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Assessment of Several Moist Adiabatic Processes Associated with Convective Energy Calculation

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ABSTRACT

Several methods dealing with the moist adiabatic process are described in this paper. They are based on static energy conservation, pseudo-equivalent potential temperature conservation, the strict pseudo-adiabatic equation, and the reversible moist adiabatic process, respectively. Convective energy parameters, which are closely related to the moist adiabatic process and which reflect the gravitational effects of condensed liquid water, are reintroduced or defined, including MCAPE [Modified-CAPE (convective available potential energy)], DCAPE (Downdraft-CAPE), and MDCAPE (Modified-Downdraft-CAPE). Two real case analyses with special attention given to condensed liquid water show that the selection of moist adiabatic process does affect the calculated results of CAPE and the gravitational effects of condensed liquid water are not negligible in severe storms. Intercomparisons of these methods show that static energy conservation is consistent with pseudo-equivalent potential temperature conservation not only in physical properties but also in calculated results, and both are good approximations to the strict pseudo-adiabatic equation. The lapse rate linked with the reversible moist adiabatic process is relatively smaller than that linked with other moist adiabatic processes, especially when considering solidification of liquid water in the reversible adiabatic process.

Key words: moist adiabatic processes, modified convective available potential energy, downdraft convective available potential energy, modified downdraft convective available potential energy, reversible moist adiabatic process, liquid water

1. Introduction

Two kinds of convective activities—dry convection and moist convention—are often mentioned when referring to severe storm forecasting. Usually dry convection only serves as a kind of adjustment or a lifting condition for severe storms. Moist convection, however, can release large amounts of latent heat, thus giving the storm the ability of self-organization and self-development, so it can be fully developed and maintained for a long life cycle. Thus, moist convection plays a more important role than dry convection.

Ordinarily, three ingredients are needed to produce deep-moist convection: instability, moisture, and lift (McNulty, 1978, 1995; Schultz and Schumacher, 1999). “Remove any one of these and there well may be some important weather phenomena, but the process is no longer deep, moist convection” (Doswell, 1987).

Conditional instability (CI) is the primary condition for most convection. It has been known for at least half a century (Showalter and Fulks, 1943) that CI is a necessary ingredient for the development of thunderstorms. Another kind of instability called convective instability, referring to a vertical temperature structure in which the wet-bulb potential temperature decreases with height, is also very important for local severe storms. This stratification of convective instability in addition to conditional instability allows the upward acceleration of rising parcels of air once these parcels move above the level of free convection (LFC). Numerous stability indices have been developed to measure conditional or convective stability. Examples include the Showalter index (Showalter, 1953), the lifted index (LI) (Galway, 1956) and the index of convective instability (IC). These indices, however, sample only a limited amount of data from an atmospheric sounding. Although some indices of this type, such as the surface-based lifted index (LIs),

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are still used, many have been replaced in recent years with more inclusive indices such as convective available potential energy (CAPE) (Moncrieff and Miller, 1976).

While CI and CAPE delineate the stability of the atmosphere, some other measurements, such as potential instability (PI), conditional symmetric instability (CSI), and potential symmetric instability (PSI), have also been developed to describe different kinds of instability for static or moving atmosphere (Schultz et al., 2000). Although differences still exist in the conceptual definitions of these indices (Sherwood, 2000), CI, PI, PSI, and CSI are nowadays widely used in various ways. Sometimes they are even overemphasized or misused (Schultz and Schumacher, 1999).

All the instabilities mentioned above are closely related to gravitational instabilities in some sense, and the traditional parcel method and Emagram (T-log$p$ diagram) analysis are often employed in their computations.

Among all these instability indices, convective energy parameters—especially CAPE—have become more widely used to denote the instability of the atmosphere (Sherwood, 2000), or used as the trigger condition for convection in mesoscale numerical simulations (Xie, 2002). They are also widely used in cumulus parameterization (Andrew and Michael, 2001). Another convective energy parameter, downdraft convective available potential energy (DCAPE), is believed to be closely linked with storm type (Gilmore and Wicker, 1998).

CAPE and DCAPE theoretically represent the possible intensity that the convection may reach. As they become more widely used, their accurate calculation becomes very important. The calculation of this kind of parameter is closely linked with the moist adiabatic processes, so proper selection of the latter should be made in order to compute the former accurately and at the same time to reflect its physical implications in the calculation.

A pseudo-adiabatic process is often employed to approximate the moist adiabatic process, but it cannot be adopted to deal with condensed liquid water. One of the unreasonable assumptions of the pseudo-adiabatic process is that the condensed liquid water or ice leaves the parcel immediately with the latent heat being left in. This assumption is contradictory to the nature of clouds and their formation. It is well known that liquid water and ice in cloud play very important roles in the evolution of severe storms, and that the effects of liquid water play a very important role in initiating downdrafts. But sensible heats of condensed liquid water and ice are totally neglected in pseudo-adiabatic processes, and they are also ignored in the calculation of convective energy. Even if liquid water and ice are occasionally introduced in some parameters, their sensible heats are rarely considered. In order to overcome these problems, we reintroduce the reversible moist adiabatic process to calculate energy in which both the gravitational effect of liquid water and its sensible heat are taken into consideration. Also, we make a further exploration of the reversible adiabatic process with the solidification of liquid water. DCAPE is reintroduced in this paper. MCAPE and MDCAPE are defined to modify the intensity of ascending and descending flow with consideration of the gravitational effect of liquid water.

A brief review of the physical concept of moist adiabatic processes is presented in Section 2. Several parameters for convective energy are given in Section 3. Two real cases are studied in Section 4 with special attention paid to the convective energy. Intercomparisions are made to find the similarities and differences of these methods in Section 5. Concluding remarks are presented in Section 6.

2. A brief review of the physical concept and mathematical method for moist adiabatic processes

The existence of instability is the primary condition for the generation of convective systems, and the intensity of convection depends on the magnitude of convective energy. The judgment of instability and the calculation of convective energy are closely linked with the selection and calculation of the moist adiabatic process. Traditional Emagram analysis is commonly used when predicting the evolution of convective systems. The key for the Emagram analysis lies in the calculation of the state curve, which usually includes a dry adiabatic line and a moist one. It is easy to deal with the dry adiabatic process according to the conservation of potential temperature. With respect to the moist adiabatic process, there are four general methods to choose from. These are based on static energy conservation, pseudo-equivalent potential temperature conservation, the strict pseudo-adiabatic equation, and the reversible moist adiabatic process, respectively. The second method is the most popular nowadays, especially in China and the U.S.

2.1 *Static energy conservation*

According to the parcel method and theory, static energy of the lifting parcel is conserved in the adiabatic process. The static energy for a saturated air parcel can be expressed as

$$E_{\mathrm{t}} = C_{\mathrm{pd}}T + L_{\mathrm{v}}w_{\mathrm{s}} + \varphi \, , \tag{1}$$

where C_{pd} is the heat capacity of dry air at constant pressure, T is the absolute temperature, L_{v} is the latent heat of condensation, w_{s} is the mixing ratio for saturated atmosphere, $\varphi = gz$ is the potential energy. Note two assumptions are included in Eq. (1). One is that no liquid water nor ice is considered in the air parcel, and the other is that the capacity of water vapor can be neglected. Ordinarily, these assumptions are acceptable and Eq. (1) can be used to solve the moist adiabatic process.

2.2 *Pseudo-equivalent potential temperature conservation*

A pseudo-adiabatic process is one in which all the condensed liquid water quits the parcel at the time it forms, leaving the latent heat in. The equation now admitted by the World Meteorology Organization for the pseudo-adiabatic process is

$$(C_{\mathrm{pd}}+C_{\mathrm{l}}w_{\mathrm{s}})d\ln T-R_{\mathrm{d}}d\ln P_{\mathrm{d}}+d\left(\frac{L_{\mathrm{v}}w_{\mathrm{s}}}{T}\right)=0\ , \quad (2)$$

where P_{d} is partial pressure of dry air, R_{d} is the gas constant for dry air, and C_{l} is the specific heat for water vapor.

Generally speaking, $C_{\mathrm{l}}w_{\mathrm{s}} \ll C_{\mathrm{pd}} + C_{\mathrm{l}}w_{\mathrm{s}}$. If the specific heat of the water vapor is totally neglected, that is, if we consider

$$C_{\mathrm{pd}} + C_{\mathrm{l}}w_{\mathrm{s}} \approx C_{\mathrm{pd}}\ , \quad (3)$$

then we can derive a conservative variable in the moist-adiabatic process:

$$\theta_e = T\left(\frac{1000}{P_{\mathrm{d}}}\right)^{R_{\mathrm{d}}/C_{\mathrm{pd}}}\exp\left(\frac{L_{\mathrm{v}}w_{\mathrm{s}}}{C_{\mathrm{pd}}T}\right)\ . \quad (4)$$

This is the well-known formulation of pseudo-equivalent potential temperature (Durran and Klemp, 1982), and it is widely used to judge the structural instability of the atmosphere (Tian, 1991; Liu et al., 2002).

2.3 *The strict pseudo-adiabatic equation and strict pseudo-equivalent potential temperature conservation*

Equation (3) is the basis for the conservation of pseudo-equivalent potential temperature in which the effect of specific heat of water vapor is negligible. If the specific heat of water vapor is involved in the calculation of the moist adiabatic process, then the corresponding pseudo-equivalent potential temperature becomes

$$\theta'_e = T\left(\frac{1000}{P_{\mathrm{d}}}\right)^{R_{\mathrm{d}}/C_{\mathrm{pd}}}\exp\left(\frac{L_{\mathrm{v}}w_{\mathrm{s}}}{C_{\mathrm{pd}}T}\right) \times\exp\left(\frac{C_{\mathrm{l}}}{C_{\mathrm{pd}}}\int_{T_{\mathrm{t}}}^{T_0} w_{\mathrm{s}}d\ln T\right)\ . \quad (5)$$

We call this the strict pseudo-equivalent potential temperature.

Equation (5) is another form of the strict pseudo-adiabatic equation. We can see θ'_e is a modification of the pseudo-equivalent potential temperature. The modifying factor is composed of an integration of w_{s} times the logarithmic temperature from the lifting condensation level T_0 to a great height T_{t} along the pseudo adiabatic line, and T_{t} is the temperature at a great height on a pseudo adiabatic line, as $z \to \infty, (p \to 0), T_{\mathrm{t}} \to 0$. It can be seen that the true conservative variable in the pseudo-adiabatic process is θ'_e rather than θ_e.

As the calculation of θ'_e is rather difficult, a simpler approximation for θ'_e is recommended by Bolton (1980):

$$\theta'_e = T\left(\frac{1000}{P}\right)^{0.2854(1-0.28w_{\mathrm{s}})} \times\exp[\left(\frac{3376}{T_{\mathrm{L}}}-2.54\right)w_{\mathrm{s}}(1+0.81w_{\mathrm{s}})]\ , \quad (6)$$

where p is the atmospheric pressure and T_{L} is the absolute temperature at the lifting condensation level.

2.4 *Reversible moist adiabatic process*

The moist adiabatic process is reversible when the condensed liquid water and ice are kept in the lifting parcel. The corresponding form for the reversible moist adiabatic process, similar to the pseudo-equivalent potential temperature, including the sensible heat contribution of the condensed liquid water and also that of the water vapor, can be expressed as

$$\theta_q = T\left(\frac{1000}{P_{\mathrm{d}}}\right)^{R_{\mathrm{d}}/C_{\mathrm{pd}}}\exp\left(\frac{L_{\mathrm{v}}w_{\mathrm{s}}}{C_{\mathrm{pd}}T}\right) \times\exp[\frac{1}{C_{\mathrm{pd}}}\int_{T_{\mathrm{t}}}^{T_0}(w_{\mathrm{s}}C_{\mathrm{l}}+w_{\mathrm{l}}C_{\mathrm{l}})d\ln T]\ , \quad (7)$$

where w_{l} is the mixing ratio of liquid water and θ_q is called the liquid water potential temperature.

From Eq. (7) we can see that the specific heat of liquid water is also taken into account in the moist adiabatic process. The differential form of Eq. (7) can be written as

$$d\left[\ln T-\frac{R_{\mathrm{d}}}{C_{\mathrm{pd}}}\ln P_{\mathrm{d}}+\frac{w_{\mathrm{s}}L_{\mathrm{v}}}{C_{\mathrm{pd}}T}+\frac{C_{\mathrm{l}}w_{\mathrm{s}}+C_{\mathrm{l}}w_{\mathrm{l}}}{C_{\mathrm{pd}}}\ln T\right]=0\ . \quad (8)$$

Define M as the entropy divided by C_{pd}, where

$$M=\ln T-\frac{R_{\mathrm{d}}}{C_{\mathrm{pd}}}\ln P_{\mathrm{d}}+\frac{w_{\mathrm{s}}L_{\mathrm{v}}}{C_{\mathrm{pd}}T}+\frac{C_{\mathrm{l}}w_{\mathrm{s}}+C_{\mathrm{l}}w_{\mathrm{l}}}{C_{\mathrm{pd}}}\ln T\ . \quad (9)$$

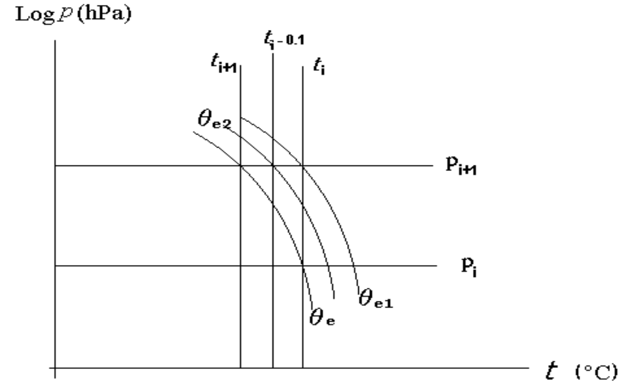

Fig. 1. Illustration of the dichotomy method.

The quantity M is also conserved in the reversible moist adiabatic process, but it is much easier to calculate compared with θ_q.

2.5 *Mathematical method for calculation*

The four methods mentioned above all have different relationships between independent variables in the conservative equations. So the essence of resolving the moist adiabatic process lies in finding a series of temperature values linked with a series of pressure values. The solution is somewhat difficult because of the complicated form of w_{s}. Iteration or a dichotomy method may be used.

Taking pseudo-equivalent potential temperature conservation as an example, the dichotomy method involves the following steps (Fig. 1):

With respect to a definite position (t_i, p_i) in the Emagram, there exists a definite value of pseudo-equivalent potential temperature θ_e. Similarly, a definite θ_{e1} exists with respect to point (t_i, p_{i+1}), and also a θ_{e2} corresponding to position $(t_i - 0.1, p_{i+1})$. According to the concept of the differential, the value of the function varies linearly with one variable's small change if the other variables remain constant. So the temperature t_{i+1} linked with θ_e at level p_{i+1} can be calculated with

$$t_{i+1} = t_i - \frac{\theta_{e1} - \theta_e}{\theta_{e1} - \theta_{e2}} \times 0.1 \,. \tag{10}$$

A series of temperature values related to θ_e can be calculated in this way, and therefore the moist adiabatic process can be resolved.

Similar steps can be taken to deal with total temperature conservation, the strict pseudo-adiabatic equation, and the reversible moist adiabatic process. An integration step is involved in calculating the potential heights on each level according to the hydrostatic approximation when the method is applied to static energy conservation.

3. Several parameters for convective energy

The most important parameter for convection is convective available potential energy or CAPE. CAPE represents the maximum available positive energy that the lifting parcel can acquire from the positive buoyancy of the environment. This kind of energy is positive for convection and can be transformed into vertical kinetic energy. As CAPE theoretically represents the intensity that the convection can reach, it has been put into direct and indirect operational use (Huntrieser et al., 1997; Desautels and Verret, 1996; Li et al., 1998).

However, there are some deficiencies in CAPE when dealing with some convective cases. Among these deficiencies, two are especially apparent. One is that CAPE is a theoretical result in which the gravitational pull on liquid and solid water in the cloud is not considered, thus it often overestimates the positive convective energy. The other is that CAPE has no relationship with downdraft flow that is often generated in severe convective storms and emerges as downbursts or thunderstorm winds. Hence MCAPE and MDCAPE are introduced to tackle such problems.

3.1 *Modified convective available potential energy* (***MCAPE***)

Taking the gravitational effect of the condensed liquid water into consideration, CAPE then can be modified (MCAPE) as

$$E_{\mathrm{MCAPE}} = g \int_{z_{\mathrm{f}}}^{z_{\mathrm{e}}} [\frac{1}{\overline{T}_{\mathrm{ve}}}(T_{\mathrm{va}} - T_{\mathrm{ve}}) - w_{\mathrm{l}}] dz \,, \tag{11}$$

where T_{va} is the absolute virtual temperature of the lifting parcel, T_{ve} is the absolute virtual temperature of the corresponding stratified atmosphere, z_{f} is the height of the free convection level, z_{e} is the equilibrium altitude, $\overline{T}_{\mathrm{ve}}$ is the average absolute virtual temperature between z_{f} and z_{e}, w_{l} is the specific content of liquid and solid water, and g is gravitational acceleration.

The evaluation of w_{l} is a little difficult when calculating MCAPE. One good but somewhat extreme method is to assume that all of the condensed liquid water stays in the parcel, and then the calculation becomes simple. If the temperature of the condensed liquid water varies consistently with that of the parcel, and if the specific heat of water vapor is also taken into account, then the moist adiabatic process is reversible, and we may use the reversible moist adiabatic process to calculate MCAPE.

In fact, the gravitational drag on liquid water is sometimes very important, especially in severe storms.

A crude evaluation of Eq. (11) shows that the downdraft effect of 4 g of liquid water in a 1 kg air-parcel can nearly offset the positive buoyancy generated by 1°C of temperature difference between the air parcel and the environment. Thus the downdraft effect of liquid water and ice cannot be neglected.

3.2 *Downdraft convective available potential energy (DCAPE) and modified downdraft convective available potential energy (MDCAPE)*

One of the most important features of severe storms is that they are always accompanied by both strong upward and downward flows. Downdrafts are the formative mechanisms for thunderstorm wind, micro-downbursts, and low-level wind shear.

When the intrusive dry cold air penetrates into the cloud cell (often in the middle layer of the troposphere), the liquid water in the cloud evaporates and the cloud cell becomes colder there, and downdraft flow occurs. Supposing the downdraft flow descends along the pseudo-equivalent potential temperature line, then DCAPE can be described as

$$E_{\mathrm{DCAPE}} = \int_{z_{\mathrm{sfc}}}^{z_{\mathrm{D}}} \frac{1}{\overline{T}_{\mathrm{ve}}}(T_{\mathrm{ve}} - T_{\mathrm{va}})dz \,, \qquad (12)$$

where z_{D} and z_{sfc} are the height of the downdraft-starting level and the height of the surface level, respectively.

One of the most difficult steps in calculating DCAPE is to judge the temperature of the parcel that starts the downdraft and its corresponding moist adiabatic line. An iso-enthalpy process presumption is suggested to solve this problem (Emanuel, 1994), and the primary temperature of the downdraft parcel equals the wet-bulb temperature there.

The above DCAPE with saturation maintained in the parcel to the ground level theoretically represents the maximum available energy that the downdraft parcel can acquire from the negative buoyancy of the environment. If the gravitational effect of the condensed liquid water is taken into consideration, then MDCAPE can be described as

$$E_{\mathrm{MDCAPE}} = g\int_{z_{\mathrm{sfc}}}^{z_{\mathrm{D}}} [\frac{1}{\overline{T}_{\mathrm{ve}}}(T_{\mathrm{ve}} - T_{\mathrm{va}}) + w_{\mathrm{l}}]dz \,. \qquad (13)$$

Similar to MCAPE, we can use the reversible moist adiabatic process to calculate DCAPE and MDCAPE so as to include the liquid water effect.

4. Two case studies

We choose two severe convective storms to show the calculations of moist adiabatic processes and their effects on convective energy. Furthermore, we employ Emagram analysis to deepen the understanding of these parameters.

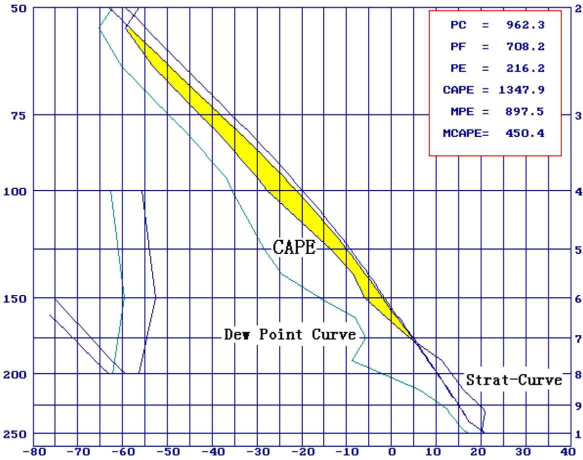

Fig. 2. Emagram (T-log$p$ diagram) for a Beijing rawinsonde at 0000 UTC 9 June 1998. The abscissa is temperature in degrees Celsius. The ordinates are logarithmic pressure (hPa). Two state curves are drawn, the relatively left one is calculated according to pseudo-equivalent temperature conservation, and the other is the reversible moist adiabatic line.

4.1 *Case 1: A hail event*

Figure 2 shows the Emagram of a Beijing rawinsonde observation at 0000 UTC 9 June 1998. Two moist adiabatic lines are drawn, one based on the conservation of pseudo-equivalent potential temperature and the other based on the reversible moist adiabatic process. A severe hail storm event occurred in the eastern part of Beijing that afternoon.

Assuming the parcel rises from the surface level $p = 1003.0$ hPa, $t = 21.0$°C, $t_{\mathrm{d}} = 18.2$°C, then the lifting condensation level (PC) is 962.3 hPa. Taking the pseudo-equivalent potential temperature conservation as an approximation to the moist adiabatic process, the level of free convection (PF) is 708.2 hPa and the equilibrium altitude (PE) is 216.2 hPa, CAPE is 1347.9 J kg^{-1} and MCAPE is 450.4 J kg^{-1}. The drag effect of condensed liquid water (MPE) offsets 897.5 J kg^{-1} of buoyant work.

If the reversible moist adiabatic process is chosen, then the level of free convection descends to 713.0 hPa and the equilibrium altitude is 206.8 hPa, CAPE increases to 1944.4 J kg^{-1}, and MCAPE increases to 1019.5 J kg^{-1}. We can see that the choice of method does affect the calculated values of convective energy.

If the reversible moist adiabatic process is adopted and there is no liquid water in the lifting parcel at the beginning, then the specific humidity is 7.94 g kg^{-1}

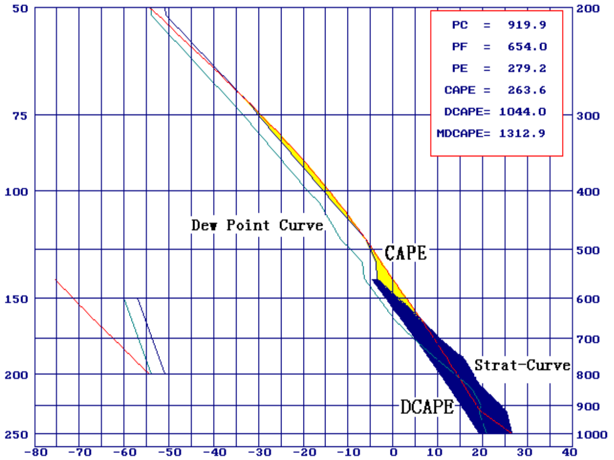

Fig. 3. Emagram for a Beijing rawinsonde at 1200 UTC 3 Aug 1998. The surface observation p = 1000.0 hPa, t = 26.8°C, $t_{\rm d}$ = 21.2°C is taken as the lift-starting point. The dark shadow represents the downdraft convection available potential energy.

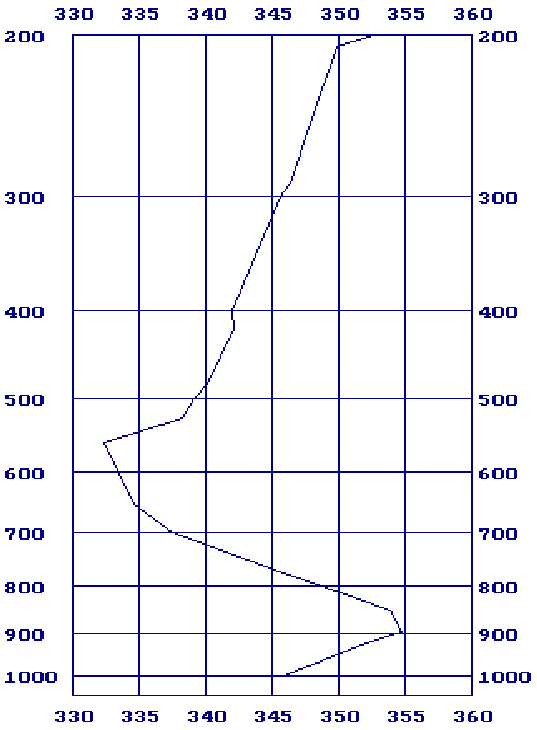

Fig. 4. Vertical profile of pseudo-equivalent potential temperature for the Beijing rawinsonde observation of Fig. 3. The abscissa is temperature in degrees Kelvin.

and the specific content of liquid water is 5.02 g kg^{-1} when it gets to the level of free convection. As it reaches the equilibrium altitude, the specific humidity is 0.05 g kg^{-1} and the specific content of solid (liquid) water reaches 12.91 g kg^{-1}. The energy reduction in the downdraft owing to the presence of adiabatic liquid water and ice from the free convection level to the equilibrium altitude is 924.9 J kg^{-1}. This reduction is of the same magnitude as CAPE itself, and thus cannot be neglected.

Furthermore, differences can obviously be seen between these two adiabatic lines at upper levels. Note that the lapse rate of the reversible moist adiabatic process is slower than that of the pseudo-equivalent potential conservation. The two lines are very close in the lower levels.

4.2 *Case 2: A thunderstorm wind event*

Figure 3 shows the Emagram of a Beijing rawinsonde observation at 1200 UTC 3 August 1998. A thunderstorm with strong surface wind occurred in Beijing around 1400UTC that evening.

Taking the surface observation p = 1000.0 hPa, t = 26.8°C, $t_{\rm d}$ = 21.2°C as the initial lifting point, the lifting condensation level is 919.9 hPa. If pseudo-equivalent potential temperature conservation is chosen, then the free conservation level is 654.0 hPa, the equilibrium altitude is 279.2 hPa, and CAPE is 263.6 J kg^{-1}.

Figure 4 shows the vertical profile of the pseudo-equivalent potential temperature for this case. We can see a relatively dry and cold intrusion at level p = 557.0 hPa. We can take p = 557.0 hPa, t = −3.5°C, $t_{\rm d}$ = −6.3°C as the starting point for the downdraft. The wet-bulb temperature at this level can be obtained through the calculation of an iso-enthalpy evaporation process there, giving us −4.8°C. The downdraft line is calculated according to the reversible moist adiabatic process.

If 10.0 g kg^{-1} of liquid water is assumed to be in the parcel before the iso-enthalpy evaporation process, then the temperature of the parcel reaches 18.9°C when it descends to the surface level, with DCAPE reaching 1044.0 J kg^{-1}. The liquid water in the downdraft parcel evaporates gradually in the reversible moist adiabatic process in order to maintain the saturated state of the parcel. The remaining specific content of liquid water is 1.0 g kg^{-1} when the downdraft parcel reaches the surface. The accumulated work of the gravitational effect on the downdraft liquid water reaches 268.9 J kg^{-1} and the modified downdraft convection available potential energy (MDCAPE) is 1312.9 J kg^{-1}.

The value of DCAPE based on the pseudo-equivalent potential temperature conservation is a little smaller than that based on the reversible moist adiabatic process. This is easily explained by the smaller temperature changes during the descending process compared to the ascending process.

In this case, if CAPE is really as little as we calculated, the storm would not become intense, and the

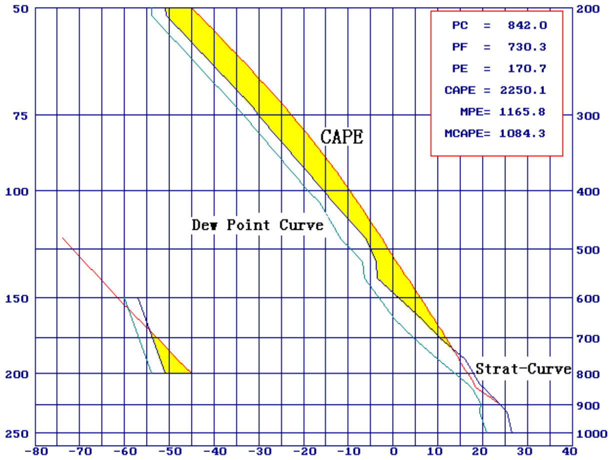

Fig. 5. As in Fig. 3, using a different lift-starting point: $p = 897.0$ hPa, $t = 23.8$°C, $t_{\rm d} = 19.5$°C.

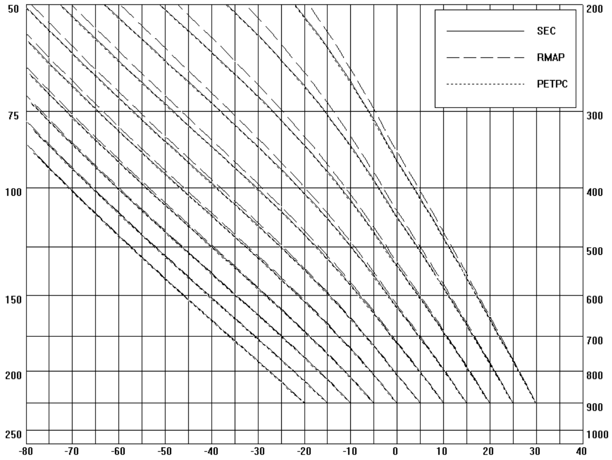

Fig. 6. Intercomparisons of different methods for moist adiabatic processes: static energy conservation lines (solid: SEC), pseudo-equivalent potential temperature conservation lines (dotted: PEPTC), and reversible moist adiabatic process lines (dashed: RMAP). Note that the first two sets of lines are superimposed and cannot be easily distinguished.

downdraft would not become very strong. Taking the surface as the lifting point is not relevant in this case because the sounding was taken through the cold pool. Many researchers in recent years take the average thermal and moisture characteristics of the lowest 100 hPa layer to calculate CAPE. As is well known, thunderstorms are caused by the release of elevated CAPE due to instability in the middle-lower layer atmosphere, so we could take the most unstable point in the lowest 300 hPa layer as the lifting point, just as Rochette (1999) did. In this case, we see from Fig. 4 that the unstable layer exists between 897.0 hPa to 557.0 hPa because of the decrease of pseudo-equivalent potential temperature. Taking the significant point $p = 897.0$ hPa, $t = 23.8$°C, $t_{\rm d} = 19.5$°C as the lifting point and taking the reversible moist adiabatic process as the method, then the Emagram changes significantly with CAPE dramatically increasing (Fig. 5). The lifting condensation level is 842.0 hPa, the free convection level is 730.3 hPa, the equilibrium altitude is 170.7 hPa, and CAPE reaches 2250.1 J kg^{-1}. The reduction energy owing to the presence of liquid water in the downdraft (MPE) is 1165.8 J kg^{-1} and MCAPE is 1084.3 J kg^{-1}. When the lifting parcel reaches the equilibrium altitude, the theoretical vertical velocity that the lifting parcel may reach is 46.6 m s^{-1}.

5. Further exploration of the similarities and differences of the moist adiabatic processes

From the last section, we can see differences between selections of the moist adiabatic process. In order to study these differences, we make further explorations. We choose 900 hPa as the lifting level and choose eleven different lifting temperatures (from 20°C to 30°C with an interval of 5°C). Furthermore, in order to simplify the calculations and comparisons, we assume air parcels are saturated there.

Figure 6 shows three sets of moist adiabatic lines corresponding to pseudo-equivalent potential temperature conservation, static energy conservation, and the reversible moist adiabatic process, respectively. It can be seen that the moist adiabatic lines corresponding to the pseudo-equivalent potential temperature conservation are very close to or even superpose those lines related to static energy conservation. This is to be expected since latent heats are both considered while specific heats of water vapor are both ignored in these two processes. In fact, static energy conservation and pseudo-equivalent potential temperature conservation are actually different measures for nearly the same physical process. However, things become quite different with respect to the reversible moist adiabatic lines. Although they are very close to the pseudo-equivalent potential temperature lines with respect to low 900 hPa lifting temperatures, obvious differences can be seen at high 900 hPa temperatures, especially at the high levels. This is easily explained by larger sensible heats accumulation due to more liquid water and relatively large temperature variations. Additionally, solidification of liquid water is ignored in the reversible adiabatic process here.

Figure 7 shows three sets of moist adiabatic lines corresponding to the reversible adiabatic process, pseudo equivalent potential temperature conservation, and strict pseudo adiabatic process, respectively. We can see the strict pseudo adiabatic lines lie between

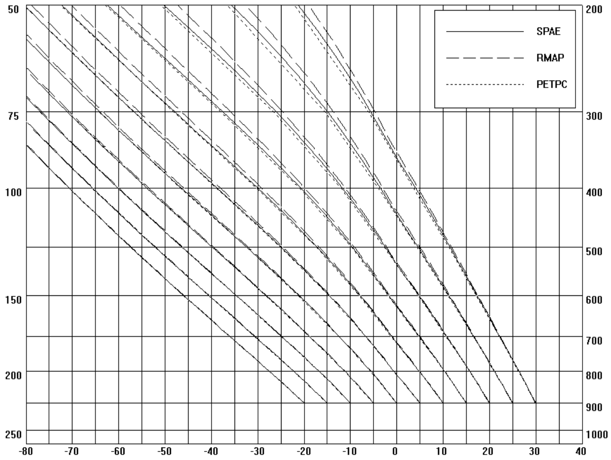

Fig. 7. Reversible moist adiabatic process lines (dashed: RMAP), pseudo-equivalent potential temperature conservation (dotted: PEPTC), and the strict pseudo adiabatic lines (solid: SPAE).

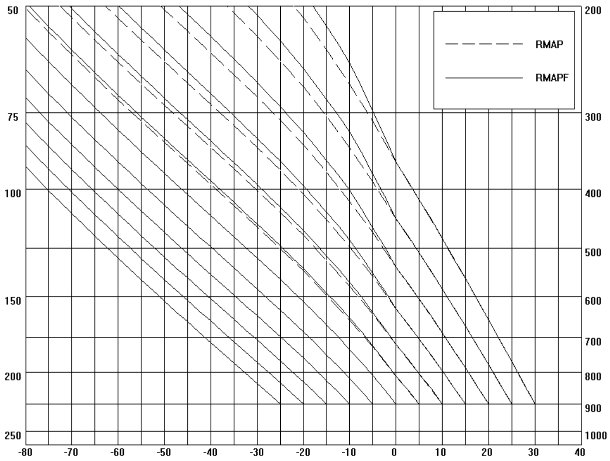

Fig. 8. Comparison of two kinds of reversible adiabatic process. One set of lines are ordinary (dashed: RMAP), the others are reversible adiabatic lines with liquid water solidification (solid: RMAPF).

pseudo equivalent potential temperature lines and reversible moist adiabatic ones, just as they are expected. The lapse rates of the reversible adiabatic process are smaller than the other moist processes for high 900 hPa temperatures, and the lapse rates of the strict pseudo adiabatic process are slightly smaller than the pseudo equivalent potential temperature process. When the lifting temperatures are low, the strict pseudo adiabatic lines are very close to the pseudo equivalent potential temperature lines. Moreover, we can see the differences between the reversible adiabatic lines and the strict pseudo adiabatic lines are larger than those between the pseudo equivalent potential temperature lines and the strict pseudo adiabatic lines. Thus, pseudo equivalent potential temperature conservation is a good approximation to the strict adiabatic process compared to the reversible adiabatic process.

In all the reversible moist adiabatic processes mentioned above, we ignore the solidification of condensed liquid water. Actually, the condensed liquid water may solidify when the temperature is below 0°C, and the heat of solidification may warm the air parcel, thus affecting the buoyancy (Williams and Renno, 1993).

Generally, liquid water can exist in convective cloud till the temperature reaches −40°C. In order to be more acceptable, we assume the liquid water starts solidifying below 0°C, and it becomes totally frozen when the temperature reaches −20°C. To simplify the calculation, we assume the solidifying process is linear, or that the liquid water diminishes linearly. This kind of reversible adiabatic process is more acceptable in theory than solidification being totally ignored.

Figure 8 presents the two kinds of reversible adiabatic process: one is calculated according to the ordinary reversible adiabatic process, the other is calculated according to the reversible adiabatic process with liquid water solidification. We can see the lapse rates are obviously smaller when considering solidification, especially to high 900 hPa temperatures. It is easily explained by the large quantity of heat due to sufficient liquid water solidification. For the same reason, we can see the sudden decrease of lapse rates with respect to solidification of liquid water between 0°C and −20°C. This result agrees with Saunders (1957), and may be invoked to interpret the behavior of a cumulonimbus whose growth suddenly increases shortly after the first traces of glaciation in its summits.

6. Conclusions

Several methods can be applied in dealing with the moist adiabatic process. Liquid water and ice are not considered in static energy conservation, pseudo-equivalent potential temperature conservation, and the strict pseudo-adiabatic equation. Therefore, these three methods are not reversible.

Two assumptions are used in the method of pseudo-equivalent potential temperature conservation: one is that the specific heat of water vapor is negligible, the other is that all the condensed liquid water quits the parcel immediately, leaving the latent heat in. The use of this method is popular, especially in China and the United States. Static energy conservation and the pseudo-equivalent potential temperature conservation are nearly the same process, and their calculated results are very similar.

The specific heat of water vapor is considered in the strict pseudo-adiabatic equation. So the lapse rate of the strict pseudo-adiabatic process is slightly smaller than static energy conservation and pseudo-equivalent potential temperature conservation, and it is larger than the reversible moist adiabatic process. And we recommend the original form of the equation when dealing with the strict pseudo adiabatic process.

In fact, convection in the atmosphere is always accompanied with more or less liquid water and ice. If the condensed liquid water and its sensible heat are considered, the moist adiabatic process is reversible and can be viewed as the reversible moist adiabatic process in thermodynamics.

There are little differences between these four methods when the initial temperatures of lifted air parcels are low. With respect to high initial temperatures, the differences are not very obvious in lower levels of the atmosphere. When they are lifted to high levels, the reversible moist adiabatic lines are distinguished by relatively smaller lapse rates of temperature due to the total sensible heats of the accumulated liquid water. When considering the heat of solidification of the large quantity of liquid water, the lapse rate is even slower and the convective energy becomes larger correspondingly. This may be one of the reasons why very strong hailstorms can develop.

The selection of the moist adiabatic process significantly affects the calculation of convective energy. The pseudo-equivalent potential temperature conservation and static energy conservation are good approximations to the strict pseudo adiabatic process, and pseudo-equivalent potential temperature conservation is traditionally adopted in the calculation of CAPE. MCAPE is the modified form of CAPE with the gravitational effect of the condensed liquid water. With the consideration of liquid water, the reversible moist adiabatic process is therefore a relatively reasonable choice.

DCAPE is a parameter that reflects the potential intensity of downdraft flow. The presumption of the downdraft descending along the pseudo-equivalent potential temperature line is not reasonable. Since the downdraft is caused by the evaporation of liquid water in the middle layers, we can assume the downdraft descends along the reversible line with the evaporation of sufficient liquid water. MDCAPE is a modified form of DCAPE with the downdraft effect of liquid water.

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