APPENDIX A3. HIGHLIGHTED ARTICLES PUBLISHED IN 2006

Atmospheric Teleconnection over Eurasia Induced by Aerosol Radiative Forcing during Boreal Spring

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(Manuscript received 18 March 2005, in final form 22 November 2005)

ABSTRACT

The direct effects of aerosols on global and regional climate during boreal spring are investigated based on numerical simulations with the NASA Global Modeling and Assimilation Office finite-volume general circulation model (fvGCM) with Microphyics of Clouds with the Relaxed–Arakawa Schubert Scheme (McRAS), using aerosol forcing functions derived from the Goddard Ozone Chemistry Aerosol Radiation and Transport model (GOCART).

The authors find that anomalous atmospheric heat sources induced by absorbing aerosols (dust and black carbon) excite a planetary-scale teleconnection pattern in sea level pressure, temperature, and geopotential height spanning North Africa through Eurasia to the North Pacific. Surface cooling due to direct effects of aerosols is found in the vicinity and downstream of the aerosol source regions, that is, South Asia, East Asia, and northern and western Africa. Significant atmospheric heating is found in regions with large loading of dust (over northern Africa and the Middle East) and black carbon (over Southeast Asia). Paradoxically, the most pronounced feature in aerosol-induced surface temperature is an east–west dipole anomaly with strong cooling over the Caspian Sea and warming over central and northeastern Asia, where aerosol concentrations are low. Analyses of circulation anomalies show that the dipole anomaly is a part of an atmospheric teleconnection pattern driven by atmospheric heating anomalies induced by absorbing aerosols in the source regions, but the influence was conveyed globally through barotropic energy dispersion and sustained by feedback processes associated with the regional circulations.

The surface temperature signature associated with the aerosol-induced teleconnection bears striking resemblance to the spatial pattern of observed long-term trend in surface temperature over Eurasia. Additionally, the boreal spring wave train pattern is similar to that reported by Fukutomi et al. associated with the boreal summer precipitation seesaw between eastern and western Siberia. The results of this study raise the possibility that global aerosol forcing during boreal spring may play an important role in spawning atmospheric teleconnections that affect regional and global climates.

1. Introduction

Recent studies have shown that aerosols may play an important role in climate change through their interaction with the global water and energy cycles (e.g., Jacobson 2001a,b, 2002; Menon et al. 2002; Lohmann and Lesins 2002; Roberts and Jones 2004; Ramanathan et al. 2001). The effect of aerosols on the earth's radiative budget is not only limited to cooling by scattering but also heating by absorption of solar radiation, depending on aerosol types. Because of their ability to deplete surface insolation from either scattering or absorption, all aerosols cause cooling at the earth surface—the so-called "solar dimming" effect (Ramanathan et al. 2005). However, the sign of atmospheric temperature change induced by aerosol forcing can vary depending on the aerosol types, their elevation, and reflectivity of the

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JCLI3871

Climate Dynamics (2006) 26: 855–864
DOI 10.1007/s00382-006-0114-z

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Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau

Received: 12 July 2005 / Accepted: 15 December 2005 / Published online: 9 February 2006

Abstract In this paper we present results of a numerical study using the NASA finite-volume GCM to elucidate a plausible mechanism for aerosol impact on the Asian summer monsoon involving interaction with physical processes over the Tibetan Plateau (TP). During the pre-monsoon season of March–April, dusts from the deserts of western China, Afghanistan/Pakistan, and the Middle East are transported into and stacked up against the northern and southern slopes of the TP. The absorption of solar radiation by dust heats up the elevated surface air over the slopes. On the southern slopes, the atmospheric heating is reinforced by black carbon from local emission. The heated air rises via dry convection, creating a positive temperature anomaly in the mid-to-upper troposphere over the TP relative to the region to the south. In May through early June in a manner akin to an "elevated heat pump", the rising hot air forced by the increasing heating in the upper troposphere, draws in warm and moist air over the Indian subcontinent, setting the stage for the onset of the South Asia summer monsoon. Our results suggest that increased dust loading coupled with black carbon emission from local sources in northern India during late spring may lead to an advance of the rainy periods and subsequently an intensification of the Indian summer monsoon. The enhanced rainfall over India is associated with the development of an aerosol-induced large-scale sea level pressure anomaly pattern, which causes the East Asia (*Mei-yu*) rain belt to shift northwestward, suppressing rainfall over East Asia and the adjacent oceanic regions.

1 Introduction

Recent studies have shown that aerosols can cause substantial alteration in the energy balance of the atmosphere and the earth surface, thus modulating the hydrologic cycle (Hansen et al. 2000; Jacobson 2001; Ramanathan et al. 2001). In the Asian monsoon regions, aerosol is a major environmental hazard that is increasing at an alarming rate, and the monsoon water cycle is the lifeline to over 60% of the world's population. Yet the effects of aerosol and possible interactions with the monsoon dynamics remain largely unknown. Hence, a better understanding of interaction of aerosols on monsoon water cycle is paramount with huge science and society benefits. Numerical experiments from a general circulation model (GCM) have suggested that atmospheric circulation anomalies induced by black carbon from coal burning may be a cause of long-term drought over northern China, and excessive rainfall over southern China and India (Menon et al. 2002). Recently, Ramanathan et al. (2005) shows that on climate change timescales, as a result of blocking of solar radiation reaching the surface by aerosol, i.e., global dimming, the earth surface cools, leading to a gradual spin-down of the tropical water cycle, and eventually weakening of the Asian monsoon. However on seasonal-to-interannual time scales, it is not clear how aerosols may impact the Asian monsoon. Absorbing aerosols such as dust and black carbon will heat the atmosphere due to shortwave absorption. Non-absorbing aerosols such as sulphate causes surface cooling by strongly scattering solar radiation, but have relatively little heating effects on the atmosphere itself. Overall, both absorbing and non-absorbing aerosols cool the earth surface by the global dimming effect. However, as we shall illustrate in this paper, for absorbing aerosols over elevated land with high surface albedo, in the presence of atmosphere and surface energy feedback, the effects may be quite different.

One of the key controls of the seasonal-to-interannual variability of the Asian summer monsoon is associated

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The Dryline on 22 May 2002 during IHOP_2002: Convective-Scale Measurements at the Profiling Site

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(Manuscript received 18 August 2004, in final form 5 July 2005)

ABSTRACT

A detailed analysis of the structure of a double dryline observed over the Oklahoma panhandle during the first International H_2O Project (IHOP_2002) convective initiation (CI) mission on 22 May 2002 is presented. A unique and unprecedented set of high temporal and spatial resolution measurements of water vapor mixing ratio, wind, and boundary layer structure parameters were acquired using the National Aeronautics and Space Administration (NASA) scanning Raman lidar (SRL), the Goddard Lidar Observatory for Winds (GLOW), and the Holographic Airborne Rotating Lidar Instrument Experiment (HARLIE), respectively. These measurements are combined with the vertical velocity measurements derived from the National Center for Atmospheric Research (NCAR) Multiple Antenna Profiler Radar (MAPR) and radar structure function from the high-resolution University of Massachusetts frequency-modulated continuous-wave (FMCW) radar to reveal the evolution and structure of the late afternoon double-dryline boundary layer. The eastern dryline advanced and then retreated over the Homestead profiling site in the Oklahoma panhandle, providing conditions ripe for a detailed observation of the small-scale variability within the boundary layer and the dryline. In situ aircraft data, dropsonde and radiosonde data, along with NCAR S-band dual-polarization Doppler radar (S-Pol) measurements, are also used to provide the larger-scale picture of the double-dryline environment.

Moisture and temperature jumps of about 3 g kg^{-1} and 1–2 K, respectively, were observed across the eastern radar fine line (dryline), more than the moisture jumps (1–2 g kg^{-1}) observed across the western radar fine line (secondary dryline). Most updraft plumes observed were located on the moist side of the eastern dryline with vertical velocities exceeding 3 m s^{-1} and variable horizontal widths of 2–5 km, although some were as wide as 7–8 km. These updrafts were up to 1.5 g kg^{-1} moister than the surrounding environment.

Although models suggested deep convection over the Oklahoma panhandle and several cloud lines were observed near the dryline, the dryline itself did not initiate any storms over the intensive observation region (IOR). Possible reasons for this lack of convection are discussed. Strong capping inversion and moisture detrainment between the lifting condensation level and the level of free convection related to an overriding drier air, together with the relatively small near-surface moisture values (less than 10 g kg^{-1}), were detrimental to CI in this case.

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MWR3054

Bayesian Estimation of Precipitation from Satellite Passive Microwave Observations Using Combined Radar–Radiometer Retrievals

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(Manuscript received 26 April 2005, in final form 14 October 2005)

ABSTRACT

Precipitation estimation from satellite passive microwave radiometer observations is a problem that does not have a unique solution that is insensitive to errors in the input data. Traditionally, to make this problem well posed, a priori information derived from physical models or independent, high-quality observations is incorporated into the solution. In the present study, a database of precipitation profiles and associated brightness temperatures is constructed to serve as a priori information in a passive microwave radiometer algorithm. The precipitation profiles are derived from a Tropical Rainfall Measuring Mission (TRMM) combined radar–radiometer algorithm, and the brightness temperatures are TRMM Microwave Imager (TMI) observed. Because the observed brightness temperatures are consistent with those derived from a radiative transfer model embedded in the combined algorithm, the precipitation–brightness temperature database is considered to be physically consistent. The database examined here is derived from the analysis of a month-long record of TRMM data that yields more than a million profiles of precipitation and associated brightness temperatures. These profiles are clustered into a tractable number of classes based on the local sea surface temperature, a radiometer-based estimate of the echo-top height (the height beyond which the reflectivity drops below 17 dBZ), and brightness temperature principal components. For each class, the mean precipitation profile, brightness temperature principal components, and probability of occurrence are determined. The precipitation–brightness temperature database supports a radiometer-only algorithm that incorporates a Bayesian estimation methodology. In the Bayesian framework, precipitation estimates are weighted averages of the mean precipitation values corresponding to the classes in the database, with the weights being determined according to the similarity between the observed brightness temperature principal components and the brightness temperature principal components of the classes. Because the classes are stratified by the sea surface temperature and the echo-top-height estimator, the number of classes that are considered for retrieval is significantly smaller than the total number of classes, making the algorithm computationally efficient. The radiometer-only algorithm is applied to TMI observations, and precipitation estimates are compared with combined TRMM precipitation radar (PR)–TMI reference estimates. The TMI-only algorithm, supported by the empirically derived database, produces estimates that are more consistent with the reference values than the precipitation estimates from the version-6 TRMM facility TMI algorithm. Cloud-resolving model simulations are used to assign a latent heating profile to each precipitation profile in the empirically derived database, making it possible to estimate latent heating using the radiometer-only algorithm. Although the evaluation of latent heating estimates in this study is preliminary, because realistic conditional probability distribution functions are attached to latent heating structures in the algorithm's database, a generally positive impact on latent heating estimation from passive microwave observations is expected.

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Structure of Highly Sheared Tropical Storm Chantal during CAMEX-4

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(Manuscript received 16 October 2003, in final form 21 December 2004)

ABSTRACT

Tropical Storm Chantal during August 2001 was a storm that failed to intensify over the few days prior to making landfall on the Yucatan Peninsula. An observational study of Tropical Storm Chantal is presented using a diverse dataset including remote and in situ measurements from the NASA ER-2 and DC-8 and the NOAA WP-3D N42RF aircraft and satellite. The authors discuss the storm structure from the larger-scale environment down to the convective scale. Large vertical shear (850–200-hPa shear magnitude range 8–15 m s^{-1}) plays a very important role in preventing Chantal from intensifying. The storm had a poorly defined vortex that only extended up to 5–6-km altitude, and an adjacent intense convective region that comprised a mesoscale convective system (MCS). The entire low-level circulation center was in the rain-free western side of the storm, about 80 km to the west-southwest of the MCS. The MCS appears to have been primarily the result of intense convergence between large-scale, low-level easterly flow with embedded downdrafts, and the cyclonic vortex flow. The individual cells in the MCS such as cell 2 during the period of the observations were extremely intense, with reflectivity core diameters of 10 km and peak updrafts exceeding 20 m s^{-1}. Associated with this MCS were two broad subsidence (warm) regions, both of which had portions over the vortex. The first layer near 700 hPa was directly above the vortex and covered most of it. The second layer near 500 hPa was along the forward and right flanks of cell 2 and undercut the anvil divergence region above. There was not much resemblance of these subsidence layers to typical upper-level warm cores in hurricanes that are necessary to support strong surface winds and a low central pressure. The observations are compared to previous studies of weakly sheared storms and modeling studies of shear effects and intensification.

The configuration of the convective updrafts, low-level circulation, and lack of vertical coherence between the upper- and lower-level warming regions likely inhibited intensification of Chantal. This configuration is consistent with modeled vortices in sheared environments, which suggest the strongest convection and rain in the downshear left quadrant of the storm, and subsidence in the upshear right quadrant. The vertical shear profile is, however, different from what was assumed in previous modeling in that the winds are strongest in the lowest levels and the deep tropospheric vertical shear is on the order of 10–12 m s^{-1}.

1. Introduction

Observational studies have generally found that large-scale vertical shear is unfavorable for tropical storm formation and intensification (e.g., Gray 1968; Zehr 2003). The vertical shear that affects tropical storm intensity is the environmental shear defined as the difference between the 200- and 850-hPa winds averaged over a large area centered on the storm (e.g., DeMaria 1996). All storms have some amount of shear and why certain storms intensify is a fundamental question in hurricane research. Numerical modeling studies have suggested the primary mechanism forcing wavenumber-1 asymmetries in rainfall distributions is vertical shear (e.g., Frank and Ritchie 2001; Bender 1997; Jones 1995). Frank and Ritchie (2001) hypothesized that a large-scale shear imposed on a storm can cause high values of potential vorticity and equivalent potential temperature (θ_e) to mix outward rather than into the eye. This results in a loss of the upper tropospheric warm core in the eye and would tend to weaken the storm by increasing the central pressure. Frank and

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Precipitation and Latent Heating Distributions from Satellite Passive Microwave Radiometry. Part I: Improved Method and Uncertainties

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(Manuscript received 11 February 2005, in final form 2 September 2005)

ABSTRACT

A revised Bayesian algorithm for estimating surface rain rate, convective rain proportion, and latent heating profiles from satellite-borne passive microwave radiometer observations over ocean backgrounds is described. The algorithm searches a large database of cloud-radiative model simulations to find cloud profiles that are radiatively consistent with a given set of microwave radiance measurements. The properties of these radiatively consistent profiles are then composited to obtain best estimates of the observed properties. The revised algorithm is supported by an expanded and more physically consistent database of cloud-radiative model simulations. The algorithm also features a better quantification of the convective and nonconvective contributions to total rainfall, a new geographic database, and an improved representation of background radiances in rain-free regions. Bias and random error estimates are derived from applications of the algorithm to synthetic radiance data, based upon a subset of cloud-resolving model simulations, and from the Bayesian formulation itself. Synthetic rain-rate and latent heating estimates exhibit a trend of high (low) bias for low (high) retrieved values. The Bayesian estimates of random error are propagated to represent errors at coarser time and space resolutions, based upon applications of the algorithm to TRMM Microwave Imager (TMI) data. Errors in TMI instantaneous rain-rate estimates at 0.5°-resolution range from approximately 50% at 1 mm h^{-1} to 20% at 14 mm h^{-1}. Errors in collocated spaceborne radar rain-rate estimates are roughly 50%–80% of the TMI errors at this resolution. The estimated algorithm random error in TMI rain rates at monthly, 2.5° resolution is relatively small (less than 6% at 5 mm day^{-1}) in comparison with the random error resulting from infrequent satellite temporal sampling (8%–35% at the same rain rate). Percentage errors resulting from sampling decrease with increasing rain rate, and sampling errors in latent heating rates follow the same trend. Averaging over 3 months reduces sampling errors in rain rates to 6%–15% at 5 mm day^{-1}, with proportionate reductions in latent heating sampling errors.

1. Introduction

Over the last decade, diagnostics of time-/space-averaged satellite rainfall estimates have helped to create a better picture of the earth's climate and its variability (e.g., Rasmussen and Arkin 1993; Xie and Arkin 1997; Curtis and Adler 2000; Adler et al. 2003). These studies have relied upon remote sensing of precipitation from infrared, passive microwave, and spaceborne radar measurements, culminating in the Tropical Rainfall Measuring Mission (TRMM; 1997–present). Moreover, it has been amply demonstrated that precipitation measurements from space have had a beneficial impact on general circulation model assimilations and numerical weather prediction model forecasts using data assimilation methods

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JAM2369

RETRIEVAL OF LATENT HEATING FROM TRMM MEASUREMENTS

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TRMM-based latent heating products—not long ago considered out of our technological reach—are beginning to contribute to global modeling, but the necessary retrieval algorithms produce varying results and will require further research.

Precipitation, in driving the global hydrological cycle, strongly influences the behavior of the Earth's weather and climate systems and is central to their variability. Two-thirds of the global rainfall occurs over the Tropics,[1] which leads to its profound effect on the general circulation of the atmosphere. This is because its energetic equivalent, latent heating (LH), is the tropical convective heat engine's primary fuel source as originally emphasized by Riehl and Malkus (1958). At low latitudes, LH stemming from extended bands of rainfall modulates large-scale zonal and meridional circulations and their consequent mass overturnings (e.g., Hartmann et al. 1984; Hack and Schubert 1990). Also, LH is the principal energy source in the creation, growth, vertical structure, and propagation of long-lived tropical

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[1] The Tropics are liberally taken as the area bounded by the 25°N–25°S latitude zone.

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-87-11-1555

In final form 26 May 2006

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D09S09, doi:10.1029/2005JD006429, 2006

Analysis of Raman lidar and radiosonde measurements from the AWEX-G field campaign and its relation to Aqua validation

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Received 27 June 2005; revised 14 September 2005; accepted 8 November 2005; published 12 April 2006.

[1] Early work within the Aqua validation activity revealed there to be large differences in water vapor measurement accuracy among the various technologies in use for providing validation data. The validation measurements were made at globally distributed sites making it difficult to isolate the sources of the apparent measurement differences among the various sensors, which included both Raman lidar and radiosonde. Because of this, the AIRS Water Vapor Experiment–Ground (AWEX-G) was held in October-November 2003 with the goal of bringing validation technologies to a common site for intercomparison and resolving the measurement discrepancies. Using the University of Colorado Cryogenic Frostpoint Hygrometer (CFH) as the water vapor reference, the AWEX-G field campaign permitted correction techniques to be validated for Raman lidar, Vaisala RS80-H and RS90/92 that significantly improve the absolute accuracy of water vapor measurements from these systems particularly in the upper troposphere. Mean comparisons of radiosondes and lidar are performed demonstrating agreement between corrected sensors and the CFH to generally within 5% thereby providing data of sufficient accuracy for Aqua validation purposes. Examples of the use of the correction techniques in radiance and retrieval comparisons are provided and discussed.

Citation: Whiteman, D. N., et al. (2006), Analysis of Raman lidar and radiosonde measurements from the AWEX-G field campaign and its relation to Aqua validation, *J. Geophys. Res.*, *111*, D09S09, doi:10.1029/2005JD006429.

1. Introduction and Background

[2] The Aqua satellite validation activity funded by NASA includes the use of different water vapor profiling radiosondes and Raman lidar systems for acquisition of measurements during Aqua overpasses. Numerous special measurement campaigns have been staged from various geographic locations in order to acquire data of the highest quality for calibration and validation of the satellite measurements and retrievals. It is fundamentally important that these special data sets possess higher absolute accuracy than required of the satellite data products for this validation technique to work. Early comparisons of many validation measurements with the Atmospheric Infrared Sounder (AIRS), through the use of the AIRS fast forward radiative transfer model, SARTA [*Strow et al.*, 2003], revealed apparent large calibration differences among the various water vapor profiling technologies being used. The differences were largest in the upper troposphere (UT) where differences between AIRS radiances and calculations of AIRS radiance using SARTA, when translated to UT relative humidity (RH), implied differences in the calibration of the water vapor measurement systems that exceeded 25% in some cases. This is to be contrasted with the Aqua retrieval accuracy goal, where a retrieval involves a minimization of differences between observed and calculated radiances, of 10% in 2-km layers. The apparent inadequacy of many of the validation measurement systems to provide data of sufficient quality to validate retrievals at this accuracy level created questions both about the validation sensor technologies and how to improve the quality of water vapor measurements used for Aqua validation. For this reason, a dedicated field program called the AIRS Water Vapor Experiment–Ground (AWEX-G) was held in October-November 2003 with the goal of resolving the measurement

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0148-0227/06/2005JD006429$09.00

A Numerical Study of Hurricane Erin (2001). Part I: Model Verification and Storm Evolution

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(Manuscript received 7 November 2003, in final form 4 February 2005)

ABSTRACT

The fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) is used to simulate Hurricane Erin (2001) at high resolution (4-km spacing) from its early development as a tropical depression on 7 September 2001, through a period of rapid intensification into a strong hurricane (8–9 September), and finally into a stage during which it maintains its intensity on 10 September. These three stages of formation, intensification, and maintenance in the simulation are in good agreement with the observed evolution of Erin. The simulation shows that during the formation and early portions of the intensification stages, intensification is favored because the environmental wind shear is weak and the system moves over a warm tongue of water. As Erin intensifies, the wind shear gradually increases with the approach of an upper-level trough and strengthening of a low-level high pressure system. By 10 September, the wind shear peaks and begins to decrease, the storm moves over slightly cooler waters, and the intensification ends. Important structural changes occur at this time as the outer precipitation shifts from the northeastern and eastern sides to the western side of the eye. A secondary wind maximum and an outer eyewall begin to develop as precipitation begins to surround the entire eye.

The simulation is used to investigate the role of vertical wind shear in the changes of the precipitation structure that took place between 9 and 10 September by examining the effects of changes in storm-relative flow and changes in the shear-induced tilt. Qualitative agreement is found between the divergence pattern and advection of vorticity by the relative flow with convergence (divergence) generally associated with asymmetric inflow (outflow) in the eyewall region. The shift in the outer precipitation is consistent with a shift in the low-level relative inflow from the northeastern to the northwestern side of the storm. The changes in the relative flow are associated with changes in the environmental winds as the hurricane moves relative to the upper trough and the low-level high pressure system. Examination of the shear-induced tilt of the vortex shows that the change in the tilt direction is greater than that of the shear direction as the tilt shifts from a northerly orientation to northwesterly. Consistent with theory for adiabatic vortices, the maximum low-level convergence and upper-level divergence (and the maximum upward motion) occurs in the direction of tilt. Consequently, both mechanisms may play roles in the changes in the precipitation pattern.

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Precipitation and Latent Heating Distributions from Satellite Passive Microwave Radiometry. Part II: Evaluation of Estimates Using Independent Data

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(Manuscript received 11 February 2005, in final form 2 September 2005)

ABSTRACT

Rainfall rate estimates from spaceborne microwave radiometers are generally accepted as reliable by a majority of the atmospheric science community. One of the Tropical Rainfall Measuring Mission (TRMM) facility rain-rate algorithms is based upon passive microwave observations from the TRMM Microwave Imager (TMI). In Part I of this series, improvements of the TMI algorithm that are required to introduce latent heating as an additional algorithm product are described. Here, estimates of surface rain rate, convective proportion, and latent heating are evaluated using independent ground-based estimates and satellite products. Instantaneous, 0.5°-resolution estimates of surface rain rate over ocean from the improved TMI algorithm are well correlated with independent radar estimates ($r \sim 0.88$ over the Tropics), but bias reduction is the most significant improvement over earlier algorithms. The bias reduction is attributed to the greater breadth of cloud-resolving model simulations that support the improved algorithm and the more consistent and specific convective/stratiform rain separation method utilized. The bias of monthly 2.5°-resolution estimates is similarly reduced, with comparable correlations to radar estimates. Although the amount of independent latent heating data is limited, TMI-estimated latent heating profiles compare favorably with instantaneous estimates based upon dual-Doppler radar observations, and time series of surface rain-rate and heating profiles are generally consistent with those derived from rawinsonde analyses. Still, some biases in profile shape are evident, and these may be resolved with (a) additional contextual information brought to the estimation problem and/or (b) physically consistent and representative databases supporting the algorithm. A model of the random error in instantaneous 0.5°-resolution rain-rate estimates appears to be consistent with the levels of error determined from TMI comparisons with collocated radar. Error model modifications for nonraining situations will be required, however. Sampling error represents only a portion of the total error in monthly 2.5°-resolution TMI estimates; the remaining error is attributed to random and systematic algorithm errors arising from the physical inconsistency and/or nonrepresentativeness of cloud-resolving-model-simulated profiles that support the algorithm.

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JAM2370

Mechanisms for Diurnal Variability of Global Tropical Rainfall Observed from TRMM

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(Manuscript received 8 April 2005, in final form 11 January 2006)

ABSTRACT

The behavior and various controls of diurnal variability in tropical–subtropical rainfall are investigated using Tropical Rainfall Measuring Mission (TRMM) precipitation measurements retrieved from the three level-2 TRMM standard profile algorithms for the 1998 annual cycle. Results show that diurnal variability characteristics of precipitation are consistent for all three algorithms, providing assurance that TRMM retrievals are producing consistent estimates of rainfall variability. As anticipated, most ocean areas exhibit more rainfall at night, while over most land areas, rainfall peaks during daytime; however, important exceptions are noted.

The dominant feature of the oceanic diurnal cycle is a rainfall maximum in late-evening–early-morning (LE–EM) hours, while over land the dominant maximum occurs in the mid- to late afternoon (MLA). In conjunction with these maxima are pronounced seasonal variations of the diurnal amplitudes. Amplitude analysis shows that the diurnal pattern and its seasonal evolution are closely related to the rainfall accumulation pattern and its seasonal evolution. In addition, the horizontal distribution of diurnal variability indicates that for oceanic rainfall, there is a secondary MLA maximum coexisting with the LE–EM maximum at latitudes dominated by large-scale convergence and deep convection. Analogously, there is a preponderancy for an LE–EM maximum over land coexisting with the stronger MLA maximum, although it is not evident that this secondary continental feature is closely associated with the large-scale circulation. Neither of the secondary maxima exhibit phase behavior that can be considered semidiurnal in nature. Diurnal rainfall variability over the ocean associated with large-scale convection is clearly an integral component of the general circulation.

Phase analysis reveals differences in regional and seasonal features of the diurnal cycle, indicating that underlying forcing mechanisms differ from place to place. This is underscored by the appearance of secondary ocean maxima in the presence of large-scale convection, along with other important features. Among these, there are clear-cut differences between the diurnal variability of seasonal rainfall over the mid-Pacific and Indian Ocean Basins. The mid-Pacific exhibits double maxima in spring and winter but only LE–EM maxima in summer and autumn, while the Indian Ocean exhibits double maxima in spring and summer and only an LE–EM maximum in autumn and winter. There are also evident daytime maxima within the major large-scale marine stratocumulus regions off the west coasts of continents. The study concludes with a discussion concerning how the observational evidence either supports or repudiates possible forcing mechanisms that have been suggested to explain diurnal rainfall variability.

1. Introduction

Diurnal variation of precipitation on planet Earth was first reported in the early twentieth century by Hann (1901, 338–346) and since that time has spawned an immense literature. In general, rainfall maxima in the late-evening–early-morning hours (LE–EM) have been reported for open-ocean environments (e.g., Kraus 1963; Andersson 1970; Gray and Jacobson 1977; Jordon 1980; Albright et al. 1985; Randall et al. 1991; Imaoka and Spencer 2000), while mid- to late afternoon (MLA) maxima have often been reported for land (e.g., Ray 1928; Cook 1939; Kousky 1980; Hamilton 1981; Garreaud and Wallace 1997). However, such generalities do not describe all the intricacies inherent to rainfall's diurnal cycle, and both past observational rainfall

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JCLI3883

Chapter 5 in **Earth Science Satellite Remote Sensing, Science and Instruments, Vol I**, edited by J. J. Qu, W. Gao, M. Kafatos, R. E. Murphy, and V. V. Salomonson, pp. 74-91, Tsinghua University Press (Beijing) and Springer-Verlag (Berlin).

5 Introduction to MODIS Cloud Products

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5.1 Introduction

The Earth's radiative energy balance and hydrological cycle are fundamentally coupled with the distribution and properties of clouds. Therefore, the ability to remotely infer cloud properties and their variation in space and time is crucial for establishing climatologies as a reference for validation of present-day climate models and in assessing future climate change. Remote cloud observations also provide data sets useful for testing and improving cloud model physics, and for assimilation into numerical weather prediction models.

The MODerate Resolution Imaging Spectroradiometer (MODIS) imagers on the Terra and Aqua Earth Observing System (EOS) platforms provide the capability for globally retrieving these properties using passive solar reflectance and infrared techniques. In addition to providing measurements similar to those offered on a suite of historical operational weather platforms such as the Advanced Very High Resolution Radiometer (AVHRR), the High-resolution Infrared Radiation Sounder (HIRS), and the Geostationary Operational Environmental Satellite (GOES), MODIS provides additional spectral and/or spatial resolution in key atmospheric bands, along with on-board calibration, to expand the capability for global cloud property retrievals.

The core MODIS operational cloud products include cloud top pressure, thermodynamic phase, optical thickness, particle size, and water path, and are derived globally at spatial resolutions of either 1- or 5-km (referred to as Level-2 or pixel-level products). In addition, the MODIS atmosphere team (collectively providing cloud, aerosol, and clear sky products) produces a combined gridded product (referred to as Level-3) aggregated to a 1° equal-angle grid, available for daily, eight-day, and monthly time periods. The wealth of information available from these products provides critical information for climate studies as well as the continuation and improved understanding of existing satellite-based cloud climatologies derived from heritage instruments.

This chapter provides an overview of the MODIS Level-2 and -3 operational cloud products. All products described in this chapter are available from the NASA Goddard Earth Sciences Distributed Active Archive Center (GES DAAC). However, the MODIS instrument has direct broadcast capability on both the Terra and Aqua platforms. Ground stations that obtain the MODIS data as the spacecraft

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L05807, doi:10.1029/2005GL024926, 2006

Comparisons of remote sensing retrievals and in situ measurements of aerosol fine mode fraction during ACE-Asia

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Received 19 October 2005; revised 16 December 2005; accepted 23 January 2006; published 8 March 2006.

[1] We present sunphotometer-retrieved and in situ fine mode fractions (FMF) measured onboard the same aircraft during the ACE-Asia experiment. Comparisons indicate that the latter can be used to identify whether the aerosol under observation is dominated by a mixture of modes or a single mode. Differences between retrieved and in situ FMF range from 5–20%. When profiles contained multiple layers of aerosols, the retrieved and measured FMF were segregated by layers. The comparison of layered and total FMF from the same profile indicates that columnar values are intermediate to those derived from layers. As a result, a remotely sensed FMF cannot be used to distinguish whether the aerosol under observation is composed of layers each with distinctive modal features or all layers with the same modal features. Thus, the use of FMF in multiple layer environments does not provide unique information on the aerosol under observation. **Citation:** Gassó, S., and N. O'Neill (2006), Comparisons of remote sensing retrievals and in situ measurements of aerosol fine mode fraction during ACE-Asia, *Geophys. Res. Lett.*, *33*, L05807, doi:10.1029/2005GL024926.

1. Introduction

[2] Automated retrievals of aerosol optical depth (AOD) by spaceborne detectors have significantly improved our knowledge of the global distribution of aerosols [*Kaufman et al.*, 2002]. In addition, they have provided a measurement based verification of aerosol forcing derived from global aerosol models [*Penner et al.*, 2002]. However, passive remote sensing techniques have not had the same degrees of success in detecting aerosol size distribution properties. A proper global characterization of size distribution properties is important because it would improve the simulation of microphysical properties in global aerosol models [*Zhang et al.*, 2002]. The concept of fine mode fraction (FMF) has been introduced to describe columnar aerosol modal features using passive spectral detectors such as MODIS [*Tanré et al.*, 1997]. FMF is defined as the ratio of the accumulation mode OD to the total OD at 550 nm. It provides quantitative information on the nature of the aerosol size distribution. The FMF is defined such that it ranges from 0 to 1. The extreme values represent pure conditions where the total radiance can be modeled by a single accumulation mode (FMF = 1) or a single coarse mode (FMF = 0). For intermediate values, both modes contribute to the total radiance with each contributing to the total AOD in proportion to FMF and 1-FMF respectively [*Remer et al.*, 2005]. Because of its close association with modal features, the MODIS FMF product has been used for discriminating between natural and anthropogenic aerosols [*Kaufman et al.*, 2005]. Few studies have been dedicated to comparisons of FMF with corresponding ground retrievals or in situ measurements. Because it is rather difficult to carry out campaigns of aircraft aerosol measurements synchronized to satellite overpass times, comparisons with in situ measurements have been limited to case studies [*Gassó and Hegg*, 2003]. *Kleidman et al.* [2005] compared MODIS FMF retrievals with collocated AOD measurements made by the AERONET network using two retrieval techniques, one based on the existing operational retrieval [*Dubovik and King*, 2000] and the other using the *O'Neill et al.* [2003] technique. The latter method relies on AOD spectral derivatives to extract FMF whereas the former is employed to retrieve aerosol modal properties from the angular and/or spectral variation of sky radiances and solar extinction measurements. Unlike the Dubovik method, the O'Neill retrieval technique is used to derive FMF directly from OD spectra. It is attractive given the significantly greater frequency and weaker cloud contamination of AOD measurements (as opposed to the less frequent measurements in the Dubovik inversion). It also has the potential of being easily implemented as a MODIS FMF retrieval algorithm, and thus provides an alternative to the existing technique. The latest version of the model is employed here [*O'Neill et al.*, 2005].

[3] We applied the O'Neill technique to AODs retrieved by the AATS-6 sunphotometer onboard the NCAR C130 aircraft deployed during the ACE-Asia campaign [*Redemann et al.*, 2003]. The same aircraft carried a suite of in situ aerosol instrumentation [*Clarke et al.*, 2004]. Of particular interest are the measurements of total and accumulation mode extinction coefficients from which it is possible to integrate over the column and obtain an in situ FMF. The analysis and comparison between these measurements and the collocated AATS-6 retrievals are reported in this study.

2. Data Set

[4] In this study, we employed the same profiles utilized by *Redemann et al.* [2003] with an additional criterion in the data selection: particle size distribution measurements had to be simultaneously available with the nephelometer and sunphotometer data. In this way, distinction of aerosol type could be made based on number and volume concentration. As a result, some of the profiles were discarded because the optical particle counter was not functioning or

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0094-8276/06/2005GL024926$05.00

3180 IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 44, NO. 11, NOVEMBER 2006

Deep Blue Retrievals of Asian Aerosol Properties During ACE-Asia

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***Abstract*—During the ACE-Asia field campaign, unprecedented amounts of aerosol property data in East Asia during springtime were collected from an array of aircraft, shipboard, and surface instruments. However, most of the observations were obtained in areas downwind of the source regions. In this paper, the newly developed satellite aerosol algorithm called "Deep Blue" was employed to characterize the properties of aerosols over source regions using radiance measurements from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS). Based upon the Ångström exponent derived from the Deep Blue algorithm, it was demonstrated that this new algorithm is able to distinguish dust plumes from fine-mode pollution particles even in complex aerosol environments such as the one over Beijing. Furthermore, these results were validated by comparing them with observations from AERONET sites in China and Mongolia during spring 2001. These comparisons show that the values of satellite-retrieved aerosol optical thickness from Deep Blue are generally within 20%–30% of those measured by sunphotometers. The analyses also indicate that the roles of mineral dust and anthropogenic particles are comparable in contributing to the overall aerosol distributions during spring in northern China, while fine-mode particles are dominant over southern China. The spring season in East Asia consists of one of the most complex environments in terms of frequent cloudiness and wide ranges of aerosol loadings and types. This paper will discuss how the factors contributing to this complexity influence the resulting aerosol monthly averages from various satellite sensors and, thus, the synergy among satellite aerosol products.**

***Index Terms*—Aerosols, desert, Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectro-Radiometer (MISR), remote sensing, satellite applications, Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Terra.**

I. INTRODUCTION

THE IMPACT of growing air pollution in Asia, and in other parts of the world, has gained attention from the scientific community in recent years. Among the many components that contribute to such pollution, airborne mineral dust plays an important role due to its biogeochemical impact on the ecosystem and its radiative-forcing effect on the climate system [8], [13]. In East Asia, dust storms frequently accompany the cold and dry air masses that occur as part of springtime cold front systems. China's capital, Beijing, and other large cities are on the primary pathway of these dust storm plumes, and their passage over such population centers causes flight delays, pushes grit through windows and doors, and forces people indoors. Furthermore, during spring, these anthropogenic and natural air pollutants, once generated over the source regions, can be transported out of the boundary layer into the free troposphere and can travel thousands of kilometers across the Pacific into the U.S. and beyond. Satellite views, as shown in Fig. 1, illustrate the vast distances over which these Asian dust plumes can extend. Once caught by the westerly jet, these pollutant clouds have been shown to reach as far as North America [28] and the French Alps [7].

Because of their complexity, it is especially important to understand the processes controlling the formation, transport, and fate of aerosol types occurring from East Asian source regions into areas downstream. The properties of Asian dust and anthropogenic pollution aerosols have been extensively studied using information collected during the ACE-Asia field campaign [15]. Yet most of the observations during the experiment were obtained in areas downwind of the source region. This is because retrieving aerosol properties over dust source regions (i.e., arid and semiarid regions) using traditional Advanced Very High Resolution Radiometer (AVHRR) channels in the visible and near-infrared wavelengths is a difficult task because of the bright underlying surfaces over such regions [18]. There have been several approaches developed to retrieve aerosol optical properties over the desert, including contrast reduction (atmospheric blurring) and thermal property techniques [26], [27]. However, since contrast reduction using visible wavelengths depends on the selection of highly contrasted areas as retrieval targets, this approach might not be straightforward for most desert regions. For thermal techniques, the separation of the signal due to mineral aerosols from that due to background temperature and water vapor signals of the terrestrial environment can be complicated and unreliable, particularly over semiarid regions. The latter (i.e., thermal approach), in particular, presents a difficult problem for retrieving aerosol properties in East Asia since the amounts of atmospheric water vapor, aerosol plume height, and surface temperature and emissivity are highly variable and not well known during spring.

In this paper, we present results on retrieved aerosol properties over source regions in East Asia by employing a newly developed aerosol algorithm called "Deep Blue" on satellite radiance measurements taken from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS). The detailed description of the Deep Blue algorithm and its application to derive aerosol properties over the Sahara Desert were previously discussed in [14]. In Section II, we first discuss the results of theoretical simulations performed to examine the advantages and disadvantages of retrieving aerosol properties using different satellite channels from the ultraviolet (UV) to the visible part of spectrum. A brief overview of the Deep Blue algorithm and the derived spectral characteristics of surface reflectance for

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Manuscript received March 8, 2006; revised May 25, 2006. This work was supported by the National Aeronautics and Space Administration's EOS program.

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Digital Object Identifier 10.1109/TGRS.2006.879540

damping. None of the above processes in early lunar evolution are well explored.

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3 April 2006; accepted 8 June 2006
10.1126/science.1128237

Smoke and Pollution Aerosol Effect on Cloud Cover

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Pollution and smoke aerosols can increase or decrease the cloud cover. This duality in the effects of aerosols forms one of the largest uncertainties in climate research. Using solar measurements from Aerosol Robotic Network sites around the globe, we show an increase in cloud cover with an increase in the aerosol column concentration and an inverse dependence on the aerosol absorption of sunlight. The emerging rule appears to be independent of geographical location or aerosol type, thus increasing our confidence in the understanding of these aerosol effects on the clouds and climate. Preliminary estimates suggest an increase of 5% in cloud cover.

Aerosol particles originating from urban and industrial pollution or smoke from fires have been shown to affect cloud microphysics, cloud reflection of sunlight to space, and the onset of precipitation (*1*, *2*). Delays in the onset of precipitation can increase the cloud lifetime and thereby increase cloud cover (*3*, *4*). Research on the aerosol effect on clouds and precipitation has been conducted for half a century (*5*). Although we well understand the aerosol effect on cloud droplet size and reflectance, its impacts on cloud dynamics and regional circulation are highly uncertain (*3*, *5–9*) because of limited observational information and complex processes that are hard to simulate in atmospheric models (*10*, *11*). Indeed, global model estimates of the radiative forcing due to the aerosol effect on clouds range from 0 to –5 W/m^2. The reduction of this uncertainty is a major challenge in improving climate models.

Satellite measurements show strong systematic correlations among aerosol loading, cloud cover (*12*), and cloud height over the Atlantic Ocean (*13*) and Europe (*14*), making the model estimates of aerosol forcing even more uncertain. However, heavy smoke over the Amazon forest (*15*) and pollution over China (*16*) decrease the cloud cover by heating the atmosphere and cooling the surface (*17*) and may balance some of this large negative forcing. Global climate models also show a reduction in cloud cover due to aerosol absorption (τ_{abs}) outside (*18*) and inside the clouds (*19*). In addition, the aerosol effect on slowing down the hydrological cycle by cooling parts of the oceans (*1*) may further reduce cloud formation and the aerosol forcing. Understanding these aerosol effects on clouds and climate requires concentrated efforts of measurement and modeling of the effects.

There are several complications to devising a strategy to measure the aerosol effect on clouds. Although clouds are strongly affected by varying concentrations of aerosol particles, they are driven by atmospheric moisture and stability. Local variations in atmospheric moisture can affect both cloud formation and aerosol humidification, resulting in apparent correlations between aerosol column concentration and cloud cover (*12*, *13*, *20*). In addition, chemical processing of sulfates in clouds can affect the aerosol mass concentration for aerosol dominated by sulfates.

We attempt to address these issues by introducing an additional measurement dimension. We stratified the measurements of the aerosol effect on cloud cover as a function of τ_{abs} of sunlight, thus merging in one experiment both the aerosol enhancement and inhibition of cloud cover. Because the concentration of the absorbing component of aerosols is a function of the aerosol chemical composition, rather than aerosol humidification in the vicinity of clouds, this concentration can serve as a signature for the aerosol effect on clouds. A robust correlation of cloud cover with aerosol column concentration and τ_{abs} in different locations around the world can strengthen the quantification of the aerosol effect on cloud cover, though a direct cause-and-effect relationship will await detailed model simulations.

Table 1. Slopes and intercepts of $\Delta f_{ci}/\Delta\ln\tau$ versus τ_{abs} (Fig. 3A) for the complete data set (All data), continental data dominated by air pollution aerosol, coastal stations, and stations dominated by biomass burning. Results are given for (i) absolute change of the independent cloud fraction Δf_{ci} versus the optical depth $\Delta f_{ci}/\Delta\ln\tau$ and for (ii) partial change $\delta f_{ci}/\delta\ln\tau$ from a multiple regression of Δf_{ci} with $\ln\tau$ and total precipitable water vapor.

	Slope versus τ_{abs}		Intercept for $\tau_{abs} = 0$	
	$\Delta f_{ci}/\Delta\ln\tau$	$\delta f_{ci}/\delta\ln\tau$	$\Delta f_{ci}/\Delta\ln\tau$	$\delta f_{ci}/\delta\ln\tau$
All data	–3.5	–2.6	0.17	0.13
Continental	–3.2	–2.6	0.16	0.13
Coastal	–3.4	–1.9	0.17	0.11
Biomass burning	–4.0	–3.5	0.18	0.14

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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D09207, doi:10.1029/2005JD006686, 2006

Impact of three-dimensional radiative effects on satellite retrievals of cloud droplet sizes

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Received 19 September 2005; revised 16 December 2005; accepted 25 January 2006; published 13 May 2006.

[1] There are several dozen papers that study the effects of cloud horizontal inhomogeneity on the retrievals of cloud optical thickness, but only a few of them deal with cloud droplet sizes. This paper is one of the first comprehensive attempts to fill this gap: It takes a close theoretical look at the radiative effects of cloud 3-D structure in retrievals of droplet effective radii. Under some general assumptions, it was found that ignoring subpixel (unresolved) variability produces a negative bias in the retrieved effective radius, while ignoring cloud inhomogeneity at scales larger than a pixel scale (resolved variability), on the contrary, leads to overestimation of the domain average droplet size. The theoretical results are illustrated with examples from Large Eddy Simulations (LES) of cumulus (Cu) and stratocumulus (Sc) cloud fields. The analysis of cloud drop size distributions retrieved from both LES fields confirms that ignoring shadowing in 1-D retrievals results in substantial overestimation of effective radii which is more pronounced for broken Cu than for Sc clouds. Collocated measurements of broken Cu clouds by Moderate Resolution Imaging Spectrometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) are used to check simulations and theory with observations. The analysis of ASTER and MODIS data and associated derived products recommends against blindly using retrieved effective radii for broken cloud fields, especially if one wants to relate aerosol amounts to cloud droplet sizes.

Citation: Marshak, A., S. Platnick, T. Várnai, G. Wen, and R. F. Cahalan (2006), Impact of three-dimensional radiative effects on satellite retrievals of cloud droplet sizes, *J. Geophys. Res.*, *111*, D09207, doi:10.1029/2005JD006686.

1. Introduction

[2] There are several dozen papers that discuss the radiative effects of cloud three-dimensional (3-D) structure on the one-dimensional (1-D) retrievals of cloud optical thickness [e.g., *Marshak et al.*, 1995; *Loeb and Davies*, 1996; *Chambers et al.*, 1997; *Davis et al.*, 1997; *Loeb and Coakley*, 1998; *Zuidema and Evans*, 1998; *Várnai and Marshak*, 2001, 2002a; *Iwabuchi and Hayasaka*, 2002; *Horváth and Davies*, 2004]. Most of these studies assume a "conventional" 10-μm droplet effective radius and variable cloud optical thickness. Though the operational remote sensing of cloud optical properties from multispectral measurements [*Nakajima and King*, 1990; *Platnick et al.*, 2003] typically retrieves cloud optical thickness and effective radius simultaneously, there are only a few papers that, in addition to cloud optical thickness, estimate the effect of cloud inhomogeneity on 1-D retrievals of the droplet effective radius [*Faure et al.*, 2002; *Cornet et al.*, 2004, 2005; *Várnai and Marshak*, 2002b; *Iwabuchi and Hayasaka*, 2003].

[3] Except for Polarization and Directionality of the Earth's Reflectances (POLDER) that retrieves (though not operationally) cloud droplet effective radius from polarization measurements of the reflected light using "cloudbow" (or rainbow) at scattering angles between 150° and 170° [*Deschamps et al.*, 1994; *Bréon and Goloub*, 1998; *Bréon and Doutriaux-Boucher*, 2005], all operational retrievals of cloud droplet size are based on spectral observations [e.g., *Nakajima and King*, 1990]. For the Moderate Resolution Imaging Spectrometer (MODIS), a pair $\{\tau, r_e\}$ that represents cloud optical thickness and droplet effective radius, respectively, is derived for each cloudy 1 km by 1 km pixel from various two band combinations: typically one bulk water-absorption band {1.6, 2.1, or 3.7 μm} and one nonabsorbing (or relatively nonabsorbing) band {0.65, 0.86, or 1.2 μm} [*Platnick et al.*, 2003]. The choice of nonabsorbing band depends on the underlying surface. Since water absorbs differently in the three MODIS absorbing bands, use of the less absorbing 1.6-μm band and the more absorbing 3.7-μm band complement use of the 2.1-μm band for assessing the vertical variation of droplet size in the

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0148-0227/06/2005JD006686$09.00

Atmos. Chem. Phys., 6, 237–253, 2006
www.atmos-chem-phys.org/acp/6/237/
SRef-ID: 1680-7324/acp/2006-6-237
European Geosciences Union

Atmospheric Chemistry and Physics

Aerosol direct radiative effect at the top of the atmosphere over cloud free ocean derived from four years of MODIS data

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Received: 3 May 2005 – Published in Atmos. Chem. Phys. Discuss.: 18 July 2005
Revised: 11 October 2005 – Accepted: 14 December 2005 – Published: 30 January 2006

Abstract. A four year record of MODIS spaceborne data provides a new measurement tool to assess the aerosol direct radiative effect at the top of the atmosphere. MODIS derives the aerosol optical thickness and microphysical properties from the scattered sunlight at 0.55–2.1 μm. The monthly MODIS data used here are accumulated measurements across a wide range of view and scattering angles and represent the aerosol's spectrally resolved angular properties. We use these data consistently to compute with estimated accuracy of $\pm 0.6\,\mathrm{W\,m^{-2}}$ the reflected sunlight by the aerosol over global oceans in cloud free conditions. The MODIS high spatial resolution (0.5 km) allows observation of the aerosol impact between clouds that can be missed by other sensors with larger footprints. We found that over the clear-sky global ocean the aerosol reflected $5.3\pm0.6\,\mathrm{Wm^{-2}}$ with an average radiative efficiency of $-49\pm2\,\mathrm{Wm^{-2}}$ per unit optical thickness. The seasonal and regional distribution of the aerosol radiative effects are discussed. The analysis adds a new measurement perspective to a climate change problem dominated so far by models.

1 Introduction

Traditionally, chemical transport and general circulation models enjoyed a monopoly on estimating the role of aerosols in the Earth's climate. Model results form the basis of almost every previous estimate of the aerosol effect on climate (IPCC, 2001). Observations of aerosols from ground-based, airborne or satellite instruments are used only to validate these models. The prevailing strategy dictates that measurements improve models, and then models, not measurements, answer climate questions. However, there is a wide range of discrepancy in model results because of the many inherent assumptions involved in modeling the aerosol effect on climate. Models must properly estimate the source terms of the many aerosol species, properly model the aerosol sink terms, and simulate the transport. Even if the model properly simulates the global distribution of aerosol concentration, assumptions have to be made of the aerosol optical properties in order to convert mass concentrations to the radiative fluxes. Because of the complexity of the problem, it is no wonder that the uncertainties in estimating aerosol effects on climate are growing, rather than shrinking.

To narrow the uncertainties associated with estimating aerosol effects on climate, the time has come to include measurement-based estimates of aerosol radiative effects and forcing. With the launch of EOS-Terra carrying the Moderate resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging (MISR) and Clouds and Radiant Energy System (CERES), we are suddenly "data rich". These instruments, along with subsequent instruments on EOS-Aqua, EOS-Aura, ICESat, and Parasol, are designed specifically to observe aerosols and the Earth's radiation budget. They provide global information in a way that previous ground-based or airborne instruments could not, and they provide quantitative information about aerosol that is not only more accurate than our heritage instruments, but also more complete in terms of aerosol characterization. With these increased capabilities, aerosol observations from satellite can provide an independent measure of some key climate parameters in parallel with model predictions.

One key measurement that satellites are able to provide is the direct shortwave radiative effect of aerosols at the top of the atmosphere. By aerosol direct shortwave radiative *effect* we mean the difference in shortwave radiative flux between having aerosols present and having no aerosols at all. This is different from aerosol shortwave direct radiative *forcing*, which is the radiative effect of anthropogenic aerosols only. Analysis suggests that by characterizing aerosol particle size from space, there is information available to the satellites to

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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D06201, doi:10.1029/2005JD006246, 2006

Performance of two cloud-radiation parameterization schemes in the finite volume general circulation model for anomalously wet May and June 2003 over the continental United States and Amazonia

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Received 20 May 2005; revised 18 October 2005; accepted 5 December 2005; published 16 March 2006.

[1] An objective assessment of the impact of a new cloud scheme, called Microphysics of Clouds with Relaxed Arakawa-Schubert Scheme (McRAS) (together with its radiation modules), on the finite volume general circulation model (fvGCM) was made with a set of ensemble forecasts that invoke performance evaluation over both weather and climate timescales. The performance of McRAS (and its radiation modules) was compared with that of the National Center for Atmospheric Research Community Climate Model (NCAR CCM3) cloud scheme (with its NCAR physics radiation). We specifically chose the boreal summer months of May and June 2003, which were characterized by an anomalously wet eastern half of the continental United States as well as northern regions of Amazonia. The evaluation employed an ensemble of 70 daily 10-day forecasts covering the 61 days of the study period. Each forecast was started from the analyzed initial state of the atmosphere and spun-up soil moisture from the first-day forecasts with the model. Monthly statistics of these forecasts with up to 10-day lead time provided a robust estimate of the behavior of the simulated monthly rainfall anomalies. Patterns of simulated versus observed rainfall, 500-hPa heights, and top-of-the-atmosphere net radiation were recast into regional anomaly correlations. The correlations were compared among the simulations with each of the schemes. The results show that fvGCM with McRAS and its radiation package performed discernibly better than the original fvGCM with CCM3 cloud physics plus its radiation package. The McRAS cloud scheme also showed a reasonably positive response to the observed sea surface temperature on mean monthly rainfall fields at different time leads. This analysis represents a method for helpful systematic evaluation prior to selection of a new scheme in a global model.

Citation: Sud, Y. C., D. M. Mocko, and S. J. Lin (2006), Performance of two cloud-radiation parameterization schemes in the finite volume general circulation model for anomalously wet May and June 2003 over the continental United States and Amazonia, *J. Geophys. Res.*, *111*, D06201, doi:10.1029/2005JD006246.

1. Introduction

[2] The decision to replace and/or significantly upgrade an existing physical parameterization scheme, such as cloud physics, in a general circulation model (GCM), with that of a new physically more desirable scheme is always a daunting endeavor because the new scheme may not improve all aspects of the model's simulations. Consequently, the performance of the new scheme must be evaluated on a variety of timescales and space scales through extensive intercomparisons with the old. Since model performance can show discernible variances on weather and climate timescales, performance evaluation on both timescales should be invoked. Moreover, it is well known that some areas of the simulations improve while others get worse; consequently, one often waits until the relatively poor aspects of the simulations are better understood and resolved. A central issue is whether the decision to adopt a new scheme should be solely governed by (1) better representation of the relevant physics and its demonstrated superiority in controlled test bed evaluation scores such as Atmospheric Radiation Measurement–Single Column Model (ARM-SCM) evaluations regardless of the impact on GCM simulations or (2) the positive impact on the GCM simulations as the primary determinant of the intrinsic value of the new scheme. The latter can only be ascertained by quantities such as improvement in skill scores on the key timescales. The second approach guarantees continually improving forecast skill, which is also a pragmatic criterion of model performance for weather and/or climate forecasts [*Phillips et al.*, 2004]. On the other hand, if a parameterization is physically more defensible, i.e., it better represents the physical processes of central importance that were either undermined or poorly represented in the old scheme, the most plausible reasons for less than superior performance of

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0148-0227/06/2005JD006246$09.00

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L21804, doi:10.1029/2006GL027150, 2006

Influence of aerosols on the shortwave cloud radiative forcing from North Pacific oceanic clouds: Results from the Cloud Indirect Forcing Experiment (CIFEX)

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Received 8 June 2006; revised 24 August 2006; accepted 9 October 2006; published 3 November 2006.

[1] Aerosols over the Northeastern Pacific Ocean enhance the cloud drop number concentration and reduce the drop size for marine stratocumulus and cumulus clouds. These microphysical effects result in brighter clouds, as evidenced by a combination of aircraft and satellite observations. In-situ measurements from the Cloud Indirect Forcing Experiment (CIFEX) indicate that the mean cloud drop number concentration in low clouds over the polluted marine boundary layer is greater by 53 cm^{-3} compared to clean clouds, and the mean cloud drop effective radius is smaller by 4 μm. We link these in-situ measurements of cloud modification by aerosols, for the first time, with collocated satellite broadband radiative flux observations from the Clouds and the Earth's Radiant Energy System to show that these microphysical effects of aerosols enhance the top-of-atmosphere cooling by -9.9 ± 4.3 W m^{-2} for overcast conditions. **Citation:** Wilcox, E. M., G. Roberts, and V. Ramanathan (2006), Influence of aerosols on the shortwave cloud radiative forcing from North Pacific oceanic clouds: Results from the Cloud Indirect Forcing Experiment (CIFEX), *Geophys. Res. Lett.*, *33*, L21804, doi:10.1029/2006GL027150.

1. Introduction

[2] The albedo of low clouds will generally increase as the total liquid water path or geometric thickness of the cloud increases. For clouds of equivalent liquid water amount, however, anthropogenic aerosols acting as additional cloud condensation nuclei (CCN) are known to increase the albedo [*Twomey*, 1977; *Coakley et al.*, 1987]. Furthermore, suppression of drizzle may impact the liquid water path and the cloud fraction [*Albrecht*, 1989; *Ackerman et al.*, 2004]. The net radiative forcing of climate attributable to these indirect aerosol effects has been determined primarily using global atmospheric models, and the magnitude remains highly uncertain [*Lohmann and Feichter*, 2005]. This study reports on the influence of aerosol variations on shortwave cloud radiative forcing over the Northeast Pacific Ocean during April 2004 using observations from the Cloud Indirect Forcing Experiment (CIFEX). In-situ measurements document the aerosol influence on cloud microphysics, and satellite observations determine the resulting influence on cloud radiative forcing.

[3] CIFEX was conducted from April 1 to 21, 2004. During 24 flights in the U. of Wyoming King Air aircraft, a full complement of microphysical measurements were made including aerosol number concentration and size distribution (Particle Cavity Aerosol Spectrometer Probe; PCASP), and cloud drop number concentration and size distribution (Forward Scattering Spectrometer Probe; FSSP). Flights were conducted from Arcata, CA (41.0°N, 124.1°W) to approximately 650 km offshore, alternating between 5–10 min. aerosol sampling below cloud base and 5–10 min. cloud sampling below cloud top. Some clouds were profiled from cloud base to cloud top.

[4] Aerosols sampled during CIFEX have been classified based on the aerosol size distribution and back trajectories [*Roberts et al.*, 2006]. The aerosol types include North American aerosols, marine boundary layer aerosols, recently cloud-processed aerosols, and aerosols linked to Asian outflow. Within the Asian air masses, cases of recent new particle formation were found, as well as cases of aged aerosols. Aerosols linked to Asian outflow were found in layers above the boundary layer. Aerosol samples used in this study are limited to those in the boundary layer (below 1500 m). Most of the boundary layer aerosols encountered during CIFEX were composed of cloud-processed and North American continental aerosols.

[5] Cloud systems observed during CIFEX were predominantly stratocumulus and broken cumulus; some precipitating cumulus and mixed-phase clouds were also encountered. Under pristine conditions, low clouds were frequently observed to be drizzling.

[6] In this study we seek to document the impact of elevated concentrations of aerosol particles coincident with low clouds on the number concentration and size of cloud drops, as well as the resulting impact on shortwave cloud radiative forcing as determined by satellite albedo measurements from broadband radiometer observations. We advance a methodology that provides a quantitative measure of the enhanced shortwave cooling owing to the first aerosol indirect effect (the Twomey effect).

[7] Measurements of cloud drop number concentration (N_d), effective radius (r_{eff}) and albedo (α) are sorted according to the number concentration of aerosol particles (N_a) in the 0.1–3.0 μm diameter range as determined from the PCASP instrument, and evaluated as a function of cloud liquid water path (*LWP*) from the AMSR-E microwave radiometer on the Aqua satellite (F. Wentz and T. Meissner, AMSR-E/Aqua L2B Global Swath Ocean Products derived from Wentz Algorithm V001, March to June 2004, http://nsidc.org/data/ae_ocean.html). Albedo is observed from the Clouds and the Earth's Radiant Energy System (CERES) instrument [*Wielicki et al.*, 1996], which is also mounted on

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0094-8276/06/2006GL027150$05.00

Tellus (2006), 58B, 463–475
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TELLUS

A test of sensitivity to convective transport in a global atmospheric CO_2 simulation

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(Manuscript received 9 January 2006; in final form 3 July 2006)

ABSTRACT

Two approximations to convective transport have been implemented in an offline chemistry transport model (CTM) to explore the impact on calculated atmospheric CO_2 distributions. Global CO_2 in the year 2000 is simulated using the CTM driven by assimilated meteorological fields from the NASA's Goddard Earth Observation System Data Assimilation System, Version 4 (GEOS-4). The model simulates atmospheric CO_2 by adopting the same CO_2 emission inventory and dynamical modules as described in Kawa et al. (convective transport scheme denoted as Conv1). Conv1 approximates the convective transport by using the bulk convective mass fluxes to redistribute trace gases. The alternate approximation, Conv2, partitions fluxes into updraft and downdraft, as well as into entrainment and detrainment, and has potential to yield a more realistic simulation of vertical redistribution through deep convection. Replacing Conv1 by Conv2 results in an overestimate of CO_2 over biospheric sink regions. The largest discrepancies result in a CO_2 difference of about 7.8 ppm in the July NH boreal forest, which is about 30% of the CO_2 seasonality for that area. These differences are compared to those produced by emission scenario variations constrained by the framework of Intergovernmental Panel on Climate Change (IPCC) to account for possible land use change and residual terrestrial CO_2 sink. It is shown that the overestimated CO_2 driven by Conv2 can be offset by introducing these supplemental emissions.

1. Introduction

The importance of characterizing transport error in forward models has been widely recognized, and substantial effort has been devoted to quantifying such error (e.g. Denning et al., 1999; Engelen et al., 2002; Palmer et al., 2003). Tropospheric constituent transport occurs by advective, diffusive and convective processes and inadequacies in any of these mechanisms will lead to error in simulated trace gas concentrations. The primary goal of this study is to explore the extent to which the treatment of convective transport impacts the atmospheric CO_2 distribution. The study uses a chemistry transport model (CTM) with specified surface flux distributions and perturbs the representation of convective transport in this system, while all other processes are held fixed. The two approximations to convective transport are referred to as Conv1 and Conv2. Following Kawa et al. (2004), Conv1 uses a constraint of the total convective mass flux (CMF), in which air parcels entrained at cloud base are transported upwards, detraining at a rate proportional to the convergence of CMF. Conv2 is a potentially more accurate approximation, using information on updraft and downdraft, as well as entrainment and detrainment rates; this allows for air parcels to be ventilated within the entire cloud ensemble and also to enter or leave the cloud environment at any altitude, subject to the same constraints on total CMF. All fields used were archived as 3 h averages from the Goddard Earth Observation System Version 4 (GEOS-4) data assimilation system (Bloom et al., 2005). Hence, the two algorithms represent cloud convective transport from a very simple to a relatively complex form. The uncertainty induced by them will represent one term in the potential cloud convection error. We will further identify regions where mixing ratios are sensitive to atmospheric convection, with an overall goal to assist regional carbon cycle simulation. This study complements a number of other approaches to quantifying transport uncertainty, in at least two ways.

First, several studies have attempted to quantify the differences between atmospheric transport using different algorithms of atmospheric convection. Mahowald et al. (1995) used a column model to quantify transport differences among seven different cumulus convection parameterizations, illustrating vastly different results that are sensitive to aspects of 'closure' (the criteria used to determine onset of convection, dependent on some

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DOI: 10.1111/j.1600-0889.2006.00212.x

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 44, NO. 5, MAY 2006

Algorithm for NO_2 Vertical Column Retrieval From the Ozone Monitoring Instrument

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***Abstract*—We describe the operational algorithm for the retrieval of stratospheric, tropospheric, and total column densities of nitrogen dioxide (NO_2) from earthshine radiances measured by the Ozone Monitoring Instrument (OMI), aboard the EOS-Aura satellite. The algorithm uses the DOAS method for the retrieval of slant column NO_2 densities. Air mass factors (AMFs) calculated from a stratospheric NO_2 profile are used to make initial estimates of the vertical column density. Using data collected over a 24-h period, a smooth estimate of the global stratospheric field is constructed. Where the initial vertical column densities exceed the estimated stratospheric field, we infer the presence of tropospheric NO_2, and recalculate the vertical column density (VCD) using an AMF calculated from an assumed tropospheric NO_2 profile. The parameters that control the operational algorithm were selected with the aid of a set of data assembled from stratospheric and tropospheric chemical transport models. We apply the optimized algorithm to OMI data and present global maps of NO_2 VCDs for the first time.**

***Index Terms*—Algorithm, nitrogen dioxide (NO_2), Ozone Monitoring Instrument (OMI), troposphere.**

I. INTRODUCTION

MEASUREMENTS of nitrogen dioxide (NO_2) are important to the understanding of tropospheric and stratospheric chemistry, particularly in relation to ozone production and loss. NO_2 takes part in catalytic destruction of ozone in the stratosphere [1], and anthropogenic NO_2 emissions are precursors for tropospheric ozone production, largely through reactions with hydrocarbons, e.g., [2]. Brewer *et al.* [3] made the first ground-based measurements of stratospheric NO_2, and extensive analysis of stratospheric NO_2 behavior and distribution was undertaken by Noxon [4]–[6], [45] and Solomon and Garcia [7]. Data from the Global Ozone Monitoring Experiment (GOME), deployed in 1995, have been used to retrieve global NO_2 column amounts, which have been used to study the behavior of stratospheric NO_2 [8]. Early results from GOME, showing enhanced NO_2 over the populated areas of the Eastern United States and Europe, were presented by Burrows *et al.* [9], who attributed the enhancements to urban tropospheric pollution. Leue *et al.* [10] and Richter and Burrows [11] attempted to quantify the tropospheric amounts. Comparisons between GOME tropospheric NO_2 and models have been carried out by Velders *et al.* [12], Martin *et al.* [13], Lauer *et al.* [14], and Heland *et al.* [15] made the first comparisons with *in situ* aircraft measurements. A new generation of satellite instruments now provides measurements of trace gases, including NO_2, at spatial resolutions that exceed GOME resolutions by factors of seven or more. One of these is the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) [16]. Martin *et al.* [17] have recently analyzed SCIAMACHY NO_2 data along with aircraft measurements to constrain NO_x emission inventories. The Ozone Monitoring Instrument (OMI), on the Earth Observing System (EOS) Aura satellite, has better spatial and temporal resolution than SCIAMACHY and is the subject of the current study.

Satellite-based Earth radiance measurements yield trace gas slant column densities (SCDs), which depend on not only the density of the gas, but on numerous other measurement parameters. Since the quantity of interest is the vertical column density (VCD), one must convert the SCD into the VCD by dividing the SCD by the *air mass factor* (AMF). The AMFs are calculated using radiative transfer models that account for optical geometry, surface reflectivity, cloud and aerosol properties, and the vertical distribution of the absorbing trace gas. For optically thin trace gases in the stratosphere and upper troposphere, the AMF depends almost entirely on the geometry alone. In the case of NO_2, which is a weak absorber and not widely distributed in the troposphere, a stratospheric AMF can be used to obtain a first-order approximation of the VCD. However, although this method is valid over much of the Earth, it underestimates total column densities in areas with significant boundary layer NO_2. Thus, more accurate analyzes of satellite NO_2 data require subtraction of the estimated stratospheric NO_2 before evaluation of the tropospheric component. Variations on this general approach have been used effectively with GOME data [10]–[13]. The correction procedures consist of two steps: 1) recognition of geographic regions that contain significant tropospheric pollution and 2) accurate evaluation of the AMF in these polluted regions. We present the considerations involved in both of these steps.

Algorithms to identify polluted regions have relied on the fact that most tropospheric NO_2 enhancements occur over land and industrially developed regions and that geographic variation in the tropospheric NO_2 occurs on smaller distance scales than that of stratospheric NO_2. Many investigators [11], [13], [14] use the *reference sector method*, in which the stratospheric component of the NO_2 column in any latitude band is approximated by the total NO_2 column value at the corresponding latitude in

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Manuscript received April 29, 2005; revised October 27, 2005.

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Digital Object Identifier 10.1109/TGRS.2005.863715

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D05304, doi:10.1029/2005JD006585, 2006

Measurements of nitrogen dioxide total column amounts using a Brewer double spectrophotometer in direct Sun mode

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Received 12 August 2005; revised 1 November 2005; accepted 23 November 2005; published 2 March 2006.

[1] NO_2 column amounts were measured for the past 2 years at Goddard Space Flight Center, Greenbelt, Maryland, using a Brewer spectrometer in direct Sun mode. A new "bootstrap" method to calibrate the instrument is introduced and described. This technique selects the cleanest days from the database to obtain the solar reference spectrum. The main advantage for direct Sun measurements is that the conversion uncertainty from slant column to vertical column is negligible compared to the standard scattered light observations where it is typically on the order of 100% (2σ) at polluted sites. The total 2σ errors of the direct Sun retrieved column amounts decrease with solar zenith angle and are estimated at 0.2 to 0.6 Dobson units (DU, 1 DU $\approx 2.7 \times 10^{16}$ molecules cm^{-2}), which is more accurate than scattered light measurements for high NO_2 amounts. Measured NO_2 column amounts, ranging from 0 to 3 DU with a mean of 0.7 DU, show a pronounced daily course and a strong variability from day to day. The NO_2 concentration typically increases from sunrise to noon. In the afternoon it decreases in summer and stays constant in winter. As expected from the anthropogenic nature of its source, NO_2 amounts on weekends are significantly reduced. The measurements were compared to satellite retrievals from Scanning Image Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY). Satellite data give the same average NO_2 column and show a seasonal cycle that is similar to the ground data in the afternoon. We show that NO_2 must be considered when retrieving aerosol absorption properties, especially for situations with low aerosol optical depth.

Citation: Cede, A., J. Herman, A. Richter, N. Krotkov, and J. Burrows (2006), Measurements of nitrogen dioxide total column amounts using a Brewer double spectrophotometer in direct Sun mode, *J. Geophys. Res.*, *111*, D05304, doi:10.1029/2005JD006585.

1. Introduction

[2] Nitrogen dioxide (NO_2) is a key species in the chemistry of both the stratosphere and troposphere. It is one of the most important ozone precursors in the troposphere and locally also contributes to radiative forcing [*Solomon et al.*, 1999]. In addition, it is known to cause human respiratory problems [e.g., *Environmental Protection Agency*, 1998]. The majority of atmospheric NO_2 is produced by anthropogenic sources. Industry and traffic produce about 50%, and biomass burning is estimated to contribute about 20%. Other important sources are lightning (~10%) and emissions from soil (~15%) [*Lee et al.*, 1997]. Stratospheric NO_2 shows a diurnal cycle with maximum concentrations around sunset and a seasonal cycle with maxima in summer and larger abundance at midlatitudes and high latitudes than in the tropics [*Noxon*, 1979; *Van Roozendael et al.*, 1997; *Liley et al.*, 2000]. In midlatitudes the stratospheric column of NO_2 varies roughly between 0.05 and 0.25 Dobson units (DU); 1 DU corresponds to a column density of $\sim 2.7 \times 10^{16}$ cm^{-2}. Quantity and temporal behavior of tropospheric NO_2 are less known. Column amounts of tropospheric NO_2 between 0 and more than 2 DU have been estimated from ground-based column measurements [*Brewer et al.*, 1973], from satellite retrievals [*Richter and Burrows*, 2002], and from in situ measurements converted into column amounts by means of chemical transport models [*Petritoli et al.*, 2004; *Ordóñez et al.*, 2006]. Satellite data, in situ measurements, and calculations with chemical transport models show seasonal cycles of tropospheric NO_2 with maximum amounts in winter [*Velders et al.*, 2001; *Petritoli et al.*, 2004; *Ordóñez et al.*, 2006].

[3] Remote sensing measurements of atmospheric NO_2 from the ground are usually performed using differential optical absorption spectroscopy (DOAS) [*Platt*, 1994] of scattered sunlight. In this technique the spectral sky radiance is measured, and the slant column density of the

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0148-0227/06/2005JD006585$09.00

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Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 65–77

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Spectral measurements of PMCs from SBUV/2 instruments

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Abstract

The SBUV/2 (Solar Backscattered Ultraviolet, model 2) instrument is designed to monitor ozone stratospheric profile and total column ozone using measurements of the Earth's backscattered ultraviolet albedo. We have previously demonstrated that the normal radiance measurements from SBUV/2 instruments, which sample 12 discrete wavelengths between 252 and 340 nm during each scan, can be used to identify polar mesospheric clouds (PMCs). Some SBUV/2 instruments also periodically view the earth in continuous scan mode, covering the wavelength range 160–400 nm with 0.15 nm sampling. Analysis of these data show PMC occurrence rates similar to the normal discrete scan results, although the observation technique reduces the number of daily measurements by a factor of six. PMC observed by SBUV/2 instruments show a monotonic variation in the residual spectral albedo over the wavelength range 250–300 nm, with maximum enhancements of 10–15% at 250 nm. This result is consistent with microphysical model predictions from Jensen [1989.A numerical model of polar mesospheric cloud formation and evolution, Ph. D. Thesis, University of Colorado]. We find no evidence for a systematic localized increase in PMC residual albedo for wavelengths near 260 nm, in contrast to the recently reported results from the MSX UVISI instrument [Carbary J.F., et al., 2004. Evidence for bimodal particle distribution from the spectra of polar mesospheric clouds. Geophysics Research. Letters 31, L13108]. This result is observed for three different SBUV/2 instruments in both Northern and Southern Hemisphere data over a 13-year span. Our Mie scattering calculations show that the location and magnitude of the 260 nm "hump" feature is dependent upon the specific scattering angles appropriate to the MSX measurements. Although it explains the MSX spectrum, the bimodal size distribution proposed by Carbary et al. (2004), cannot explain the lack of scattering angle dependence of the SBUV/2 spectral shapes. The spectral signature of the SBUV/2 continuous scan PMC data is thus inconsistent with the bimodal particle size distribution suggested by Carbary et al. (2004).

Keywords: Polar mesospheric cloud; PMC; Noctilucent cloud; Remote sensing; Scattering

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1. Introduction

Polar mesospheric clouds (PMCs), also known as noctilucent clouds, are optically thin clouds that are formed at extremely high altitudes (80–85 km). PMCs are normally observed only at high latitudes (>55°) in each hemisphere, during a limited season

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doi:10.1016/j.jastp.2005.08.006

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L17809, doi:10.1029/2006GL026492, 2006

Sensitivity of Arctic ozone loss to polar stratospheric cloud volume and chlorine and bromine loading in a chemistry and transport model

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Received 4 April 2006; revised 6 July 2006; accepted 1 August 2006; published 9 September 2006.

[1] The sensitivity of Arctic ozone loss to polar stratospheric cloud volume (V_{PSC}) and chlorine and bromine loading is explored using chemistry and transport models (CTMs). One simulation uses multi-decadal winds and temperatures from a general circulation model (GCM). Winter polar ozone loss depends on both equivalent effective stratospheric chlorine (EESC) and polar vortex characteristics (temperatures, descent, isolation, polar stratospheric cloud amount). The simulation reproduces a linear relationship between ozone loss and V_{PSC} in agreement with that derived from observations for 1992–2003. The relationship holds for EESC within ∼85% of its maximum (∼1990–2020). For lower EESC the ozone loss varies linearly with EESC unless $V_{PSC} \sim 0$. A second simulation recycles a single year's winds and temperatures from the GCM so that polar ozone loss depends only on changes in EESC. This simulation shows that ozone loss varies linearly with EESC for the entire EESC range for constant, high V_{PSC}. **Citation:** Douglass, A. R., R. S. Stolarski, S. E. Strahan, and B. C. Polansky (2006), Sensitivity of Arctic ozone loss to polar stratospheric cloud volume and chlorine and bromine loading in a chemistry and transport model, *Geophys. Res. Lett.*, *33*, L17809, doi:10.1029/2006GL026492.

1. Introduction

[2] *Rex et al.* [2004] (hereinafter referred to as R2004) report a linear relationship between winter-spring loss of Arctic ozone and the volume of polar stratospheric clouds (PSCs). R2004 used data for 10 winters between 1992 and 2003, a period when inorganic chlorine in the upper stratosphere was close to its maximum. R2004 suggest this relationship as an element of Chemistry Climate Model (CCM) evaluation and point out that additional stratospheric cooling could lead to more PSCs and additional polar ozone loss. Chemistry and transport models (CTMs) are driven by input meteorological fields and ignore feedback processes that are included in CCMs, but still should reproduce this relationship. R2004 show that the sensitivity of polar ozone loss to the volume of PSCs (V_{PSC}) in a version of the SLIMCAT CTM, driven by meteorological fields from the United Kingdom Meteorological Office UKMO, is less than that derived from observations. *Chipperfield et al.* [2005] show that a modified version of SLIMCAT reproduces the observed relationship.

[3] Here we focus on simulations using the GSFC CTM driven by meteorological output from a General Circulation Model (GCM). *Stolarski et al.* [2006] show that simulated mean total ozone for 60°S–60°N reproduces many aspects of Total Ozone Mapping Spectrometer observations. Here we show the realism of the simulated polar vortex by comparing N_2O and its horizontal gradients with N_2O observed by the Microwave Limb Sounder (MLS) on NASA's Aura satellite [*Waters et al.*, 2006]. We show that the sensitivity of simulated winter chemical loss of ozone to V_{PSC} follows the R2004 relationship for 1990–2020, years when the equivalent effective stratospheric chlorine (EESC), i.e., chlorine and bromine available in the stratosphere to destroy ozone, is within 85% of its maximum. This simulation used standard photochemical input data and a standard scenario for chlorine and bromine source gases. We also investigate the dependence of polar ozone loss on EESC for fixed V_{PSC}.

[4] Simulations use the GSFC CTM and the Global Modeling Initiative (GMI) CTM [*Douglass et al.*, 2004], described in Section 2. Section 3 shows comparisons with N_2O to support the realism of the simulated polar vortex and verifies the method used to account for the ozone increase due to transport. Results are presented in section 4 followed by discussion and conclusions.

2. Chemistry and Transport Models

[5] *Stolarski et al.* [2006] describe the GSFC CTM and the primary simulation used here. Meteorological fields from a 50-year integration of the GEOS-4 GCM (Goddard Earth Observing System, Version 4, General Circulation Model) are input to the CTM. The GCM and its implementation are described elsewhere [*Stolarski et al.*, 2006, and references therein]. Aspects of the CTM important to this analysis follow. Rate constant data and cross sections are taken from JPL Evaluation 14 [*Sander et al.*, 2003] (hereinafter referred to as JPL2003). The polar stratospheric cloud parameterization follows *Considine et al.* [2000] and accounts for denitrification through PSC sedimentation. The *Lin and Rood* [1996] constituent transport scheme is used. The horizontal grid is 2.5° longitude and 2° latitude. The 28 vertical levels between the surface and 0.4 hPa use a terrain following coordinate in the troposphere and pressure above the interface at 247 hPa. Vertical spacing is about 1 km near the tropopause and increases to 4 km near the upper boundary. Surface boundary conditions for source gases including CFCs, halons, methane and nitrous oxide are specified from Scenario A2 in Appendix 4B of the Scientific Assessment of Ozone Depletion: 2002 [*World Meteorological Organization*, 2003].

[6] A second simulation investigates the dependence of ozone loss on EESC for fixed V_{PSC}. The Global Modeling

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0094-8276/06/2006GL026492$05.00

1272 IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 44, NO. 5, MAY 2006

First Results From the OMI Rotational Raman Scattering Cloud Pressure Algorithm

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***Abstract*—We have developed an algorithm to retrieve scattering cloud pressures and other cloud properties with the Aura Ozone Monitoring Instrument (OMI). The scattering cloud pressure is retrieved using the effects of rotational Raman scattering (RRS). It is defined as the pressure of a Lambertian surface that would produce the observed amount of RRS consistent with the derived reflectivity of that surface. The independent pixel approximation is used in conjunction with the Lambertian-equivalent reflectivity model to provide an effective radiative cloud fraction and scattering pressure in the presence of broken or thin cloud. The derived cloud pressures will enable accurate retrievals of trace gas mixing ratios, including ozone, in the troposphere within and above clouds. We describe details of the algorithm that will be used for the first release of these products. We compare our scattering cloud pressures with cloud-top pressures and other cloud properties from the Aqua Moderate-Resolution Imaging Spectroradiometer (MODIS) instrument. OMI and MODIS are part of the so-called A-train satellites flying in formation within 30 min of each other. Differences between OMI and MODIS are expected because the MODIS observations in the thermal infrared are more sensitive to the cloud top whereas the backscattered photons in the ultraviolet can penetrate deeper into clouds. Radiative transfer calculations are consistent with the observed differences. The OMI cloud pressures are shown to be correlated with the cirrus reflectance. This relationship indicates that OMI can probe through thin or moderately thick cirrus to lower lying water clouds.**

***Index Terms*—Cloud, Raman, retrieval, scattering.**

I. INTRODUCTION

PART OF THE mission of the Ozone Monitoring Instrument (OMI) [1] on NASA's Earth Observing System (EOS) Aura satellite is to continue the 25-year record of high-quality total column ozone retrievals from the total ozone mapping spectrometer (TOMS). The higher spectral and spatial resolution, coverage, and sampling of OMI, as compared with TOMS will allow for improved ozone retrievals, including estimates of tropospheric ozone as well as retrievals of other trace gases such as SO_2, NO_2, BrO, and HCHO [2].

The retrieval of tropospheric ozone has been accomplished with TOMS using cloud-slicing techniques [3], [4]. These methods have been previously implemented using cloud-top pressures derived from thermal infrared (IR) measurements or other assumptions about clouds, e.g., that some highly reflecting clouds either reach close to the tropopause or contain very little tropospheric ozone within and above them. A similar approach [5] has been used with data from the Global Ozone Monitoring Experiment (GOME) [6] aboard the European Space Agency's (ESA) Second European Remote Sensing Satellite (ERS-2). In that work, cloud pressures were derived simultaneously with GOME using measurements in the oxygen A-band [7], and it was shown that most convective cloud pressures were between 300 and 500 hPa and do not extend to the tropical tropopause.

Using cloud pressures derived from simultaneous ultraviolet (UV) observations in place of climatological IR cloud-top pressures improves estimates of the above-cloud column ozone [8]. Therefore, it is reasonable to assume that estimates of tropospheric ozone from cloud-slicing will also be improved by using simultaneous measurements in the UV.

Cloud pressures can be retrieved with OMI using either atmospheric rotational Raman scattering (RRS) in the UV [9] or O_2-O_2 absorption near 477 nm [10]. Both techniques are based on the fact that clouds screen the atmosphere below them from satellite observations. Therefore, clouds reduce the amount of RRS or O_2-O_2 absorption seen by satellite-borne instruments. Both approaches are being pursued with OMI data. Here, we focus on the RRS retrieval algorithm.

RRS is an inelastic component of molecular scattering in the atmosphere that produces photons that differ in frequency from the incident light. The frequency difference is related to rotational properties of O_2 and N_2 molecules. Approximately 4% of total scattered energy is contained in the RRS lines. The RRS energy is transferred to both longer wavelengths (Stokes lines) and shorter wavelengths (anti-Stokes lines). The RRS wavelength shifts in the UV are of the order of 2 nm.

RRS produces filling-in (depletion) of solar Fraunhofer lines cores (wings). This filling-in, also known as the Ring effect, was first observed in ground-based measurements [11] and later in satellite backscatter observations (e.g., [12]). The Ring effect is present throughout the ultraviolet.

The concept of retrieving cloud pressure using properties of RRS was first demonstrated in [13] using a Lambertian-equivalent reflectivity (LER) cloud model. Later, de Beek *et al.* [14] showed that holding all else constant, the amount of filling-in decreases with increasing cloud optical thickness (τ) for $\tau <\sim 50$ and saturates for $\tau > 50$. The filling-in computed using their Mie scattering radiative transfer model compared well with ground-based measurements and satellite-based observations from GOME.

Joiner *et al.* [9] refined the approach of retrieving a scattering cloud pressure using the LER model with a spectral fitting algorithm and high-spectral resolution GOME measurements.

Manuscript received January 20, 2005; revised November 18, 2005. This work was supported by NASA through funding for the EOS Aura OMI science team.

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Digital Object Identifier 10.1109/TGRS.2005.861385

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L05812, doi:10.1029/2005GL025650, 2006

QBO as potential amplifier of solar cycle influence

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Received 29 December 2005; accepted 17 January 2006; published 10 March 2006.

[1] The solar cycle (SC) effect in the lower atmosphere has been linked observationally to the quasi-biennial oscillation (QBO) of the zonal circulation. Salby and Callaghan (2000) in particular analyzed the QBO covering more than 40 years and found that it contains a large SC signature at 20 km. We discuss a 3D study in which we simulate the QBO under the influence of the SC. For a SC period of 10 years, the relative amplitude of radiative forcing is taken to vary with height: 0.2% (surface), 2% (50 km), 20% (100 km and above). This model produces in the lower stratosphere a relatively large modulation of the QBO, which appears to come from the SC and qualitatively agrees with the observations. The modulation of the QBO, with constant phase relative to the SC, is shown to persist at least for 50 years, and it is induced by a SC modulated annual oscillation that is hemispherically symmetric and confined to low latitudes (Mayr et al., 2005). **Citation:** Mayr, H. G., J. G. Mengel, C. L. Wolff, and H. S. Porter (2006), QBO as potential amplifier of solar cycle influence, *Geophys. Res. Lett.*, *33*, L05812, doi:10.1029/2005GL025650.

1. Introduction

[2] *Labitzke* [1982, 1987] and *Labitzke and Van Loon* [1988, 1992] discovered that the temperatures at northern polar latitudes in winter are positively and negatively correlated with the solar cycle (SC) when the quasi-biennial oscillation (QBO) of the zonal circulation is in its negative and positive phase respectively. At mid-latitudes they observed opposite correlations. *Dunkerton and Baldwin* [1992] and *Baldwin and Dunkerton* [1998] found evidence of a quasi-decadal oscillation correlated with the QBO and SC.

[3] *Salby and Callaghan* [2000] analyzed the 40-year record of the observed QBO zonal winds at about 20 km altitude. The power spectrum in their Figure 1 shows a sharp peak at 0.41 cycles per year (cpy), corresponding to a QBO period of about 29 months. Smaller neighboring maxima in the spectrum at 0.5 and 0.59 cpy reveal difference frequencies that represent the 11-year SC modulation of the QBO and its second harmonic of 5.5 years. To isolate the SC signature, Salby and Callaghan synthesized the QBO with its spectral side-lobes. It shows that, correlated with the SC, the wind power at 20 km varies from about 150 to 400 m^2/s^2, corresponding to a large variation in the winds from about 12 to 20 m/s. Analyzing 50 years of wind observations, *Hamilton* [2002] confirmed the quasi-decadal modulation inferred by Salby and Callaghan but concluded that the connection to the SC is not as clear in the extended data record.

[4] The observations by *Salby and Callaghan* [2000] were the stimulus for the 3D modeling study discussed here, in which we simulate the SC modulation of the QBO.

2. Wave Driven Quasi-Biennial Oscillation (QBO)

[5] The QBO, with periods between 22 and 34 months and reviewed by *Baldwin et al.* [2001], is confined to low latitudes where it dominates the zonal circulation of the lower stratosphere. Associated with the QBO is the semiannual oscillation (SAO), which dominates the equatorial circulation of the upper stratosphere and mesosphere [*Hirota*, 1980]. It was demonstrated by *Lindzen and Holton* [1968], *Holton and Lindzen* [1972], and others [e.g., *Plumb*, 1977; *Dunkerton*, 1985] for the QBO, and by *Dunkerton* [1979] and *Hamilton* [1986] for the SAO, that these equatorial oscillations can be driven by planetary waves. More recently, modeling studies with observed planetary waves have led to the conclusion that small-scale gravity waves (GW) appear to be more important [e.g., *Hitchman and Leovy*, 1988]. Except for a few attempts at simulating the QBO with resolved GWs [e.g., *Takahashi*, 1999], these waves need to be parameterized for global-scale models [e.g., *Giorgetta et al.*, 2002]. Applying the GW parameterization of *Hines* [1997a, 1997b], we were among the first to reproduce with our Numerical Spectral Model (NSM) the QBO and SAO [e.g., *Mengel et al.*, 1995; *Mayr et al.*, 1997]. In agreement with our model results, the analysis of *Haynes* [1998] showed how a globally uniform wave source can generate the zonal circulation of the QBO confined to low latitudes as observed.

[6] The QBO amplitude and its period are strongly influenced by external time dependent forcing. In the seminal theory for the QBO by *Lindzen and Holton* [1968], the seasonal cycle and resulting SAO were invoked to seed, and thereby influence the QBO. This influence was confirmed with a 2D study [*Mayr et al.*, 1998], where QBO like oscillations were generated, (a) for perpetual equinox and (b) with the seasonal cycle of solar heating. The seasonal cycle lengthened the period of the QBO from 17 to 21 months and more than doubled its amplitude in the lower stratosphere.

[7] Driven by waves, but strongly influenced by the seasonal variations, the QBO then could be affected significantly also by the SC whose signature then would extend to lower altitudes. Two factors are important for this. First, at equatorial latitudes where the Coriolis force vanishes, the wave source accelerates primarily the zonal winds without

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0094-8276/06/2005GL025650$05.00

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L12814, doi:10.1029/2005GL025232, 2006

When will the Antarctic ozone hole recover?

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Received 20 December 2005; revised 9 May 2006; accepted 22 May 2006; published 30 June 2006.

[1] The Antarctic ozone hole demonstrates large-scale, man-made affects on our atmosphere. Surface observations now show that human produced ozone-depleting substances (ODSs) are declining. The ozone hole should soon start to diminish because of this decline. We demonstrate a parametric model of ozone hole area that is based upon a new algorithm for estimating chlorine and bromine levels over Antarctica and late spring Antarctic stratospheric temperatures. This model explains 95% of the ozone hole area's variance. We then use future ODS levels to predict ozone hole recovery. Full recovery to 1980 levels will occur around 2068 and the area will very slowly decline between 2001 and 2017. Detection of a statistically significant decrease of area will not occur until about 2024. We further show that nominal Antarctic stratospheric greenhouse gas forced temperature change should have a small impact on the ozone hole. **Citation:** Newman, P. A., E. R. Nash, S. R. Kawa, S. A. Montzka, and S. M. Schauffler (2006), When will the Antarctic ozone hole recover?, *Geophys. Res. Lett.*, *33*, L12814, doi:10.1029/2005GL025232.

1. Introduction

[2] As ozone-depleting substances (ODSs) decline, full ozone hole recovery over Antarctica is expected about 2050 [*Hofmann et al.*, 1997; *World Meteorological Organization* (*WMO*), 2003]. *Hofmann et al.* [1997] fit ozone with ODS amounts over 12–20 km to estimate the recovery date. *WMO* [2003] estimated recovery based upon an ensemble of three-dimensional (3-D) models. Ozone recovery is expected in three phases: 1) a cessation of ozone decline, 2) a turnaround where ozone begins to increase, and 3) full recovery to 1980 levels. We define, for the ozone hole, phase 1 as a cessation of the growth of the ozone hole area, phase 2 as the year of peak area, and phase 3 as the date when the ozone hole has zero area.

[3] Recent analyses have shown that the ozone hole has entered this first phase of recovery because it is no longer growing [*Newman et al.*, 2004; *Huck et al.*, 2005; *Yang et al.*, 2005]. These analyses are based upon empirical fits of ozone hole diagnostics to effective equivalent stratospheric chlorine (EESC) and stratospheric temperatures. EESC is a convenient measure of ozone depleting stratospheric chlorine (Cl) and bromine (Br) levels that is estimated from ground-based measurements of halocarbons with assumptions about transit times into the stratosphere and rates at which halocarbons become destroyed in the stratosphere [*Prather and Watson*, 1990; *Daniel et al.*, 1995; *Montzka et al.*, 1999; *World Meteorological Organization* (*WMO*), 1999].

[4] This paper describes an estimate of the ozone hole's future based upon a parametric fit of the ozone hole's area to Cl and Br abundances and stratospheric temperature during the past 25 years.

2. Ozone Hole Area

[5] The ozone hole over Antarctica expanded rapidly in the 1980s, but that expansion slowed in the early 1990s, and appears to have stopped in the last few years. Figure 1 shows Total Ozone Mapping Spectrometer (TOMS) observed average ozone hole area (gray line). The area is determined from version 8 TOMS data for 21–30 September 1979–2004 (TOMS was not operational in 1995) and Ozone Monitoring Instrument data in 2005. The area is contained by the 220-DU contour in the Antarctic region. Values below this represent anthropogenic ozone losses over Antarctica [*Newman et al.*, 2004]. The ozone hole peak occurs during 21–30 September, prior to the late spring breakup when Antarctica is fully illuminated. Large area variations result from variations of stratospheric dynamics.

[6] While vortex collar ozone losses are driven primarily by the abundance of reactive Cl and Br species derived from ODSs [*Anderson et al.*, 1991], the temperature of the polar vortex collar region has a secondary impact on ozone-hole area [*Newman et al.*, 2004]. While Antarctic meteorological analyses are observationally derived, multidecadal observations of ODSs, and inorganic Cl and Br levels over Antarctica are unavailable. Therefore, it is necessary to estimate Cl and Br inside the stratospheric polar vortex from trace-gas measurements at Earth's surface and consideration of atmospheric mixing. *Newman et al.* [2004] fit ozone-hole area using polar vortex collar temperature and an estimate of EESC with a 6-year lag to account for the delay of ODSs and their products to arrive over Antarctica. They showed that the ozone hole is decreasing quite slowly because of the slow decrease of ODSs.

3. Estimates of Inorganic Chlorine and Bromine Abundances in the Stratosphere

[7] The gases that cause ozone loss (e.g., chlorofluorocarbons or CFCs and other gases) are released at Earth's surface, and are then carried from the troposphere into the stratosphere in the tropics. The Brewer-Dobson circulation transports these chemicals upward through the stratosphere and mesosphere in the tropics and subtropics and then

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0094-8276/06/2005GL025232$05.00

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L21805, doi:10.1029/2006GL026820, 2006

An ozone increase in the Antarctic summer stratosphere: A dynamical response to the ozone hole

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Received 5 May 2006; revised 31 August 2006; accepted 19 September 2006; published 7 November 2006.

[1] Profiles of ozone concentration retrieved from the SBUV series of satellites show an increase between 1979 and 1997 in the summertime Antarctic middle stratosphere (~25–10 hPa). Data over the South Pole from ozone sondes confirm the increase. A similar ozone increase is produced in a chemistry climate model that allows feedback between constituent changes and the stratospheric circulation through radiative heating. A simulation that excludes the radiative coupling between predicted ozone and the circulation does not capture this ozone increase. We show that the ozone increase in our model simulations is caused by a dynamical feedback in response to the changes in the stratospheric wind fields forced by the radiative perturbation associated with the Antarctic ozone hole. **Citation:** Stolarski, R. S., A. R. Douglass, M. Gupta, P. A. Newman, S. Pawson, M. R. Schoeberl, and J. E. Nielsen (2006), An ozone increase in the Antarctic summer stratosphere: A dynamical response to the ozone hole, *Geophys. Res. Lett.*, *33*, L21805, doi:10.1029/2006GL026820.

1. Introduction

[2] The ozone loss leading to the Antarctic ozone hole has been observed to occur during springtime, in the lower stratosphere, between altitudes of about 12 and 22 kilometers (~150–25 hPa) [*Hofmann et al.*, 1997]. This paper examines the seasonal variation of ozone trends in the 25–10 hPa layer using data from the Solar Backscatter Ultraviolet (SBUV) series of instruments and from ozone sondes launched from the South Pole station. Time series analysis of this data indicates small negative trends in ozone concentration, except during the summer months when trends are positive.

[3] Chemistry/transport models (CTMs) reproduce many observed behaviors of stratospheric ozone and other minor constituents [e.g., *Douglass et al.*, 2004; *Stolarski et al.*, 2006]. CTMs do not have the feedback processes between trace gases and the radiation field that provide a mechanism for changes in trace gases to affect the circulation of the stratosphere and modify the trace-gas response to forcing. The importance of these feedbacks can be estimated with a model that allows interactions among its radiative, chemical, and dynamical components. Chemistry/climate models (CCMs) combine a general circulation model (GCM) with a representation of photochemistry developed for CTMs [e.g. *Austin et al.*, 2003; *Eyring et al.*, 2006]. We combined the GEOS-4 GCM (Goddard Earth Observing System, Version 4, General Circulation Model) with the photochemistry from our stratospheric CTM to produce the GEOS CCM.

[4] Prior studies have examined changes associated with the Antarctic ozone hole, but have neither focused on the region of ozone increase that overlies the region of depletion nor isolated the signature of ozone increase in observations. The ozone increase is surprising and is not a direct effect of the increase in chlorine or bromine, which are expected to increase the loss of ozone throughout the stratosphere. Several CCMs have calculated a warmer layer in the Antarctic spring above the cooled region of the ozone hole [e.g., *Kiehl et al.*, 1988; *Mahlman et al.*, 1994]. Similar ozone changes to those reported here are evident in prior CCM studies [e.g., *Austin*, 2002; *Langematz et al.*, 2003; *Manzini et al.*, 2003] but the cause of the increase has not been discussed in detail.

[5] In the following section we describe the ozone increase as seen in ground- and space-based observations. The GEOS CCM and the simulations used here are described in Section 3, and are used to explain the formation and generation of the observed ozone enhancement in Section 4.

2. Observed Trends in the Antarctic Summer Ozone Profile

[6] A series of SBUV instruments yields stratospheric ozone profiles between 50 and 1 hPa. The Version 8 (V8) processing algorithm derives profiles with information on vertical scales of about 5 km [*Bhartia et al.*, 1996; *DeLand et al.*, 2004; *Bhartia et al.*, 2004; *Taylor et al.*, 2003]. The V8 processing algorithm homogenizes the data record through re-calibration of each SBUV instrument. Use of a time-independent *a priori* in the retrievals and the calibration of each SBUV instrument to the same scale prevents artificial trends in the data set.

[7] Following *Stolarski et al.* [2006], statistical analysis of the time series of SBUV retrievals between 1979 and 2003 was performed for months that are sunlit at high southern latitudes (October–April). Explanatory variables in the statistical model include seasonal cycle, equivalent effective stratospheric chlorine (EESC), the quasi-biennial oscillation, volcanic aerosols and the solar cycle. The ozone trend for 1979–1997 is the projection on to EESC term, which increases linearly in this period, before leveling off.

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0094-8276/06/2006GL026820$05.00

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D19303, doi:10.1029/2006JD007089, 2006

Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Transport Model

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Received 19 January 2006; revised 20 April 2006; accepted 14 June 2006; published 5 October 2006.

[1] Ozone measurements from the OMI and MLS instruments on board the Aura satellite are used for deriving global distributions of tropospheric column ozone (TCO). TCO is determined using the tropospheric ozone residual method which involves subtracting measurements of MLS stratospheric column ozone (SCO) from OMI total column ozone after adjusting for intercalibration differences of the two instruments using the convective-cloud differential method. The derived TCO field, which covers one complete year of mostly continuous daily measurements from late August 2004 through August 2005, is used for studying the regional and global pollution on a timescale of a few days to months. The seasonal and zonal characteristics of the observed TCO fields are also compared with TCO fields derived from the Global Modeling Initiative's Chemical Transport Model. The model and observations show interesting similarities with respect to zonal and seasonal variations. However, there are notable differences, particularly over the vast region of the Saharan desert.

Citation: Ziemke, J. R., S. Chandra, B. N. Duncan, L. Froidevaux, P. K. Bhartia, P. F. Levelt, and J. W. Waters (2006), Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Transport Model, *J. Geophys. Res.*, *111*, D19303, doi:10.1029/2006JD007089.

1. Introduction

[2] Many of the current techniques for deriving tropospheric ozone are based on the tropospheric ozone residual (TOR) method, which derives tropospheric column ozone (TCO) by subtracting concurrent measurements of stratospheric column ozone (SCO) from total column ozone measured by the Total Ozone Mapping Spectrometer (TOMS) instrument [*Fishman and Larsen*, 1987; *Fishman et al.*, 1990]. The TOR concept, which has recently been used by *Fishman et al.* [2003] using the TOMS and Solar Backscatter Ultraviolet (SBUV) combination, and by *Chandra et al.* [2003] using the TOMS and Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) combination, has been implemented to derive TCO and SCO fields from the Aura satellite where total column ozone is measured by the Dutch-Finnish Ozone Monitoring Instrument (OMI) [*Levelt et al.*, 2006a], and SCO is measured by the MLS instrument [*Waters et al.*, 2006]. The use of MLS on board Aura for measuring SCO is a significant improvement in alleviating some of the problems associated with the use of SBUV or UARS MLS. The SBUV measurements have difficulty in retrieving ozone in the lower stratosphere below the ozone number density peak (∼25 km altitude), and while UARS MLS may be extended down to 100 hPa in ozone profile measurements, this limits maps of SCO to mostly tropical and subtropical latitudes. An important issue for the TOR method involving independent satellite instruments is interinstrument calibration which may seriously impact an accurate determination of TCO. Such calibration [*Chandra et al.*, 2003] can be obtained at locations where OMI can directly measure SCO using the Convective Cloud Differential (CCD) method [*Ziemke et al.*, 1998]. A main advantage of the new Aura MLS and OMI measurements is that near-global maps of calibrated TCO can be obtained on a daily basis which was not possible with previous satellite measurements.

[3] The OMI and MLS instruments on board the Aura spacecraft platform [*Schoeberl et al.*, 2004] have been providing global measurements of total and stratospheric column ozone soon after the launch of Aura on 15 July 2004 (Aura webpage: http://aura.gsfc.nasa.gov/). This has enabled near global measurements of TCO on almost a day-to-day basis from late August 2004 to present. The continuous global nature of the measurements allow the data to be compared with global models of tropospheric ozone in more detail than in previous studies. The previous studies were generally limited to tropical and subtropical latitudes [*Martin et al.*, 2000, 2002; *Peters et al.*, 2002; *Chandra et al.*, 2002;

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0148-0227/06/2006JD007089$09.00