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A view of Earth, the 'Blue Planet', taken from Apollo 17 in 1972 (NASA)

→ EXPLORING THE WATER CYCLE OF THE 'BLUE PLANET'

The Soil Moisture and Ocean Salinity (SMOS) mission

Mark Drinkwater
Directorate of Earth Observation, ESTEC, Noordwijk, The Netherlands

Yann Kerr
CESBIO, Toulouse, France

Jordi Font
SMOS-BEC, Institut de Ciències del Mar, CSIC, Barcelona, Spain

Michael Berger
Directorate of Earth Observation, ESRIN, Frascati, Italy

Known as ESA's 'Water Mission', SMOS will improve our understanding of Earth's water cycle, providing much-needed data for modelling of the weather and climate, and increasing the skill in numerical weather and climate prediction.

One of the highest priorities in Earth science and environmental policy issues today is to understand the potential consequences of modification of Earth's water cycle due to climate change. The influence of increases in atmospheric greenhouse gases and aerosols on atmospheric water vapour concentrations, clouds, precipitation patterns and water availability must be understood in order to predict the consequences for water availability for consumption and agriculture.

In a warmer climate, increased evaporation may well accelerate the water cycle, resulting in changes in the patterns of evaporation over the ocean and land, and an increase in the amount of moisture circulating through the atmosphere. Many uncertainties remain, however, as illustrated by the inconsistent results given by current numerical weather and climate prediction models for the future distribution of precipitation.

Today, there are insufficient data available to help improve our scientific knowledge and understanding of the processes influencing the water cycle. So ESA teamed up with the French space agency CNES and Spanish Centre for the Development of Industrial Technology (CDTI) to address this key scientific challenge – by delivering a fundamentally new satellite tool to create these new global datasets.

The resulting regular and consistent measurements will be used to improve our understanding of the way in which both the time-varying distribution of soil moisture and ocean salinity regulate the water cycle of our planet. The Soil Moisture and Ocean Salinity (SMOS) mission promises to be one of the trail-blazers that comprise ESA's Earth Explorers.

The importance of water

The total amount of water in the Earth system is believed to remain constant, though the portion residing in each of the primary 'subsystems' (land, ocean, cryosphere and atmosphere) is constantly changing in response to the complex set of processes that link them.

On the land, the amount of water held in soil at a given location varies as a function of seasonal rates of evaporation and precipitation, percolation and 'runoff' – as governed by the type of soil, vegetation and topography. Similarly, in the ocean, subtle variations in the salinity of the surface brine are brought about by addition or removal of freshwater due to changes in evaporation and precipitation, river runoff, or by melting or freezing of ice in the polar oceans. It is evident that any changes in the processes that modulate these rates of exchange of water can have a dramatic impact on Earth's water cycle.

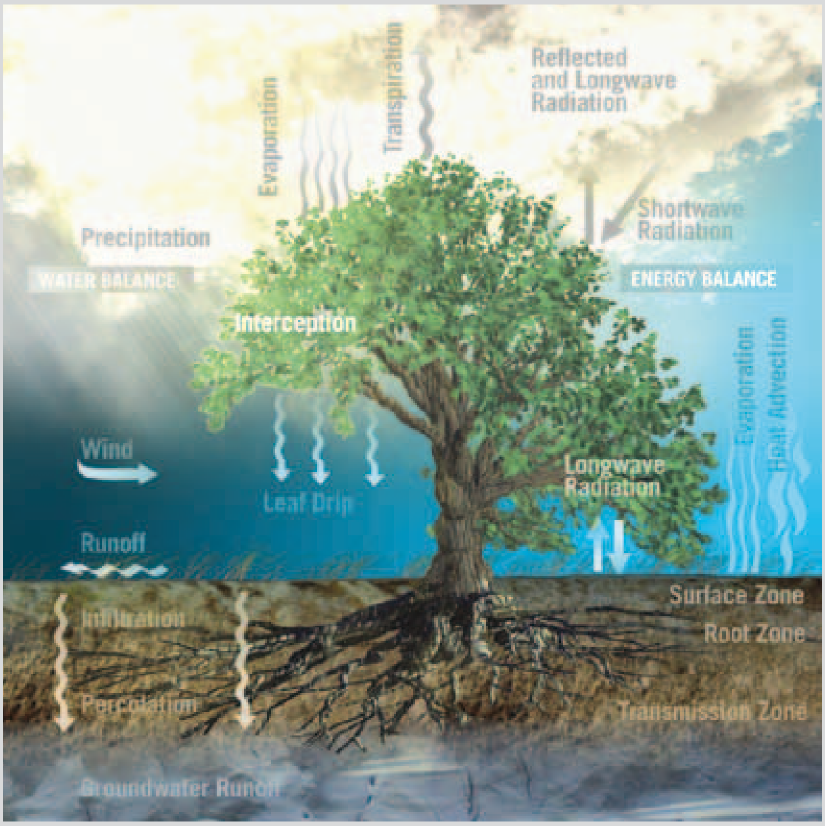
In most parts of the world, the amount and temporal evolution of water present in the soil is the dominant factor influencing plant growth. However, the retention of water in the soil is crucial not only to sustain primary productivity, but is also strongly linked to our weather and climate. This is because soil moisture is a key variable controlling the exchange of water and energy between the land and atmosphere through evaporation and plant transpiration. As a result, soil moisture plays a key role in the development of weather patterns over the land surface.

In spite of the water cycle being one of the most fundamental life-sustaining processes on our planet, this system remains relatively poorly understood. SMOS is a direct response to the current lack of global observations of soil moisture and ocean surface salinity, and has a primary objective to observe these key variables over a mission lifetime of at least three years.

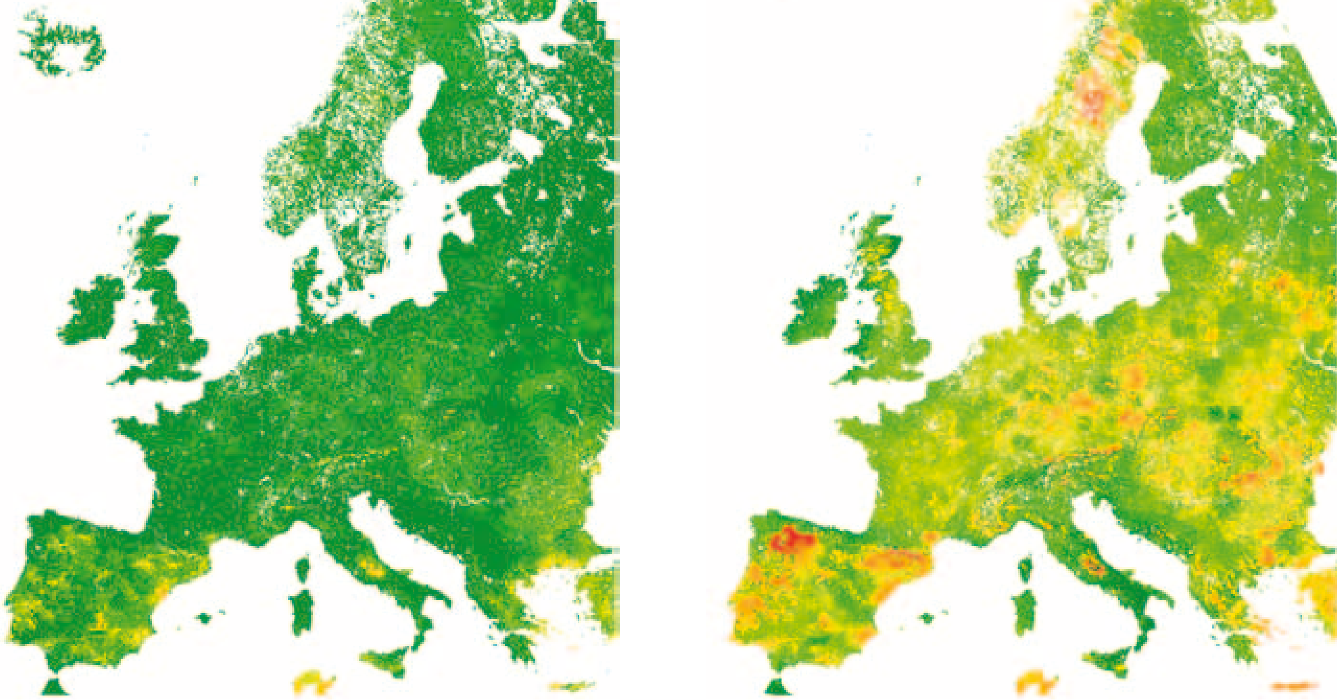
Mission objectives

Soil moisture

It is a challenge to define soil moisture, or water content of soil, because it means different things to people in different



The energy and water balance of a physical climate system including the main land and atmosphere components of the water cycle (AOES Medialab/ESA)



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Daily estimate of soil moisture in Europe and the associated 10-day forecast of soil moisture anomalies based on meteorological forecasts and soil properties. Comparison of the forecast with the long-term average conditions over the period 1958–2001 gives an indication of whether the soil is wetter (green) or drier (red) than the 44-year average (ECMWF/JRC LISFLOOD)

disciplines. A farmer's concept of soil moisture, for instance, differs from that of a water resources manager or a weather forecaster. Generally, soil moisture is the water held in the spaces between soil particles. Surface soil moisture is the water in the upper soil, whereas root-zone soil moisture is the water available to plant roots.

In terms of a quantity, soil moisture is the amount of water expressed in either a volumetric or gravimetric basis. It is often expressed as a ratio ranging from 0 (completely dry) to the value of the soil porosity at saturation. Volumetric soil moisture is defined as a ratio between the volume occupied by the water and the volume of the soil (i.e. m^3 water/ m^3 soil) and is expressed as a percentage (or fraction) and typically occupies a range between values of 0 and 40% (or 0.4).

Usually, soil moisture is considered over different depths depending on the application. The first few centimetres (down to 2–4 cm depth), for instance, drives evaporation, while vegetation pumps water through its root system between the surface and depths of up to 1 m. Groundwater is generally stored in deeper layers.

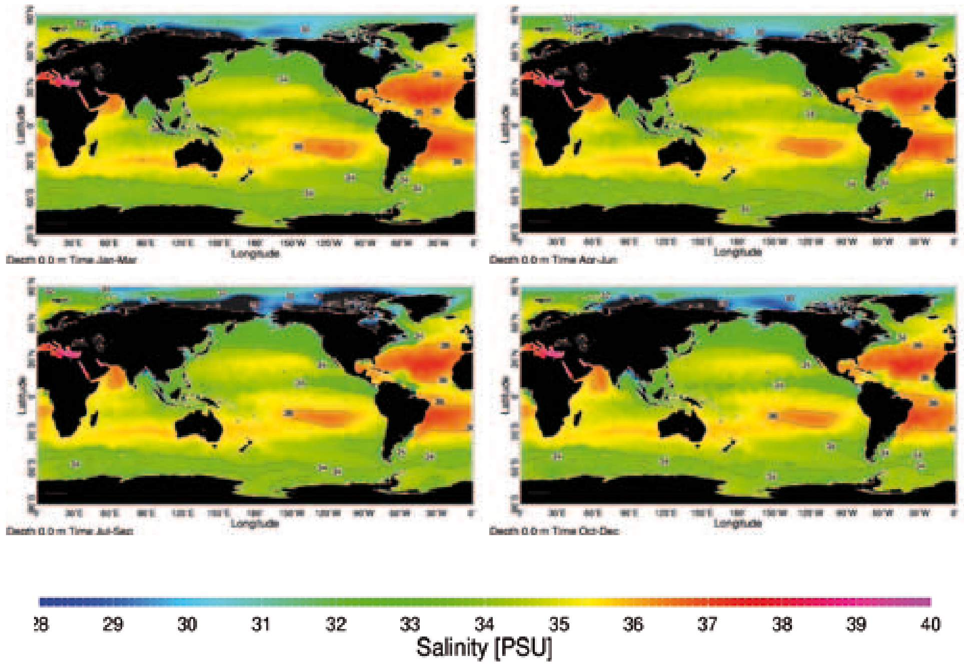
Soil moisture is a variable required by many scientific and operational applications such as climate monitoring, flood/ drought forecasting, studies of ecology or bio-geochemical cycles. For example, plant water supply is the dominant factor affecting plant growth and crop yield monitoring. Measuring soil moisture is a valuable way to detect periods of water 'stress' (excess or deficit) for yield forecasting or biomass monitoring, especially in regions where weather stations are sparse.

Surface soil moisture is crucial in regulating water and energy exchanges between the land surface and lower atmosphere. Its measurement as a variable is important for various reasons: in hydrology and meteorology, the water content of the surface soil layer is a descriptor of the balance between precipitation and evaporation between the surface and the atmosphere. In addition, it is used for estimating the partitioning of precipitation between surface runoff or storage, and for calculating several key variables of land surface energy and water budget, such as albedo or soil hydraulic properties.

Furthermore, through photosynthesis and respiration, plants regulate the CO_2 gas exchanges from and to the atmosphere via their pores (stomata). Since the processes are controlled in the plants by the available water, an estimation of the available root-zone soil moisture is very important for estimating and monitoring the terrestrial CO_2 cycle.

Regular measurements of soil moisture at the 10–100 km scale would provide valuable input for the representation of vegetation in land surface schemes. Soil-vegetation-atmosphere transfer schemes currently used in meteorological and hydrological models are designed to describe the basic evaporation processes and the redistribution of water between vegetation transpiration, drainage, surface runoff and soil moisture variations. Though the latest computer models manage to describe first-order responses, they are still unable to capture the complete behaviour of the system, especially at the landscape scale. One of the main limitations is the ability to constrain the models by appropriate observations of soil moisture.

Today, the quality of estimates of soil moisture used in model forecasts is limited by the sparse point measurements made by the global network of weather stations, rain gauges and precipitation radars. Constraining the modelling by routine observations of the surface soil moisture will



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Sea-surface salinity maps generated from all available historical data, indicating seasonal changes characterised by freshening of the Arctic and North Atlantic during northern hemisphere summer, due to snow and ice melt, and the typical pattern of a saltier Atlantic compared to the Pacific ocean. The eastern Mediterranean and Red Seas stand out as the saltiest seas on Earth, with values of around 40 psu. (World Ocean Atlas 2005)

therefore provide a better representation of land surfaces in computer models, with broad-reaching benefits.

Ocean salinity

All water, even rainwater, contains dissolved chemicals or 'salts'. However, the average concentration of dissolved salt in the ocean is equivalent to about one teaspoon of salt in a glass of water. This is over 200 times saltier than fresh lake water. In scientific terms, the average salinity value is about 35 practical salinity units (psu), which equates to 35 grams of assorted dissolved salts to 1 kg (around 1 litre) of water.

Changes in ocean surface salinity from one part of the globe to another, and over time, are a response to large-scale variations in the workings of the global hydrological cycle. They reflect the way in which the different components of the Earth system interact and exchange freshwater. Water transfer between the large reservoirs: ice and snow, the atmosphere, the geosphere, the biosphere and the ocean is driven by a combination of the dynamic and thermodynamic processes that underpin all climate variability.

Observing the freshwater signal in the ocean, and its complement ocean salinity, is an extremely challenging prospect in these global-scale reservoirs. This is because the processes that govern variability in ocean salinity operate from the local to global scale.

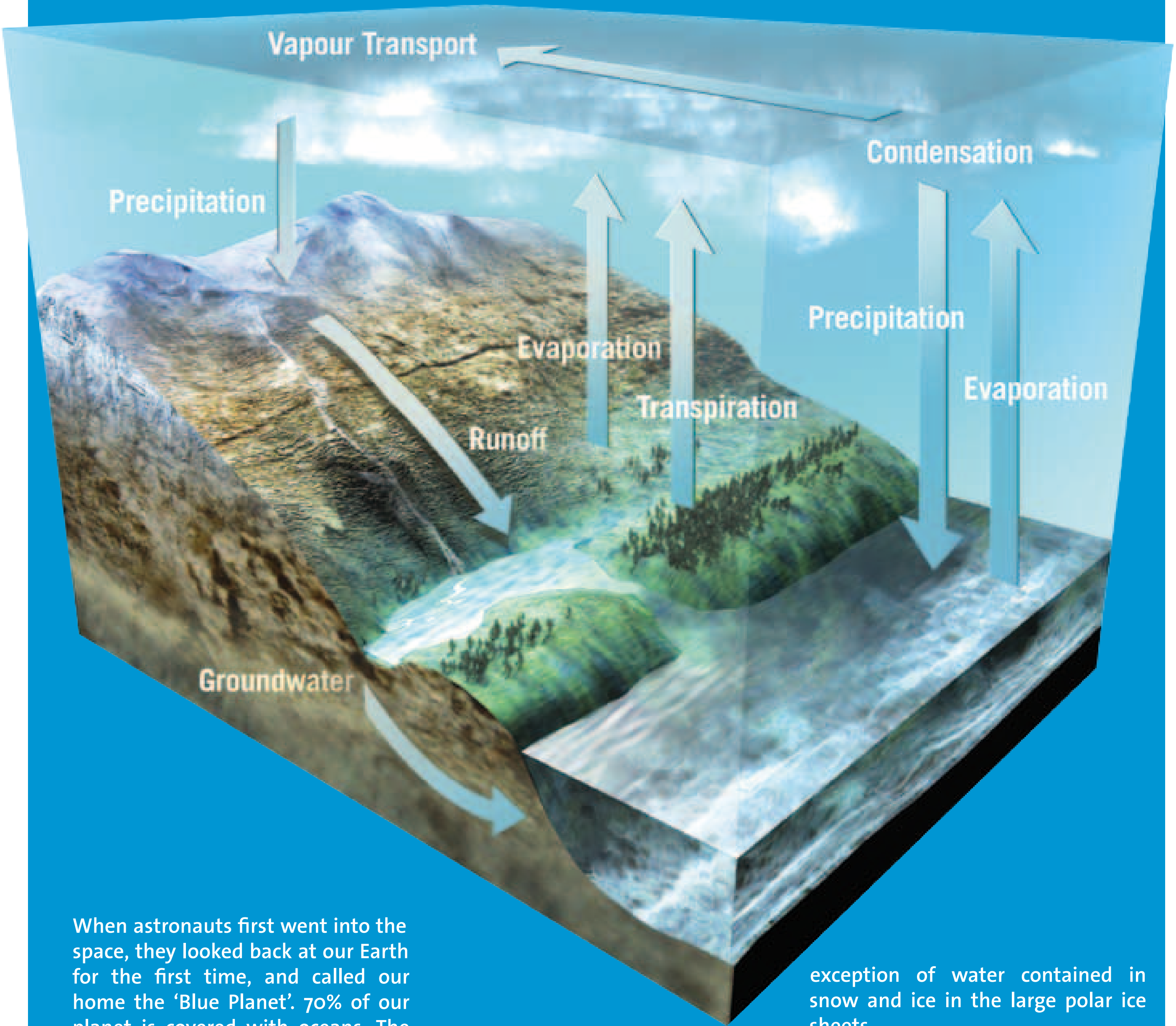
The salinity of surface seawater is largely controlled by a balance between evaporation and precipitation. An estimated 334 000 km^3 of water evaporates from the ocean and is transferred to the atmosphere each year, to return as precipitation on land and sea. The balance among these processes leads to a global average salinity value of around 35 psu, and values in the open ocean typically ranging between 32 to 38 psu. Salinity is at its greatest in subtropical latitudes, where evaporation exceeds precipitation. Meanwhile, surface waters near the Equator and at higher latitudes are generally less saline because of greater rainfall and melting ice (or snowfall) respectively.

Due to its part in determining seawater density, salinity has a direct effect on the buoyancy of a water mass and the extent to which it will sink due to gravity. Salinity-driven densification of surface ocean water in certain parts of the globe plays a fundamental role in forcing the surface ocean water to sink and mix, and to be replaced by other water masses. This vertical element of the ocean circulation is a key component of the temperature and salinity-driven global ocean circulation pattern known as the 'thermohaline circulation'. This three-dimensional 'conveyor belt' circulation links all the ocean basins around the globe and is an important element regulating weather patterns and Earth's climate.

In the context of global climate change detection, the practical value and distribution of historical ship-borne measurements of surface salinity data are largely limited by the sparse distribution of standard vessel routes. More recently, the Argo float programme has made a significant step in providing regular assessments of the distribution of salinity in the oceans. However, almost all of these autonomous Argo profiling devices are limited to operations in the open ocean (away from sea-ice cover) and to measurement at depths below approximately 10 m. This means that the salinity of a huge proportion of the surface ocean remains unsampled, while large parts of the high-latitude oceans remain unsampled at all depths.

Since ocean surface salinity is closely linked to estimates of net evaporation minus precipitation (known as E-P), it remains of fundamental importance to assess this aspect of the freshwater balance from the global to regional scale. The benchmark sampling requirement to enable detection of

→ The ‘water cycle’



When astronauts first went into the space, they looked back at our Earth for the first time, and called our home the ‘Blue Planet’. 70% of our planet is covered with oceans. The remaining 30% is the solid ground, rising above sea level.

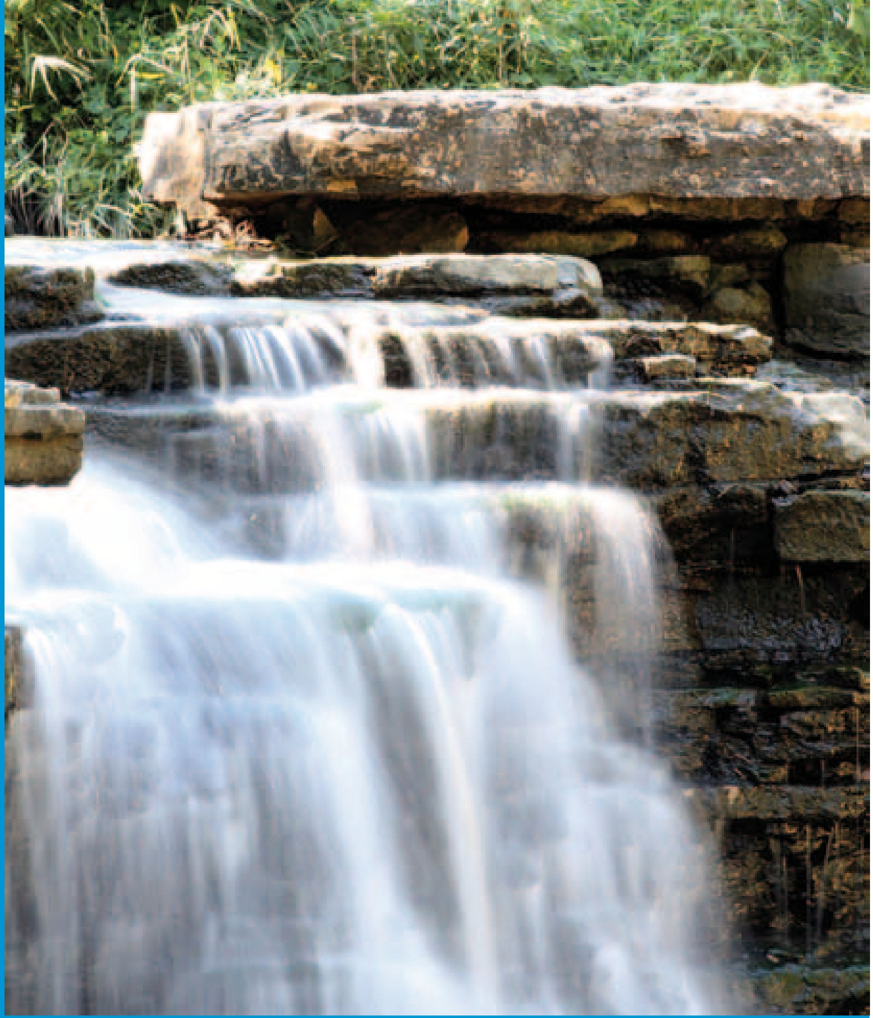
Although water features in everyone’s daily lives, this fact was a relatively dry statistic until it was reinforced in the pictures of Earth taken by these first astronauts. It is hardly surprising that the study of water, or the science of hydrology, is one of the key aspects of ESA’s Living Planet programme.

Water is a compound that is found in all parts of the Earth system. Water in its solid (ice and snow), liquid (water), and gas (water vapour) states can be found in the ocean, the atmosphere, the cryosphere and the lithosphere. Water provides Earth with the capacity of supporting life.

A simplified description of the hydrological or ‘water cycle’ is shown above. This indicates the primary mechanisms by which water is moved around the planet, with the exception of water contained in snow and ice in the large polar ice sheets.

The external heat engine of Earth, powered by the Sun, is responsible for driving the water cycle. It does so by evaporating water from the surface of the warm tropical oceans, which rises and condenses to form clouds. Winds transport this water in the atmosphere to locations where it eventually falls as snow or rain. Much of the rain soaks into the ground by infiltration adding to the groundwater. Water that does not soak into the soil collects as ‘runoff’ and finds its way into streams or rivers to return to the ocean. Some water in the ground may return directly into the atmosphere by evaporating through the soil surface. Some water may be used by plant roots, carried up to leaves and returned to the atmosphere by transpiration.

The oceans contain approximately 96.5% of Earth's water, while the land including glaciers, ice sheets and ground water contains approximately 3.5%. By contrast, the atmosphere holds less than 0.001%, which may seem surprising because of the important role water plays in the weather. The annual precipitation for Earth is more than 30 times the atmosphere's total capacity to hold water. This fact reinforces the rapid recycling of water between Earth's surface and the atmosphere. Around 90% of the atmospheric water vapour originates in the oceans, while the remaining 10% originates from plant transpiration and soil evaporation.



Water source	Water volume (km³)	% of freshwater	% of total water
Oceans, seas, bays	1 338 000 000	-	96.5
Ice caps, glaciers and permanent snow	24 064 000	68.7	1.74
Groundwater (fresh)	10 530 000	30.1	0.76
Groundwater (saline)	12 870 000	-	0.94
Ground ice and permafrost	300 000	0.86	0.022
Lakes (fresh)	91 000	0.26	0.007
Lakes (saline)	85 400	-	0.006
Soil moisture	16 500	0.05	0.001
Atmosphere	12 900	0.04	0.001
Swamp water	11 470	0.03	0.0008
Rivers	2120	0.006	0.0002
Total	1 386 000 000*	-	100

1 cubic km = 1 km³ = 1000 x 1000 m = 1 x 10⁶ m³ = 1 million m³
*Includes biological 'waste', approx. 1120km³

Estimates of global water distribution (adapted from P.H. Gleick, 1996: Water resources. In *Encyclopaedia of Climate and Weather*, Ed. S.H. Schneider, Oxford Univ. Press, New York, vol. 2, pp. 817-823) weather and climate relevant variability in E-P is to obtain at least one mean value per 100 km square every month with an accuracy of 0.1 psu. Depending on the scale of the process to be addressed, this may be relaxed to one mean value per 200 km square every 10 days with an accuracy of 0.2 psu or better.

Today the surface salinity distribution and E-P balance remains difficult to measure accurately or regularly over the global ocean with any conventional means. Clearly, satellite-based maps of global and regional-scale surface features in sea-surface salinity offer the only solution to this problem today. Additionally, while satellites are needed to measure and characterise the large-scale time and space variability, the in situ measurement techniques can be used to complement these information at smaller scales or in the three-dimensional picture of the ocean.

SMOS mission requirements

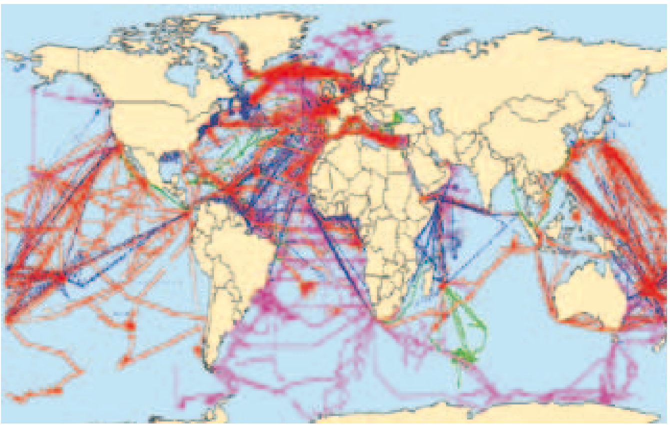
The scientific requirements for SMOS have been formulated such that the measurements should allow retrieval of surface soil moisture and ocean salinity with sufficient accuracy to capture the range of natural variability in these parameters.

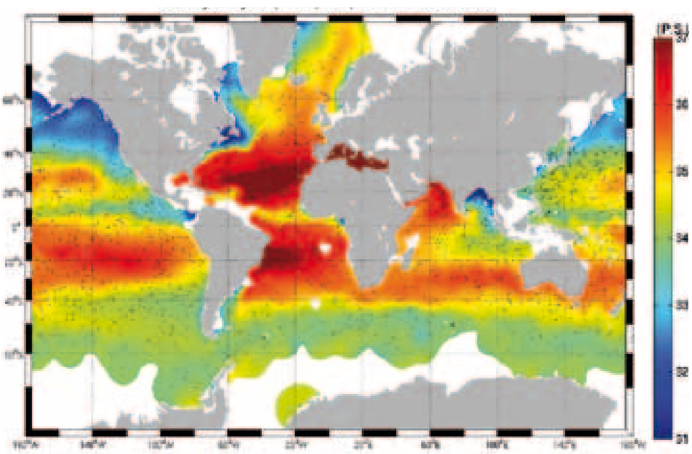
For bare soils, for which the influence of near-surface soil moisture on surface water fluxes is strong, a residual random uncertainty of less than 4% is acceptable, and allows good estimation of the evaporation and soil transfer parameters. To illustrate the challenge, this soil moisture measurement requirement is equivalent to being able to detect less than one spoonful of water mixed in a large handful of dry soil.

The forecasting ability of global atmospheric models can be significantly improved if provided with surface soil moisture fields. To achieve this goal, a 50 km spatial resolution is required. Moreover, this scale will allow hydrological modelling with sufficient detail to capture variability in the world's largest hydrological basins.

Ideally, the diurnal cycle in soil moisture should be monitored with twice daily measurements, but this would require multiple satellites for global mapping. With only one satellite, an interval of 1–3 days between surface soil moisture measurements at a particular location can fulfil the requirement for tracking the drying period after rain has fallen. This gives the ability to deduce the soil hydraulic properties needed to retrieve the root-zone soil-moisture content and the soil moisture available for plant processes. Optimally, a 1–2 day revisit interval would be needed to characterise the quickest drying soils. Thus, the designated 1–3 day repeat interval will successfully cover requirements for most soils all the time, while addressing the more challenging, faster-changing soils most of the time.

According to model simulations, ocean surface salinity variations in regions are typically in the range of 0.05 to 0.5 psu, thus posing an extremely challenging requirement. Stronger variability of up to 2 psu may be observed in the





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Relying on commercial vessels to measure ocean salinity/ temperature leaves large areas of the oceans unsampled. Left, all surface temperature and salinity data acquired since the early 1990s by voluntary observations made by ships underway using thermosalinographs (*www.ifremer.fr/gosud/*)

Right, the distribution of 3190 Argo drifters (black dots) as of September 2008. Colours indicate the daily analysis of salinity at an uppermost depth of 10 m. White areas indicate where there remain insufficient data with which to resolve salinity or temperature (*www.coriolis.eu.org*)

→ Measuring moisture and salinity from space

SMOS is not the first L-band radiometer in space, and will undoubtedly not be the last. The S-194 instrument on the NASA Skylab space station in 1973/74 provided the first demonstration of the sensitivity of an L-band radiometer to sea-surface salinity, together with the impact of the sea-state and surface temperatures on the measured antenna temperatures.

The Skylab experiment conclusively demonstrated the value of L-band radiometers over the ocean, and in particular paved the way for plans for subsequent instruments.

In addition to SMOS, the Aquarius/SAC-D mission is currently under joint development by NASA and the Argentinian space agency (CONAE). Aquarius will follow up the successful Skylab demonstration mission and employs a combined L-band real-aperture radiometer with an L-band scatterometer.

The combined measurements will be focused on measurement of global sea-surface salinity. Aquarius recently successfully completed its critical design review and is scheduled for a 2010 launch.

Aquarius will cover the oceans in 8 days with a spatial resolution of 100 km, though its sensitivity to salinity will be better than that of SMOS due to its different design.

The Soil Moisture Active and Passive (SMAP) mission is one of four NASA missions recommended by a US National Research Council

Parameter	Accuracy	Spatial resolution	Revisit interval
Soil moisture	0.04 $m^3 m^{-3}$	< 50 km	≤ 3 days
Ocean salinity	0.2–0.1 psu	200–100 km	10–30 days

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The primary SMOS mission requirements for soil moisture and ocean salinity

tropical oceans, coastal upwelling regions and large river outflows, and regions of strong mixing and dynamics associated with frontal instabilities and large current systems. To observe this ocean variability on scales relevant to ocean modelling, the observations must allow features in the 200–300 km range, characterising large-scale salinity gradients, to be resolved.

Ocean model simulations show that, even at reduced spatial resolution, seasonal features will be observed with much better accuracy than the present knowledge of global seasonal sea-surface salinity variations. Many individual measurements can be accumulated in space and time grid cells while preserving the required measurement resolution. Together with collocated wind and temperature data, retrieval experiments have demonstrated that averaging of the accumulated SMOS measurements sufficiently reduces random noise to the point where the 0.1 psu requirement may be met.

To fulfil both sets of scientific requirements there is a common need for the orbit to allow global coverage within a band of latitude from 80° North to 80° South or wider. Though there are several possibilities for the local observation time, early morning at around 06:00 is preferable. This is when ionospheric effects are expected to be least, while surface conditions are expected to be as close as possible to thermal equilibrium (i.e. to avoid measurement biases).

Acknowledgements

ESA would like to acknowledge the important contributions made by members of the SMOS Science Advisory Group and researchers from various institutions and teams around the world during the scientific preparation and development of the mission.

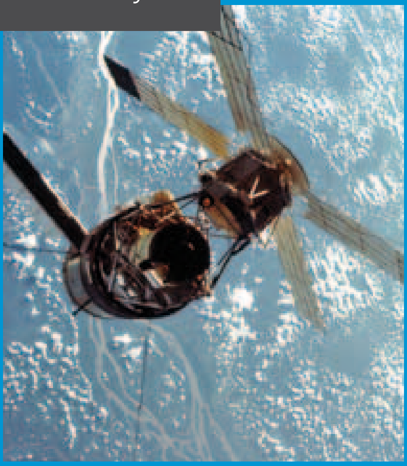
Committee on Earth Science and Applications from Space for launch in the 2010-13 timeframe. SMAP will use a combined L-band radiometer and high-resolution radar to measure surface soil moisture and freeze-thaw state. Its measurements will contribute to improving our knowledge of regional and global water cycles, ecosystem productivity and the processes that link the water, energy, and carbon cycles.

Soil moisture and freeze/thaw state information provided by SMAP at high resolution will enable improvements to weather and climate forecasts, flood prediction and drought monitoring, and measurement of net CO_2 uptake in forested regions (particularly at high latitudes).

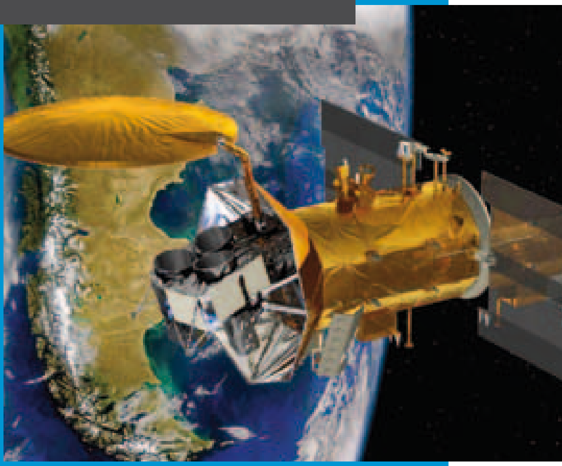
Globally, the SMAP spatio-temporal sampling is the same as that of SMOS, but with the added radar/radiometer synergy to help disaggregate the soil moisture information to 3–10 km scale. However, this advantage is offset by the single view angle, which makes soil moisture retrieval potentially more challenging.

Hopefully, these three missions will overlap in time, so as to enable intercalibration and intercomparison of their respective data. This will help in building longer, seamless soil moisture and ocean salinity time series such as to develop a new fundamental climate data record.

↓ NASA's Skylab



↓ The Aquarius/SAC-D satellite



→ ESA's SMOS satellite