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"Forecast Model Applications of Satellite-derived Cloud Parameters"

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Principal Investigators
Dr. Melanie Wetzel and Dr. Steven Chai
Atmospheric Sciences Center
Desert Research Institute
University and Community College System of Nevada

Project Summary

Research is being conducted in the design and implementation of methods for obtaining cloud physical parameters from satellite remote sensing data, and the use of these methods to improve short-term forecasting with the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) prediction model. The correct representation of clouds, and the resulting effects on radiative propagation, the surface radiation budget, evaporation and precipitation is vital to the usefulness of forecast models. In the first year of this two-year project, the procedures have been demonstrated for the satellite retrieval techniques and the merging of these retrieved parameters with COAMPS model output. A field research experiment has also been planned, in collaboration with the Naval Research Laboratory, the University of Wyoming and Oregon State University. The experiment is scheduled for 4 August - 4 September 1999 in the region of coastal Oregon, and will allow detailed case studies of marine stratus forecasting and analysis procedures using the satellite retrieval methods, COAMPS model forecasts, and instrumented aircraft observations. In conjunction with the first year activities, three research meetings have been held at NRL-Monterey, at which the satellite research plan and collaborative activities have been discussed. These meetings have been arranged by Dr. Wetzel in cooperation with Tom Lee and Dr. William Thompson of NRL, and were attended by several scientists from NRL, the Desert Research Institute, the University of Wyoming, the Naval Postgraduate School, and Oregon State University.

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6. AUTHORS
Melanie A. Wetzel
Steven K. Chai

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Desert Research Institute
University and Community College System of Nevada
2215 Raggio Parkway
Reno, NV 89512-1095

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1. Background

Microphysical characteristics in maritime cloud have significant control on cloud layer evolution, electromagnetic propagation, cloud-aerosol interactions, visibility, and aircraft flight hazards. While the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) model may not in the immediate future explicitly represent cloud microphysical parameters, the relationship of cloud structure to the predicted variables must be assessed, particularly when considering physical or radiative parameterizations.

Electromagnetic signal propagation through the atmosphere is directly influenced by the size and composition of atmospheric particles. Cloud droplet size, particularly at cloud top in the marine atmospheric boundary layer (MABL), plays a role in the rate at which turbulent entrainment produces aerosol via evaporation or removes aerosol via collection by droplets. The droplet size distribution also controls the effectiveness of the stochastic collision-coalescence process in producing drizzle or rain, thereby also impacting the evaporative source (or collection loss) of aerosol during drop sedimentation below cloud. These processes can be incorporated into combined aerosol-cloud simulation models by explicit or parameterized treatments.

Cloud-aerosol interactions play a major role in marine meteorology, including the effects of cloud condensation nuclei on cloud droplet size, and the influence that aerosol size and chemical composition can have on precipitation development (Levin et al., 1996). These interactions follow temporal patterns on daily and longer time scales. In a study of the global climatology of stratus cloud droplet size derived from satellite data, Han et al. (1994) found that for open-ocean stratus regions, droplet effective radius increases by 2 μm from morning to afternoon, and is associated with a decrease in cloud optical depth.

Information on the second moment of the droplet size distribution (droplet size) can add considerably to the quantitative characterization of cloud radiative fluxes and microphysical processes. Martin et al. (1994) discuss aircraft measurements which show a direct relationship between droplet effective radius, droplet concentration, and liquid water content within marine stratocumulus clouds. Slingo and Schrecker (1982) demonstrated direct dependance on cloud droplet effective radius of cloud optical thickness, single scattering albedo and asymmetry factor.

Further, cloud bulk reflectivity is a function of both effective radius and cloud liquid water path. Even small changes in cloud droplet size will significantly alter cloud shortwave albedo and thus the shortwave-longwave flux divergence profiles (Slingo 1990). Quantitative information on the spatial distribution of cloud droplet size is thus needed in order to permit numerical weather prediction models accurate radiative flux calculations (Jones and Slingo, 1996).

2. Project Results during Year 1

2.1 Retrieval of Satellite Parameters

Multispectral satellite data from the NOAA AVHRR instrument have been used to develop methods for combined analysis of cloud microphysical parameters with the Navy's COAMPS forecast model simulation results. Remote sensing retrieval methods demonstrated by Wetzel et al. (1996) for satellite estimation of stratiform cloud droplet size and optical depth.

Satellite data are utilized from the NOAA polar-orbiter Advanced Very High Resolution Radiometer (AVHRR) sensor and the GOES geostationary Imager sensor. The primary channels used are the visible Channel 1 (0.57-0.72 μm on Imager and AVHRR) ; near-infrared, Channel 2 on Imager (3.78-4.03 μm), and AVHRR Channel 3 (3.55-3.93 μm) and the thermal infrared windows, Channel 4 (10.2-11.2 μm on Imager, and 10.3-11.3 μm on AVHRR) and Channel 5 (11.5-12.5 μm on Imager, 11.4-12.4 or 11.5-12.5 μm on AVHRR). The near-infrared channels provide daytime cloud reflectance data from which droplet size can be deduced, in combination with the thermal infrared data to remove the thermal emission effects from the near-infrared, and utilizing the visible radiances to normalize the near-infrared reflectance for cloud albedo effects.

The Discrete Ordinates model (Stamnes et al., 1988) has been used to generate tabular data for multiple cloud droplet size, cloud optical depth and solar/viewing geometry conditions, covering the ranges of possible image passes and cloud types. The Streamer software package (Key, 1996; Meier et al., 1997) is a UNIX-based program which applies the Discrete Ordinates Model with gaseous absorption and aerosol extinction effects, and this was implemented for the satellite channels and stratus cloud characteristics simulated for this study. Use of this radiative transfer method has demonstrated the influence of aerosol on marine stratus cloud droplet size (Borys et al., 1998).

From the satellite image data, cloud-covered pixels were selected using channel threshold tests, and the cloud optical depth and cloud droplet size are found by interpolation from the observed satellite pixel reflectances in the visible and near-infrared channels to the arrays of pre-calculated radiative transfer model reflectances. Cloud optical depth is defined as

$$\delta = \int \beta_{ext,0.6}(z)dz$$

where the extinction coefficient (β_{ext}) is defined for 0.6 μm wavelength and the optical depth is integrated through the depth (Δz) of the stratus cloud. Model-calculated reflectance in the satellite visible channel is directly related to optical depth for the range of microphysical conditions observed in stratus cloud, so that satellite-observed reflected radiance can be directly used with model-calculated reflectances to retrieve cloud optical depth (Platnick and Valero, 1995). Figure 1 presents an example of the relationship between visible reflectance and cloud optical depth for a range of relative sun-satellite azimuth angle.

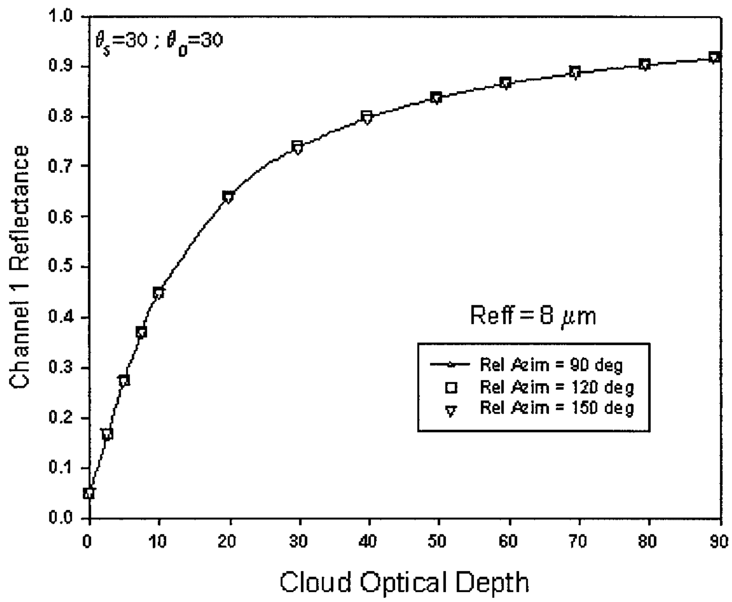

Fig 1. AVHRR Channel 1 reflectance calculated using the Discrete Ordinates radiative transfer model for stratus cloud of increasing optical depth, at three values of the sun-satellite relative azimuth angle (ϕ), the indicated conditions of satellite zenith angle (θ_s) and solar zenith angle (θ_0), and with cloud droplet effective radius (Reff) of 8 μm.

Secondly, the near-infrared reflectance obtained from the GOES Imager Channel 2 or the AVHRR Channel 3 decreases significantly as cloud droplet size increases, such that results for the range of sun-satellite viewing angles, cloud optical depth and droplet size can be utilized with observed satellite radiances to estimate droplet size. This relationship is most robust for the size distribution parameter known as the effective radius (R_{eff}), which is defined as a the ratio of the volume-weighted and area-weighted integrals of the size distribution, n(r):

$$R_{eff} = \frac{\int r^3 n(r) dr}{\int r^2 \, n(r) dr}.$$

Figure 2 presents an example of the cloud near-infrared reflectance in the AVHRR Channel 3 as droplet size increases. The thermal emission contribution to near-infrared radiance is removed by using the thermal infrared brightness temperature and an initial estimate of near-infrared emissivity for the cloud. The blackbody temperature is inverted to calculate the near-infrared blackbody radiance, and this is subtracted from the satellite-observed near-infrared radiance to obtain the reflected near-ir radiance.

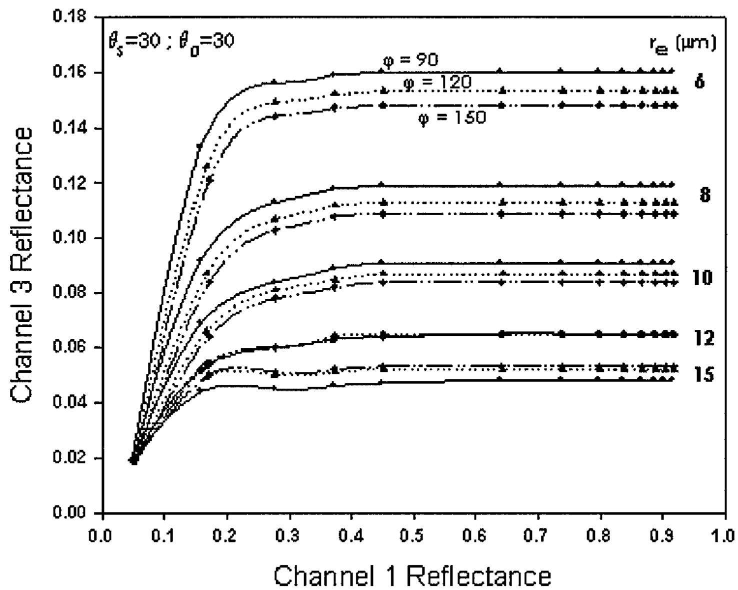

Fig.2. AVHRR Channel 3 and Channel 1 reflectance curves calculated using the Discrete Ordinate model for a family of cloud layers with droplet effective radius increasing from 6 to 15 μm, at three different sun-satellite relative azimuth angles (ϕ) and the indicated conditions of satellite zenith angle (θ_s) and solar zenith angle (θ_0).

Cubic spline interpolation was implemented to first estimate cloud optical depth from the AVHRR Channel 1 reflectances, then to retrieve cloud droplet effective radius from the cloud near-infrared reflectances. Figure 3 shows an example of the cloud optical depth image product for a region off of the central California coast. Values of optical depth for this case range from 4 to 23. Two specific dates (12 and 15 June 1996) were selected to allow demonstration of the procedure during times at which the COAMPS model simulations were available. The image has been remapped into the map projection used by the COAMPS simulation. Figure 4 presents an image of the retrieved cloud droplet effective radius for the same satellite overpass time, with values in the range 5-16 μm.

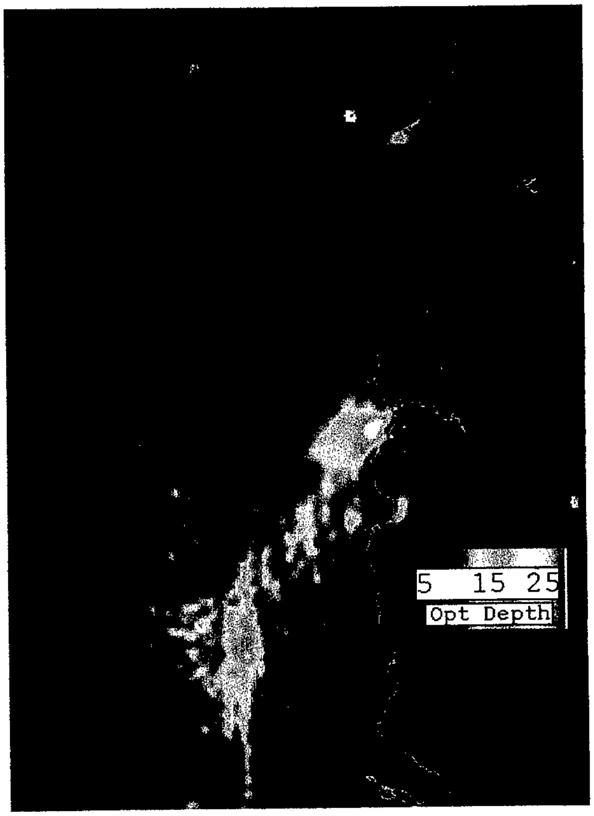

Fig. 3. Satellite-estimated cloud optical depth for 12 June 1996.

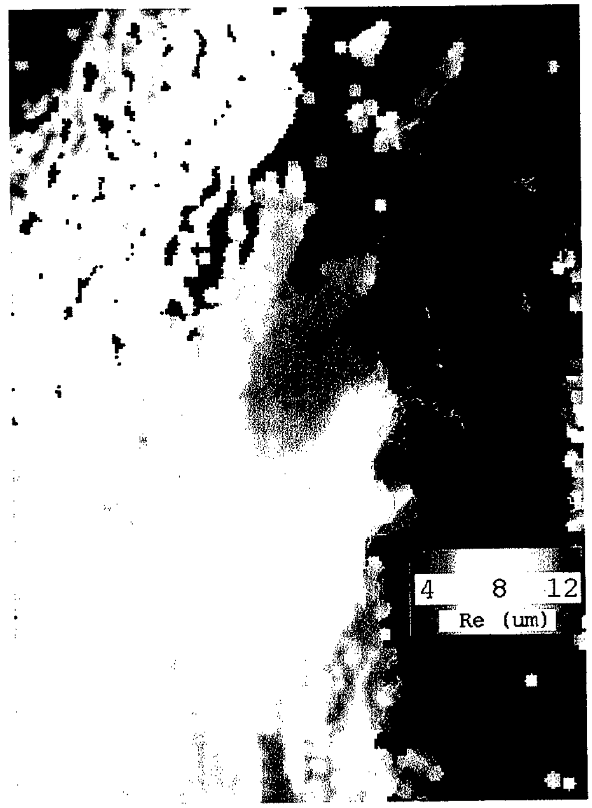

Fig. 4. Satellite-estimated cloud droplet effective radius for 12 June 1996.

Aside from the use of cloud optical depth in the method for droplet size retrieval, optical depth is also valuable in determining visual range, and electromagnetic extinction for specific sensors and guidance systems. In combination with COAMPS model fields providing cloud base and cloud top levels, more accurate line-of-propagation data can be obtained from the satellite-mapped cloud optical depth. Parameterizations of transmittance at multiple wavelengths can be evaluated using the 0.6-µm optical depth. The satellite-estimated cloud droplet effective radius can be applied to further refine the scattering and absorption of radiation along electromagnetic propagation paths. Droplet size is not available from the COAMPS model, so that information on the spatial and temporal distributions of droplet size supplies significant enhancements to our ability to monitor stratus evolution and radiative characteristics.

2.2 Merging Satellite Parameters with COAMPS Model Data

Derivation of secondary products has also been demonstrated, combining the COAMPS model gridded data with the satellite retrieval results. The COAMPS model simulations performed for the COAST '96 stratus research experiment were utilized. Model parameters of interest included the cloud liquid water content at each model grid level, the top and base height of predicted cloud, the precipitation mass content, and sea surface temperature. For example, the vertical profile information on cloud liquid water content (g m^{-3}) was integrated through the entire cloud depth to obtain cloud liquid water path (g m^{-2}), while vertical profiles of precipitation water content yielded the vertically-integrated precipitation water path. For comparative analysis with satellite data, a parameterization (Stephens, 1978) for cloud liquid water path (LWP) was adopted, where

$$LWP \approx \frac{2}{3}\,\delta\, R_{eff} \quad .$$

Figure 5 presents a comparison between the actual value of cloud liquid water path for cloud layers prescribed for the radiative transfer (RT) calculations, and the parameterized shown above. The values of optical depth and effective radius were obtained from the RT model input conditions. The strong correspondence between the prescribed (model) and parameterized values suggests that satellite-estimated values of cloud optical depth and droplet effective radius can be used to estimate cloud liquid water path.

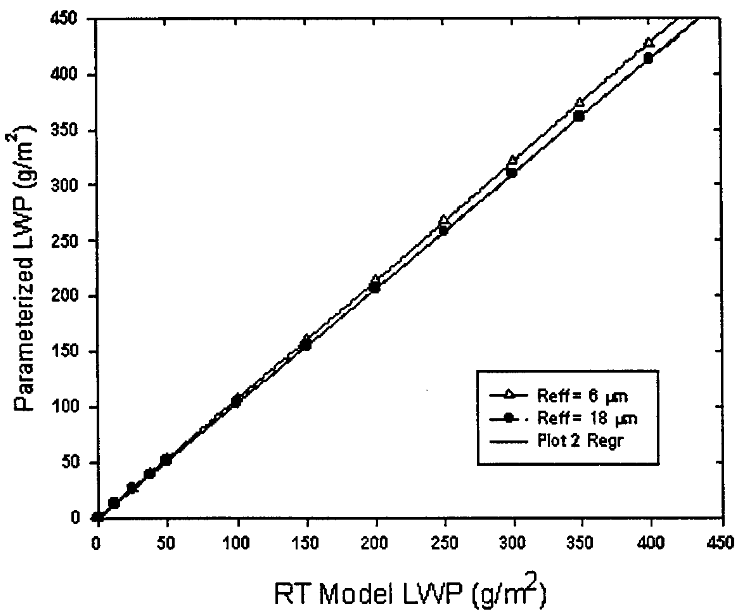

Fig. 5. Comparison of parameterized and model-prescribed stratus layer liquid water path.

Since liquid water path is a parameter directly forecast by the COAMPS model, then intercomparisons as well as model initialization or verification can be accomplished. The LWP produced by the parameterization using satellite-derived optical depth and effective radius is shown in Figure 6, and the COAMPS-derived cloud liquid water path for the near-simultaneous time period is shown in Figure 7.

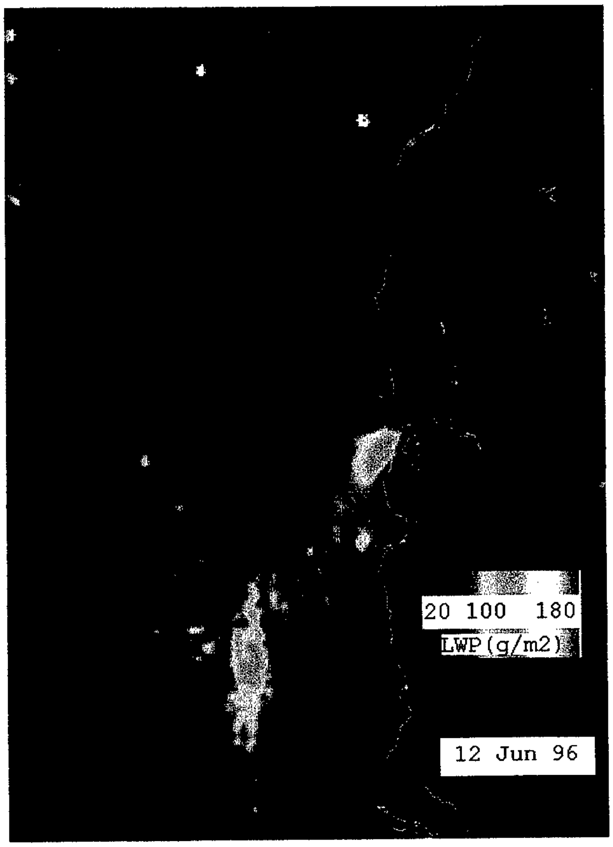

Fig. 6. Cloud liquid water path obtained from the parameterization from satellite-estimated cloud optical depth and droplet effective radius.

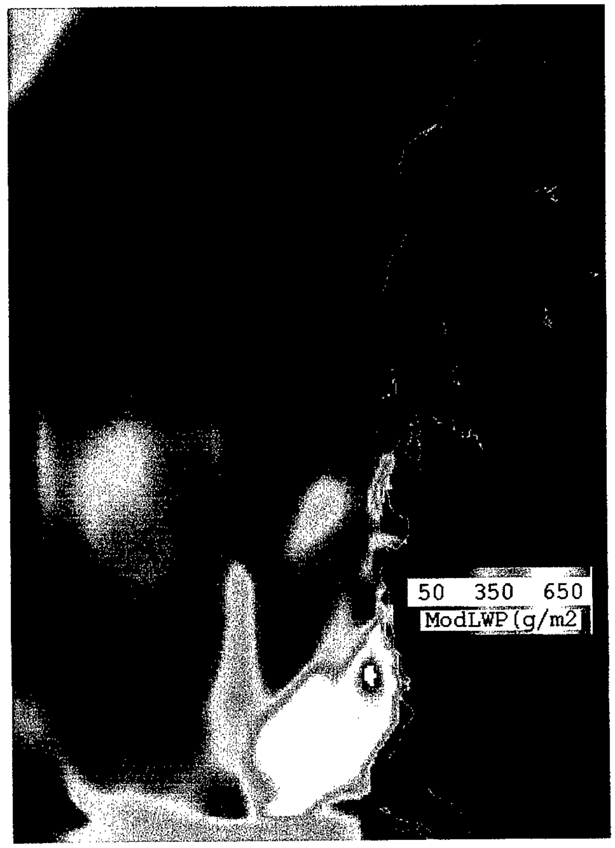

Fig. 7. COAMPS model-derived stratus liquid water path, calculated by vertical integration of liquid water content through the cloud.

For this case, we note agreement in the spatial pattern of cloud cover and cloud liquid water path. Note that in the off-shore region to the west of northern California (upper left region of image), the overall pattern in LWP is similar in the model and satellite product images, although the magnitudes indicated by the color enhancments are different. Model LWP for this region reaches 300 g m^{-2}, while the satellite estimates are approximately 100 g m^{-2}. Recent improvements in the cloud physics of the COAMPS model is expected to reduce these discrepancies. Another improvement may be possible by more accurate model initialization of sea surface temperature. A second case study demonstrated much larger LWP magnitudes from COAMPS, and analysis of the sea surface temperature revealed values several degrees warmer in the model initialization than was actually indicated by the thermal infrared satellite imagery. A warm bias in the sea surface temperature initialization causes strengthened surface fluxes and overestimates of cloud liquid water production.

The COAMPS model can provide cloud base and temperature profile information which is not available from satellite sources. Cloud base height is extremely important in the interpretation of visual range and radiative extinction along a line of sight. The presence of drizzle or rainfall below cloud base cannot be directly evaluated from the GOES or AVHRR satellite data. However, the probability of precipitation formation is increased as cloud optical depth and droplet effective radius increase. Comparisons of these parameters with the COAMPS values of precipitation liquid water path demonstrate that satellite products may be useful in mapping droplets falling below cloud base.

Precipitation liquid water path was calculated from the COAMPS model results for the two study cases, by vertical integration of precipitation specific humidity over the depth of stratus cloud. Figure 8 and Figure 9 present these parameter distributions for 12 June and 15 June, respectively. A simulated aircraft track is overlaid as a path of red dots, to allow along-path sampling of the model and corresponding satellite retrieval results. The western (leftmost) leg of this flight track indicates a region where the stratus layer was producing precipitation. Figure 10 shows a point-by-point comparison of COAMPS precipitable water path (PWP) and the satellite-estimated droplet effective radius corresponding to Figure 8 (12 June), while results in Figure 11 matches the PWP image in Figure 9. These figures each indicate that cloud droplet size increased along the sampling trajectory, with largest droplet sizes near the endpoint. In this region the precipitation begins to appear in the COAMPS results, and the comparison suggests that the model precipitation coincides with areas where Reff > 8 μm.

Merger of data fields such as this allows verification and design of data assimilation procedures which take advantage of the complementary information in the satellite and COAMPS products. In order to validate the satellite and forecast model parameters with observed marine stratus conditions, a field project is being planned for summer 1999, as described below.

Fig. 8. COAMPS model-predicted precipitation

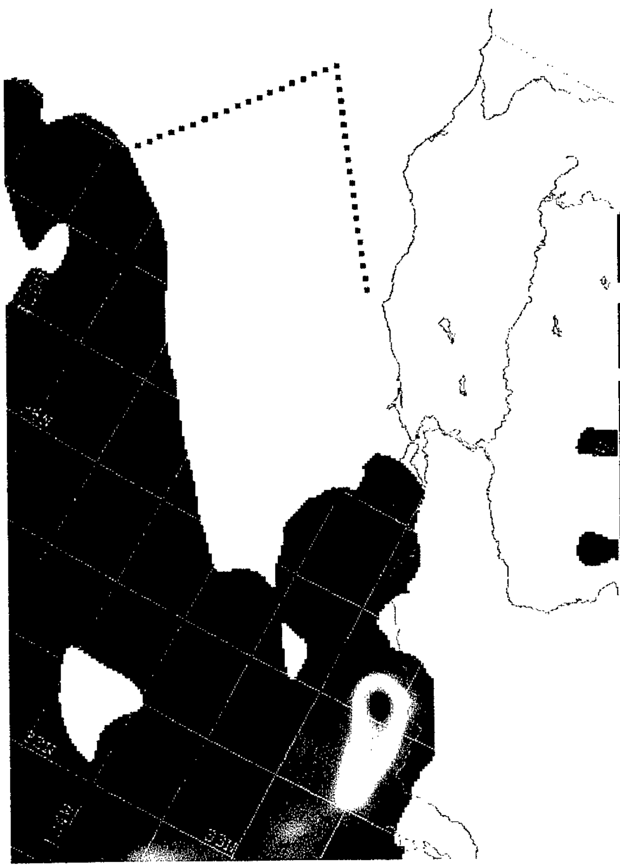

Fig. 8. COAMPS precipitation water path forecast for 12 June 1996.

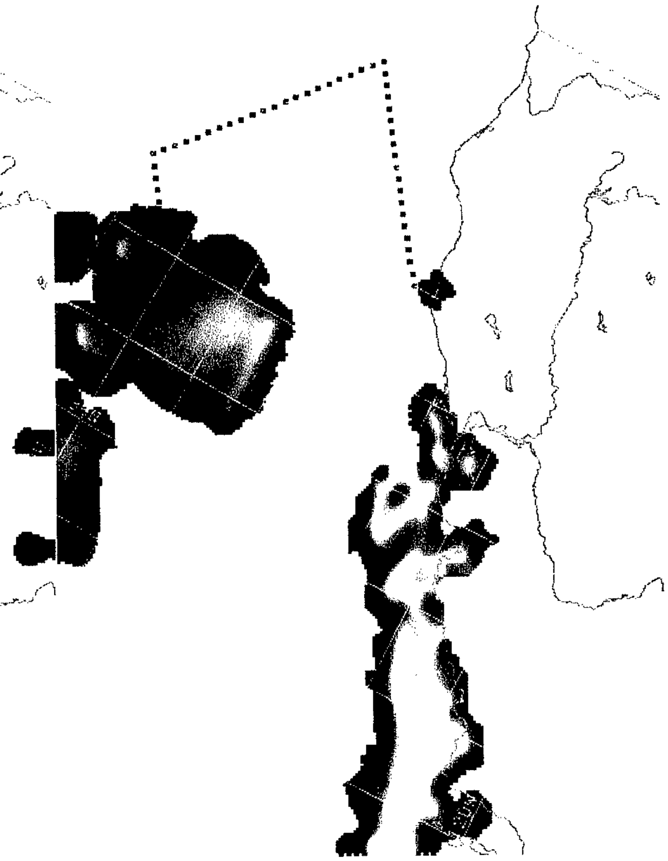

Fig. 9. COAMPS precipitation water path forecast for 15 June 1996.

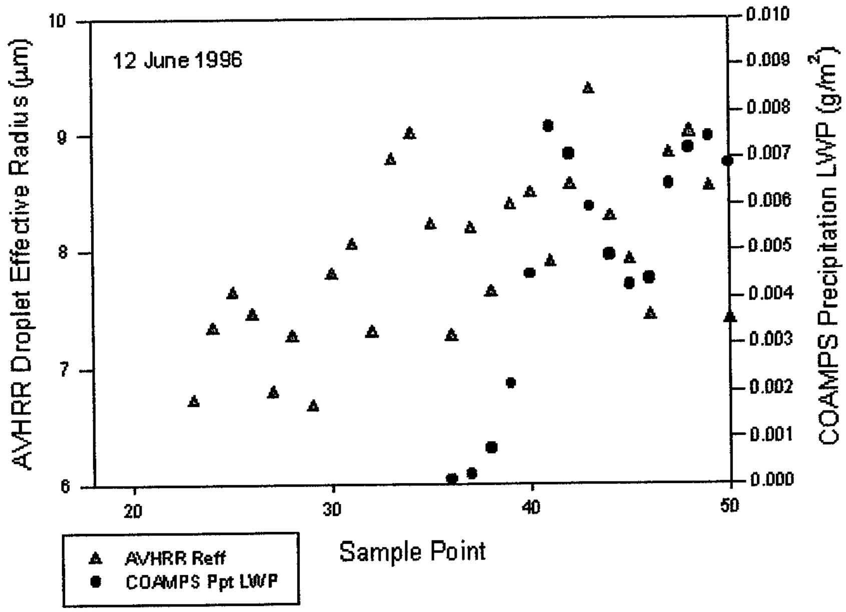

Fig. 10. Point-by-point comparison of satellite-derived droplet effective radius and COAMPS precipitation liquid water path along a simulated flight track for the 12 June 1996 case.

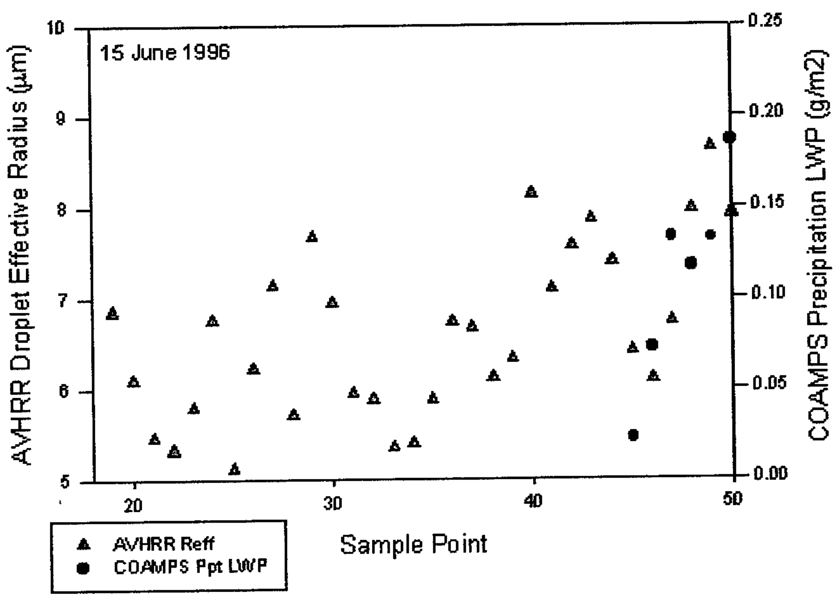

Fig. 11. Point-by-point comparison of satellite-derived droplet effective radius and COAMPS precipitation liquid water path along a simulated flight track for the 15 June 1996 case.

2.3 COSAT Field Validation Experiment

A field research program has been developed as part of this project, which is a collaborative effort between the Desert Research Institute, the University of Wyoming, Oregon State University, and the Naval Research Laboratory. The project has been named the COAMPS Operational Satellite and Aircraft Test (COSAT), and will take place during 4 August - 4 September from Corvallis, Oregon. The COAMPS model will be used to produce 24-hour forecasts each day, for the coastal region of Oregon, and simultaneous satellite data processing will produce cloud and related parameters and satellite-model merged products such as those described above.

Satellite products will be produced at 1-km and 4-km resolution in realtime from the GOES multispectral data, while the COAMPS model will be implemented with three nested grids, and a fine-scale inner grid resolution of 9 km. The University of Wyoming King Air instrumented research aircraft will be a projected 50 hours into stratus layers, with stair-step, contant-altitude, and spiral sampling trajectories designed to characterize the cloud physics and thermodynamic conditions of the stratus.

The 24-hour hour forecasts from COAMPS, and auxiliary forecast and nowcast products, will supply the information for daily flight planning and post-flight analysis. Data will be archived for further detailed study of stratus cases, with particular emphasis on the merging of COAMPS model output with satellite-derived cloud and aerosol parameters. An all-hands field project meeting is planned for Corvallis in late August to review the observations and results to date. A follow-up meeting of the research collaborators is planned at the University of Wyoming during the autumn.

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