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IGOS OCEAN THEME PAPER

The IOC is a member of the Partnership for an Integrated Global Observing Strategy (IGOS-P), which unites several UN agencies, plus ICSU and certain major research programmes including the WCRP and IGBP, with CEOS, the Committee on Earth Observation Satellites. The aim of the strategy is to develop a collective and efficient approach to earth system observation. The strategy is being developed through *themes*, the first of which is the Oceans Theme. The objective of this theme is to set out the main challenges for remote sensing and *in situ* observation of the oceans, and for the integration of these observations into comprehensive models from which accurate forecasts or predictions can be made. The Oceans Theme will provide guidance on priorities to individual operational or co-ordinating agencies (such as IOC) as well as to funding agencies and governments. The IOC is intimately involved in development of the Oceans Theme through participation by the GOOS Project Office and experts from GOOS advisory panels. The latest draft of the Oceans Theme paper is provided for information in the form in which it was submitted to the meeting of the IGOS Partners in Geneva on June 6-7, 2000.

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AN OCEAN THEME FOR THE IGOS PARTNERSHIP

Revision: 1 May, 2000

EXECUTIVE SUMMARY

The Integrated Global Observing Strategy Partnership (IGOS-P) established, in 1999, a thematic approach to the implementation of the IGOS. Recognising that other themes will emerge, the "Ocean Theme" was chosen to be the "pathfinder" in this approach and an Ocean Theme Team was assembled to formulate guidance. One goal of the Ocean Theme Team is to consider and study the full range of current and planned observations, while identifying potential gaps in future observations that might compromise ocean observational records. This document presents a proposed set of long-term ocean observations and identifies a number of challenges for the improvement of knowledge about both the oceans and observing techniques. The set of observations is based on an evaluation of the range of requirements that have already been presented by GOOS, GCOS, and GODAE. The next five years must include development of institutional structures committed to (1) managing the total data flow (*in situ* as well as satellite); (2) managing the production, distribution and quality assessment of relevant data products; and (3) working with end-users to ensure that the evolving system is responsive to their needs. It is also recognised that observation protocols evolve with time and, therefore, that the stated observational requirements will need to be reviewed in future. It is the recognised applications that ultimately drive the shape of the requirements for the ocean observing system. The observations on which we focus here are needed to address important issues in ocean science, and through combinations of measurements and models, to support the production of an extensive range of products for a broad community of users. The applications are directly linked to societal needs, including among other things numerical weather prediction, seasonal-to-interannual climate forecasts, and climate assessment. The data are needed for deriving fields of information about the ocean and for initialising and validating the models used to derive other products. Aside from observations we also need to improve, through the Global Ocean Data Assimilation Experiment (GODAE) and the Ocean Biology Project, how we assimilate the data into models.

In terms of a long-term continuity challenge, the observations and key issues and objectives may be summarised as follows.

Ocean Topography: Continuation of a TOPEX/Poseidon-class high-precision satellite (*i.e.* Jason-1), an ERS/ENVISAT-class altimeter and the implementation of the Array for Real-time Geostrophic Oceanography (ARGO) profilers. The key issues are the future funding of Jason beyond Jason-1 and of the ARGO profilers. The principal data product is a 10-day global map of sea-surface height (SSH) at a resolution of 0.5°.

Ocean Vector Winds: Continuation of a morning and afternoon, ERS/QuikSCAT-type of data service, with a coverage equivalent to, or better than, a dual-sided scatterometer. The key issues here concern the closing of gaps in global coverage by two scatterometers in the 2000-2003 and 2005-2008 time periods. Principal products include 5-day averaged winds at the ocean's surface.

Ocean Biology: Continuation of global satellite missions for ocean colour, such as SeaWiFS and MODIS. The issues are to realise and help define the NASA-NPOESS bridging mission for the post-2005 time frame, refine and co-ordinate the products that can be derived from ocean colour missions,

establish routine and autonomous measurements of *in situ* ocean biology and optics, and establish routine measurements of the CO_2 system. Principal products include an 8-day global composite at a resolution of 9km, and local-area coverage (on request).

Sea Surface Temperature (SST): Continuation of the geostationary, and low-earth-orbit meteorological satellites that produce merged sea-surface temperature data products. The provision of sufficient high-quality, *in situ* data to blend with satellite data remains a key issue. A second issue is to consider how to transform ATSR-class instruments to operational systems. Principal products include 5-day, global, 0.33°x0.33° SST obtained from a variety of *in situ* sources and satellite data.

Sea Ice: Continuation of the DMSP passive microwave systems, Radarsat and EOS Terra and post-ENVISAT systems to provide for long-term observations of ice extent and type. A key issue is the funding of Radarsat-2. Principal products include: ice drift, ice deformation and thin ice age (Radarsat), and ice extent, ice concentration, and ice drift (SSM/I). Salinity: Continuous, large-scale, systematic collections of surface and subsurface salinity data are required but do not presently exist. In terms of the Knowledge Challenge the key issues and objectives are as follows.

Precision Gravity Field or Geoid: To implement the GRACE/GOCE class missions and provide a high quality Geoid.

Salinity: To develop and demonstrate space technologies (*e.g.* SMOS) that can eventually provide long-term, global data to complement the *in situ* measurement systems.

Sea Surface Temperature: To pursue the development needed to attain sea-surface temperature estimates to significantly better than ± 0.5°C on a routine and global basis.

Sea **State and Atmospheric Pressure:** To pursue developments in Synthetic Aperture Radar and other methods for space-based measurements.

Ocean Biology: To develop algorithms and data products to describe primary productivity and other biological processes in the ocean and in coastal seas.

Sea Ice Thickness: To develop satellite systems capable of determining ice thickness (*e.g.* CRYOSAT).

AN OCEAN THEME FOR THE IGOS PARTNERSHIP:

INTERIM REPORT FROM THE OCEAN THEME TEAM*

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1. BACKGROUND

The Integrated Global Observing Strategy (IGOS) Partnership (IGOS-P) was established in June 1998 as a natural convergence of a number of international agencies concerned with global environmental issues, research, and Earth observations. In brief, the Partnership comprises the programme offices of the three Global Observing Systems (Ocean, Land, and Climate), the Committee on Earth Observation Satellites (which co-ordinates member space agencies), entities involved in implementing and encouraging research programmes on global change (IGBP, WCRP, IGFA), and the international agencies which sponsor the Global Observing Systems (FAO, ICSU, IOC-UNESCO, UNEP, UNESCO, WMO). The goal of the partnership is to create a strategic planning process that links research, long-term monitoring, and operational programmes in a structure that helps to determine observational needs and to identify resources to fill those needs. In early 1999, the IGOS-P requested guidance in strategic planning through a thematic approach. The "Ocean Theme" was chosen to initiate the theme approach, that is, to be the "pathfinder." An Ocean Theme Team was assembled to formulate guidance. Within IGOS, it is recognised that other themes will emerge with recommendations and calls for action. Co-ordination will be required between the themes in order to optimise observing systems for the ocean, land, and the Earth's climate.

This interim report from the Ocean Theme Team focuses on some of the immediate decisions required by satellite agencies if there is to be an orderly transition from research to a fully operational Ocean Observing System. There are many other actions that need to occur in parallel and that build on the pilot activities (*e.g.*, GODAE, and regional experiments such as PIRATA). New demands will be placed on existing *in situ* measurement systems (*e.g.* SST), and major investments are required in a number of areas, both regional and scientific. In particular, the next five years must include (1) the development of institutional structures committed to managing the total data flow (*in situ* as well as satellite); (2) the management of production, distribution and quality assessment of relevant data products, and (3) a commitment to working with end-users to ensure that the evolving system is responsive to their needs. Depending on the countries involved, an array of agencies is responsible for these facets of the system. It will likely take years to secure the budgets required to maintain essential ongoing observational programmes in an operational system, and to acquire the additional funds to spin up the advances needed to make it fully comprehensive and fully global. Co-ordinating the activity will require a phased implementation. The implementation plan must include (1) a succinct statement of the overall vision, (2) criteria for success for the Observing System, (3) programme milestones that demonstrate the progress, and (4) specific timelines and responsibilities for each stage of implementation.

2. MOTIVATION FOR THE OCEAN THEME

The overarching vision for the Ocean Theme is to develop and maintain continuity of observing capabilities for the global ocean, and to advance to a permanent, Global Ocean Observing System.

The objective of the Ocean Theme is to demonstrate how ongoing, internationally co-ordinated planning of observational requirements by various groups can be made comprehensive and coherent, to provide the basis for an integrated action plan that can be used in national decision-making in the area of ocean observing. Such a strategy needs to be well focused, truly international, and integrated both between agencies and with regard to space-based and *in situ* observing. And, because it is new, the strategy needs to be implemented in a phased and evolutionary manner consistent with existing commitments.

The work of the Ocean Theme Team is motivated by the following axioms.

2.1. *The human need for global ocean observations is well established.* In weather forecasting, ocean observations can be expected to provide increased predictive capabilities both through better understanding of the ocean processes and in providing a pattern-history. Just as a network of ocean observations has provided information to protect people from the ravages of hurricanes, and the like, so too ocean observations will lead to better prediction of ocean conditions enabling our safe use of the sea. We will be able to increase the predictability of phenomena such as sea-state, coastal erosion, and harmful algal blooms, and better manage food sources from the ocean, and input of waste products to the ocean. Since the ocean is the most important component of climate, observation-based prediction over longer periods will aid in understanding and forecasting climate change. In addition, the health of the oceans can only be understood with global, comprehensive, and integrated observations. Knowledge of the ocean transcends borders.

2.2. *The economic importance of oceans.* Oceans are both directly and indirectly of major benefit to mankind. The state of the ocean influences climate and the energy and water cycles. Hence, the ocean affects agriculture, and water and energy supplies. The state of the ocean also affects the intensity of hurricanes and tropical cyclones, which cause hundreds of millions of dollars in property damage and alter the economic fortunes of business in the affected areas. The El Niño/La Niña phenomenon of the tropical Pacific widely impacts the economics of crop production in the tropics and mid-latitudes. World-wide trade, 90% of which goes by sea, is expected to double over the next decade, requiring improved now-casting and forecasting services to enable cost-effective operations through safe navigation. The march of the oil and gas industry into deeper water, with productive wells now occurring at depths of 2000 meters, also demands improved now-casts and forecasts of marine conditions. Demands for ocean information are growing, too, in coastal waters, in response to population pressure, an increase in runoff of waste-products and fertilisers from land, and in response to the increased use of coastal seas for recreational activities, fishing, and aquaculture. Here we see a demand for environmental monitoring and habitat assessment in addition to weather and ocean now-casting and forecasting. To meet these various demands in coastal seas, we are seeing the establishment of an increasing number of well-instrumented, local-area, observation grids. It is increasingly apparent, however, that these local grids require a better understanding of transfers with the open ocean because conditions away from coasts frequently influence coastal conditions.

2.3. *The capability to observe the ocean and to deliver useful ocean data products is well established.* Sampling capabilities in oceanography have evolved greatly in the last twenty years. The advent of satellite-based remote sensing of sea-surface temperature, sea level, winds, and ocean colour, has made oceanography a truly global science. *In situ* sampling systems, compatible with remote sensing, have also been developed. Notably, neutrally-buoyant floats, that also profile with depth, have been developed as part of the global change programmes World Ocean Circulation Experiment (WOCE) and Tropical Ocean Global Atmosphere (TOGA), which are components of the World Climate Research Programme (WCRP). Likewise, during this period, numerical models of ocean circulation have advanced rapidly, and are now being coupled to ecosystem models, keeping pace with the increasing speed and capacity of super-computing technology.

2.4. *The policy imperative for a global ocean observing system is well established.* Through international negotiations, national governments have agreed to numerous conventions that although not explicitly stated, embody the requirements for measuring various ocean parameters globally, and in a concerted, systematic way. The list of relevant conventions is growing and presently includes: the Convention on the Law of the Sea; the Framework Convention on Climate Change; the Biodiversity Convention; Agenda 21 (agreed at the United Nations Conference on Environment and Development in Rio in 1992); the Global Plan of Action for the Protection of the Marine Environment from Land-Based Activities; the London Dumping Convention; and the Agreement on Highly Migratory and Straddling Stocks. Governments need coherent information and improved understanding of the ocean to meet their obligations under these Conventions. The Conventions identify requirements and needs which can only be satisfied by the concerted action of a large number of countries. The UNFCCC, at its fourth meeting in Buenos Aires in November 1998, called for increased sampling of the ocean, especially to fill present data gaps, as essential for monitoring climate change.

2.5. *Improved knowledge of the ocean is essential to further development of a global ocean observing system.* The operational global observing system of the future will be built initially by capitalising on the observing systems of today, many of which were developed for research purposes at academic institutions. As research continues, there will be further improvements in the operational observing system. Indeed, experience has proven that the full involvement of academic institutions and scientists is required in GOOS since the technology and research available at such institutions has helped to guide the development of the system. Expertise from the commercial, communications, and other user communities is also required for technical reasons and to refine present observing systems for optimum effectiveness. It is already apparent that in order to have a higher-quality observing system in the near-future, certain research experiments will have to be undertaken now to add value in the areas of technology (such as a salinity sensing from space), data assimilation, and algorithm development. In addition, certain lines of fundamental research are needed to advance areas where users want information that is not provided by present observing systems. The involvement of academic institutions and scientists in GOOS is happening in several ways. For example there is the development of the Partnership for Observations in the Ocean (POGO), involving the world's major research institutions. Involvement is also occurring through the dedication of the research community to the development of new measuring systems in the ARGO project, and in GODAE. In addition, the scientific community continues to be one of the many users of an ocean observing system. The report entitled "GOOS - 1998" (now available via Internet at http://ioc.unesco.org/goos) is a detailed source of information on, and motivation for, the Global Ocean Observing System.

3. THE IGOS OCEAN THEME

To date there has been a significant amount of progress in the development of ocean observations, and the foundations for a global ocean observing system are in place. Following experiments such as the WOCE, an Initial Observing System for GOOS has been established through the co-ordination of a number of observing systems sponsored by IOC, WMO, ICSU, UNEP, FAO, and CEOS. The initial system includes global arrays of moored buoys, drifters, voluntary observing ships, sea-level gauges, and some satellite systems.

New projects are already underway. These include the Global Ocean Data Assimilation Experiment (GODAE), set up under the Ocean Observations Panel for Climate and adopted by the CEOS Strategic Implementation Team (SIT). It aims to demonstrate the utility of civilian operational oceanography. In addition, the International Ocean Colour Co-ordinating Group (IOCCG), an affiliate of SCOR, is overseeing the Ocean Biology Project, initiated by the CEOS SIT. The goal of the Ocean Biology Project is to implement a strategy for understanding biogeochemical and ecosystem processes in the ocean by combining long-term ocean colour and other remote sensing satellite data with in-situ measurements. As a result of endeavours such as these, improved and more complete integration of the *in situ* and space-based components of the observing system is progressing.

Organisationally, countries are in the process of setting up GOOS national committees or similar organising mechanisms. An objective is to establish the mandate within government agencies for the long-term support of global ocean observations. At an initial GOOS meeting at UNESCO, in Paris (July 1999), several countries made commitments of significant parts of their national observing systems to GOOS. This is a good start. Countries are also organising regionally, as witnessed by the growing GOOS regional organisations and pilot projects. These include EuroGOOS, NEAR-GOOS (Northeast ASIA), SEACAMP (southeast ASIA), MED-GOOS (Mediterranean), PacificGOOS, WIOMAP (Indian Ocean), IOCARIB-GOOS (Caribbean) and PIRATA (tropical Atlantic), to name a few.

The challenge for the present is a commitment to long-term continuity of an operational series of ocean observations, as well as to continuing the development of new technology for ocean observations and forecasts. Establishing these commitments and the supporting organisational structures are major objectives of the Integrated Global Observing Strategy. Progress toward the commitments is shown in Appendix 1, which lists for each space agency, the status of satellite and satellite-related missions for operational oceanography. The continuity challenge is at a crucial point in time. Almost all the observations dedicated to the ocean are funded from non-operational R&D sources, and thus, by definition, their long-term continuity cannot be guaranteed. It is assumed that certain *in situ* systems are "operational" for most practical purposes. These include a global network of tide gauges, voluntary observing ships, surface drifters, plus some equatorial moored arrays, and also an embryonic array of profiling floats (ARGO). But while these capabilities have evolved over many years, as a result of both scientific requirements and local applications, funding is still subject to annual science budgets. The one exception is the secondary use of meteorological observations and these are funded by the weather services.

While it can be argued that the basic technical capability is available, establishing continuity of funding for ocean observations is a challenge in itself. A major issue is organisational, in defining who is responsible, and this often varies on a country-by-country basis. There is also the need to transfer the existing skills from the scientists to the operational users, an area where industry can assist.

Demonstrating the potential benefits that would accrue from the expenditure of public funds on the oceans is one of the most important requirements. Here, scientific case studies based on understanding of weather and climate are in place, and many of the basic economic benefits are known. However, there is a need to demonstrate better the link between the need for observations and the benefits in terms of both the public and economic perception. There is also the need to increase awareness of potential benefits among the relevant communities of both scientists and end-users. All the IGOS partners need to be active in publicising the necessities for ocean observations.

At this time, we have enough experience to design observing systems for individual variables. Individual variables will have their own observational constraints in terms of, for example, spatial resolution, frequency, and precision. The challenge we face, therefore, is to design an observing system that integrates all the variables of interest, and does so in an optimal way, and that also combines *in situ* and space-based components.

And we expect that the continuity of existing capabilities will not be sufficient as the level of understanding improves. New knowledge and observations will be necessary to predict future trends in, for example, the ocean circulation. These activities will require the continued application of R&D funds in new technology for the observation of the oceans. The ocean panels of the Observing Systems and national agencies are formulating the requirements in the area of technology developments.

4. CHALLENGES FOR OCEAN OBSERVATIONS

4.1. INTRODUCTION

This section sets out the high-level needs, existing coverage, and issues for the future, under the headings of the continuity and knowledge "challenges." The detailed specification of the requirements is not included here; some specific references for further reading are given at the end of this document. Importantly, we draw on the Conference Statement from the 1st International

Conference for the Ocean Observing System for Climate (http://WWW.BoM.GOV.AU/OceanObs99/). The Conference was held at St. Raphael, France in October 1999, and the Statement published in March 2000. The St. Raphael Conference Statement is an excellent summary of a strategy for a sustained global ocean observing system. It contains charts that map out the direction for an implementation in terms of observing platforms (both space-based and *in situ*) and networks. The Conference, however, confined itself to physical measures of the ocean and is directed toward climate prediction. Biological measurements are less mature in their operational utility, but included in the Ocean Theme Report in strategic terms.

In addition, App. 1 lists the various satellite missions by space agency. Despite the fact that specific observing system opportunities are mentioned, we do not advocate specific technical solutions to the ocean measurement problem. These are issues that need to be defined and discussed at the implementation level. Identification of presently known opportunities is meant to highlight the need for critical near-term implementation decisions.

While the observing system will monitor the oceans globally, and in an integrated way, the users are varied in their needs and in the way they apply the products of the system. For many there is a need to establish long-term continuity of a specific series of observations, For others, the challenge is to improve knowledge of ocean processes, or of ocean technology, or utilising knowledge to predict change. Marine forecast systems (*e.g.*, for navigation and fishing) are another benefit of an observing system. However, to enlarge the current limited spatial extent and short-term forecasts now available will require establishing networks of telemetry and communications for information transfer, analysis, and delivery of data products. Nevertheless, all agree that the combination of an integrated set of satellite-based and in-situ observations is critical. Meeting the "continuity challenge" would make reliable environmental data readily available through an expansion of operational oceanography. The question of continuity is addressed in Section 4.2. The "knowledge challenge," on the other hand, covers a diverse range of problems that require research for observing system development. That is addressed in Section 4.3.

4.2. THE LONG-TERM CONTINUITY CHALLENGE

4.2.1. Ocean Surface Topography

GODAE, GOOS, and CLIVAR have described the requirements for ocean surface topography. TOPEX/Poseidon and ERS have demonstrated that satellite altimetry may be utilised in a wide range of ocean research such as planetary waves, tides, and global sea level change, seasonal-to-interannual climate prediction, defence, environmental prediction, and commercial applications. The accuracy, and spatial and temporal needs vary but can be satisfied by a combination of missions. To support the ongoing products derived from altimetry, the long-term need is for continuity of a high-precision mission (*e.g.* Jason series) and a polar-orbiting altimeter to enhance temporal/spatial coverage of the global ocean (*e.g.* ERS, ENVISAT). An array of *in situ* sea-level gauges and a few highly instrumented calibration sites must supplement satellite altimeters to produce accurate global determinations of the variability in surface topography and for sea level change. For ocean circulation applications and estimation of the 3-dimensional baroclinic structure, the altimeter data must be complemented by *in situ* measurements to assist in the projection of the surface topography measurements into deeper water. ARGO profilers, ships of opportunity and various other methods are being used for this purpose.

The issues are:

1. The need to identify the mechanism and funding to ensure the operational continuity of Jason-series with a capability at least as good as TOPEX/Poseidon.

2. To maintain at least one ERS-class altimeter in a near polar orbit.

3. The need to fund, deploy, and maintain the ARGO floats.

4.2.2. Ocean Vector Winds

High-resolution vector winds at the sea surface are required in models of the atmosphere and ocean-surface waves. They are also used to force ocean models of ocean circulation. The need for, and utility of, accurate, high-resolution winds is widely recognised (*e.g.* GOOS, CLIVAR, and GODAE requirements). To support ongoing scientific and practical uses of ocean vector winds, the long-term need is for coverage by two broad-swath scatterometers, one in each of morning and afternoon polar orbits.

The single-swath scatterometer on ERS-2 and dual-swath on QuikSCAT provide present coverage. Global coverage by two broad-swath scatterometers is not likely until the planned launches of the dual-swath scatterometers, Seawinds on ADEOS-2 and ASCAT on METOP SeaWinds and ASCAT (although an extended QuikSCAT mission may overlap with SeaWinds/ADEOS-II). At present, there is a gap in coverage by two broad-swath scatterometers in the post-2006 era; however, the proposed Japanese mission, GCOM-B1, may carry a NASA-supplied scatterometer to complement the ongoing ASCAT measurements on METOP. In terms of accuracy, wind vectors should be estimated at about 1 m/s, 20° direction, with a sampling frequency of every 12 hours.

Single-look polarimetric radiometry is planned for implementation on NPOESS in 2008, with a space-borne test of a dual-look polarimeter to be flown by the U.S. Navy/NPOESS "Windsat" mission in 2002. The simultaneous flight of Windsat with SeaWinds on ADEOS-2 and ASCAT on METOP will allow a direct comparison of the different methods.

1. To realise a SeaWinds follow-on on the proposed GCOM-B1 and ensure continuity of service between ADEOS-2 and GCOM-B1.

2. To assess the capability of NPOESS single-look microwave polarimetry for determining surface vector winds using dual-look data from Windsat.

4.2.3. Ocean Biology and the Surface Carbon Flux

Since OCTS and POLDER missions on ADEOS in November 1996, and SeaWiFS since September 1997, there has been a nearly uninterrupted data-stream in ocean colour. Within the next 3-5 years, the MODIS sensor on the EOS Terra (2000-2005) and EOS Aqua (2002-2007) satellites, SeaWiFS, MERIS on ENVISAT, OCM on IRS-P4, and GLI on ADEOS-2, will also serve ocean biology. Beyond these research missions, the U.S. NPOESS Programme Office has plans to develop a visible and infrared sensor (VIIRS) that could fulfil the observation needs of both scientific and operational users. The NPOESS preparatory programme (NPP) would also deploy prototypes of this sensor on a mission to be launched in the 2004-2005 time frame. SGLI on GCOM, and succeeding ocean colour instruments are planned to span a fifteen-year period.

Products will be the developed through the Ocean Biology Project initiated by CEOS and presently co-ordinated by the International Ocean Colour Co-ordinating Group (IOCCG). The goal of the Ocean Biology Project is to implement a strategy for understanding ocean biogeochemical and ecosystem processes by combining long-term ocean colour and other remote sensing data with in-situ measurements. NASA's SIMBIOS (Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies) Project was established in 1997 to provide a co-ordinated programme of sensor calibration and product validation, and to develop a strategy for merging ocean colour data from a variety of sensors. The ultimate goal of SIMBIOS is to produce a decades-long time series of ocean colour for the global ocean.

Remote sensing measurements of ocean colour, *i.e.*, the detection of phytoplankton pigments, provide our only global-scale focus on the biology and productivity of the ocean's surface layer. Currently there are few routine *in situ* measurements of biological processes in the ocean. Among them are those made by the continuous plankton recorder (CPR) programme of the Sir Alastair Hardy Foundation for Ocean Science. The CPR Programme provides data from selected regions. Fisheries and other biologically-based agencies also provide time series data for a few locales. The time series observatories established by JGOFS, in the tropical Pacific (Hawaii Ocean Time Series, or HOT) and Atlantic (Bermuda Atlantic Time Series, or BATS), provide a comprehensive set of measurements. Indeed, HOT and BATS, spanning the last 10 years, have identified critical problems in the ocean's carbon cycle and also caused a revolution in our thinking about plankton responses to long-term temporal changes. Ultimately what is required is a global network of ecological, bio-optical, and biogeochemical observations, as the basis for calibrating, validating, and adding value to remotely sensed ocean colour data.

Ocean biology is important not only for understanding ocean productivity and biogeochemical cycling, but also because of its impact on oceanic CO_2 and the flux of carbon from the surface to the deep ocean (*i.e.*, the 'biological pump'). Through JGOFS and WOCE, we have a new global understanding of oceanic distributions and air-sea fluxes of CO_2. Although CO_2 measurement technology currently remains within the research community, CO_2 measurements are becoming routine, both from ships and from buoys (*e.g.* as at present at JGOFS time series sites, HOT and BATS). CO_2 system measurements, integrated with routine ocean colour and ecological/biogeochemical observations, are critical for understanding the interactions between physics, biology, chemistry, and climate. CO_2 measurements are also important for making climate forecasts, and for satisfying the needs of the climate conventions.

The issues are:

1. To refine and co-ordinate the products that can be derived from ocean colour missions.

2. To realise that the NASA-NPOESS Preparatory mission and proposed Japanese GCOM-B1 mission are both critical to continuity of high quality ocean-colour data products.

3. To establish routine, *in situ*, measurements of ocean biology and bio-optics, from autonomous profilers, like ARGO.

4. To establish routine measurements of pCO_2 and $\sum CO_2$ from voluntary observing ships, moored sensors, and drifters, to an accuracy of ± 2-3 microatmospheres and ± 2 micromoles respectively.

4.2.4. Sea Surface Temperature

Sea surface temperature (SST) is one of the most important boundary conditions for the general circulation of the atmosphere. SST is also very sensitive to changes in the ocean circulation, as demonstrated time and again by the ENSO cycle. From ships of opportunity, a relatively thin network of moored and drifting buoys, other *in situ* observations, and SST estimates from operational geostationary and low Earth orbit satellites, are merged to derive quasi-synoptic global SST fields, for a variety of applications. The science community currently depends on these operational SST products for climate and physical oceanographic research, even though the accuracy achieved (circa 0.5°C) is marginal for some scientific investigations. Because the operational satellites are funded through the meteorological network, continuity at this level is foreseen. But there is no continuity beyond ENVISAT for the ATSR-class of instrument.

The issues are:

1. The expansion and refinement of the *in situ* network.

2. To consider how ATSR-class instruments can be introduced into operational systems.

4.2.5. Sea Ice Concentration, Extent, and Drift

Sea ice modulates planetary heat transport by insulating the ocean from the cold polar atmosphere, and also by modulating the thermohaline circulation of the World Ocean through the process. Moreover, the high albedo of ice further insulates the polar oceans from solar radiation and introduces yet another positive feedback in the climate system. Time series of sea-ice concentration data are also critical for identifying interannual and decadal fluctuations that could point to the existence of significant changes in oceanic and atmospheric circulation at high latitude.

The motion of sea ice creates patterns of ice convergence and divergence that play a critical role in determining energy and momentum fluxes between the ocean and atmosphere at high latitudes. Furthermore, the production of new ice in areas of ice opening influences the formation of deep-water masses. The Radarsat "Arctic Snapshot" programme has provided SAR coverage of the majority of the Arctic every few days since 1996, and ERS and ENVISAT also offer this service.

These data are now being used to generate wide-area sea-ice motion and deformation products for the north polar region.

Systematic global observation of sea-ice extent and concentration, inferred from data from passive-imaging microwave radiometry, has already produced a 20-year record of global sea-ice concentration. The Advanced Microwave Scanning Radiometer provided by Japan on the EOS Aqua mission and operational satellite sensors (DMSP/SSM/I; NPOESS/CMIS) ensure the continuity of the global sea-ice concentration record in the near-term. Also, the continuation of Radarsat class missions is seen as important in further elucidating sea ice processes.

The issue here is for the agencies to continue with their existing and planned missions.

4.2.6. Salinity

Salinity observations are currently not possible from satellite systems. But the need for extensive and accurate observations of salinity has emerged in the operational and research communities as a high priority item. As a first step, the ARGO is a programme of temperature/salinity-profiling floats which offers a means to provide extensive salinity profile data on a regular basis. The availability of the profile data will provide a much-improved basis to assess further the impact of these measurements on the estimation of the state of the ocean and in prediction.

The issue for continuity is thus to ensure the funding and deployment of the ARGO *in situ.*

4.2.7. Summary

Combined, the above observations of winds, ocean surface topography, ocean colour, and sea surface temperature, sea ice, and salinity, constitute a set of measurements that can constrain models of the ocean wind-forcing, oceanic response, ocean primary production, ocean fish production, and ocean boundary conditions for the atmosphere. Each requires an integrated suite of remotely sensed and *in situ* observations. Indeed, *in situ* observations are the only way to observe the ocean interior. The remotely-sensed observations constitute a body of information providing us with integral constraints on the global ocean circulation and its coupling to the climate system. The *in situ* measurements provide the calibration, validation, and process information required to interpret and utilise the global observations provided by satellites. Ocean models and data assimilation provide the tools by which we can transform the integrated suite of observations into consistent global data products. It is the intent of GODAE to demonstrate this capability for "data fusion" in the period 2003-2005.

4.3. THE KNOWLEDGE CHALLENGE

4.3.1. Salinity

Ocean salinity, more than temperature, controls the dynamics of the deep ocean circulation and long-term climate. Sea surface salinity (SSS) determines the depth to which cold surface water may sink to form intermediate and water masses in the deep ocean. World-wide, there is a lack of systematic ocean salinity measurements, except for occasional oceanographic cruises and automatic salinity measurements on vessels that support the voluntary observing system. Thus, global remote sensing of SSS to a useful level of accuracy (better than 1 Practical Salinity Unit) would be a very significant achievement. Developing microwave remote sensing techniques for global observation of sea surface salinity from space is a NASA priority being pursued together with the observation of soil moisture. As part of its Earth Explorer programme, the European Space Agency is also currently conducting design studies for a Soil Moisture and Ocean Salinity measuring mission (SMOS) using a 2-dimensional interferometric synthetic aperture radiometer system.

The issue here is to develop and prove the technologies that will complement *in situ* salinity measurements and lead to an integrated space/*in situ* system.

4.3.2. Precision Gravity Field or Geoid

The Gravity Recovery and Climate Experiment (GRACE), an Earth System Science Pathfinder mission, currently being implemented in partnership between the United States and Germany, is expected to deliver even more precise information (accuracy on the order of ± 1 cm over scales of 300 km or longer). GRACE will provide information on variations in the Earth gravity field over an initial period of five years. GRACE should be able to detect the minute changes in the Earth gravity field associated with transient variations in fluid mass at the surface of the Earth. Oceanographers would then be poised to exploit the extreme accuracy of present and future space-based gravity measurements for remote sensing, for the time-dependent distribution of ocean water masses (equivalent to a global measurement of ocean bottom pressure). This would be the first remote sensing application for Earth based on the detection of a signal other than electromagnetic radiation.

4.3.3. Sea Surface Temperature

The limitation of the current suite of SST products has been briefly described above (section 4.2.4). There are several different definitions of SST data products possible, differentiating between skin or bulk validation, day-only or night-only acquisition, and different space-time averaging scenarios. The appropriate choice of definition varies with the application in which the SST product is to be used. The challenge for SST measurement needs to be considered no longer in terms of a specified temperature accuracy, but in terms of the underlying objective, *e.g.* "capable of detecting a global rise in upper-ocean temperature of 0.1 K", or "able to determine air-sea heat fluxes to a specified accuracy." For many scientific studies and climate applications the accuracy needed is significantly better than 0.5°C, and preferably closer to 0.1°C.

The issue is to pursue the research and development needed to realise sea surface temperature estimates to an accuracy of ± 0.1°C on a routine and global basis.

4.3.4. Ocean Biology and the Surface Carbon Flux

Given the current range of demonstration missions planned in this field, the overwhelming need is for research to be carried out in the development of products that accurately describe the biological processes and productivity of the ocean in coastal waters. This need covers areas such as the future development of hyperspectral algorithms for case II waters (waters with significant optical contributions from other than phytoplankton), which will allow much wider application of ocean colour data in the coastal zone. Among the serious challenges for the coastal ocean is the detection, forecasting, and monitoring of potentially harmful algal blooms. There is an immediate need to coordinate the development of common standards and to develop a global network of bio-optical measurements at coastal sites.

There are important research issues for the open ocean, as well. Improvements in understanding oceanic productivity must come from improved knowledge of the temporal and spatial variability in phytoplankton, from simple improvements in temporal and spatial resolution to the detection of episodic blooms. Part of the knowledge challenge is that not all phytoplankton is found at the surface, where it can be seen by satellite, but down several tens of meters below the surface, and sometimes concentrated at interfaces like the thermocline, or nutricline, thus requiring monitoring by *in situ* means. To understand the link between these signals and those at the surface detected by remote sensing requires intensive study of three things. First, *in situ* systems must be able to capture ocean biological data (*e.g.* via optical or acoustic means) on the same time and space scales as we capture physical data. Second, we need to be able to relate these data to the surface signal observed by satellites. Third, we need to improve models of the behaviour of the biological system *in situ*, both at the surface and as a function of depth.

From the point of view of climate variability, monitoring zooplankton and higher trophic levels may provide the most diagnostic evidence of interannual and inter-decadal change, thereby making now-casting and forecasting of these long-term changes more feasible. That sort of insight requires, at least for the near-term, *in situ* sampling.

One important means to attain knowledge of variability in productivity is from continuous and systematic global observations of ocean colour. It is believed that much of the flux of carbon from the surface to the deep sea occurs as a result of blooms of specific types of phytoplankton. In addition, much of the biogeochemistry of the ocean is determined by phytoplankton community structure. Hyperspectral algorithms should allow discrimination of different groups of phytoplankton, and enhance the information to be retrieved from the spatio-temporal variability of ocean colour.

Another issue concerns the optical signals contributed by coloured dissolved organic matter (CDOM) which contaminates the plankton signal observed from satellite and *in situ* bio-optical sensors. Additionally, there is the need to develop and test regional-specific algorithms for the conversion of remotely-sensed colour signals to biological variables (such as pigment concentration) and processes (such as productivity), to calibrate these signals with local *in situ* data, and to relate plankton processes to the carbon flux across the sea-surface and to the deep-sea.

It is essential that the comparability of the different colour sensors currently being flown be established by calibration, to ensure compatibility of results where sensors are monitoring different wavelengths.

However, solving the algorithm problem is not the only issue, and space-based measurements are not the only answer. The best way to 'monitor' ocean productivity is to start from accurate models of the ocean ecosystem which have yet to be created. Once available, they can then be driven by the assimilation of observational parameters measured, on the one hand, as remotely-sensed data from the ocean surface (which is where the algorithms are utilised), and on the other hand, as *in situ* surface and sub-surface data collected at high frequency (*i.e.*, hourly). Controlled experimentation is needed to define what the models require as input parameters, such that the right variables get measured. The measurements should include biogeochemical states and fluxes, particularly with regard to the carbon cycle.

A further and equally serious issue is the dearth of information about the biology of the global ocean. The solution to this problem may be some kind of census of marine life- a kind of "biological World Ocean Circulation Experiment," as proposed in a recent issue of Oceanography Magazine (see reference list), and which reports the results of a series of workshops sponsored by the Sloan Foundation.

4.3.5. Sea Ice Drift and Thickness.

Sea-ice thickness is a critical variable for estimating changes in the sea-ice mass and freshwater budget (sea-ice growth and melting), determining sea-ice mass transport (or equivalent freshwater transport) by ocean currents, and inferring energy and momentum fluxes across the ice-covered ocean surface. No technique currently exists for the direct determination of sea-ice thickness from space but CRYOSAT and ICESAT are both aimed at this goal.

The issue here is to develop systems capable of providing sea ice thickness. This represents the "Holy Grail" of sea-ice observations, being so critical to the estimation of energy and momentum fluxes between the ocean and atmosphere and yet eluding practical measurement from space.

4.3.6 Sea-State and Atmospheric Pressure

The state of the sea and surface pressure are two features of the weather that are important to commercial use of the sea (ship routing and safety, fisheries), and safety of coastal habitats. Synthetic Aperture Radar (SAR) can provide information about the properties of the sea-surface and the wave spectrum, however there are significant limitations to its use operationally. As conditions in the ocean and atmosphere change, so too do the perceived signals. Currently, there are no space-based observations available for measuring atmospheric pressure over the ocean.

The issues for these measurements are to develop further the capabilities for measuring and forecasting sea state and atmospheric pressure.

4.4. DATA SERVICES, MODELS, PRODUCTS, AND APPLICATIONS

Up to this point, the Report has discussed observational requirements and challenges for an ocean observing system. The next step is the requirement for a data system that is compatible for data structures and formats and for assuring data quality. The logic behind this requirement is that the extension of local observing systems will require telecommunications networks, and rapid data delivery among the networks and to end-users will require use of common data structures and formats.

The next step is data assimilation. Both space-based and *in situ* observations are discontinuous in space and time. Thus for operational oceanography, ocean forecasting, and validation, the observational data need to be combined with, or assimilated into, models. Data assimilation has been used in meteorological forecasting for decades, and is beginning to be used in physical oceanography. For biological oceanography, the topic is in its infancy. Through GODAE and the Ocean Biology Project, the Ocean Theme will develop data assimilation as a tool for operational oceanography. The result of data assimilation (observations plus model) is a data product.

Operational meteorology is well-established, but since the atmosphere changes faster than the ocean, while being much less spatially variable, the data products and applications for operational oceanography will be very different. And compared to basic research, applications resulting from an ocean observing system will in general require higher spatial and temporal resolution in the data products produced. The need for highly-resolved pictures of, for example, sea-surface height or fronts, points to the importance of networks of more localized observational systems. Applications fall into the categories of various kinds of forecasts, from short-term sea-state predictions and storm surge, to interannual climate forecasts. To be sure, the characteristics of some forecasts will be dependent on the available data products. Thus, there will have to be an on-going dialog between end-users and the providers of data products.

4.4.1. Archives.

All providers need to ensure maintenance of an archive of all data and products offered and provide a statement of the access conditions in terms of the mechanics and policies. These should describe how users could obtain the data and whether there are any restrictions on access or usage. There should also be a well-documented statement of the ancillary data needed to understand and use basic data sets and products.

The issue here is for all data and product providers to ensure their archived data are in a form that is understandable and documented.

4.4.2. Quality Control.

Assuring that the data and products have a defined and understandable quality assurance attached to them is important. Furthermore, for long-term continuity, the history of quality control needs to be well described. The objective should be to ensure that a potential user knows and can rely on the quality assurance assigned to a product or data set. For complex products this can be a difficult task but is essential. One means of achieving better quality control is to establish a standardised method for calibrating sensors used in the Observing System.

The issue here is for data providers to describe adequately and in a uniform way the quality of their data and products, and to subscribe to a uniform standard of calibration procedures for sensors.

5. AWARENESS

There is a constant need to inform the relevant bodies at a national and international level of the importance of a sustained and systematic approach to ocean observations. Equally important is for the general public to be made aware of the benefits of understanding the processes that drive the ocean system, and of the need for ocean observations. 'Awareness' can take many forms but the issue is to create mechanisms to be able to reach communities outside the oceanographic world. All partners within IGOS have a role in this area, to develop an overall plan, and then keep each other informed of the activities undertaken.

The issues are first to create a means for keeping the IGOS partnership abreast of plans for the Observing System, and second, to publicise the activities and benefits of ocean observations to the general public.

6. CONCLUSION

This document has set out the overview of the observational requirements for the long-term observations of the oceans, and that need to be addressed within the next few years. It identifies a series of issues that the IGOS Partners need to address to build and maintain the existing commitments. Clearly these issues are subject to review and change but it is believed they presently provide the basis for setting realistic and achievable targets when viewed against the wide range of groups, institutions, and national entities who have set out their own specific needs.

The IGOS partners are invited to discuss the document and if it is agreed upon, decide how to address the issues raised.

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APPENDIX

Updated 04/20/00

OCEAN SATELLITE MISSION STATUS

AGENCY	**MISSIONS**	**LEAD AGENCY**	**CATEGORY (*)**
NASDA	ADEOS-II/SeaWinds	NASDA	1
NASDA	ADEOS-II/GLI	NASDA	1
NASDA	ADEOS-II/AMSR	NASDA	1
NASDA	ALOS/PALSAR	NASDA	1
NASDA	EOS-PM/AMSR-E	NASA	1
NASDA	GCOM-B1/AlphaSCAT	NASDA	4
NASDA	GCOM-B1/SGLI	NASDA	2
NASDA	GCOM-B1/AMSR F/O	NASDA	2
NASDA	POLDER-2	CNES	1
NOAA	GOES I,J,K,L;M	NOAA-NESDIS	1
NOAA	GOES N,O,P,Q	NOAA-NESDIS	1
NOAA	SEI (GOES Special Events Imager)	NOAA-NESDIS	3/4
NOAA	POES – K,L,M,N,N'	NOAA-NESDIS	1
NOAA	WindSat/Coriolis	U.S. Navy – Naval Research Laboratory	1
NOAA	DMSP (Defense Meteorological Satellite Program)	U.S. Air Force	1
NOAA	NPP (NPOESS Preparatory Project)	NOAA/NPOESS/Integrated Program Office	3
NOAA	NPOESS (National Polar-Orbiting Operational Environmental Satellite	NOAA/NPOESS/Integrated Program Office	1
NOAA	System	NASA/CNES	3
NOAA	JASON-2 (Altimeter)	NOAA on behalf of	3
NOAA	ARGO: A Global Array of Profiling Floats	NOPP	5
	Modelling Products		
EUMETSAT	MSG Series 1-3	EUMETSAT	1
EUMETSAT	EPS METOP	EUMETSAT	1
EUMETSAT	Jason-2	CNES/NASA	3
EUMETSAT	Relay (DPC)		
CNES	TOPEX/POSEIDON	CNES/NASA	1
CNES	Jason-1	CNES/NASA	1

(Cont'd)

CNES	Jason-2	CNES/NASA	3
CNES	Altika	CNES	4
CNES	Polder-2	CNES	1
CNES	Advanced Wide FOV	CNES	4
CNES	VAGSAT	CNES	2
CNES	ARGOS	CNES/CLS	1
CNES	SMOS	CNES/ESA	1
CNES	Modelling MERCATOR	CNES	5
CNES	Multimission (PAC + Ground Segment)	CNES	5
INPE	CBERS-2	CAST	1
INPE	SCD-3	INPE	2
INPE	CBERS-3	CAST	2
INPE	CBERS-4	CAST	2
INPE	CBERS-5	CAST	2
DLR	CHAMP	DLR	1
DLR	MAPP-MERIS Application and Regional Products Project	DLR	4
DLR	ISIS	DLR	5
DLR	GRACE	NASA	1
DLR	MOS on IRS-P3	DLR	1
DLR	EOWEB	DLR	5
NRSCC	HY-1 Chinese Ocean Color Satellite	CNSA (China National Space Administration)	1
NASA	TOPEX-POSEIDON	NASA/CNES	1
NASA	QuickSCAT	NASA	1
NASA	Aqua-MODIS	NASA	1
NASA	Terra-ASTER,CERES, MISR, MODIS, MOPITT	NASA	1
NASA	SeaWIFS	NASA	1
NASA	Radarsat 1	CSA	1
NASA	Jason-1	NASA/CNES	1
NASA	Follow-on Altimeter Mission (Jason-		3
NASA	2)	NASDA	1
NASA	Seawinds/ADEOS-2	NASDA	4
NASA	Follow-on Scatterometer (alphaScat)	NASA, NOAA	3
NASA	NPOESS Bridging Mission		1
NASA	ICESAT	NASA	1
NASA	GRACE	NASA	5
NASA	EOS Data Information System	NASA	5
NASA	(EOSDIS)	NASA	4

(Cont'd)

NASA NASA	Modelling/Data Assimilation Salinity Technical Demo TRMM GPM	NASA/NASDA NASA/NASDA	1 2
ESA ESA ESA ESA ESA	ERS-2 ENVISAT GOCE CRYOSAT SMOS	ESA ESA ESA ESA ESA	1 1 1 1 1
BNSC BNSC	Research Program on: Ice Thickness, Geoid retrieval Small satellite initiative: GANDER	 NERC NERC	 5 2
CSA CSA CSA	Radarsat 1 Radarsat 2 Products from SAR	CSA CSA CSA	1 1 5

(*) 1 = confirmation and timing of missions already planned; 2 = proposed missions using known technology; 3 = transitioning of research instruments/missions into operational; 4 = development of new technologies, products or missions; 5 = data and information systems