NOTES AND CORRESPONDENCE

Infrared Cooling in Cloudy Atmospheres: Precision of Grid Point Selection for Numerical Models

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ABSTRACT

The infrared layer temperature change in a cloudy atmosphere normally shows warming at the base of the cloud and intense cooling at the top of the cloud. In a model that uses broad-band radiative transfer to calculate atmospheric temperature changes, errors on the order of 6.0 K day^{-1} can occur at the top of a cloud if only selected grid points are used. Calculations using grid points at discrete intervals produce a smoothing effect over the entire cooling profile and increase errors. Two case studies were used to demonstrate these problems.

1. Introduction

The need for accurate determination of the radiative heating and cooling of the atmosphere and surface on a regional and global basis is a growing problem. The increases in anthropogenic and natural (volcanic) aerosols and CO_2 have led to many controversies concerning the potential climatic effects of these changes. The interest in the effects of cloud and moist layer distributions in the atmosphere on mesoscale/regional weather prediction has increased. There is evidence that urban and industrial contaminants are changing the thermal and optical properties of the atmosphere at least on a regional basis (Stearns *et al.*, 1982). Scientists have turned to numerical models to predict the effect of aerosols and clouds on atmospheric optics and on cooling rates (Grassl, 1973; Harshvardhan and Cess, 1976; Stephens, 1976; Ackerman *et al.*, 1976; Zdunkowski and McQuage, 1972; Mitchell, 1971; Paltridge, 1980; Cox, 1971; Liou and Ou, 1981).

Numerical models for mesoscale/regional forecasting have reached a high degree of sophistication, and perhaps a point where infrared cooling due to clouds and aerosols may be included. Each model depends on the careful selection of grid points for its calculations (Wakefield and Shubert, 1981; Deardorf, 1980). It is the purpose of this note to demonstrate the importance of proper spacing in the selection of those grid points for the model outputs. Careful selection of grid points can help to preserve the nature of the infrared effects and, conversely, careless selection can tend to average or smooth that nature if the number of grid points is limited or confined to discrete intervals. Unfortunately, computer costs often raise the need to reduce the number of grid points used.

2. Grid point selection

A broad-band approximation program (Kuhn, 1963a) has been used to investigate the effect of point choices on changes in layer cooling due to clouds. This model was chosen to demonstrate cooling effects because it simulates the results of a more complex band-by-band model which uses the line strengths of McClatchey *et al.* (1973) to obtain the optical transmittances. Broad-band models may lead to cooling rate problems (Rodgers and Walshaw, 1966) unless the emissivities are properly treated (Rodgers, 1967). The degree of blackness (grayness) of the cloud must be considered since the water vapor is seldom uniform within its boundaries. In this approximation model, the emittance of the layer is determined. If it exceeds 95%, the layer is treated as a blackbody and the flux calculations continue on this basis. Water vapor dominates the radiative transfer and the band structure is complicated. Thus in order to compensate for overlap by CO_2 and rotational water vapor, at $\sim$15.0 μm, flux emissivities of CO_2 were reduced by 12%. Ozone, continuum and atmospheric haze were not included in the model. Further discussion of the model can be found in Kuhn (1963a,b). Assuming horizontal stratification in the atmosphere, the upward or downward flux at a reference level r may be written as

$$F_r(u, T) = \int_0^u \sigma T^4(u)[\partial\epsilon_f(u)/\partial u]du, \qquad (1)$$

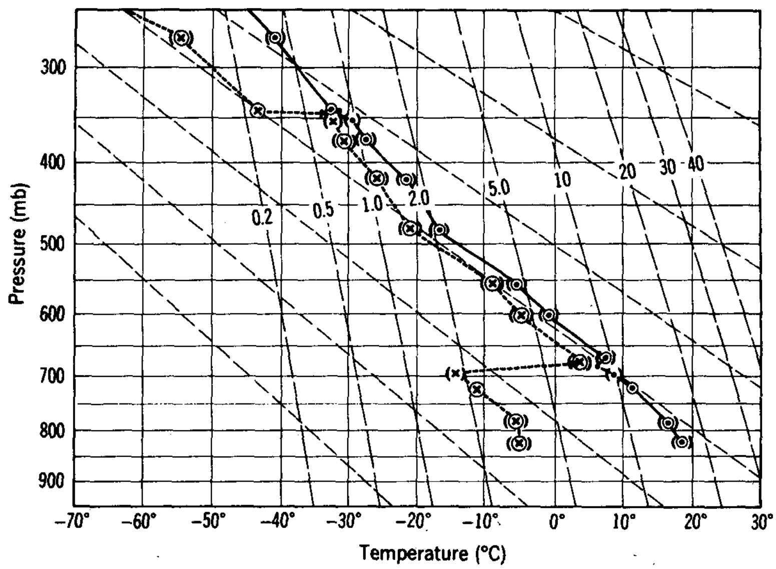

FIG. 1. Sounding near Boulder, Colorado on 12 October 1966, showing temperature and dew point profiles. Values of grid 1 are circled; values of grid 2 are enclosed by parentheses. Diagonal lines are dry adiabats, and slanted lines are saturation mixing ratios.

where u is the temperature- and pressure-corrected optical depth of an absorbing gas (in this case water vapor and carbon dioxide), σ the Stefan-Boltzmann constant, $\bar{T}$ the layer temperature average, and ϵ_f the flux emissivity, defined by the ratio of the layer flux divided by the blackbody flux (σT^4) at the same temperature. The rate of atmospheric temperature change of a layer due to radiative flux divergence is obtained by

$$\Delta T/\Delta t = -(g/C_p)(\Delta F_{net}/\Delta P),$$

where g is the acceleration of gravity, C_p the specific

TABLE 1. Sounding data for Boulder, Colorado, 12 October 1966. P is pressure (mb), T temperature (°C), Q mixing ratios (g kg^{-1}).

All points			Grid 1			Grid 2			Grid 3		
P	*T*	*Q*	*P*	*T*	*Q*	*P*	*T*	*Q*	*P*	*T*	*Q*
822.1	18.5	0.32	822.1	18.5	0.32	822.1	18.5	0.32	822.1	18.5	0.32
822.	18.4	3.20	822.	18.4	3.20	822.	18.4	3.20	822.	18.4	3.20
782.	16.5	3.18	782.	16.5	3.18	782.	16.5	3.18	800.	17.4	3.19
722.	11.2	2.20	722.	11.2	2.20				750.	13.7	2.66
698.	8.6	1.80				698.	8.6	1.80	700.	8.8	1.03
680.	7.0	7.32							650.	4.6	6.55
673.	7.3	7.56	673.	7.3	7.56	673.	7.3	7.56	600.	−1.2	4.40
602.	−1.0	4.44	602.	−1.0	4.44	602.	−1.0	4.44	550.	−6.4	3.28
556.	−5.5	3.44	556.	−5.5	3.44	556.	−5.5	3.44	500.	−14.1	1.99
482.	−16.8	1.52	482.	−16.8	1.52	482.	−16.8	1.52	450.	−19.3	1.78
420.	−21.6	1.08	420.	−21.6	1.08	420.	−21.6	1.08	400.	−24.0	0.96
375.	−27.1	0.80	375.	−27.1	0.80	375.	−27.1	0.80	350.	−30.1	0.71
353.	−29.5	0.74				353.	−29.5	0.74	300.	−37.2	0.15
345.	−31.2	0.66							272.	−40.5	0.09
343.	−32.2	0.24	343.	−32.2	0.24				202.	−53.4	0.02
272.	−40.5	0.09	272.	−40.5	0.09	272.	−40.5	0.09	102.	−67.9	0.0024
202.	−53.4	0.02	202.	−53.4	0.02	202.	−53.4	0.02	51.	−61.9	0.0024
102.	−69.7	0.0024	102.	−67.9	0.0024	102.	−67.9	0.0024	20.	−53.0	0.0024
51.	−61.9	0.0024	51.	−61.9	0.0024	51.	−61.9	0.0024	10.	−47.9	0.0024
20.	−53.0	0.0024	20.	−53.0	0.0024	20.	−53.0	0.0024	1.	−10.0	0.0024
10.	−47.9	0.0024	10.	−47.9	0.0024	10.	−47.9	0.0024	0.6	7.0	0.0024
1.	−10.0	0.0024	1.	−10.0	0.0024	1.	−10.0	0.0024	0.2	−27.0	0.0024
0.6	7.0	0.0024	0.6	7.0	0.0024	0.6	7.0	0.0024	0.1	−272.0	0.0024
0.2	−270.0	0.0024	0.2	−270.0	0.0024	0.2	−270.0	0.0024			
0.1	−272.0	0.0024	0.1	−272.0	0.0024	0.1	−272.0	0.0024			

heat at constant pressure, ΔF_{net} the change of net flux ($F\uparrow - F\downarrow$) from one layer to the next, and ΔP the change in pressure for the same layer. In two cases, grid points were chosen from an original sounding but the number of levels was reduced or levels were set at discrete intervals, namely 50 mb.

The first case study was taken from a sounding made near Boulder, Colorado on 12 October 1966 (Fig. 1). Table 1 lists the input data. The weather was clear. A moist layer was inserted between 680 and 345 mb so that the extreme effects of a cloud could be calculated. The first calculation was based on 25 layers including the background. Two subsequent calculations (grids 1 and 2) eliminated only four layers from the original 25. Grid 3 was calculated from the 50 mb interpolated sounding. The layer temperature change was plotted as a solid line (Fig. 2). The expected features appear, namely a slight warming under the base of the cloud and strong cooling at the top. The warming under the base disappears especially in grid 1 where the layer value is 1.6°C day^{-1} cooling instead of 0.7°C day^{-1} warming as in the original. The severe cooling at the top of the cloud is extremely modified in that although an increased cooling is noted, it is 6.0°C day^{-1} warmer in grid 1, 5.3°C day^{-1} warmer in grid 2, and 5.6°C day^{-1} warmer in the interpolation grid 3.

The second sounding studied was obtained at Lihue during the Hawaii Mesoscale Energy and Climate Project (HAMEC) in the summer of 1980 (Fig. 3). In requesting this sounding, I asked only that it contain a cloud or moisture layer. Therefore, it represented a modelers choice of a sounding with a moist layer. It contained 40 layers including the background. Grid values that were provided were employed in a mesoscale numerical model for simulating warm rain over the complex terrain of Hawaii (Nickerson, 1979). The pressure temperature and mixing ratios are listed in Table 2. The grid points used in

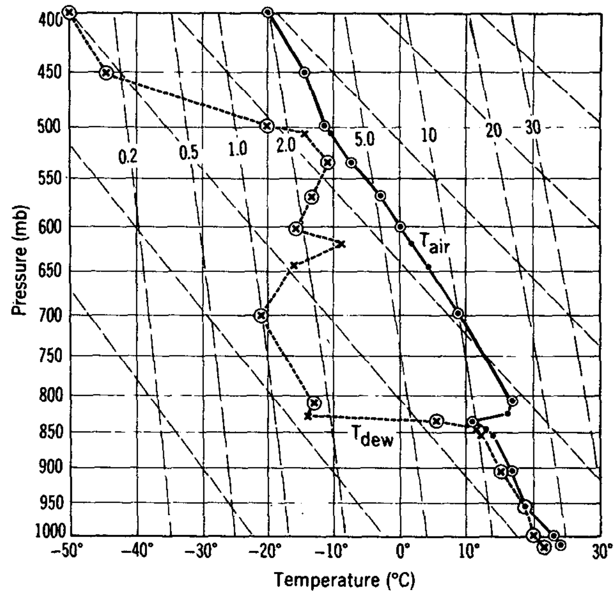

FIG. 3. Sounding at Lihue, Hawaii on 19 June 1980, showing temperature and dewpoint profiles. Values of grid 1 are circled. Diagonal lines are dry adiabats, and slanted lines are saturation mixing ratios.

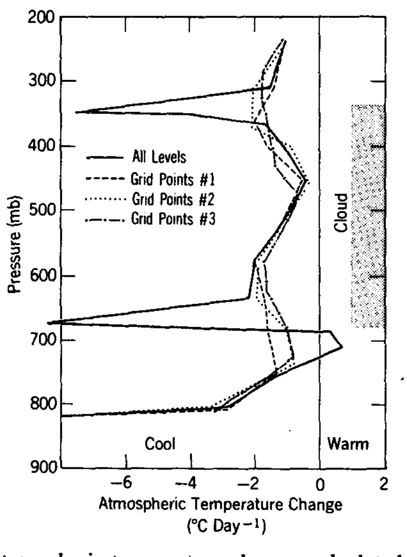

FIG. 2. Atmospheric temperature changes calculated using the Boulder, Colorado sounding. The solid line represents values obtained using the initial sounding that includes all levels.

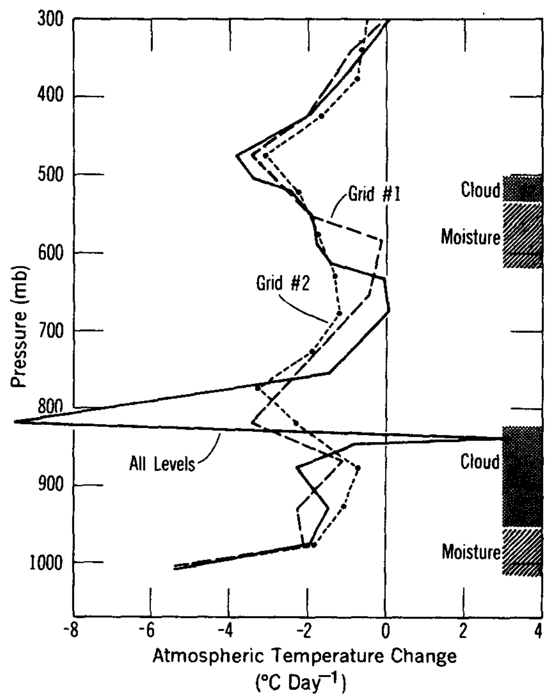

FIG. 4. Atmospheric temperature changes calculated using the Lihue, Hawaii sounding. The solid line represents values obtained using the initial sounding that includes all levels.

TABLE 2. Sounding data for Lihue, Hawaii, 19 June 1980 (*P*, *T*, *Q* as in Table 1).

All points			Grid 1			Grid 2		
P	*T*	*Q*	*P*	*T*	*Q*	*P*	*T*	*Q*
1016.4	23.8	16.1	1016.4	23.8	16.1	1016.4	23.8	16.1
1000.	22.9	15.2	1000.	22.9	15.2	1000.	22.9	15.2
953.	18.4	14.1	953.	18.4	14.1	950.	18.3	14.0
903.	16.3	12.2	903.	16.3	12.2	900.	16.1	12.1
850.	13.1	11.1				850.	13.1	11.1
844.	12.6	11.0				800.	15.9	2.3
834.	10.6	6.9	834.	10.6	6.9	750.	12.3	5.5
824.	16.1	3.5				700.	8.6	1.0
808.	16.5	1.68	808.	16.5	1.68	650.	4.2	2.6
700.	8.6	1.0	700.	8.6	1.0	600.	−0.3	1.9
644.	3.7	1.67				550.	−5.8	2.8
619.	1.2	3.15				500.	−11.4	1.52
602.	−0.1	1.85	602.	−0.1	1.85	450.	−14.8	0.16
569.	−3.3	2.40	569.	−3.3	2.40	400.	−20.1	0.095
535.	−7.7	3.10	535.	−7.7	3.10	350.	−28.3	0.056
506.	−11.0	2.43				300.	−36.1	0.030
500.	−11.4	1.52	500.	−11.4	1.52	250.	−45.7	0.0194
451.	−14.7	0.16	451.	−14.7	0.16	200.	−56.4	0.0137
400.	−20.1	0.095	400.	−20.1	0.095	150.	−66.2	0.0081
326.	−32.2	0.037	326.	−32.2	0.037	100.	−66.4	0.0024
300.	−36.1	0.030	300.	−36.1	0.030	50.	−60.8	0.0024
283.	−39.9	0.027				1.	−10.0	0.0024
250.	−45.7	0.0194	250.	−45.7	0.0194	0.6	7.0	0.0024
200.	−56.4	0.0137	200.	−56.4	0.0137	0.1	−272.0	0.0024
160.	−65.0	0.0092						
150.	−66.2	0.0081	150.	−66.2	0.0081			
135.	−67.6	0.0064						
127.	−66.2	0.0055						
108.	−68.2	0.0033						
100.	−66.4	0.0024	100.	−66.4	0.0024			
80.	−68.7	0.0024						
70.	−66.0	0.0024						
56.	−59.9	0.0024						
50.	−60.8	0.0024	50.	−60.8	0.0024			
30.	−54.8	0.0024						
24.	−52.0	0.0024						
10.	−45.0	0.0024						
1.	−10.0	0.0024	1.	−10.0	0.0024			
0.6	7.0	0.0024	0.6	7.0	0.0024			
0.1	−272.0	0.0024	0.1	−272.0	0.0024			

Nickerson's model are called grid 1; the only exception made was the change in background from 0 mb at −52.0°C to the radiation background. Grid 2 represents the interpolated sounding to 50 mb intervals.

There is no cloud base warming, because a moist layer extends to the interface. However, the cloud top is fairly well defined, and there is extreme cooling above the top (Fig. 4). Another thin layer of clouds at 535–506 mb is evident, and a layer of high relative humidity extends from 619–500 mb.

The severe cooling at the top of the lower cloud is 6.2°C day^{-1} less in grid 1, if compared to the original sounding calculation. Also, although both soundings show a similar profile tendency, the original sounding calculation does show a slight warming under the middle cloud which is missed in the grid values. The cooling at the top of the cloud of grid 1 is only 0.4°C day^{-1} different from the original. The alterations in the cooling profile diminish if the cloud is thinner and less well defined. As in the first case, the interpolated grid values tend to smooth the effects of clouds, producing a difference of 1.2°C day^{-1} at the base of the middle cloud and 0.7°C day^{-1} at the top. Fortunately, most models do not employ this technique of choosing model input data.

In summary, extreme care must be taken in selecting grid points for computing infrared warming/cooling layers especially in the areas of the cloud tops and bases. Although calculating and averaging the cooling rate over a thicker height interval may reduce the differences between coarse and fine grid cases, this option is often not left to the modeler who has to reduce the number of grid points before the calculation. If the cooling layer is erroneously described, the prediction of growth or dissipation of clouds or haze layers can be in error.

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