SATELLITE MEASUREMENTS OF SALINITY

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Introduction

Surface salinity is an ocean state variable which controls, along with temperature, the density of sea water and influences surface circulation and formation of dense surface waters in the higher latitudes which sink into the deep ocean and drive the thermohaline convection. Although no satellite measurements are made at present, emerging new technology and a growing scientific need for global measurements are stimulating efforts to launch salinity observing satellite sensors within the present decade. Salinity remote sensing is possible because the dielectric properties of sea water which depend on salinity also affect the surface emission at certain microwave frequencies. Experimental heritage extends over the past 30 years, including laboratory studies, airborne sensors, and one instrument flown briefly in space on Skylab. Requirements for very low noise radiometers and large antenna structures have limited the advance of satellite systems, and are now being addressed. Science needs, primarily for climate studies, dictate a resolution requirement of 100 km spatial grid, observed monthly, with a 0.1‰, error (or 1 part in 10 000), which demand very precise radiometers and that several ancillary errors be accurately corrected. Measurements will be made in the 1.413 GHz astronomical hydrogen absorption band to avoid radio interference. The first satellite could be launched as early as 2005.

Definition and Theory

How Salinity is Defined and Measured

Salinity is the concentration of dissolved inorganic salts in sea water (grams of salt per kilogram sea water, or parts per thousand, and given by the symbol ‰). Oceanographers have developed methods based on the electrical conductivity of sea water which permit accurate measurement by use of automated electronic *in situ* sensors. Salinity is derived from conductivity, temperature, and pressure with a set of empirical equations known as the practical salinity scale. Accordingly, the literature sometimes quotes salinity measurements in practical salinity units (PSU), which is equivalent to ‰ or grams per kilogram salt. Salinity ranges from near zero adjacent to the mouths of major rivers to >40‰ in the Red Sea. Aside from such extremes, open-ocean surface values away from coastlines generally fall between 32‰ and 37‰ (**Figure 1**).

This global mean surface salinity field has been compiled from all available oceanographic observations. A significant fraction of the 1° latitude longitude cells have no observations, requiring such maps to be interpolated and smoothed over several hundred kilometer scales. Seasonal to interannual salinity variations can only be resolved in very limited geographical regions where the sampling density is suitable. Data are most sparse over large regions of the Southern Hemisphere. Remote sensing from satellites will be able to fill this void and monitor multi-year variations globally.

Remote sensing theory Salinity remote sensing with microwave radiometry is likewise possible through the electrically conductive properties of sea water. A radiometric measurement of an emitting surface is given in terms of a brightness temperature (T_B), measured in degrees Kelvin (K). T_B is related to the true absolute surface temperature (T) through the emissivity coefficient (e):

$$T_B = eT$$

For sea water, e depends on the complex dielectric constant (ε), the viewing angle (Fresnel laws), and surface roughness (due to wind waves). The complex dielectric constant is governed by the Debye equation:

$$\varepsilon = \varepsilon_{\infty} + \frac{\varepsilon_S(S,T) - \varepsilon_{\infty}}{1 + i2\pi f\tau(S,T)} - \frac{iC(S,T)}{2\pi f\varepsilon_0}$$

and includes electrical conductivity (C), the static dielectric constant (ε_S), and the relaxation time (τ) which are all sensitive to salinity and temperature (S, T). The equation also includes radio frequency (f) and terms for permittivity at infinite frequency (ε_{∞}) which may vary weakly with T, and permittivity of free space (ε_0) which is a constant. The relation of electrical conductivity to salinity and temperature is determined through laboratory measurements or derived from the practical salinity scale. The static dielectric and time constants have been modeled by making laboratory measurements of ε at various

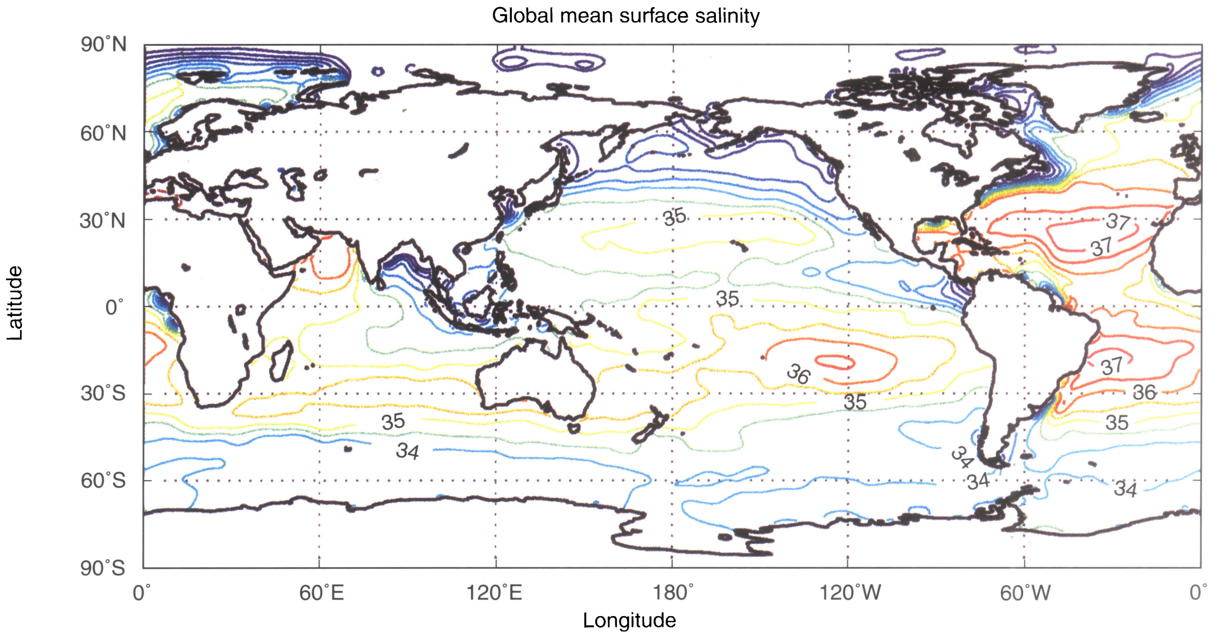

Figure 1 Contour map of the mean global surface salinity field based on the *World Ocean Atlas, 1998* (WOA98). Generated from data obtained from the US Department of Commerce, NOAA, National Oceanographic Data Center (www.nodc.noaa.gov).

frequencies, temperatures and salinities, and fitting ε_S and τ to polynomial expressions of (S, T) to match the ε data. Different models in the literature show similar variations with respect to (f, S, T).

Emissivity for the horizontal (H) and vertical (V) polarization state is related to ε by Fresnel reflection:

$$e_H = 1 - \left[\frac{\cos\theta - (\varepsilon - \sin^2\theta)^{1/2}}{\cos\theta + (\varepsilon - \sin^2\theta)^{1/2}}\right]^2$$

and

$$e_V = 1 - \left[\frac{\varepsilon\cos\theta - (\varepsilon - \sin^2\theta)^{1/2}}{\varepsilon\cos\theta + (\varepsilon - \sin^2\theta)^{1/2}}\right]^2$$

where θ is the vertical incidence angle from which the radiometer views the surface, and $e_H = e_V$ when $\theta = 0$. The above set of equations provides a physically based model function relating T_B to surface S, T, θ, and H or V polarization state for smooth water (no wind roughness). This can be inverted to retrieve salinity from radiometric T_B measurements provided the remaining parameters are known. The microwave optical depth is such that the measured emission originates in the top 1 cm of the ocean, approximately.

The rate at which T_B varies with salinity is sensitive to microwave frequency, achieving levels practical for salinity remote sensing at frequencies below about 3 GHz. Considerations for selecting a measurement radio frequency include salinity sensitivity, requisite antenna size (see below), and radio interference from other (mostly man-made) sources. A compromise of these factors, dominated by the interference issue, dictates a choice of about a 20 MHz wide frequency band centered at 1.413 GHz, which is the hydrogen absorption band protected by international treaty for radio astronomy research. This falls within a frequency range known as L-band. Atmospheric clouds have a negligible effect, allowing observations to be made in all weather except possibly heavy rain. Accompanying illustrations are based on applying $f = 1.413$ GHz in the Debye equation and using a model that included laboratory dielectric constant measurements at the nearby frequency 1.43 GHz. Features of this model function and their influence on measurement accuracy are discussed in the section on resolution and error sources (below).

Antennas Unusually large radiometer antennas will be required to be deployed on satellites to measure salinity. Radiometer antenna beam width varies inversely with both antenna aperture and radio frequency; 1.413 GHz is a significantly lower frequency than found on conventional satellite microwave radiometers, and large antenna structures are necessary to avoid excessive beam width and accordingly large footprint size. For example, a 50 km footprint requires about a 6 m aperture antenna, whereas conventional radiometer antennas are around 1–2 m. To decrease the footprint by a factor of two requires doubling the antenna size. Various filled and thinned array technologies for large antennas have now reached a development stage where application to salinity remote sensing is feasible.

History of Salinity Remote Sensing

The only experiment to date to measure surface salinity from space took place on the NASA Skylab mission during the fall and winter 1973–74, when a 1.413 GHz microwave radiometer with a 1 m antenna collected intermittent data. A weak correlation was found between the sensor data and surface salinity, after correcting for other influences. There was no 'ground truth' other than standard surface charts, and many of the ambient corrections were not as well modeled then as they could be today. Research leading up to the Skylab experiment began with several efforts during the late 1940s and early 1950s to measure the complex dielectric constant of saline solutions for various salinities, temperatures, and microwave frequencies. These relationships provide the physical basis for microwave remote sensing of the ocean as described above.

The first airborne salinity measurements were demonstrated in the Mississippi River outflow and published in 1970. This led to renewed efforts during the 1970s to refine the dielectric constants and governing equations. Meanwhile, a series of airborne experiments in the 1970s mapped coastal salinity patterns in the Chesapeake and Savannah river plumes and freshwater sources along the Puerto Rico shoreline. In the early 1980s, a satellite concept was suggested that might achieve an ideal precision of about 0.25‰ and spatial resolution of about 100 km. At that time, space agencies were establishing the oceanic processes remote sensing program around missions and sensors for measuring surface dynamic topography, wind stress, ocean color, surface temperature, and sea ice. For various reasons, salinity remote sensing from satellites was then considered only marginally feasible and lacked a strongly defined scientific need.

Interest in salinity remote sensing revived in the late 1980s with the development of a 1.4 GHz airborne Electrically Scanning Thinned Array Radiometer (ESTAR) designed primarily for soil moisture measurements. ESTAR imaging is done electronically with no moving antenna parts, thus making large antenna structures more feasible. The airborne version was developed as an engineering prototype and to provide the proof-of-concept that aperture synthesis can be extrapolated to a satellite design. The initial experiment to collect ocean data with this sensor consisted of a flight across the Gulf Stream in 1991 near Cape Hatteras. The change from 36‰ in the offshore waters to <32‰ near shore was measured, along with several frontal features visible in the satellite surface temperature image from the same day. This Gulf Stream transect demonstrated that small salinity variations typical of the open ocean can be detected as well as the strong salinity gradients in the coastal and estuary settings demonstrated previously.

By the mid-1990s, a new airborne salinity mapper Scanning Low Frequency Microwave Radiometer (SLFMR) was developed for light aircraft and has been used extensively by NOAA and the US Navy to survey coastal and estuary waters on the US east coast and Florida. A version of this sensor is now being used in Australia, and a second generation model is presently being built for the US Navy.

In 1999 a satellite project was approved by the European Space Agency for the measurement of Soil Moisture and Ocean Salinity (SMOS) with projected launch in 2005. The SMOS mission design emphasizes soil moisture measurement requirements, which is done at the same microwave frequency for many of the same reasons as salinity. The T_B dynamic range is about 70–80 K for varying soil moisture conditions and the precision requirement is therefore much less rigid than for salinity. The greater requirement is for spatial resolution on the ground where SMOS will employ a large two-dimensional phased array system that will produce a minimum 35 km resolution around the center swath. The imaging system will yield measurements at various incidence angles and H and V polarization. Retrieval algorithms for salinity and the eventual measurement accuracy will be developed and evaluated prior to launch. Other satellite concepts with primary emphasis on ocean salinity rather than soil moisture are being investigated and may be proposed in 2001.

The focus will be on optimizing salinity accuracy and addressing the error sources presented in the following section.

Requirements for Observing Salinity from Satellites

Scientific Issues

Three broad scientific themes have been identified for a satellite salinity remote sensing program. These themes relate directly to the international climate research and global environmental observing program goals.

Improving seasonal to interannual climate predictions This focuses primarily on El Niño forecasting and involves the effective use of surface salinity data (1) to initialize and improve the coupled climate forecast models, and (2) to study and model the role of freshwater flux in the formation and maintenance of barrier layers and mixed-layer heat budgets in the tropics. Climate prediction models in which satellite altimeter sea level data are assimilated must be adjusted for steric height (sea level change due to ocean density) caused by the variations in upper layer salinity. If not, the adjustment for model heat content is incorrect and the prediction skill is degraded. Barrier layer formation occurs when excessive rainfall creates a shallow, freshwater stratified, surface layer which effectively isolates the deeper thermocline from exchanging heat with the atmosphere with consequences on the air–sea coupling processes that govern El Niño dynamics.

Improving ocean rainfall estimates and global hydrologic budgets Precipitation over the ocean is still poorly known and relates to both the hydrologic budget and to latent heating of the overlying atmosphere. Using the ocean as a rain gauge is feasible with precise surface salinity observations coupled with ocean surface current velocity data and mixed-layer modeling. Such calculations will reduce uncertainties in the surface freshwater flux on climate timescales and will complement satellite precipitation and evaporation observations to improve estimates of the global water and energy cycles.

Monitoring large-scale salinity events and thermohaline convection Studying interannual surface salinity variations in the subpolar regions, particularly the North Atlantic and Southern Oceans, is essential to long timescale climate prediction and modeling. These variations influence the rate of oceanic convection and poleward heat transport (thermohaline circulation) which are known to have been coupled to extreme global climate changes in the geologic record. Outside of the polar regions, salinity signals are stronger in the coastal ocean and marginal seas than in the open ocean in general, but large footprint size will limit near-shore applications of the data. Many of the larger marginal seas which have strong salinity signals might be adequately resolved nonetheless, such as the East China Sea, Bay of Bengal, Gulf of Mexico, Coral Sea/Gulf of Papua, and Mediterranean.

Science requirements The science themes lead to four specific study topics to benefit from satellite observations. Each topic has accuracy and spatial and temporal resolution requirements as follows. (1) Barrier layer effects on tropical Pacific heat flux: 0.2‰, 100 km, and 30 days. (2) Steric adjustment of heat storage from sea level: 0.2‰, 200 km, and 7 days. (3) North Atlantic thermohaline circulation: 0.1‰, 100 km, and 30 days. (4) Surface freshwater flux balance: 0.1‰, 300 km, and 30 days. Thermohaline circulation and convection in the North Atlantic and other subpolar seas have the most demanding requirements, and are the most technically challenging because of the reduced T_B/salinity ratio at low seawater temperatures (see below). This can serve as a prime satellite mission requirement, allowing for the others to be met by reduced mission requirements as appropriate. The suite of science requirements can be addressed with a spatial grid resolution of 100 km, observed monthly with a 0.1‰ error (or 1 part in 10 000).

Resolution and Error Sources

Model function **Figure 2** shows that the dynamic range of T_B is about 4 K over the range of typical open-ocean surface salinity and temperature conditions. T_B gradients are greater with respect to salinity than to temperature. At a given temperature, T_B decreases as salinity increases, whereas the tendency with respect to temperature changes sign. The differential of T_B with respect to salinity ranges from -0.2 to -0.7 K per ‰. Corrected T_B will need to be measured to 0.02–0.07 K precision to achieve 0.1‰ resolution. The sensitivity is strongly affected by temperature, being largest at the highest temperatures and yielding better measurement precision in warm versus cold ocean conditions. Random error can be reduced by temporal and spatial averaging. The degraded measurement precision in higher latitudes will be somewhat compensated by the greater sampling frequency from a polar orbiting satellite.

The T_B variation with respect to temperature falls generally between $\pm 0.15\,\mathrm{K}\ ^{\circ}\mathrm{C}^{-1}$ and near zero over a broad S and T range. Knowledge of the surface temperature to within a few tenths of a degree Celsius will be adequate to correct T_B for temperature effects and can be obtained using data from other satellite systems. T_B values for the H and V polarizations have large variations with incidence angle and spacecraft attitude will need to be monitored very precisely.

Other errors Several other error sources will bias T_B measurements and must be either corrected or avoided. These include ionosphere and atmosphere effects, cosmic and galactic background radiations,

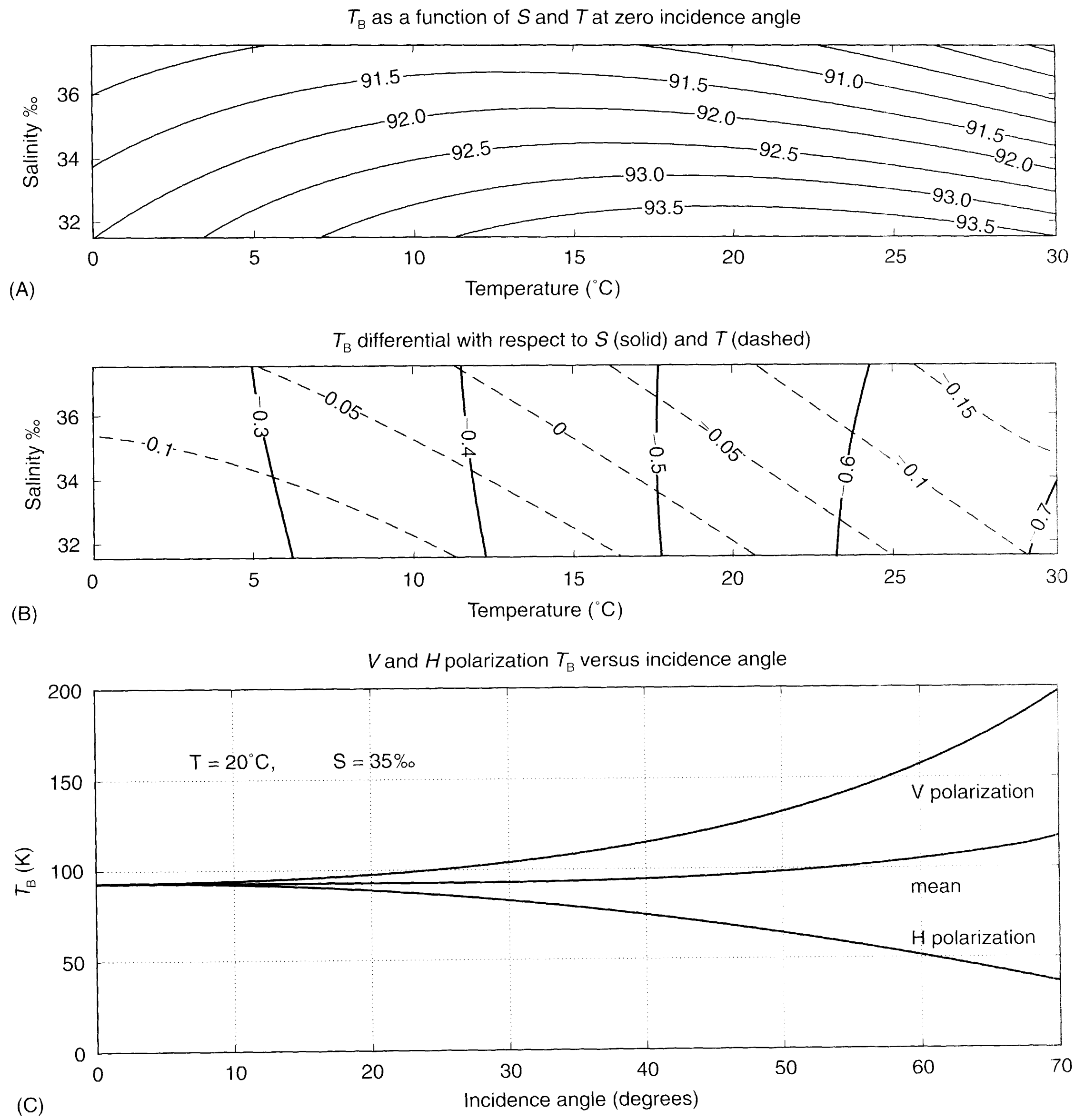

Figure 2 Brightness temperature (T_B) Properties as a function of S, T, and incidence angle for typical ocean surface conditions. (A) T_B contours. (B) T_B derivatives relative to S (solid curves) and T (dashed curves). (C) T_B variation versus incidence angle for H and V polarization. (Calculations based on formulas in Klein and Swift, 1977.)

surface roughness from winds, sun glint, and rain effects. Cosmic background and lower atmospheric adsorption are nearly constant biases easily corrected. An additional correction will be needed when the reflected radiation from the galactic core is in the field of view. The ionosphere and surface winds (roughness) have wide spatial and temporal variations and require ancillary data and careful treatment to avoid T_B errors of several K.

The ionosphere affects the measurement through attenuation and through Faraday rotation of the H and V polarized signal. There is no Faraday effect when viewing at nadir ($\theta = 0$) because H and V emissivities are identical, whereas off-nadir corrections will be needed to preserve the polarization signal. Correction data can be obtained from ionosphere models and analyses but may be limited by unpredictable short-term ionosphere variations. Onboard correction techniques have been developed that require fully polarimetric radiometer measurements from which the Faraday rotation may be derived. Sun-synchronous orbits can be selected that minimize the daytime peak in ionosphere activity as well as sun glint off the surface.

The magnitude of the wind roughness correction varies with incidence angle and polarization, and ranges between 0.1 and 0.4 K/(ms^{-1}). Sea state conditions can change significantly within the few hours that may elapse until ancillary measurements are obtained from another satellite. Simultaneous wind roughness measurement can be made with an onboard radar backscatter sensor. A more accurate correction can be applied using a direct relationship between the radar backscatter and the T_B response rather than relying on wind or sea state information from other sensors.

Microwave attenuation by rain depends on rain rate and the thickness of the rain layer in the atmosphere. The effect is small at the intended microwave frequency, but for the required accuracy the effect must be either modeled and corrected with ancillary data, or the contaminated data discarded. For the accumulation of all the errors described here, it is anticipated that the root sum square will be reduced to 0.1‰ with adequate radiometer engineering, correction models, onboard measurements, ancillary data, and spatio-temporal filtering with methods now in development.

See also

Abrupt Climate Change. Aircraft Remote Sensing. Data Assimilation in Models. El Niño Southern Oscillation (ENSO). El Niño Southern Oscillation (ENSO) Models. Freshwater Transport and Climate. Ocean Circulation. Open Ocean Convection. Primary Production Distribution. Satellite Oceanography, History and Introductory Concepts. Satellite Altimetry. Satellite Passive Microwave Measurements of Sea Ice. Satellite Remote Sensing Microwave Scatterometers. Satellite Remote Sensing of Sea Surface Temperatures. Thermohaline Circulation. Upper Ocean Heat and Freshwater Budgets. Upper Ocean Mixing Processes. Upper Ocean Time and Space Variability. Water Types and Water Masses.

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