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Observing the Ocean from Space: Emerging Capabilities in Europe

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Abstract – *During the first decade of the 21st century Earth observation from satellites will be faced with two major demands: provision of continuity missions and launch of new exploratory missions. This paper addresses European plans for new Earth observations in the context of Ocean Observing System for Climate at the onset of this new millennium. It highlights three quantities: ice mass fluctuations, sea surface salinity and fine resolution marine geoid. Their relevance and importance for climate are briefly reviewed in connection with important processes such as, for example, thermohaline circulation, sea level change, and evolution of large scale salinity events. The associated satellite mission concepts approved by ESA are then presented in light of their objectives, scientific observation requirements and degree of complementarity and synergy with other relevant missions.*

Introduction

During the first decade of this millennium, relatively long time series (in some cases almost 30 years) of satellite-derived quantities (including sea surface temperature, ocean wave field, near-surface wind, ocean colour, sea surface topography and sea ice extent, types and concentration) will become available. As an essential element of integrated ocean observing systems (in combination with an *in situ* data collection system and model tools), the need for continuous access to calibrated and corrected satellite data is indisputable. The challenge is, however, to ensure the continuity of existing Earth observation data while at the same time developing new observation techniques.

Three geophysical quantities that in different ways are relevant for important processes within the fields of cryosphere and oceanography will be highlighted in this paper, namely:

- the ice mass fluctuations;
- sea surface salinity; and
- the marine geoid (and steady-state ocean circulation).

So far none of these quantities has been adequately observed from satellite. It is generally agreed that the lack of these observations inhibits the development of scientific interpretation and understanding of basic processes that contribute to the ocean circulation and the effects of the ocean at seasonal to multi-decadal climate change.

In this paper some of the major scientific questions at stake will be reviewed regarding these three quantities followed by a consideration of the associated candidate satellite mission concepts.

Scientific questions

In Table 1 some of the important processes and interactions occurring in the ocean are listed in the context of the three quantities mentioned above.

By gaining new and advanced understanding of these quantities and their associated contribution to the processes listed in Table 1, opportunities for improved seasonal to interannual climate predictions are created. This is further elaborated in the next three sections..

Observing the Oceans in the 21st Century, C.J. Koblinsky and N.R. Smith (Eds), GODAE Project Office and Bureau of Meteorology, Melbourne.

Table 1. Connection between the three geophysical quantities and oceanic processes that in different ways are contributing to the climate.

Processes	**Parameters**		
	Ice mass	**Ocean salinity**	**Marine geoid***
Thermohaline circulation	X	X	X
Sea level change			
	X	(X)	X
Air–sea–iceinteraction (+ albedo effect)	X		
Evaporation minus precipitation		X	
Mass and heattransport		X	X
Large-scale frontal dynamics		X	X
Evolution of large-scale salinity event	X	X	

*Note: We are mostly considering the marine geoid in support of radar altimetry.

Sea ice mass fluctuations

The cryosphere has a central role in the Earth's radiation budget imposed by the large albedo due to the presence of ice and snow. In the context of the greenhouse effect loss of sea ice is predicted to cause a larger warming in the Arctic than elsewhere on the Earth, whereas uncertainty in ice sheet and glacier mass balances are the largest error sources on present sea level change (Wingham, et al., 1999). Moreover, thermohaline circulation and deepwater formation are affected by changes in sea ice and ice sheet masses.

Trends in the supply of freshwater from the cryosphere may profoundly affect the characteristics and strength of this thermohaline circulation. Recent analyses have established reductions in the Arctic sea ice extent of about 3% per decade since 1978 (Bjørgo et al., 1997) whereas (Østerhus et al., 1999) have reported a decreasing trend in overflow of cold (less than 3°C) water from the Greenland–Iceland–Norwegian seas to the North Atlantic. In cases when the surface water at high latitudes is replaced by fresher water supplied through sea ice and ice sheet melting, the deep water formation can be reduced or prevented (Aagaard, 1994). Moreover, coupled ocean–atmosphere models show a decline in the Northern Hemisphere poleward transport in response to increased freshwater supply (Manabe and Stouffer, 1988) and/or greatly increased latitudinal variability (Weaver and Sarachik, 1991). Such changes in the present state of the thermohaline circulation pattern are expected to have the greatest impact on areas such as Europe. However, as the current trends in ice mass changes are far from accurately known, the corresponding freshwater fluxes and their quantitative importance for thermohaline circulation cannot be properly estimated and accounted for in climate models.

Episodical changes in the freshwater and heat fluxes in the Southern Hemisphere are also known to take place. The formation of the Weddell Sea Polyna in the mid-seventies (Zwally et al., 1983) and the collapses of the Antarctic Peninsula ice shelves (Rott et al., 1996) are recent examples. Little is known of the variability and frequency of occurrence of these episodic events, and their consequences on the thermohaline circulation is far from entirely understood It is a challenge to come up with a full explanation for the changes that has taken place in sea level rise in the 20th century since a number of competing geophysical processes, each of which is a complex process in itself, are contributing. Among these are interior Earth tectonics, the redistribution of water from ice sheet and glacier retreat, the rebound of the lithosphere and mantle and the effect of these on the Earth's gravity field, the thermal expansion of the oceans, the extraction of ground water, and changes in coastal sedimentation and erosion. The largest potential source is, nonetheless, the cryosphere. The rise in the 20th century corresponds to approximately 0.2% of the Antarctic Ice Sheet mass. However, little is known about the magnitudes of fluctuations in the ice sheets on this timescale. In comparison, it appears that glacier retreat in Europe and North America may explain 4 cm of the present rise (Meier, 1984), whereas the thermal expansion of the ocean associated with global warming is also estimated to have contributed perhaps 4 cm this century.

Predicting future sea level change depends on better knowledge of fluctuations in marine and land ice mass fluxes. Present observations are deficient in time and space. Satellite observations are the unique source of these measurements at large space and time scales.

Sea surface salinity

The distribution of salt in the global ocean and its annual as well as interannual variability are crucial in understanding the role of the ocean in the climate system. *in situ* salinity measurements are only sparsely distributed over the oceans. In fact, 1° x 1° boxes distributed over the global oceans show that for only about 70% of them do salinity measurements exist at all (Levitus and Boyer, 1994). A far smaller fraction of such areas has been monitored more than once. This means that the average structures of the ocean salinity field are known to some extent, but details about its variability even on seasonal and interannual scales remain hidden. Consequently the scientific design plan for the Global Ocean Observing System states:

> *The improvement of the ocean salinity data base must have high priority since it is an important constraint in ocean models, an indicator of freshwater capping, and may have predictive uses in the tracking of high latitude salinity anomalies that could affect the thermohaline circulation and the regional climate.*

The joint Argo profiling float program (see Argo Science Team, this volume) and sea surface salinity satellite mission are focused on this priority.

Knowledge of salinity distribution is also necessary to determine the equation of state. For the calculation of dynamic height anomalies the salinity distribution must be known. For instance, when calculating geostrophic currents using satellite altimetric measurements, better knowledge of the ocean salinity structure would improve the accuracy of the estimates (e.g. a 0.5 psu error in sea surface salinity (SSS) accounts for 3.8 cm/s error in geostrophic velocity at 1 km depth calculated from the corresponding surface value).

The need, importance and requirements for SSS observations can be further substantiated (Delcroix and Hénin, 1991; Donguy, 1994; Drange et al., 1999; and Lagerloef and Delcroix, this volume). The SSS varies as a result of exchange of water between the ocean and the atmosphere, via sea ice freezing and melting, and from continental runoff. Salt affects the thermohaline circulation and therefore the distribution of mass and heat. Salinity may control the formation of water masses, which allows its use for tracer studies. Salinity is also thermodynamically important as salinity stratification can influence the penetration depth of convection at high latitudes and may determine the mixed layer depth in equatorial regions.

Positive surface temperature anomalies in the North Atlantic are suggested to be associated with anomalously strong thermohaline circulation (Timmermann et al., 1998). It is possible that the atmospheric response to this is an enhanced North Atlantic Oscillation (NAO). Occasionally a strong NAO, in turn, leads to anomalous freshwater fluxes off Newfoundland and in the Greenland Sea. The resulting surface salinity anomalies are advected by the sub-polar gyre and finally reach the convectively active region south of Greenland (Belkin et al., 1998). The weakening in deep water formation and subsequent change in thermohaline circulation may reduce the poleward oceanic transport which in turn forms negative surface temperature anomalies. The duration of this cycle is roughly 35 years. Whether such a cyclic process was associated with the formation of the observed great salinity anomalies in the North Atlantic during the 1970s is not yet clear.

In tropical areas salinity is useful as an indicator of precipitation and evaporation, thus it plays an important role in studies of surface fresh-water fluxes. For example, during heavy rainfall, freshwater lenses are produced on the ocean surface, which are stable features. They mix slowly with the bulk sea water and can persist from hours to weeks depending on the wind speed conditions. Heavy rainfall such as typically encountered in the tropics can cause a drop in surface salinity of 7 psu for short periods and still be 4 psu in hourly averages (Paulson and Lagerloef, 1993). The area coverage of single freshwater lenses is of the order 50–100 km, depending on the size and lifetime of the convective rain cell as well as their horizontal displacement with time. Their role in the formation and maintenance of barrier layers and mixed layer thermodynamics is far from fully understood. The role of salinity and its change by freshwater fluxes at the atmosphere–ocean interface have also to be included for a full understanding of the entire ENSO process (Lukas and Lindstrom, 1991).

Sea surface salinity has not been observed from space so far (except for the very short duration of the *Skylab* experiment in the early 1970s). Such space observations would be very welcome as the current knowledge of SSS is rather poor and insufficient to account for the role of salinity in the ocean climate system.

Marine geoid and steady-state ocean circulation

In the current climate state, the ocean circulation is responsible for half of the poleward heat transport, the other half being contributed by the atmosphere (Peixoto et al., 1992). By the time the warm water from the Gulf Stream has reached northern Europe and the Nordic Seas, the surface water has given up much of its heat to the atmosphere and can subsequently become dense enough to sink through convective overturning and thus maintain the thermohaline circulation pattern. This process is takes place during the winter season. However, quantitative knowledge and estimates are incomplete, and predictions of how such poleward heat transport and fluxes through the air–sea interface would be modified by enhanced greenhouse forcing are even coarser.

While variations of the sea level and thus of the ocean currents can be derived directly from satellite altimeter data, the absolute value of the ocean dynamic topography, and hence the absolute surface circulation, requires the independent determination of what would be the elevation of an ocean at rest, that is the geoid. The latter is not known at present with sufficient precision. The typical elevation scale of the dynamic topography is of the order of 0.1–1 m, while the precision of present geoid models is on the scale of many ocean circulation features.

With current altimetric missions (such as TOPEX/POSEIDON, ERS-1 and ERS-2) providing such effective measurements of ocean circulation variability, and with future missions (JASON, ENVISAT) likely to continue the measurements well into the next century, it is reasonable to ask why oceanographers need to know the mean circulation itself to such spatial detail. There are several reasons, as thoroughly discussed in ESA (1999).

First, modelled and real oceans undoubtedly contain short spatial-scale components of mean flows. It is important to be able to measure the locations and magnitudes of such short-scale features by means of altimetry and gravity, to compare them to information from conventional hydrography, to understand their relationships to bathymetry and other controlling factors, and to assess their importance for oceanic mass and heat flux estimation. It is known that it is through mean flows as well as variabilities (e.g. eddies) that the ocean transports its heat, fresh water and dissolved species and through which it controls climate, and the aggregated short-scale mean flows could prove to be of importance to climate.

Second, it is through instabilities in the mean flows that the ocean generates eddies and that it is possible to generate different degrees of variability in different numerical models depending on the mean flows programmed into them, and on the way in which the factors controlling the means are parameterized (e.g. interactions with bathymetry). Consequently, in dealing with non-linear processes, and in studying transient perturbations of the system, it is essential to start from as good a description as possible. This was essentially the motivation for the WOCE 'decadal snapshot' of the ocean, to provide a data set on which models might be based with potential for predictive capability.

Third, it is clear that data assimilation schemes for 'ocean forecasting' have reached a stage of development wherein optimal use of altimetric variability information can be achieved as long as the mean ocean state (i.e. the absolute ocean circulation) can be parameterized. In this case, the dynamic topography obtained from the mean sea surface height minus geoid acts as a powerful model constraint on the assimilation of inevitably noisy altimeter variability information, providing a window on ocean processes at depth.

Fourth, knowledge of the short spatial-scale geoid will be essential to computations of fluxes through basin-size oceanic sections, again by providing model constraints to the assimilation of other information (altimetry, hydrography), which will contain measurement uncertainties.

Therefore, it is clear that understanding the mean and the variability of the ocean circulation must go hand-in-hand, particularly with regard to the construction of a next generation of numerical ocean models with the potential for a better description of the role of the ocean in the global climate system. Dedicated satellite gravity field missions will be essential elements in the establishment of such improved understanding.

Satellite mission concepts

The present technology, including use of remote sensing by satellites and a large array of *in situ* measurements (many of which are expendable) as well as the existence of models for climate change prediction and analysis, makes the implementation of a truly global ocean observing system feasible now. But further development is necessary and this relies heavily on more complete and more accurate data sets.

The need to explore new Earth observation capabilities aimed at bringing new scientific data has been elaborated in ESA's Earth Explorer Programme (ESA, 1998) composed of the Opportunity Mission and the Core Mission elements. This program has been drawn up following extensive consultation with the Earth Observation community. It is intended to reflect not only their ideas and aspirations but also to be a response to concerns about climate change and man's impact on it. Likewise, the US Earth Observing System (EOS) Science Plan (EOS, 1999) draws the attention to major scientific issues of concern in the context of climate change derived from several years of discussion and debate among the EOS scientific investigators. Additional and complementary views and plans for Earth observations regarding global climate change are implemented among other space agencies including CNES, NASDA, ISRO and EUMETSAT, and also addressed in the Ocean Theme for the IGOS Partnership (IGOS, 2000).

The geophysical quantities highlighted above are considered by three candidate mission of ESA's Earth Explorer Programme.

- The Opportunity mission CryoSat will observe fluctuations of ice masses on land and in the ocean.
- The Opportunity mission SMOS (Soil Moisture and Ocean Salinity) will provide for the first time spaceborne observations of the sea surface salinity (as well as soil moisture over land).
- The Core mission GOCE (Gravity Field and Steady-State Ocean Circulation) will give new knowledge of the marine geoid with high accuracy and fine spatial resolution.

The objectives and mission concepts for each of these missions are briefly summarized below. (On the website http://www.estec.esa.nl/explorer/ it is possible to obtain regular updates about the evolution of these three missions.) They are complemented by NASA's plans for the Ice, Clouds and Land Elevation Satellite (ICESat) mission, the joint NASA/DLR Gravity Recovery and Climate Experiment (GRACE) mission and also to some extent by the ongoing joint NASA/NASDA Tropical Rainfall-Measuring Mission (TRMM) and its planned follow-on Global Precipitation Mission (GPM).

Sea ice mass fluctuations

The primary goal of the CryoSat mission is to estimate trends in the ice masses of the Earth. This will be achieved by measuring the change in sea ice and ice sheet thickness with a radar altimeter using interferometric and synthetic aperture techniques for resolution enhancement. Of principal importance is the need to determine:

- the regional and basin-scale trends in perennial Arctic sea ice thickness and mass due to global warming; and
- the regional and total contributions to global sea level of the Antarctic and Greenland Ice Sheets.

These objectives are relevant and important to the Climate Variability and Predictability Program (CLIVAR) and the Arctic Climate System Study (ACSYS).

Three operating modes of CryoSat are foreseen: synthetic aperture operation for sea ice with an along-track sampling interval of 300 m, conventional pulse-limited operation for ice sheet interior (and ocean if desired), and dual-channel synthetic aperture/interferometric operation for ice sheet margins (interferometer baseline of 1 m). An illustration of the satellite is shown in Fig. 1.

The CryoSat mission (Wingham et al., 1999) will determine trends in ice mass through repeated measurements of ice thickness during its mission lifetime of about 3 years. A residual uncertainty in the mass and thickness trends of sea ice and land ice will remain at the end of the mission. The scientific requirements of the mission specify the magnitude of this residual uncertainty. It cannot be smaller than the natural variability in thickness. The task is to characterize the natural variability of thickness followed by determination of the measurement accuracy, which makes the residual uncertainty close to the natural variability. This is the required measurement accuracy. These considerations have led to the following science and measurement requirements (see Table 2).

Table 2. The Cryosat science and measurements requirements specified for different characteristics spatial scales over sea ice and ice sheets.

Requirement	**Arctic sea ice 10^5 km^2**	**Ice sheets 10^4 km^2**	**Ice sheets 13.8 x 10^6 km^2**
Residual uncertainty	3.5 cm/year	8.3 cm/year	1 cm/year (i.e 130 Gt/year)
Measurement accuracy	1.6 cm/year	3.3 cm/year	0.7 cm/year

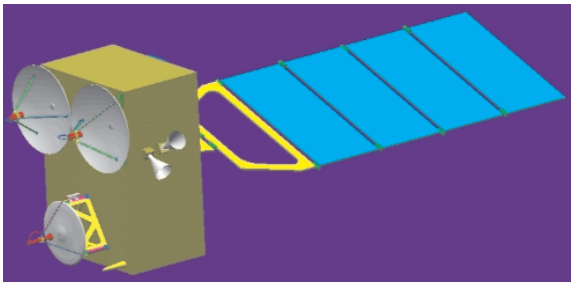

Figure 1. CryoSat satellite configuration.

The CryoSat technical development passed the system design review in February 2001 and is proceeding in compliance with a launch in late 2003. CryoSat will provide nearly complete and continuous coverage of the cryosphere, but is limited in its resolution. The US ICESat mission planned for launch in 2001 is of particular complementary importance to CryoSat. ICESat aims to provide details of the sea ice and land ice roughness spectrum by using a fine resolution (100 m scale) laser altimeter technique. The limits imposed by cloud cover (in the Polar regions typically ranging from 50% to 90%) will reduce sea ice thickness measurements and change measurements at fixed ice sheet locations. With a launch date in late 2003, combination of the CryoSat radar altimeter and the ICESat laser altimeter data is foreseen.

Sea surface salinity

The primary scientific objectives of the ocean salinity observations provided by the SMOS opportunity mission are, inter alia, to:

- improve seasonal to inter-annual climate predictions by effective use of SSS data to initialize and improve the coupled climate forecast models;
- improve oceanic rainfall estimates and global hydrologic budgets via the new and improved knowledge of the SSS variability;
- monitor large-scale salinity events.

These objectives are particularly relevant for the major international ocean programs and their observing system and experiments planned for the next 5–7 years including the Global Ocean Observing System (GOOS), CLIVAR, the Global Ocean Data Assimilation Experiment (GODAE), and the Global Climate Observing System (GCOS), which is established to coordinate the provision of data for climate monitoring, climate change detection and response monitoring. Moreover, the provision of SSS nicely complements the thermohaline structure observed with the Argo profiling floats (Argo Science Team, this volume). Additional value of SSS data from remote sensing is realized by obtaining better information on the spatial gradients, particularly along-track, and by better space–time resolution over and above that obtained by *in situ* systems such as Argo.

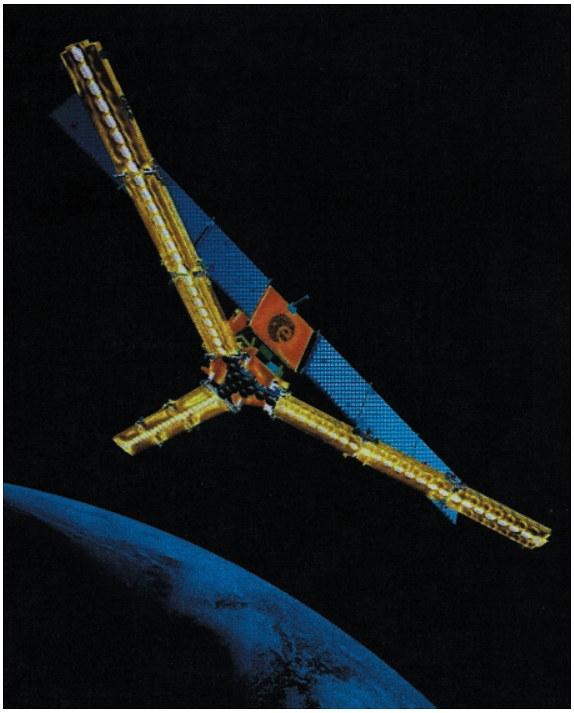

Figure 2. Artistic view of the SMOS satellite with the three-legged (4.5 m) passive microwave L-band antenna (Kerr et al., 1999)

The spatial resolution requirements for spaceborne passive microwave imaging of ocean salinity (and soil moisture) at L-band (= 21 cm) lead to large antenna apertures such as proposed by the two dimensional interferometric approach for the Microwave Imaging Radiometer Aperture Synthesis (MIRAS) instrument (Martin-Neira and Goutoule, 1997; Kerr et al., 1999). This approach uses a Y-shaped antenna (each arm about 4.5 m long) with equally spaced antenna elements for redundant spacing calibration (Fig. 2). The structure exhibits many advantages in terms of ground resolution and can be accommodated on board a satellite. This instrument will be tilted by 20°–30° with respect to nadir ensuring an incidence angle range from 0° to 50°. The spatial resolution will be 35 km within the central part of field of view with a swath of about 1000 km.

The sensitivity of L-band (1.4 GHz) passive microwave radiometer measurements of oceanic brightness temperature to SSS is well established (Lagerloef et al., 1995). However, the sensitivity is a function of the sea surface temperature (SST) decreasing from 0.5 K/psu in 20°C water to 0.25 K/psu for an SST of 0°C (Skou, 1995; Lagerloef et al., 1995). Hence, strong demands are put on the SSS retrievals from space in polar and sub-polar regions where the water masses are very sensitive to small changes in SSS (below 0.1 psu). Other oceanic factors which will influence the brightness temperature retrievals at L-band are surface roughness (wind speed and direction) and foam. Precise estimates for the uncertainties associated with these features are required in order to obtain sufficiently accurate SSS retrievals from SMOS, in particular since this opportunity mission will not carry a second, higher frequency, antenna.

The characteristics of the surface salinity variability and its effects on the ocean show large regional differences from the equatorial and tropical region via the mid-latitudes to the high latitudes. An overview of these characteristics in terms of required retrieval accuracy and corresponding resolution for the sea surface salinity measurements is given in Table 3.

In general, temporal and spatial averaging improves the retrieval accuracy as long as excellent stability and calibration of the radiometer is ensured (Kerr et al., 1999). From Table 3 it follows that an accuracy of 0.1–0.2 psu over a distance of 100–200 km for an averaged sampling time of about a week to a month is adequate for description and quantification of many central ocean processes. As such it will satisfy the requirement given for SSS measurements in the context of the Global Ocean Data Assimilation Experiment (GODAE; http://www.bom.gov.au/GODAE/). Further scientific support studies initiated by ESA are currently underway. These studies explore the salinity variability indicated in Table 3 in the context of more refined observation requirements.The technical developments related to SMOS are progressing as planned, and system definitions support studies and end-to-end performance simulation studies have recently been initiated. The mission duration is planned for a minimum of 3 years in order to cover two complete seasonal cycles, with a candidate launch date in 2005. Complementarity and synergy with other operating passive and active microwave system are foreseen and in particular it will provide extremely valuable data for constraining the evaporation minus precipitation budget over the tropical oceans provided a TRMM follow-on such as GPM is flown simultaneously.

Marine geoid and steady-state ocean circulation

The scientific objectives of the GOCE Mission are based on the unique measurements by the gravity gradiometer to provide an accurate and detailed global model of the Earth's gravity field and geoid (ESA,1999). This model will, in turn, serve the following multi-disciplinary scientific objectives:

- to provide new understanding of the physics of the Earth's interior including geodynamics associated with the lithosphere, mantle composition and rheology, uplifting and subduction processes;
- to provide, for the first time, a precise estimate of the marine geoid, needed for the quantitative determination, in combination with satellite altimetry, of absolute ocean currents and their transport of heat and other properties;
- to provide estimates of the thickness of the polar ice sheets through combination of bedrock topography derived from space gravity and ice sheet surface topography;
- to provide a better global height reference system for datum connection which can serve as a reference surface for the study of topographic processes, including the evolution of ice sheets and land surface topography.

Table 3. Overview of sea surface salinity variability for given areas and processes together with the characteristic temporal and spatial scales as well as retrieval accuracy (Drange et al., 1999)

Area and process	Accuracy	Horizontal resolution	Temporal resolution
Coastal processes	1 psu	20 km	1–10 days
ENSO	0.1 psu	100 km	1 month
Tropical Circulation (buoyancy driven)	0.3 psu	50 km	1–3 days
High latitude fronts/eddies	0.2 psu	50–100 km	10 days
Freshwater lenses	0.1–1.0 psu	50 km	1–10 days
Great salinity anomalies	0.1 psu	100 km	1–6 months

The oceanic objective fits well within the goals of CLIVAR under the World Climate Research Programme, the Global Climate Observing System (GCOS) and GOOS under the joint Intergovernmental Oceanographic Commission (IOC) and World Meteorological Organization (WMO). In addition the implementation and execution of the Argo array of profiling floats will provide a significant complement to the GOCE mission in combination with altimetric missions.

The GOCE mission has been conceived and designed taking into account scientific requirements and technological solutions, to provide the most accurate, global and high resolution map of the gravity field and its corresponding geoid surface. It will combine the satellite gradiometry and satellite-to-satellite high–low tracking (SST-hl) techniques (Fig. 3), which have been found to be optimal for providing the required high quality, high resolution static gravity field. To ensure the global completeness of the derived gravity model, which also impacts on its accuracy, a quasi-polar orbit must be chosen. The mission duration is planned for about 20 months with candidate launch date in 2005.

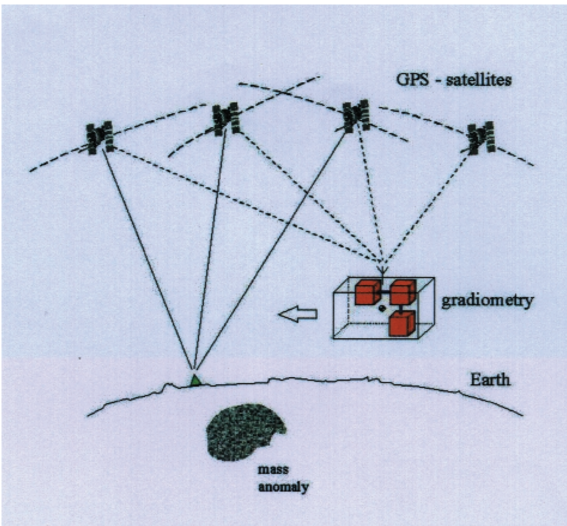

Figure 3. Schematic illustration of the principles of combined satellite gradiometry and satellite-to-satellite tracking in high–low configuration (ESA, 1999). *As for Table 1 we are mostly considering the marine geoid in support of radar altimetry.

The quantitative requirements for the different scientific goals are derived in terms of geoid height and gravity anomaly accuracies and linked to the corresponding spatial resolution to which they apply (expressed in half wavelength). Specifically, in the context of meeting the scientific objectives addressed under oceanography, notably absolute ocean circulation, the key requirements are to :

- determine (from the measured gravity anomaly field) the geoid with an accuracy better than 1 cm radially; and
- achieve these measurements at a length scale of 100 km or less.

These requirements are also relevant to studies of sea level change as explained in ESA (1999). The technical development of the space segment is proceeding well, and the recent outcome of a comprehensive end-to-end performance study (Sünkel et al., 2000) shows excellent results with regards to the scientific observation requirements.

Recent simulation studies (LeGrand and Minster, 1999; Le Provost et al., 1999) show that the accurate knowledge of the marine geoid provided by GOCE can lead to significant reduction in ocean transport uncertainties, notably in the upper ocean. Using the present day EGM96 gravity model to produce the reference geoid error variance they report on reductions being as large as 30–50% for selected sections in the South and North Atlantic, and reaching up to 60% in narrow and intense current paths. In absolute terms, this is typically in the range of 1–4 Sv with maximum exceeding 10 Sv.

GOCE does not need data from other missions to achieve its primary goals. However, its complementarity with GRACE has been evaluated by Balmino et al. (1998). GRACE will be the first gravity field mission using the principal of satellite-to-satellite low-low tracking (SST-ll). It will improve the accuracy of the spherical harmonic coefficients at the long and medium spatial scales (<~500 km) by up to three orders of magnitude. This will allow measurement of the temporal variations in the gravity field to be recovered at 30–90 days interval over a period of about 5 years (planned to begin in 2001). Over the ocean this means that bottom pressure variations can be derived at a typical horizontal scale of 1000 km whereas changes in the ice masses can be studied over Antarctica and Greenland Ice Sheets. The aim (and challenge) is then to convert these sea floor pressure variations to changes in global ocean circulation.

Conclusion

During this decade, Earth observation from satellites, as an integral part of the global ocean observing system for climate, will be faced with two major requirements, namely: operation of 'continuity' (operational) missions, and launch of new exploratory missions. In this paper we have briefly reviewed the latter type of missions, which are research driven, in regards to three geophysical quantities, i.e. ice mass fluctuations, sea surface salinity, and fine resolution and accurate marine geoid, which so far have not been adequately observed from space. The recommendations for these three mission concepts have been derived in close cooperation with the scientific user communities, and the level of complementarity is also quite good as shown in Table 4.

However, it must be emphasized that the overall long term design criteria of the ocean observing system for climate, as expressed by the Oceans Observation System Development Panel (OOSDP) is:

> *to monitor, describe and understand the physical and biogeochemical processes that determine ocean circulation and the effects of the ocean on seasonal to decadal climate change, and to provide the observations necessary for climate predictions.*

A critical factor in this sense is the requirement for long-term measurements, both *in situ* and from satellite. No space agency by itself can ensure to meet such a continuity requirement. International cooperation in implementation and operation of key missions is therefore highly necessary. This will also avoid duplication and ensure complementarity, and should lead to significant reductions in the costs of each agency in addressing the objectives of the ocean observing system for climate.

We think it would be useful to distinguish the nature of geoid measurements. GOCE is an example of an exploratory remote-sensing

Table 4. Connection between the three geophysical quantities, the oceanic processes and the candidate satellite missions.

Processes	**Parameters**		
	Ice mass	**Ocean salinity**	**Marine geoid***
Thermohaline circulation	ICESat, CryoSat	SMOS	GOCE, (GRACE)
Sea level change	ICESat, CryoSat, GRACE, GOCE		GOCE
Air-sea-ice interaction (+ albedo effect)	ICESat, CryoSat		
Evaporation minus precipitation		SMOS, + TRMM follow-on	
Mass and heat transport		(SMOS)	GOCE, (GRACE)
Large-scale frontal dynamics		SMOS	GOCE
Evolution of large-scale salinity event	(ICESat, CryoSat)	SMOS, +TRMM follow-on	

*Note: We are mostly considering the marine geoid in support of radar altimetry.

with a fixed lifetime, but with potential lasting benefits for the long-term observing system (topography measurements have a similar role).

Future plans and implementation of new Earth Observation satellite missions must also maintain a degree of flexibility to ensure optimum adjustment and complementarity with development and improvements of models and their subsequent need for data. The same is valid vis-à-vis technology development for *in situ* instruments, for which there have been significant advances in autonomous expendable system and unmanned observing vehicles that return data via telemetry. The deployment of up to 3000 profiling Argo floats within the timeframe of 2005 is one such example of a new and powerful element of a comprehensive international system for observing the global ocean. In the Conference Statement it is argued that these data, in combination with complementary ocean topography observations derived from satellite radar altimetry and new improved spaceborne estimates of the marine geoid and ocean surface salinity, will be very important for ocean prediction and seasonal-to-interannual climate applications.

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