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a. Research Objectives

This project has been using a three-dimensional numerical cloud model, residing at NCAR's scientific computing facility, to address two main areas relating to geostationary satellite observations of severe convective storms: (1) the dynamics of cold/warm cloud-top thermal couplets such as have been observed atop some severe storms with strong internal rotation, and (2) whether significant differences exist in cloud-top height/temperature structure between storms with and without strong internal rotation.

b. Significant Accomplishments

The main accomplishments during February through July 1985 have been: (1) three comparative modeling experiments designed to investigate the effects of stratospheric lapse rate on cloud top height/temperature fields, and (2) conversion of diagnostic programs for air parcel trajectory computations to the CRAY-1.

Secondarily, as listed in section (d), a paper has been formally published in Monthly Weather Review, concerning the effects of upstream-biased third-order phase error correction terms on multidimensional Crowley advection schemes, a topic relevant to portions of the numerics used in the 3D convective cloud model.

(1) COMPARATIVE MODELING EXPERIMENTS FOR VARIABLE STRATOSPHERIC LAPSE RATES

Three comparative 60-min experiments were performed, each using the same vertical profiles of wind, relative humidity and tropospheric temperature as in the earlier experiment Case B described elsewhere (Schlesinger, 1984; JAS 41, 1551-1570), though raising the upper boundary from 18.0 to 19.8 km via two additional vertical grid levels (27x27x22 instead of 27x27x20). In particular, the assumed wind profile featured strong vertical shear, with pronounced anticyclonic turning of the hodograph through the lower troposphere and a moderate jet straddling the tropopause. The assumed stratospheric temperature profiles in the three experiments were isothermal, a 3 $C^o km^{-1}$ lapse, and a 3 $C^o km^{-1}$ inversion.

The experiments used new schemes for flux-conservative advection of heat and moisture as well as for parameterizing turbulent diffusion. These new schemes, implemented in the model code during 1984, were designed to reduce implicit and explicit diffusion, both of which had been suspected to be excessive in Case B (Schlesinger, 1984). Water vapor and liquid water were advected using a two-step algorithm of Smolarkiewicz (1983; MWR 111, 479-486), with corrections for "cross space" error in the temporal differencing (Smolarkiewicz, 1984; J. Comput. Phys., 54, 325-362) and for phase error in the spatial differencing; potential temperature deviations were advected using the flux-conservative counterpart of the non-conservative modified Crowley scheme (Schlesinger, 1985; MWR 113, 1109-1130) used for advecting momentum, also with corrections for "cross space" and phase errors. The turbulence parameterization, while continuing to use first-order "K-theory" as had been the case all along in the model code, took thermal stability into account via a local Richardson number dependency adapted from Lilly (1962; Tellus 14, 148-172), Hill (1974; JAS 31, 646-673) and Clark (1979; JAS 36, 2191-2215).

Kinematic storm structure was very similar in all cases, especially in the troposphere. A strong quasi-steady updraft evolved, splitting into a dominant cyclonic overshooting right-mover and a weaker anticyclonic left-mover. Strongest downdrafts occurred at low to middle levels between the split updraft regions, and in the lower stratosphere a few kilometers upshear or downshear of the updraft summit.

Cloud summit height became lower as stratospheric stability was increased. A cloud-top thermal couplet, coldest near and upshear of the summit and with a "close-in" warm region downshear, occurred in all cases. Both cold and warm regions became warmer, and with significant changes in their appearances, as stratospheric stability was increased, though with little effect on the amplitude.

Overall, the cold region was offset most strongly upshear of the summit in the inversion run. It showed at least a transient "U" or "V" shape, with the arms pointing downshear, though persistently so only for the inversion.

With the 3 $C^{o}km^{-1}$ lapse (weakest stratospheric stability), the warm region was small and separated into two spots with secondary cold spots further downshear, but became larger and remained single for increased stratospheric stability. In each experiment, the warm regions were not accompanied by corresponding cloud-top height minima except very briefly.

These modeling results were accepted for oral presentation at the American Meteorological Society's Fourteenth Conference on Severe Local Storms, to take place in Indianapolis, Indiana from 29 October 1985 to 1 November 1985.

(2) DIAGNOSTIC PROGRAMS FOR AIR PARCEL TRAJECTORY COMPUTATIONS

Three diagnostic programs, each relating to computation of air parcel trajectories backward in time for completed model experiments, have been in existence since 1978, when they were coded for the CDC 7600 computer that resided at NCAR from 1971 until its removal in April 1983:

i) The first program reads "airflow tapes" written during execution of the model experiment, with the 3D wind fields stored at every time step, to compute the trajectories of 12 selected air parcels. Trajectory computations use two-step modified Euler differencing in time, while spatial interpolation of wind components between model grid points is bicubic in the horizontal and linear in the vertical (Schlesinger, 1980; JAS 37, 395-420). Parcels are tracked backward over a specified time interval, insofar as possible (tracking is discontinued for a parcel if it is advected to a lateral boundary). The program prints out positions, three-dimensional wind components and three-dimensional acceleration components for each parcel at each time step of interest (setting all values to zero for parcels that have become lost), and saves the parcel positions for those time stages corresponding to the regular model history tape, which has saved model fields every 3 min of simulated time in each major experiment run thus far under NASA Grant NAG5-23.

ii) The second program, which reads off the history tape as well as the parcel position data saved by the first program, generates microfilmed horizontal and vertical projections of the parcel positions at each relevant time stage, and also provides information on whether a parcel is in cloud (all eight corners of the containing grid cell have cloud water present), in clear air (no corners have cloud water present), on the cloud edge (one to seven corners have cloud water present), or lost.

iii) The third program, which reads off the same data sources as the second, spatially interpolates various dynamical and thermodynamic quantities to points along each parcel trajectory at each relevant time stage. These quantities, which are interpolated in the same manner as the wind components in the first program (except that physically non-negative quantities such as mixing ratios are re-set to zero in case the bicubic horizontal interpolation yields a negative value), include potential temperature deviations, pressure deviations, eddy coefficients, turbulent kinetic energy, horizontal pressure gradient force components, and vertical momentum forcing terms other than friction (moist thermal buoyancy, pressure buoyancy, vertical perturbed pressure gradient force and liquid water drag).

These trajectory programs have been modified for compatibility with the CRAY. This task has involved only minor coding modifications, largely because the CPU time required to run these diagnostic programs is far too short to justify vectorization; also, since spring 1984, all model-generated tapes generated on the CRAY-1 have been written out the same way as had been done on the 7600. Each of the three programs now resides in two versions, one for backward trajectory computations as originally intended, and the other for analogous forward trajectory calculations, the forward version having been derived from the backward version by copying with incorporation of suitable limited code modifications.

c. Current Research

For each of the three stratospheric lapse rate experiments, the parcel trajectory diagnostics have been run on forward trajectories starting in the main cloudy updraft just below tropopause at 36 min. The twelve tracked parcels start out as a 4x3 rectangular array at adjacent model grid points (2 km apart in both horizontal directions) at a common level of 11.25 km, 0.45 km below tropopause.

Analysis of the outputs is just underway, in order to determine the dynamical characteristics of the updraft parcels as they overshoot their initial level (and, in most instances, the tropopause) and then undergo rapidly damping oscillations that begin with appreciable descent.

To list a few results emerging from this incipient analysis:

i) The four southwesternmost parcels from the 4x3 starting array, having larger initial upward velocities than the other eight parcels, overshoot the tropopause by the largest margins and also attain the largest peak downward velocities in the subsequent descent.

ii) The three easternmost parcels from the starting array, at the eastern periphery of the updraft, fail to reach the tropopause, attain the smallest peak downward velocities, and take the least time to reach peak descent rates.

iii) The parcel having the largest upward velocity, in the middle of the westernmost starting column, differs significantly from the other eleven parcels in that it has about a 50% greater margin of overshoot than any other parcel and also takes over twice as long (reckoned from the 36-min release time) until peak descent, although this parcel does not attain either the largest downward acceleration or the largest descent rate of the twelve.

iv) Each of the above characteristics holds for all three experiments.

v) As stratospheric stability is increased from one experiment to another, the peak magnitudes of both the overshoot margin and the subsequent descent (in those parcels having marked overshoots) decrease, by roughly 30% from the 3 C$^{\circ}$km^{-1} lapse run to the 3 C$^{\circ}$km^{-1} inversion run, and the length of time for the most strongly overshooting parcel to achieve peak descent also shows a similar run-to-run decrease.

It is planned to run backward trajectory analyses for each experiment, involving parcels on and slightly beneath selected local temperature extrema on the cloud top at 60 min. There are to be four cloud-top points in each run, two cold and two warm in the 3 C$^{\circ}$km^{-1} lapse run, three cold and one warm in each of the other two experiments. The other eight of the tracked parcels are to start out 0.54 and 1.08 km directly beneath the cloud-top features in question.

d. Formal Manuscripts

Schlesinger, R. E., 1985: Effects of upstream-biased third-order space correction terms on multidimensional Crowley advection schemes. *Mon. Wea. Rev.*, *113*, 1109-1130.

e. Conference Preprints

Schlesinger, R. E., 1985: Effects of stratospheric lapse rate on numerically simulated thunderstorm cloud top structure. To appear in Preprints, *Fourteenth Conf. Severe Local Storms*, Indianapolis, Ind., Amer. Meteor. Soc.