

Implications of Satellite Sea-Surface Salinity Observations for Operational Microwave Radiometry

Eric Bayler

Center for Satellite Applications and Research

National Environmental Satellite, Data, and Information Service

National Oceanic and Atmospheric Administration

Room 701

5200 Auth Road

Camp Springs, MD 20746 USA

Abstract- Global satellite sea-surface salinity (SSS) observations are now a reality; consequently, the influences of SSS on operational microwave radiometry need to be considered. At the same time, the in-progress transition of operational agencies from salinity-independent radiative transfer modeling (RTM) to a salinity-dependent RTM exposes non-negligible sources of error and uncertainty in past operational passive microwave retrievals; consequently, the impact of improved modeling of SSS influences on ocean surface permittivity, as a principal component of ocean surface emissivity, is examined. Both reductions and continuing elements of uncertainty due to SSS are explored. Ocean surface emissivity's interwoven dependencies on salinity, temperature, and frequency are highly nonlinear; consequently, impacts due to salinity will depend on the instrument, application, and situation.

INTRODUCTION

With European Space Agency's (ESA) Soil Moisture – Ocean Salinity (SMOS) mission and, soon, the United State National Aeronautics and Space Administration's (NASA) Aquarius mission providing global observations of sea-surface salinity (SSS), a closer look is needed at how salinity is employed in microwave radiometry retrievals. In particular, the radiative transfer models for 1-100 GHz vary notably on how the influence of salinity is represented in the calculation of ocean permittivity (also known as the dielectric constant), thereby affecting the surface emissivity needed for passive microwave retrievals of ocean surface and atmospheric parameters. These differences represent uncertainty in the permittivity and resulting emissivity calculation, which subsequently traces through to uncertainty in the desired retrieval. The choice of permittivity model will also introduce biases. Efforts are in progress to implement a new ocean permittivity model as a component of the new FASTEM4 microwave emissivity model [1] included in the recent release of version 10 of the Radiative Transfer Model for the (Advanced) TIROS-N Operational Vertical Sounder (RTTOV-10) radiative transfer model employed at the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). The FASTEM4 is also on track for operational implementation in the Community Radiative Transfer Model (CRTM) [2] at NOAA in mid-2011. This study examines the non-linear variability of ocean emissivity due solely to the range of SSS and sea-surface temperature (SST) values for representative operational microwave frequencies across zenith angles. The significance of variability observable through SMOS and Aquarius observations is examined with respect to top-of-atmosphere brightness temperature (T_b). Switching permittivity models will lead to a discontinuity in the retrieval record for an instrument, resulting in a need to reprocess an instrument's data record for climatology applications.

The European Centre for Medium-range Weather Forecasts (ECMWF) and UK Met Office operational radiative transfer model (RTTOV-9) employs the ocean permittivity model described in [3] (FASTEM3) for the microwave frequencies within the range of 10-220 GHz. This model is an empirical fit to permittivity measurements of synthetic seawater with a fixed salinity of 35/1000 (equivalent to 35 on the Practical Salinity Scale of 1978 (PSS-78) [4]) for frequencies between 30 and 105 GHz. The model in [3] has no dependency on salinity, which, while approximately true for frequencies above 30 GHz, is clearly not true for frequencies below 30 GHz [5], [6], [7], [8]. Yet, the RTTOV-9 implementation applies this model to frequencies down to 10 GHz, which includes, for example, operational satellite frequencies for the Envisat Microwave Radiometer (MWR), the MetOp Advanced Microwave Sounding Unit-A (AMSU-A), and the U.S. Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager / Sounder (SSMI/S), as well as a number of developmental instruments. Similarly, the U.S. National Oceanic and Atmospheric Administration (NOAA) currently employs the FASTEM3 model in [3] down to 20 GHz, applying the salinity-dependent model in [6] and [7] for frequencies below 20 GHz, down to 3 GHz.

SSS climatology data is exceedingly sparse in both time and space; consequently, the SSS observations currently being provided by the SMOS mission and soon the Aquarius mission are beginning to fill the data void with first ever measurements. The composite of the first SMOS cycle (Fig. 1.a) from [9] clearly depicts much finer detail than is evident in annual climatological composites, as well as monthly climatologies, such as in [10] (Fig. 1.b). ESA's SMOS mission provides global coverage every three days (non-exact-repeat orbit), but spatial and temporal averaging to monthly 200-km resolution data sets is needed to achieve its target accuracy of 0.1 PSS-78. NASA's Aquarius mission has a seven-day exact-repeat orbit and also requires temporal and spatial averaging (monthly 150-km resolution) to achieve its target observation accuracy of 0.2 PSS-78.

Both missions will notably improve both climatological and near-real-time SSS values through vastly improved spatial coverage and, thus, microwave retrievals by improving accuracy and reducing uncertainty.

The paper discusses methodology in Section 2, identifying the role of salinity in emissivity calculations; addresses and compares salinity sensitivities/impacts in the current operational FASTEM3 and the new FASTEM4 in Section 3; discusses the results and implications in Section 4; and provides a summary and conclusions in Section 5.

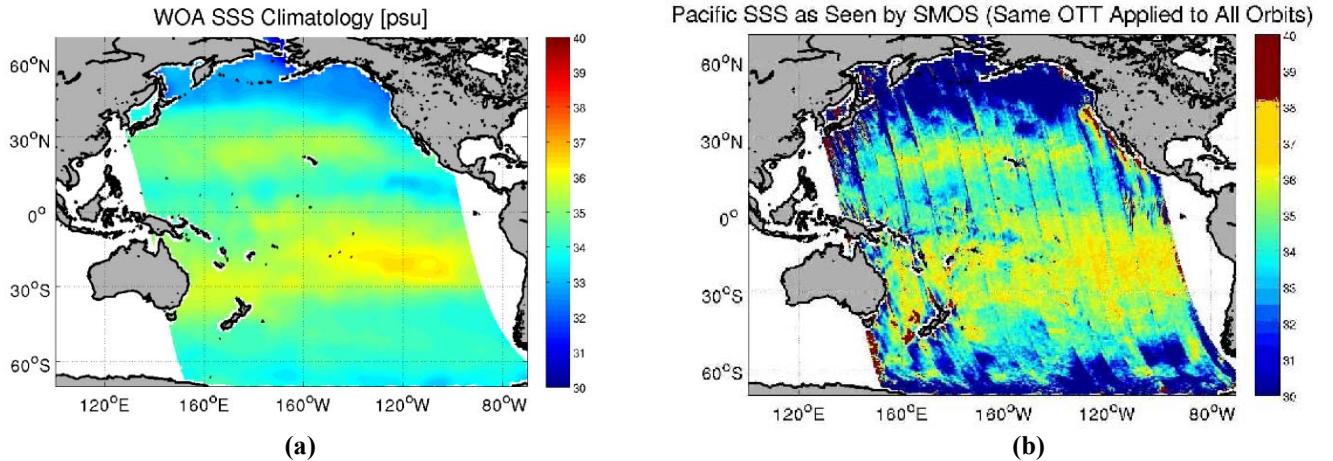


Fig. 1 Global Salinity: a) World Ocean Atlas climatology for January [9], [10], b) SMOS Cycle-1 [9], produced by J. Tenerelli, CLS, Brest, 10 Feb 2010.

ANALYSIS APPROACH

To understand the role of SSS in passive microwave radiometry, a brief simplified description of the factors and relationships follows. A passive satellite microwave instrument measures brightness temperature (Tb), which comprises contributions from the surface and the atmosphere. Since atmospheric components are not a function of salinity, they will not be discussed. The ocean surface component of Tb can be described in terms of the ocean surface emissivity, the surface temperature, the transmissivity of the atmosphere through which the component contribution must pass. Generically, from [11],

$$Tb_p(\theta) = Tb^{\uparrow}(\theta) + \tau_{atm}[E_p(\theta)T_{sfc} + Tb_p^s(\theta)], \quad (1)$$

where $Tb_p(\theta)$ is the polarized top-of-atmosphere brightness temperature, θ is the zenith angle (incident angle), p is polarization (V-vertical or H-horizontal), $Tb^{\uparrow}(\theta)$ is up-welling atmospheric brightness temperature, τ_{atm} is atmospheric transmittance, $E_p(\theta)$ is polarized surface emissivity, and $Tb_p^s(\theta)$ is reflected sky brightness temperature. Focusing on the term with salinity dependence, a generic equation for emissivity [12] [13] comprises emissivity from the flat ocean surface (ϵ_{flat}) plus modifications to that emissivity due to a rough surface (ϵ_{rough}), e.g., wind-driven waves, and due to foam (ϵ_{foam}):

$$\epsilon_{sfc}(v, \theta, p, SST, SSS, U, \phi) = \epsilon_{flat}(v, \theta, p, SST, SSS) + \epsilon_{rough}(\epsilon_{flat}, U, \phi) + \epsilon_{foam}(U, \theta), \quad (2)$$

where v is frequency, θ is zenith angle, SSS is sea-surface salinity, SST is sea-surface temperature, p is polarization, U is surface wind speed, and ϕ is wind direction. The flat surface emissivity component, the contribution due to the ocean permittivity, contains the sensitivity to salinity. The Fresnel reflectivity equations, as implemented in FASTEM3 and FASTEM4 and applied to the complex values of ocean microwave permittivity to produce polarized emissivity values, are:

$$E_v = \left(\frac{P_r \cos \theta - \sqrt{P_r - 1 + \cos^2 \theta}}{P_r \cos \theta + \sqrt{P_r - 1 + \cos^2 \theta}} \right)^2 + \left(\frac{P_i \cos \theta - \sqrt{P_i - 1 + \cos^2 \theta}}{P_i \cos \theta + \sqrt{P_i - 1 + \cos^2 \theta}} \right)^2, \quad (3)$$

$$E_h = \left(\frac{\cos \theta - \sqrt{P_r - 1 + \cos^2 \theta}}{\cos \theta + \sqrt{P_r - 1 + \cos^2 \theta}} \right)^2 + \left(\frac{\cos \theta - \sqrt{P_i - 1 + \cos^2 \theta}}{\cos \theta + \sqrt{P_i - 1 + \cos^2 \theta}} \right)^2, \quad (4)$$

where ϵ_v and ϵ_h are the vertically and horizontally polarized Fresnel reflectivity equations, respectively for the emissivity; P_r and P_i are the real and imaginary components, respectively, of the ocean permittivity, and θ is zenith angle.

Reference [14] provides the equation form for the ocean permittivity

$$\varepsilon = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1+j2\pi\nu\tau} - j\frac{\sigma}{2\pi\nu\varepsilon_0}, \quad (5)$$

where ε is the complex permittivity, ε_{∞} is the high-frequency permittivity, ε_s is the static permittivity, ε_0 is the permittivity of free space, τ is the relaxation time, ν is the electromagnetic frequency, σ is the ionic conductivity, and π is the constant pi. Subsequent implementations, e.g., FASTEM3 [3] and FASTEM4 [1] have introduced a second middle term, same in form as the one above, to accommodate a second relaxation time. Multiple empirical models have been formulated for the permittivity of seawater, e.g., [1], [3], [5], [6], [7], [8], typically with ε_s , τ , and σ having a salinity dependency. Consequently, new and improved SSS data directly impact the core of passive microwave observations over the ocean.

For this study, the FASTEM3 [3] and FASTEM4 [1] empirical permittivity models, as well as the model described in [6] were coded and used to compute the permittivity across the range of frequencies sensitive to salinity (1-100 GHz), and spanning a broad range for SST (270°-310° K) and SSS (0-42 PSS-78). The model in [6] (for frequencies less than 20 GHz) in combination with the model in [3] (for frequencies greater than or equal to 20 GHz) form NOAA's current operational CRTM. For comparison and to isolate the influences of salinity, the depicted results assume: nadir-viewing (zenith angle = 0), flat sea (no wind), no foam, and an instrument footprint uncontaminated by land, precipitation, sea ice, etc. Thus, resulting emissivity would comprise only the permittivity contribution, allowing the salinity influences to be traced to Tb variations. Subsequently, the influence of salinity on emissivity across zenith angles is examined. Specific operational microwave frequencies are examined to assess the uncertainty introduced by salinity accuracy and variability issues. Because the FASTEM4 code has not yet been implemented in the operational CRTM, the top-of-atmosphere (TOA) Tb changes due to the new model are computed by evaluating the percent change between the current and new emissivity models and then applying corresponding change percentages to the current TOA Tb results.

RESULTS

Employing the FASTEM3 model as a base reference, given that this model does not incorporate a salinity dependency, the real (Fig. 2.a) and imaginary (Fig. 2.b) components of ocean surface permittivity are plotted as a function of salinity and frequency for a selected temperature (SST=288K), exposing the shape of the permittivity's dependency on frequency. Approximating that FASTEM3 and FASTEM4 have closely similar representations for ocean permittivity SST and frequency dependencies, the difference between the salinity-dependent FASTEM4 and FASTEM3 was computed (Figs. 2.c, d) to highlight the now modeled influence of salinity on permittivity. Fig. 2 principally illustrates where the revised ocean permittivity model in [1] introduces salinity effects, recognizing that improvements to the SST and frequency dependency representations are also incorporated. The modifications have the largest difference at the lowest frequencies and for lower salinities due to the known decreasing effect of salinity on permittivity as frequency increases, particularly above 20 GHz, and the known assumption of a constant 35 PSS-78 salinity in FASTEM3.

What is important is how the salinity modifications to the empirical permittivity model translate into changes in polarized emissivity and Tb . For nadir-viewing calculations, only the vertical polarization results are shown. It is important to note that the salinity impact has a temperature dependency overlaying the frequency dependency. The salinity-dependent emissivities at two SSTs representing a range of possible temperatures, 275° K (2° C) and at 305° K (32° C), are differenced to illustrate a linear approximation of the dependency. Getting at this relationship first requires that frequency-only effects be removed; consequently, the frequency-dependent emissivity at salinity 35 PSS-78 and specific temperature is subtracted from each of the two specific-temperature salinity-dependent fields. Subsequently, the two temperature-specific salinity-dependent fields are differenced to produce Fig. 3. It is noted that Fig. 3 differences are relative to the emissivity produced with a salinity of 35 PSS-78. Another way to view the temperature-dependent salinity uncertainty is to examine how, within a salinity range commonly observed in the open ocean (e.g., approximately 30 – 38 PSS-78), an instrument-specific Tb dramatically changes as temperature changes. At nadir zenith angle and across this typical range of open-ocean surface salinities, the Special Sensor Microwave Imager/Sounder's (SSMI/S) vertically-polarized Channel 14 (22.235 GHz) Tb for SST values 275°, 280°, 285°, 290°, 295°, and 300° K, varies, respectively, 0.22°, 0.51°, 0.58°, 0.65°, 0.71°, and 0.76° K, which, in the absence of adequate SSS data, results in significant non-linear SSS-dependent uncertainty for Tb retrievals.

Fig. 4 further depicts salinity's impact on emissivity as a function of zenith angle, for a specific frequency, 23 GHz, at 273°K (0° C), 288° K (15° C), and 303° K (30° C). The freshwater emissivity for the same parameters was subtracted out to highlight the salinity-dependent influence. Observe how the character of salinity dependency, for the polarized emissivity as a function of zenith-angle, changes with increasing temperature. Clearly, the uncertainty introduced by non-representative salinity values employed in retrievals is highly-dependent on the instrument and the specific values of SSS and SST relevant to the retrieval.

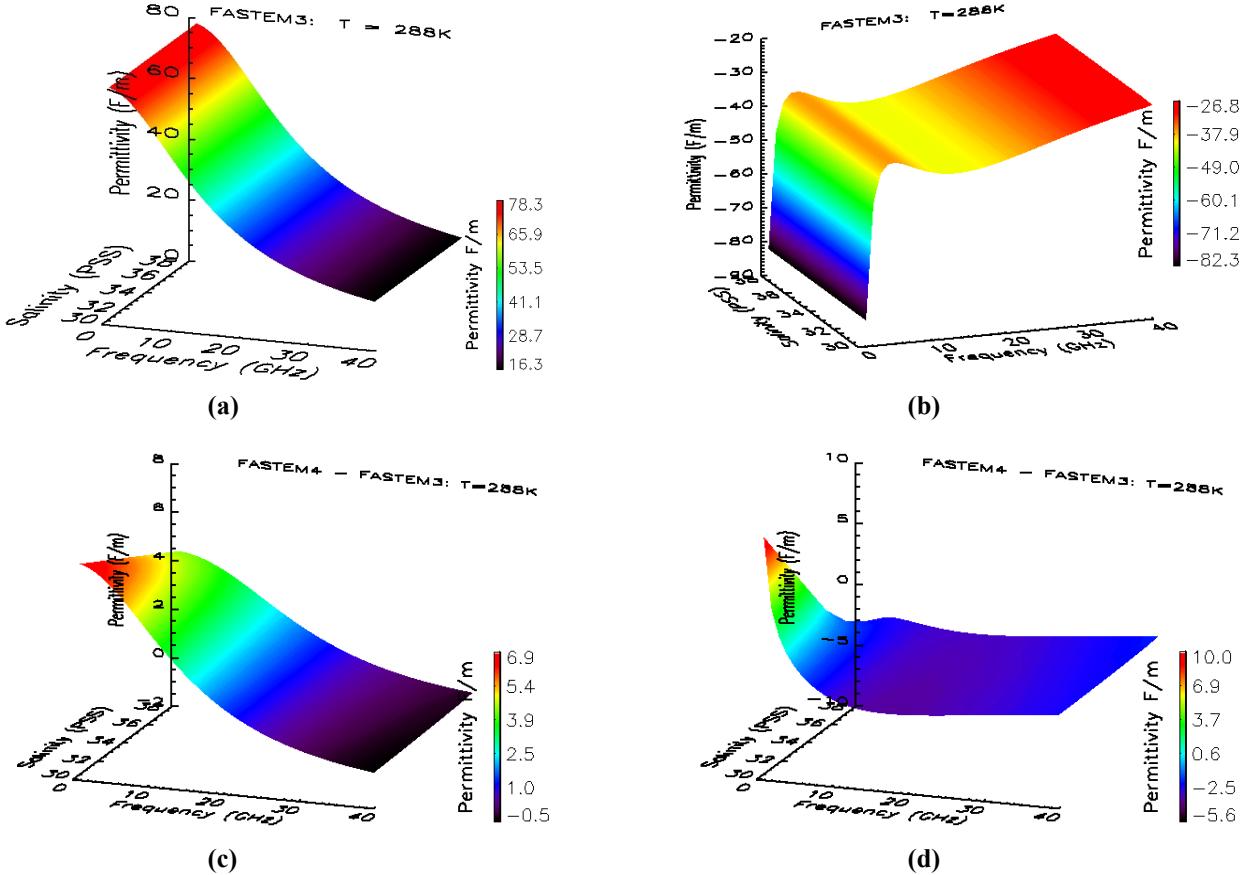


Fig. 2 Modeled Ocean Permittivity at 288° K (15° C): FASTEM-3 a) real component; b) imaginary component; and difference (FASTEM-4 – FASTEM-3) c) real component; and d) imaginary component.

The basic character of the surfaces remains similar as frequency changes (not shown). Differences can be described as shifts along a complicated surface, with the domain boundaries capturing slightly different aspects.

Using the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) vertically-polarized channel at 23.80 GHz as an example for the impact from transitioning from FASTEM3 to FASTEM4, the emissivity computed for the range of expected SST and SSS will change as depicted in Fig. 5.a, with the resulting maximum change in emissivity within typical open ocean salinities (30-38 PSS-78) being 0.0147. While the differences in emissivity appear small, what matters are the resulting changes in T_b (Fig. 5.b). The addition of SSS sensitivity to FASTEM4 results in modeled AMSR-E T_b values varying by 0.47° K at 273° K (0° C), 0.63° K at 288° K (15° C), and 0.78° K at 303° K (30° C), across typical open ocean salinities (30-38 PSS-78). Across a broader range of observed salinities, 0 to 42 PSS-78, accommodating the lower salinities observed due to river outflows and freshwater lenses, T_b at a given temperature can vary as much as 2.07° K at 273° K (0° C), 1.52° K at 288° K (15° C), and 2.57° K at 303° K (30° C). These impacts are computed for a frequency that is considered to be insensitive to salinity within the current operational microwave emissivity models at NOAA's National Weather Service, the ECMWF, and the UK Met Office!

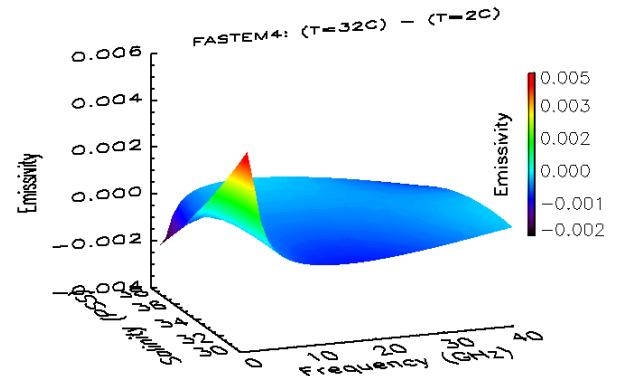


Fig. 3 FASTEM-4 temperature-dependent salinity influence on emissivity (no wind, flat sea, nadir zenith angle, vertical polarization) over a typical open-ocean salinity range (30-38 PSS-78), computed as the difference between emissivity for SSTs 305° K (32° C) and 275° K (2° C), with the frequency-only effects removed and plotted as a difference with respect to the emissivity produced by a salinity of 35 PSS-78.

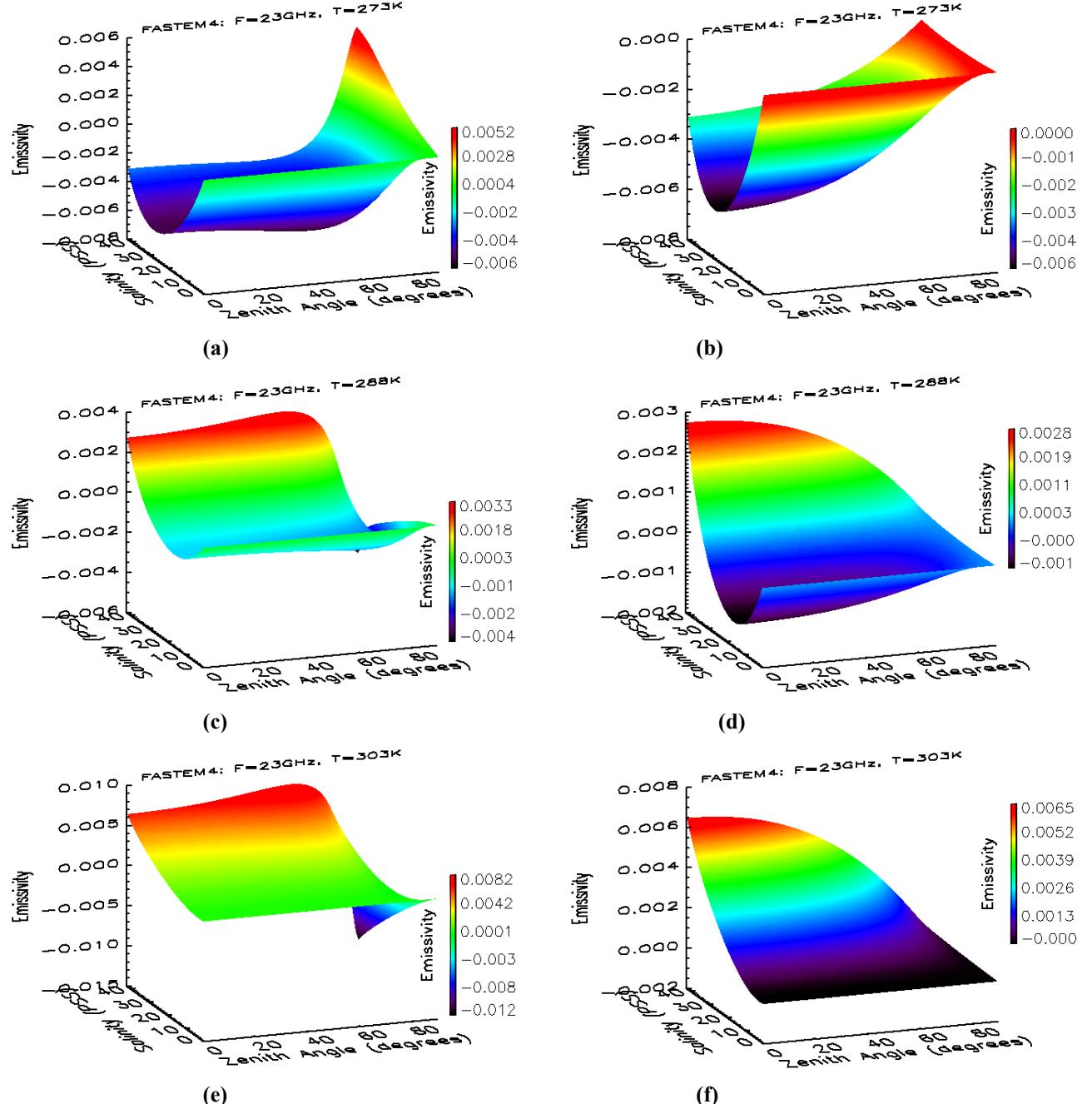


Fig. 4 FASTEM4 salinity impact on emissivity (no wind, flat sea) as a function of zenith angle for 23 GHz at: 273° K (0° C) a) vertical polarization, b) horizontal polarization; 288° K (15° C) c) vertical polarization, d) horizontal polarization; and 303° K (30° C) e) vertical polarization, f) horizontal polarization.

DISCUSSION

Operational microwave radiometry has an interest in understanding and reducing the uncertainty in retrievals due to salinity and its variability. Fig. 6 highlights the impact (FASTEM4 – FASTEM3) of adding SSS sensitivity to emissivity modeling as a function of SSS and SST at representative frequencies for operational instrument channels: 11 GHz for AMSR-E, WindSat, and TMI; 19 GHz for AMSR-E, WindSat, SSMIS, Jason MWR, and TMI; 23 GHz for AMSR-E, WindSat, SSMIS, AMSU-A2, ATMS, Jason MWR, and TMI; and d) 37 GHz for AMSR-E, WindSat, SSMIS, AMSU-A2, ATMS, Jason MWR, and TMI. Understanding and reducing the uncertainty in passive microwave retrievals due to salinity involves addressing several different

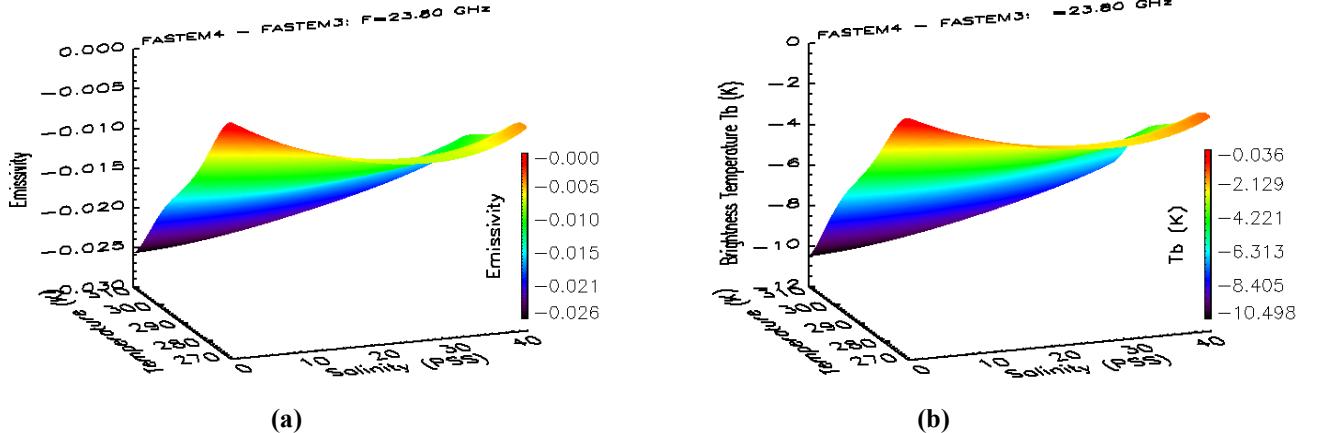


Fig. 5. Difference (FASTEM4 – FASTEM3) with respect to SSS and SST at 23.80 GHz for the AMSR-E instrument (no wind, flat sea, nadir zenith angle, vertical polarization): a) emissivity, b) brightness temperature T_b (K).

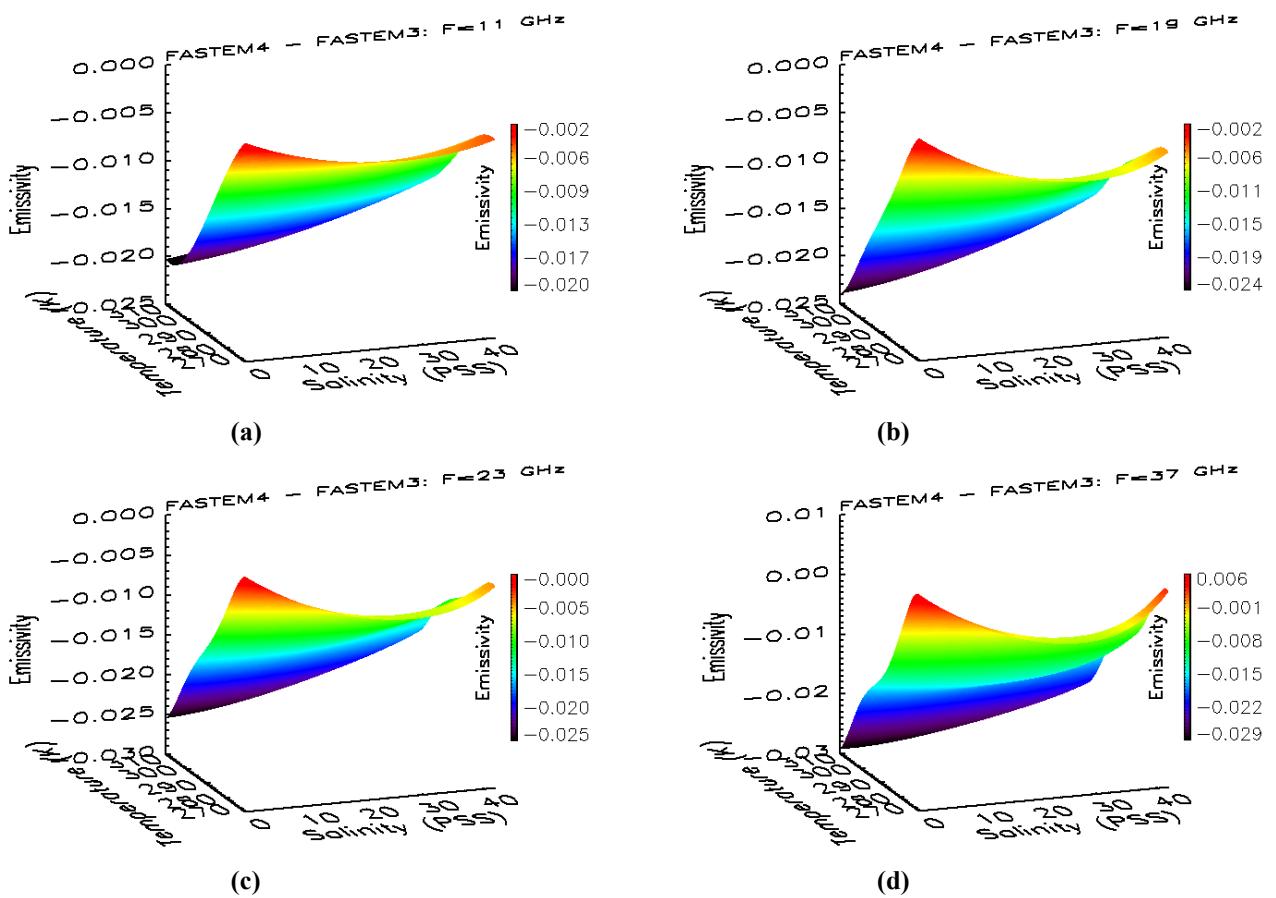


Fig. 6. Impact (FASTEM4 – FASTEM3) of adding SSS sensitivity to FASTEM4 emissivity as a function of SSS and SST at representative operational frequencies (no wind, flat sea, nadir zenith angle, vertical polarization): a) 11 GHz, b) 19 GHz, c) 23 GHz, and d) 37 GHz.

aspects of the retrieval process. First, is employing better estimations of SSS. Until the availability of SMOS SSS data, if incorporating SSS in the emissivity calculation, a climatological data set had to be used. SSS climatology data is exceedingly sparse in both time and space, contributing to SSS-dependent uncertainty when using climatological values for retrievals. As previously depicted in Figs. 1.a and 1.b, the additional resolution of climatological SSS features, including seasonal variability that will result from updating the current SSS climatologies with satellite observations, will notably reduce the uncertainty

introduced by using climatological values. Second, there is uncertainty introduced into retrievals from the satellite SSS retrieval accuracy. NASA's Aquarius mission objective for SSS observation accuracy is 0.2 PSS-78 and ESA's SMOS's target accuracy is 0.1 PSS-78, both of which will differ from *in situ* observations, *e.g.*, ARGO float data, due to differences between the skin measurements (less the 1 cm penetration) by the satellite instruments and the near-surface *in situ* measurements, which are typically taken between 1m and 5m of depth. For passive microwave retrievals, the skin SSS and SST values are what are needed for the emissivity calculation. Evaporation and precipitation, in conjunction with surface heating, convective mixing, and mechanical mixing, as tempered by spiciness and vertical stability, potentially introduce variances between the skin and near-surface observation and, thus, uncertainty when using salinity data that include *in situ* observations. Third, there is uncertainty inherently associated with an ocean permittivity model because it is empirically computed; consequently, the emissivity values resulting from different models of the SSS-SST-frequency domain serve to illustrate and quantify uncertainty associated with the choice of empirical ocean permittivity model. Examining how the emissivity varies with respect to varying SSS across the SST and frequency domains, in conjunction with the choice of salinity input used (*e.g.*, fixed value, *in situ* climatology, near-real-time satellite observation), is one piece to evaluating uncertainty. SSS-dependent emissivity variability at a specified temperature for the selected operational frequency provides an initial estimate of uncertainty that is constrained by the range of salinities being considered. This uncertainty due to salinity is modified by any uncertainty associated with the knowledge of the SST; although, this secondary uncertainty will be relatively small, given the current ability to evaluate the permittivity model input SST (approximately 0.5°-1° K). The uncertainty can be refined through consideration of the accuracy of input salinity value. The spatial and temporal resolutions of the salinity value further inform the evaluation of uncertainty for a specific sensor or application. The uncertainty exposed by differences between comparable empirical ocean permittivity models needs to be added to the uncertainty from within an ocean permittivity model. Added to this uncertainty is uncertainty associated with the skin SSS measurement, to include measurement accuracy and MW observation latency with respect to the SSS observation as modified by influences to the skin SSS, *e.g.*, precipitation, evaporation, ice melt, runoff, and mixing. Understanding, quantifying, and constraining SSS-related uncertainty in passive microwave radiometry are essential when assimilating the microwave observations into numerical models of both the ocean and atmosphere. This analysis highlights the need to integrate SSS data, ideally the new satellite SSS observations once they are refined, into the operational passive microwave data assimilation system.

SUMMARY

Sea-surface salinity has a non-negligible role in microwave radiometry, particularly for frequencies less than about 30 GHz, introducing uncertainty to the ocean surface emissivity of passive microwave retrievals through the representativeness in space and time of the salinity values used and as functions of temperature and frequency in the empirical ocean permittivity model employed. SSS climatology data is exceedingly sparse in both time and space, contributing to significant SSS-dependent uncertainty when using climatological values for retrievals, yet using these values is preferable to the simple assumption of a constant 35 PSS-78, as is used in the operational FASTEM3 emissivity model employed by the UK Met Office and ECMWF. FASTEM3's assumption of no salinity dependence notably mischaracterizes ocean permittivity at the lower microwave frequencies. The new FASTEM4 helps address the complex relationships between salinity, temperature, frequency, and permittivity, leading to improved representation of ocean surface emissivity and resulting calculated brightness temperatures. The next challenge is employing improved SSS observations in the retrieval process. ESA's SMOS mission and NASA's Aquarius mission provide the opportunity for improved climatological data sets and a first step towards the integration of near-real-time SSS observations into passive microwave retrievals. While salinity influences may be relatively small, but not negligible, across a typical range of open-ocean salinities, passive microwave retrievals need to be alert to ocean conditions that may adversely affect atmospheric retrievals, as well as ocean retrievals. The salinity range can dramatically increase in the presence of a significant freshwater source, such as a major river plumes or freshwater lenses produced by precipitation. The freshwater, being lighter in density, will remain at the surface, altering the surface emissivity and creating a bias in the observed brightness temperature.

In summary, it is seen, as shown by many others, that salinity has progressively stronger influence with decreasing microwave frequency, with the strongest influence on brightness temperature around 1 GHz. For a specific frequency, plotting emissivity as a function of temperature and salinity clearly depicts at any selected temperature the uncertainty introduced by either the accuracy and timeliness of the salinity measurement used or the range of salinities incorporated within the climatology employed. That uncertainty, in conjunction with salinity as a factor relevant to the viewing angle and channel polarization employed, translates directly to instrument-specific and application-specific brightness temperature uncertainty.

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