8.2 ANALYSIS AND PREDICTION OF MICROWAVE REFRACTIVITY PROFILES IN NOCTURNAL MARINE CLOUD LAYERS

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1. INTRODUCTION

Accurate representation of the complete diurnal cycle of dynamical and cloud physical processes associated with the marine atmospheric boundary layer (MABL) is essential to many aspects of global weather and climate. The stratiform cloud prevalent at the top of the MABL provides evidence of the persistent effect of the subsidence inversion in subtropical and mid-latitude regions, but the cloudy MABL is continually undergoing adjustment that influences many aspects of near-surface meteorology. During the daytime, solar-driven evaporation augments the effect of persistent winds in supplying water vapor to the MABL and helps to feed convective processes. During nighttime, radiative cooling from cloud tops coupled with the large-scale atmospheric subsidence strengthens the low-level inversion, often sharpening the vertical gradients of temperature and moisture and contributing to parcel mixing from cloud top.

Several past field experiments have focused on the MABL cloud cover and dynamics. These include the First ISCCP Regional Experiment (FIRE; Cox et al. 1987), the Atlantic Stratocumulus Transition Experiment (ASTEX; Albrecht et al. 1995), Dynamics and Chemistry of Marine Stratocumulus (DYCOMS; Lenschow et al. 1988), COAMPS™ Operational Satellite and Aircraft Test (COSAT; Wetzel et al. 2001) and DYCOMS II (Stevens et al. 2003), and these have produced greater knowledge of turbulent processes and cloud-aerosol interactions. However, accurate prediction of the MABL diurnal evolution is still limited by the scarcity of meteorological measurements over oceanic regions, and improved methods for merging satellite remote sensing data with numerical prediction models would have numerous benefits, particularly because many satellite data sources are available at high temporal resolution that would be valuable for operational assimilation to forecast models.

The large vertical gradients of temperature and moisture that typically cap the MABL greatly affect the refractive index of the atmosphere and propagation of electromagnetic waves. Weather observation radar is affected by such phenomenon as trapping of microwave energy. Observed radar signatures may be significantly degraded in terms of magnitude or location. Generally the height of a radar target is not well interpreted when signal trapping occurs. Cellular and other radio communication systems can also be affected by this phenomenon (Haack and Burk, 2001), which increases risk for shipping and marine recreation activities.

Satellite image analysis of cloud top temperature has been successfully used in the past (Helvey et al., 1995) to diagnose conditions of microwave ducting in the MABL environment. The present study is focused on observations of boundary layer cloud structure and microwave refractivity near the coastal region of southern California. Model simulation data are compared to DYCOMS II observational data sets to evaluate the effectiveness of a new model initialization method using satellite-derived parameters for the MABL structure. The numerical model predicted parameters are validated using available research aircraft flight measurements, dropsondes and satellite observations.

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2. THE DYCOMS II FIELD PROGRAM

The DYCOMS II multi-investigator research program (Stevens et al. 2003) was conducted 7-28 July 2001 offshore of southern California. Nine research flights with the NCAR C-130 aircraft were carried out, collecting valuable nighttime measurement data for study of entrainment, drizzle cloud microstructure and cloud-aerosol relationships. A diverse set of sensors were aboard the C-130, and archived parameters included temperature, winds, water vapor, liquid water, cloud microphysics and radiation measured at 1HZ as well as many other parameters at 1 Hz and higher sampling rates. During the experiment, sets of dropsondes were also deployed from the aircraft on 10, 11, 13, 17, 18, 24, 25, and 26 July 2001. Dropsondes provided vertical profiles at high resolution including measurements of temperature, humidity, wind speed and direction, and balloon position**.**

3. MODEL SIMULATIONS

3.1 MM5

The Fifth Generation PSU/NCAR Mesoscale Model Version (MM5) is developed and maintained by the National Center for Atmospheric Research (Grell et al. 1997). This model is based on three-dimensional primitive non-hydrostatic equations. The Arakawa B-grid scheme is applied in this model. Vertical and horizontal resolutions are variable to user specification, and the model domain is globally re-locatable. The sigma coordinate system is used to specify MM5 vertical levels.

MM5 uses parameterizations for radiation, cumulus convection and microphysical processes. Cyclones, fronts, severe weathers, mountain waves and many additional phenomena have been studied using this model. The MM5 model setup and specifications for this study (Figure 1) are: Coarse (x,y,z) grid 149 x 191 x 44 with horizontal grid spacing 9 km, and an inner nested grid of 244 x 214 x 44 with horizontal grid spacing of 3km. The 44 vertical levels increase in depth from the surface upward, with a layer depth of 37m at the lower boundary.

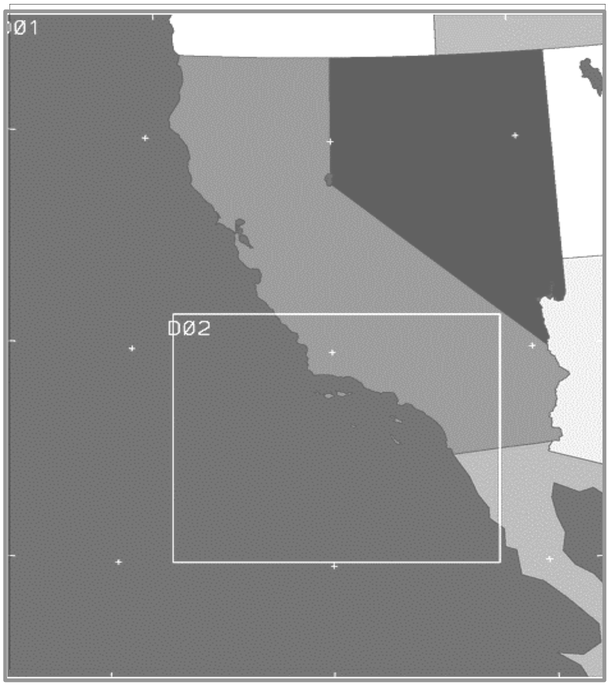

Figure 1: MM5 model setup with the following grid specification --
•Coarse grid 149 x 191 x 44 Hor. Res.: 9 km
•Nested grid 244 x 214 x 44 Hor. Res.: 3 km

3.2 COAMPS

The U.S. Navy's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS™) is a model developed by the Naval Research Laboratory, Marine Meteorological Division (Hodur 1997). The governing equations represent three-dimensional non-hydrostatic compressible flow. The model uses an Arakawa-C grid scheme and is applicable to any number of nested grids. It is very flexible for horizontal as well as vertical resolution, with typical horizontal resolution ranging from 1-81 km, although horizontal resolution as low as 333m has been used (Hodur 1997). Vertical resolution typically ranges from 20m at lowest level to several thousand meters at the model top (Hodur 1997). The coordinate system is Cartesian, spherical or polar for the horizontal grid and stretched sigma coordinate for the vertical grid.

Parameterizations for radiation, cumulus convection, and stable precipitation parameterizations are used in the model. Atmospheric phenomena such as mountain waves, land sea breezes, terrain-induced circulations, tropical cyclones, and mesoscale convective systems have been simulated using COAMPS™. The following model specifications are used in the present study: tree nested domains, 61 grid points in E-W direction, 49 grid points in the N-S direction, and 30 levels in the vertical. Inner horizontal grid resolution is 6 km.

3.3 Integration of satellite data for MM5 simulations

The MM5 model was applied to conduct a baseline simulation (without satellite data input), and then in an enhanced simulation (by assimilating satellite-derived profiles of MABL temperature and humidity). Satellite remote sensing can provide frequent temporal sampling that allows more detailed analysis of diurnal cycles, and observations that cover wide regions of the oceans where direct monitoring is very difficult.

GOES Imager data were used in a multichannel cloud classification (Wetzel et al., 2001) that provided nighttime stratus distribution and cloud top temperature over the MM5 model nested grid (see Figure 1). These were combined with satellite-derived sea surface temperatures (available twice daily over the model domain) to produce a spatial distribution of inversion base height (IBH) and MABL temperature/humidity profiles at the nested domain gridpoints. These gridded fields were incorporated into the initial conditions of the MM5 model (Koracin et al., 2003). The following steps summarize this procedure:

- GOES Imager multichannel satellite data were used to determine cloud top temperature (CTT) at the top of the MABL
- TRMM Microwave Imager (TMI) satellite data provided sea surface temperature (SST)
- The satellite data were mapped to the MM5 inner grid to create initial fields of inversion base height, SST and CTT, where Inversion Base Height (IBH) is estimated from,

$$IBH(km) = \frac{(CTT - SST)}{\Gamma_d} \qquad (1)$$

with Γ_d = -9.8 ^{o}C/km, *CTT* = cloud top temperature (^{o}C), and *SST* = sea surface temperature (^{o}C).

These calculated heights agreed well with the measured heights obtained from DYCOMS II aircraft sampling and dropsonde profiles. The MABL temperature profile was linearly interpolated with height between the surface and cloud top temperature values. Humidity profiles corresponding to the temperature profiles were produced under the assumption of 85% relative humidity in the MABL. This was the condition observed at the surface using dropsonde profile data. Alternatively, a near-saturated humidity profile could be used in the upper MABL region to more closely represent the effect of moist adiabatic lapse rate in the upper portion of the MABL. The initial condition MABL profiles were assimilated to the model only at startup, using the multi-quadric method of objective reanalysis. The MABL profiles were combined with first-guess upper-level profiles above the MABL. The upper-level data were obtained from the NCEP-NCAR Reanalysis Project (NNRP).

4. CALCULATION OF REFRACTIVITY PARAMETERS

Information on the vertical and horizontal distribution of modified refractivity can provide excellent diagnosis of the microwave signal trapping that often occurs due to temperature and humidity gradients at the top of the MABL (Helvey et al., 1995; Burk and Thompson, 1996). However, temperature and humidity profile observations in the MABL are sparse over the majority of oceanic regions, and hence the need for model predictions and remote sensing analyses of these conditions. Modified Refractivity (M) is defined as:

$$M = \frac{77.6}{T}\left(P + 4810\frac{e}{T}\right) + \left(\frac{Z}{R_e}\times 10^6\right) \qquad (2)$$

where T= air temperature (K), P= pressure (mb), e= water vapor pressure (mb), Z = altitude (m), and R_e= mean radius of earth (m) (Battan, 1973).

A negative vertical gradient of modified atmospheric refractivity (dM/dZ<0) results in anomalous propagation of microwave radiation. If meteorological conditions cause a trapping layer to occur aloft it is referred to as an elevated duct or elevated trapping layer. This phenomenon is common offshore of the west coast of U.S. (Haack and Burk, 2001). For elevated trapping layers, the base of this layer is typically coincident with the base of the MABL inversion, and the top is located where a minimum value in the M profile occurs above the base elevation. The difference between M at these two heights defines the duct strength, which is determined primarily by the vertical humidity profile and to a lesser extent by the temperature profile across this layer.

5. CASE STUDY ANALYSIS

Analyses were carried out of the distribution of cloud water mixing ratio, air temperature, specific humidity and modified atmospheric refractivity parameters on 10 July 2001 for the MM5 simulations and COAMPS™ operational forecast output. Five dropsondes were released on 10 July at 0741, 0755, 1338, 1345 and 1352 UTC. The cloud field at 12 UTC 10 July 2001 (Figure 2) shows a relatively uniform cover in the region. This bi-spectral image is a difference of the GOES IR and near IR channels to provide more distinct definition of cloud field structure at night.

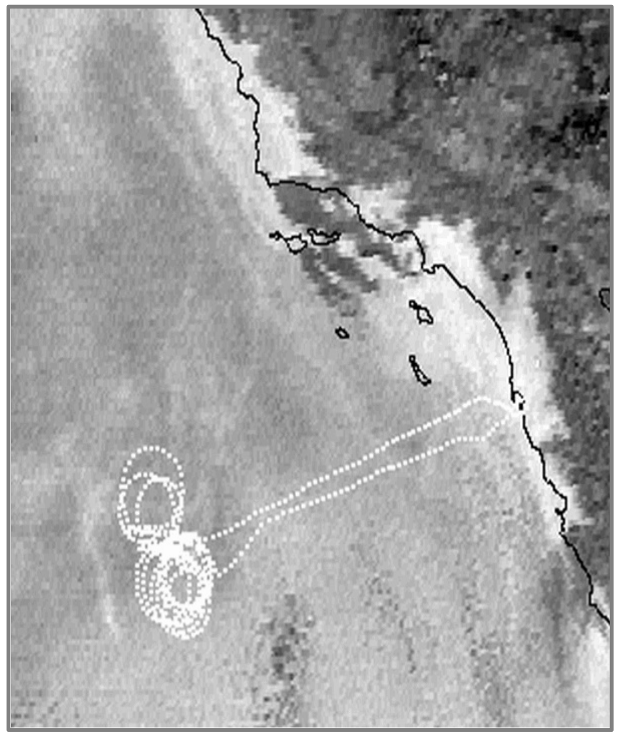

Figure 2: Bispectral nighttime satellite image at 1200 UTC on 10 July 2001 with the DYCOMS II flight track.

Figure 3a and Figure 3b present horizontal cross-section plots from MM5 model simulation output (baseline and enhanced runs) for total cloud mixing ratio and horizontal winds at 600 m at 14 UTC on 10 July 2001. For both plots the MM5 simulation started at 06 UTC 10 July 2001. Figure 3a shows results for the MM5 baseline simulation, indicating cloud water mixing ratio values in the range 0.3 g kg^{-1} in the region of the DYCOMS II aircraft sampling (west end of the east-west transect shown). Figure 3b corresponds to the MM5 enhanced simulation, using the satellite-derived MABL initial profiles. This plot shows higher values of cloud water mixing ratio (up to 0.6 g kg^{-1}) in a more extensive region of the study area, and a more convectively-organized stratocumulus cloud field. Another notable difference is the appearance of cloud along on the coast. The features in Figure 3b provide a closer match to the satellite imagery in Figure 2 and the aircraft-observed cloud layer structure.

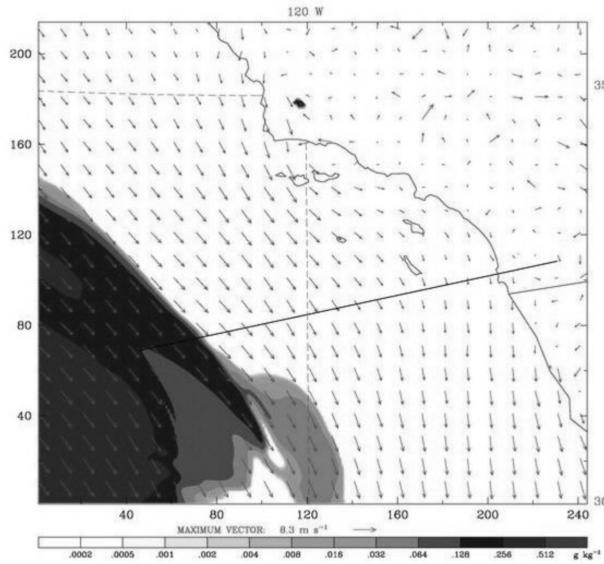

Figure 3a: MM5 baseline model surface plot of total cloud mixing ratio (range 0-1 g kg^{-1}) and horizontal winds at 600m for 1400 UTC 10 Jul 2001, initialized at 0600 UTC.

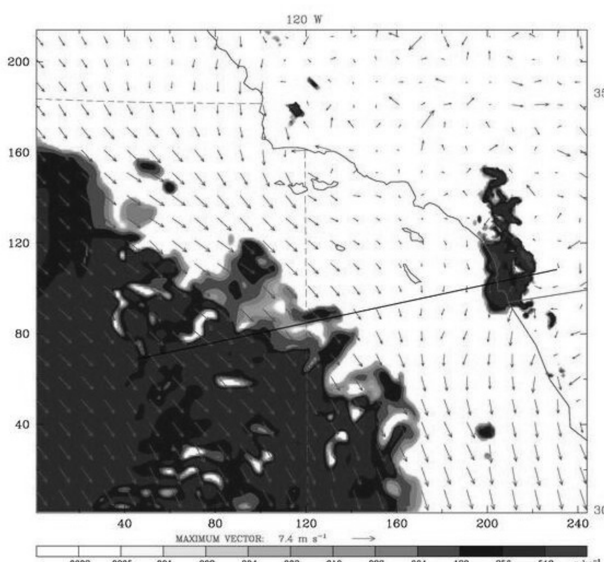

Figure 3b: MM5 enhanced model surface plot of total cloud mixing ratio (range 0-1 g kg^{-1}) and horizontal winds at 600m for 1400 UTC 10 Jul 2001, initialized at 0600 UTC.

Figure 4 is the MM5 enhanced model vertical cross-section plot for total cloud mixing ratio (g kg^{-1}) and air temperature (^{o}C). The transect (line shown in Figure 3b) depicts the MABL structure extending from the coast to the DYCOMS II experiment area. The air temperature contours at the top of the marine cloud layer are closely spaced (associated with the MABL inversion) and this pattern lowers towards the coast. The strength of the vertical gradients of temperature and moisture, as well as the slope and distribution of these gradients often found in the vicinity of coastlines, are important characteristics influencing the microwave signal propagation environment.

Analysis of MM5 results using the satellite-derived MABL information indicates improvement in the short-term model evolution. Air temperature profiles from the enhanced MM5 simulation are compared to dropsonde data and COAMPS^{TM} operational forecasts in Figure 5. The enhanced MM5 model output has a higher IBH and more accurate MABL temperature profile below the IBH. The COAMPS^{TM} operational results are limited in vertical resolution for the upper MABL region. The potential for improving model forecasts by routinely using satellite-estimated IBH information may justify the additional time and resources needed to run the operational model with greater vertical resolution in the region 300-1200 m.

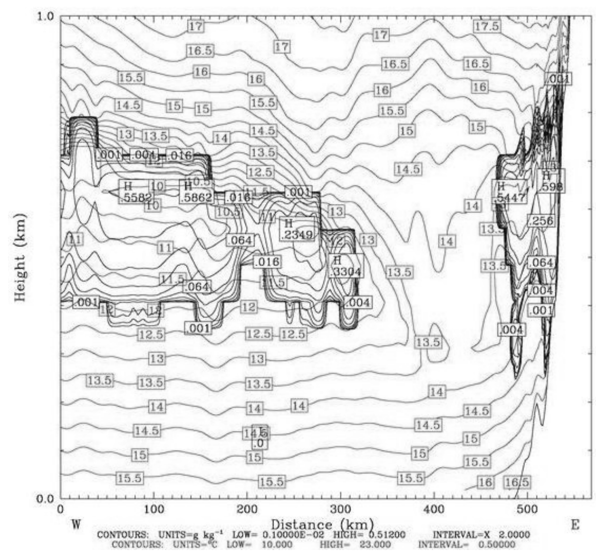

Figure 4: MM5 enhanced model vertical cross-section of total cloud mixing ratio (g kg^{-1}) and temperature (^{o}C) for 1400 UTC 10 Jul 2001, initialized at 0600 UTC.

The specific humidity (q) profile for the enhanced MM5 (Figure 6) is closer to dropsonde-measured values up to almost 800 m. However, the COAMPS™ provides a much better definition of the dry layer above 800m, even with the more coarse vertical resolution that the COAMPS model grid has in the upper MABL. Note that the MM5 simulations were run from ‘cold start’ initial fields while the COAMPS™ results are from operational runs that were re-initialized at 00 and 12 UTC throughout July 2001 for the DYCOMS II project. The modified refractivity is strongly dependent on q and less dependent on temperature and pressure, so the q profile representation would likely benefit from routine assimilation of the satellite-estimated MABL structure into the operational forecast cycle that can carry information on the dry layer above the inversion.

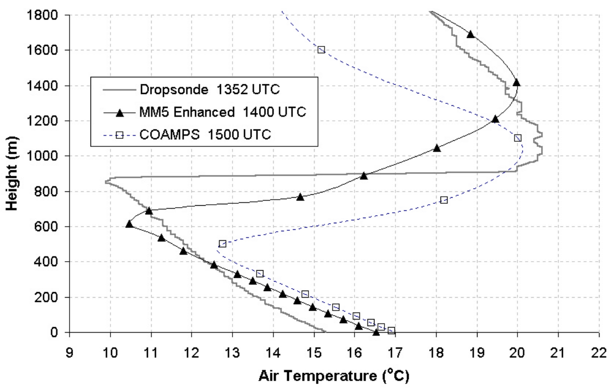

Figure 5: Air temperature profiles from the dropsonde deployed at 1352 UTC, the enhanced MM5 forecast valid at 1400 UTC, and the COAMPS™ forecast valid at 1500 UTC on July 10 2001.

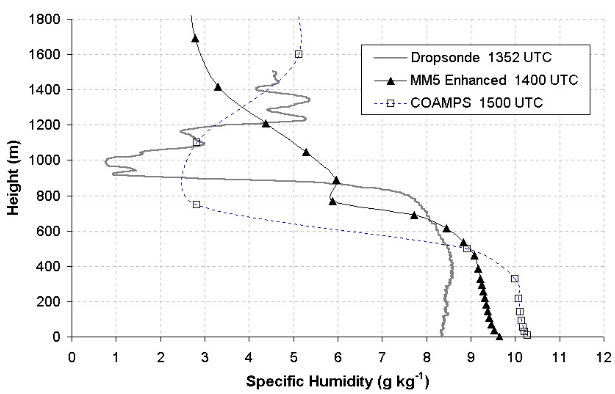

Figure 6: Specific humidity (g kg^{-1}) profiles from dropsonde, enhanced MM5 and COAMPS™ results for 10 July 2001.

The influence of these factors can be seen in the vertical profiles of modified refractivity (Figure 7). The dropsonde-derived profile of M shows a strong trapping layer with base at approximately 800 m. The enhanced MM5 simulation indicates a trapping layer with base at 700m but the lack of a strong dry layer above (as seen in Figure 6) restricts the accuracy of M(Z) above 800m. While COAMPS™ predicted a strong trapping layer, it's base and top tops heights are much lower than observed, attributed in part to the coarse vertical grid resolution.

The enhanced MM5 simulation improves its representation of the M profile. A trapping layer with base at 700 m is indicated for this model in Figure 7. However, the trapping layer is too shallow and weak compared to dropsonde analysis, due to inadequate development of the dry layer above the MABL. The next step in this study is to carry out longer simulations with routine assimilation of the satellite-defined MABL profile parameters, to reduce the effects of the "cold start" used in the previous MM5 simulations. The methodology can be applied to both MM5 and COAMPS™ model configurations that have sufficient vertical resolution to take advantage of the satellite estimates of inversion base height. The CTT data for are available at high temporal resolution from geostationary satellites so that assimilation can be performed at frequent intervals (assuming SST can also be sufficiently defined using the less-frequent availability of TMI data), to document model improvement in forecasting the diurnal evolution of microwave refractivity conditions.

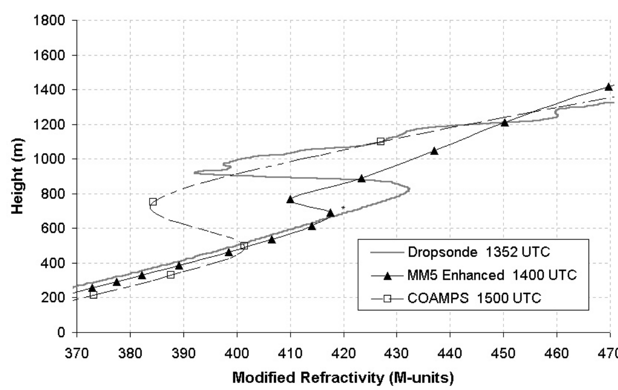

Figure 7: Modified refractivity profiles of dropsonde (1352 UTC), enhanced MM5 valid at 1400 UTC and COAMPS™ operational forecast valid at 1500 UTC on 10 July 2001.

6. SUMMARY

The DYCOMS-II experiment provided valuable research data to characterize nocturnal MABL properties. Aircraft data have been used to evaluate model predictions using an enhancement of MABL thermodynamic profile initial conditions based on satellite data. Dropsonde data profiles for 10th of July 2001 were compared to nearest available model times and gridpoint data from COAMPS™ and MM5 simulation results. The improvement in the enhanced

MM5 simulation is seen as increased cloud depth, more convective development of the stratocumulus, and increased cloud liquid water content that more closely matches aircraft observations. The enhanced MM5 simulation provides better forecasts of the trapping layer base height related to microwave refractivity conditions. It also indicated some improvement in the humidity profile a short time into the simulation, but had not yet developed the strong dry layer necessary to adequately represent the refractivity profile above the trapping layer base. In further study, we plan to focus on improvement of MABL prediction through routine assimilation of the satellite-derived inversion parameters into longer simulation runs.

7. ACKNOWLDGEMENTS

This research was funded by ONR grant N00014-01-1-0295 from the Office of Naval Research to the Desert Research Institute. The authors express thanks to the Naval Research Laboratory and U.S. Navy for collaborative support regarding the use of data from the COAMPS™ operational model runs, and also to the DYCOMS II field program research team. Significant contributions were also made to the MM5 data assimilation by Dr. Jordan Powers of the National Center for Atmospheric Research.

8. REFERENCES

Albrecht et al, 1995: The Atlantic Stratocumulus Transition Experiment -- ASTEX. *Bull. Amer. Meteor. Soc*., **76**, 889-904.

Battan, L. J., 1973: Radar Observations of Atmosphere. University of Chicago Press, 324pp.

Cox, S. K., et al., 1987: FIRE-the first ISCCP Regional Experiment. *Bull. Amer. Meteor. Soc.,* **67,** 114-118.

Grell, G., J. Dudhia, and D. Stauffer, 1994: A description of the fifth generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398 1 STR, 117 pp.

Haack, T., and S. D. Burk, 2001: Summertime marine refractivity conditions along coastal California. *J. Appl. Meteor.,* **40,** 673–687.

Helvey, R., J. Rosenthal, L. Eddington, P. Greiman, and C. Fisk, 1995: Use of satellite imagery and other indicators to assess variability and climatology of oceanic elevated ducts. *AGARD/NATO Conf. on Propagation Assessment in Coastal Environments*. Bremerhaven, Germany, NATO, 1-14.

Hodur, R. M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Mon. Weath. Rev*., **125**, 1414-1430.

Koracin, D., J. Powers, M. Wetzel, S. Chai, and N. Adhikari, 2003: Improving prediction of the marine coastal clouds using satellite and aircraft data. *Fifth Conference on Coastal Atmospheric and Oceanic Prediction and Processes.* Amer. Meteor. Soc., Seattle, WA, 6-8 Aug 2003.

Lenschow, D.H., I.R. Paluch, A.R. Bandy, R. Pearson, S.R. Kawa, C.J. Weaver, B.J. Huebert, J.G. Kay, D.C. Thornton, A.R. Driedger, 1988: Dynamics and Chemistry of Marine Stratocumulus (DYCOMS) Experiment. *Bull. of Amer. Meteor. Soc.*, **69**, 1058–1058.

Rogers, David P., Xiaohua Yang, Peter M. Norris, Douglas W. Johnson, Gill M. Martin, Carl A. Friehe , Bradford W. Berger, 1995: Diurnal evolution of the cloud-topped marine boundary layer. Part I: Nocturnal stratocumulus development. *J. Atmos. Sci.,* **52**, 2953–2966.

Stevens, B., D. H. Lenschow, G. Vali, H. Gerber, A. Bandy, B. Blomquist, J.-L. Brenguier, C. S. Bretherton, F. Burnet, T. Campos, S. Chai, I. Faloona, D. Friesen, S. Haimov, K. Laursen, D. K. Lilly, S. M. Loehrer, S. P. Malinowski, B. Morely, M. D. Petters, D. C. Rogers, L. Russell, V. Savcic-Jovcic, J. R. Snider, D. Straub, M. J. Szumowski, H. Takagi, D. C. Thorton, M. Tschudi, C. Twohy, M. Wetzel, M. C. van Zanten, 2003: Dynamics and chemistry of marine stratocumulus – DYCOMS II. *Bull. Amer. Met. Soc.,* **84**, 579-593

Wetzel, M. A., W. T. Thompson, G Vali, S. K. Chai, T. Haack, M. J. Szumowski, R. Kelly 2001: Evaluation of COAMPS forecasts of coastal Stratus using satellite microphysical retrievals and aircraft measurements. *Weather and Forecasting*, **16,** 588-599.