educational affairs

A Graduate Radiation Course Based upon Numerical Methods

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ABSTRACT

The authors describe a short, graduate radiation course that is based upon exercises with modern numerical radiation codes.

1. Introduction

In recent years, a great deal of effort has been made to incorporate the basic concepts of atmospheric radiation into numerical programs. Users need have few reservations about the quality of these programs, which are being continually updated by specialists. It seems out of place, therefore, to expect most students to master all of the detailed analysis upon which these programs are based, for few will be called upon to reconstruct or to modify them. They *do* need to understand thoroughly the physical processes upon which the programs are based, they need to know how to use them and what data may be obtained from them, and they must be aware of their limitations and the reasons for these limitations. These were the three objectives of the course that will be described.

The starting point for the course was the 1994 Houghton Lectures at the Center for Meteorology and Physical Oceanography at the Massachusetts Institute of Technology (MIT). The course was also taught in 1995, with significant differences in the laboratory between the two years. Except where otherwise noted we describe our experiences in 1995.

The following programs are some of those that are available at many institutions [we obtained most of them from the Jet Propulsion Laboratory (JPL), California Institute of Technology]. HITRAN (Rothman et al. 1992) is a database rather than a program, a listing of all known spectral lines of all relevant atmospheric molecules. Line-by-line programs (effectively unlimited spectral resolution) use this database to calculate transmissions and radiances for arbitrary atmospheric structures. The three most commonly used line-by-line programs in the United States are FASCODE from the Air Force Phillips Laboratory, LBLRTM from Atmospheric and Environmental Research, and GENLN from Oxford University [see Anderson et al. (1994) for a historical survey of radiative transfer codes and many references to them]. Both are based on the integral solution to the equation of transfer and do not include multiple scattering.

MODTRAN and LOWTRAN are two fast, low-spectral-resolution programs for radiance calculations (1 cm^{-1} and 20 cm^{-1}, respectively), also from the Phillips Laboratory. They contain a two-stream multiple-scattering program and are based on band models, so that the accuracy is not high. They are, however, essential for exploring the field, particularly the visible spectrum. A doubling-and-adding program from The University of Arizona allows multiple scattering to be calculated to any required precision for stratified atmospheres formed from discrete slabs

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(Hansen and Travis 1974). A Mie theory program (Hansen and Travis 1974) permits detailed calculations of scattering by spheres. JPL has a sorting algorithm for a correlated-*k* approach to spectral detail (Goody et al. 1989) that bridges the gap between line-by-line calculations and a calculation suitable for a general circulation model (GCM). Finally, radiative–convective models are elementary GCMs. The radiative–convective model of Renno et al. (1994) was available in a PC version, called RADCON.

Some of these programs are quite difficult to use in their native form: Fortran source code. In some cases the codes are platform dependent, making them difficult to adapt quickly. In addition, input parameters must typically be specified in a text file with an inflexible, counterintuitive, and poorly documented format. Also, graphical display of results must in most cases be arranged by the user, as the programs provide only numerical output. In 1994, the students spent valuable time trying to master these difficulties.

In 1995 we were presented with PC versions of some of the most important programs, HITRAN-PC, PCModWin, and PCLnWin. These three programs are marketed by the ONTAR Corporation of North Andover, Massachusetts. HITRAN-PC enables the student to explore the contents of the HITRAN database and to perform transmission calculations. It was prepared by D. Killinger of the University of South Florida. PCModWin enables radiance calculations with both MODTRAN and LOWTRAN. PCLnWin is a PC version of FASCODE. All three programs are extensively documented. The PC versions feature Windows interfaces that handle specification of run parameters and graphical display of the output.

2. The course

We were invited by the center faculty to give a short radiation course over a period of four weeks, as part of the first semester of a two-semester sequence on atmospheric chemistry, radiation, and cloud microphysics, which is required of all graduate students in atmospheric science. Graduate students at the center come for the most part to study chemistry or dynamics; the relatively short time devoted to radiation in the curriculum reflects this emphasis.

Three classroom hours were available per week plus approximately 10 hours for work in the laboratory. The lectures were based upon chapters 3, 4, and 5 of Goody (1995). This book was prepared for physics and chemistry majors, and it was generally suitable for the first-year class at the center. The material is very compact and omits all but the essentials. Each chapter contains no more than 25 pages of text, including figures and tables. The class material was in four parts, as follows:

Part I: Introduction—Solar and thermal radiation; overview of radiation climatology; the first law of thermodynamics; and the fate of a solar photon.

Part II: Absorption and scattering—Lambert's law; extinction, absorption, scattering; lines and continuua; electronic bands; vibration–rotation bands; contents of the HITRAN database; Lorentz and Doppler line shapes; treatment of far wings of lines; Mie theory; Rayleigh scattering for small particles; and anomalous diffraction for large particles.

Part III: Radiative transfer—the source function and the equation of radiative transfer; the Planck function; source functions for primary and for multiple scattering; the integral solution; the interaction principle and doubling and adding; approximations; the correlated-*k* method for frequency integration; the two-stream differential equations; and radiation to space.

Part IV: Constraints on thermal structure—a two-stream, semigray solution; a convective troposphere; the Chapman layer; meridional structure and energy balance models; climate sensitivities; and remote sensing.

Part I was a brief introduction. The substance of the lectures was contained in parts II and III, corresponding to chapters 3 and 4 in the textbook. Chapter 5 was not treated in full, but it was important to leave the students with the understanding that what they had learned was relevant to their future research.

There was no final exam. Instead, the performance of the students was judged on the quality of four papers, one each for four exercises based on different numerical programs. This left the maximum time for the exercises. From the quality of the papers and our discussions with the students, we were satisfied that we were able to grade the students as accurately as is customary at the center.

The success of these exercises depended on the existence of the PC programs. Most (but surprisingly, not all) students were adepts at DOS and Windows, and could run significant calculations within half an hour of starting on a new program. The number of calculations was, therefore, not a limitation; rather, the limitation was the students' abilities to absorb and understand what they were doing.

The PC programs that we used were RADCON, HITRAN-PC, and PCMod-Win; there was no time for PCLnWin. The fourth program that we used was doubling and adding, which could be compiled on computers at the center. The input and output of this program are simple, and it is easy to master. We did not use the Mie program or the JPL sorting algorithm for correlated-*k* for lack of time.

The center computers were not compatible with the PC programs, but we were fortunate to be able to purchase four modern PCs and a printer dedicated to the course. Some of the students had PCs available elsewhere, and these arrangements proved to be satisfactory for a class of 12 students.

3. The exercises

A brief description of the four exercises follows. Students were provided with comments on the programs and a series of tasks. Many variants on these tasks would probably serve equally well. Where appropriate they could consult the ONTAR documentation and the brief documentation available on RADCON. References to the literature were also provided. In practice, the students learned a lot from the teaching assistant who was present during laboratory sessions and available at other times.

a. Exercise I: PCModWin

The students started this exercise immediately after the first introductory class, knowing little or nothing about gaseous absorption or radiative transfer. They had to use intuition and common sense to learn from the exercise but could return to it later with better understanding.

The students were asked to use MODTRAN to plot the outgoing radiance from the 1976 U.S. standard atmosphere and the atmospheric transmission spectrum for the same conditions (see Fig. 1). They were asked to identify the spectral features from data in a textbook and to discuss how the absorption and emission spectra might be related. They were asked to plot similar data for other available model atmospheres and to think about the differences between them.

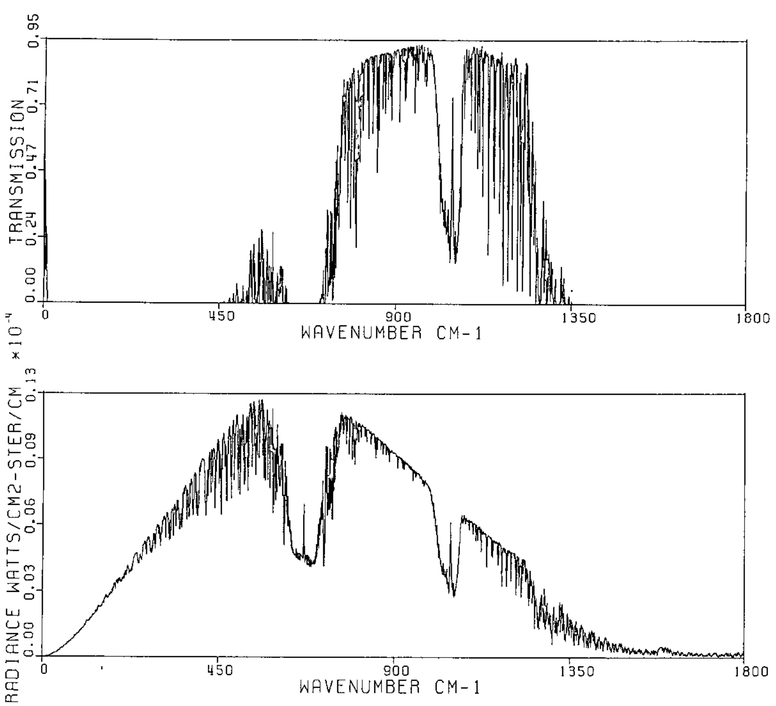

FIG. 1. MODTRAN calculations based on the 1976 U.S. standard atmosphere. The spectral resolution is approximately 1 cm^{-1}. Upper panel: vertical transmission of the entire atmosphere. Lower panel: outgoing radiance in the vertical direction.

The students were asked to calculate energy fluxes approximately, and hence to estimate the average heating for one of the model atmospheres. From blackbody curves plotted on the same scale as the radiances, they were asked to assign emission temperatures to some features. Given that an opaque atmosphere emits as a Chapman layer, they could go into the tabulated ascent data and find the emission levels for interesting features. The final task for thermal radiation was to include a cirrus cloud into a calculation and to think about its effect on the radiance.

The students were asked to do one task in the visible spectrum using LOWTRAN. This consisted of calculating the spectrum of light scattered from a cirrus cloud between 9500 and 11 500 cm^{-1} and of identifying the τ, σ, and ρ bands of water vapor.

b. Exercise II: HITRAN-PC

HITRAN-PC consists of three programs, SEARCH, PLOT, and TRANS. The SEARCH program allows students to look at the HITRAN database. The upper section of Fig. 2 shows some of the tabulated data in

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  M  I     wn(cm-1)      S(T)      g(T)   gs         E''           v''
-----------------------------------------------------------------------
CO2  2    667.00033 3.124E-25 .0708 .0956  2127.55737        03301
CO2  4    667.00224 2.162E-26 .0666 .0751  2150.86011        02201
CO2  3    667.00287 7.121E-25 .0615 .0625  1775.56177        00001
CO2  4    667.00580 2.172E-23 .0877 .1204     2.27170        00001
CO2  4    667.00692 2.162E-26 .0666 .0751  2150.85547        02201
CO2  1    667.02625 1.887E-23 .0728 .0998  2052.02417        11102
CO2  2    667.03843 1.260E-24 .0893 .1228  1372.40039        10001
CO2  3    667.04085 4.604E-25 .0681 .0852  1648.00928        10002
CO2  4    667.04450 4.105E-27 .0615 .0625  2495.28735        01101
CO2  1    667.04455 2.801E-24 .0620 .0633  2444.32373        01101
CO2  2    667.05524 2.209E-24 .0863 .1190  1377.85645        10001
CO2  4    667.06674 1.858E-26 .0664 .0744  2186.52905        02201
CO2  4    667.07163 6.998E-24 .0663 .0738   889.80219        00001
CO2  4    667.07183 1.858E-26 .0664 .0744  2186.52393        02201
CO2  4    667.07956 5.019E-25 .0668 .0765  1414.71326        01101
CO2  2    667.08166 3.061E-24 .0836 .1141  1386.43005        10001
CO2  2    667.08811 7.411E-26 .0849 .1154  2044.91174        11101
CO2  1    667.09809 2.346E-26 .0666 .0751  3641.17432        20001

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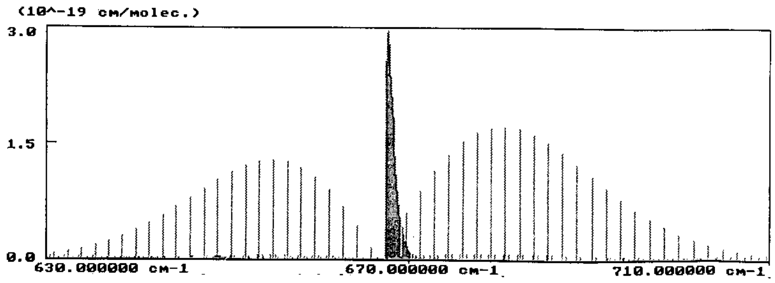

FIG. 2. Molecular line data in the 15-µm CO_2 band. Above: some tabulated data; M = molecule, I = isotope code, wn = wavenumber, $S(T)$ = line strength, $g(T)$ = air-broadened line width, gs = self-broadened line width, E'' = energy of lower state, v'' = vibrational quantum number of lower state. Below: a stick-plot of line strengths in the 15-µm band.

the 15-µm CO_2 band. They were asked to do simple sums concerning the absorption at the center of one of the lines, given a Michelson–Lorentz line shape, and the temperature variation of two line strengths from Boltzmann's law.

The PLOT program produces stick plots, as shown in the lower part of Fig. 2. The students were asked to put the Q branch of the 15-µm band under a microscope (any frequency resolution can be employed) and to discuss the fine detail. They were asked to consider the P and R branches as examples of *regular bands,* and then to look at some weak underlying water lines as an example of a *random band.*

TRANS enables the calculation of transmissions, and the student could simulate a laboratory experiment. The transmission of an array of lines (band models) was fundamental to the teaching of atmospheric radiation before the advent of correlated-k. Band models were given no time in the classes; this is where the student learned what the issues are.

Carbon monoxide lines between 2150 and 2160 cm^{-1} form a convenient regular array and the student was asked to experiment with transmissions based on a Michelson–Lorentz line shape. The effect of pressure on the wings of strongly absorbed lines could be studied, and the mean transmission of an Elsasser band could be estimated. This could be compared to Elsasser-band tabulations to be found in standard text books.

c. Exercise III: Doubling and adding

The purpose of this exercise was to show the student that multiple scattering problems could be solved quite rapidly to an arbitrary degree of accuracy. The student was asked to set up an atmosphere with a few discrete layers, to calculate thermal and solar radiances for circumstances in which both scattering and absorption are important, and to interpret the results.

Specifically, the student was asked to set up the calculation for a very thick, isothermal cloud and to calculate fluxes of thermal emission and of scattered solar radiation at the top of the cloud as a function of the single-scattering albedo and (in the scattering case) the solar zenith angle. These results could be compared with formulae available in the textbooks for a two-stream approximation, giving the student an idea of the accuracy of this low-order approximation (see Fig. 3).

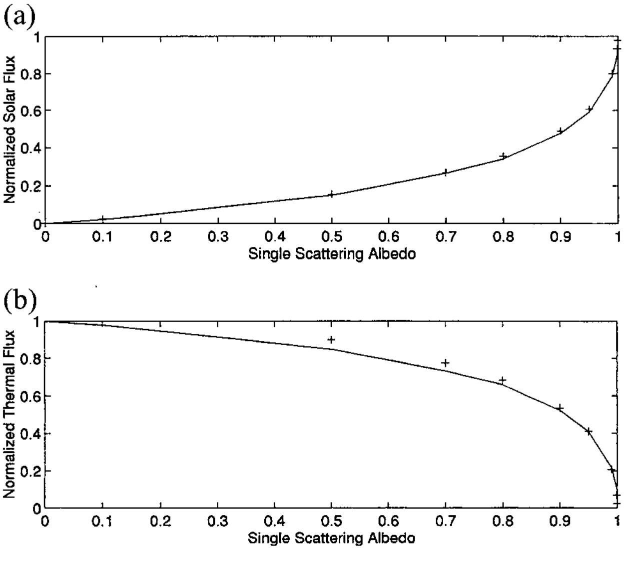

FIG. 3. Doubling-and-adding calculations for (a) reflected solar and (b) thermal fluxes at the top of a thick cloud as a function of single-scattering albedo. The lines are doubling-and-adding calculations while the points are from a two-stream approximation.

d. Exercise IV: RADCON

This exercise allowed the student to study the interaction between the radiation field and a dynamical model, in this case a cumulus convection model based on microphysical (and some macrophysical) processes. The model took hundreds of days to reach a steady state (see Fig. 4). The output file contains vertical distributions of temperature, humidity, and the radiative cooling rate.

The students were asked to make short runs to learn the characteristics of the model and its responses to changing inputs; for example, the imposed vertical and horizontal wind speeds. Long runs were needed to study climate sensitivities to CO_2 doubling, changes in the solar constant, and changes in the planetary albedo (doubling CO_2 leads to an increase of 1.25 K in the sea surface temperature).

Finally, the students were asked to calculate the change in the outgoing radiation field that could be measured from a satellite. Vertical profiles before and after a CO_2 change were read into MODTRAN, which with 1 cm^{-1} resolution gives a fair imitation of a high-resolution infrared sounder. From this exercise the student could gain an idea about the difficulty of establishing the reality of a climate change.

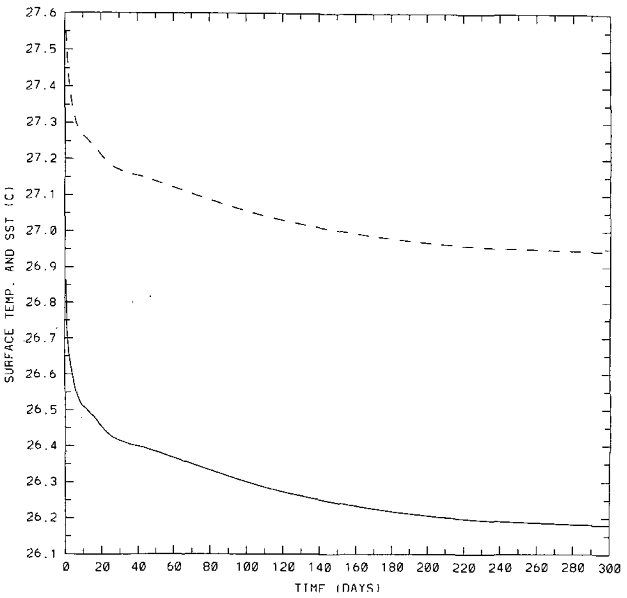

FIG. 4. Sea surface temperature (upper curve) and surface air temperature (lower curve) from a 300-day run with RADCON: CO_2, 330 ppm; average insolation at 7° latitude; surface albedo, 0.31; surface wind 7 m s^{-1}; no vertical velocities.

4. How successful was the course?

There is no objective way to answer this question. However, from previous experience with similar students in a full semester course at Harvard there was no doubt that the students were doing much more advanced work than could be achieved in a longer, conventional course. We gauged student reactions in two ways. First, we could tell from grading the students' exercises which concepts had been absorbed by most of them and which gave them difficulties. The second source of information was student comments, communicated confidentially. We asked two specific questions: the appropriateness of using computer programs to learn radiative transfer as opposed to a more conventional analytical approach; and how successful they judged the overall course, lectures plus laboratory, to be. These two sources of information gave us a consistent picture of what worked well and what could stand improvement.

A cynical view might be that the students would naturally prefer user-friendly PC programs as an alternative to lengthy and difficult analytical manipulations, because they make it much easier to reach an answer to the questions posed to them. Of course, there is a certain fascination to the use of pull-down menus, icons, and color graphics, but that misses the point of what we attempted to achieve.

Our working assumption was that since radiation theory is mature, and now embodied in available computer programs, the most important thing is for the students to acquire the ability to *think critically* about the results in terms of basic physical principles rather than to master difficult procedures to *obtain* the results. If the relevant physics is understood, only a modest degree of computer literacy and some investment of time will be required to master any code that the student may come across in future research. Given our assumption, it follows that the best teaching method is that which allows, consistently with a sound understanding of physical principles, the widest range of results to be achieved most quickly. Then more time can be allotted to interpretative questions that challenge the student to construct a coherent and correct explanation of why a result is what it is. An additional bonus is that the programs that we used are state-of-the-art codes that the student may wish to use for future research.

MIT students take pride in their analytic abilities; nevertheless, for the most part, the students in the course in both years agreed with the appropriateness of using numerical methods in place of analytical methods. Of course, the students had no basis for direct comparison, but because most of their other course work stresses analytical methods we can give them credit for understanding the point at issue. One of us (A.S.) did have the experience of taking a conventional radiation course at MIT in 1993. He has no doubt about the superiority of the teaching technique, provided that the necessary hardware and software is set up well so that students do not need to grapple with technical computer problems. After two years we feel that this stage has been reached.

The students did not find all of the exercises to be easy. A few managed to do all of the runs correctly and to give thoughtful answers to the interpretative questions. These few were the students who spent considerable time consulting the teaching assistant. He was generous in providing assistance to students who had clearly formulated a question. We thought it best to get students to the stage of running the programs and getting results as quickly as possible. One unintended but, in hindsight, foreseeable consequence was that those students who were most aggressive in seeking help got more out of the course than those who were more independent. We shall seek a way to correct this in future. But no students failed to achieve an acceptable level of understanding in both years.

The most common difficulty for the students was that the exercises were considered to be too long for the time allotted. We realized in advance that this might be so and instructed the students to do as much as they had time for, but to do it well. But the students were uncomfortable with this instruction because it ran against the grain of their accustomed approach to course work. In future courses the exercises will be shortened, the time to do them extended, or both. A related difficulty was that the students sometimes thought that the exercises were not defined clearly enough. This was deliberate on our part. Our questions were often put in the form, "You should follow this (sketchily outlined) procedure to explore (a general scientific issue)." This approach can be successful if students have the time and the maturity to respond well, but when either resource is limited, it is probably more appropriate to shift the emphasis toward more specific instructions. An increased time allotment would help us to move the students out of an undergraduate course format.

Some students felt that they did not have enough background from the lectures to understand what they were supposed to do. The quality of their written papers indicated that this complaint was only partially justified. The material in the textbook and in some recommended articles would have covered this point had the students had more time to study them. Again, four weeks is a rather short time to explore a major topic in atmospheric physics, but the discrepancy is not great.

5. Future developments

In sum, we are satisfied that this approach to teaching atmospheric radiation is effective, particularly for the usual MIT graduate student, who is either a dynamicist or a chemist and who does not expect to do research in this topic. However, the relationship between the lectures and the exercises, as it was in 1994 and 1995, left something to be desired. We started by emphasizing the classes and used the exercises to support them. We now prefer to think of the exercises as the focal point of the course, with the lectures in a supporting role. The course was a lot for four weeks, even though MIT students are accustomed to demanding course requirements; we think it better that the course be extended to 6 weeks with no additional material. The ONTAR Corporation has expressed an interest in developing educational materials. The PC programs that now exist were developed more for technical applications than for educational purposes. Many aspects could be improved for a graduate course. For MODTRAN, for example, it would be valuable to be able to manipulate (subtract, ratio) outputs; energy fluxes and heating rates should be a part of the program; and there should be a brightness temperature option. We would also like to increase the sophistication of RADCON and to develop PC versions of doubling and adding, Mie scattering, and correlated-*k*.

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