Surface emissivity effects on thermodynamic retrieval of IR spectral radiance

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ABSTRACT

The surface emissivity effect on the thermodynamic parameters (e.g., the surface skin temperature, atmospheric temperature, and moisture) retrieved from satellite infrared (IR) spectral radiance is studied. Simulation analysis demonstrates that surface emissivity plays an important role in retrieval of surface skin temperature and terrestrial boundary layer (TBL) moisture. NAST-I ultraspectral data collected during the CLAMS field campaign are used to retrieve thermodynamic properties of the atmosphere and surface. The retrievals are then validated by coincident in-situ measurements, such as sea surface temperature, radiosonde temperature and moisture profiles. Retrieved surface emissivity is also validated by that computed from the observed radiance and calculated emissions based on the retrievals of surface temperature and atmospheric profiles. In addition, retrieved surface skin temperature and emissivity are validated together by radiance comparison between the observation and retrieval-based calculation in the "window" region where atmospheric contribution is minimized. Both simulation and validation results have lead to the conclusion that variable surface emissivity in the inversion process is needed to obtain accurate retrievals from satellite IR spectral radiance measurements. Retrieval examples are presented to reveal that surface emissivity plays a significant role in retrieving accurate surface skin temperature and TBL thermodynamic parameters.

Keywords: Remote sensing, hyperspectrum, inversion, surface skin temperature and emissivity, TBL moisture.

1. INTRODUCTION

The determinations of terrestrial surface skin temperature and terrestrial boundary layer (TBL) moisture are two of the most important objectives in satellite remote sensing for Earth observation. High accuracy of these parameters is mandatory to global change monitoring, global climate research, numerical model initialization for weather forecasts, etc.[1-3]. Long-term and large-scale observations needed for global change monitoring and other research can only be supplied by remote sensing[4]. Future satellite remote sensors for Earth observation, such as the Interferometer Atmospheric Sounding Instrument (IASI) and the Cross-track Infrared Sounder (CrIS) are in development. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed Interferometer (NAST-I) was designed to provide radiometric measurements similar to those of satellite sensors[5].

The retrieval accuracy of the skin temperature and lower tropospheric moisture can be affected by several minor, but significant, contributors such as trace gases, aerosols, and surface emissivity[6]. Surface emissivity (ε) is often used as a constant in the retrieval process for satellite measurements due to lack of emissivity knowledge and computational time. A fast and accurate inversion algorithm which becomes critical when dealing with high-spatial and ultraspectral resolution remote sounding data has been developed[7]; and the performance of this technique in retrieving the surface emissivity has been evaluated[8]. This algorithm retrieves surface emissivity while simultaneously accounting for accurate skin temperature, TBL moisture and temperature retrievals. The scope of this letter is to illustrate the sensitivity of the skin temperature and lower tropospheric water vapor retrieval accuracy to the surface emissivity from an infrared nadir-observing Fourier transform spectrometer (such as NAST-I, IASI, and CrIS). Measurements made by NAST-I during the

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Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) field experiment[9] during the summer of 2001 are used to demonstrate the retrieval methodology and surface emissivity effects on surface skin temperature and lower tropospheric moisture retrievals in conjunction with some validations.

2. SENSITIVITY ANALYSIS

Assuming that the contributions to the observed spectra can all be separated into the upwelling atmospheric and surface emission as well as upwelling surface reflected downward atmospheric radiation, then it is possible to determine the surface skin temperature and emissivity with an additional assumption that the surface radiates as either a specular or diffusive reflector. Given a set of historical radiosonde measurements (with assigned surface prosperities) and associated simulated spectral radiance, the relationship between an atmospheric state with surface properties and associated radiances is expressed statistically in terms of regression coefficients. Radiance is calculated from the radiosonde atmospheric state and assumed surface properties. The surface emissivity spectrum assigned for each radiosonde profile is randomly selected from a set of laboratory measured emissivity spectra[10] for a wide variety of surface types. Using amplitudes of radiance eigenvectors as the predictors filters the radiance noise and effectively stabilizes the retrieval. Laboratory measured emissivity spectra for a wide variety of surface types are used to compute the emissivity eigenvectors and the eigenvector amplitudes which are actually used in the statistical training; currently the first 5 amplitudes are used to represent a surface emissivity spectrum. The surface emissivity eigenvector amplitudes, the surface temperature, and the atmospheric parameters are then predicted using the radiance eigenvector amplitudes derived from NAST-I measured radiances[7].

Radiosonde training profiles from 1 June 2000 to 1 August 2000 for the CLAMS field experiment were randomly selected (totaling 778)[11]. Radiosonde-station latitudes were from 25º N to 45º N, and longitudes were from 59º W to 85º W. Two sets of NAST-I radiances were simulated under cloud and aerosol free conditions to compute associated regression coefficient matrices: one was simulated with the surface emissivity equal to one while another was simulated with randomly selected surface emissivity spectrum from a wide variety of surface types suitable for the CLAMS geographical location. Simulated NAST-I spectral radiance from a radiosonde with the channels used for retrieval highlighted in black is shown in Figure 1a. The mean surface emissivity spectrum for this set of laboratory measured emissivity spectra is plotted in Figure 1b; the vertical bars show the STD (standard deviation) of the dataset with a wide diversity of surface types including a variety of water, see foam, Indian grass, coniferous soil, deciduous soil, sandstone, soil float, green whitepine needles, and dead whitepine needles.
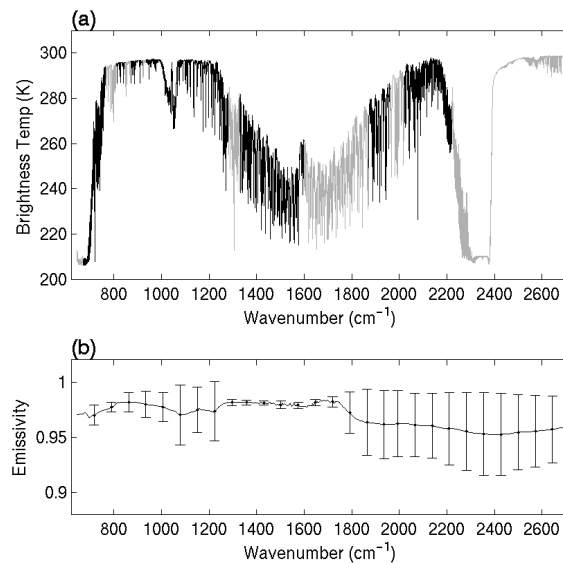

Figure 1. (a) Simulated NAST-I spectral radiance from a radiosonde with the channels used for retrieval highlighted in black. (b) The mean surface emissivity spectrum for a set of laboratory measured emissivity spectra for a wide variety of surface types suitable for the CLAMS geographical location. The vertical bars show the STD of the emissivity for this dataset.

Two sets of retrievals are produced over a set of artificial but realistic radiances with instrument noise included using physical regression with and without variable surface emissivity. Statistical analysis results from these samples for water vapor retrieval RMSE (root-mean-square-error) profiles produced by eigenvector regression retrievals are shown in Figure 2a. When the emissivity is variable in the retrieval scheme, the RMSE of the water vapor mixing ratio retrieval at an altitude below 2 km is reduced. It is noted that the temperature profile RMSE is changed insignificantly. In similar statistical retrieval analysis, the RMSE of the surface skin temperature is improved by 0.36º K (i.e., from 0.68º K to 0.32º K). The retrieved emissivity can then be compared with that initially used in the radiance simulation. RMSE of surface emissivity produced from the simultaneous eigenvector regression retrieval is plotted in Figure 2b. A relatively large emissivity RMSE in the shortwave region (i.e., from 1750 cm-1 and beyond) may be explained by (1) a relatively larger standard deviation in the emissivity database, (2) fewer window channels in the shortwave region, and (3) relatively lower instrumental signal-to-noise. Nevertheless, these simulated results imply that simultaneously retrieved surface emissivity improves the retrieval accuracy of skin temperature and TBL moisture.
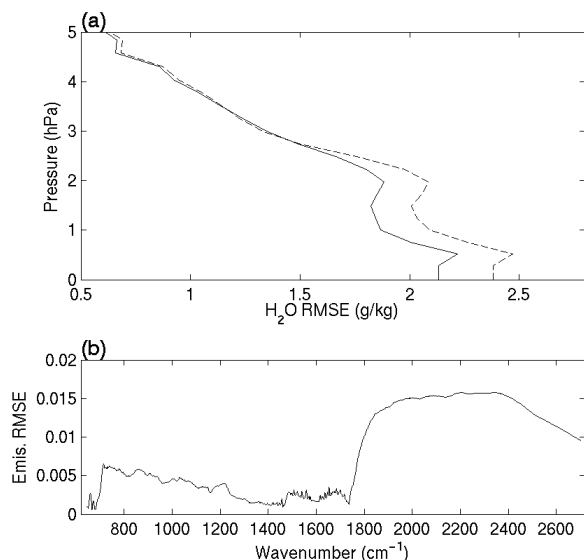

Figure 2. (a) Water vapor retrieval RMSE profile produced by the retrieval for dependent samples with and without variable surface emissivity as shown by the solid and dashed curves, respectively. (b) RMSE of surface emissivity produced from the simultaneous retrieval.

3. NAST-I RETRIEVAL, VALIDATION, AND DISCUSSION

One of the NAST-I flights during the CLAMS field campaign (~16:00 UTC, 14 July 2001) is used here to demonstrate the retrieval results using the technique described above. A full set of retrievals from the same NAST-I flight can be found elsewhere[9]. The observations covering different surface types (e.g., land, bay, and ocean) were taken during local daytime under mostly cloud-free conditions. Retrieved surface skin temperature, emissivity at 11 μm, and at 8.6 μm are shown in Figures 3a, 3b, and 3c, respectively. These images are combined by three flight tracks parallel to longitude lines. The skin temperatures change from the relatively warmer land to the cooler open ocean. The surface emissivity distribution shows expected separation of land and water along the coastline. The Chesapeake Lighthouse (i.e., NOAA buoy site CHLV2 at 36.91º N Latitude and 75.71º W Longitude) is indicated by an open triangle, where in-situ measurements were made (i.e., sea surface temperature, radiosonde).

Data from a small area surrounding the Chesapeake Lighthouse (within ±0.1º latitude and longitude) are used to validate the retrievals. Shown in Figure 4a is standard deviation of difference (STDE) between observed radiances and those calculated using the retrievals (over 91 spectra) from the longwave "window" region where the atmospheric effect is minimal. Spikes are due to fast model errors of spectroscopy and trace gases. The STDE is equivalent to the instrument noise level, which indicates that the surface properties are accurately obtained. Retrieved surface emissivity is also validated by that computed

from the observed radiance and calculated emissions based on the retrievals of surface temperature and atmospheric profiles. The emissivity of some "window" channels has been derived using observed radiance R_{obs} and the radiative transfer calculation using the retrieval. The radiative transfer equation can be written as $\varepsilon = (R_{obs} - A^\uparrow - A^\downarrow) / (B_s \tau_s - A^\downarrow)$, where $A^\uparrow$ and $A^\downarrow$ are upwelling and downwelling atmospheric emissions, and $B_s \tau_s$ is surface emission (B_s and τ_s are surface Planck radiance and surface transmittance, respectively). These terms (i.e., $A^\uparrow$, $A^\downarrow$, B_s, and τ_s) can be calculated by using retrieved surface skin temperature and atmospheric profiles of temperature and moisture.
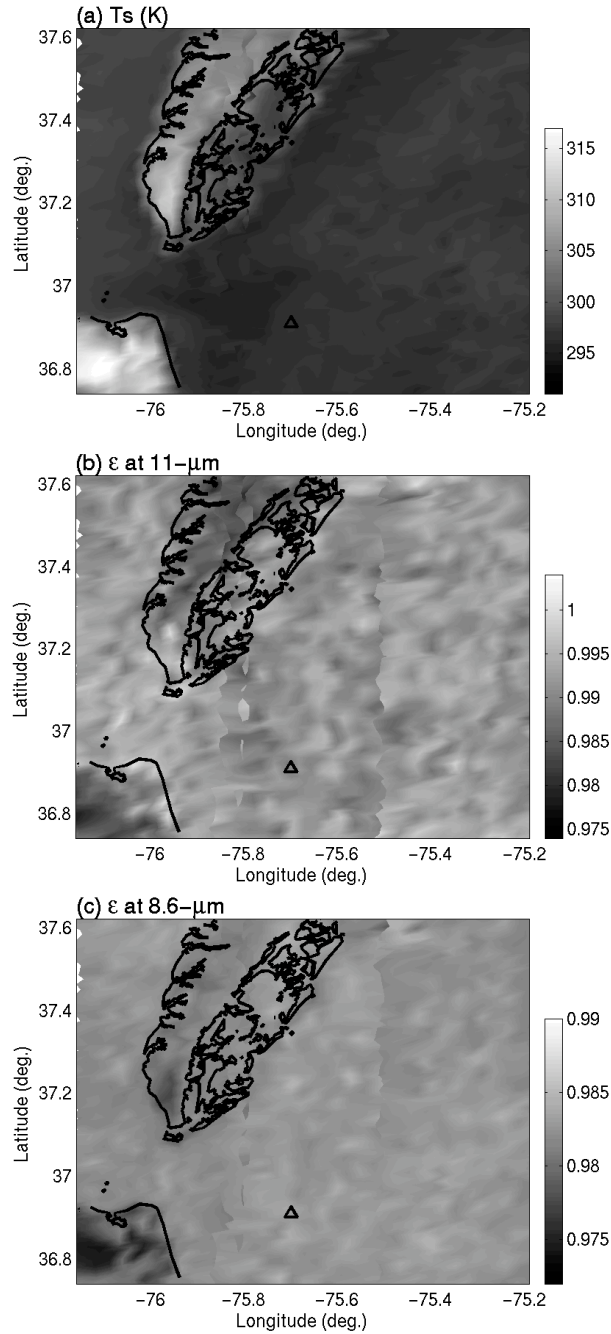

Figure 3. Retrievals of (a) surface skin temperature, (b) surface emissivity at 11 μm, and (c) surface emissivity at 8.6 μm from NAST-I observations on 14 July 2001. The Chesapeake Lighthouse site is shown by the open triangle.

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In Figure 4b, the emissivity values of these "window" channels are plotted (in dots) in conjunction with NAST-I retrieval mean emissivity surrounding the Chesapeake Lighthouse (dashed curve) and laboratory measured seawater emissivity (solid curve) for comparison. The differences between these emissivity values are within the expected uncertainty as shown in Figure 2b. It is noticed in Figure 4b that retrieved emissivity in the shortwave is more deviated from laboratory measurement than that of in the longwave. This is expected as discussed earlier with the simulations (Figure 2b). In addition, this set of data was collected during the daytime and the influence of solar radiation is not accounted for in the retrieval. Although the selected retrieval channels are not significantly affected by the solar radiation, the negligence of solar radiation can introduce an additional error in the emissivity.
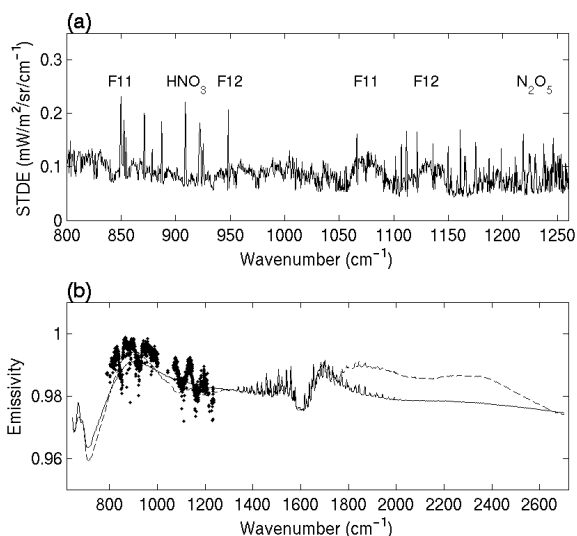

Figure 4. (a) Standard deviation of the difference between observed radiances with those calculated using the retrievals. Spikes are due to the fast forward model error. (b) Seawater emissivity comparison between laboratory measured (solid curve), NAST-I retrieved mean (dashed curve), and "window" channel inferred (dots).

NAST-I retrieved mean skin temperature (within ±0.02° latitude and longitude of the buoy) is 296.89° K with a STD of 0.21° K, which is 0.56° K cooler than the sea surface temperature (i.e., the bulk sea surface temperature) of 297.45° K coincidently measured at NOAA buoy site CHLV2. The retrievals without variable surface emissivity (i.e., assuming $\varepsilon = 1$) produce a mean sea skin temperature of 295.91° K with a STD of 0.19° K, which is 1.54° K cooler than the sea surface temperature of the NOAA buoy measurement. The sea skin temperature retrieved from NAST-I radiance is expected to be cooler than the sea surface temperature, explained by strong evaporative cooling[2, 12]. A bias (normally within a few tenths of a degree) existing between infrared sensed and in-situ measured sea surface temperature is the physical difference between sea surface skin temperature and in-situ sea surface temperature measured at some depth[2]. An unexpected 1.54° K cooler temperature is mainly introduced by the assumption of a constant surface emissivity ($\varepsilon = 1$). Therefore, the accurate skin temperature is explained by retrieval improvement to include variable surface emissivity.

Retrieved atmospheric temperature and moisture profiles are also validated by a radiosonde released at the Chesapeake Lighthouse. In Figure 5a, the mean profiles of moisture retrievals surrounding the Chesapeake Lighthouse produced with and without variable surface emissivity are plotted in dashed and dash-dotted curves, respectively, in comparison with the radiosonde plotted in a solid curve. Figure 5b plots the difference (i.e., retrieval - radiosonde). It is noticed that NAST-I moisture retrieval accuracy is up to 15%, and the emissivity over the water has a relatively small impact on the retrieval. The water vapor retrieval with variable surface emissivity shows a better agreement with the radiosonde, especially in the TBL. The horizontal increment distributions (i.e., discrepancy) of skin temperature and water vapor at 900 hPa (i.e., ~1 km) from the retrievals conducted without variable surface emissivity to those conducted with variable surface emissivity are plotted in Figures 6a and 6b, respectively. These discrepancies are associated with the surface emissivity distribution shown in Figures 3b and 3c. The discrepancy is more pronounced over the land where the retrieved land emissivity is further deviated from one.
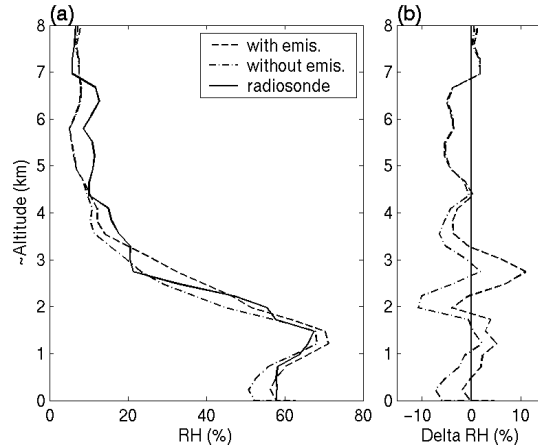
Figure 5. (a) Inter-comparison between the radiosonde (solid curve) and retrievals conducted with and without variable surface emissivity (dashed and dash-dotted curves, respectively) over sea water. (b) The difference between the radiosonde and retrievals.
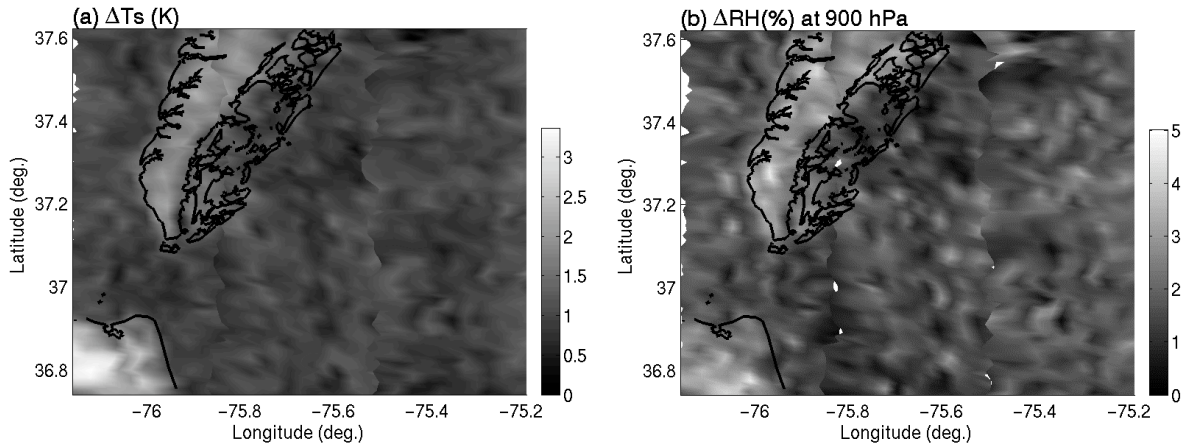

Figure 6. Retrieval discrepancies of (a) skin temperature and (b) relative humidity at 900 hPa (about 1 km above the sea level) produced by the surface emissivity from a constant of 1 to a retrieved value.

Retrieval of atmospheric and surface properties from ultraspectral radiance is used to demonstrate that surface emissivity can significantly affect other retrieved parameters, especially the surface skin temperature and the TBL moisture. The retrieved seawater emissivity (Figure 4b) is relatively good as a diverse database of surface types was used in the retrieval. This implies that the same technique can be applied to land where the surface emissivity is largely not well known. The same inversion algorithm has been applied to the Atmospheric InfraRed Sounder (AIRS)[13] data from the AQUA satellite[14]. As the satellite data covers a large variety of surface and atmospheric conditions, the retrieval scheme is tested with a large variety of conditions. Initial study with AIRS data has been performed[14] and more detailed validation over the land will be conducted. Here we use the same emissivity database for AIRS data shown in Figure 7. One granule of AIRS data from 10 September 2004 (~01:00 UTC; local nighttime) covers water and land including the vicinity of the Sahara Desert. The AIRS single field of view (SFOV; ~13.5 km at nadir) data are used; few cloudy spots were seen in Figure 7 as the effective skin temperature contains cloud features (i.e., cooler "skin temperature"). However the most part of this granule was under cloud-free conditions. The distribution of the surface emissivity near 8.15 μm is plotted, capturing the feature of the surface emissivity variation. The spectacular features over the land especially in the vicinity of the Sahara Desert are clearly evident. Typical emissivity spectra retrieved from water, land, and desert are plotted in comparison with laboratory measurements. These reasonable retrieved surface properties greatly support the accurate atmospheric retrievals which are found elsewhere[14]. Preliminary validation analyses on land

emissivity retrieval have been performed[8]; however, additional validations over different surface types are strongly desired in order to provide more-definitive conclusions.
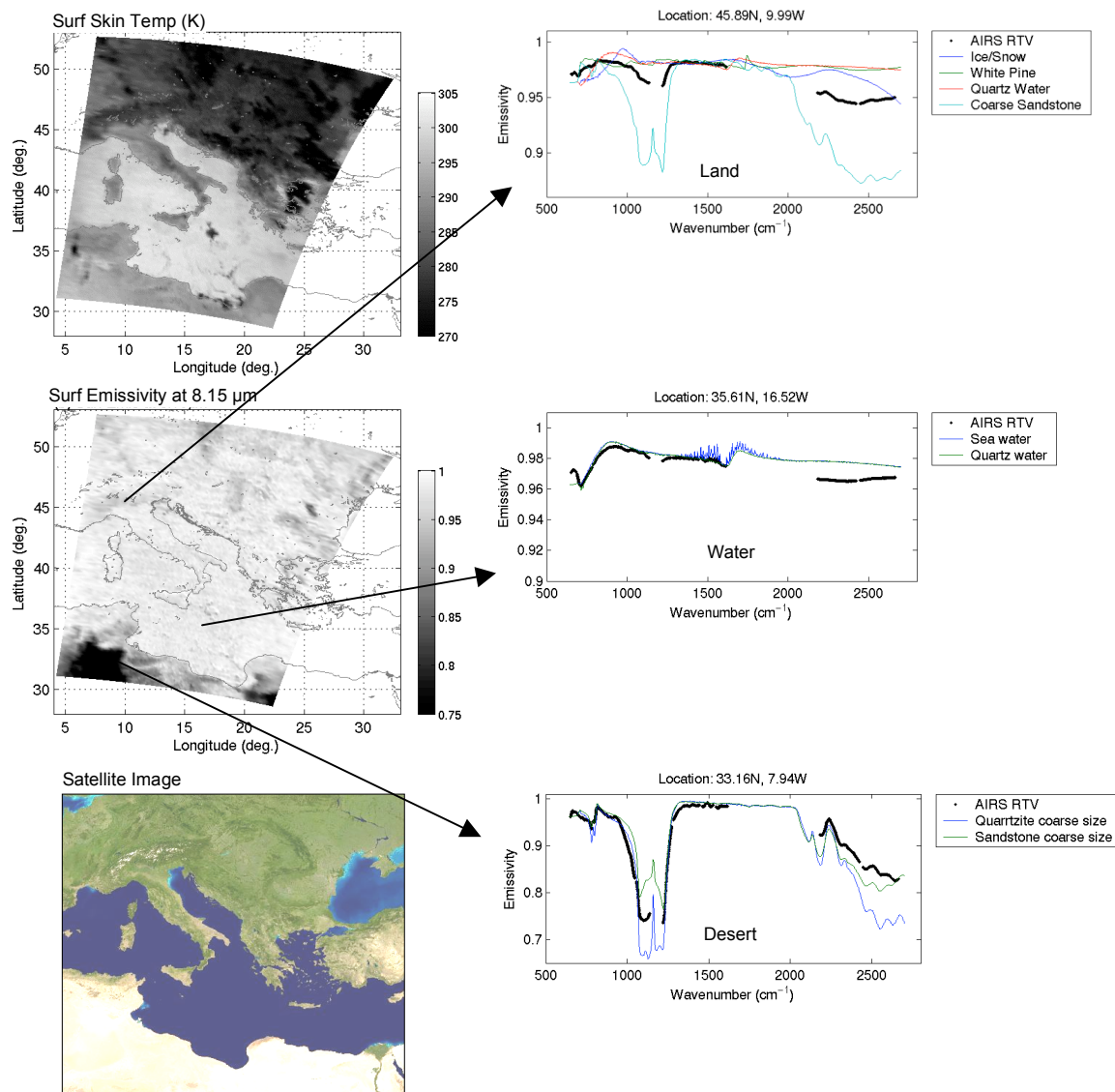

Figure 7. AIRS surface skin temperature and emissivity indicating a large variety of surface types is captured by this inversion scheme (see text).

4. SUMMARY AND FUTURE WORK

The sensitivity analyses of surface emissivity to skin temperature and TBL water vapor have been performed using infrared ultraspectral radiances. Retrievals from both simulations and measurements have demonstrated the importance of simultaneous emissivity retrieval. The validation results from the CLAMS field campaign have indicated that the retrievals of surface skin temperature and TBL water vapor are improved when emissivity is taken into account in the inversion scheme. This work also validates the retrieval scheme having surface emissivity retrieved simultaneously. The same retrieval algorithm is also applied to AIRS satellite data indicating a large variety of surface types may be captured. This greatly improves the accuracy of surface skin temperature and atmospheric parameter retrieval when the surface emissivity

is not well known. This retrieval algorithm can be improved by using the emissivity when the surface is well known such as open ocean and by retrieving emissivity when the surface type is not well known. Nevertheless, the surface emissivity is one of the key elements for accurately retrieving other thermodynamics parameters which are important to numerical weather prediction application.

ACKNOWLEDGEMENTS

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