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Project Summary

Estimating Cloud Paramters for Neros I

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Geosynchronous Orbiting Earth Satellite infrared and visible imagery were combined with surface and upper-air meteorological observations to determine cloud amounts and cloud-top heights over the Northeast Regional Oxidant Study grid for 1200, 1500, and 1800 EDT, on August 3, 4, and 13, 1979. Cloud amounts were determined for cumulus clouds alone and for all clouds. Cloud-top heights were determined specifically for cumulus clouds.

A study was begun to develop a model that could be used to estimate the parameters of the cloud ozone flux. Several models were developed to estimate the average maximum cloud vertical velocity; the best model developed was a multiple linear regression model. The model input parameters were the cloud-top height and the cloud amount, which were derived from satellite imagery. This model yielded an average correlation coefficient of -0.78 and a root mean square difference of ±0.8 m/s^{-1}. On the average, with the use of the multiple linear regression model, there was a 24% error in the estimated average cloud vertical velocity. However, the modeling results were not statistically significant because of the limited data available for developing the model. The total number of data points was nine, but only seven were useful.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate raport of the same title (see Project Report ordering information at back).

Introduction

In July and August of 1979, the U.S. Environmental Protection Agency (EPA) conducted the first phase of the Northeast Regional Oxidant Study (NEROS). The primary purpose of the study was to measure concentrations of oxidant and oxidant precursor on a regional scale in the boundary layer. From these data, physical processes could be parameterized in numerical models and numerical model simulations evaluated.

Solar radiation is a significant factor in the formation of oxidants from oxidant precursors; the concentration of pollutants within a layer of the atmosphere can be influenced significantly by the vertical flux via cumulus cloud venting. To estimate the amount of solar radiation penetrating the boundary layer, imagery from the Geosynchronous Orbiting Earth Satellite (GOES) was used to estimate cloud parameters over grid squares approximately 20 km by 20 km in the Northeastern United States. The GOES imagery also was used to derive a physical relationship between cumulus cloud-top growth and vertical velocity within cumulus clouds so that the vertical flux of oxidants and oxidant precursors could be estimated.

Another principal objective of this research project was to determine cloud parameters (spatial and vertical extent) that could be used in modeling the production of ozone in the boundary layer during specified periods in the NEROS program. The study area was bounded by 38° and 45°N latitude and 69° and 84°W longitude. Major objectives realized during the research project were:

1. To determine the fractional coverage of cumulus clouds (when these clouds alone existed) in each of the 1/4° longitude by 1/6° latitude NEROS grid squares, using GOES imagery and synoptic meteorological observations for 1200, 1500, and 1800 EDT on August 3, 4, and 13 (1979).
2. To determine the average height of cumulus cloud tops across each NEROS grid square using the GOES infrared imagery and available upper-air temperature profiles.
3. To determine the fractional coverage of all clouds (other than cumulus or multilayer clouds that might include cumulus) for each NEROS grid square.

A secondary objective of the project was to study the period during which the so-called "cloud buster" experiments were performed to determine cloud parameters such as those discussed above; study of those parameters relative to *in situ* measurements of vertical velocity made in cumulus clouds would help to determine if a functional relationship could be developed between the satellite cloud parameters and the cloud vertical velocities. This relationship could then be used to model the vertical ozone flow in cumulus clouds. The specific approach is outlined below.

1. Available GOES infrared and visible imagery in or very near the periods of the "cloud buster" experiments (i.e., 1430 to 1530 EDT on 22 August 1979, and 1400 to 1700 EDT on 28 August 1979) were used to determine the fractional coverage of cumulus clouds and the average height of the cumulus clouds within a fixed 20-km grid squared along aircraft transects in southeastern Pennsylvania and New Jersey.
2. *In situ* measurements made from the aircraft of the peak vertical velocity in the cumulus clouds, the average vertical velocity in the clouds, the ozone concentration in and around the clouds, and the upward- and downward-looking radiometer temperature in the vicinity of the clouds were determined along the transects from the data provided by EPA.
3. The vertical velocity data provided from the *in situ* measurements were compared with the cloud parameters obtained from the GOES data to determine if functional relationships exist.

Determination of Cloud Parameters for the NEROS Grid

The principal data used were the GOES infrared and visible images obtained for August 3, 4, and 13 (1979). GOES visible images were available over the region of interest on these days at 1130, 1430, and 1730 EDT. The GOES data were collected in hard copy image form and on magnetic tape by the Research Triangle Institute's Satellite Receiving Station in North Carolina.

Synoptic weather data for 1200, 1500, and 1800 EDT from the first-order, surface-synoptic weather stations in the region were used, as well as upper-air data for 0200, 0800, and 1400 EDT from the National Weather Service Upper-Air Stations The 1400 EDT upper-air data were used extensively because they fell within the period 1200 to 1800 EDT. These weather data were obtained either from the National Climatic Center in Asheville, NC or from EPA.

The steps employed to determine cloud amounts and cloud-top heights over the NEROS grid are as follows:

1. To facilitate interpretation of the satellite data, the gray scale of the GOES infrared and visible images was enhanced (i.e , the gray scale was confined to a range of temperature and reflected radiation that gave the most useful information), using the data on magnetic tape and the facilities available at the RTI satellite receiving station.
2. The enhanced GOES visible and infrared (IR) images were photographically enlarged uniformly to further facilitate interpretation of the satellite data.
3. A NEROS grid overlay was developed on transparent Mylar for the GOES imagery.
4. The cloud amounts, cloud types, and cloud-base heights from surface synoptic data were plotted on another transparent Mylar overlay.
5. An analysis delineating areas of clear skies, cumulus alone, and multiple cloud layers or clouds other than cumulus were developed using the GOES visible and IR imagery and the plotted cloud data from the surface synoptic stations
6. Analyses of cloud cover in areas of cumulus only, and of multiple cloud layers or clouds other than cumulus, were performed using the GOES visible and IR imagery and the surface synoptic cloud data
7. An analysis of cumulus cloud-top temperature was performed using the GOES infrared imagery and calibration data available from the GOES User's Guide.
8. Cumulus cloud-top heights were derived using the cloud-top temperatures combined with the radiosonde data.
9. The cumulus only cloud amounts (α_c), cloud amounts for conditions other than cumulus alone (α_a), and the cumulus-top heights (H_c) were selected at each of the NEROS grid points, formatted, and punched on computer cards.

Cloud parameters from the surface synoptic data were plotted on transparent Mylar overlays using the GOES visible imagery The plotted cloud data and the GOES visible and infrared images were then used to define regions of cumulus alone, clear skies, and multiple cloud layers. The visible images were used to interpolate in areas between synoptic weather stations. The infrared images were examined along with the visible imagery to determine if there was a change in cloud structure between synoptic stations that might indicate a change in cloud type. Similarly, an analysis of cloud amounts was performed using the GOES visible imagery, the plotted cloud data, and the analysis delineating areas of cumulus, clear skies, and multiple cloud layers. Once again, the visible imagery data were used to interpolate in areas between the synoptic weather stations.

To obtain the cloud-top heights for the cumulus clouds, the gray scale for each of the GOES infrared images was calibrated with respect to temperatures, using data available from the GOES User's Guide. For each GOES infrared image, patterns of shades of gray were analyzed on transparent Mylar overlays, and the patterns of gray scale were assigned temperatures using the calibrated gray scale. The satellite temperature in the area of cumulus clouds (T_s) and the temperature in the area of clear skies (T_a) nearest the cumulus clouds were determined. The cumulus cloud-top temperature can be estimated using the following formula

$$T_c = T_a - \frac{1}{\alpha_c} (T_a - T_s)$$

where α_c is the amount of cumulus clouds in tenths, and T_c is the cumulus cloud-top temperature.

The cumulus cloud-top height (H_c) was determined using the cumulus cloud-top temperature and the temperature profile obtained from the radiosonde stations nearest the cloud of interest. In all cases, the 1400 EDT radiosonde data were used. The cumulus cloud-top temperature and cloud-top height were also estimated using the 1400 EDT radiosonde data and standard techniques (i.e., a parcel of air was lifted dry adiabatically to the lifting condensation level, then moist adiabatically to the level of free convection and the equilibrium level — the level of neutral buoyancy; the cloud-top height was assumed to be the height of the equilibrium level). These values were compared with those values determined using the satellite data. When major discrepancies (differences $\geq$ 1000 m) were found, attempts were made to justify the differences. About 25 percent of the data given satellite analysis could not be verified using the calculations from the soundings. These discrepancies were generally due to the development of isolated large cumulus congestus and cumulonimbus clouds.

Afterwards, a transparent Mylar overlay of the NEROS grid was placed on the analysis of cloud amounts and the cloud-top height to determine those parameters at the grid points. These data were formatted and punched on computer cards, which were delivered to EPA with an explanation of the format.

Modeling Cloud Vertical Velocity

A second objective of this project was to develop a model which would estimate the average maximum-cloud-vertical velocity using parameters obtained from satellite data: the cloud amount and cloud-top height. The model was to be used to parameterize the cloud vertical flux of oxidants and oxidants precursors. Since this was the first attempt to develop such a relationship, and since the data resources were limited, the result of this study may be considered as a guideline for more comprehensive studies in the future. The vertical velocity data were obtained by aircraft as a part of the so-called "cloud buster" experiment. The purpose of this experiment was to collect data for studying the vertical flux of ozone in clouds.

The principal data set utilized to determine the cloud amounts and cloud-top heights for the cloud buster experiments was the GOES infrared and visible imagery for 22 and 28 August 1979. Since the aircraft data for the cloud buster experiment were sampled from 1430 to 1530 EDT on 22 August and from 1400 to 1700 EDT on 28 August, the GOES visible and infrared images for 1430 and 1500 EST, respectively, were used for this study. The GOES data were collected in hard copy image form and on magnetic tape by RTI

Synoptic weather data from the first-order surface weather stations were also used in the region and for the time period defined by the flight tracks (over southeastern Pennsylvania and New Jersey). The 1500 EDT weather data were used in all cases, and the 1400 EDT upper-air data were also used to determine cloud-top heights. Cloud amounts and cloud-top heights were determined in 20-km x 20-km squares centered along the flight track of the aircraft, using the methodology discussed earlier.

Various *in situ* measurements were made by an aircraft along the transects. The aircraft data were used to determine the average maximum vertical velocity in cumulus clouds over a 20-km portion of the flight track coinciding with the 20-km x 20-km region where cloud parameters were determined using satellite data (i.e., the peak vertical velocity was determined for each cloud in the 20-km portion of the flight track and an average was computed over all clouds in the cell). The upward- and downward-looking radiometer temperatures were used to verify the existence of clouds.

The data reduction yielded nine independent data points from the various transects over the two days. Two data points were obtained along a transect that bordered two distinct regions of cloud amounts and cloud-top heights. For that reason, it was difficult to specify cloud amount or cloud-top height in these cases. The values given are associated with a cloud system with low cloud-top height and an approximate cloud amount of 0.3. The other cloud system had cloud-top heights on the order of 5,000 m and cloud amounts of approximately 0.6. Because of the problem of selecting proper cloud amounts and cloud-top heights in this case, it was decided that these two data points would be ignored in the analysis that follows. Discarding these two data points left only seven data points for the analysis.

Results

The following models were used with the seven data points to develop a relationship between the average maximum vertical velocity in the cloud and the cloud amount and top height derived from satellite data: a multiple linear regression model; polynomial models in which the average maximum cloud vertical velocity was related to the cloud amount; and the polynomial models in which the average maximum cloud vertical velocity was related to the cloud-top height. The analysis indicated that increasing the degree of the polynomials to a value greater than three did not significantly improve the models. Table 1 lists statistics on the various models including the correlation coefficient and the root mean square difference (RMSD) between the estimated and the observed average maximum cloud vertical velocity. The coefficients of the models were determined via a standard regression algorithm developed for the Tektronix Model 4051 computer.

The data in Table 1 indicate that both the cloud-top height and the cloud amount are negatively correlated with the average maximum cloud vertical velocity: as the cloud amount increases or the cloud-top height increases, the average maximum cloud vertical velocity decreases. As the degree of the polynomial models increased for both the cloud amount and the cloud-top height, the magnitude of the correlation coefficient increased and the magnitude of the RMSD decreased. The statistical data in Table 1 suggest that the multiple linear regression model yielded the best relationship between the average maximum cloud vertical velocity and the cloud amount and the cloud-top height.

The specific form of the multiple linear regression model for the average maximum cloud vertical velocity (with seven data points) is

$$w_e = 7.8 - 4.4\,\alpha_c - 0.0011\,H_T$$

where w_e is the estimated average maximum cloud vertical velocity, α_c is the cloud amount, and H_T is the cloud top height. Table 2 gives a comparison of the estimated and observed average maximum cloud vertical velocities. Also given is the residual and the RMSD. On the average, the error in the estimated

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Table 1. *Statistical Analysis Of The Various Model Types Yielding Estimates Of The Average Maximum Cloud Vertical Velocity (w_e) As A Function Of The Cumulus Cloud-Top Height (H_T) And The Cumulus Cloud Amount (α_c), Which Were Derived From Satellite Data.*

Model	R*	RMSD**
$w_e = 7.8 - 4.4\ \alpha_c - 0.0011\ H_T$	-0.78	±0.8
$w_e = 7.7 - 0.0014\ H_T$	-0.56	±1.1
$w_e = 4.5 - 6.1\ \alpha_c$	-0.67	±1.0
$w_e = 0.05\ H_T - 0.000009\ H_T^2 - 74.2$	-0.72	±1.0
$w_e = 6.1 - 18.1\ \alpha_c + 17.4\ \alpha_c^2$	-0.67	±1.0
$w_e = 131 - 0.15\ H_T + 0\ 00006\ H_T^2 - 0.000000007\ H_T^3$	-0.75	±0.9
$w_e = 1 - 19\ \alpha_c + 20.8\ \alpha_c^2 - 3.3\ \alpha_c^3$	-0.75	±0.8

**R is the correlation coefficient*

***RMSD is the root mean square difference between the observed and estimated average maximum cloud vertical velocity (m/s^{-1}).*

Table 2. *A Comparison Of The Observed (w_c) And Estimated (w_e) Average Maximum Vertical Velocities (m/s^{-1}).*

w_c (m/s)	w_e (m/s)	Residual
1.5	1.2	0.3
4.4	3.8	0.6
2.9	3.8	-0.9
1.8	3.1	-1.3
4.5	4.1	0.4
4.5	3.6	0.9
4.4	4.5	-0.1

RMSD = ±0.8 m/s.

average cloud vertical velocity is 24% and the error decreases as the vertical velocity increases. However, it should be noted that these results are not statistically significant because of the limited data available for the development of the model.

Conclusion

The fact that the cloud amount and cloud-top height were negatively correlated with the average maximum cloud vertical velocity was surprising and may be a result of the small data set. However, there is a possibility that the results may be real. As clouds develop, both the horizontal and vertical dimensions increase (the cloud amount and the cloud-top height). Eventually, the cloud reaches a mature state where the vertical velocity begins to decrease and approaches zero or begins to become negative if hydrometers fall. Therefore, one can hypothesize that the maximum vertical velocity in isolated cumulus would be reached when the cloud is relatively small (i.e., in its development stage and not in its mature stage). However, such speculation can be verified only if the data set were to be increased substantially.

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The complete report, entitled "Estimating Cloud Parameters for NEROS I," (Order No. PB 82-186 552; Cost: $7.50, subject to change) will be available only from:

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