Satellite Sounder Observations of Contrasting Tropospheric Moisture Transport Regimes: Saharan Air Layers, Hadley Cells, and Atmospheric Rivers

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ABSTRACT

This paper examines the performance of satellite sounder atmospheric vertical moisture profiles under tropospheric conditions encompassing moisture contrasts driven by convection and advection transport mechanisms, specifically Atlantic Ocean Saharan air layers (SALs), tropical Hadley cells, and Pacific Ocean atmospheric rivers (ARs). Operational satellite sounder moisture profile retrievals from the *Suomi National Polar-Orbiting Partnership* (*SNPP*) NOAA Unique Combined Atmospheric Processing System (NUCAPS) are empirically assessed using collocated dedicated radiosonde observations (raobs) obtained from ocean-based intensive field campaigns. The raobs from these campaigns provide uniquely independent correlative truth data not assimilated into numerical weather prediction (NWP) models for satellite sounder validation over oceans. Although ocean cases are often considered "easy" by the satellite remote sensing community, these hydrometeorological phenomena present challenges to passive sounders, including vertical gradient discontinuities (e.g., strong inversions), as well as persistent uniform clouds, aerosols, and precipitation. It is found that the operational satellite sounder 100-layer moisture profile NUCAPS product performs close to global uncertainty requirements in the SAL/Hadley cell environment, with biases relative to raob within 10% up to 350 hPa. In the more difficult AR environment, bias relative to raob is found to be within 20% up to 400 hPa. In both environments, the sounder moisture retrievals are comparable to NWP model outputs, and cross-sectional analyses show the capability of the satellite sounder for detecting and resolving these tropospheric moisture features, thereby demonstrating a near-real-time forecast utility over these otherwise raob-sparse regions.

1. Introduction

Hyperspectral infrared/microwave (IR/MW) sounding systems have continuously flown onboard environmental satellites in low-Earth orbit beginning with the launch of the Atmospheric Infrared Sounder (AIRS) on board the U.S. National Aeronautics and Space Administration (NASA) *Aqua* satellite in 2002 (Chahine et al. 2006). Since the launch of AIRS, the U.S. National Oceanic and Atmospheric Administration (NOAA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) have committed to long-term operational satellite missions featuring IR/MW sounding systems, these being the U.S. Joint Polar Satellite System (JPSS; Goldberg et al. 2013) and the EUMETSAT Polar System. The *Suomi National Polar-Orbiting Partnership* (*SNPP*) satellite launched in 2011 features the hyperspectral Cross-track Infrared Sounder (CrIS) and Advanced Technology Microwave Sounder (ATMS) system. The follow-on JPSS series will feature CrIS/ATMS on board four satellites launched in the same orbit over the next two decades beginning in 2017. These instruments are designed

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to retrieve atmospheric vertical temperature and moisture profiles under nonprecipitating conditions with the best possible vertical resolution allowed by passive measurements.

The current operational retrieval algorithm for *SNPP* is the NOAA Unique Combined Atmospheric Processing System (NUCAPS) developed at NOAA.[1] The NUCAPS retrieval is based upon the heritage AIRS/Advanced Microwave Sounding Unit (AMSU) system, with the combined IR/MW retrieval algorithm being a modular implementation of the AIRS Science Team algorithm, version 5 (Susskind et al. 2003, 2011). Operational users of the *SNPP* NUCAPS retrievals include NOAA/National Weather Service (NWS) Weather Forecast Offices [viz., Advanced Weather Interactive Processing System (AWIPS)].

To support intensive calibration/validation (cal/val), JPSS has funded ship-based dedicated radiosonde observations (raobs), including NOAA Aerosols and Ocean Science Expeditions (AEROSE; Morris et al. 2006; Nalli et al. 2011, 2013) in the tropical Atlantic Ocean and the CalWater campaign in the North Pacific Ocean (Ralph et al. 2016). With an eye toward weather forecast and science user applications, we use data from these campaigns to demonstrate the performance of NUCAPS *SNPP* satellite sounder moisture profile retrievals for observing a variety of hydrometeorological phenomena spanning moisture transport regimes that are theoretically difficult to resolve but located in critical raob-sparse regions over oceans, specifically Saharan air layers (SALs), Hadley cells, and atmospheric rivers (ARs).

Saharan air layers are stable layers of dry, warm air of desert origin that advect across the tropical Atlantic Ocean, often accompanying high levels of Saharan dust aerosols (Carlson and Prospero 1972) and bounded to its south by the intertropical convergence zone (ITCZ; Tsamalis et al. 2013). Previous research has shown that these stabilizing conditions impact hurricane activity over the Atlantic (e.g., Karyampudi and Pierce 2002; Dunion and Velden 2004; Wong and Dessler 2005; Evan et al. 2006). Nalli et al. (2005) assembled trans-Atlantic cross sections of relative humidity (RH) from 3-hourly raobs showing the SAL during a major dust outflow event, and Nalli et al. (2006) showed collocated cross sections from the AIRS. Shu and Wu (2009) later utilized AIRS RH retrievals for studying SAL impact on tropical cyclone intensity (finding both positive and negative influence), but also acknowledged that "uncertainty should be considered [in a future study] in the AIRS/*Aqua* RH profiles."

Hadley cells are global-/synoptic-scale circulation cells consisting of thermally driven uplift along the ITCZ axis and associated poleward divergence aloft, until subtropical subsidence eventually causes drying and warming, leading to deep tropospheric columns of extremely dry air with stabilizing inversions at their bases. The resulting tropical RH distribution is of importance in the context of climate change feedbacks (e.g., Dessler and Sherwood 2009), as well as in ascertaining and monitoring the expansion of the tropical belt in response to climate change (e.g., Seidel et al. 2008).

Finally, ARs are narrow channels of moisture transport that are associated with midlatitude storm systems and that can extend thousands of kilometers offshore (e.g., Dettinger et al. 2015; Dacre et al. 2015; Ramos et al. 2016). Understanding ARs is important for forecasting coastal precipitation (e.g., the U.S. West Coast), and as "drought busters" (Dettinger 2013) they have received more attention in light of the record 2012–15 California drought (e.g., Swain 2015). There has been some debate about whether the moisture sources of ARs are nonlocal (i.e., tropical/subtropical moisture export and continuous long-range transport) or local (i.e., moisture conveyor belts associated with midlatitude storms; e.g., Bao et al. 2006; Dacre et al. 2015). However, it appears that there has been recent consensus that they variously incorporate both local and nonlocal sources (e.g., Dettinger et al. 2015; Ramos et al. 2016).

2. Assessing performance within moisture transport regimes

We use data collected during boreal winter (January–February) from the 2013 AEROSE and the 2015 CalWater Atmospheric Radiation Measurement (ARM) Cloud Aerosol Precipitation Experiment (ACAPEX), both on board the NOAA ship *Ronald H. Brown*. Because SAL and AR phenomena impact the development of landfalling weather systems, focused "spot assessments" of NUCAPS water vapor performance under these conditions is desirable. Satellite cal/val truth datasets acquired during AEROSE and ACAPEX consist of dedicated raobs from Vaisala RS92 radiosondes launched $\simeq$15–60 min prior to satellite overpasses. The AEROSE raob data have undergone Global Climate Observing System (GCOS) Reference Upper-Air Network processing (Bodeker et al. 2016). Because the AEROSE and CalWater/ACAPEX data were intentionally not assimilated into numerical weather prediction (NWP) models, they constitute independent correlative truth data ideally suited for satellite cal/val (Nalli et al. 2011). Collocations of NUCAPS footprints with dedicated raobs are facilitated via the NOAA Products Validation System (Reale et al. 2012).

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[1] For more on NUCAPS, the reader is referred to Gambacorta et al. (2012, 2013).

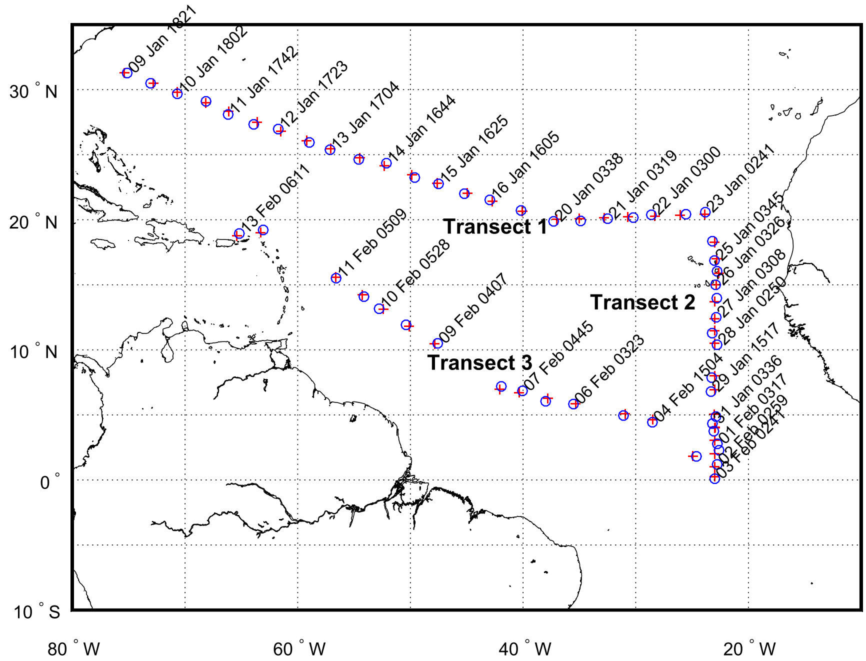

FIG. 1. Dedicated Vaisala RS92 radiosonde launch locations (red plus signs) and nearest collocated (accepted or rejected) NUCAPS footprints (blue circles) for the 2013 AEROSE campaign with three transects defined by northwest–southeast (9–23 Jan), north–south (from 23 Jan to 2 Feb), and southeast–northwest (3–13 Feb).

The ability of the NUCAPS *SNPP* moisture profile product to detect and resolve coherent moisture structures over oceans is highlighted below through rigorous quantitative statistical analyses of water vapor layer abundance and qualitative cross-sectional analyses of RH. Root-mean-square error (RMSE), bias, and standard deviation σ statistics versus raob[2] are calculated on forward model layers ($\delta z < 2\,\mathrm{km}$) for NUCAPS retrievals within 50–75 km of launches and 0–70 min prior to overpasses, using methodologies detailed in Nalli et al. (2013).

a. *Tropical Atlantic Saharan air layers and Hadley cells*

During the 2013 AEROSE, 69 raobs were acquired for *SNPP* overpasses. Figure 1 shows the launch locations along with the single-closest collocated *SNPP* footprints (used in the cross-sectional analysis below). A statistical summary of the NUCAPS moisture profile retrievals versus raob (RMSE and bias $\pm 1\sigma$) is given in Fig. 2 for all retrievals within 75 km of launches (results only for cases accepted by the quality flag are shown in Fig. 2, bottom). For reference, results from collocated model output (analysis or forecast nearest in time with satellite overpasses) from the European Centre for Medium-Range Weather Forecasts (ECMWF) are also shown. JPSS requirements for moisture are defined for global performance (RMSE uncertainty for accepted cases over three broad tropospheric layers; cf. Nalli et al. 2013); there are no regional requirements. Although it is not expected that the moisture retrievals would meet the global requirement for these difficult cases on finer forward model layers ($\delta z < 2\,\mathrm{km}$), they are nevertheless seen to be very close up to $\simeq$350 hPa, with only a small dry bias $\lesssim |10|\%$ (Fig. 2, right), even if including rejected cases (Fig. 2, top right). A moist bias is apparent above 350 hPa, but this may be associated in part with dry bias in the raobs (e.g., Miloshevich et al. 2009) as well as combined uncertainties in measuring extremely small water vapor amounts; similar relative biases are exhibited in the ECMWF (magenta lines). NUCAPS exhibits smaller RMSE over $\simeq$550–250 hPa, which may be the result of AEROSE raobs being uniquely independent data—not only were they not assimilated, but they were acquired hundreds to thousands of kilometers away from any other such assimilated raob sites.

A qualitative understanding of the satellite sounder capability for observing hydrometeorological features is given by cross-sectional contour analyses of RH in Fig. 3. We consider the raob cross sections (labeled in the figure) first, where we see a well-defined and

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[2] Vaisala reports measurement uncertainty for RS92 radiosondes to be 0.5°C and 5% RH.

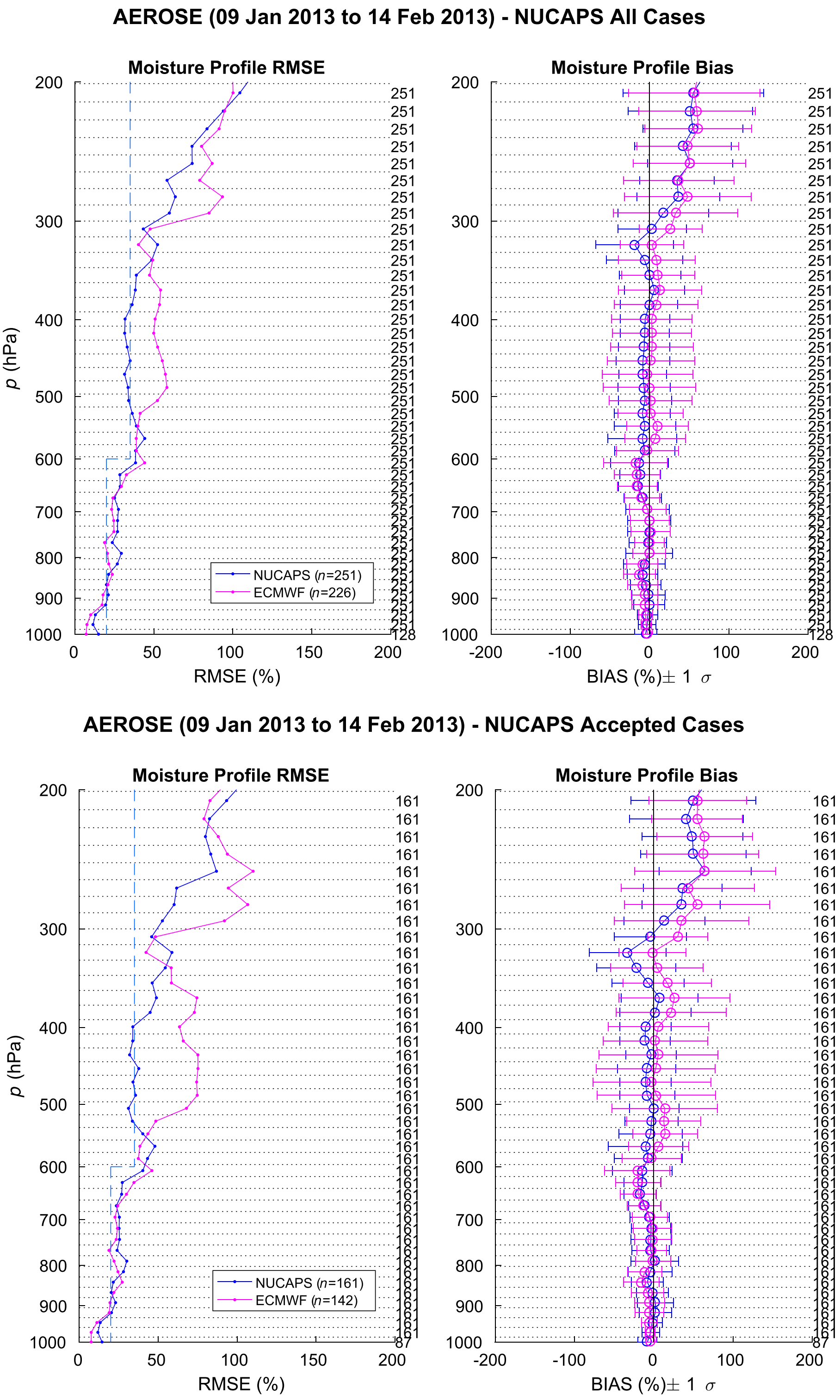


FIG. 2. Statistical assessment of the NUCAPS satellite sounder moisture profiles vs dedicated raob collocations for retrievals within $\delta x \leq 75$ km of raob launch locations during 2013 AEROSE campaign for (top) all cases (accepted or rejected by quality flag) and (bottom) accepted cases only showing (left) RMSE and (right) bias $\pm 1\sigma$ on forward model layers up to 200 hPa. NUCAPS performance is given in blue along with ECMWF in magenta for reference, with NUCAPS sample size for each layer given in the right margins. The light blue dashed line in the RMSE plots designate the JPSS level 1 global performance requirements for moisture.

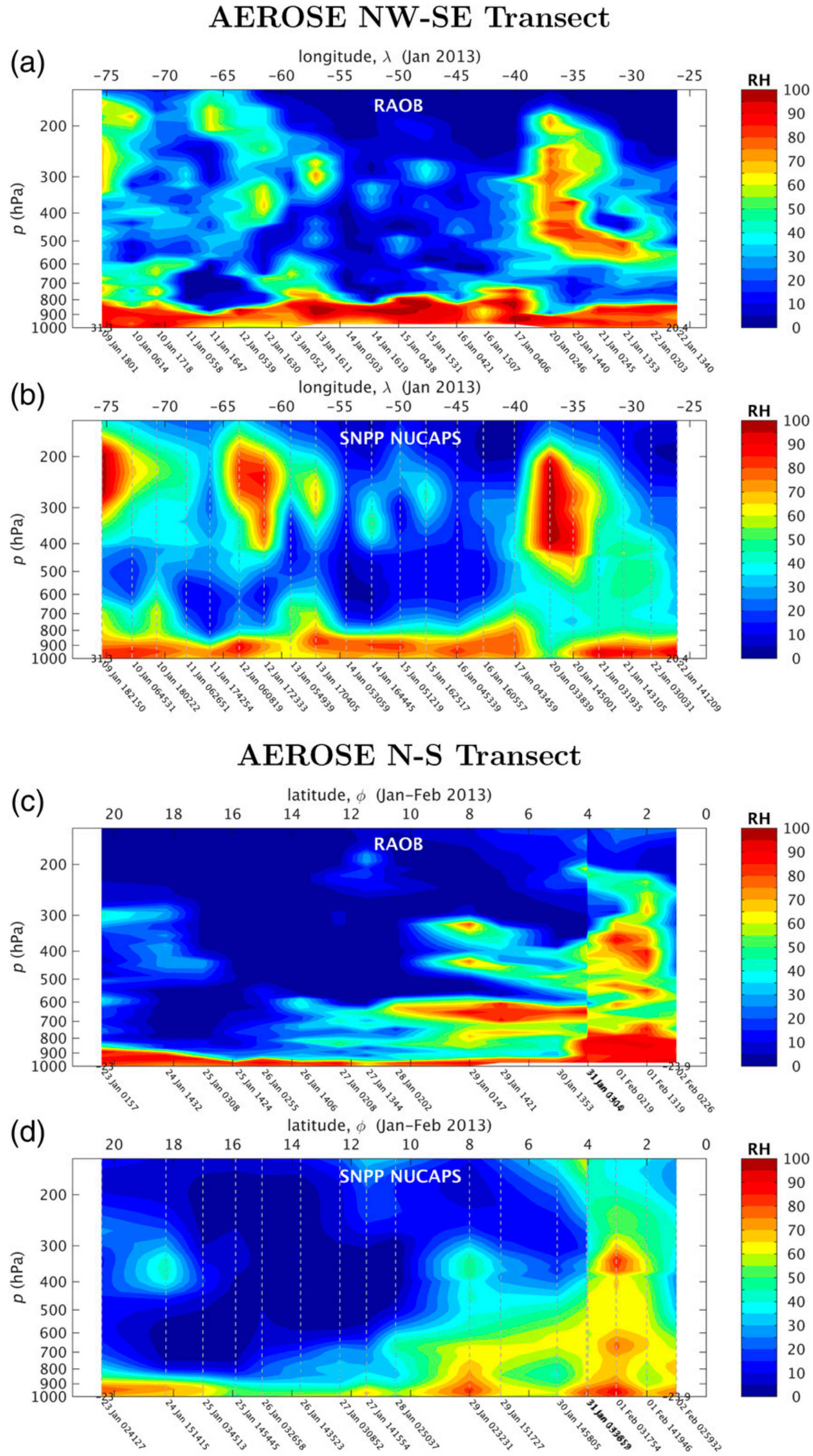


FIG. 3. Zonal cross-sectional analyses of RH for 2013 AEROSE (a),(b) northwest–southeast and (c),(d) north–south transects where (a),(c) show the raob RH and (b),(d) show NUCAPS *SNPP* satellite sounder derived RH from the nearest collocated (accepted or rejected) retrievals. Discontinuities (e.g., 4°N, north–south transect) are due to changes in ship speed and heading, including stations.

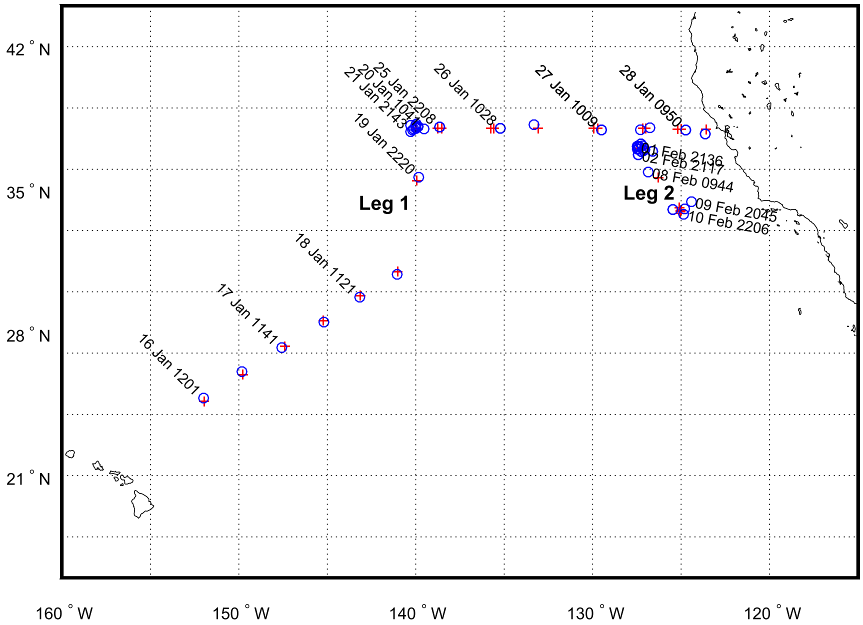
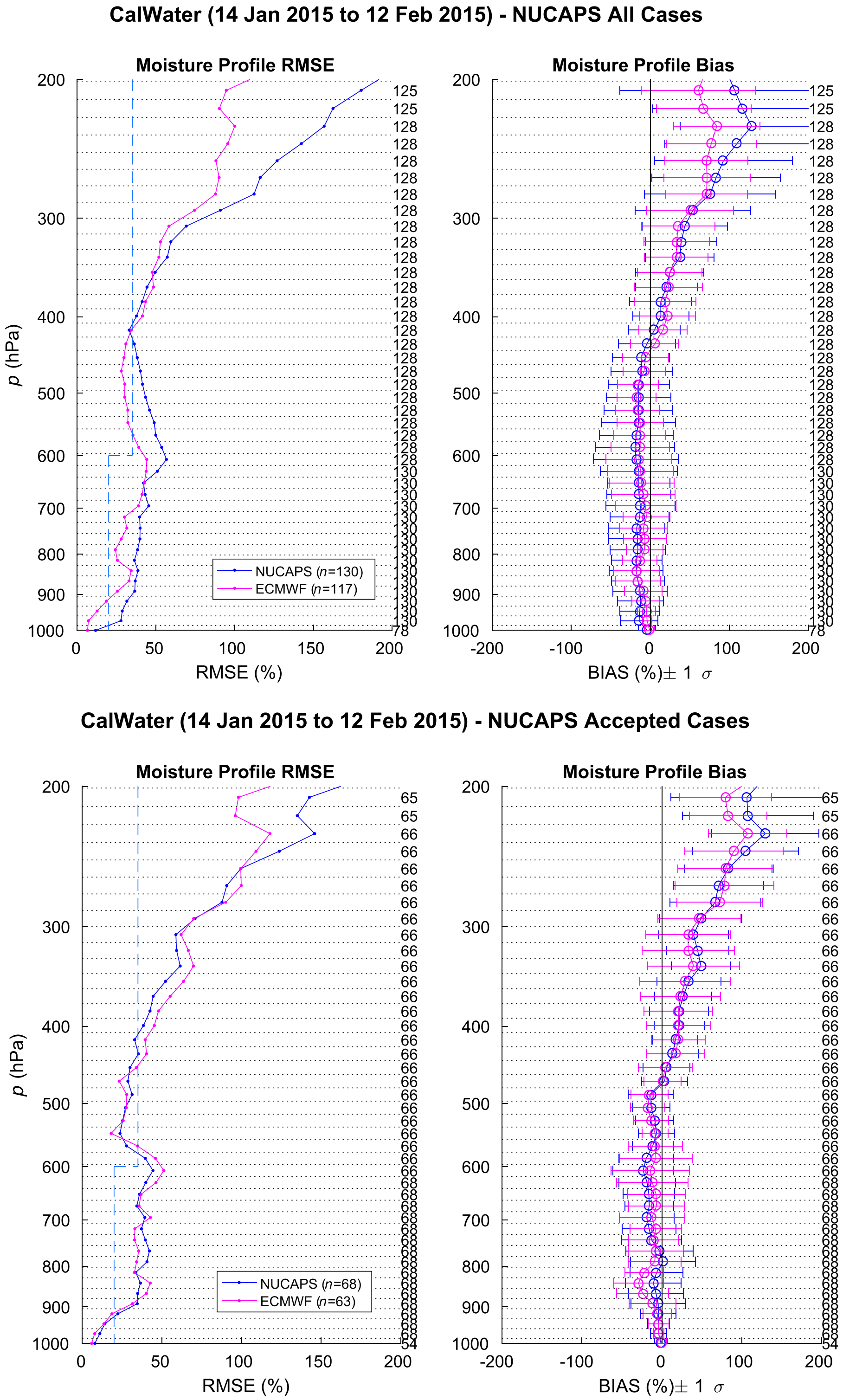


FIG. 4. As in Fig. 1, but for the 2015 CalWater/ACAPEX campaign, with leg 1 (16–29 Jan) consisting of the Honolulu to San Francisco track and leg 2 (2–11 Feb) consisting primarily of two stations held just outside the U.S. exclusive economic zone at approximately (37°N, 127.25°W) and (34°N, 125°W).

persistent marine boundary layer (MBL) with high RH values generally at or below 800 hPa. In the northwest–southeast transect (Fig. 3a), the MBL hovers roughly between 850 and 800 hPa. There is a gradual northwest–southeast drying out of the free troposphere (above 800 hPa) beginning around 70°–65°W, with the exception of a moisture pocket in the mid- to upper troposphere (above 600 hPa) appearing around 38°–30°W that overlies a dry layer from 800 to 500 hPa. Following this, the cruise track turned south. The north–south raob cross section (Fig. 3c) shows extensive tropospheric drying throughout the column, with the MBL becoming increasingly shallower until the ITCZ axis is reached around 4°N. The mid- to upper-tropospheric drying is related to subtropical Hadley subsidence, whereas the lower-level dry layers are SAL phenomena bordered to the south by the ITCZ (e.g., Tsamalis et al. 2013). Although tropospheric moisture associated with the ITCZ is found north of the axis, the MBL remains suppressed with a shallow dry layer sandwiched around 900 hPa. Overall, the collocated NUCAPS moisture cross sections (Figs. 3b,d) correctly capture, in both placement and magnitude, gross features such as the ITCZ, MBL, and large dry regions associated with subtropical Hadley cell subsidence. Shallow SAL filaments are difficult to resolve or detect by a passive sounder, but low-level dryness associated with moderate dust outflow observed beginning around 25 January is clearly seen along with suppressed vertical development of the MBL.

b. *Eastern Pacific Ocean atmospheric rivers*

The CalWater campaign was conducted during January–March 2015 as a joint collaborative effort (Ralph et al. 2016). Several aircraft were deployed as well as the *Ronald H. Brown*, the latter hosting the ACAPEX subcampaign and Second ARM Mobile Facility (AMF2); this work focuses solely on the ACAPEX dataset. There were a total of 66 radiosondes dedicated to *SNPP* overpasses; Fig. 4 shows the launch locations and collocated *SNPP* footprints. During both legs of ACAPEX the ship spent a large fraction of time holding station at three locations within the vicinity of ARs. As in section 2a, Fig. 5 provides the statistical summaries of NUCAPS and ECMWF moisture versus raobs (retrievals within 50-km radii) on forward model layers. NUCAPS moisture retrieval statistics for these extremely difficult atmospheric cases are here seen to be reasonably close to ECMWF up to $\simeq$300 hPa, with a dry bias $\lesssim|20|\%$ up to 400 hPa, even for the sample including rejected cases (Fig. 5, top); reduced RMSE is noticeable for accepted cases (Fig. 5, bottom), although the yield is $\simeq$52%. "Hard cases" involving convection or uniform cloud cover tend on being rejected (due to insufficient cloud clearing), yet these are often where the weather systems of interest are located.



CalWater (14 Jan 2015 to 12 Feb 2015) - NUCAPS All Cases

CalWater (14 Jan 2015 to 12 Feb 2015) - NUCAPS Accepted Cases

FIG. 5. As in Fig. 2, but for the 2015 CalWater/ACAPEX campaign.

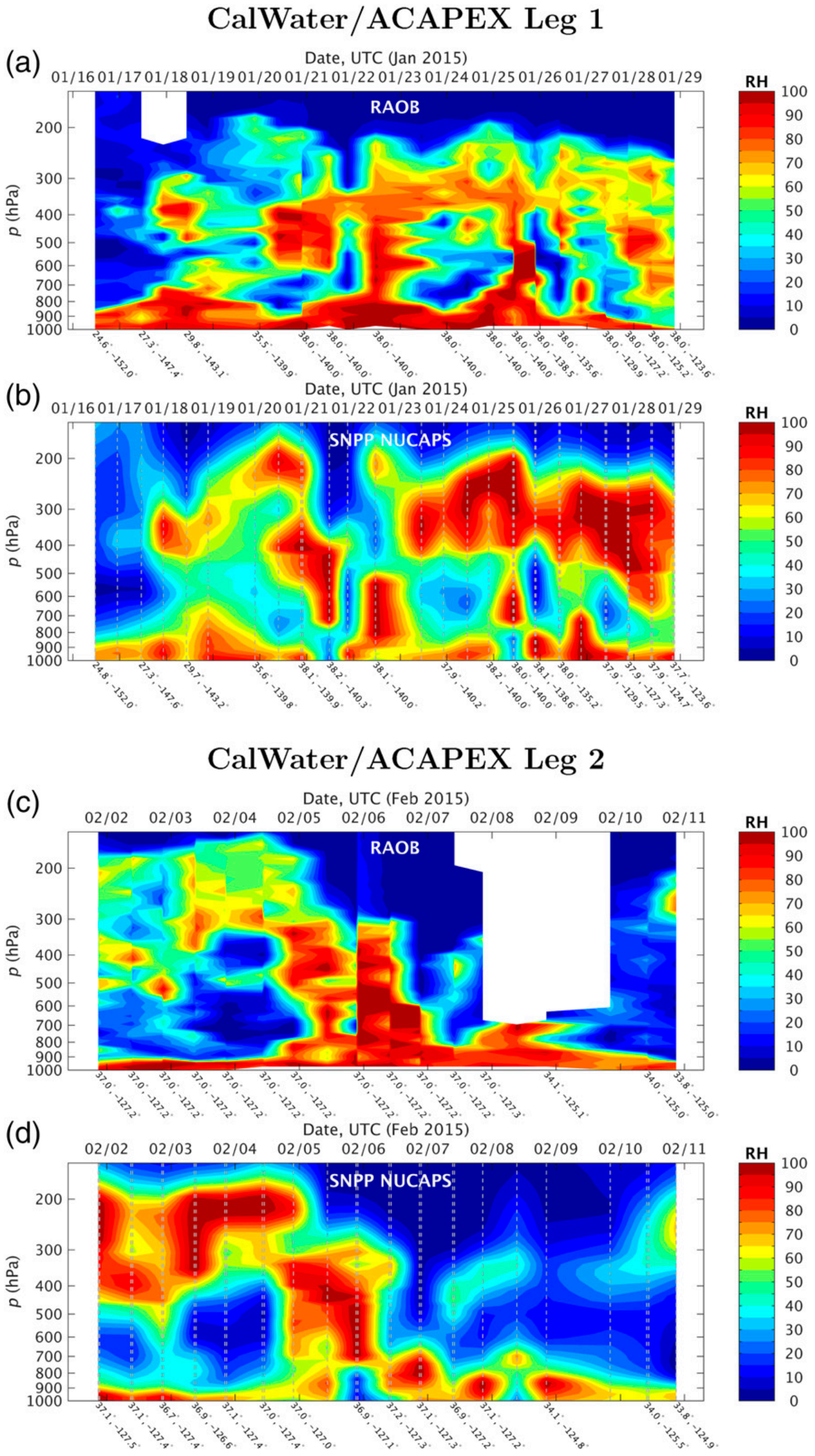


FIG. 6. As in Fig. 3, but for the 2015 CalWater/ACAPEX (a),(b) leg 1 and (c),(d) leg 2. Discontinuities are due to changes in ship speed and heading, including stations, and the white areas are from data loss due to radiosonde malfunctions.

Because the ship remained stationary while holding stations, RH cross sections are plotted as a function of time (instead of space) in Fig. 6. In the cross-sectional analyses the AR phenomena are clearly evident in both the raob and satellite NUCAPS data as ribbons of moisture throughout the troposphere extending up to 200 hPa. This is in stark contrast with the extremely dry tropospheric conditions observed during AEROSE (Fig. 3). Under these conditions, the satellite sounder primarily has difficulty in regions of heavy convection manifested by thick, uniform cloud cover and/or precipitation, which are opaque in the IR spectrum and difficult to cloud-clear sufficiently. An example of this was the missed vertical extent of moisture above 500 hPa on 22 January (Fig. 6b) and below 700 hPa just before 6 February (Fig. 6d); note that both of these cases were rejected by the NUCAPS quality flag. However, in spite of these difficulties, we find that the NUCAPS satellite sounder retrievals still provide offshore AR moisture information in what would otherwise be sounding data voids in near-real-time forecast user applications.

3. Discussion

This work illustrates satellite sounder moisture profile performance based upon a unique collection of datasets obtained over the Pacific and Atlantic Oceans during boreal winter (January–February) under very different hydrometeorological conditions associated with moisture transport mechanisms (advection and convection) of interest to forecast and science users. In cross-sectional analyses of RH, the NUCAPS *SNPP* satellite sounder moisture retrievals are shown to be capable of providing information about the distribution of tropospheric water vapor, including mesoscale SALs (associated with desert outflows including low-level stable inversions and aeolian mineral dust) and ARs (associated with large moisture fluxes leading to upstream precipitation over the U.S. West Coast), as well as synoptic-scale Hadley subsidence cells and ITCZ. Statistical analyses of the *SNPP* NUCAPS retrievals (including rejected cases) versus independent dedicated raobs in these domains were found to be reasonably close to JPSS global performance specifications and ECMWF model output. While ocean cases are often considered ‘‘easy’’ within the satellite sounder community, our cases featured atmospheric conditions that pose difficulties for passive sounder retrievals, including significant inversions associated with the SAL and subsidence, tropical convection within the ITCZ, heavy uniform cloud cover and precipitation associated with ARs, and IR attenuation from Saharan dust aerosols. Although this paper has focused on the *SNPP* NUCAPS product, we expect similar performance for other satellite hyperspectral sounders and retrieval algorithms (e.g., AIRS).

As a final note regarding SAL and AR phenomena, it is our observation that, although they result from different underlying dynamics, they may be conceptually viewed as inverses of one another in terms of their nonlocal impact due to moisture transport. The latter are defined by narrow water vapor corridors of marine convective origin that advect moisture over the continent downstream, whereas the former are narrow layers of dry, warm air of desert origin that advect stabilizing ‘‘negative moisture’’ over the ocean downstream.

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