nutrients via heat fluxes (and the relationship with nitrate) or precipitation. Other estimates are based on nutrient uptake as derived from changes in SST (Goes et al, 2000) or heat content (Carr et al. 2000).

Community structure: Information on the role of community structure and export fluxes can be employed for those situations in which one or more functional group can be identified with space-based observations. A few organisms have been identified from space, namely coccolithophorids (Brown and Yoder, 1994) and the diazotroph *Trichodesmium* (Subramaniam et al 1999). The concentration of calcium carbonate (CaCO3) is derived routinely from ocean color and work is ongoing to improve algorithm implementation for both SeaWiFS and MODIS (Gordon et al, in prep.). Other efforts are underway to distinguish *Phaeocystis* and diatoms, usually with the help of one or more sensors and ancillary in situ information.

Partioning of carbon species: It is important that we distinguish the partitioning of carbon species (POC, DOC). A recent study has provided an estimate of POC using reflectance measurements (Stramski et al 1999). Although applied to the Southern Ocean, this method may be extended, with proper in situ validation, to the global ocean. Although there are algorithms to quantify colored dissolved organic matter (CDOM) (e.g. Hoge and Lyon, 1999, or Siegel et al, submitted), the relationship between CDOM and DOC is not straightforward (Nelson et al. 1998).

Photochemistry: Dissolved organic carbon undergoes transformation due to the effect of visible and ultraviolet light, generating dissolved inorganic carbon, DIC (Blough, 1992). This photochemical conversion of dissolved organic matter can also be addressed with remote sensing information (Cullen et al, 1997, 1999; Johanssen et al, 2000). Various models, similar to PP algorithms, can be applied to gases which play an important role in atmospheric processes, such as carbon disulphide, carbon monoxide, non-methane hydrocarbons (NMHCs), and dimethyl sulfide.

Aerosol concentrations: Aerosol concentrations can be measured using reflectance sensors designed for other applications such as AVHRR, SeaWiFS, or MODIS, or those designed with that objective such as TOMS or MISR. Atmospheric aerosols are diverse, including smoke and dust, and methods are being developed to distinguish between the various absorbing components.

Small-scale variability: Satellites also provide an unprecedented opportunity to quantify variability and processes that are unresolved by coarse models and necessarily inadequate sampling campaigns. The TOPEX/Poseidon altimeter enables improved quantification of eddies for biogeochemical applications (Siegel et al 1999) and for ocean circulation models. Coastal processes, which require higher spatial and temporal resolution than is usually possible from sun-synchronous sensors, can benefit from geostationary platforms and multispectral reflectance measurements.

Conclusions

Satellite data are neither perfect nor complete. Though the standard products of most sensors are of high quality (in most places), compound products (such as PP, new production, functional type, etc.) should not be taken at face value.

It is extraordinarily important that emphasis be placed on satellite observations concurrently with field programs. The contribution that satellites can provide are:

- the best possible coverage in space and time, thus enabling extrapolation of point or line measurements

- a context for oceanographic processes both in space and time (e.g. presence of eddies or plumes, shifts in wind direction) which can lead to improved understanding of the underlying oceanography
- data to force, assimilate into, or constrain models
- an estimate of scales of variability which are not accessible except via process studies (e.g. eddies, wind events, bloom dynamics).

It is important that the sea-going community request new and improved sensors. For example, the salinity mission will have impact on better determinations of global pCO2 patterns and variability.

Satellite data cannot replace field observations, but they play a vital complementary role. Both field and remote sensing approaches are necessary to tackle the goals of understanding and quantifying global patterns in carbon dynamics.

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