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A regime-dependent retrieval algorithm for near-surface air temperature and specific humidity from multi-microwave sensors

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ABSTRACT

Near-surface specific humidity (q_a) and air temperature (T_a) over the global ocean are important meteorological variables, but they cannot be retrieved directly from remote sensing. Many efforts have been made to develop algorithms that derive q_a and T_a from multisensor microwave and/or infrared observations using in situ measurements as training datasets. However, uncertainty remains large in the resultant q_a and T_a retrievals. In this study, 147 moored surface buoys are used to examine how buoy measured q_a and T_a are related to satellite microwave brightness temperature (Tb) on the spatial scale from the warm/humid tropics to the cold/dry high latitudes. It is found that the Tb – q_a and Tb – T_a relations are structured along two distinct, near-linear bands, with the primary band in the warm/humid regime and a secondary (weaker) band in the cold/dry regime. The step-like transition (or separation) between the two regimes occurs at 8–10 g kg^{-1} for q_a and 14–17 °C for T_a. The evidence suggests that one algorithm may not be sufficient to extract q_a and T_a from Tb in all regimes. Therefore, a high-latitude enhancement is added to the global algorithm so that the q_a and T_a retrievals in the dry/cold regime can be specifically addressed. The new algorithms are applied to 11 microwave sensors, including SSM/I, SSMIS, and AMSU-A, from 1988 to 2016. Based on the 475,717 buoy collocations during the 29-year period, the retrieved q_a and T_a have root-mean-square differences of 0.82 g kg^{-1} and 0.51 °C, respectively.

1. Introduction

Near-surface air temperature (T_a) and specific humidity (q_a) over the global ocean are important meteorological variables. They set one of the driving conditions for turbulent exchanges of heat and water vapor at the air-sea interface (Stephens, 1990; Yu and Weller, 2007; Lorenz et al., 2010), and influence many ocean and atmospheric processes that are central to the Earth's weather and climate (Bretherton et al., 2004; Sherwood et al., 2010). Water vapor is a nature greenhouse gas. With the rise of atmospheric temperature in response to the addition of anthropogenic gases, there are more evaporation of water vapor from the ocean (Yu, 2007) and more absorption of water vapor in the air (Held and Soden, 2006) which further increase atmospheric temperature. This positive water vapor feedback is regarded as a key driver of the amplification of any warming caused by changes in atmospheric CO_2 (Manabe and Wetherald, 1967; Hansen et al., 1984). Thus, there is a pressing need for well-calibrated, consistent, and continuous long-term data records for T_a and q_a to keep tracking variability and long-term change of the near-surface thermal conditions and to improve the quantification and modeling of the water vapor feedback.

Measurements of T_a and q_a are conventionally obtained at sea by moored buoys and ships of opportunity, but these observations are sparse in both space and time (e.g. Kent and Taylor, 1996; Dai, 2006; Willett et al., 2008; Berry and Kent, 2009). Space-borne sensors that provide continuous global coverage would be a desirable observing platform. However, retrieving T_a and q_a at a level of a few meters above the surface proves difficult for the space-borne technology, because the measured radiation is emitted from relatively thick atmospheric layers rather than from single levels (Schulz et al., 1993). Making use of satellite measured total column of water vapor (or total precipitable water (PW)) to estimate q_a and T_a at the near surface has been actively investigated ever since the pioneer work by Liu and Niiler (1984), Liu (1986, 1988), and Liu et al. (1991). The Liu studies showed that most of the spatial and temporal variability of water vapor is confined in the lower part of the atmospheric column. The decoupling of the atmospheric boundary layer from the higher atmosphere enables the vertical coherence of the humidity variability, leading to a high correlation between the surface-level q_a and the total PW observed by radiosondes. Liu (1988) indicated that PW measured by scanning multichannel microwave radiometer (SMMR) on Seasat is similar in form to the PW observed by radiosondes (Liu and Niiler, 1984; Liu, 1986), both of which can be used to estimate q_a on monthly timescales with a root-

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Table 1
Summary of the Qa/Ta algorithms developed in the past 30 years.

Algorithm	Sensors	Retrieval methodology for q_a	Training data	Retrieval methodology for T_a
Liu (1986)		First algorithm to relate q_a to IWV	Radiosonde soundings	N/A
Liu (1988)	SSM/I	N/A	Radiosonde soundings	Obtained from surface mixing ratio assuming a constant relative humidity of 80%
Schulz et al. (1993)	SSM/I	Linear regression using IWV in the lower 500 m boundary layer.	Radiosonde soundings	N/A
Chou et al. (1995)	SSM/I	EOF-based approach using IWV in the lower boundary layer.	Radiosonde soundings	N/A
Schlüssel et al. (1995)	SSM/I	Linear regression using Tb from five channels (19v, 22v, 37v, 19 h, and 37 h).	Radiosonde soundings	N/A
Jones et al. (1999)	SSM/I	First neural network approach using SSMI/I IWV and NCEP SST.	OISST (NCEP version)	Simultaneously retrieved
Bentamy et al. (2003)	SSM/I	Similar to Schlüssel et al. (1995) but using a 4-channel regression (no 37v)	Ship observations	N/A
Kubota and Hihara (2008)	AMSR-E	Similar to Schlüssel et al. (1995) but using a 12-channel regression	NCEP and Ship observations	N/A
Shi (2001)	AMSU-A	N/A	NCEP	Neural network approach
Jackson et al. (2006, 2009)	AMSU-A SSM/I SSM/T-2	Multivariate linear regression	Ship Observations	Simultaneously retrieved
Shi et al. (2012)	HIRS	Neural network approach	ECMWF and ships	Simultaneously retrieved
Roberts et al. (2010, 2012)	SSM/I	Neural network approach	Research vessels and buoys	Simultaneously retrieved
This paper	AMSU-A SSM/I SSMIS	A 4-Channel nonlinear regression with high-latitude enhancement	Buoys	Simultaneously retrieved

mean-square (rms) error of about 0.4 g kg^{-1} in the tropics and 0.8 g kg^{-1} over the global ocean. Hsu and Blanchard (1989) examined the PW–q_a relation in the context of 13 field experiments over the oceans, and suggested that the relation should also work for instantaneous surface humidity retrievals. Subsequent algorithm developments have been particularly boosted by the availability of a series of Special Sensor Microwave/Imager (SSM/I) onboard the Defense Meteorological Satellite Program (DMSP) satellites since July 1987, and by the launch of the Advanced Microwave Sounding Unit-A (AMSU-A) on the National Ocean and Atmospheric Administration (NOAA) series of polar orbiting meteorological satellites in May 1998. The SSM/I is a conically scanning microwave radiometer with seven frequency channels. The AMSU-A is a multi-channel microwave radiometer that performs atmospheric sounding of temperature and moisture levels by passively recording atmospheric microwave radiation in multiple wavelengths. A survey of the algorithms that have been developed in the past 30 years is provided in Table 1.

As shown in Table 1, the algorithm development can be loosely categorized into three stages. The first stage is represented by the work of Schulz et al. (1993) and Chou et al. (1995), who used the SSM/I measurements to first determine the water vapor in the lowermost 500 m of the atmosphere and then predict q_a. This approach underscores the fact that for most oceanic situations, the water vapor in the homogenous atmospheric boundary layer can be related to q_a by a simple linear regression (Taylor, 1982). The second stage is ushered in by Schlüssel et al. (1995), who proposed a direct q_a retrieval from SSM/I Tb in 5 channels (19v, 22v, 37v, 19 h, and 37 h GHz, with h and v denote horizontal and vertical polarization, respectively). This approach seems to be able to reduce the error propagation associated with the two-step procedure of Schulz et al. (1993), leading to an improved q_a retrieval. The approach was subsequently extended to Tb measurements from other platforms including the Advanced Microwave Scanning Radiometer for EOS (AMSR-E), the WindSat Polarimetric Radiometer, and the Special Sensor Microwave Imager/Sounder (SSMIS) (Jones et al., 1999; Bentamy et al., 2003; Jackson et al., 2006, 2009; Kubota and Hihara, 2008; Roberts et al., 2010). The third stage features the use of atmospheric soundings from instruments like the AMSU, the High-resolution Infrared Radiation Sounder (HIRS), and the Special Sensor Microwave Water Vapor Profiler (SSM/T and SSM/T-2). The sounders do not directly provide shallow surface measurements, but the detailed profile information observed by the sounders can help to remove the variability in the total column measurements that are not associated with the surface. Utilization of microwave and infrared sounders, with or without microwave radiometers, to estimate q_a and T_a has been explored by Shi (2001), Shi et al. (2012), Jackson et al. (2006, 2009), and Jackson and Wick (2010).

Ironically, despite the efforts and the progress that have been made, q_a and T_a remain the leading error source for satellite-based air–sea heat flux datasets (Curry et al., 2004; Jackson et al., 2006; Prytherch et al., 2014). Jin et al. (2015) conducted a buoy-based evaluation of two satellite-derived products: one is the q_a product by the Goddard Satellite-based Surface Turbulent Fluxes (GSSTF) v3 (Chou et al., 1995; Shie et al., 2012) and the other is the q_a and T_a products from the multi-instrument microwave regression (MIMR) by Jackson et al. (2006, 2009) and Jackson and Wick (2010). Evaluation with the 137 air-sea buoys over the global scale showed that the biases in q_a and T_a are strongly regime dependent, featuring warm and wet biases in the tropical warm/humid region and cold and dry biases in the extratropical cold/dry region. For instance, the mean difference between MIMR and buoy q_a changes from a wet bias of 0.8 g kg^{-1} in the tropical latitudes between 10°S – 10°N to a dry bias of -0.8 g kg^{-1} at high latitudes poleward of 45°. Jin et al. (2015) eventually obtained an improved analysis on 0.25° resolution through implementing a buoy-based bias correction to MIMR and GSSTF3 followed by an objective synthesis with the 1°-gridded q_a analysis produced by the Objectively Analyzed air-sea Fluxes (OAFlux; Yu and Weller, 2007; Yu et al., 2008). However,