8.11 TOWARD A THREE-DIMENSIONAL NEAR-REAL TIME CLOUD PRODUCT FOR AVIATION SAFETY AND WEATHER DIAGNOSES

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1. INTRODUCTION

Satellite data have long been used for determining the extent of cloud cover and for estimating the properties at the cloud tops. The derived properties can also be used to estimate aircraft icing potential to improve the safety of air traffic in the region. Currently, cloud properties and icing potential are derived in near-real time over the United States of America (USA) from the Geostationary Operational Environmental Satellite (GOES) imagers at 75°W and 135°W. Traditionally, the results have been given in two dimensions because of the lack of knowledge about the vertical extent of clouds and the occurrence of overlapping clouds. Aircraft fly in a three-dimensional space and require vertical as well as horizontal information about clouds, their intensity, and their potential for icing. To improve the vertical component of the derived cloud and icing parameters, this paper explores various methods and datasets for filling in the three-dimensional space over the USA with cloud water.

2. DATA

The USA domain covers 25°N - 50°N and 66°W - 125°W. The datasets used here include half-hourly GOES-10 and GOES-12 4-km spectral radiances and the cloud and icing properties retrieved from them (Minnis et al. 2004a). The results from each satellite are stitched together at 99°W. The cloud parameters of interest are the cloud phase, retrieved cloud temperature *Tc* to cloud-top height z_c, cloud thickness h, cloud base height z_b, liquid water path *LWP*, ice water path *IWP*, effective droplet size *re*, effective ice crystal diameter *De*, and aircraft icing probability.

The Rapid Update Cycle (RUC) analyses (Benjamin et al., 2004) provide hourly profiles of temperature and humidity at spatial resolutions of 40 and 20 km before and after April 2002, respectively. The RUC data have a vertical resolution of 25 hPa and can be used to estimate the probability of cloud occurrence within a layer using the results of Minnis et al. (2004b). Cloud base heights z_{bc} estimated from ceilometer data taken at a variety of locations around North America are part of the Automated Surface Observing System (ASOS), which provides data on an hourly basis.

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3. APPROACH

No single dataset can provide an accurate three-dimensional (3-D) characterization of the actual cloud fields over a large area because of limitations in each dataset. Multilayered and broken cloud systems are extremely difficult to interpret with passive satellite instruments. Active sensors such as radars and lidars can give a more complete vertical profile of cloudiness within a given area, but the area is typically confined to thin curtain profile that characterizes the clouds over a tiny area as a function time (surface-based) or as a function of distance (air or space-borne). Obtaining radar/lidar profiles with significant areal coverage and high time resolution is a prospect for the distant future. Meanwhile, combinations of datasets can be brought to bear to estimate the 3-D fields.

The approach proffered here is simply a basis for future improvement using enhanced satellite retrievals and new sources of surface data. The process begins with the satellite observations and adjusts the satellite data according wherever disagreement exists between the ceilometer and satellite cloud base heights. This process should help determine where a low cloud exists underneath a high cloud in those locations with an ASOS site. Model-based estimates of cloud profiles within a given atmospheric column could then be used to help determine in which layers the low level clouds exist. Using the model temperature profiles, it should be possible to locate where aircraft icing is likely even when it is not possible to determine the presence of a supercooled cloud from satellite data because an ice cloud blocks the view of the lower levels of the troposphere where icings are most common.

4.1 Ceilometer-satellite merging

Figure 1 shows a comparison of z_b (Fig. 1a) and z_{bc} (Fig. 1b) over the USA and portions of Canada and Mexico, hereafter referred to as USA for simplicity. This case, discussed by Minnis et al. (2004a), is quantified in more detail here. The cloud bases are compared to correct the GOES-derived values. It is assumed that the two datasets are not significantly different if the absolute value of the difference,

$$\Delta b = z_{bc} - z_b, \quad (1)$$

is less than 0.3 km. If this rather arbitrary criterion is not

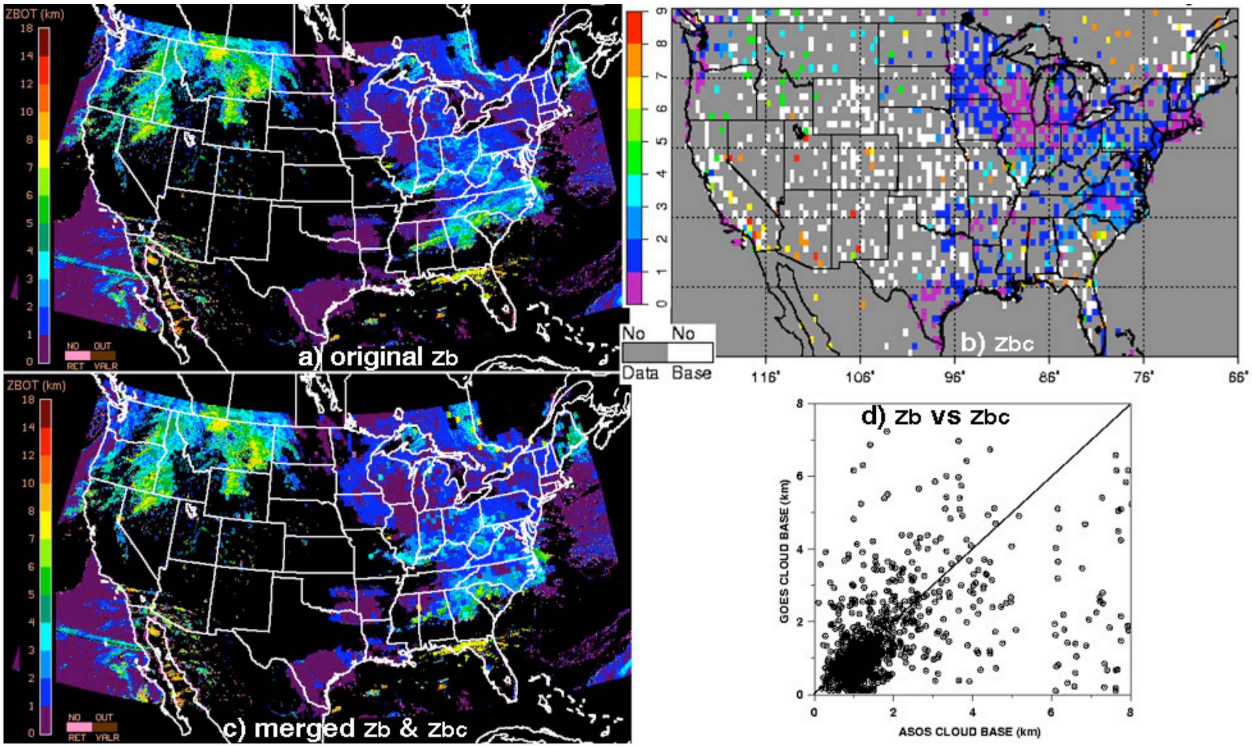

Fig. 1. Comparison and merging of cloud base heights measured at 1845 UTC, 18 March 2004.(a) merged GOES-10 and 12 4-km resolution cloud bases, (b) mean ceilometer cloud base for 1° regions, (c) merged ceilometer and GOES cloud base heights, (d) scatterplot of matched data from (a) and (b).

met for the average cloud base within a 1° box, then additional tests are performed. For example, if

$$z_c < z_{bc}, \quad (2)$$

then Δb is added to both z_c and z_b. If $\Delta b < 1.5$ km and no GOES pixels fall in the range of z_b for the given box, then the value of Δb is added to both z_c and z_b. Otherwise, if $\Delta b < 1.5$ km, then the box is flagged as being a multilayer box, and it will be adjusted later using z_{bc} as the base of the low cloud layer. Again, the cutoff of 1.5 km as a separation between layers is arbitrary at this point and will be changed as more is learned about this process.

The resulting merged dataset is shown in Fig. 1c. The changes relative to Fig. 1a are difficult to see, but are discernible upon close inspection. Cloud base height increased over parts of Texas and Louisiana, northwestern Wisconsin and some areas near the Quebec-Ontario border. It decreased over North Carolina, Georgia, Alabama, and eastern Oregon. The large decreases typically correspond to areas of cloud overlap where the satellite cannot discern the presence of the low cloud. The greater cloud base height increases occur over areas where thin cirrus is detected but placed at the wrong height as a result of overestimating the cloud optical depth. This type of error is more common over snow-covered regions where the bright background dramatically increases the uncertainty in the satellite retrieval. Smaller increases are simply due to the uncertainty in the empirical cloud thickness estimate or to smaller errors in cloud-top height resulting from errors in the vertical temperature profiles.

In general, the satellite and ceilometer base altitudes are relatively close, as seen in Fig. 1d. On average, z_b is 0.35 km lower than z_{bc}. The standard deviation of those differences is 1.53 km. The majority of the differences is less $\pm$0.5 km, but when overlapped or thin cirrus are observed, the errors are much greater as indicated in Fig. 1d.

4.2 Comparison of satellite and model data

Minnis et al. (2004b) developed an empirical relationship between probability of cloud amount and the atmospheric state parameters, relative humidity, temperature, and vertical velocity. The latter were taken from hourly RUC-40 reanalyses and the former was from the cloud boundary results from radar and lidar measurements taken continuously over the Atmospheric Radiation Measurement Program Southern Great Plains Central Facility in north central Oklahoma during 2000. Assuming that the relationships are valid for other locations within the USA and also hold for the RUC-20 data used here, the probability of cloud occurrence within a given 25-hPa layer can be estimated for each 20 x 20-km grid box every hour from RUC-20 data.

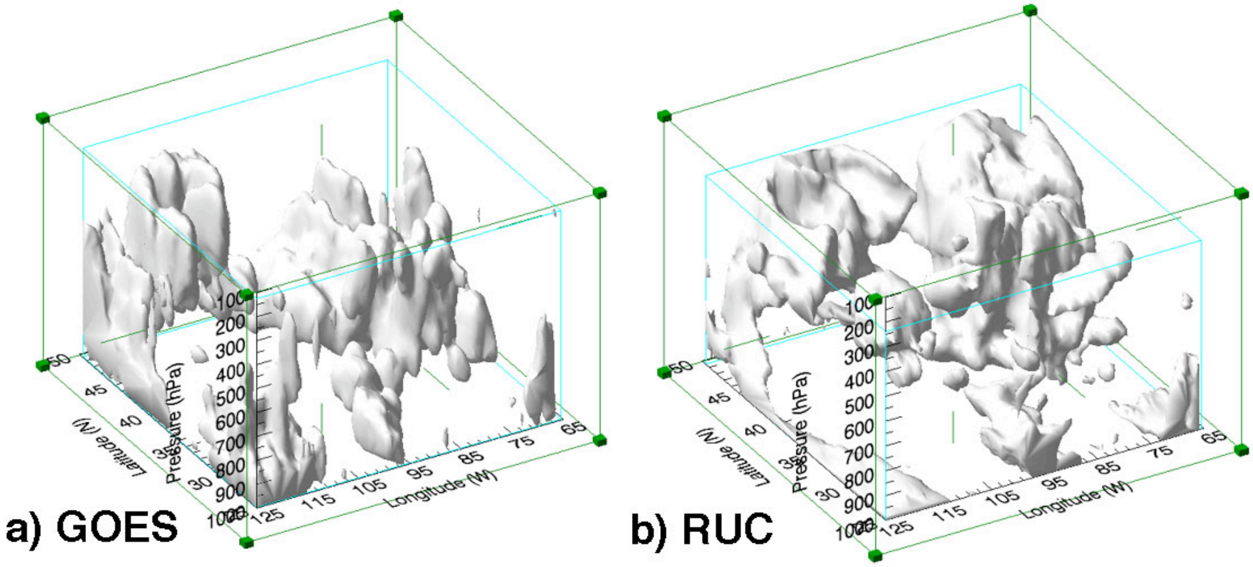

Fig. 2. Three-dimensional cloud fields at 1845 UTC, 18 March 2004 over USA.

The presence of a cloud within any volume can also be estimated from the GOES data by assuming that the space between z_t and z_b is occupied by the observed cloud. Thus, a 3-D cloud field can be constructed using any grid with a resolution lower than 5 km or so.

Figure 2 shows 3-D cloud fields created from GOES (Fig. 2a) and RUC-20 (Fig. 2b) data for the case in Fig. 1. The GOES fields are constructed using the results from any 20-km box having a cloud fraction greater than 10%, while the RUC clouds correspond to any box volume having a cloud probability greater than 40%. While these types of plots are notoriously difficult to interpret, some similarities and differences are readily apparent. For example, the RUC produces the same general characteristics and locations of the major cloud fields but often places the tops of higher clouds at lower pressures than derived from GOES data. Around 48°N, the RUC tops are 100 hPa lower in the west and almost 300 hPa higher in the east. This difference is probably realistic, at least in the east, because it is consistent with the cloud base comparisons in the same area (Fig. 1). Conversely, the RUC shows fewer clouds and less depth over the Pacific coastal area north of 40°N. If anything, the ceilometer data would agree better with the GEOS than the RUC in this area.

For multilayered clouds, the RUC might aid interpretation of the layering. Over the southwestern part of the domain, the GOES analysis interprets the overlapped clouds as a broken, but nearly vertically continuous cloud field from 300 to 950 hPa, while the RUC indicates well separated layers at 300, 500, and 1000 hPa. In that area, the GOES analysis yields some icing conditions that are probably false because the ice-over-water-cloud combination is sometimes interpreted as a supercooled liquid cloud. Although the heights of the lower cloud may be too low, the separation is probably more realistic and could be used to help adjust the retrievals to minimize false icing reports.

The differences are a little easier to see in horizontal slices at different levels. Figure 3 shows a comparison of the two cloud fields at 500 hPa. Generally, where the probability (Fig. 3b) is high (e.g., > 80%), the cloud fraction exceeds at least 30%. Some exceptions include the Pacific coast and central Michigan. In the latter case, the model suggests more cloud cover than is observed, while the reverse is true over Oregon and British Columbia.

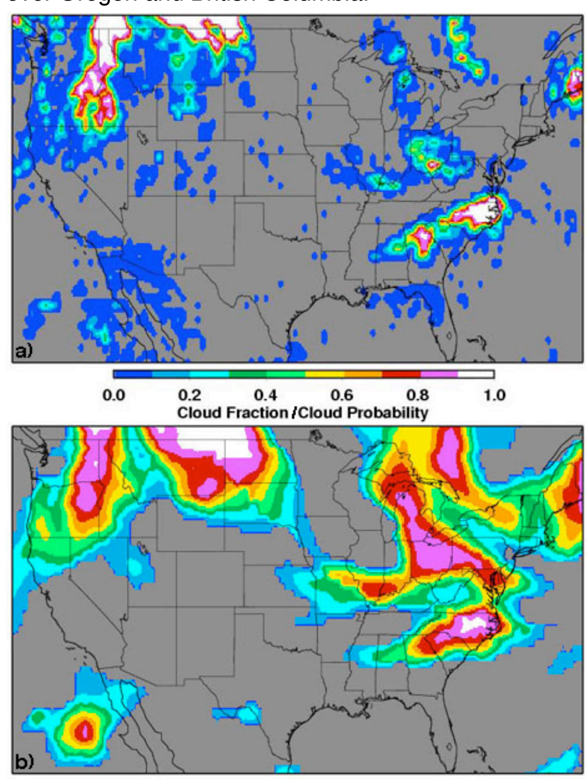

Fig. 3. Clouds at 500 hPa, 1845 UTC, 18 March 2004. (a) GOES cloud fraction, (b) RUC probability.

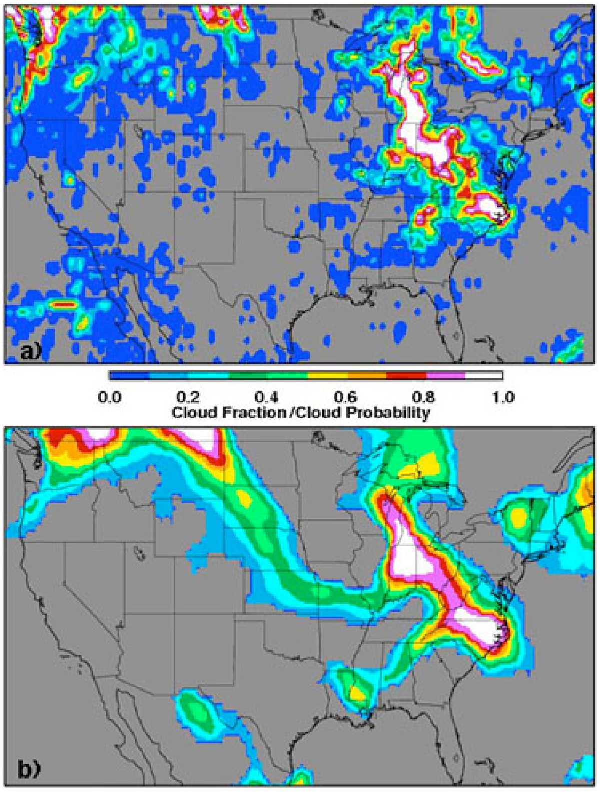

Fig. 4. Same as Fig. 3, except for 700 hPa.

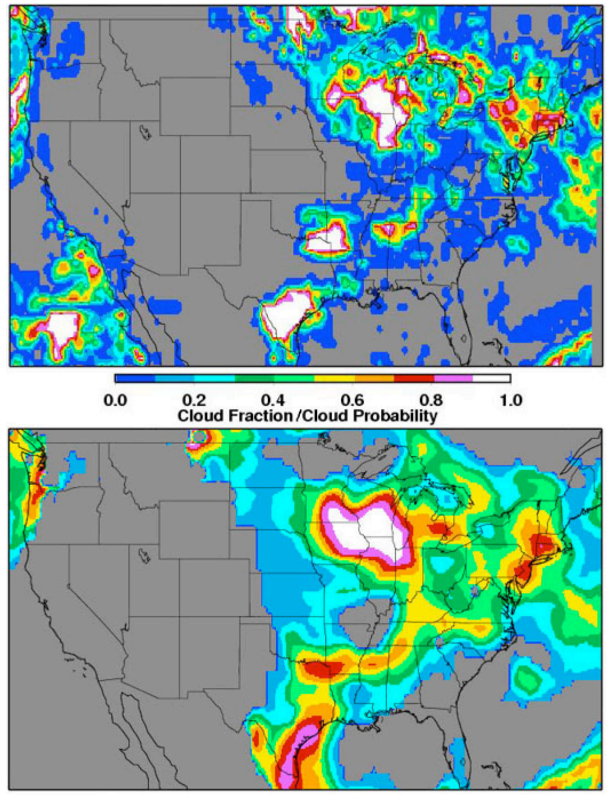

Fig. 5. Same as Fig. 3, except for 900 hPa.

Figures 4 and 5 show the comparisons at 700 and 900 hPa, respectively. The GOES analysis shows more clouds along the Pacific Northwest coast than expected from the RUC probabilities, while again, the GOES most likely retrieves too many clouds at 700 hPa off the Baja and southern California coasts. The position of the high probability area in Saskatchewan is farther west than the observed clouds in Fig. 4. The patterns in 700-hPa probability over the Midwest and North Carolina are quite similar to the large cloud amounts inferred from GOES. Exceptions include the maxima north of Lake Erie and over eastern Lake Superior that are not found in the RUC data. The RUC places these clouds higher at 500 hPa (Fig. 3b).

At 900 hPa, the patterns again are very similar but for a few exceptions. The low clouds west of Baja in Fig. 5a are placed at 1000 hPa by the RUC and therefore are not found in Fig. 5b. The main centers of high probability line up nicely with the large cloud fractions over Wisconsin, Arkansas, Texas, New Jersey and New England but there is a large hole over northern Minnesota and southern Manitoba where low clouds are found by the satellite and the ceilometer data (Fig. 1b). These differences indicate that the GOES retrieval can complement the RUC data in certain areas and vice versa. For example, the RUC probabilities suggest that some low clouds are present over north central North Carolina, but few 900-hPa clouds are inferred from the GOES data because of the presence of high-level clouds.

4. CONCLUDING REMARKS

This paper has begun the process of comparing different sources of cloud information with the ultimate goal of merging the different datasets to obtain an optimal 3-D characterization of clouds, especially those that would cause aircraft icing. Although some large differences exist, particularly in the heights of high clouds, the satellite-derived cloud fields agree remarkably well with both ceilometer and model analyses. The latter incorporates cloud-top altitudes form a different cloud product, so it is not surprising that there is agreement in many areas. It is clear, however, that the RUC analyses alone will not determine all of the areas where icing occurs. Blending of the various datasets like that used by Bernstein et al. (2004) should provide an optimal product.

Much additional improvement of the satellite products is needed, especially in the thin-ice-over-thick water cloud cases seen off the Baja coast. Multispectral techniques (e.g., Huang et al., 2004) are under development and will soon be tested. Nevertheless, it is clear that the GOES products can be used now to improve the determination of icing conditions and should be included in a 3-D cloud field/icing potential product to minimize errors in horizontal location and difficult-to-model cases like those over Minnesota. Logic for distributing the cloud water vertically and blending the datasets will need to be developed to fully utilize the information unique to each dataset.

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