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Thermodynamic and cloud parameter retrieval using infrared spectral data

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Abstract. High-resolution infrared radiance spectra obtained from near nadir observations provide atmospheric, surface, and cloud property information. A fast radiative transfer model, including cloud effects, is used for atmospheric profile and cloud parameter retrieval. The retrieval algorithm is presented along with its application to recent field experiment data from the NPOESS Airborne Sounding Testbed – Interferometer (NAST-I). The retrieval accuracy dependence on cloud properties is discussed. It is shown that relatively accurate temperature and moisture retrievals can be achieved below optically thin clouds. For optically thick clouds, accurate temperature and moisture profiles down to cloud top level are obtained. For both optically thin and thick cloud situations, the cloud top height can be retrieved with an accuracy of approximately 1.0 km. Preliminary NAST-I retrieval results from the recent Atlantic-THORPEX Regional Campaign (ATReC) are presented and compared with coincident observations obtained from dropsondes and the nadir-pointing Cloud Physics Lidar (CPL).

1. Introduction

Observations from an aircraft, or a spacecraft, flown infrared spectrometer can be used to infer the atmospheric temperature, moisture, and concentration of other chemical species using radiative transfer equation inversion techniques. The retrievals of atmospheric state (i.e., temperature and moisture profiles) obtained from infrared radiometric measurements will contain intolerable error near and below the cloud level if the attenuation of infrared radiation emitted from the Earth's surface and the atmosphere below the clouds are not properly accounted for in the retrieval process. Since there are vast cloudy regions of the globe, a great deal of effort has gone into the cloud detection and cloud-clearing processes [*Smith et al.*, 2004]. Nevertheless, the schemes dealing with cloud detection and cloud-clearing [*Smith*, 1968] remain a major source of error in the final retrieval products. Some schemes limit themselves to dealing with the observations unaffected by clouds [e.g., *Chedin et al.*, 1985], while others make direct use of the cloudy radiances and attempt to retrieve temperature and moisture along with the cloud parameters [e.g., *Susskind et al.*, 1984]. Recently, fast molecular and cloud transmittance models have been developed to enable the infrared radiances to be used under cloudy conditions with the accuracy required for sounding retrieval processing. Here, the EOF (i.e., empirical orthogonal function) statistical regression retrieval algorithm [e.g., *Smith and Woolf*, 1976; *Zhou et al.*, 2002] is expanded to include realistic cloud parameters (e.g., cloud top height, effective particle diameter, and optical depth) to deal with the cloudy as well as cloud-free observations. With this improved algorithm, cloud parameters, as well as atmospheric profiles, are retrieved from the spectral radiance observations.

The NPOESS (National Polar-orbiting Operational Environmental Satellite System) Airborne Sounder Testbed (NAST) has been successfully operating on high altitude aircraft since

1998 [e.g., *Cousins and Smith*, 1997; *Smith et al.*, 2005]. NAST-I is designed to support the development of future satellite temperature and moisture sounders such as the IASI (Interferometer Atmospheric Sounding Instrument) on the METOP satellite, the CrIS (Cross-track Infrared Sounder) on the NPP and the follow-on NPOESS series of satellites, as well as the HES (Hyperspectral Environmental Sensor) to fly on the GOES-R satellite series. Both simulated and measured NAST-I data are used in this study. The retrieval accuracy, which depends on cloudiness, is discussed. Retrieval of cloud properties and atmospheric properties from NAST-I observations retrieval results are compared with coincident observations obtained from the nadir-pointing Cloud Physics Lidar (CPL) and dropsondes, respectively.

2. Radiance simulations, training, and regression

The infrared radiances measured under cloudy conditions are simulated by combining the Optimal Spectral Sampling (OSS) fast molecular radiative transfer model [*Liu et al.*, 2003; *Moncet et al.*, 2003], with the physically based cloud radiative transfer model based on DIScrete Ordinate Radiance Transfer (DISORT) [*Stamnes et al.*, 1988] calculations performed for a wide variety of cloud microphysical properties [e.g., *Yang et al.*, 2001]. Here, a maximum of 2 cloud levels is used; a single cloud layer (either ice or liquid) and another optically thick cloud layer can be assumed to exist at a lower level when the radiosonde detects two, or more, layers of cloud. These cloud layers, along with the radiosonde profile, are used to simulate NAST-I radiances. Cirrus clouds are assumed to exist at the higher levels. The cloud microphysical properties are also simulated. A random number generator is used to specify cloud visible optical depth within a pre-specified range. Parameterization of balloon and aircraft cloud microphysical database [*Heymsfield et al.*, 2003] is used to specify cloud effective particle radius from the cloud optical depth. A random error of 10% is added to parameterized effective radius to account for real data scatter. At the lower cloud level, the opaque cloud representation (i.e., isothermal/saturated) is assumed and the profile is treated as isothermal below the lower cloud level. This lower level cloud is represented as an equivalent cloud-free isothermal temperature condition in the radiative transfer calculation.

Detailed description of NAST-I retrieval methodology can be found elsewhere [e.g., *Zhou et al.*, 2002; *Smith et al.*, 2005]. Here, the NAST-I EOF statistical regression methodology has been expanded to include cloud parameters. Regression relations are generated not only for predicting thermodynamic parameters, but also for predicting cloud top height and the cloud microphysical properties. Because the radiance is highly non-linear with respect to cloud height, statistics are formulated for one class of data which contains all cloud height conditions and seven other classes for which the cloud height has been stratified to within approximately 1.5 km of the mean for that class. The classes are also separated by the cloud phase (ice and/or water). The final cloud height class to be used for the retrievals is obtained by iteration beginning with the unclassified class to predict the initial cloud height stratification for the retrievals. Usually, the final cloud height class is defined within five iterations of the cloud height prediction process. The cloud phase results from the spectral signatures observed within micro-window channels and the sensed cloud top temperature. However, sufficient numbers of radiosondes, approximately 800 soundings per each cloud height group per cloud phase, are used to ensure that the observations are well covered by the statistical representation. For semitransparent and/or scattered clouds with an effective optical depth less than one, the correct profile below the cloud retrieved. If a lower level cloud underlies the semitransparent and/or scattered upper level cloud, the lower level cloud is treated as an equivalently clear isothermal condition as described for the opaque cloud condition retrieval. EOF regression enables both the cloud height and the cloud microphysical properties of the highest-level cloud to be estimated.

3. Retrieval simulation with clouds

Retrieval simulations have been performed over a set of winter hemispheric data (Cloudy soundings from 1 November to 10 January, from 1995 to 2003; latitude from 33°N to 54°N; longitude from 58°W to 85°W), which is also used for statistic training for the recent Atlantic-THORPEX Regional Campaign (ATReC) from 18 November to 15 December, 2003 [e.g., *Shapiro and Thorpe*, 2004]. In order to evaluate the ability to retrieve profiles below thin cirrus clouds, the radiances are simulated with only one level cloud having an optical depth within a certain range. The retrievals are performed (with dependent EOF regression coefficients) using radiances simulated with instrument noise. Different EOF statistical regression coefficients are derived for the following conditions: (1) clear conditions only (denoted as CLE), (2) clear and an equivalently clear isothermal conditions (denoted as MIX), (3) cloudy conditions without cloud height grouping (denoted as CLD), and (4) cloudy conditions with cloud height grouping (denoted as GRP). The retrieval results are compared with the retrieval from clear radiances using clear sky condition regression coefficient as a reference (denoted as REF). The statistical analyses are performed for a set of nearly 6000 soundings.

The cloud parameters, such as the cloud top pressure (P_c in mb), visible optical depth (τ vis.), particle effective diameter (D_e in μm), and cloud phase (i.e., ice or liquid), are used in the cloud radiative transfer calculations. For the winter hemispheric data used here, most of the cirrus clouds are in the form of ice particles, so the statistical analysis with respect to the cloud phase is excluded for this case. The statistical results for the cloud parameter retrievals are listed in Table 1 showing the retrieval accuracy improvement from the general cloudy to cloud top height grouping retrieval. Since the effective cloud feature is present in the spectral radiances at the cloud top level, the cloud parameter retrieval accuracy is somewhat independent of the cloud optical thickness. EOF regression enables both the cloud height and the cloud microphysical properties of the highest-level cloud to be inferred. It is also shown in Figure 1 that the GRP retrieval accuracy above the clouds is somewhat independent of the cloud optical depth; and, as expected, the retrievals based on the MIX coefficients are better than the retrievals based on the CLE coefficients. However, the retrieval accuracy under the clouds is greatly improved over the optically thinner clouds, and the accuracy of GRP retrievals for the optical depth of less than one is close to that of the clear sky reference sounding retrieval accuracy. Thus, EOF regression enables thermodynamic properties to be inferred through thin cirrus clouds.

4. NAST-I retrievals and inter-comparisons

NAST-I instrumentation, measurements, calibration, and radiance validation are documented elsewhere [e.g., *Cousins and Smith*, 1997; *Zhou et al.*, 2002; *Smith et al.*, 2005]. NAST-I provides relatively high spectral resolution (0.25 cm^{-1}) measurements in the spectral region of 645–2700 cm^{-1}. While a large amount of data have been collected since 1998 under a variety of meteorological conditions, results from only a very limited data set are presented herein for the purpose of "cloudy" retrieval demonstration. Retrievals from the recent ATReC are used to demonstrate this inversion methodology. These data, together with the radiosonde and dropsonde released from the NOAA G-4 aircraft that flew below the NASA ER-2 aircraft, provide a unique data set for detailed analysis of retrieval resolution and accuracy. During this field campaign, cloud properties were also provided by the nadir-pointing Cloud Physics LIDAR

(CPL) on board the NASA ER-2 aircraft [e.g., *McGill et al.*, 2002]. All coincident observations obtained during this experiment are used to understand the atmospheric state and cloud microphysical properties for validating NAST-I retrievals.

The experiment of 5 December 2003 is chosen to test and demonstrate this inversion scheme with a realistic cloud radiative transfer model. The target scenes (latitude from 32°N to 42°N, longitude from 68°W to 76°W) covered a variety of conditions desired by the experiment scientific objectives. These included a variety of cloud conditions, such as medium-level altocumulus, as well as low-level cumulus, thunderstorms, and extensive high cirrus in the ATReC region covered by the ER-2 and G-4.

Figure 2a plots NAST-I retrieved cloud top height from the nadir observations against CPL measured cloud top heights of the top 2 layers, and Figure 2b shows the cloud optical depth inferred from NAST-I measurements against that of CPL 1064 nm channel measurements. It is noted that NAST-I horizontal resolution (at the cloud height) of a linear resolution (at nadir) is 13% of the distance between the aircraft altitude and the cloud height (i.e., 1.56 km when the cloud height is at 8 km and the ER-2 is at 20 km), while the CPL horizontal resolution is about 0.2 km; furthermore, the NAST-I vertical resolution is about 1 km while the CPL vertical resolution is 0.03 km. Despite the differences of the instruments and of their spatial resolutions, the cloud top heights inferred from NAST-I compare very well with CPL measurements for the variety of cloud conditions observed. The measurement sensitivity and accuracy of cloud optical depth inferred from the infrared measurement is expected to be much poorer than that measured by the CPL because of the nature of the two instruments. Even so, NAST-I cloud optical depth retrievals compare favorably to CPL observations.

NAST-I retrieved temperature and relative humidity vertical cross sections are shown in Figure 2c and 2d, respectively. The areas whited out are under the clouds where the cloud optical depth is larger than one. The variation of atmospheric conditions is captured very well by NAST-I retrievals, not only for the clear regions above optically thick clouds, but also for regions below optically thin clouds. These soundings are also validated by the dropsondes released from the G-4 aircraft. The dropsondes are used to reveal the retrieval sounding accuracy under cloud conditions. As shown in Figures 2c and 2d, retrievals of temperature and moisture above the clouds are not disturbed by the clouds below, and retrievals are reasonably accurate beneath optically thin clouds ($\tau<1.0$). Inter-comparisons between each dropsonde and retrieval are not presented here due to the space limitation; however, the sample shown in Figure 3 is a very representative example of all the cloudy sounding retrieval comparisons. In general, the retrievals show a good agreement above the clouds; the sounding comparison continues to show a good agreement under the (optically thin) cloud to the second layer cloud if it indicated by the CPL [*Zhou et al.*, 2005].

5. Conclusion and future work

Clouds greatly complicate the interpretation of infrared sounding data. The new hyperspectral resolution infrared sounding systems alleviate much of the ambiguity between cloud, atmospheric temperature, and moisture contributions. However, in heavily clouded situations, the thermodynamic profile information to be retrieved is limited to the atmosphere above the clouds. The results of this study indicate some success in the ability to retrieve information below scattered and partially transparent cirrus clouds (i.e., clouds with effective optical depths of less than one). The thermodynamic profile information might be obtained by a combination of cloud clearing and by direct retrieval from the clouded radiances using a realistic cloud radiative transfer model. Results achieved with airborne NAST-I observations show that accuracies close to those achieved in totally cloud-free conditions can be achieved down to cloud top levels. The accuracy of the profile retrieved below cloud top level is dependent upon the optical depth and fractional coverage of the clouds. This EOF regression has laid an initial step dealing with infrared sounding data under cloudy conditions, which might be further improved by a physical iteration inversion. The correct implementation still requires a considerable research development effort. However, cloudy sky radiative transfer models now exist which should enable the extraction of profile information from cloud contaminated radiances suitable for numerical weather prediction (NWP) application. These cloudy observations for NWP analyses are under investigation.

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Table 1. Cloud parameters retrieval accuracy over dependent samples.

τ=0-1; D_e=25-58 μm				
	Standard Deviation Error		Mean Error	
	CLD	GRP	CLD	GRP
P_c (mb)	105	30	-27.0	-9.2
τ vis.	0.78	0.17	-0.03	-0.02
D_e (μm)	5.7	4.6	-0.4	-0.2
τ=0-4; D_e=25-90 μm				
	Standard Deviation Error		Mean Error	
	CLD	GRP	CLD	GRP
P_c (mb)	109	31	-24.8	-9.2
τ vis.	0.54	0.40	-0.09	-0.04
D_e (μm)	7.6	5.6	-0.5	-0.2

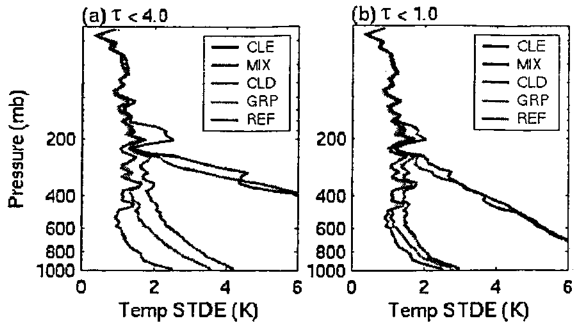

Fig. 1. Retrieval accuracy analyses through semi-transparent clouds: (a) for optical depth (visible) less than 4, (b) for optical depth (visible) less than one.

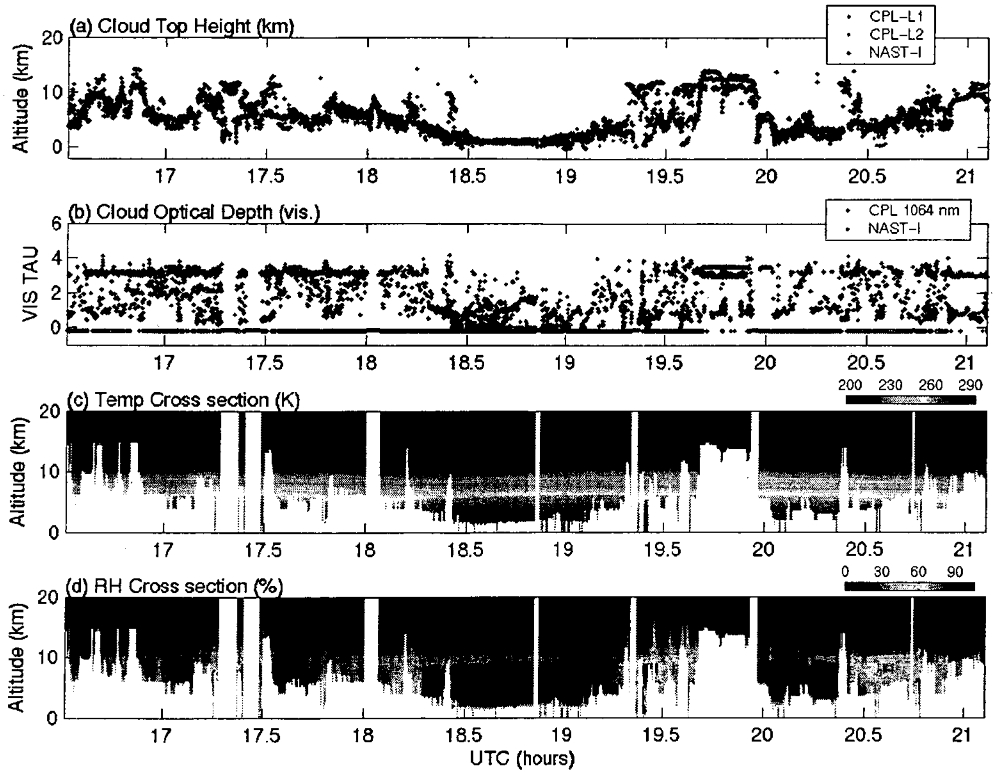

Fig. 2. Panel (a) NAST-I retrieved cloud top height compared with the CPL measured cloud top heights of top 2 layers. Panel (b) NAST-I retrieved cloud optical depth (effective visible) compared with the CPL measurement. Panels (c) and (d) plot NAST-I retrieved temperature and relative humidity vertical cross sections, respectively. The areas wiped off are under the top layer clouds where the cloud visible optical depth is larger than one and under the lower "opaque" cloud.

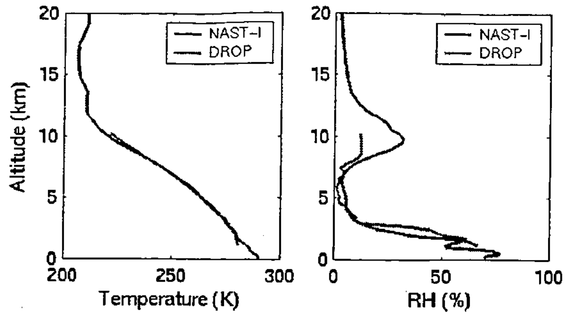

Fig. 3. NAST-I retrieval compared with coincident dropsonde.