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13. ABSTRACT

The Phoenix 2 data analysis project was aimed at developing techniques for applying Doppler radar to observations of the turbulent boundary layer and at defining the important statistical properties and the large eddy structure more completely than is generally possible with direct sensors. An array of direct sensors was applied for comparison and to observe some of the finer scales of turbulence not accessible to the radar. A large eddy simulation experiment was also carried out for the purposes of observational comparison and improved interpretation. The original emphasis was on technique development in an environment thought to be moderately well understood. In outcome the technological developments are mixed in quality and some remain incomplete, while the scientific results

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Abstract

The Phoenix 2 data analysis project was aimed at developing techniques for applying Doppler radar to observations of the turbulent boundary layer and at defining the important statistical properties and the large eddy structure more completely than is generally possible with direct sensors. An array of direct sensors was applied for comparison and to observe some of the finer scales of turbulence not accessible to the radar. A large eddy simulation experiment was also carried out for the purposes of observational comparison and improved interpretation. The original emphasis was on technique development in an environment thought to be moderately well understood. In outcome the technological developments are mixed in quality and some remain incomplete, while the scientific results are much more interesting than originally expected.

Important improvements were made in single and dual Doppler processing, and satisfactory comparisons made between them. The errors in vertical velocity from the dual Doppler remain unpleasantly large in the upper levels and the effective resolution for some fields disappointingly coarse. An encouraging result is that most of the errors appear to be random and uncorrelated, so that covariance statistics, such as fluxes, tend to be more accurate than the variances of the fields contributing to them. A technique was developed for managing large eddy calculations intended to simulate an observed flow which forces some of the observed mean flow parameters while allowing the turbulent structure to develop freely.

The observed environment, thought to be dominated by buoyant convection, is shown to be surprisingly strongly affected by the mean shear. The nature of these effects is apparently well-represented by the data and also by the corresponding numerical simulations. Results cast some new light on how the Rocky Mountain heat source develops and maintains the southerly jet in the western plains.

Text, Final Report, 1986-89

1. Purpose and Goals

The Phoenix 2 analysis project was based on the existence of data acquired during the observational phase in 1984. The purpose was to explore the large eddy structure of a heated boundary layer in what was thought to be a rather simple flow regime. The principle observational facilities used were 5 Doppler radars, operating singly and in pairs, supported by turbulence measurements from a research aircraft, an instrumented tower, and a micro-network of surface stations. Important parts of the project were supported by the National Science Foundation, including substantial work since the end of the ARO contract.

The specific goals of the ARO analysis were, first, to determine the three-dimensional wind field, pressure, and virtual temperature in at least one of the two dual Doppler observation regions, and during at least two of the 20 plus observational days. Second, the statistics of these fields were to be compared with those obtained from the more conventional instrumentation facilities and also with the statistics obtainable from the single K-band Doppler. It was expected that the much larger sampling capabilities of the radar would substantially improve the accuracy of those statistics. Third, the results were to be compared with numerical simulations to be carried out under similar environmental constraints. The purpose was to test the accuracy of the simulations, and to aid in interpreting the observational data. Simulations provide an internally self-consistent data set which is never fully available from observations, including some parameters which are individually very difficult to measure, such as non-hydrostatic pressure fluctuations above the surface.

2. Attainment of goals

The initial step of the dual Doppler radar processing, the basic 3-d wind field determination, was considerably more difficult than had been anticipated, especially the computation of the vertical velocity field. Complete success was not attained, in that the vertical velocity variance in the upper parts of the boundary layer is found to be larger than that observed by instrumented aircraft. The techniques which we developed and found to be most satisfactory represent a substantial improvement over most conventional methods, however. Thermodynamic quantities were obtained by use of the Gal-Chen and Hane algorithms, again with moderate success, though some spatial filtering was required.

Single Doppler processing was simpler, being based on the VAD technique. Several choices need to be made, however, in weighting the statistics obtained at different elevation angles and ranges. Although, by present technology, it is not capable of complete large eddy sampling, single Doppler operation for statistical sampling offers the operational advantages of simplicity and also of resolution. Since generally no gridding or filtering is done, the spatial and temporal resolution is exactly that of the equipment, whereas for dual radar operation the necessity of combining data taken at different times and with different sizes and shapes of pulse volumes requires a lowest common denominator approach, which always degrades resolution.

Aircraft data processing was also relatively straightforward, although some doubt remains as to the accuracy of the mean wind profiles. Schuler oscillations in the aircraft inertial platform are a possible source of error, which is unfortunately not now subject to correction. Tower and surface micronet data reduction was also relatively straightforward. The surface micronet, which was arrayed with a spacing similar to the radar resolution, was compared with the lowest levels of radar data. The principal purpose was to determine how well surface layer divergence could be approximated by that at the lowest radar level. Results were somewhat negative in establishing a close connection, which leaves an undetermined residual error in vertical velocity determination.

The important turbulent statistics, including momentum and heat flux and other terms going into the turbulent momentum, energy, and heat budgets, are probably the most significant scientific output of the program to date. They show that the Colorado summer boundary layer is more complex than had been anticipated, but nevertheless fairly readily interpretable from the data. The rather unexpected importance of shear forcing in and above the convective layer is clearly documented. In addition the results provide a clearer understanding of the function of the Rocky Mountain heat source in developing the low level southerly jet of the central and southern plains. Further scientific results still in process include visual interpretation of large eddy structures through computer-generated cross-sections and three-dimensional motion sequences

The proposed numerical simulations were carried out (by P. Mason of the British Meteorological Office) near and after the end of the ARO support period, and are still being analyzed under other support. The method is somewhat unique and the results appear to be quite successful.

3. Techniques developed

We have extended the VAD single Doppler radar analysis technique for quadratic quantities (velocity variances and covariances) in several ways. These include the use of second moment radar data, which allows evaluation of contributions from scales smaller than the radar pulse volume. This allows an accurate evaluation of the variances and covariances close to the ground, where the dominant scale is near or smaller than the radar resolution. Results were compared with the BAO tower and with the dual Doppler determinations, and agree within the limitations which the differing sampling volumes impose.

For the dual Doppler analysis, we had planned to use a reduction technique developed originally for use in convective storm analysis. It is an iterative procedure, in which the motion field is first assumed to be purely horizontal, with vertical velocities and corrected horizontal velocities then computed sequentially until they converge. We found the procedure to be unstable, as had been theoretically predicted by Gal-Chen but not previously verified. The instability is significant for high elevation angle data close to the radar baseline, which includes parts of our data volumes. After several attempts in other directions, the problem was eventually solved by using the coplane integration scheme, originally proposed by Armijo. The form we developed is designed for data interpolated to a Cartesian grid. Fig. 1 shows the geometry. The continuity equation is effectively integrated upward along an arc around the baseline, using data interpolated to lie on that arc. Fig. 2 shows profiles of standard deviation of vertical velocity calculated in various ways.

We believe that the remaining inaccuracies in vertical velocity are partly due to unobserved data near the surface, and partly an inherent consequence of random noise in the Doppler velocity measurements, perhaps amplified by the Cressman grid interpolation procedure. The noise of the raw velocity determinations was about 0.2-0.4 m s^{-1}, which is very good by most standards of atmospheric measurement. The noise variance accumulates, however, when dual Doppler signals are applied to determine vertical velocity by integration of the continuity equation, and leads to errors of order 0.5-1 m s^{-1} at levels near the top of the boundary layer. Fig. 2 shows that the radar standard deviation is larger than that observed by the aircraft at the levels. Although this error variance can be forcibly reduced in the calculations, leading to apparently more realistic profiles, such a procedure also removes the correct parts of the signal, and therefore does not improve, and for some purposes (for example momentum flux correlations) degrades, the data. Spatial and temporal averaging procedures also reduce the error amplitudes, but at a cost in resolution. Note on Fig. 2 that the aircraft standard deviations are greater than those from the radar at the lower levels. This is because the radar does not measure the smaller scales of motion, which become an important part of the variance below about 1 km.

We gained considerable experience, at least some of which is verbally transferrable, in using the Gal-Chen and Hane thermodynamic retrieval techniques. The temperature determination involves additional spatial and temporal derivatives, which generate noise. The error statistic developed by Gal-Chen is widely used as a criterion for retrieval accuracy. Spatial filtering was found necessary in order to obtain results which were temporally well correlated and satisfied the Gal-Chen criterion. The resulting temperature field is limited to wavelengths greater than about 1 km. For determination of correlations such as heat flux, on the other hand, unfiltered or weakly filtered data provides apparently better results than that more heavily filtered, since the noise is apparently uncorrelated between fields (see Fig. 3). In levels below about 1 km, however, where aircraft data show the predominance of thermals and plumes with scales of order 100 m, the radar observations do not resolve the principal large eddy structures or their covariance statistics.

Our best determined vertical velocities and excellent horizontal velocities allow (we believe) good estimates of momentum flux, which is one of the most difficult statistics to measure by direct sensing above the surface layer. Flux profiles vary slowly with time, and are robust to moderate spatial filtering. How well the sampling volume represents a larger environment is uncertain, however, since fluxes calculated over subvolumes differ significantly between each other. The data indicate that the Colorado site of the Phoenix observations undergoes unexpectedly strong baroclinic forcing. This does not necessarily represent a defect in the program design or siting, but rather shows what can be deduced from Doppler radar observations beyond the expected boundary layer structure.

All terms of the kinetic energy balance are available from the radar data except dissipation, which must be evaluated as a residual. Its profile shows positive values almost everywhere, however, and is in reasonably good agreement with aircraft observations.

A series of numerical (large eddy) simulation experiments was initiated through a visit by D. Lilly and J. Schneider to the British Meteorological Office. The experiments are being conducted by Dr. Paul J. Mason, using a model which has been developed and tested for several years. The most unique feature of these experiments is the method by which some of the statistical properties are maintained. Our observational data, especially aircraft soundings, provided strong evidence that advective heating off the mountains is a major element in the heat budget, and the associated east-west pressure gradient in the lower levels is a dominant effect on the momentum balance. Since these effects are produced on scales much larger than the model domain, it was found appropriate to force the model to fit the observed mean state. With the model required to maintain the same mean velocity and temperature profiles as the observational data, but without further constraints on flow details, the unspecified fluxes and large eddy structures are found to be similar to those observed. Further analysis of these simulations is continuing under other support.

An additional kind of technique development has mostly begun since the end of the ARO support, which is the visualization of large eddy structures through computer graphical display. Both our observational and numerical simulation data contain a rich array of identifiable dynamic elements. The inherent three-dimensionality and transient nature of these structures represents, however, a severe challenge in presentation and structural analysis. Modern work stations, such as the Silicon Graphics Iris and the Stellar, now in use at the OU Geosciences Computer Network, provide major assistance in these directions. Video tape presentations were made at the AMS Turbulence and Diffusion Conference at Roskilde, showing some examples of the analysis techniques and structural details. Unfortunately, good quality presentations require almost as much technological support as their preparation. A video tape of some of the graphical analysis results is presented with this report.

4. Scientific results

The principal results fall into three general categories. First are the conclusions on boundary layer structure and dynamics reached directly from fairly conventional turbulence statistics, such as the two- and three-component correlations between velocity and thermodynamic fields. Second, and somewhat unexpected, are some new interpretations on the role of the boundary layer in producing the southerly low level jet to the east of the Rocky Mountain heat source. Third are the new and still rather exploratory results, partly dependent on numerical simulation and computer visualization, on the nature and role of the large eddy structures in a regime of strong buoyant and shear forcing.

Sequential profiles of the westerly momentum flux, $\overline{u'w'}$ (see Fig. 4), show near-zero (slightly positive from single Doppler estimates) values near the surface, corresponding to the weak surface easterlies, and strong negative values at 1-2 km, decreasing aloft, except for curve L, which was under the influence of a convective downburst. The flux is generally down the velocity gradient, corresponding to positive eddy viscosity. When combined with other terms in the mean westerly momentum equation, it is clear that the low level gradient of momentum flux must be balanced by at pressure gradient in the lower levels, decreasing eastward, and not readily observed directly in the variable mesoscale terrain. This pressure gradient and its relaxation aloft is associated with a westward increasing temperature field, evidently a consequence of the Rocky Mountain heat source. Air in the boundary layer over the mountains is warmer in the daytime than that at the same levels over the plains, and is advected eastward by the prevailing westerlies near and above mountaintops. The temperature gradient is maintained as the flow moves eastward, but, as the westerly shear is reduced by the momentum flux curvature, the pressure gradient must be balanced by quasi-geostrophic southerlies over the eastern Colorado and Kansas plains.

Results of the kinetic energy budget analysis indicate that transfer from the mean flow is generally greater than buoyant generation. Deardorff originally proposed the scaling of velocities in a convectively mixed layer by w*, where

$$w^{*3} = \left(g \frac{\overline{w'\theta_v'}}{\theta_o} H \right)$$

where H is the depth of the mixed layer. For the strongly sheared layer which we observe we propose use of an enhanced velocity scale, w^*_+, given by

$$w^{*3}_{+} = 2 \int_{o}^{H} \left(g \frac{\overline{w'\theta'_v}}{\theta_o} - \overline{\mathbf{V}'w'} \cdot \frac{\partial \overline{\mathbf{V}}}{\partial z} \right) dz$$

The enhanced scale would be approximately the same as w* in the absence of shear, under the usual assumption of heat flux decreasing linearly with height.
Figure 5 shows profiles of the standard deviation of vertical velocity at various times during an observational day, first scaled by w* and second by $w*_+$. The data collapses fairly convincingly for the latter scaling.

The numerical simulations carried out by Mason with maximal resolution (60x64x98 grid points) and a 12 km square domain show similar statistics, particularly the momentum flux profile and energy balance, to our observational data. Perhaps the most interesting results will be comparisons of large eddy structures between the simulations and the observations. Simulations of a convective domain without shear show a strongly cellular structure in the low levels, with the strongest cells extending nearly to the top of the mixed layer. The simulations for our environment show less well-defined cells in the low levels, which are also less well correlated with the structures at high levels. Apparently the tendency toward downshear rolls which occurs in sheared laboratory convection and shallow cloud layers must compete with a tendency toward cross-stream Kelvin-Helmholtz waves in the weakly stable air above the convective layer.

Figure captions

1. Illustration of coplane integration. The velocity component parallel to the arc is obtained by upward integration along the arc. The end point of the vector R is at a Cartesian grid point.

2. The standard deviation of vertical velocity calculated in several ways. The curved marked "simple" ignores the non-zero elevation angle and the time difference between different parts of the observed volume. Other curves include time interpolation, a spatial filtering step, and time averaging. The curve marked "coplane" is done using coplane geometry. The points marked "A" are from aircraft flight data.

3. The vertical flux of temperature using temperature fields computed with increasingly heavy spatial filters, with the heaviest the "3-step" filter.

4. 20-minute averaged profiles of easterly momentum flux, $\overline{u'w'}$, at approximately 40 minute intervals starting at about 1300 LST (curve G).

5. Profiles of the standard deviation of the vertical velocity over sequential 20 minute averages as in Fig. 4. The abscissa are made dimensionless by w^* in the upper plate and by w^*_+ in the lower plate.

Conference Preprints in chronological order

Schneider, J. M., and D. K. Lilly, 1986: Phoenix II dual Doppler data analysis and preliminary results. *Preprints 23rd Conference on Radar Meteorology*, Amer. Meteor. Soc., JP214-JP217.

Lilly, D. K., J.-J. Lin, J. M. Schneider, and L. Mahrt,1986: Gravity waves generated by overshooting convective plumes. *Preprints 2nd Conference on Mesoscale Meteorology,* Amer. Meteor. Soc.

Lee, S. and T. Gal-Chen, 1988: Turbulence statistics from dual-Doppler radar, surface stations, and instrumented tower. *Preprints 8th Symposium on Turbulence and Diffusion*, Amer. Meteor. Soc.

Lilly, D. K., T. Gal-Chen, J.-J. Lin, and J. M. Schneider, 1988: Phoenix II analysis results - mean state, variances, and spectra. *Preprints 8th Symposium on Turbulence and Diffusion*, Amer. Meteor. Soc.

Schneider, J. M., and D. K. Lilly, 1988: Convective boundary layer fields as observed by Doppler radar. *Preprints 8th Symposium on Turbulence and Diffusion,* Amer. Meteor. Soc.

Lilly, D. K., and J.-J. Lin, 1988: Kinetic energy balances in and above a heated bounday layer, as observed by aircraft and Doppler radar. *Preprints 8th Symposium on Turbulence and Diffusion,* Amer. Meteor. Soc.

Gal-Chen, T., M. Xu, D. K. Lilly, and J. M. Schneider, 1989: Single Doppler radar measurements of the convective boundary layer. *Preprints 24th Conference on Radar Meteorology*, Amer. Meteor. Soc.

Lilly, D. K., and J. M. Schneider, 1990: Dual Doppler measurement of momentum flux: results from the Phoenix II study of the convective boundary layer. *Preprints 9th Symposium on Turbulence and Diffusion,* Amer. Meteor. Soc., 98-101.

Schneider, J. M., and D. K. Lilly, 1990: The hunt for the big eddy: a visual exploration of the vortical structures in a heated, sheared PBL. *Preprints 9th Symposium on Turbulence and Diffusion,* Amer. Meteor. Soc.

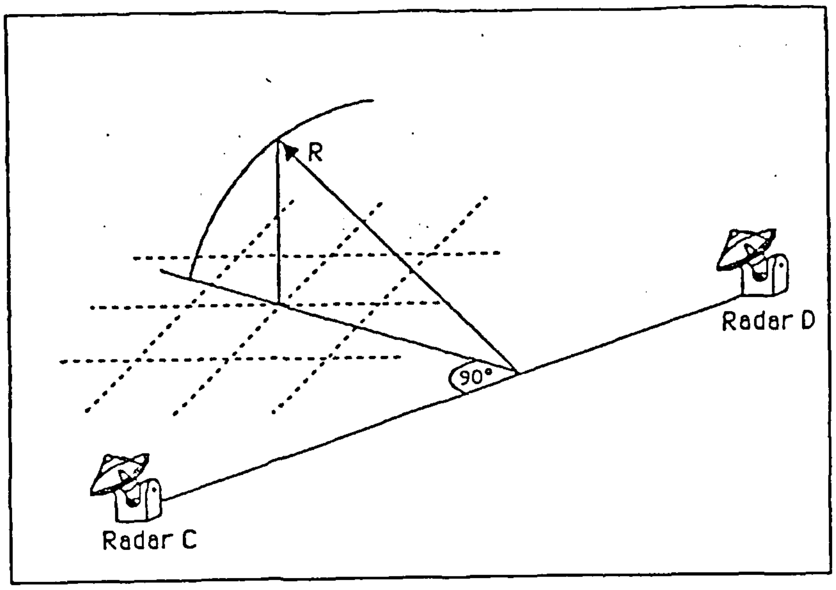
Lilly, D. K., and P. J. Mason,1990: A numerical simulation of an observed heated and sheared boundary layer with mesoscale forcing. *Preprints 9th Symposium on Turbulence and Diffusion,* Amer. Meteor. Soc.

Theses and Dissertations:

Lin, J.-J. (Roger), MS Thesis completed and accepted, Nov. 17, 1988. Title: Spectral and Energy Budget Analysis of the Phoenix II Aircraft Data.

Lee, Sukyoung, MS Thesis completed and accepted, Dec. 1 1987. Title: Turbulence Statistics Derived from the Portable Automated Mesonet (PAM), Dual-Doppler Radar, and Instrumented Tower.

MS thesis work in progress by M. Xu, Ph. D. dissertation work in progress by J. Schneider, both with expected completion in 1990.



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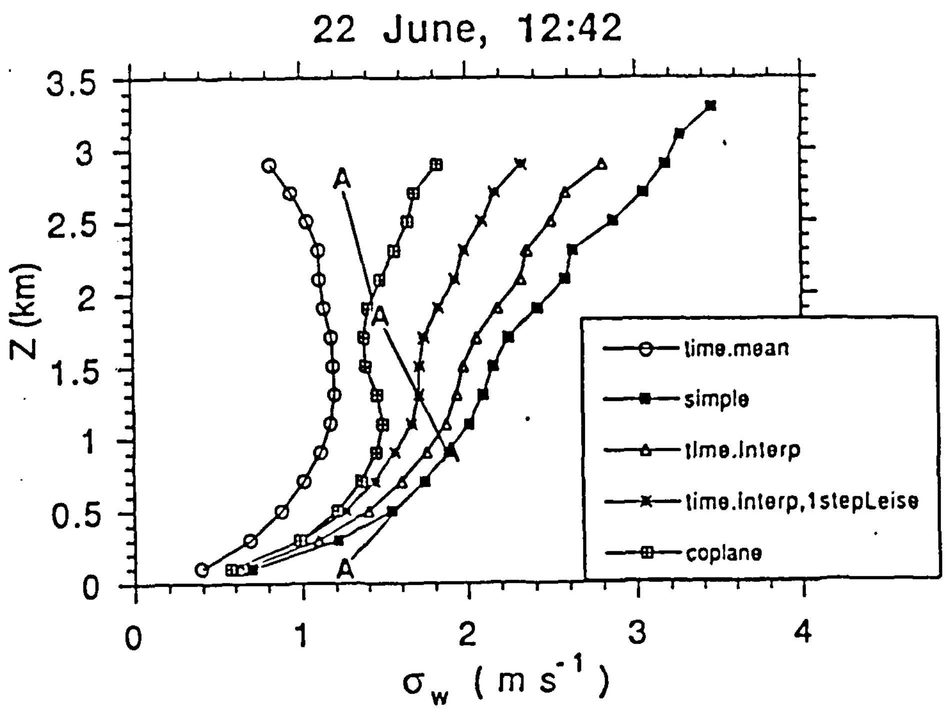

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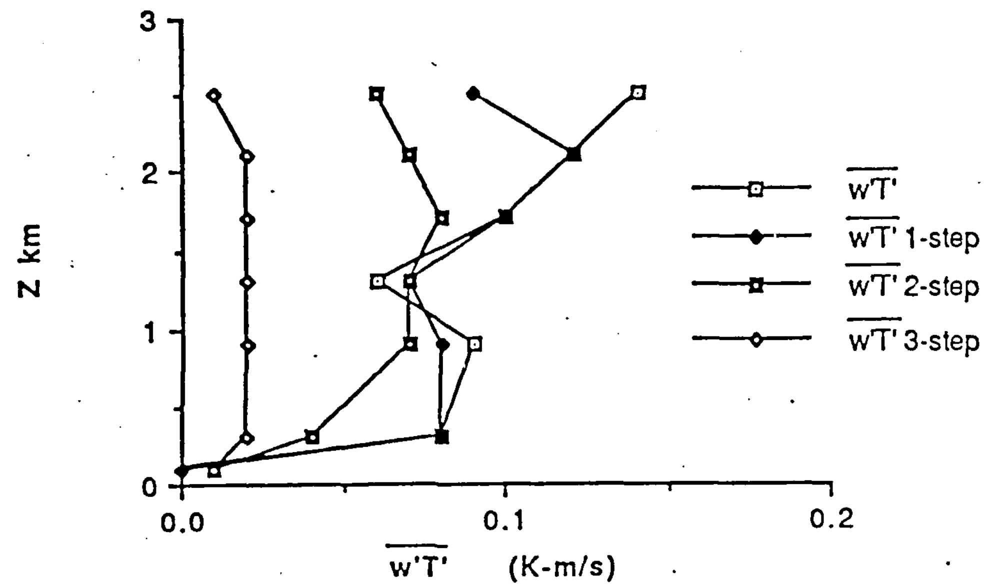

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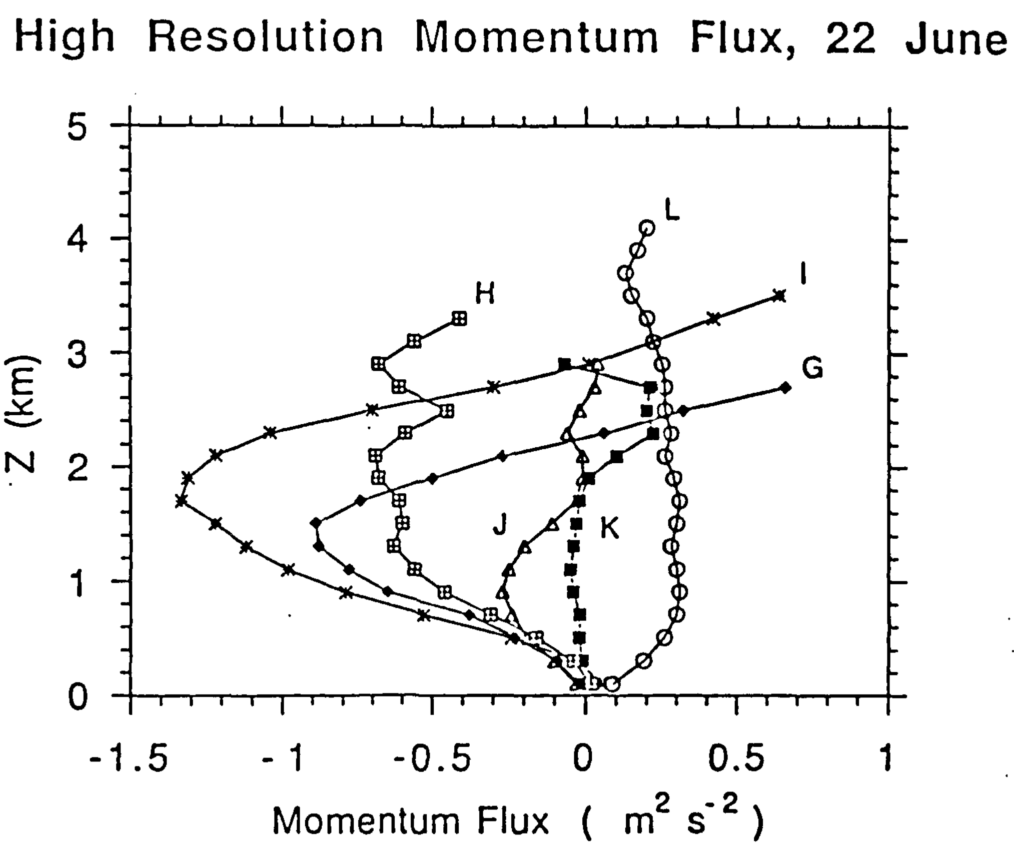

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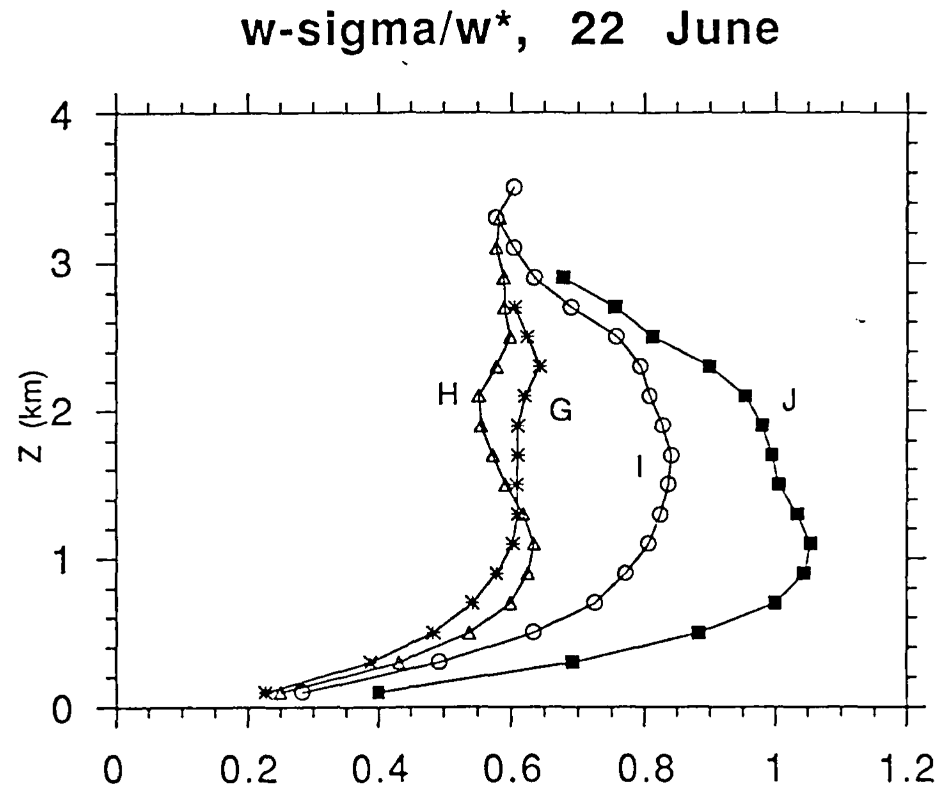

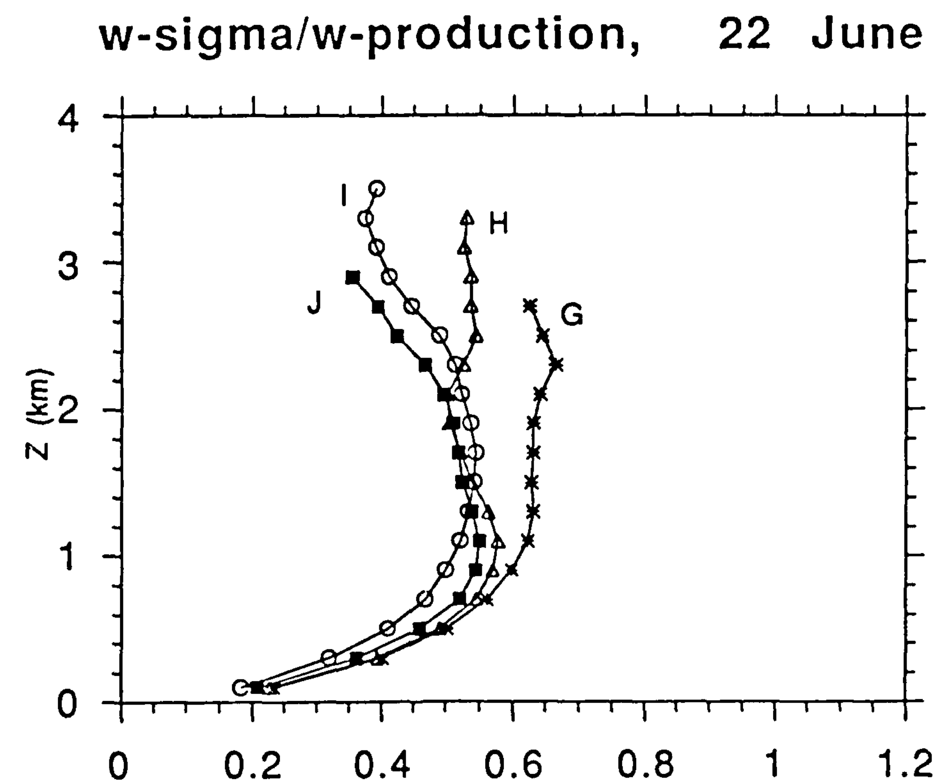

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