The Soil Moisture and Ocean Salinity Mission - SMOS

Yann H. Kerr (1), Jordi Font (2), Philippe Waldteufel (3) and Michael Berger (4)

(1) CESBIO, Toulouse, France, (2) ICM-CSIC, Barcelona, Spain
(3) IPSL-CETP, Velizy, France, (4) ESA-ESTEC, Noordwijk, The Netherlands

Following the scientific advice of the Earth Science Advisory Committee late May 1999, the Soil Moisture and Ocean Salinity Mission (SMOS) was selected for implementation as the second Earth Explorer Opportunity mission. SMOS has broad and ambitious scientific objectives based on innovative and proved concepts. It will exploit an L-band 2-D interferometer to observe and monitor two crucial variables of the Earth climate system: soil moisture over land and ocean salinity over oceans. Significant advances in the research fields of the cryosphere are also expected. It is the scope of this article to outline the mission objectives and the derived scientific and mission requirements of the SMOS mission planned for launch in 2005.

Human activities seem to have a significant influence on the climate of our planet and public awareness of possible climate changes has increased in the last few years. The scientific community thus faces a challenging task answering the most pressing questions:

Is the climate actually changing and, if yes, what is the rate and, more importantly, what will be the consequences, particularly with respect to the frequency of occurrence of extreme events?

To address these questions, it is necessary to develop reliable models to predict the future evolution of the climate and to forecast extreme events.

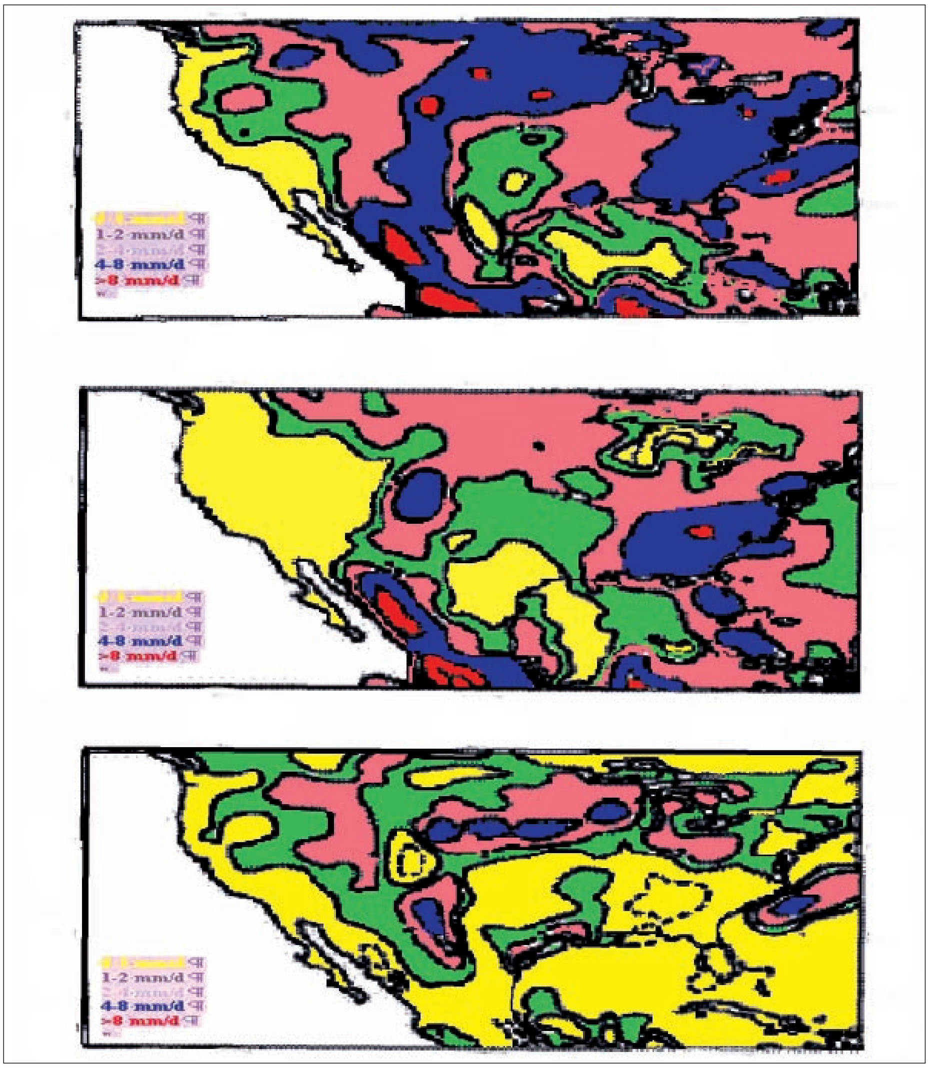

Figure 1: Impact of different soil moisture levels on the precipitation over North America (from [Beljaars et al., 1996]): Rainfall amounts obtained from two simulations with a wet and a dry surface. The difference between the two outputs is shown in the bottom map. This simulation shows the drastic impact of soil wetness on the predicted rainfall pattern.

Significant progress has been made in terms of weather forecasting, climate monitoring and extreme event forecasting during recent years, using sophisticated models fed amongst other things by data acquired with operational satellites and analysed using super-computers. However, as recently pointed out by working groups and in workshop reports, further improvements now depend to a large extent on the availability of global observations of two crucial variables, Soil Moisture (SM) and Sea Surface Salinity (SSS). To date this information is lacking because *in situ* measurements are far from global, and so far no dedicated, long-term, SM and SSS space mission has been attempted.

This led to the formulation of the *S*oil *M*oisture and *O*cean *S*alinity (*SMOS*) mission, the European Space Agency's second Earth Explorer Opportunity Mission planned for launch in 2005. The SMOS mission was proposed by a team of scientists from 10 European countries and the USA, bringing together most of the available expertise in the related fields (see <*http://www-sv.cict.fr/cesbio/smos/*>).

The main objective of the SMOS mission is to demonstrate the observation from space of SSS over oceans and SM over land, in order to advance climatological, meteorological, hydrological and oceanographical science. In addition, the SMOS mission should also lead to significant advances in the research fields related to the cryosphere, by improving the assessment of the snow mantle and of the multi-layered ice structures.

Scientific Rationale for the Observation of Soil Moisture

Over land, water and energy fluxes at the surface/atmosphere interface are strongly dependent upon SM. Evaporation, infiltration and runoff are driven by it. It also regulates the rate of water uptake by vegetation in the vadose zone. SM is thus a key variable in the hydrologic cycle. SM, and its spatio-temporal evolution, is an important variable for numerical weather and climate models, and should be considered in hydrology and for vegetation monitoring.

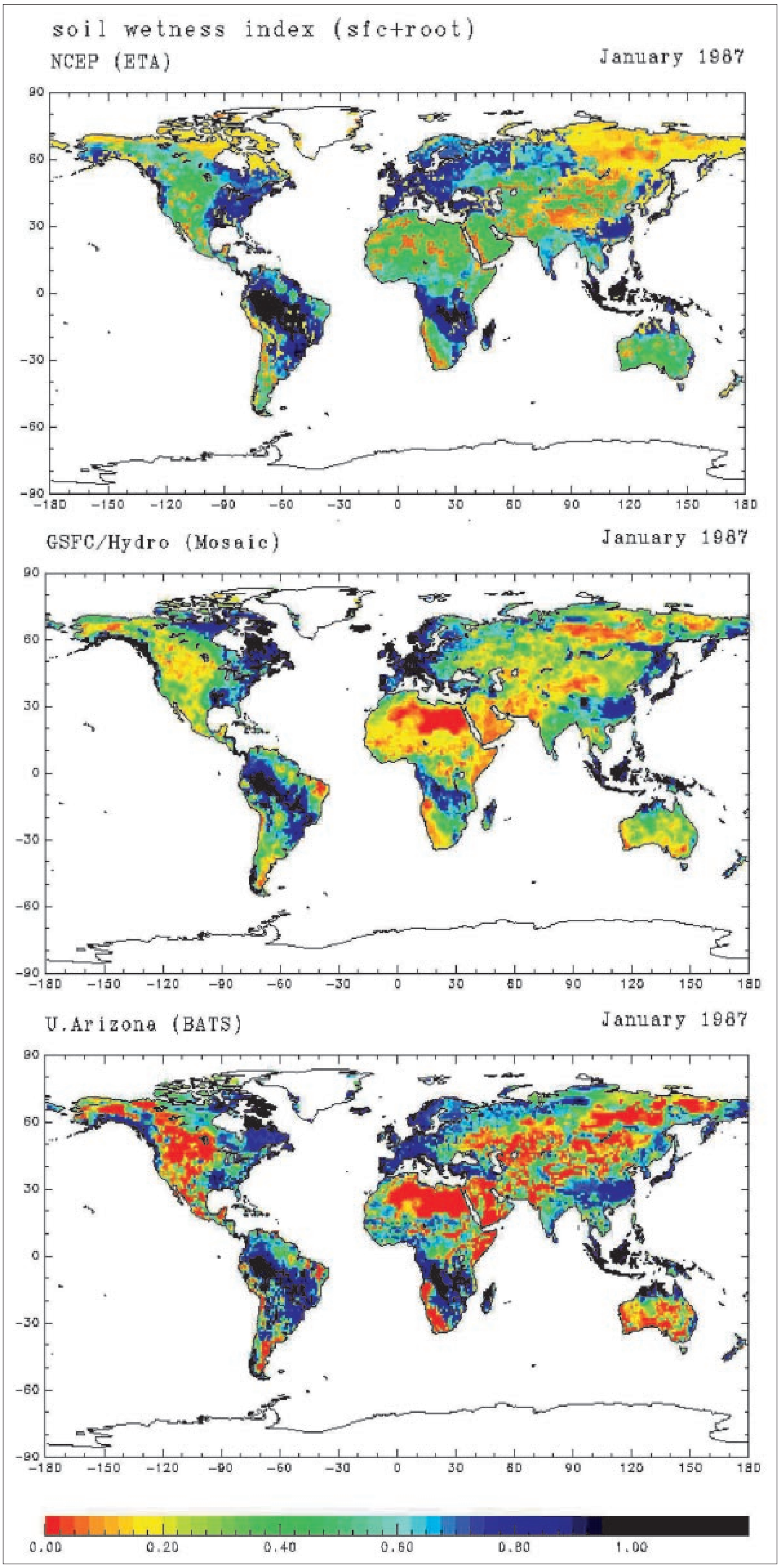

Figure 2: Illustration of the need for soil moisture measurements: Soil moisture fields obtained with three different models (GCM) for the same conditions. The analysis shows the discrepancies, highlighting the need for actual estimates of soil moisture (courtesy E.G. Njoku)

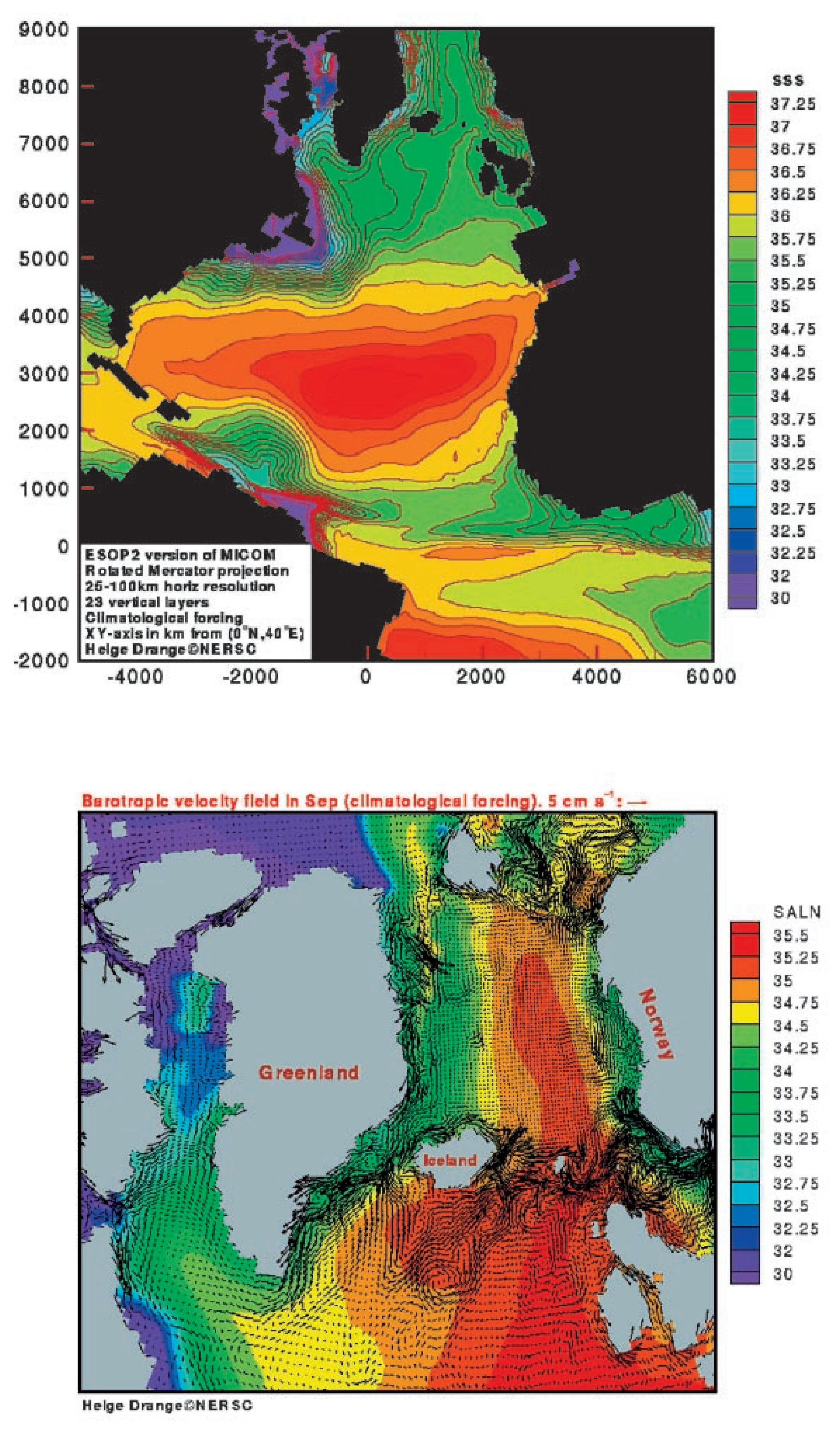

Figure 3: Illustration of the need for SSS fields: a) Simulated SSS distribution in the North Atlantic by an Ocean Circulation Model. b) Difference of surface salinity when the model is used without monthly relaxation to SSS climatological fields. The figures illustrate the model used to assess the ocean dynamic and thermodynamic response to constructed SSS fields. It also indicates the spatial resolution and accuracy of remotely sensed SSS fields required for a basin scale climate model (from [Drange et al., 1999]).

Of all the lower boundary conditions that drive the atmosphere, land-surfaces are of particular interest, as their state and changes are of direct importance to human activities. Describing and characterising land-surfaces for meteorological and climatological applications is challenging, because they are very variable over a broad range of temporal and spatial scales. Diurnal variations of temperatures and fluxes are one order of magnitude larger than over the ocean. Another specificity is that moisture for evaporation, while available in limited supplies, constitutes at the same time a memory for the system. In other words the temporal evolution of the soil moisture after rain depends, amongst other things, on the soil moisture present before the rain.

The surface hydrology is one of the keys to our understanding of the interaction between continental surfaces and the atmosphere. It determines the partitioning of energy between different fluxes. The science issues considered here relate to the parameterisation of land surface processes, in order to improve the representation in mesoscale and global models of surface fluxes, soil moisture content, soil hydraulic characteristics and plant stress. The initialisation of soil moisture in atmospheric (including numerical weather forecast) models is of great concern and a subject of active research. The current methods of estimating soil moisture are indirect and new methods, with global coverage, for inferring soil moisture are needed.

For watershed hydrologic model applications, there is an urgent need to have regular access to distributed soil water fluxes over large areas. The yearly integrated land surface and base flow water budgets are generally well predicted by the latest generation of hydrologic models. However, the estimation of the ratio between base flow and surface run-off, as well as the ratio between deep drainage and soil

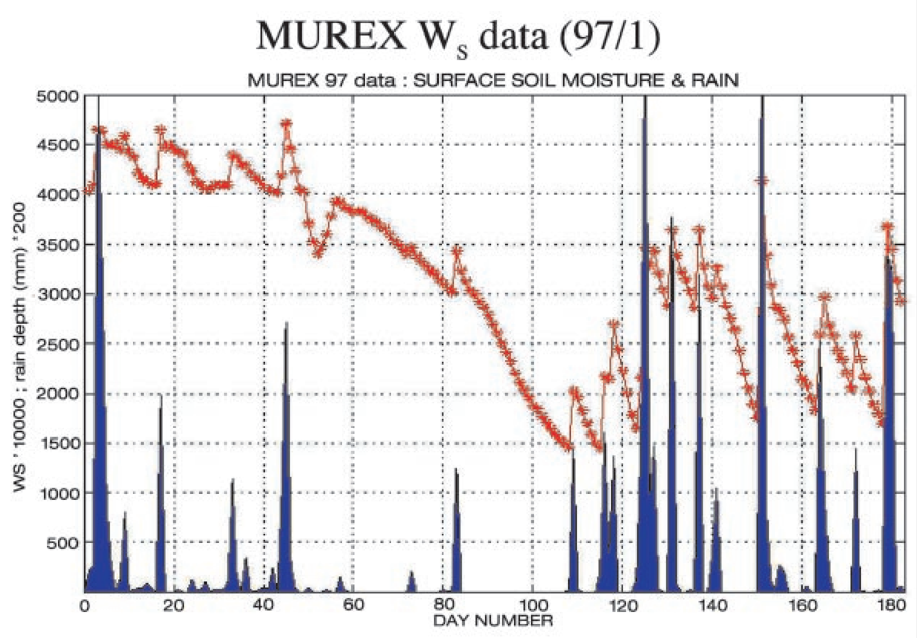

Figure 4: Example of relation between SM and rainfall from the MUREX experiment (from [Calvet et al., 1999]). The w_S values are those at 6 am. The "relaxation" between two rain events is driven by evaporation, infiltration and runoff.

moisture content, is still very imprecise. The soil stratum and in particular the unsaturated zone (vadose zone) between the soil surface and the groundwater table, plays a crucial role. The estimation of soil moisture in the vadose zone is an important issue for short and medium term meteorological modelling, hydrological modelling, and the monitoring of plant carbon dioxide (CO_2) assimilation and plant growth. Attempts to monitor water quality and flooding risks often fail, because the vadose zone hydrology is inaccurately described.

Once surface moisture is known, it is possible to infer root zone soil moisture. Recent studies show that such data, obtained through microwave radiometry during a continuous hydrological event (e.g. a drying period), provide estimates of the corresponding surface hydraulic conductivity value. A similar approach was used to obtain soil moisture content and field capacity from *in situ* measurements of surface soil moisture, w_S.

While the main objective of SMOS on land surface is to monitor w_S [*Kerr et al*., 1998], the vegetation's optical thickness is also of interest and can be obtained from SMOS, assuming that the physical temperature, T_S, is known from external sources (other space-borne sensors) to an accuracy of about 2 K.

In most cases, the vadose zone hydrology and the surface fluxes are controlled by vegetation. Modelling the rate of soil water extraction by the plant roots and the stomatal feedback is important for atmospheric, hydrologic and environmental studies. The current models manage to describe first order responses, but do not encompass the complete behaviour of the plant, especially at the mesoscale, where several different landscapes may contribute to the surface fluxes. In most of the world, plant water supply is the dominant factor that affects plant growth and crop yields. Monitoring soil moisture is a valuable way to detect periods of water stress (excess or deficit) for yield forecasting or biomass monitoring, especially in areas where climatic stations are sparse. Mesoscale time series of soil moisture would also be a very interesting input to the representation of vegetation in land surface schemes.

In addition, estimates of soil moisture are of interest for assessing surface emission at higher frequencies. These would enable better descriptions of the surface-atmosphere boundary conditions to be formulated and may advance microwave sounder retrievals for the lower layers of the atmosphere. Finally, knowledge of the time history of soil moisture may provide direct information about the amount of rainfall over the land surfaces.

Scientific Rationale for the Observation of Sea Surface Salinity

Knowledge of the global distribution of salt in the ocean and of its annual and inter-annual variability, is crucial in helping to understand the role of the ocean in the climate system. Ocean circulation is mainly driven by the momentum and heat fluxes through the atmosphere-ocean interface, which can be traced by observation of SSS. In addition, salinity also determines ocean density and hence thermohaline circulation. In some regions (e.g. the Arctic), salinity is the most important variable as it controls processes such as deep water formation by determining the density. This process is a key component in the ocean thermohaline circulation "conveyor belt". Ocean salinity is also linked to the oceanic carbon cycle, as it determines the ocean circulation and plays a part in establishing the chemical equilibrium which in turn regulates the CO_2 uptake and release. Therefore, the assimilation of SSS into global ocean biogeochemical models could improve estimates of the absorption of CO_2 by the oceans.

Monitoring SSS could also be used to improve the quality of ENSO (El Niño - Southern Oscillation) prediction by numerical models. Presently the models assimilate temperature and/or altimeter-derived sea level data only. The lack of salinity measurements results in major discrepancies between modelled near-surface and observed currents. For example, a 0.5 psu (psu = practical salinity unit which is equivalent to 0.1% mass – the oceans typically range from 32 – 37 psu) error accounts for a 3.8 cm/s error in geostrophic velocity at 1 km depth calculated from the corresponding surface value. This is particularly important in the Western Equatorial Pacific where there is a strong ENSO-related near-surface salinity signal and where zonal advection is of major importance for ENSO mechanisms.

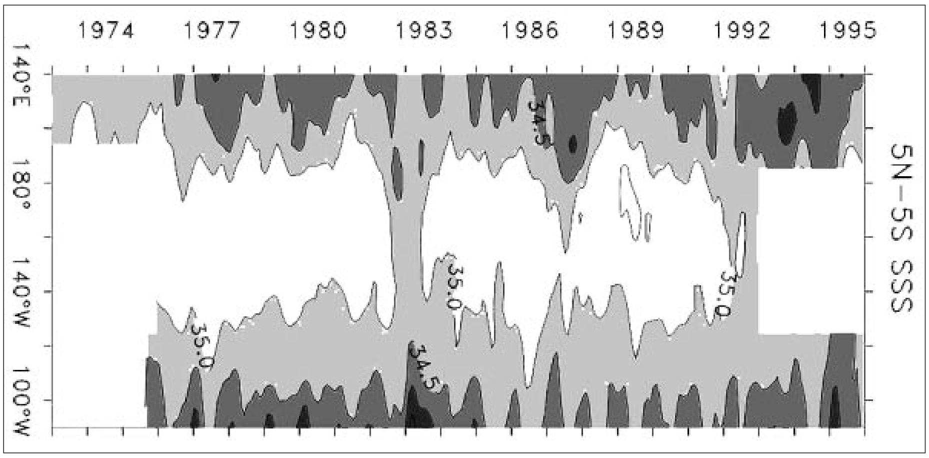

Figure 5: Longitude-time distribution of 5°S-5°N averaged SSS in the Pacific Ocean, as deduced from ship measurements [Delcroix, 1998]. Eastward (westward) displacements of low-salinity water (S<35) which mark the eastern edge of the warm pool are clearly related to respectively El Niño and La Niña events, as in 1982-83, resp. 1987, and 1992 resp. 1988-89. Radiometer measurements should help to fix the width and location of the sea surface salinity gradient between low-salinity water in the warm pool and saltier water in the equatorial upwelling. Such a gradient is related to changes in local mixed-layer T (temperature) and S (salinity), and to barrier layer thickness, its formation and variability. It is clear that remotely sensed SSS would complement in situ measurements, which are by nature accurate but limited in spatial and temporal extent, to characterise spatial and temporal variations of the SSS fronts. (Copyright: American Geophysical Union).

SSS is correlated with estimates of the net “evaporation minus precipitation” (E-P) balance. (E-P) is difficult to measure accurately over the ocean, so global maps of SSS would provide a constraint on estimates of (E-P) on the global scale. This would give insights into the phenomena driving the thermohaline circulation and also provide a check on latent heat flux estimates. The fresh water flux through the sea surface is critical for the stratification of the surface layer of the ocean, and strongly influences the mixed layer depth and the intensity of surface currents.

In situ salinity measurements are only sparsely distributed over the oceans. Examining available data in 1° × 1° boxes over the global oceans shows that salinity measurement exist for only about 70% of them. An even smaller fraction of the boxes contains more than one measurement. Thus, only the average structure of the SSS field is currently known to some degree, but major features of its variability, even on seasonal and inter-annual time-scales, remain unknown. As for other oceanographic variables, global monitoring by *in situ* measurements is an extremely expensive and logistically complicated issue. Only satellite remote sensing, as presently achieved for sea surface temperature (SST) and sea surface height, appears to be an efficient approach. Consequently the scientific design plan for the Global Ocean Observing System (GOOS) 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”.*

Primary scientific objectives for a SSS remote sensing mission where defined by the International *S*alinity and *S*ea *I*ce *W*orking *G*roup (*SSIWG*) as:

- *Improving seasonal to inter-annual (ENSO) climate predictions:* Effective use of SSS data to initialise and improve the coupled climate forecast models, and to study and model the role of freshwater flux in the formation and maintenance of barrier layers and the mixed layer heat budget in the tropics;
- *Improving ocean rainfall estimates and global hydrologic budgets*: The “ocean rain gauge” concept shows considerable promise in reducing uncertainties on the surface freshwater flux on climate time scales, given SSS observations, surface velocities and adequate mixed layer modelling.
- *Monitoring large-scale salinity events*: This may include ice melt, major river runoff events, or monsoons. In particular, tracking inter-annual SSS variations in the Nordic Seas is vital to long time scale climate prediction and modelling.

In early 1997, the *G*lobal *O*cean *D*ata *A*ssimilation *E*xperiment (*GODAE*) concept emerged from discussions of the *O*cean *O*bservation *P*anel for *C*limate (*OOPC*). The concept was developed in the belief that attracting the resources necessary for an adequate long-term global ocean observing system for monitoring the ocean depends upon a clear demonstration of feasibility and value of such a system. The GODAE optimised requirement for open ocean

SSS is 0.1 psu over 200 × 200 km boxes every 10 days; the minimum requirement is 1 psu over 500 x 500 km boxes every 10 days.

Retrieving SM from Brightness Temperature Observations

After more than 20 years of research on the use of microwave radiometry for soil moisture sensing, the basic capabilities are well understood. Due to the large dielectric contrast between dry soil and water, the soil emissivity ε at a microwave frequency (F) depends upon moisture content. Over bare fields, ε is almost linearly related to the moisture content of a soil layer. The penetration depth depends upon F (~3-5 cm at L-band). The vegetation cover attenuates soil emission and contributes to the radiation temperature T_B.

However, at L-band (1.4 GHz), this attenuation is quite moderate and so T_B is sensitive to SM for vegetated areas with biomass ≤ 5 kg m^{-2}, which represent about 65% of the Earth's land surface. Previous research has shown the strong advantages of L-band microwave radiometry for measuring surface soil moisture. At L-band the sensitivity to soil moisture is very high, whereas sensitivity to atmospheric disturbances and surface roughness is minimal. At higher frequencies, vegetation attenuation increases and so much smaller portions of the Earth's land surface would be accessible.

While both active and passive microwave techniques have all-weather capabilities, the signal-to-noise ratio from dry to wet soils is significantly higher for a radiometer than for radar. Furthermore, the radar signal is more sensitive to structural features of the surface, such as soil roughness or canopy geometry.

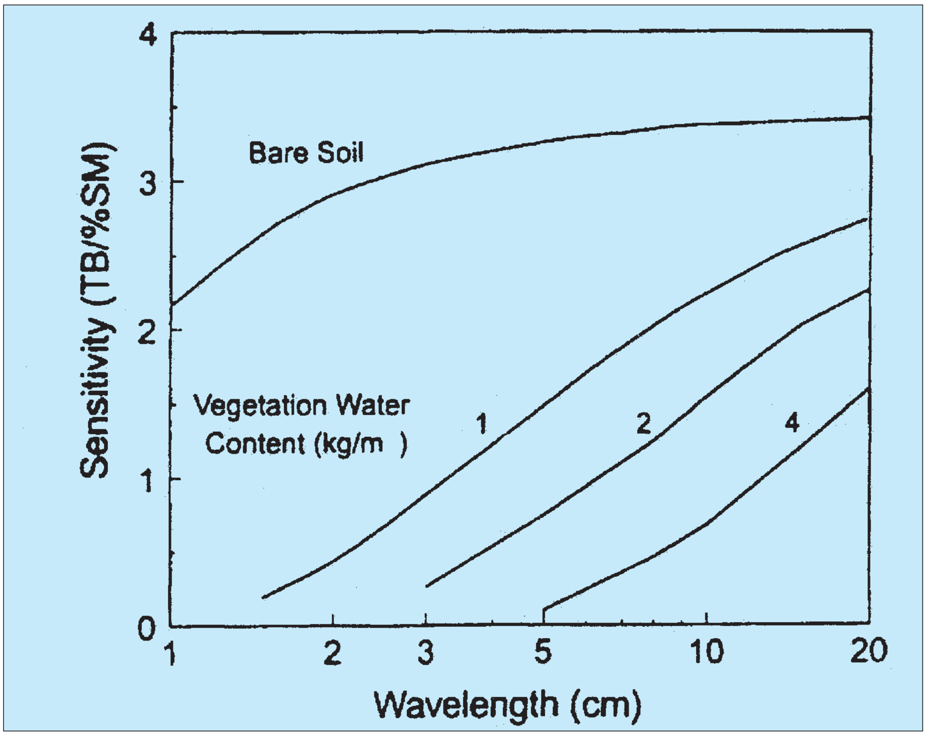

Figure 6: Sensitivity to soil moisture as a function of frequency for different levels of vegetation cover [Jackson et al., 1991].

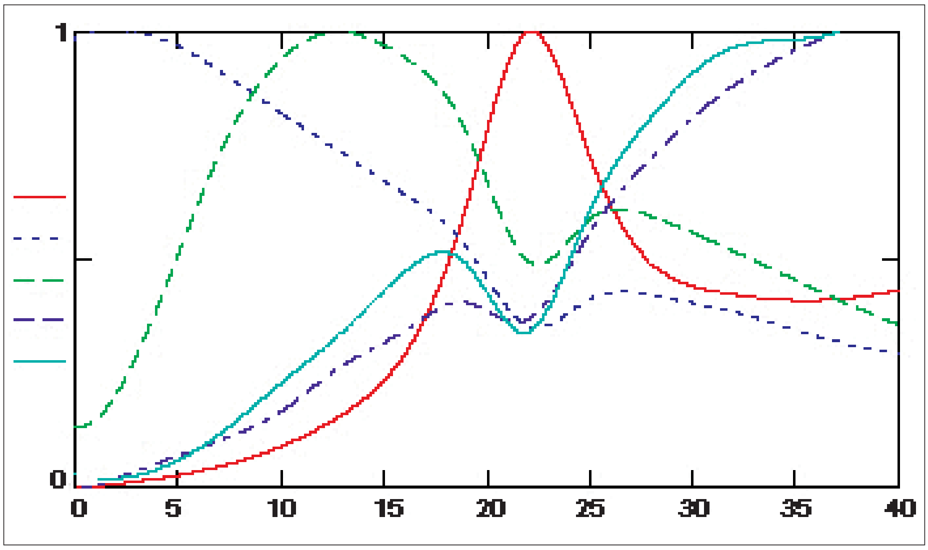

Figure 7: Sensitivity to surface and atmospheric parameters as a function of frequency [Kerr, 1996].

The brightness temperature T_B depends on three important surface variables, namely: soil moisture, w_S ($m^3\ m^{-3}$), vegetation layer optical depth, τ (Nepers) and effective surface temperature, T_S (K). To help discriminate between three factors, radiometry offers the possibility of acquiring data for several polarisations, P (H & V), incidence angles, ι (0° to about 55°) and different frequencies, F. Theoretical models have been developed to investigate the sensitivity of the passive observations to P, ι and F.

Retrieving SSS from Brightness Temperature Observations

The dielectric constant for seawater is determined by the electrical conductivity (which depends on both SSS and SST) and the microwave frequency. The ocean surface emissivity is a function of the dielectric

ground resolution:		< 50 km,
high level data product accuracy:	soil moisture:	4% within a spatial resolution of better than 50 x 50 km.
	sea surface salinity:	0.1psu within 200 x 200 km every 10 days.
revisit time:	1 to 3 days, depending on the latitude, nature of the target and location within the instrument field of view.	

constant and the state of the surface (roughness, foam, etc.). In principle it is possible to retrieve SSS from brightness temperature measurements, as long as variables influencing the brightness temperature signal can be accounted for, for example by the use of different viewing angles, polarisations and frequencies. The sensitivity of T_B to SSS is maximum at low microwave frequencies and good conditions for salinity retrieval are found at L-band. However, it must be stressed that at this frequency the sensitivity of T_B to SSS is low (0.5 K per psu for an SST of 20°C, decreasing to 0.25 K per psu for an SST of 0°), placing demanding requirements on the performance of the instrument.

Mission requirements

The following mission requirements were derived from the scientific objectives:

Requirements for SM observations:

- Soil moisture accuracy (0.04 m^3 m^{-3}(4%) or better). For bare soils, for which the influence of w_S on surface water fluxes is strong, it was shown that a random error of 4% allows an acceptable estimation of the evaporation and soil transfer parameters. Moreover this value corresponds to the typical rms dispersion of in situ w_S observations.
- Spatial Resolution (>50 km): A 20 km pixel size (smaller whenever possible) would be adequate. A size greater than about 50 km is too large for mesoscale models; moreover, the number of watersheds covered by a sufficient number of pixels (40 or more) would be small.
- Revisit time (3-5 days): To track the quick drying period after rainfall, which is very informative in determining soil hydraulic properties, a one- or two-day revisit time is optimal. A 3 - to 5-day revisit time is also acceptable to define w_{VZ} and evapotranspiration but ancillary information on rainfall is then required.
- Time acquisition: The precise time of the day for data acquisition is not critical. However, in the early morning dew may affect the w_S estimation, while the probability of heavy rain is great at high latitudes; late afternoon is prone to heavy-rain events at low latitudes. As Faraday rotation is of concern over the oceans, 6 am is the best option.

Requirements for SSS observations:

Salinity is a significant variable for the upper ocean dynamics at very high latitudes (near-freezing temperatures and ice formation lead to a salinity-dominated stratification), in the western Pacific warm pool (very high precipitation and evaporation), and in subtropical high salinity regions (excess E-P). The warm pool is also the region where surface freshwater flux induces a shallow salt stratification and a “barrier layer” that isolates the surface from the main thermocline, with important consequences for surface layer heating. Salinity has also a strong influence (halosteric effect) on the calculation of the surface layer heat storage from observed sea level. The application of remotely sensed SSS to the study of these different ocean

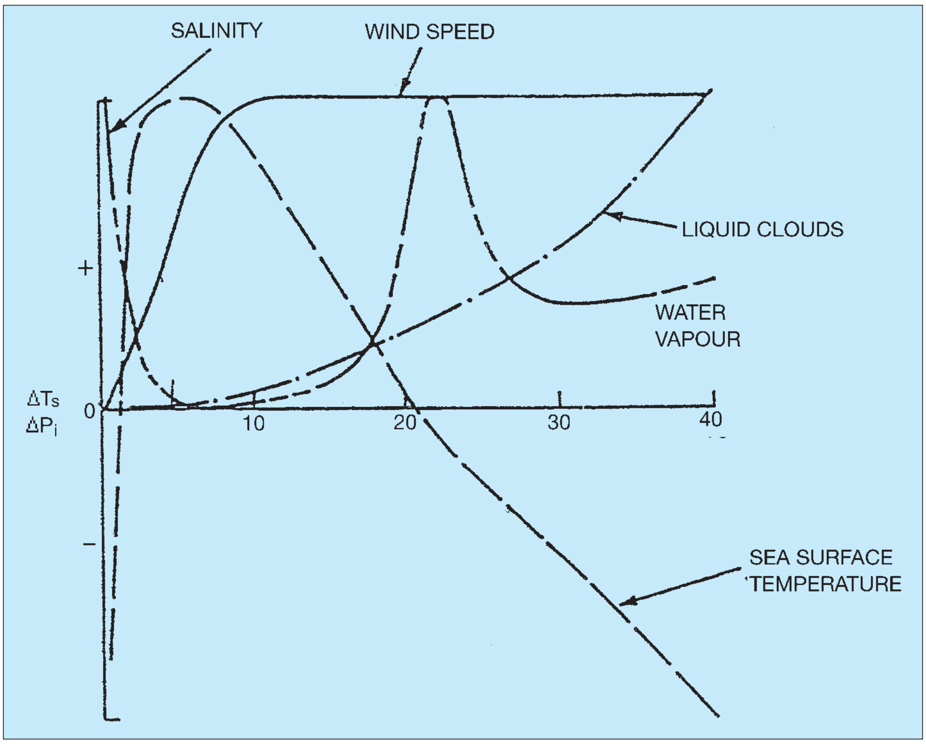

Figure 8: Impact of salinity, SST, wind speed, water vapour and clouds on ocean T_B as a function of frequency, from 0 to 40 GHz.

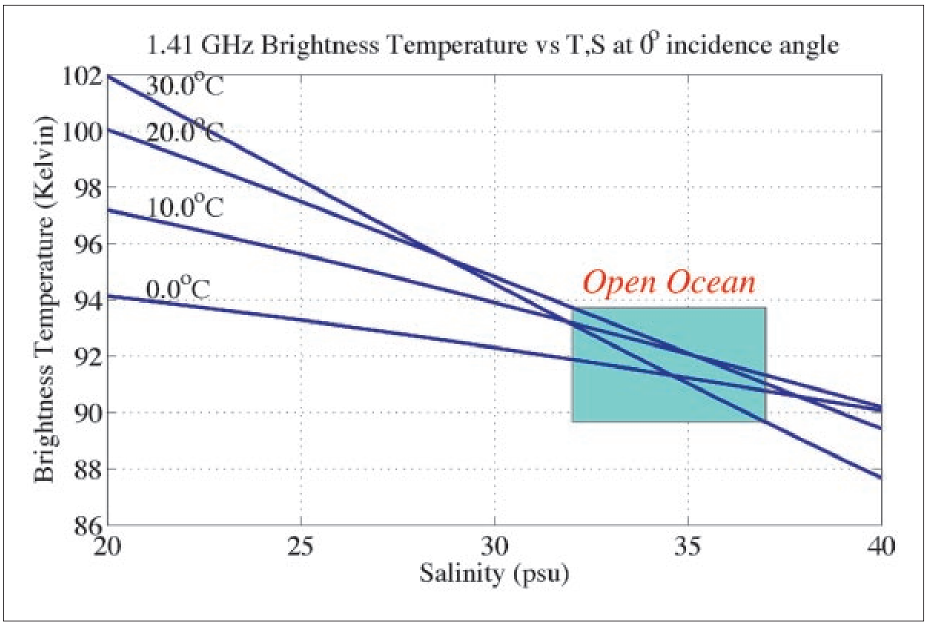

Figure 9: Variation of T_B due to SSS at L-band as a function of SST, for an incidence angle of 0° (from [Lagerloef et al., 1995]).

dynamics phenomena implies different requirements on space, time and even salinity resolution, due to the different scales involved and the contrast in surface water characteristics. Typical values required to resolve some of specific phenomena are:

- Barrier layer effects on tropical Pacific heat flux: 0.2 psu, 100 x 100 km, 30 days
- Halosteric adjustment of heat storage from sea level: 0.2 psu, 200 x 200 km, 7 days
- N. Atlantic thermohaline circulation: 0.1 psu, 100 x 100 km, 30 days
- Surface freshwater flux balance: 0.1 psu, 300 x 300 km, 30 days

The North Atlantic thermohaline circulation and convection in the subpolar seas has the most demanding requirements, and is the most technically challenging, because of the lower brightness/SSS ratio at low water temperatures. A compromise for all these different requirements would be met by considering the GODAE optimised requirements as a general goal for the mission.

The SMOS Mission

One of the most significant drawbacks of L-band radiometry is the size of the antennas. A space-borne L-band instrument is thus technologically challenging. Even though the concept was established by early L-band space experiments, such as that on SKYLAB in the 1970's, no dedicated space mission followed, because achieving a suitable ground resolution (≤ 50 km) required a prohibitive antenna size (≥ 4 m).

However, the recent development of the so-called interferometry design, inspired by the Very Large Baseline (VLB) antenna concept (radio astronomy), now makes such a venture possible. The idea consists of deploying small receivers in space (located on a deployable structure), then reconstructing a brightness temperature (T_B) field with a resolution corresponding to the spacing between the outmost receivers. The idea was put forward by D. LeVine et al., in the 1980's (the ESTAR project) and validated with an airborne system.

In Europe, an improved concept was next proposed to ESA. While MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) capitalises on the ESTAR design, it embodies major improvements. The two-dimensional MIRAS interferometer allows T_B to be measured at large incidences, for two polarisations. Moreover, the instrument records a whole scene instantaneously. As the satellite moves, a given point within the 2D field of view is observed from different view angles. A series of independent measurements is then obtained, which allows the retrieval of surface parameters with improved accuracy.

The baseline instrument of the SMOS mission, which was adopted from MIRAS, is a L-band (1.4 GHz) two-dimensional interferometric radiometer, with a Y shaped antenna, three arms, each 4.5 m long, and a total payload mass (including electronics and structure) of 175 kg. The radiometer will be capable of acquiring dual-polarisation data at several incident angles (0 – 55°). The requirements and the technical feasibility of a polarimetric design are currently being investigated. The instrument would be accommodated on a generic PROTEUS platform. However, the folded satellite would be compatible with most launchers.

It is proposed to launch SMOS on a sun synchronous (a 6:00 a.m. local timeascending node provides reduced atmospheric disturbances as well as conditions close to temperature equilibrium), 757 km circular orbit, resulting in raw data with the following characteristics:

Currently a minimum mission duration of 3 years is foreseen; as 5 years are envisaged.

In order to process SMOS data, corrections due to atmospheric, ionospheric and galactic effects have to be applied. SSS retrieval requires knowledge of sea surface temperature and sea roughness. Over land surfaces, knowledge of the temperature is needed. Over ice,