

Validation of the TUV module in CWRP using USDA UV-B network observations

Min Xu^{a*}, Xin-Zhong Liang^a, Wei Gao^b, James Slusser^b, Kenneth Kunkel^a

^aIllinois State Water Survey, University of Illinois at Urbana-Champaign, USA

^bUSDA UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory,
Colorado State University, Fort Collins, CO

ABSTRACT

Ultraviolet (UV) radiation is the source energy for tropospheric photolysis processes, while harmful for living organism of the earth. It is thus necessary to incorporate UV radiation for an integrated earth modeling system to predict interactions between climate, chemistry and ecosystem processed. The widely-used NCAR TUV (Tropospheric Ultraviolet and Visible) radiation model has been coupled with the state-of-the-art mesoscale CWRP (Climate extension of the Weather Research and Forecasting model) to predict the UV dependence of local climate conditions and its impacts on air quality and crop growth. The original TUV v4.2 has been significantly improved by (1) replacing the core radiation transfer solver, DISORT v1.1 with the latest v2.0beta; (2) adding a new aerosol scheme based on the Shettle (1989); (3) recoding the entire model to follow the CWRP F90 standard with dynamic memory allocation and modular design; and (4) developing a flexible interface for coupling with CWRP.

Given the lack of detailed cloud information in observations, this study focuses on validation of the TUV module in a standalone mode against the USDA UV-B data under clear-sky conditions. To facilitate this, a cloud detection scheme based on Long and Ackerman (2000) is incorporated to distinguish clear versus cloudy sky conditions from the UV-B observations. The model input includes in situ measurements of the column ozone and total aerosol optical depth; TOMS retrievals of the column ozone (in case missing in situ) and climatologically surface reflectivity; and the NARR (North American Regional Analysis) meteorological conditions. The TUV results agree well with the UV-B measurements at 7 narrow spectral bands (300, 305, 311, 317, 325, 332, 368 nm).

Key Words: Validation, radiation, ozone, aerosol, UV-B, TUV, CWRP, DISORT

1. INTRODUCTION

The finding that the stratospheric ozone layer, which prevents most of the ultraviolet (UV) radiation from reaching the Earth's surface, is depleted due to human activities has prompted our interest in studying the changes of UV radiation⁵. Studies have shown that the enhanced ultraviolet radiation has serious impacts on plants and animals. Some well-known UV effects on biological materials include cell death, chromosome changes, mutations and morphologic transformation of cells; weaken immune system, and skin cancer, and cataract or photokeratitis and DNA damage². In addition, UV radiation plays a significant role in tropospheric chemistry and air quality. The UV interaction with chemical composition in the atmosphere is the basic process of atmospheric photoreactions^{2,14}. Hence, it is imperative to monitor and predict the changes of UV radiation reaching the atmosphere and the Earth surface.

The changes of UV radiation, however, are very complex and are highly sensitive to the changes of atmospheric conditions, total column ozone amount, cloud cover, atmospheric aerosols and ground surface reflectivity, as well as the solar zenith angle. Numerical modeling is an effective approach to study the UV variability and responsible mechanisms. The widely-used NCAR TUV (Tropospheric Ultraviolet and Visible) solar radiation model has been continuously updated and well documented¹²⁻¹³. The model calculates the spectral irradiation, spectral actinic flux, photodissociation coefficients (J-values), and biologically effective irradiance (dose and rates) over the wavelength range 121-750 nm. CWRP, the climate extension of the WRF (Weather Research and Forecasting model), is built upon the most advanced supercomputing technologies and promises great efficiency in computation and flexibility in new module incorporation.

* Corresponding author address: Dr. Min Xu, Illinois State Water Survey, University of Illinois at Urbana-Champaign, 2204 Griffith Dr., Champaign, IL 61820-7495. E-mail: minxu@uiuc.edu

Remote Sensing and Modeling of Ecosystems for Sustainability III, edited by Wei Gao, Susan L. Ustin,
Proc. of SPIE Vol. 6298, 62980N, (2006) · 0277-786X/06/\$15 · doi: 10.1117/12.680122

This extension incorporates inclusively all WRF functionalities for numerical weather predictions while enhancing the capability for climate applications^{8-10,20}. To study the UV variability, we have thus coupled the latest TUV version 4.2 with CWRf. The significant modifications to the TUV source code includes (1) replacing the core radiation transfer solver, DISORT¹⁸ v1.1 with the latest v2.0beta; (2) integrating the CWRf radiation scheme monthly mean atmospheric O₃ 3-D distributions⁷; (3) adding a new aerosol scheme based on the Shettle (1989); (4) recoding the entire model to follow the CWRf F90 standard with dynamic memory allocation and modular design; and (5) developing a flexible interface for coupling with climate models such as CWRf, CMM5 or observational reanalysis such as NCEP North American Regional Reanalysis (NARR)¹⁵. We have also incorporated the observed surface reflectivity, total aerosol optical depth and total ozone amount from TOMS measurements^{6,19}. When the TUV module is fully coupled with CWRf, both temperature and cloud vertical profiles that vary with location and time, are provided by CWRf. As such, the coupled model results can be directly validated with the remote sensing data, including satellite and ground measurements, and subsequently used to predict UV-B under changing atmospheric and surface conditions. In this study, the TUV module of CWRf is validated by the UV-B network observations in a standalone mode so that a CWRf climate bias will no affect the TUV performance.

2. MODEL SIMULATION AND VERIFICATION DATA

The high resolution ATLAS-3 spectrum is chosen as the extraterrestrial solar flux. The atmospheric conditions, including temperature and pressure profiles, are provided by NARR such that most realistic climate conditions are used to objectively evaluate the performance of TUV itself without the impact of any meteorological bias from CWRf. The NARR has 3-hourly data at 32 km horizontal resolution and 29 vertical pressure levels up to 100 hPa. Assuming that the vertical structure is unchanged, the column ozone amount is constrained to agree with the near-real time daily measurements, which is currently provided by UV-B network observations or TOMS (in case missing in situ). The TUV module also requires specification of spectrally-dependent surface albedo. The current approximation is to use the surface reflectivity retrieved from the TOMS data at 360nm. In addition, the TUV module takes into account of the aerosol effect, which needs the input of aerosol optical depth. We use the TOMS total aerosol optical depth at 380 nm combined with the vertical scaling of Shettle (1989). All data are interpolated to specific monitoring stations for direct verification as in this study or to CWRf 30-km grid mesh for the coupled model evaluation. Given the intrinsic difficulties in properly observing and modeling the optical attributions of clouds, the effects of clouds on UV radiation are not well understood². As an initial study, here we evaluate the TUV module against the measured UV irradiances under clear sky conditions. To facilitate this, an automatic method based on Long and Ackerman (2000) was incorporated to detect the periods of clear skies in the UV-B observed datasets. The details are given in section 3.

The measured seven narrowband UV irradiances are used to validate the TUV module. The USDA Ultraviolet Radiation Monitoring and Research Program (UVMRP) has been monitoring UV radiation since 1994. A Yankee Environmental System (YES) UV multi-filter rotating shadowband (narrowband) radiometer (UV-MFRSR), a YES UVB-1 broadband meter, and a YES visible multi-filter rotating shadowband (narrowband) radiometer (VIS-MFRSR) are major measuring instruments to make a long-term monitoring in a USDA UVMRP site^[1]. The UV-MFRSR measures seven-channel (center wavelengths are 300, 305, 311, 317, 325, 332, 368nm; nominal 2-nm full-width-at-half-maximum, FWHM) horizontal global, diffuse and direct normal UV irradiances at 20s intervals and aggregated to 3-min averages in near-real time^{1,4}. The VIS-MFRSR is a seven-channel, 10nm FWHM radiometer that measures horizontal global, diffuse and direct normal visible irradiances at 415, 500, 610, 665, 860 and 940nm nominal center wavelengths and an additional unfiltered solar irradiance that spans the nominal wavelength range of 300 to 1040 nanometers⁴. Measurements are made as 15-s samples and averaged to 3-min intervals to be stored. The observed unfiltered horizontal global, diffuse solar irradiance from VIS-MFRSR are used to identify the periods of clear skies. The retrieved total column ozone amount⁶ and aerosol optic depth⁴ in situ also are provided by the UVMRP and, when available, are used as inputs instead of the TOMS data.

3. CLEAR-SKY IDENTIFICATION

Given surface downwelling global and diffuse broadband solar irradiances measured by UVMRP VIS-MFRSR at the unfiltered silicone photodiode channel, we adopt Long and Ackerman (2000) to detect clear sky conditions. To eliminate data that occur under cloudy skies, this method involves four individual tests for normalized total shortwave magnitude; maximum diffuse shortwave; change in magnitude with time; and change in magnitude with time. Only the

measurements that pass all four tests are flagged to be representative of clear skies. Since four empirical parameters required by the detective method for irradiances normalization are neither measurable nor known in priori, we must seek an objective way to specify them. Given daily records of 3-minute UVMRP measurements, we choose an iterative approach based on the Nonlinear Constrained Optimization Solver FSQP (Feasible Sequential Quadratic Programming)²¹ to obtain these parameters that minimize the differences in the total solar irradiance and diffuse to total irradiance ratio between the empirical fitting and measurements.

First, a guess set of the four parameters is assigned to conduct the initial search of clear sky conditions. Second, when a sufficient number of 3-minute measurements distributed more or less evenly during the daytime are identified with clear sky conditions, the FSQP optimization takes place and a new set of the parameters are estimated. Third, for that, we repeat the first and second steps until the optimization reaches or the convergence of derived parameters occurs. We go through all days in each calendar month to identify all days with sufficient clear sky conditions and corresponding optimized empirical fitting parameters and then apply a linear interpolation of parameters from adjacent these clear sky days for the days with mostly cloudy conditions. Figure 1 shows the results of the clear-sky identification for the case of July 28, 2004. The broadband global solar irradiances detected as clear are superposed on the global record. The presence of clouds can be observed after local noon, and the solar direct irradiance is attenuated by clouds while the diffuse part was increased due to enhanced scattering by clouds.

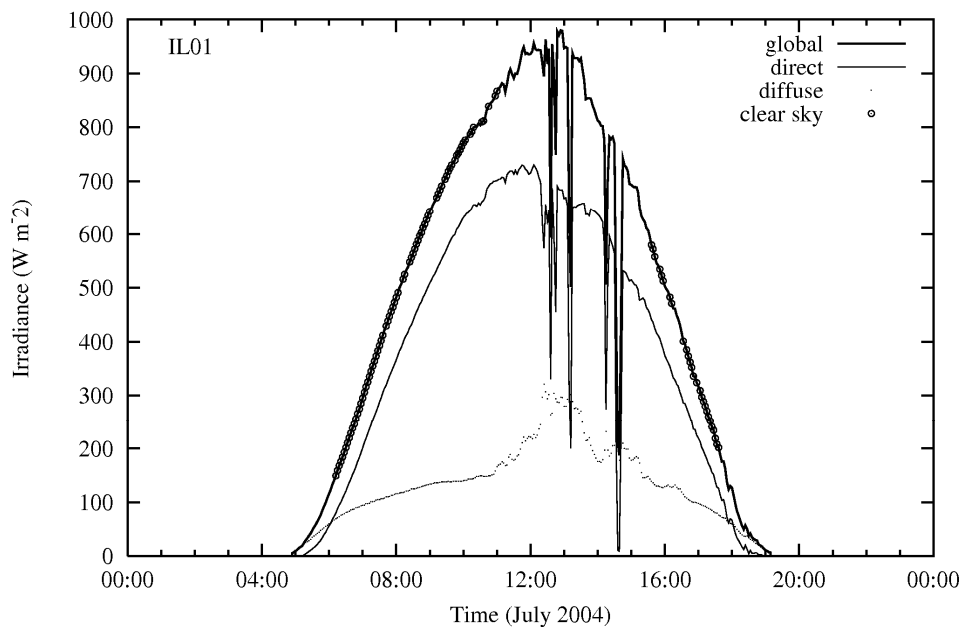


Figure 1 Measurements identified as clear-sky (circle) superposed on the downwelling global solar irradiance (heavy line), direct irradiance (thin line) and diffuse irradiance (dot line)

4. RESULTS

The ground-level UV spectra of July 2004 that span from 280nm to 420nm with 0.1 nm intervals resolution were simulated by the CWRP TUV module driven by NARR meteorological data at 33 UV-B observation sites. By comparing the simulated UV irradiances (time resolution is 3 hours) with UV-B narrowband observations (time resolution is 3 minutes) at 7 UV-B wavelengths, we found that the results of TUV are well consistent with the observed irradiances in general. Three sites CA22 (Holtville, California), IL02 (Bondville, IL), and CO02 (Nunn, Colorado) were chosen here to illustrate the comparison of the simulations and observations. At site CA22, nearly all days were observed with clear sky conditions. In contrast, we can only identify very few clear-sky days at other two sites: July 27-28 for IL02 and July 11-12, 2004 for CO02. Figures 2-4 show the selected two-day evolutions of UV irradiances at 7 UV-B wavelengths at sites CA22, IL02, and CO02 respectively. For all 3 sites, not only the global irradiances but also the direct and diffuse irradiances from the TUV module agree well with measurements under clear sky conditions at the wavelengths less than 311nm. Note, however, TUV tends to overestimate the UV irradiances at the wavelengths larger than 311nm, especially

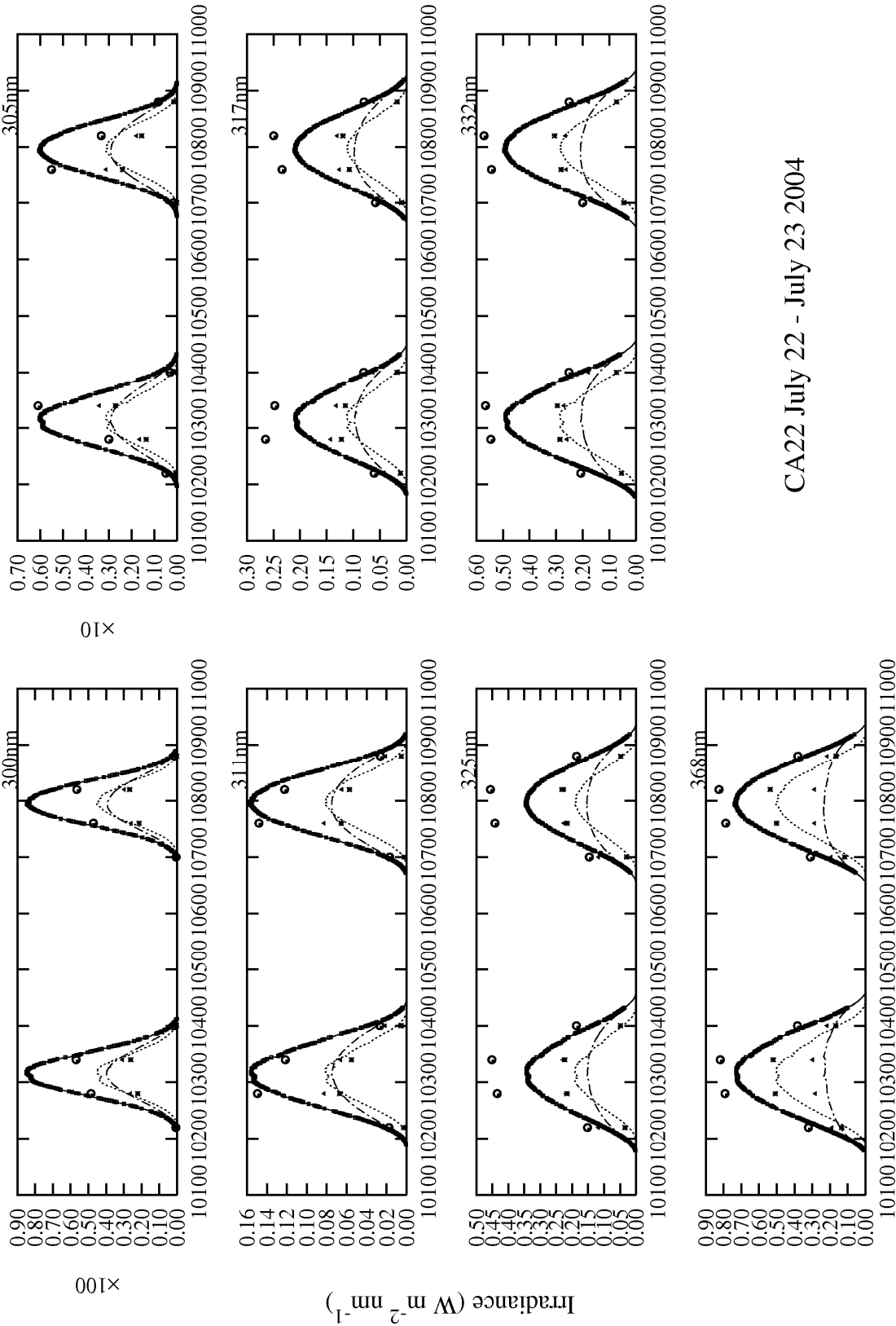


Figure 2. The diurnal cycles of the USDA UV-B measured global irradiances identified as clear skies (square) superposed on the measured global (thin line), direct (dot line), diffuse (dot-dash line) and simulated global (circle), direct (star), diffuse (triangle) irradiances in 7 spectral bands (300, 305, 311, 317, 325, 332, and 368 nm) on 22-23 July, 2004 at CA22

CA22 July 22 - July 23 2004

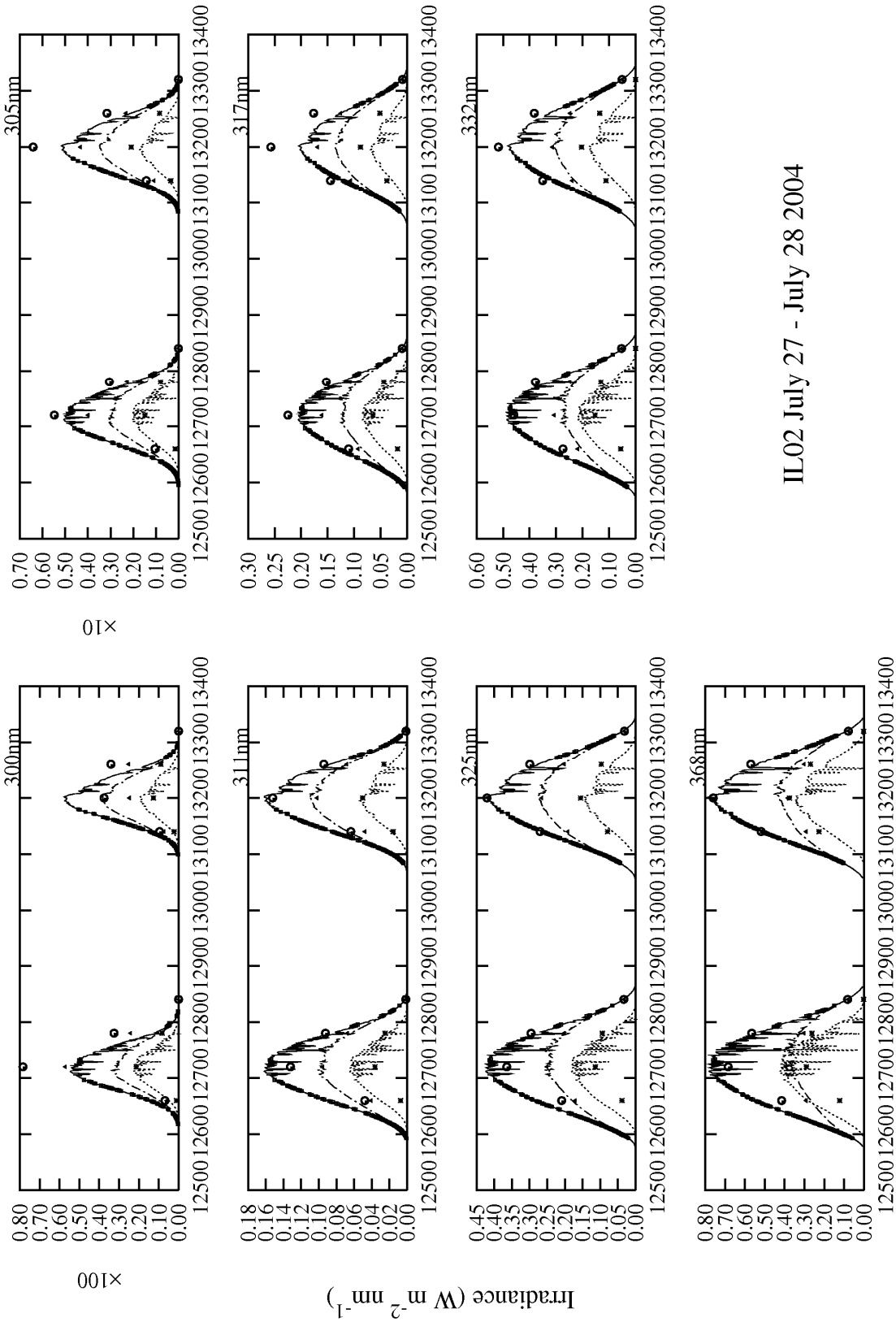
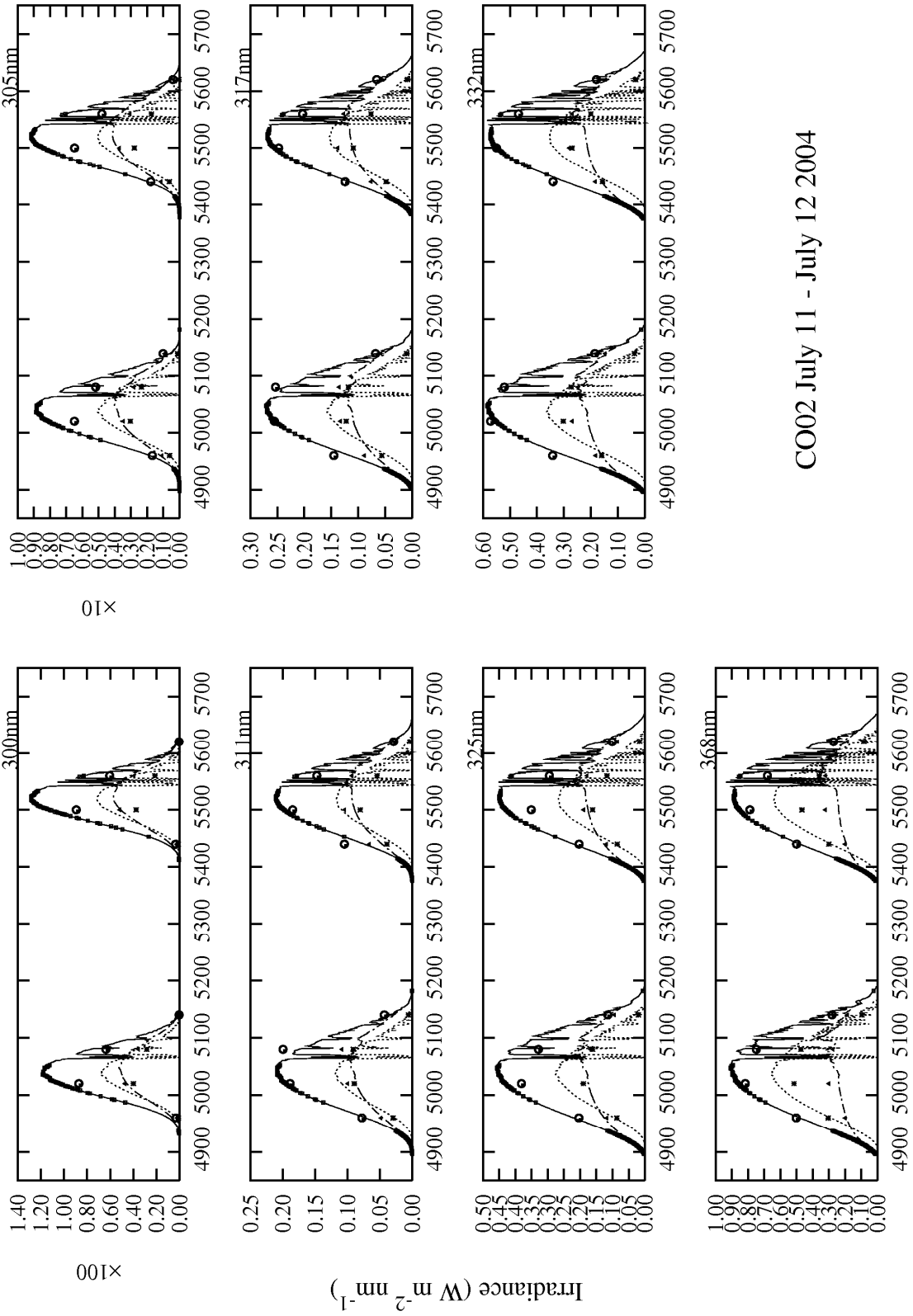


Figure 3. Same as Figure 2, but is for 27 -28 July 2004 at site IL02



CO02 July 11 - July 12 2004

Figure 4. Same as Figure 2, but is for 11 - 12 July 2004 at site CO02

at the low solar zenith angle at site CA22. This overestimation could be partially due to the use of verification data based on the calibration of UV-B measurements by lamp. Recently, we have compared two UV-B observational data sets that were calibrated by the lamp and Langley methods and found that the former values are systematically lower than the latter. To this moment, we do not know which set is more accurate. In addition, the model to observation difference may also result from the inaccurate inputs of aerosol attributions (such as AOD, aerosol single scattering albedo, Ångström coefficients and aerosol asymmetry factor) that lack high-quality measurements. Further study is needed to address the result sensitivity to the observational uncertainties in column ozone, aerosol optical depth and surface reflectivity as well as the cloud forcing impact under full sky conditions.

Acknowledgements. This research was partially supported by the United States Department of Agriculture UV-B Monitoring and Research Program grant to University of Illinois at Urbana-Champaign (AG CSU G-1502-5). Thank Gwen Scott and Becky Olson from UVMRP for providing the UV and VIS irradiance data. Also thank George Janson from UVMRP for the comments on the unfiltered silicone photodiode radiations. The data processing was mainly conducted on the NCSA/UIUC supercomputing facility. The views expressed are those of the authors and do not necessarily reflect those of the sponsoring agencies or the Illinois State Water Survey.

REFERENCES

1. Bigelow, D.S., J.R. Slusser, A.F. Beaubien and J.H. Gibson, "The USDA Ultraviolet Radiation Monitoring Program", *Bull. Amer. Meteorol. Soc.*, **79**, 601-615, 1998.
2. Calbo, J., D. Pages, J.A. Gonzalez, "Empirical studies of cloud effects on UV radiation: A review", *Reviews of Geophysics*, **43**, RG2002, doi: 10.1029/2004RG000155, 2005.
3. Gao, W., J.R. Slusser, J.H. Gibson, G. Scott, D.S. Bigelow, J. Kerr and B. McArthur, "Direct-Sun Column Ozone Retrieval by the Ultraviolet Multi-filter Rotating Shadow-band Radiometer and Comparison with Those From Brewer and Dobson Spectrophotometers", *Applied Optics*, **40**, No 19, 3149-3155, 2001.
4. Harrison, L., J. Michalsky and J. Berndt., "Automated Multi-Filter Rotating Shadowband Radiometer: An Instrument for Optical Depth and Radiation Measurements", *Appl. Opt.*, **33**, 5118-5125, 1994.
5. Herman, J.R., P.K. Bhartia, J. Ziemke, Z. Ahmad and D. Larko, "UV-B increases (1979-1992) from decreases in total ozone", *Geophys. Res. Lett.*, **102**, 16911, 1996.
6. Herman, J.R., and E.A. Celarier, "Earth surface reflectivity climatology at 340-380 nm from TOMS data", *J. Geophys. Res.*, **102**, 28003-28011, 1997.
7. Liang, X.-Z., W.-C. Wang, and J.S. Boyle, "Atmospheric ozone climatology for use in general circulation models", PCMDI Report No. 43, UCRL-MI-125650, 25 pp, 1997.
8. Liang, X.-Z., H. Choi, K.E. Kunkel, Y. Dai, E. Joseph, J.X.L. Wang, and P. Kumar, "Development of the regional climate-weather research and forecasting model (CWRf): Surface boundary conditions", Illinois State Water Survey Scientific Research, ISWS SR 2005-01, 32 pp. [Available at <http://www.sws.uiuc.edu/pubs/pubdetail.asp?CallNumber=ISWS+SR+2005%2D01>], 2005.
9. Liang, X.-Z., M. Xu, W. Gao, K.E. Kunkel, J. Slusser, Y. Dai, Q. Min, P.R. Houser, M. Rodell, C.B. Schaaf, and F. Gao, "Development of land surface albedo parameterization bases on Moderate Resolution Imaging Spectroradiometer (MODIS) data", *J. Geophys. Res.*, **110**, D11107, doi:10.1029/2004JD005579, 2005.
10. Liang, X.-Z., M. Xu, J. Zhu, K.E. Kunkel, and J.X.L. Wang, "Development of the regional climate-weather research and forecasting model (CWRf): Treatment of topography", In *Proceedings of 2005 WRF/MM5 User's Workshop*, Boulder, CO, June 27-30, 5 pp, 2005.
11. Long, C. N., and T.P. Ackerman, "Identification of clear skies from pyranometer measurements and calculation of downwelling shortwave cloud effects", *J. Geophys. Res.*, **105**, 15 609–15 626, 2000.
12. Madronich, S. and S. Flocke, "Theoretical estimation of biologically effective UV radiation at the Earth's surface", In *Solar Ultraviolet Radiation - Modeling, Measurements & Effects* (C. S. Zerefos and A. F. Bais, eds.) NATO ASI Series I: Global Environmental Change, Vol. 52, 23-48, Springer-Verlag, Berlin, 1997.
13. Madronich, S., and S. Flocke, "The role of solar radiation in atmospheric chemistry", In *Handbook of Environmental Chemistry*, P. Boule (Ed.), Springer-Verlag, Heidelberg, pp. 1-26, 1999.
14. Mao, H., W.-C. Wang, and X.-Z. Liang, "Modeled geographical and seasonal variations of O₃ and NO₂ photodissociation rate coefficients", *J. Geophys. Res.*, **108**, 4216, doi:10.1029/2002JD002760, 2003.

15. Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P.C. Shafran., W. Ebisuzaki, D. Jović, J. Woollen, E. Rogers, E.H. Berbery, M.B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, W. Shi, "North American Regional Reanalysis", *Bull. Amer. Meteorol. Soc.*, **87**,343-360, 2006.
16. Reddy, K. Raja, Vijaya Gopal Kakani, Duli Zhao, Sailaja Koti, and Wei Gao, "Interactive effects of ultraviolet-B radiation and temperature on cotton physiology, growth, development and hyper spectral reflectance", *Photochemistry and Photobiology*, **79(5)**, 416-427, 2004.
17. Shettle, E.P., "Models of aerosols, clouds and precipitation for atmospheric propagation studies", In *Atmospheric Propagation in UV, Visible, IR and MM-Region and Related System Aspects*, AGARD Conf. Proc., **454**, 15-1-15-3, 1989.
18. Stamnes, K., S. Tsay, W. Wiscombe, and K. Jayaweera, "A numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media", *Applied Optics*, **27**, 2502-2509, 1988.
19. Torres O., P.K. Bhartia, J.R. Herman and Z. Ahmad, "Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation. Theoretical Basis", *J. Geophys. Res.*, **103**, 17099-17110, 1998.
20. Xu, M., X.-Z. Liang, W. Gao, K. R. Reddy, J. Slusser, and K. E. Kunkel, "Preliminary results of the coupled CWRP-GOSSYM system", In *Remote Sensing and Modeling of Ecosystems for Sustainability II*. W. Gao and D. Shaw (Eds.), Vol. 5884, SPIE Press (Bellingham, WA), pp. 68-74, 2005.
21. Zhou, J. L., A. L. Tits, and C. T. Lawrence, "User's guide for FFSQP version 3.7: A FORTRAN code for solving constrained nonlinear (minimax) optimization problems, generating iterates satisfying all inequality and linear constraints", Tech. Rep. SRC-TR-92-107r5, 44 pp., Inst. for Syst. Res., Univ. of Md. at College Park. (Available at <http://www.aemdesign.com/downloadfsqp.htm>), 1997.