A model of the development of droplet effective radius in convective cloud

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SUMMARY

A model is presented of a growing cumulus turret which is used to investigate the sensitivity of the droplet effective radius in a convective cloud to variations in the cloud-base temperature, the liquid-water content, the vertical wind speed at cloud base, the cloud condensation nucleus (CCN) spectrum entering the cloud base, and dry-air entrainment. It is found that the existence of large quantities of dry-air entrainment has a major impact on the evolution of the cloud microphysics. Near to the cloud base the growth of newly nucleated droplets causes a rapid increase in the droplet effective radius with height. Higher in the cloud, dry-air entrainment results in new nucleation of small droplets at all heights in the cloud and the complete evaporation of some of the pre-existing droplets. The effect of this is that the horizontally averaged effective radius becomes a very weak function of height. The value of the effective radius is most strongly influenced by the CCN spectrum entering through the cloud base. This means that differences between oceanic and continental clouds are reflected in different values for the effective radius. The effects of entrainment do, however, tend to reduce the sensitivity of the effective radius to the initial CCN spectrum. In addition, the very broad droplet-size distribution produced by the effects of entrainment may be very important in the development of the ice phase in these clouds. The droplet effective radius produced by the entraining model is less sensitive to temperature than the effective radius predicted by adiabatic growth. The result is also insensitive to differences between the CCN distribution entering the cloud base and the CCN population entrained from the environment within reasonable limits.

1. INTRODUCTION

The treatment of clouds in atmospheric general circulation models has been substantially improved. Mitchell et al. (1989) have shown, using a sophisticated cloud parametrization scheme, that the role of clouds is very important in determining the sensitivity of climate to changes in the concentrations of greenhouse gases. It has been shown, by Slingo (1990) for example, that the radiative properties of clouds are very sensitive to the droplet-size distribution in the cloud. This is often represented by an effective radius, defined as

\[ R_{\text{eff}} = \frac{\sum_i (n_i r_i^2)}{\sum_i (n_i)} \]

where \( n_i \) is the number of droplets of radius \( r_i \). The droplet effective radius is strongly influenced by the number and size distribution of cloud condensation nuclei (CCNs) entering the cloud base and the updraught speed near the cloud base which will determine the peak supersaturation achieved, and hence the number of cloud droplets which are activated. Consequently, for a given liquid-water content, the effective radius will be very different over land and oceans and will vary between different cloud types. In addition, it has been demonstrated that the mixing of a cloud with its environment can have a major influence on its microphysics and dynamics (Baker et al. 1980; Hill and Choularton 1985; Blyth and Latham 1985; Bower and Choularton 1988). The effects of dry-air entrainment tend to have a much greater influence on the droplet effective radius and liquid-water content in convective clouds than in layer clouds, as discussed by Bower.

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and Choularton (1992). Although not as widespread over the oceans as stratocumulus, convective clouds cover extensive regions of the tropical and mid-latitude oceans and continents.

In this paper a model of convective cloud is used to investigate the importance of the mixing process in determining droplet effective radius. This is compared with the influence of the cloud-base vertical wind and the CCN spectrum on effective radius.

2. THE MODEL

The model that is used is a development of the one presented by Hill and Choularton (1986). The essential physics are summarized in a schematic diagram of the model, see Fig. 1.

The main details of the model are as follows. Starting at cloud base, a cloud parcel (henceforth referred to as the cloud) is initially allowed to rise adiabatically until after a random time interval a volume of dry environmental air is entrained. The model then

![Diagram of the entrainment process in the cloud model.](image)

**Figure 1.** A schematic diagram of the entrainment process in the cloud model.
becomes two interacting cloud models in which the momentum, water vapour, heat and microphysics of the surrounding cloud are mixed into the entrained blob. The blob becomes saturated, and continues to rise in the model if the entrained momentum is sufficient to overcome the negative buoyancy generated by the evaporation of liquid water. A brief pulse in supersaturation develops until CCNs (produced either by evaporation of cloud droplets or by entrainment in from the environment with the parcel) become activated. The growth of cloud droplets mixed into the region during this period is also calculated.

After a further time interval another entrainment event occurs. A blob of dry air, again with the properties of the environment at the new level of entrainment, is mixed into the cloud. The old entrained region now assumes the role of the cloud which then begins to mix into the new blob. The cloud continues to evolve in this way until the whole cloud entity becomes negatively buoyant and the model run is terminated.

The equations describing the development of the cloud are dependent on the state of evolution of the cloud. The growth of the cloud before the first entrainment event, and the subsequent growth of the cloud region surrounding the entrained blob, are described by the general equations governing the evolution of a one-dimensional cumulus turret (e.g. as given in Pruppacher and Klett (1978)). These will not be reprinted here. The droplet-growth equation was used in the modified form presented by Hill and Choularton (1986). This avoids the need for any specific knowledge about the chemical composition and mass distribution of the initial aerosol spectrum.

When a blob of dry air is entrained into the cloud it mixes rapidly with the surrounding cloud as discussed in Hill and Choularton. The blob entrains momentum, heat and water (vapour and liquid) from the surrounding cloud. The equations describing this are as follows.

\[
\frac{dW_b}{dt} = \frac{g}{(1 + \gamma)} \frac{\left(T_{vb} - T_v\right)}{T_v - q_{vb}} + \left(M_b(1 + \gamma) - W_v\right) - W_b.
\]

If the blob is unsaturated

\[
\frac{dT_b}{dt} = M_b(T_c - T_v) - M_b L \frac{q_{vb}}{c_p} - gW_b/c_p.
\]

If the blob is saturated

\[
\frac{dT_b}{dt} = M_b(T_c - T_v) - gW_b/c_p - \frac{L}{c_p} \frac{dq_{vb}}{dt}
\]

\[
\frac{dq_{vb}}{dt} = M_b(q_c - q_v).
\]

Here subscripts b and c refer to the blob and the surrounding cloud respectively, and primed parameters refer to environment values. Hence, \(T_c\) and \(T_v\) are the virtual temperatures of the cloud and the environment respectively. \(T\) is the standard dry-bulb temperature and \(W\) is the vertical velocity. \(q_v\), \(q_l\) and \(q\) are the vapour, liquid water and total water mixing ratios respectively. \(M_b\) is the mixing rate between the blob and the cloud and is set at 0.06 s\(^{-1}\). The constant \(\gamma\) is set equal to 0.5 and takes account of the reaction force on the parcel due to the displacement of surrounding air. \(L\) is the latent heat of vaporization, \(c_p\) the specific heat of dry air at constant pressure, \(t\) the time and \(g\) the acceleration due to gravity.

The equations in the model were integrated forward with a time step of 0.01 s. For the model runs presented, water vapour, momentum, liquid water and heat were mixed into the entrained volume every second. Cloud droplets were mixed in at time intervals of 10 seconds for computational economy. This latter assumption has very little effect on the results obtained (as discussed in detail in Hill and Choularton (1986)).
The CCN spectrum used as the cloud-base input in the model consists of 24 size categories, requiring a minimum supersaturation of 2% for all categories to activate. This is much higher than the maximum supersaturation produced in the modelled cloud and ensures that some categories remain unactivated. The concentration of CCNs in the entrained environmental air was set at one fifth of the corresponding sub-cloud-base value. This is a rather arbitrary assumption but makes allowance for the commonly observed altitude changes with cleaner air aloft. The sensitivity of the results to this assumption is examined.

As discussed in Hill and Choularton, the model is well able to reproduce droplet-size distributions observed in growing cumulus turrets. It is also capable of simulating the non-homogeneous microphysical structure observed in different regions of these clouds. In a single run, however, the model is not able to reproduce the average cloudpass parameter values at any particular level in a cloud (as reported, for example, in Bower and Choularton (1992)). To simulate these pass-average observations, the model was run a number of times for a given set of atmospheric conditions, but with variations in the rate at which entrainment events occurred. Nine or ten runs of the model were seen to be sufficient to reproduce sensible pass-average values of liquid-water content, droplet-number concentration and droplet effective radius as a function of height above the fixed cloud base.

3. RESULTS

Figure 2 shows a sample output from the model. The results are a combination of ten runs of the model, which differed only in the rate (and hence altitudes) at which blobs of dry air were introduced into the cloud (i.e. the interval between the occurrence of entrainment events was different). All runs were initiated at the same cloud-base altitude of 2.2 km. This was chosen so as to correspond to the observed cloud base of

![Figure 2. Droplet effective radius plotted against height above cloud base for the standard continental case (see Table 1). Curve (a) is for adiabatic growth, curve (b) the mixing-model predictions.](image-url)
clouds studied during the Cooperative Convective Precipitation Experiment (CCOPE) on 20 June 1981. Other input conditions were also chosen so that the cloud properties were comparable with those observed on that day. These conditions, including the environmental profile, are summarized in Table 1. The ten model runs represent different mixing histories which could possibly be observed within different parts of the same cloud.

**Table 1. The Input Conditions for the Model Run for the Standard Case**

| Cloud base | | |
|------------|-----------|-------------|----------|-----|
| Temperature | CCN distribution | Updraught | Height | Pressure |
| 287 K | $C = 900 \ k = 0.5$ | 3.5 m s$^{-1}$ | 2200 m | 770 mb |

<table>
<thead>
<tr>
<th>Environmental profile</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Height (m)</td>
<td>Temperature (K)</td>
<td>Water vapour mixing ratio (kg kg$^{-1}$)</td>
</tr>
<tr>
<td>1940</td>
<td>290</td>
<td>0.01</td>
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<tr>
<td>3020</td>
<td>281</td>
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<td>5960</td>
<td>260</td>
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</table>

The CCN distribution is in the standard form of $N = C s^k$, where $N$ is the number of droplets activated, $C$ the number of droplets activated at 1% supersaturation, $s$ the supersaturation, and $k$ the power constant. At each height the CCN concentration was set at 1/5 of the cloud-base value.

Figure 2 shows a comparison between the droplet effective radius as a function of height predicted by the model and the results predicted from an adiabatic parcel rising from the cloud base. The adiabatic parcel had the same updraught as the cloud model in the vicinity of the cloud base, but a much higher vertical wind speed at higher levels in the cloud. This, however, does not affect the microphysical evolution of the adiabatic cloud. It can be seen that the droplet effective radius in the model increases with height above the cloud base in the region close to the cloud base. At higher levels in the cloud (more than about 500 m above cloud base) the scatter in effective radius is increased, tending to mask a slight upward trend. This upward trend is very much less than the upward trend in the effective radius predicted by the adiabatic model.

The reasons for this behaviour in the model are as follows.

1. Close to the cloud base the adiabatic growth of small droplets, forming on the spectrum of CCNs activated at the cloud base, dominates. The growth of these droplets continues up through the cloud in the adiabatic case.

2. Higher in the cloud the form of the droplet-growth equation dictates that the rate of increase in radius of the larger droplets is smaller. This is true both for the cloud and adiabatic models.

3. The entrainment of the dry-air parcels has two effects. Firstly, many droplets from the surrounding cloud are completely evaporated as they mix into the undersaturated air. This means that the mean droplet lifetime is reduced so that the growth of the majority of droplets is retarded. Secondly, new nucleation of small droplets also occurs as the upward-moving entrained parcel becomes supersaturated. This ensures that at any level in the cloud some newly activated very small droplets are to be found.
At any level in the cloud, therefore, the average droplet spectrum will consist of some small recently activated droplets produced by the most recent mixing event. A larger number of medium-sized droplets, dispersed over a range of sizes that were activated following earlier mixing events, will also be present. Finally, there will be a smaller number of droplets that will have survived unevaporated from the cloud base. These droplets will be larger than they would have been in a purely adiabatic cloud as a result of experiencing the supersaturation peaks following the mixing events in which new droplets were activated.

Figure 3 presents a typical droplet spectrum produced by the model after several mixing events, illustrating the features discussed above. This is compared with the adiabatic spectrum at the same altitude. On the graph, region 1 corresponds to droplets that have been recently activated following the most recent entrainment event, region 2 corresponds to the bulk of medium-sized droplets that were activated in earlier mixing events, and region 3 contains a few droplets that have survived from the cloud base and are now larger than they would have been after purely adiabatic growth. This behaviour is observed in real clouds (see below).

4. Comparison of model results with field data

The data presented in Figs. 2 and 3 approximately model the conditions prevailing during the CCOPE. The variation of effective radius with height in these clouds has been discussed by Bower and Choularton (1992). Essentially a near-constant effective radius with increasing height in the cloud is observed away from the near-cloud-base region. Figure 4 shows the variation of droplet effective radius with height obtained from a series of aircraft passes at different heights through a field of cumulus clouds. Each data point represents the average value of the droplet effective radius for a complete horizontal pass.

![Comparison of the model and adiabatic droplet spectra 2.8 km above cloud base. Regions 1, 2 and 3 represent different droplet histories (see text).](image-url)
Figure 4. Pass-averaged values of droplet effective radius plotted against height above cloud base from the Cooperative Convective Precipitation Experiment.

Figure 5 presents droplet-size distributions from two neighbouring regions of cloud from the CCOPE, one region of which was suspected (see Bower and Choularton (1988)) to have recently been affected by dry-air entrainment (curve (a)) and the other less recently affected (curve (b)).

The nearly constant droplet effective radius for a wide range of heights above the cloud base, predicted by the model and observed in the real cloud, may be explained in very much the same way. When a dry blob is entrained it is initially a droplet-free volume which is gradually humidified by the evaporation of droplets from regions of cloudy air in the immediate vicinity of the blob and mixing into it. When the blob becomes saturated a droplet-size distribution develops that is similar to that of the surrounding cloud as further parcels are mixed in, but the parcel has a much lower number concentration. If the blob has sufficient momentum and buoyancy to ascend, a supersaturation develops and CCNs either entrained with the blob, or generated by the evaporation of droplets mixed in from the surrounding cloud, are activated. This produces a bimodal spectrum (see Fig. 3 for the model and Fig. 5 for the real cloud) but the small droplets initially contribute very little to the droplet effective radius. The data from the two neighbouring regions in the real cloud (Fig. 5) show, consistent with the argument presented above, that the region which has most recently suffered entrainment contains fewer medium-sized droplets (as a result of evaporation and dilution) but more of the smallest droplets (as a result of recent evaporation).

5. Model sensitivity studies

(a) Sensitivity of the model results to changes in the CCN activity spectrum

(i) Sensitivity to the cloud base CCNs. Figure 6 illustrates how predicted values of cloud effective radius, and adiabatic comparison values, vary with height above the cloud base
Figure 5. Cloud droplet size distributions from two neighbouring regions of cloud observed during the Cooperative Convective Precipitation Experiment. Curve (a) represents a spectrum from a region of cloud recently affected by entrainment, curve (b) represents a spectrum from a region of cloud less recently affected by entrainment.

for two different CCN activity spectra, corresponding to an extremely continental and a mixed maritime and continental case (Figs. 6(a) and 6(b) respectively). These should be compared with the continental case of Fig. 2. In each case the entrained CCN population from heights above the cloud base was set at 20% of the number entering at cloud base. In all other respects the initial conditions for the runs were unchanged. It is immediately apparent that whilst the effective radius is smaller at a given height above cloud base in the more continental cases (because of the larger number of CCNs activated) the sensitivity of the model predictions to the activity spectrum is much less than for the adiabatic predictions. This is due to the nature of the mixing process and the secondary activation of CCNs higher in the cloud.

An important feature of the secondary activation process is that it occurs in the presence of substantial numbers of droplets entrained from the surrounding cloud. For a given mixing rate the total droplet surface area in the blob is larger in a continental cloud than in a maritime cloud. This is due to the larger number of smaller droplets in the continental cloud than in the maritime cloud for a given liquid-water content. The net effect of this is that, during the secondary activation events, the peak supersaturation in the continental cloud is suppressed relative to the maritime cloud. This further reduces the number of new droplets activated in the continental cloud and reduces the differences in droplet number concentration and effective radius between the maritime and continental cumulus clouds.

(ii) Sensitivity to entrained CCNs. Very few measurements of CCN activity spectra as a function of altitude in the atmosphere are available in the literature.

A sensitivity analysis was carried out to examine how varying the proportion of the cloud base CCNs found in the entrained air parcels affected the predicted variation of droplet effective radius with height above cloud base for the continental CCN case.
Values of 1/3 and 1/8 of the cloud-base number concentration were used (in comparison with the 1/5 value used in the standard case of Fig. 2) as the entrained concentrations of CCNs respectively. The results obtained were seen to be very insensitive to this parameter. The reasons for this are, firstly, that many of the CCNs available for secondary activation in the region affected by entrainment are produced by evaporation of droplets
from within the cloud. Secondly, the same negative feedback mechanism to changes in the CCN spectrum discussed in the preceding section (i.e. the differences in peak supersaturation developed in the presence of different numbers of CCNs and different numbers of residual droplets) limits the sensitivity of the entraining model to changes in the CCN activity spectrum.

(b) Sensitivity of the results to changes in the temperature of the atmosphere

The radiative properties of clouds will change as the temperature and vapour content of the atmosphere increase. At higher temperatures adiabatic liquid-water contents will be larger. It is, therefore, important to assess any changes in droplet effective radius that may enhance or reduce this change in the optical properties of the cloud.

To investigate this sensitivity, the standard version of the model with continental CCNs (Fig. 2) was run with cloud-base temperatures firstly reduced by 10 degC and secondly increased by 5 degC. In each case the environmental temperatures were also reduced by 10 degC and increased by 5 degC respectively. The water vapour mixing ratio in the environment was adjusted so that the relative humidity remained unchanged. The results of this study, again comparing the calculated droplet effective radius as a function of height to the adiabatic calculation, are presented in Figs. 7(a) and 7(b). Considering first the adiabatic results, it is immediately obvious that the predicted effective radius for a given height increases at higher temperatures owing to higher liquid-water contents with similar droplet number concentrations. In the case of the entraining model, however, this sensitivity is much reduced with only a small variation in the droplet effective radius occurring over this wide variation in temperature. The main reason for this is that well above cloud base, the model predicts that the liquid-water contents in the warmer clouds are similar to those in the colder clouds (i.e. around 1 g m\(^{-3}\) at all levels, as opposed to greater than 4 g m\(^{-3}\) in the adiabatic clouds in the vicinity of the cloud top). This is because the increased water vapour deficit in the warmer dry entrained air eventually overcomes the higher liquid-water contents produced by the ascent of the warmer saturated cloud-base air.

(c) Sensitivity of the results to changes in the environmental humidity

Figure 8 illustrates the effect of halving the water vapour mixing ratio of the environmental humidity profile (presented in Table 1) on the variation in droplet effective radius with height above cloud base. This is again compared with the adiabatic prediction on the same graph. Comparing this figure with the results for the model under standard conditions (Fig. 2) it can be seen that the effect of reducing the environmental humidity further reduces the sensitivity of the effective radius to variations in height above cloud base. This is achieved by increasing the fraction of cloud droplets evaporated in the entrained dry air and so further reducing the average lifetime of the droplets in the cloud. Dryer entrained air also results in a loss of buoyancy in the cloud, which reduces the vertical velocity and may inhibit its vertical growth. Overall, however, the sensitivity of the droplet effective radius to this parameter is not large. Even with this very large change in environmental humidity the effective radius is only reduced by 1 \(\mu m\) close to the cloud top. The effects of increasing the relative humidity are of a similar magnitude. Even if the entrained air is assumed to be saturated with respect to water, the droplet effective radius still falls markedly below the adiabatic value. This is because of the dilution effect of the entrained cloud-free parcels followed by the activation of newly entrained CCNs.
Figure 7. Droplet effective radius plotted against height above cloud base, illustrating the effects of changing the cloud-base temperature. (a) Cloud-base temperature 10 degC colder than the standard case and (b) cloud-base temperature 5 degC warmer than the standard case. In each case curve (a) is the adiabatic prediction and curve (b) the mixing-model prediction.

(d) Sensitivity of the results to changes in the updraught at the cloud base

The updraught in the region of the cloud base for all previous model runs was around 3.5 m s⁻¹. In order to investigate the sensitivity of the results to this parameter the temperature at the cloud base was raised by 5 degC without altering the environmental temperature. All other parameters were as presented in Table 1. This had the effect of
Figure 8. Droplet effective radius plotted against height above cloud base, illustrating the effects of reducing the environmental humidity. In this case the environmental mixing ratio is set at half the standard-case values for all heights above the cloud base. Curve (a) is the adiabatic prediction and curve (b) the mixing-model prediction.

raising the updraught at the cloud base to about 6 m s\(^{-1}\) and resulted in the activation of more droplets at the cloud base.

The results are presented in Fig. 9 which shows a comparison between the model predictions and the adiabatic cloud. For the adiabatic cloud the droplet effective radii are only very slightly larger than for the standard case (Fig. 2) owing to a higher liquid-water content associated with the warmer cloud. The effects on the droplet effective radius in the mixing model are, however, greater. This is particularly true higher up in the cloud, where the increased temperature difference between the cloud and the environment results in very high updraughts of 22 m s\(^{-1}\) compared with 14 m s\(^{-1}\) for the standard case. This causes a larger number of droplets to be activated following the mixing events. This reduces the average effective radius by at least 1 µm and considerably increases the scatter between successive pass-average predictions.

6. DISCUSSION

A model has been presented that is able to reproduce the observations in convective clouds which indicate that, except in the lowest few hundred metres above cloud base (where adiabatic growth of droplets is dominant), the droplet effective radius is roughly independent of height above cloud base. This model describes the non-homogeneous mixing process between the cloud and the environmental air in a way which is consistent with aircraft studies in these clouds. It is this mixing process that is central to the large differences between the effective radius distribution in the real clouds, and simulations assuming the adiabatic growth of droplets.

The value of the droplet effective radius is largely determined by the gross differences between maritime and continental CCNs entering the cloud base. The effective radius high up in the cloud is reduced somewhat in very vigorous clouds that strongly entrain.
This is due to the activation of many CCNs following mixing events in these regions of cloud. The effective radius is, however, much less sensitive to changes in the CCN population than would be suggested by an adiabatic model. It is found that the droplet effective radius is insensitive to the detail of the assumptions made about the CCN population present in the entrained air. It is also apparent that both the droplet effective radius and the cloud liquid-water content (well above the cloud base) are insensitive to the atmospheric temperature over the range of variation that is likely to occur due to global climate change.

It is therefore suggested that for strongly entraining convective clouds, changes in temperature or in CCN production near the surface are unlikely to modify the radiative properties of these clouds sufficiently to produce a feedback effect. Changes in cloud amount may be very important, but this is not addressed in this paper.

This paper has been concerned only with the question of droplet effective radius in ice-free clouds. The clouds considered do have temperatures which drop substantially below 0 °C. It is, therefore, likely that under some circumstances the clouds will become glaciated. The presence of ice in the clouds can affect the droplet effective radius by evaporating cloud liquid water. It can also affect the water budget of the cloud by efficiently converting cloud water to precipitation. Finally, if present in sufficient concentrations, the radiative properties of the clouds can be directly altered.

It is generally accepted that ice generation additional to primary nucleation is important if significant concentrations of ice are to be observed in the clouds. Rangno and Hobbs (1991) have reviewed a number of secondary-ice-particle production mechanisms. It is clear that many of these require large droplets or a wide range of droplet sizes to be present in the cloud. The production of ice particles during riming at temperatures around −6 °C (the Hallett-Mossop process) requires droplets of a large range of sizes, including droplets larger than 20 μm. It has been suggested that the
freezing of large droplets may result in the ejection of ice splinters (Chisnell and Latham 1976) or the instant conversion of these large droplets to rime particles that can produce splinters by the Hallett–Mossop process. Rangno and Hobbs have suggested that the onset of droplet growth by coalescence may result in considerably enhanced supersaturations inside a cloud, enhancing markedly the number of ice crystals produced by primary nucleation.

The production of large drops, required by many of these secondary-ice-generation mechanisms, is strongly favoured by the inhomogeneous mixing process as first discussed by Baker et al. (1980). In the model described in this paper the small fraction of droplets which survive several entrainment events are substantially larger than they would have been in a purely adiabatic cloud. This is because these statistically favoured droplets experience several peaks in supersaturation, following the mixing events, without suffering any evaporation. It would, therefore, seem likely that active dry-air entrainment may be very important to the development of the ice phase in many clouds.

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REFERENCES


