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"Observation of Upper and Middle Tropospheric Clouds"

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The goal of this research has been to identify and describe the properties of climatically important cloud systems critically important to understanding their effects upon satellite remote sensing and the global climate. These goals have been pursued along several different but complementary lines of investigation: the design, construction, testing and application of instrumentation; the collection of data sets during Intensive Field Observation periods; the reduction and analysis of data collected during IFO's; and completion of research projects specifically designed to address important and timely research objectives.

In the first year covered by this research proposal, three papers were authored in the refereed literature which reported completed analyses of FIRE I IFO studies initiated under the previous NASA funding of this topic area. microphysical and radiative properties of marine stratocumulus cloud systems deduced from tethered balloon observations were reported from the San Nicolas Island site of the first FIRE marine stratocumulus experiment. Likewise, in situ observations of radiation and dynamic properties of a cirrus cloud layer were reported from first FIRE cirrus IFO based from Madison, Wisconsin. In addition, application techniques were under development for monitoring cirrus cloud systems using a 403 MHz Doppler wind profiler system adapted with a RASS (Radio Acoustic Sounding System) and an infrared interferometer system; these instrument systems were used in subsequent deployments for the FIRE II Parsons, Kansas and FIRE II Porto Santo, ASTEX expeditions. In November 1991 and in June 1992, these two systems along with a complete complement of surface radiation and meteorology measurements were deployed to the two sites noted above as anchor points for the respective IFO's.

Subsequent research activity concentrated on the interpretation and integration of the IFO analyses in the context of the radiative properties of cloud systems and our ability to remotely observe radiative, thermodynamic and dynamic properties of these cloud systems.

Radiative Properties of Cloud Systems:

[Smith, W. L., Jr., et al., 1990] On 28 October 1986 the NCAR Sabreliner observed a cirrus cloud layer in the vicinity of Green Bay, Wisconsin. A portion of each flight leg was conducted over western Lake Michigan and over the adjacent western shore. The cirrus layer would be qualitatively described as optically thin and tenuous, yet broadband infrared effective emittances were found between about 0.4 and 0.6 while broadband shortwave extinction values ranged from as low as 5% to 32%. This investigation examines the bulk radiative properties of the cirrus layer and the horizontal variability of these radiative properties. In addition, the microphysical characteristics and the dynamic properties of the layer are presented and analyzed. The broadband infrared volume absorption coefficients were deduced for the cirrus layer and found to be very similar in terms of a dependence on temperature to results recently presented by other authors. Infrared radiative heating rates were calculated and found to be typical of the optically thin cirrus layer examined here. The horizontal structures of the radiative properties of the cirrus cloud layer and the vertical velocity observations were very similar. Both showed a smaller scale variation at the top of the cirrus layer which merged into larger scale common elements near the bases of the layer. Power spectra analyses of along-wind and cross-wind components near the base of the clouds sampled exhibited a steep spectral slope of k^{-3} at the smaller wave numbers (scale-lengths greater than 1 km). This k^{-3} slope is characteristic of two-dimensional eddies. The same k^{-3} slope is present in the power spectra of the radiative properties. It is probable that these radiative properties, which are modulated by the cloud elements, have their scales determined by the eddies detected in the analysis of wind components.

[Withrow, John R., Jr., et al., 1994] Evaluations of the possible effects on tropospheric warming and stratospheric cooling by cirrus clouds arising from their radiative properties have been based upon the assumption that cirrus particles behave radiatively like ice spheres. We have extended this approximation to circular cylinders and disks. The scattering information for such particles is investigated using two models, one employing the Discrete Dipole Approximation and the other Anomalous Diffraction Theory. The study begins with a general overview of the current state of cirrus research leading to the appropriateness of this study. An exhaustive display of the current theoretical and experimental knowledge of the problem of scattering off of cylindrical particles is then provided. Cylindrical particles with length-to-diameter ratios ranging from .1 to 10 and with effective radius values up to about 6 are then modeled for four refractive indices ranging from nonabsorbing to strong absorbing. Results are given for the extinction efficiency, Q_{ext}, the single scatter albedo, ω_0, and the asymmetry parameter, g. The results for ω_0 and g are extended to larger sized particles through the fitting of corresponding Mie curves to the cylinder data. Similar extensions for Q_{ext} are performed through comparisons with results from a second model employing Anomalous Diffraction Theory. An analysis of the DDA and ADT results is given, yielding a voluminous supply of information, both quantitative and qualitative. The quantitative information is displayed in a myraid of appendices which are referenced by the chapters. Briefly, the first three appendices show the entirety of the DDA results for Q_{ext}, ω_o, and g, respectively, information which will be most useful to subsequent studies which have an interest in the scattering results of individual particles. In addition, the latter three appendices show a series of tabulated results, the curve-fit extension factors which should make the rapid reproduction of cylinder information from currently parameterized information more feasible. Qualitatively the results are analyzed to arrive at some of the mechanisms involved in the scattering from cylindrical particles as well as some initial insights as to the biases introduced in radiative transfer models through the representation of cirrus particles as equivalent volume spheres.

These results should ultimately begin to provide the necessary information for a subsequent two-stream radiative transfer model in which cirrus heating rates and radiative cloud forcings can be calculated to a second approximation from spheres, that of cylinders and disks. Although this study performs an analysis only on individual particles, some educated assertions can now be made in terms of the biases generated by the use of equivalent volume spheres in a modeled cirrus cloud. In general it is found that the equivalent volume sphere approximation should result in an underestimation of absorption as well as an overestimation of the amount of forward scatter for small particles. Also for small particles the infrared optical depth should in most cases be overestimated. Lastly, the use of Anomalous Diffraction Theory in the depiction of cirrus particle radiative properties should in most cases result in a slight underestimation of absorption and optical depth.

[Beck, Gordon, H. et al., 1994] Infrared spectral window emittances of mid-latitude and sub-tropical cirrus clouds have been inferred from surface-based interferometric measurements obtained during the FIRE II and ASTEX. The emittance values are derived at 1 cm^{-1} resolution over the 800 cm^{-1} to 1200 cm^{-1} bandpass. A nested iteration technique which includes cirrus cloud reflectance in the derivation of the cirrus emittances is described. The impact of including the reflectance properties of the cirrus layer in the inference of the emittances is shown to be significant.

For this set of observations, it is shown that the emittances of sub-tropical cirrus are generally higher than those of mid-latitude cirrus (0.006-0.749 as compared to 0.029-0.926, respectively). A comparison between the surface radiative forcings for the two classes of clouds showed that the absolute surface radiance changes due to the onset of cirrus were similar although the relative impact of the mid-latitude cirrus was larger than that of the sub-tropical cirrus. The roles of the subcloud layer and the layer above the cloud in modifying heating rates within the cirrus cloud layer and in the subcloud layer are examined.

[Heidinger, Andrew K. et al., 1996] As numerical weather and climate predication models demand more accurate treatment of clouds, the role of finite-cloud effects in longwave radiative transfer clearly warrants further study. In this research, finite-cloud effects are defined as the influence of cloud shape, size, and spatial arrangement on longwave radiative transfer. To show the magnitude of these effects, radiometer data collected in 1992 during the Atlantic Stratocumulus Transition Experiment (ASTEX) were analyzed. The ASTEX data showed that radiative transfer calculations that ignored the vertical dimensions of the clouds underestimated the longwave cloud radiative surface forcing by 30%, on average. To study further these finite-cloud effects, a three-dimensional 11-μm radiative transfer model was developed. Results from this model, which neglected scattering, agreed with the measurements taken during ASTEX on 14 June 1992. This model was also used to reiterate that, for optically thick clouds, knowledge of cloud macrophysical properties can be more crucial to the modeling of the transfer of longwave radiation than the detailed description of cloud microphysical properties. Lastly, techniques for the inclusion of these finite-cloud effects in numerical models were explored. Accurate radiative heating rate profiles were achieved with a model that assumed a linear variation of the cloud fraction with the cloud layer. Parameterizations of the finite-cloud effects for the marine stratocumulus observed during ASTEX are presented.

[Gillies, Sean C., et al., 1995] As part of the ASTEX campaign in June of 1992, intensive observations were made of the surface solar irradiance on the island of Porto Santo. From these data, the net surface irradiance has been derived for the period of June 1-28, 1992 and reduced into visible and infrared and direct and diffuse components. By comparison of data collected under partially-clouded and overcast conditions, the enhancement of the surface solar irradiance due to the finite properties of marine boundary layer clouds has been determined.

A parameterization has been developed to account for the finite geometry and horizontal inhomogeneity of the marine boundary layer clouds. Accounting for the finite size and vertical extent of cloud is shown to increase the effective cloud amount relative to the horizontal cloud cover. Accounting for the horizontal inhomogeneity in cloud liquid water path is shown to lead to an effective optical thickness that is smaller than the average optical thickness of the cloud. This parameterization is validated by comparison to the observations, using observed cloud liquid water paths and cloud cover in a simplified radiative transfer model. The reduced optical thickness parameterization is shown to be an improvement over the conventional parameterization which use an anomalously low amount of clouds which are uncharacteristically thick.

Dynamic Properties of Cloud Systems:

[Song, Ran, et al., 1994] The development of doppler radar wind profilers and their subsequent deployment have dramatically improved the spatial and temporal resolutions of wind observations. While the horizontal winds deduced from these observations are generally reliable, serious questions remain on the ability to reliably observe the vertical wind component. In an upper tropospheric cirrus cloud environment often characterized by weak back scatter signal strength, small magnitude vertical motions, high altitude and short life cycle, this problem is especially difficult. A review of the echo generating mechanisms for a 400 MHz radar system is presented. This study further examines the feasibility of determining reliable vertical motion fields from both individual and a network of wind profiler observations. Data employed in this research were collected during the FIRE II experiment in November and December of 1991. Vertical motions were calculated in three ways: directly from the doppler radial velocity observations, from a quasi-VAD method utilizing the four non-zenith profiler beams, and by applying the kinematic method to profiler network data. The deduced vertical wind fields from each method are compared. This research also includes a diagnostic study of a jet streak system observed on 26 November 1991; this study emphasizes the thermal and dynamic instability structures, the vertical forcing and the ageostrophic circulation. Results from the diagnostic and previous theoretical studies are compared with the vertical velocity fields deduced from wind profiler observations.

[Lappen, Cara-Lyn, et al., 1994] The object of the Atlantic Stratocumulus Experiments (ASTEX) was to measure and examine properties of the marine atmosphere. Since instruments were placed on the island of Porto Santo, however, some degree of contamination of pure marine conditions was experienced due to the local effects of island topography. In order to assess the expected differences between a pure marine environment and measurements taken on the island of Porto Santo, a numerical model- the Regional Atmospheric Modelling System (RAMS) was used in direct comparison with observational data for the case of June 10, 1992. Specifically, this study focuses on the mean wind fields simulated by RAMS and compares them to the winds measured by the United Kingdom's C130 Meteorological Research Flight, a 400MHz wind profiler, and rawinsondes. The model's inability to resolve a 100m cliff on the windward side of the island was found to cause a phase shift between the mode-produced and the actual wind fields. This was determined to be a 1-2km upward phase shift and a 300m to 500m windward phase shift for the RAMS data. After applying this correction, and comparing these four sources of data, the extent of the island's effects in the horizontal as well as the vertical was determined. In the horizontal, the effects decrease with distance from the island until approximately 2km upwind or downwind where the effect was minimal. In the vertical, the effect of the island was detectable up to 3.5km, but not felt continuously. The maximum effect was found at the ground and at approximately 1.2km. Wind data taken at Porto Santo must be filtered at the ground, and near the 1.2 km and 3.5km levels. In between these levels, wind measurements taken on the island would appear to provide an accurate representation of the pure marine environment.

Remote Sensing of Cloud Systems:

[Hein, Paul F., et al., 1993] Remote sensing of the atmospheric winds provides the observer with many advantages as well as some limitations. Wind profiling gives the observer on the ground a high temporal depiction of winds at various heights in the atmosphere. Unfortunately the wind profiler sometimes senses and measures other phenomena besides wind. The removal of these spurious measurements and an assessment of the quality of the measurement that are the foci of this report.

[Keith, Chan W., et al., 1994] Initial analysis of the data from the laser ceilometer used during the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE) and Atlantic Stratocumulus Transition Experiment (ASTEX) programs indicated that clouds were sometimes not reported even though clouds were visible over the ceilometer. In order to understand this inconsistency, a model using Monte Carlo techniques has been refined to study the effect that multiple scattering and other physical processes have on near infrared laser ceilometer returns. The model traces photon paths through three orders of scattering within various scattering media and determines the photon's probability of returning to the receiver at each scattering point. The Monte Carlo model allows for a limited number of horizontal and vertical inhomogeneities in the extinction coefficient and scattering phase function within the scattering media. Clear air and background aerosol scattering, based on published standards are also introduced within the model. Results from the current model are compared with previously published results. Specific atmospheric media and laser ceilometer parameters are modeled, and a factor, α, is defined to measure the effects of each. Results from the model indicate that precipitation and extinction by the subcloud layer have the most significant impact upon the return signal. For clouds with the same optical depth, those with an increasing extinction with depth exhibited a flatter, smaller magnitude return signal than those with a constant or decreasing extinction. Rayleigh scattering and background aerosols in the subcloud layer decrease the return signal from the cloud and introduce a background level of return from below the cloud. Rain in the subcloud layer lowers the return signal from the cloud, but increases the signal from the subcloud layer due to its relatively large extinction, while realistic levels of absorption have no significant impact. Lastly, a quantitative assessment of detectability for clods is made, based on α_{min} as a threshold. Model results indicate that conditions can exist where a cloud may not be identified by the laser ceilometer.

[Feigelson, Eva, M. et al., 1992] CSU scientists collaborated with their colleagues in the former Soviet Union working on problems of common interest in the area of clouds and radiation. The primary collaborations were with FSU scientists from the Russian Academy of Sciences. The FSU scientists participated in both FIRE II IFO expeditions and continue to collaborate on the data analyses from the FIRE II program and its counterpart in Russia. This counterpart program is outlined below.

In connection with WCRP, the Soviet programme of clouds and radiation climatology (SCRCP) was organized in 1985. In this context, beginning in 1986 Soviet scientists undertook collaborative activities to study the radiative properties of cirrus clouds as well as factors which determine these properties. The Institute of Atmospheric Physics of the USSR Academy of Sciences (IAPh) assumed the organizing role and scientific leadership. Three field experiments in the month of May of 1986, 1987, and 1989 were carried out at the Zvenigorod Scientific Station (Z.S.S.) of IAPh (60 km from Moscow). Together with IAPh, the Central Aerological Observatory (CAO) of the USSR State Hydrometeorology Committee participated in the experiments and provided lidar measurements, radiosonde data (Station Dolgoprudny 80 km from Zvenigorod) and analyses of the synoptic situation. The CAO flying laboratory aircraft II-18 took part in the experiment of 1989. The microphysics parameters, water content, scattering coefficients and integral fluxes of solar radiation were measured on board the aircraft.

Surface actinometric observation (spectral and integral fluxes of direct, diffuse and global radiation), as well as visual observations of clouds were provided by Meteorological Observatory of the Geography faculty of the Moscow State University (MSU).

The Moscow Instrument-making Institute took part in the experiments of 1986-87 and measured the cloud emissivities.

The Institute of Experimental Meteorology (IEM) together with IAP developed the optical models of ice clouds.

The employees of the Hydrometeorological Centre analyzed the information from the satellite NOAA-II AVHRR (1989 experiment).

The IAPh provided the measurements of spectral optical thicknesses of clouds, the theoretical investigations and in 1989 the measurements of downward integral fluxes of thermal radiation.

Main results of 1986-88 experiments and theory were presented in the Abakumova, G.M., et al., 1989. The results of 1989-90 as well as summarizes of all experimental and theoretical works during the five year period (1986-90) are described in this issue.

In evaluating these results, let us note that:

We are merely beginning to effectively use the combination of surface, aircraft and satellite data and in these studies basically concentrated on the connection between different data from surface measurements and theory.

The existence of data of the directly measured main optical parameter, i.e. the optical thickness of clouds, together with data of cloud heights and thicknesses, vertical distribution of extinction coefficients of the visible light within cloud and actinometric information, allows us to produce rather complete descriptions of radiative and optical properties of ice clouds; these investigations have four main thrusts:

1. The statistics of radiative fluxes arriving at the Earth's surface.
2. The construction of optical models from measurements of the spectral transmittance, from solutions of inverse problems and from calculations of particles optical parameters.
3. The development of regression relationships between optical and meteorological parameters.
4. The evaluation of the radiation balance at the boundaries of the atmosphere and clouds.

ADMINISTRATIVE ACTIVITIES

This grant has supported Professor Cox in his administrative capacity as Co-chair of the FIRE Science Team. In this capacity Professor Cox has organized and chaired FST meetings and assisted the FIRE Project Office in conceptualization, organization and execution of the FIRE program.

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Project Period: 5/90-5/95

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Keith, C. W. and S. K. Cox, 1994: Monte Carlo Modeling of Laser Ceilometer. 74th AMS Annual Meeting, Nashville, Tennessee, January 23-28, 1994.

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STUDENTS SUPPORTED:

STUDENTS	YEAR GRADUATED	DEGREE
Gordon Beck	1994	M.S.
Andrew Heidinger	1994	M.S.
Cara-Lyn Lappen	1994	M.S.
Ran Song	1994	M.S.
John Withrow	1994	M.S.
Sean Gillies	1995	M.S.
Norman Wood		M.S.