Development and Experimental Evaluation of Oceanic Evaporation Duct Models Based on the LKB Approach

Steven M. Babin
MS 9-200, Submarine Technology Department
The Johns Hopkins University Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel, MD 20723-0699
phone: (240) 228-6704 fax: (240) 228-5026 email: steven.babin@jhuapl.edu

G. Daniel Dockery
MS 6-243, Air Defense Systems Department
The Johns Hopkins University Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel, MD 20723-0699
phone: (240)-228-5461 email: dan.dockery@jhuapl.edu

Grant #: N000149910796
http://www.onr.navy.mil/sci_tech/ocean/onrpgabr.htm

LONG-TERM GOAL

Our long-term goal is to contribute to the development and objective evaluation of an operational evaporation duct model for use in microwave propagation prediction.

OBJECTIVES

The first objective is to develop a metric, involving one or more parameters, to replace evaporation duct height as a fundamental basis for comparison and objective evaluation of evaporation duct models. Because electromagnetic propagation is determined by vertical gradients of modified refractivity (M) and because these gradients are more uniquely determinant of propagation conditions that duct height alone (Dockery 1988, Reilly and Dockery 1990, Gehman 2000), evaporation duct height is often inadequate for accurately describing propagation conditions. Another objective is to use experimental data to evaluate four LKB-based (where LKB refers to Liu et al 1979) evaporation duct models using the metrics found in the first objective.

APPROACH

Field experiments were conducted in which the R/V CHESSIE was deployed off the coast of Wallops Island, VA. JHU/APL engineers John Rowland and Charles Etheridge developed a profiling buoy for making fine-scale measurements of temperature and humidity profiles between about 0.1 and 0.8 m above the sea surface. A package containing fast response sensors records data at a 1.1 Hz rate as it travels up and down a mast with a one-way transit time of seven minutes. The mast is mounted on a wave-riding catamaran to reduce wave effects. This catamaran is at the end of a 46 m tether attached to the stern and upwind side of the R/V CHESSIE. The measurements made by this profiling buoy were compared with profiles generated by four LKB-based evaporation duct models. These models

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
30 SEP 2001

2. REPORT TYPE

3. DATES COVERED
00-00-2001 to 00-00-2001

4. TITLE AND SUBTITLE
Development and Experimental Evaluation of Oceanic Evaporation Duct Models Based on the LKB Approach

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
MS 9-200, Submarine Technology Department,,The Johns Hopkins University Applied Physics Laboratory,,11100 Johns Hopkins Road,,Laurel,,MD, 20723

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Our long-term goal is to contribute to the development and objective evaluation of an operational evaporation duct model for use in microwave propagation prediction.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

use air temperature, humidity, wind speed, pressure and sea surface temperature (SST) as input. These inputs were measured by sensor packages mounted on masts on the R/V CHESSIE (data collected on the upwind mast to reduce ship contamination) and by an SST buoy at the end of a 46 m tether attached to the bow and upwind side of the R/V CHESSIE. This SST buoy was about 15 m from the profiling buoy when deployed. These measurements were saved as five-minute averages. Because the profiling buoy individual profiles last seven minutes and the model inputs were five-minute averages, the minimum time for contemporaneous measurements is 35-minutes. In order to reduce the effects of turbulence in the data and because the LKB models were intended to produce ensemble average profiles, 70-minute averages of all data were used.

WORK COMPLETED

Software for reading, analyzing and plotting the data was written. Several alternatives to evaporation duct height as a criterion for model comparison were considered. Three of these criteria were examined in detail and were used to compare model generated profiles with data from the JHU/APL profiling buoy: 1) The mean M slope root-mean-square (RMS) difference criterion is determined by taking the mean of all the M slopes between each contiguous pair of data points and each pair of model-derived points over the height range of profiling buoy data. For each set of data, there is then a mean data M slope and, for each model, a mean model M slope. The difference between these means for each set of profiles is then calculated, this difference is squared, and the square root of the mean of all these squared differences for all data sets is the final criterion. 2) The RMS M value criterion is determined by taking the M at each height in a profile, subtracting the mean M of that profile and taking the RMS difference between these M values for a model and the data. 3) The RMS M slope difference criterion is determined by making a log-linear curve fit to the buoy profile, finding the M slopes for each 0.02 m segment of this curve-fit profile and the corresponding altitude segment in a model profile, and finding the mean RMS difference for all the profiles.

Four LKB-based evaporation duct models were compared. They include the NPS model (Frederickson et al 2000), the NWA model (written by Kurt Kral of the Naval Warfare Assessment Station and based on Liu and Blanc, 1984), the NRL model (written by John Cook and based on Liu and Blanc, 1984), and the BYC model (Babin et al 1996). The primary difference among these models is that they use different Ψ functions. These functions are used by Monin-Obukhov similarity theory (Monin and Obukhov 1954) to account for differences in temperature, humidity and wind profiles from those in neutral stability. Although the equations were derived primarily from experiments over land, Monin-Obukhov similarity (MOS) theory is considered valid within the surface layer for both stable and well-mixed conditions and for z/L values ranging from –5 to +2 (Stull 1994). Fairall et al (1996) used LKB surface layer theory and other modifications to extend MOS to conditions over water. Their results were verified by comparison with over 10,000 hours of measurements, although they encountered mostly unstable conditions. Therefore, the Ψ functions for stable conditions used by all evaporation duct models were derived from experiments over land. Furthermore, wave effects are not explicitly parameterized by any of these models.

A total of 421 M profiles were collected during field tests in November 1998, the Y2K Wallops Microwave Propagation Measurement System (MPMS) Experiment in April-May 2000 and other field experiments in August and September 2000. Examples of single profiles are shown in Figs. 1 and 2, where the air-sea virtual temperature differences were –4.7C and 3.2C, respectively. Recall that it takes 7 min for the sensor to transit the mast. Note how there is more scatter for unstable than for stable conditions. Also, note the waviness in the profiles. While we did not have wave measurements for corroboration, it is possible that this waviness in the profiles is induced by waves in the ocean. Fig. 3 shows a comparison between the model profiles and the April 30 averaged profiling buoy data. Fig. 4 is similar to Fig. 3 but for the September 22 unstable case. Fig. 5 shows just the model profiles for this case to illustrate how they diverge at altitudes above 1 m, and also to illustrates why a model duct height is better determined using dM/dz=0 instead of the minimum M value.

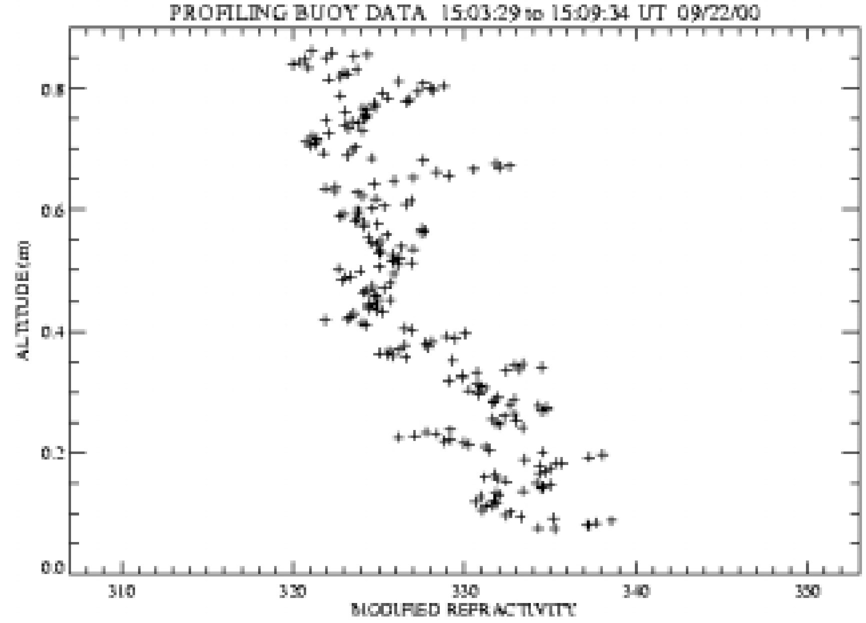

Figure 1 (Unstable)

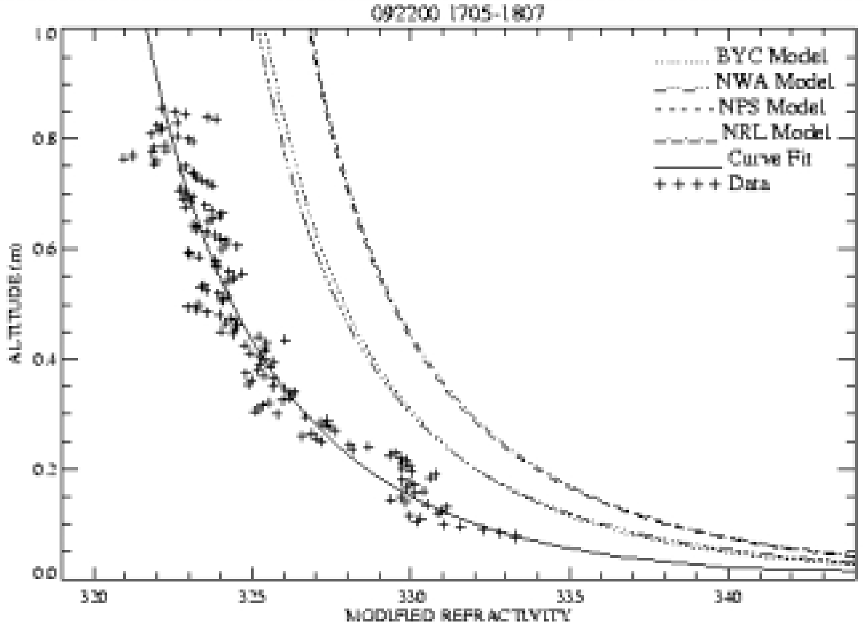

Figure 3

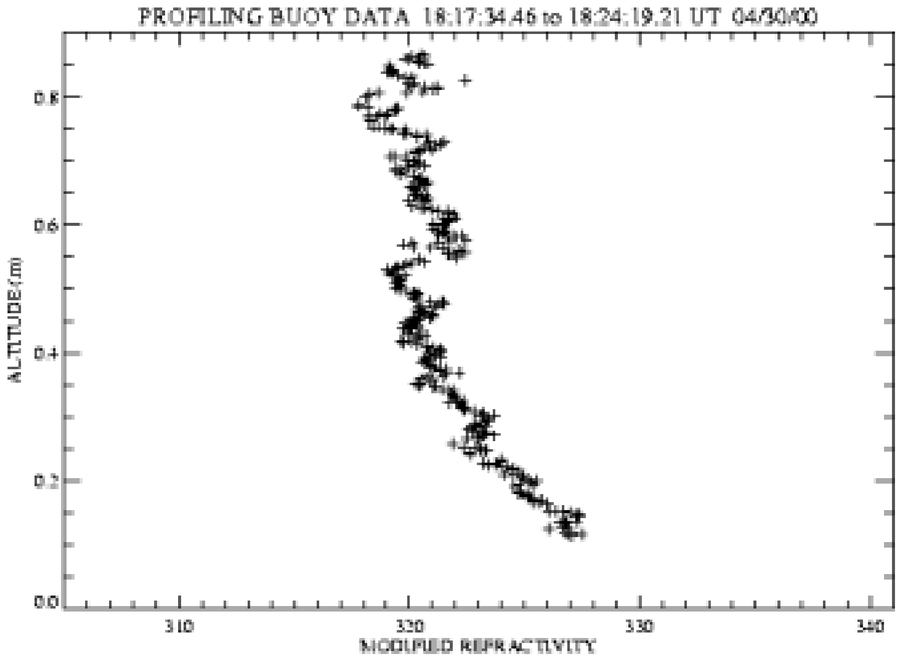

Figure 2 (Stable)

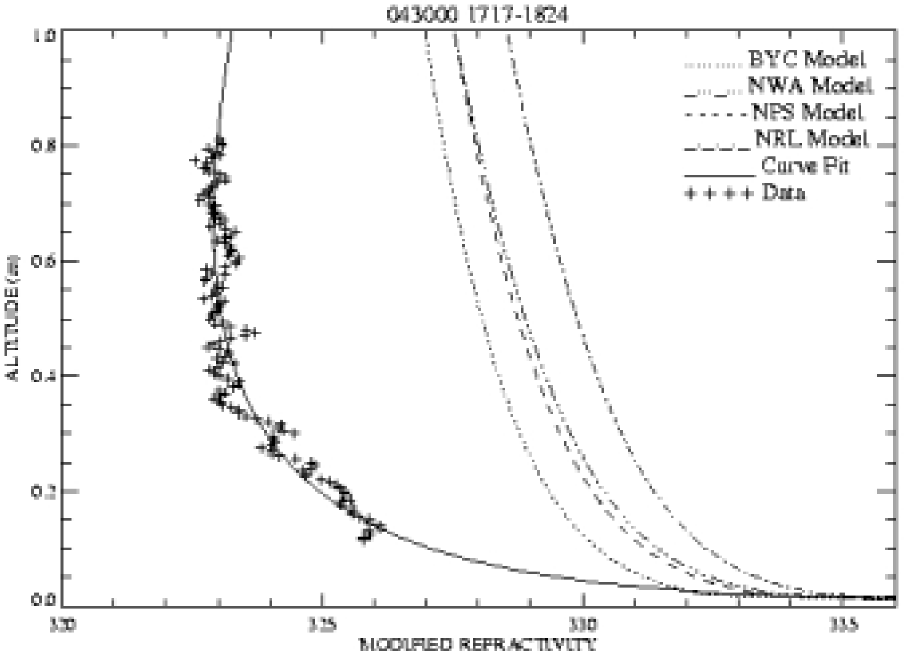

Figure 4

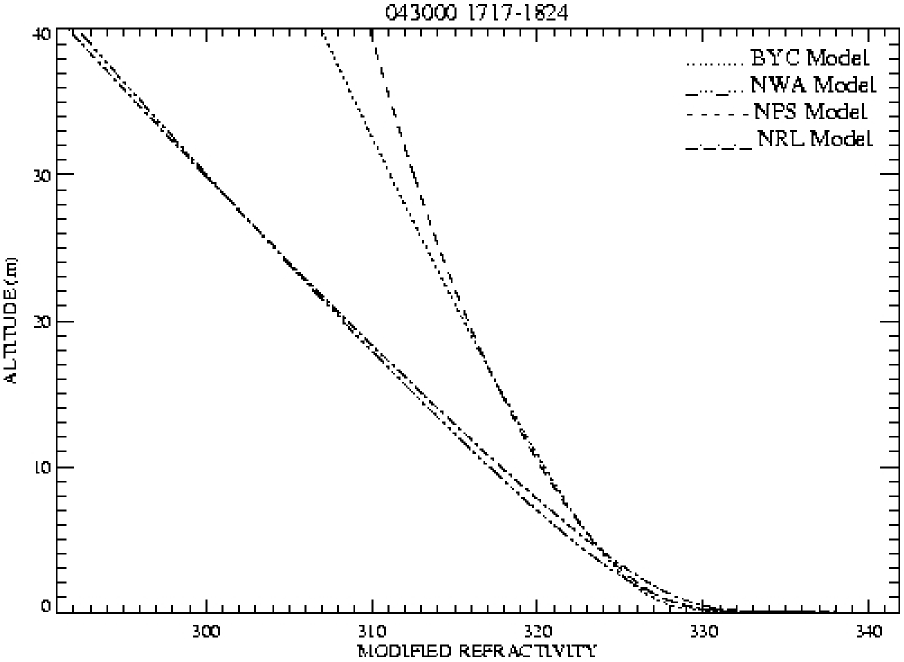

Figure 5

RESULTS

A variety of atmospheric conditions were observed, with air-sea virtual temperature differences ranging from –4.7C to 3.2C, wind speeds ranging from 2.8 to 8.6 m/s and z/L values ranging from –1.1 to +0.7. Using profiles adjacent in time, a total of thirty-four 70-minute averages were obtained that had contemporaneous model input data from R/V CHESSIE and the SST buoy. These 34 data sets were examined using the comparison criteria above. While 70-minute averages were used for the comparison, the overall individual profile shapes were fairly repeatable.

When the RMS M slope difference criterion (number 3 above) is used, the NPS model performs the best for stable and near-neutral conditions, while the BYC model performs the best for unstable conditions. Overall, the RMS M slope differences were on the order of 2 M/m for stable conditions, less for near-neutral conditions and more for unstable conditions. A plot of the RMS M slope differences for the NPS model versus air-sea virtual temperature difference is shown in Fig. 6. Plots for the other models show a similar variation with stability. When the RMS M difference after mean removal criterion is used (number 2 above), the BYC model performs the best for all conditions. Overall, the RMS M value differences were on the order of 2 M units for unstable conditions and less than 1 M unit for stable and near-neutral conditions. A plot of the RMS M difference for the NPS model versus air-sea temperature difference is shown in Fig. 7. When the criterion comparing the mean slope of the entire profile between the model and the data (number 1 above) was used, the results were the same as those for the RMS M slope difference (number 3 above). The mean M slope RMS differences were on the order of 3 M/m for unstable conditions and 1 M/m for near-neutral and stable conditions. What these slope differences mean in terms of propagation is a question yet to be resolved. To resolve it would require running propagation code (e.g., TEMPER) using complete M profiles that combine our profiling buoy profiles matched with those at higher altitudes.

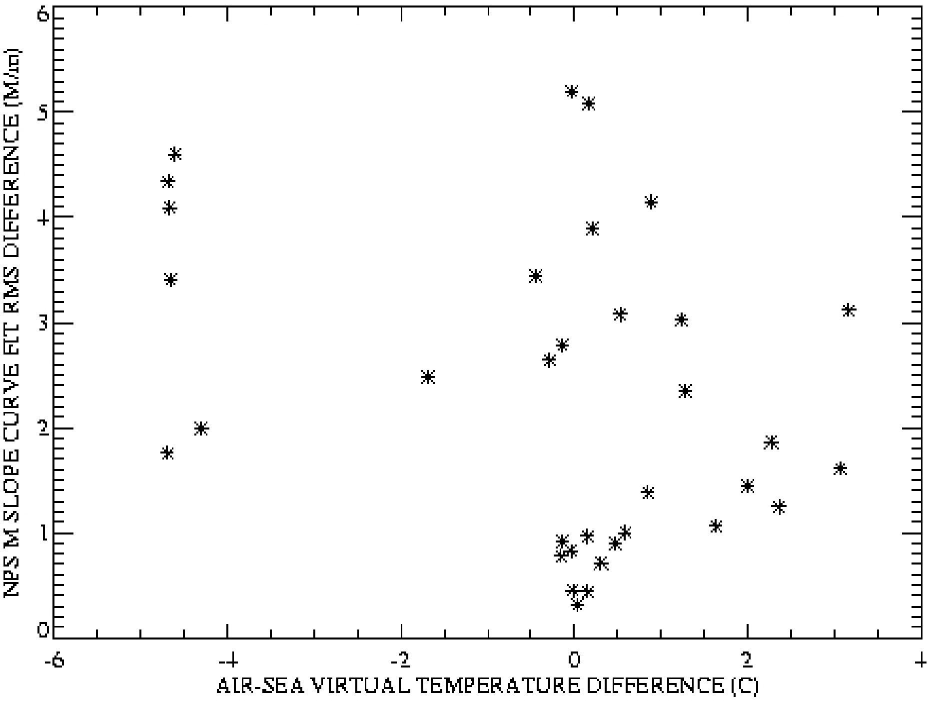

Figure 6

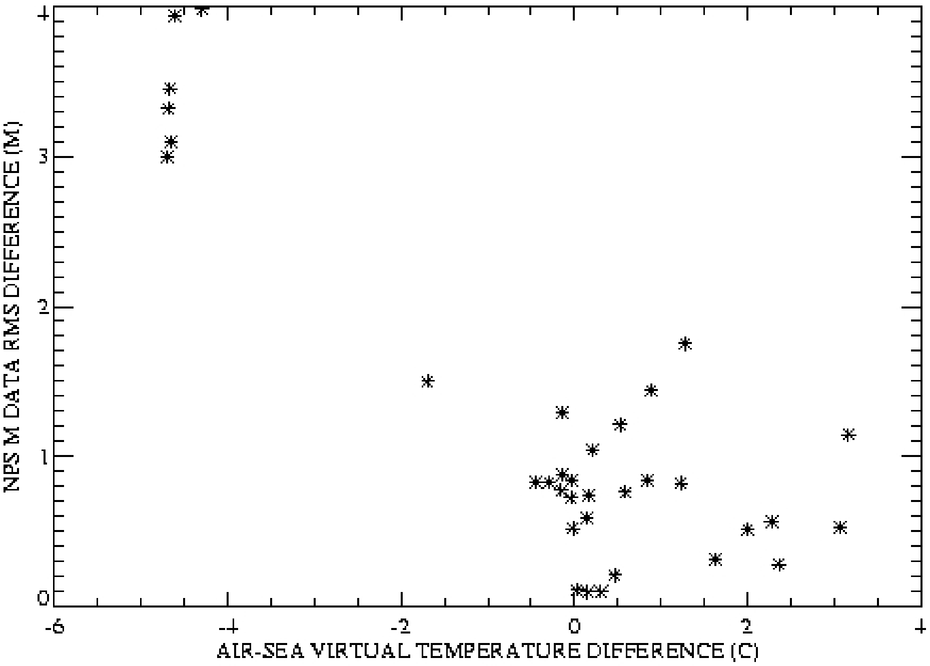

Figure 7

Because there are cases in which the models do a relatively poor job of matching profile shape, it seems likely that there are some phenomena occurring in the region below 1 m that is missing from the models. Observations of the waviness about a mean profile shape appearing in both individual profiles and in the 70-minute averages lead us to suspect that this phenomena is primarily the effects of wave motion. Unfortunately, we do not have coincident wave measurements to corroborate that this is from wave motion. It is also interesting to note that, while the model profiles often look similar to one another below 1 m, there may be quite a divergence at higher altitudes (Fig. 5). It appears that the different Ψ functions used by the models have an important effect in this region. It would therefore be necessary to resolve the issue of which Ψ function is best for stable and unstable conditions over the ocean. One can conclude that a profiling buoy capable of measuring higher altitudes and measuring wave effects would be valuable in resolving these questions.

It has been observed that when evaporation duct height is obtained from LKB-based models, the output is more sensitive to input under stable conditions than under unstable conditions. Furthermore, while the original Ψ functions for both stable and unstable conditions were developed using the results of experiments over land, the TOGA-COARE experiments resulted in modifications to the Ψ functions for unstable conditions. In our study, we have the interesting result that any one of the four LKB-based models provides better results for stable than unstable conditions. The difference is that we are comparing profile curvature instead of duct height. Because electromagnetic propagation models determine propagation using M slope, this should be a more reliable comparison than duct height.

These results should be interpreted with caution because of the small size of the data set. While the small number of cases makes it difficult to assign a clear winner model, the analytical concept used here has been shown to be a valid way of comparing model profile curvatures. The small altitude range of the JHU/APL profiling buoy also limited us. This altitude range of about 0.1-0.8 m is a very small fraction of the 0-40 m range produced by the models. A new buoy is being developed that will cover altitudes up to about 8 m. Applying the analytical techniques developed in this study to an expanded data set using the new buoy should provide a more robust answer to the question of evaporation duct model performance. Obtaining this answer becomes even more important as radar frequencies go from S band to X band.

IMPACT/APPLICATION

Operations of radar and communications may be severely affected by refractive index gradients in the lower troposphere, especially over the ocean. For accurate microwave propagation prediction, there is a critical need for an evaporation duct model that provides realistic fine-scale vertical refractivity gradients using a minimum of surface layer measurements. One such application would be using data from the MORIAH/SMOOS(R) system for propagation prediction. Once reliable meteorological modeling has been achieved, computer code simplifications can be made for operational purposes. The origin and magnitude of any errors resulting from these operational simplifications can then be determined. It would also be useful to use the resulting evaporation duct model with the near-surface grid point outputs of a mesoscale model such as the US Navy's Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS) to provide mesoscale refractivity forecasts.

TRANSITIONS

As mentioned under Impacts above, the results of this effort should lead to useful operational products for future use by the US Navy. For example, these products would provide a way of using data from the SMOOS(R)/MORIAH system for propagation prediction of evaporation duct effects.

RELATED PROJECTS

None at this time.

REFERENCES

Babin, S. M., G. S. Young, and J. A. Carton, 1997: A new model of the oceanic evaporation duct. *J. Appl. Meteor.,* **36**, 193-204.

Dockery, G. D., 1988: Modeling electromagnetic wave propagation in the troposphere using the parabolic equation. *IEEE Trans. Antennas Propag.,* **36**, 1464-1470.

Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson, and G. S. Young, 1996: Bulk parameterization of air-sea fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment. *J. Geophys. Res.,* **101**, 3747-3764.

Frederickson, P. A., K. L. Davidson and A. K. Goroch, 2000: Operational Bulk Evaporation Duct Model for MORIAH, Naval Postgraduate School Report, Draft Version 1.2, May, 70 pp.

Gehman, J. Z., 2000: Importance of Evaporation Duct Stability in Propagation-sensitive Studies, JHU/APL Technical Report A2A-00-U-3-008, June, 8 pp.

Liu, W. T., and T. V. Blanc, 1984: The Liu, Katsaros and Businger (1979) Bulk Atmospheric Flux Computational Iteration Program in FORTRAN and BASIC, NRL Memorandum Report 5291, 8 May.

Liu, W. T., K. B. Katsaros, and J. A. Businger, 1979: Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints at the interface. *J. Atmos. Sci.,* **36**, 1722-1735.

Monin, A. S., and A. M. Obukhov, 1954: Basic laws of turbulent mixing in the atmosphere near the ground. *Tr. Akad. Nauk. SSSR Geofiz. Inst*., **24**(151), 163-187.

Reilly, J. P., and G. D. Dockery, 1990: Influence of evaporation ducts on radar sea return. *IEE Proc., Part F,* **137**(2), 80-88.

Stull, R. B., 1994: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Pub., Norwell, MA, 666 pp.

PUBLICATIONS

Babin, S. M. and Dockery, G. D., 2001: Comparison of LKB-based evaporation duct models with in situ atmospheric data. Presented at the URSI National Radio Science Meeting, Boulder, CO, 8 January. Preprints, 2001 USNC/URSI National Radio Science Meeting, 90.

Babin, S. M. and Dockery, G. D., 2002: LKB-based evaporation duct model comparison to buoy data. Accepted by *Journal of Applied Meteorology*, October 2001.