摘要 谱带划分(band dividing)是进行大气辐射计算的基础，基于各种需要的谱带结构会直接影响大气辐射的精度和速度；本文给出了五种针对不同需要的谱带结构，并对它们对大气辐射通量和冷却率的影响进行了详细的比较，给出可用于目前气候模式的带划分方案(scheme)。*k*-分布间隔点(k-interval)的选取是相关 *k*-分布方法计算的基础，如何选取 *k*-分布间隔点是目前大气辐射计算中没有解决的问题之一。本文通过数值计算指出：在其它条件相同的情况下，谱带划分和 *k*-分布间隔点的选取是影响大气辐射计算精度的两个较为重要的因子。如果计算机能力允许，增加谱带和 *k*-分布间隔点的个数是提高大气辐射计算精度的有效手段。计算结果表明，辐射计算精度对 *k*-分布间隔点的增加存在饱和度。本文提出了 *k*-分布间隔点选取的优化原则和方法，并在此基础上，给出了可应用于气候模式的多种大气吸收辐射计算方案。

Abstract: Band dividing is the basic of atmospheric radiation calculation, so structure of bands founded on various demands would directly influence the precision and speed of atmospheric radiation. This article lists 5 kinds of bands structure contraposing to different demands, draws a particular comparison among the impact of them on atmospheric radiation flux and cooling rate, and also gives a scheme of band dividing available for the present climate patterns. Selection of k-interval is the foundation of *ck*-D method, and the problem of how to do the selection still remain unsettled. This article points out through numerical computation that band dividing and selection of k-interval are the major factors influencing the precision of atmospheric radiation calculation, under the circumstances of other conditions be equal. If the ability of computer permitting, to increase bands and number of k-intervals are efficient means for improving the precision of calculation. The outcomes show that there is a kind of saturation of the precision in contrast to the increase of k-intervals. This article puts forward some optimum principles and methods for k-interval choice, and based on it, gives many schemes for calculation of the absorption by gases of radiation applied to climate patterns.

目前，气候模拟和气候预测成为世界各国科学家研究的焦点和难点问题。而辐射过程作为气候模拟中最为关键控制因子之一，将在很大程度上影响气候模拟的结果。长波辐射在影响天气、气候和气候对外部辐射强迫的敏感性上起着关键的作用；太阳辐射是地球气候最终的能量源，在短波辐射加热率计算中的一个小的误差就可能引起气候模拟中很大的误差。随着模式空间和时间分辨率的增加和物理过程的改进，气候模拟对一个高精度、高速度的辐射模块的需求显得越来越迫切。

At the present time, climate modeling and climate prediction are the focal points and difficulty with research of scientists all over the world. The process of radiation, being one of the most crucial controlling factor of climate modeling, will affect the result to a large extent. Long wave radiation plays a very important role in influencing weather, climate, and sensitivity of climate to external radiation force. Solar radiation is the foremost source of energy for Earth climate, so a minor error in calculation of the heating rate about short wave radiation may cause a prodigious mistake in climate modeling. Along with advance of space and time resolution and betterment of physical process in the modeling pattern, the need for a high precision, high speed module of radiation grows more and more exigent.

虽然逐线积分方法的计算精度较高，但由于需要的计算时间长，导致计算成本大大增加，所以不能直接应用在气候模式中[1，2]。进入 20 世纪 90 年代以后，相关*k*-分布方法作为对逐线积分方法的高精度和低成本近似，已被广泛用于气候模拟研究中[3~11]。但是，即使利用相关*k*-分布方法进行计算，也要在精度和速度之间做出选择[11]。对大多数相关*k*-分布方法，对大气透过率的计算是采用高斯积分或其它数学公式积分进行的[7~12]。*k*-分布间隔（高斯节点）和*k*-分布（高斯）权重的选取对大气透过率的计算精度有很大影响。关于如何计算*k*-分布间隔点上的吸收系数，在Zhang et al.(2003)[11]和Mlawer et al.(1997)[7]已给出详细的研究。到目前为止，*k*-分布权重的计算有三种方法：第一种是采用改进的高斯-勒让德积分间隔来调整积分权重[7] ;第二种是对原始高斯积分进行某种变换，使得能在*k*-分布曲线变化剧烈的部分选取较多的*k*-分布间隔点，以来提高计算精度[9~12]；第二种就是通过SQP（Successive-Quadrature Program）非线性优化方法，由迭代法和试错法来选取*k*-分布间隔点数和积分权重[8],但是,该方法容易出现负权重和迭代不收敛[11]。关于如何选取*k*-分布间隔点数的研究较少，除上述SQP非线性优化方法外，一般采用固定点法[7,9,10,12,13]，该方法通常在某一计算谱区间内以选取较多的*k*-分布间隔点数，即，增加计算量，从而降低计算速度为代价来提高计算精度。实际上，本文研究发现，对某一固定谱区间，计算精度对*k*-分布间隔点数的增加存在一定的饱和度，超过该饱和度，即使再增加点数，也不会增加计算精度。本文将着重讨论如何划分谱带和选取*k*-分布间隔点，以及不同谱带划分方案、不同*k*-分布间隔点数对大气辐射通量和冷却（或加热）率的影响，并在此基础上，给出可用于气候系统模式的多种大气吸收辐射计算方案。

Although precision of line-by-line integration(LBL) method is high, it would take a long time to calculate, resulting in the cost increases greatly, so it cannot be immediately used in climate patterns[1~2]. After the 1990s, the *ck*-D method has been widely applied in climate modeling research, as it is close to the high accuracy and low cost of LBL method[3~11]. However, even using *ck*-D method, there should be a choice between precision and velocity[11]. For most of *ck*-D method, atmospheric transmittance is calculated by Gaussian integral or integration of other mathematical formulas[7~12]. Selection of k-interval(Gaussian node) and its (Gaussian) weight have a strong impact on the precision of atmospheric transmittance. About how to reckon the absorption coefficient on k-intervals, Zhang *et al.*(2003)[11] and Mlawer *et al.* (1997)[7] have done detailed research. Up to now, there are 3 methods to calculate *ck*-D weight: the first is using modified Gauss-Lerard integration interval to adjust the weight[7]; the second is doing certain transform to original Gaussian integral, so as to select more k-intervals where the *ck*-D curve varies acutely, in order to promote the precision[9~12]; and the third one is adopting non-linear optimization method of Successive-Quadrature Program(SQP), to choose k-interval and the weight by iterated method and trial-and-error method[8]. Yet, negative weight or non-convergent iterated results are likely to appear with the third method[11]. There has been less research on how to decide the number of k-intervals: beside the SQP method, fixed-point method is commonly used[7,9,10,12,13] which usually chooses a lot of k-intervals in a certain band section to increase amount of calculation, so as to improve precision at the expense of reducing efficiency. Actually, the author discovered that a saturation exists with the precision in a fixed band section, when the saturation is exceeded, even though the number of k-intervals increases once more, precision will not improve any longer. This article emphasizes on discussing how to divide the bands and select k-intervals, as well as the influence of different schemes and number of k-intervals on atmospheric radiation flux and cooling(or calefaction) rate, and based on them, gives diversiform schemes for calculation of the absorption by gases of radiation available for climate patterns.

1 计算方法

由于LBLRTM (Line-By-Line Radiative Transfer Model)[14~16] 是目前国际上较为公认的逐线积分辐射传输模式，本文将采用LBLRTM计算吸收气体（包括H_2O，CO_2，O_3，N_2O，CH_4，O_2）的线吸收系数和H_2O，CO_2，O_3和O_2的连续吸收系数。辐射传输方法采用张华等（2004）[2]给出的计算方案，下面将给予简要介绍。对长波辐射传输的计算方法，对平面平行大气均匀子层，主要采用Lacis 和 Oinas(1991) [6]孤立层热辐射的思想，并利用改进的漫射率因子近似方法[17]，用作为光学厚度函数的漫射率因子来计算通量透过率；对非均匀大气，可以用多个均匀子层来表示大气的垂直非均匀性。对吸收系数随压力和温度的变化，假定各子层内都是均匀的，但具有一种层内的温度梯度，然后用累加法来计算各层向上和向下的辐射通量。对短波辐射传输，首先将非均匀大气分成许多均匀的子层，对每一个均匀子层，将求解漫射辐射传输矩阵方程问题转化为寻找均匀大气反射率，透过率和源函数矩阵的本征值问题。首先利用矩阵算子来表示反射率，透过率和源函数[18]，并采用$\delta-$二流近似[19]，将反射率、透过率和源函数矩阵转化为标量；对非均匀大气层采用相加法[20]。详细算法参见文献[8]。

1 Algorithmic Method

Since the LBLRTM(Line-By-Line Radiative Transfer Model)[14~16] is internationally recognized, it will be adopted in this article to calculate the linear absorption coefficient of absorptive gases(including H_2O, CO_2, O_3, N_2O, CH_4, O_2) and sequential absorption coefficient of H_2O, CO_2, O_3 and O_2. The author will briefly introduce the method of Radiation Transfer put forward by Zhang Hua *et al.*(2004)[2]. In the calculation of long wave radiation transfer, for well-proportioned sub-layers of planar parallel aerosphere, permeation ratio of flux is computed by modified approximation-technique of diffusion ratio factor[17] which is regarded as an optical thickness function, according to the theory about thermal radiation of isolated layer explained by Lacis and Oinas(1991)[6]. Whereas for asymmetrical atmosphere, vertical asymmetry could be expressed by many symmetrical sub-layers. As for the variation of absorption coefficient along with pressure and temperature, presuming that it is symmetrical within each sub-layer, but there is grads of temperature inside a layer, then accumulate radiation flux of each layer upwards and downwards. When it comes to short wave radiation transfer, primarily dividing the asymmetrical atmosphere into lots of symmetrical sub-layers, thus translating the problem of seeking answer to matrix equation of diffusive radiation transfer into that of seeking reflectivity, permeation ratio of symmetrical atmosphere and latent value of source function matrix. The latter ones are indicated by matrix arithmetic operators[18], and transformed into scalar quantity by δ –Minor Approximation-technique[19]; logical addition is applied for asymmetrical aerosphere[20]. Detailed arithmetic see also Reference[8].