

Real-Time Mesoscale Forecast Support During the CLAMS Field Campaign

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ABSTRACT

This paper reports the use of a specialized, mesoscale, numerical weather prediction (NWP) system and a satellite imaging and prediction system that were set up to support the CLAMS (Chesapeake Lighthouse and Aircraft Measurements for Satellites) field campaign during the summer of 2001. The primary objective of CLAMS was to validate satellite-based retrievals of aerosol properties and vertical profiles of the radiative flux, temperature and water vapor. Six research aircraft were deployed to make detailed coincident measurements of the atmosphere and ocean surface with the research satellites that orbited overhead. The mesoscale weather modeling system runs in real-time to provide high spatial and temporal resolution for forecasts that are delivered via the World Wide Web along with a variety of satellite imagery and satellite location predictions. This system is a multi-purpose modeling system capable of both data analysis/assimilation and multi-scale NWP ranging from cloud-scale to larger than regional scale. This is a three-dimensional, non-hydrostatic compressible model in a terrain-following coordinate. The model employs advanced numerical techniques and contains detailed interactive physical processes. The utility of the forecasting system is illustrated throughout the discussion on the impact of the surface-wind forecast on BRDF (Bidirectional Reflectance Distribution Function) and the description of the cloud/moisture forecast versus the aircraft measurement.

Key words: CLAMS field campaign, mesoscale numerical weather prediction, forecast support

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1. Introduction

For an effective *in situ* study of atmospheric phenomena, it is essential to know where and when to fly the appropriate instrumented aircraft. The Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) program, was no exception to this requirement. CLAMS, a campaign led by National Aeronautics and Space Administration (NASA) Langley Research Center and sponsored by programs such as CERES (Clouds and the Earth's Radiant Energy System), MISR (Multi-angle Imaging Spectroradiometer), MODIS-Atmospheres (MODIS: Moderate-Resolution Imaging

Spectroradiometer), and the National Aeronautics and Space Administration/Global Energy and Water Cycle Experiment (NASA/GEWEX) Global Aerosol Climatology Project (GACP), was conducted over waters surrounding the U. S. Coast Guard's Chesapeake Lighthouse, about 15 miles east of Virginia Beach, Virginia from 10 July to 2 August 2001. Equipment that was either mounted on the lighthouse itself or on the six research aircraft in conjunction with the orbiting Terra research satellite, measured the various atmospheric aerosol, radiation, and ocean characteristics (Smith et al., 2001). The major goal of this experiment was to combine long-term, surface-based ocean spectral observations with satellite and aircraft mea-

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surements to enhance our knowledge of the surface reflectance of the ocean and aerosols, thereby providing a better understanding of the Earth's energy budget and global climate change. Specific flight objectives included coincident measurements over a range of aerosol loadings over water, especially near the Chesapeake Lighthouse, with both satellite and remote sensing aircraft for a variety of wind speeds. An accurate forecasting system was crucial for bringing the experimental assets together with the desired weather conditions in the effort to meet each set of mission objectives.

During the past decade, regional numerical prediction efforts have proliferated as local computer power has increased, and with this, mesoscale modeling systems have become easier to use and more readily available. Numerical modeling analyses and forecasts from the national weather centers have become increasingly accessible over the Internet (e.g., Mass and Kuo, 1998). To aid the planning of aircraft operations with enough lead time, a specialized mesoscale forecasting system was set up and run over the experimental target region during the CLAMS field campaign. A typical operational numerical forecasting, such as that produced by National Centers for Environmental Prediction (NCEP), is neither high enough in resolution, both temporally or spatially (~ 29 km of NCEP Eta model), nor is it detailed enough for the 3-D cloud fields to allow for explicitly resolving-cloud studies. Furthermore, the available high-resolution extensive observations (e.g., Doppler radar data, surface mesonet data) are not used by the operational forecasts. This forecasting system provides accurate forecasts of 4-D atmospheric fields over the experimental area with both high spatial and temporal resolution. Furthermore, the high-resolution 4-D gridded forecasting data can also provide the meteorological background fields necessary for extensive observational analysis and theoretical studies of the mission data collected during the real time campaign and in the post-field phase. This system was combined with a web-based satellite position prediction routine and near-real time high-resolution satellite imagery to ensure coordination between the weather, satellite retrievals, and aircraft positioning. This paper documents the state-of-the-art mission prediction capability used for CLAMS.

2. Forecasting system and operational configuration

The forecasting tool used for this study is a fully automated, functionally complete system. It was originally based on the ARPS (Advanced Regional Prediction System; Xue et al., 2000, 2001) that was de-

veloped by CAPS (Center for Analysis and Prediction of Storms) at the University of Oklahoma during the past decade. ARPS was designed for both research and operational applications at scales ranging from cloud/storm-scale to regional large-scale. It has not only been tested extensively since the mid-1990s as a research tool (e.g., Wang et al., 1996, 1999, 2001; Xue et al., 2003), but also in real-time operations by universities, the National Oceanic & Atmospheric Administration (NOAA) National Weather Service, the US military and some private companies (e.g., Droege-meier et al., 1996; Carpenter and Bassett, 2001).

The dynamics and physics of ARPS were fully described by Xue et al. (2000, 2001). Some unique features are noteworthy here, for instance, ARPS is a three-dimensional, non-hydrostatic, compressible model in a vertically-stretched terrain-following coordinate system. It also has the multiple-nesting capability to cover the cloud-scale domain and mesoscale domain at the same time. The model employs advanced numerical techniques (e.g., a flux-corrected transport advection scheme, a positive definite advection scheme and a split-time step) and computational designs (can be run on all computers including those of the massive parallel class). The most unique physical processes included in the model system are those of the 3-phase ice microphysics, a soil-vegetation land-surface model, a 1.5-order turbulence kinetic energy (TKE) scheme and the PBL (Planetary Boundary Layer) parameterization, cloud-radiation-interaction, atmospheric-radiation transfer scheme and some cumulus-parameterization schemes used for coarse grid-sizes. There are 11 available soil categories and 13 available vegetation categories both with 1 km resolution across the U. S.

During the CLAMS experimental period, forecasts were made daily and were initiated at 0000 UTC and continued for the subsequent 36 hours. The domain, for the real-time forecasts, had a physical horizontal size of 1200×1200 km² and was centered at the Chesapeake Lighthouse (36.91°N , 75.71°W). It has an 83×83 horizontal grid with a 15-km resolution, and 43 vertically-stretched levels with a grid space varying from 20 m at sea level to nearly 1 km at the model top (20 km). The major model physics options used for the real-time forecasting included the 1.5-order TKE-based sub-grid-scale turbulence and PBL parameterizations, a two-layer land surface model, explicit grid-scale ice microphysics and the NASA/GSFC radiation package. The Kain-Fritsch cumulus parameterization scheme was used with explicit ice microphysics on this 15-km grid as well.

For real-time runs, the background field for the model initialization and the time-dependent lateral

boundary fields were provided by NOAA NCEP's Eta model. The initial conditions of the model were objectively analyzed through inserts of surface, upper-level and satellite observed data by using the ARPS Data Analysis System (ADAS; see Brewster, 1996), which was founded upon the Bratseth (1986) successive correction objective analysis scheme. The initialization analysis also enhanced the cloud and precipitate fields for the model.

3. Satellite observations

The forecast model was complemented by a web-based system for predicting satellite overpass times and viewing angles along with a variety of satellite imagery (<http://angler.larc.nasa.gov/clams>). The latter included custom loops of the Eighth Geostationary Operational Environmental Satellite (GOES-8) multi-spectral 1 and 4-km visible and 4-km infrared pictures, as well as the 1-km resolution Terra MODIS, SeaWiFS (Sea-viewing Wide Field-of-view Sensor), and NOAA-14 Advanced Very High Resolution Radiometer multi-spectral images. The digital radiance data for each image were archived along with the GOES-8 imagery that included the overlaid flight tracks for each aircraft that was operating during a given mission. Because they were posted in near-real time on the World Wide Web (WWW), the satellite imagery was immediately available for consideration by all members of the mission team and was used in planning and executing each mission.

4. Model forecasting

Model forecasts were produced for each day's mission plan and were used by the mission forecaster during the daily weather briefings. The model forecast products and some examples are discussed in the following section.

4.1 Operations summary

The mesoscale forecast model, running on a local SGI Origin 3000 with 16 processors, required approximately 4 CPU hours for a given 36-hour forecast, with a memory requirement of 210 million bytes. The forecasting system was started at 0300 UTC and all 36-hour forecasts were available at 0700 UTC. The model forecasting fields were output in both graphical format with 3-hour time resolution and in GRIB-format files at 1-hour time intervals for archiving. The graphical files were delivered via the WWW (<http://asd-www.larc.nasa.gov/model/clams>). The files included plots of the variables, including surface properties such as land-surface/soil moisture, cloud cover and precip-

itation, upper-air level values of temperature, humidity, and winds, and the vertical cross-sections of the same. The parameter values could be displayed as contours, color shading, overlays, and in animation. These products could be easily accessed from anywhere for daily weather summaries and forecasts to assist aircraft flight planning and post flight scientific data analyses.

4.2 Wind and sun glint

The mission flown on 10 July 2001 was designed to measure the aerosol optical depth (AOD) and the bidirectional-reflectance distribution function for the clear ocean with some coordination with the Terra overpass. Figure 1 shows the EOS (Earth Observing System) Terra MODIS image, the GOES-8 visible image and the model forecasted surface winds on 10 July 2001. The RGB composite image (Fig. 1a), which is centered over the Chesapeake Lighthouse, was produced from the MODIS spectral bands 1 (Red channel), 4 (Green channel) and 3 (Blue channel). It shows the glaring signature of sun glint, which are the enormous and near-specular reflections observed as blue-white over the water.

The clouds in Fig. 1a are depicted as a pale white, as confirmed through comparison with the GOES-8 image presented in Fig. 1b. Most of the GOES-8 image is clear, with a different viewing geometry from MODIS (Fig. 1a) having been used. No glint is detectable from GOES-8 (Fig. 1b). But as seen in Fig. 1a, no glint is evident for ~50 km off the coast in the MODIS RGB image, which is the region where the sea remains blue. The effect is due to the nearly calm winds on the coast. Sun glint is the result of specular reflectance of sunlight. In calm seas, the surface reflects like a mirror, for which the angle of incidence equals the angle of reflection. The sun glint area is very small with a very high reflectance. The area and incident angles that are affected by sun glint, increase with increasing wind speeds. This dramatic illustration stresses the importance of the wind fields for the proper interpretation of observations of BRDF (Bidirectional Reflectance Distribution Function) over the ocean, an important boundary condition for satellite remote sensing. The model-forecasted, surface-wind-speed field (Fig. 1c) shows that the area of the sea surface without glint corresponds to a region where a minimum surface wind speed occurs. The wind speed increased further east, in the areas that are further removed from the coast. That increased wind evidently led to a more active capillary wave, thereby causing a spread and general displacement of the cone of the reflected short-wave light from the sea surface. At the Chesapeake Lighthouse site, the model-forecasted sur-

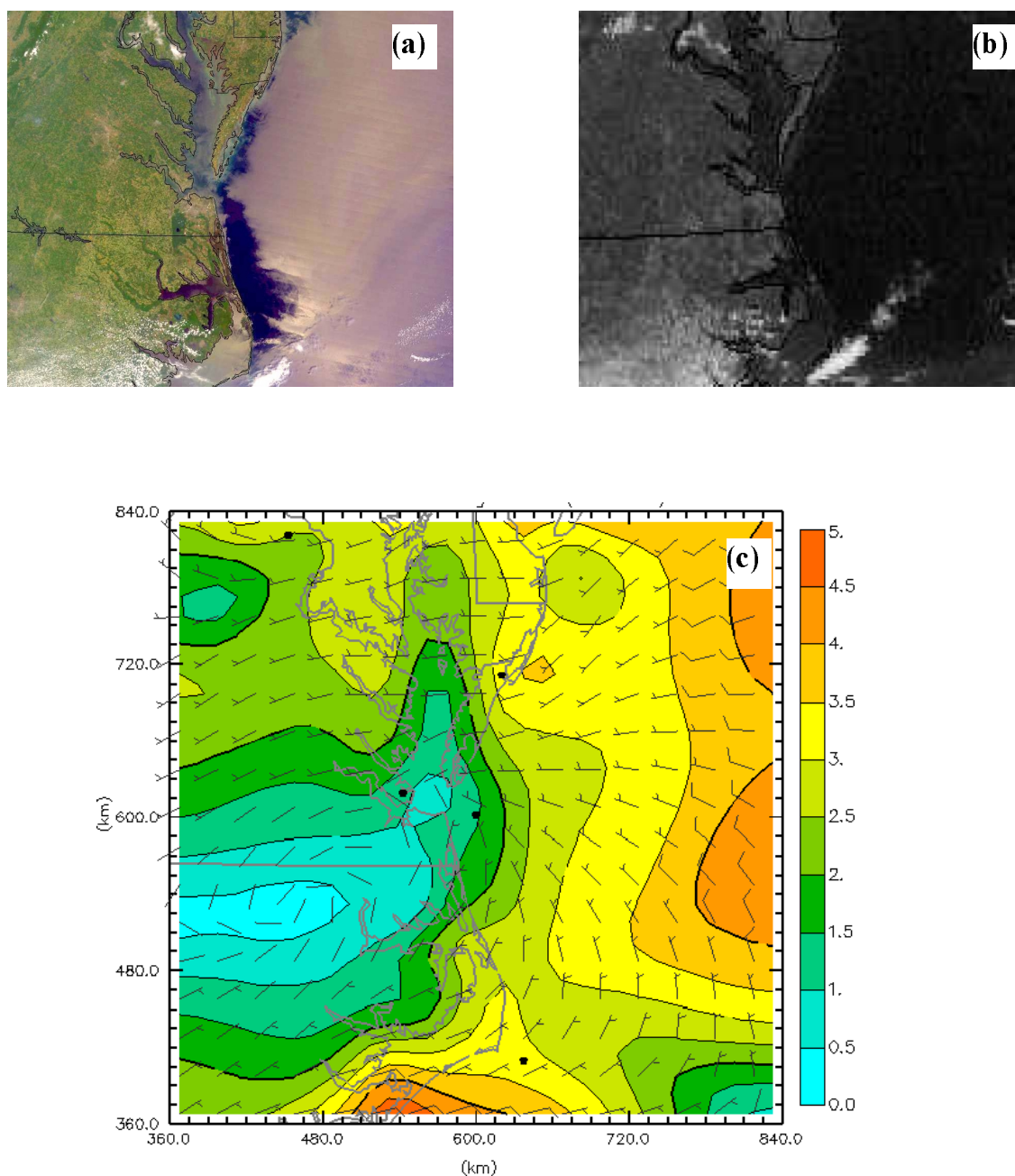


Fig. 1. Sun glint and the forecasted surface wind on 10 July 2001 for (a) the Terra MODIS RGB image showing sun glint, (b) the GOES-8 visible image showing clear skies over the targeted region and (c) the 18-hour model forecasted surface wind speed (shaded, m s^{-1}) and wind bar.

face wind speed was 1.3 m s^{-1} , which was close to the observation of 1.0 m s^{-1} from COVE (CERES Ocean Validation Experiment).

The effect of the wind speed on BRDF can be illustrated by the discrete ordinate calculations (Yongxiang Hu, personal communications) for a Cox-Munk ocean at 0.65 microns (Cox and Munk, 1954). In the case of a wind speed of 2 m s^{-1} , the reflected beam has already spread about a cone of ± 35 degrees. If the

wind speed is 12 m s^{-1} , the cone is wider, and the direction of the peak reflectance has shifted considerably toward the horizon. For wind speeds below 2 m s^{-1} , the cone of reflection should be quite small. This explains the MODIS observations shown in Fig. 1a. The planning of a field mission to validate the retrievals of AOD from MODIS is greatly enhanced if the areas affected by sunglint can be reliably predicted, because such retrievals are typically not performed if the re-

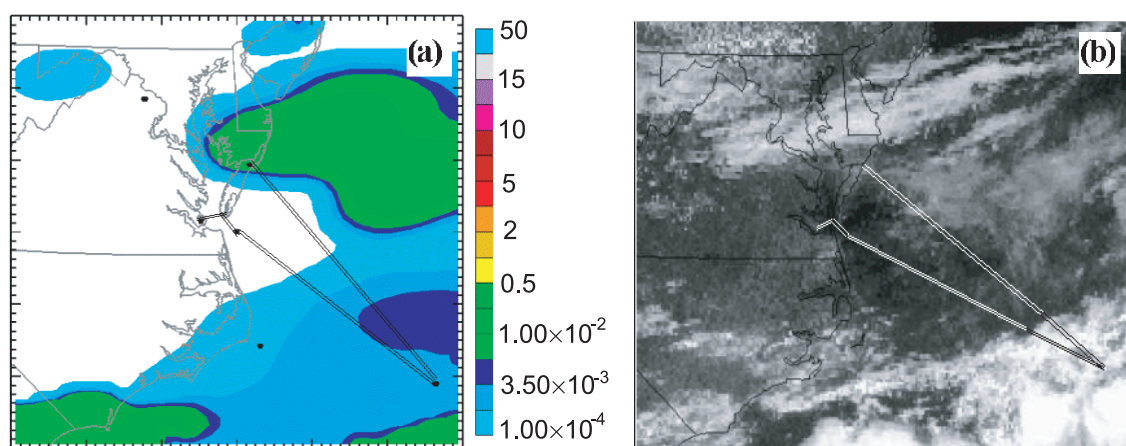


Fig. 2. Cloud forecasts and GOES-8 observations for (a) a 15-hour model forecasted total condensate path (shaded, kg m^{-2}) that was valid at 1500 UTC 12 July 2001 and (b) the GOES-8 visible image of clouds at 1515 UTC 12 July 2001.

flectance field is significantly affected by sun glitter. In this case, the forecasted winds indicated that, despite the MODIS viewing angles, there would be minimal sun glint effects near the coast during the Terra overpass and it would be beneficial to fly an aerosol validation mission. Additionally, knowledge of the wind parameters is important for flying BRDF missions. It is desirable to measure the BRDF over a wide range of wind speeds to accurately characterize the BRDF variability. The ability to accurately predict the winds speeds thereby enables flight planners to determine if and when to fly the BRDF missions.

4.3 Cloud/moisture and aircraft measurements

Planning for high-altitude missions to study the radiation from clouds is less flexible than that for low-level *in situ* flights because of the additional pilot preparation required for low-pressure conditions and the greater sensitivity to surface winds for takeoffs and landings. Thus, forecasts of both the surface and high-altitude conditions are extremely important. During CLAMS, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed-interferometer (NAST-I) was flown on a high-altitude aircraft, Proteus, at 18 km, while other instruments were flown on the NASA ER-2 at 20 km. NAST-I provided multi-dimensional geophysical retrievals from its highly spatially and hyper-spectrally resolved infrared data (e.g., Smith et al., 2001; Zhou et al., 2002). Measurements of cirrus clouds and high-altitude moisture were required in one of the Proteus flights during CLAMS. The cloud conditions, in the form of column-integrated cloud condensate, were predicted with the forecast model each day. Figure 2a

shows the 1500-UTC cloud condensate for 12 July 2001 with an overlay of the Proteus flight track. The predicted cloud condensate was the smallest (light blue) directly to the east of southern Virginia and was the greatest to the north and south. These predictions were in generally good agreement with the clouds in the 1515-UTC GOES-8 image (Fig. 2b). However, the heavier cloudiness to the north extended further south than the model over the open ocean and the model-predicted clouds were too thin relative to those in the southern portion of the image. The best agreement was found near the coast, where the flights occurred. NAST-I provided higher spatial resolution (2 km) images along the Proteus flight tracks that are shown in Figs. 2a and 2b for 12 July 2001. This flight track covered the areas of clear and different cloud types that were apparent in the GOES-8 image in Fig. 2b and the model-forecasted cloud field in Fig. 2a. In spite of the red vertical streaks that were due to the attenuation by the clouds, the moisture cross section indicated that the top of the cirrus clouds was at about the 15 km level and extended downward to about the 6 km level (Fig. 3). Both the model forecast (Fig. 3b) and the NAST-I measurement (Fig. 3c) indicated the presence of a dry layer below the cirrus clouds and above the marine boundary-layer moisture. The top of the marine boundary layer extended from approximately 2 km upward to the cirrus cloud level, where some lower clouds were created from the northern to the southern end of the track, respectively. Over the southern end of the track, the model accurately represented the high cirrus clouds (Fig. 3a) that were also evident in the GOES-8 image. The apparent over- and underestimates of the cloud water by the model further out over the ocean were probably due to the lack

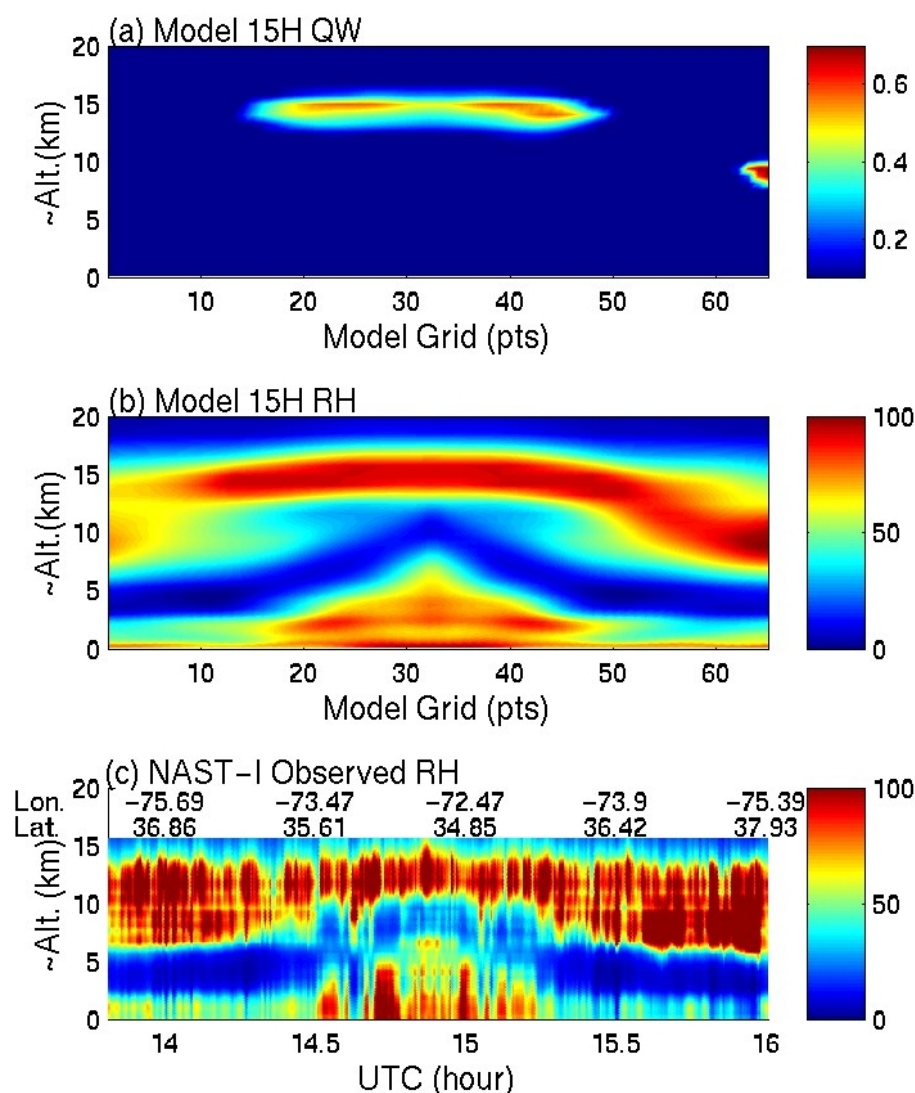


Fig. 3. The vertical cross-sections of the cloud and moisture fields along the aircraft Proteus flight track that were shown in Fig. 2 for (a) a 15-hour model-forecasted, cloud-water mixing ratio ($10^{-2} \text{ g kg}^{-1}$) that was valid at 1500 UTC 12 July 2001, (b) is the same as (a) except using the forecasted relative humidity and (c) the relative humidity as measured by NAST-I.

of sufficient observations in the initial conditions for those areas.

5. Summary

This paper illustrates the utility of a specialized, real-time, mesoscale forecasting system in the operation of a field campaign. The present effort is a good attempt to apply a state-of-the-art mesoscale forecasting system, performing in real-time mode, for numerical weather forecasting in support of a NASA field experiment. The model forecasts were delivered via the Internet in real-time. The products were used to

prepare daily weather summaries and were also used to conduct extensive observational analysis and theoretical investigations of the satellite/aircraft measurements during the real-time campaign and in the post-field phase. These forecasts, in conjunction with near-real time satellite imagery and satellite overpass and viewing angle prediction routines, greatly enhanced the mission planner's chances for success.

The surface wind played an especially important role in forcing the optical properties of the ocean. Unfortunately, *in situ* wind measurement by an anemometer covered only one point. While some down-looking radiometer measurements covered only

small areas, most short-wave and microwave instruments were deployed to sample regions covering at least several square kilometers. To estimate the wind conditions for any such region, it was very helpful for a remote sensing group to use such a forecasting model for analysis. As shown from the moisture comparison between the model forecast and the aircraft observation, the high spatial resolution, remote-sensing data (i.e., NAST-I) will be useful in efforts to improve the NWP (Numerical Weather Prediction) model and forecasting through validation. This successful effort is an encouragement for using a similar mesoscale NWP forecasting system in the support of future field experiment programs.

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