MASTER

**THE EFFECTS OF ATMOSPHERIC
VARIABILITY ON ENERGY
UTILIZATION AND CONSERVATION**

by

**Elmar R. Reiter, Principal Investigator,
E. Dreiseitl, G.R. Johnson, H.H. Leong,
B.C. MacDonald, W.L. Somervell, Jr.,
A.M. Starr, and K.O. Timbre**

**Environmental Research Papers
COLORADO STATE UNIVERSITY
Fort Collins, Colorado**

14

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Research on the environment constitutes an important component of the graduate programs pursued by a number of Colorado State University departments. The more noteworthy results of these research efforts are normally published in the conventional professional journals or conference proceedings, but in very much abridged form. ENVIRONMENTAL RESEARCH PAPERS has been established to provide a formal means of disseminating such CSU accomplishments in all significant details, in order that individuals concerned with related interests at other institutions may review a more comprehensive treatment of the research reported than is customarily available.

Price \$3.00 in USA

EDITORIAL BOARD

Dr. Myron L. Corrin, Department of Atmospheric Science

Professor Lewis O. Grant, Department of Atmospheric Science

Dr. Judson M. Harper, Agricultural Engineering

Dr. Elmar R. Reiter, (Editor), Department of Atmospheric Science

Dr. David W. Seckler, Department of Economics

Dr. Rodney K. Skogerboe, Department of Chemistry

Dr. Evan C. Vlachos, Department of Sociology

Subscriptions and correspondence to these papers should be addressed to: Secretary of Environmental Research Papers, Department of Atmospheric Science, Colorado State University, Solar Village, Ft. Collins, CO 80523.

THE EFFECTS OF ATMOSPHERIC VARIABILITY ON ENERGY UTILIZATION AND CONSERVATION

Final Report of Research Conducted Between
1 November 1976 and 31 October 1977

Under Contract EY-76-S-02-1340 A002

THE U.S. DEPARTMENT OF ENERGY

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

By

Elmar R. Reiter, Principal Investigator,
E. Dreiseitl, G.R. Johnson, H.H. Leong, B.C. Macdonald,
W.L. Somervell, Jr., A.M. Starr and K.O. Timbre

Department of Atmospheric Science
Colorado State University
Solar Village
Fort Collins, Colorado 80523

February 1978

No. 14

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

gb
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PREFACE

Our efforts on this research grant started on 1 July 1975. The results obtained from that date until 31 October 1976 are contained in Environmental Research Paper No. 5, Colorado State University, bearing the same title as this report, and having been compiled by E.R. Reiter (Principal Investigator), G.R. Johnson, W.L. Somervell, Jr., E.W. Sparling, E. Drieseitl, B.C. Macdonald, J.P. McGuirk and A.M. Starr. Copies of that report are available upon request from the Department of Atmospheric Science, Colorado State University.

The present report covers our team research efforts for the period 1 November 1976 through 31 October 1977. As in the previous grant period, our research efforts proceeded simultaneously on several parts. Five major areas of investigation are defined as follows:

1. Modelling of the energy consumption for space heating by a community as a function of environmental factors.
2. Development of economically feasible building census techniques.
3. Characterization of urban climate parameters, which influence energy consumption for space heating.
4. The interannual variability of the ocean-atmosphere system.
5. Surface temperature variability especially over the eastern United States, and its relation to large-scale flow.

Major achievements have been made in each of these areas. Nevertheless, we are still short from our ultimate goal, which is to model the energy consumption and its dependence on weather for wide regions of the United States and to tie this modelling capability to short-, medium- and long-range projections of weather anomaly patterns. Our original proposal of August 1975 called for a five-year program to reach this goal. We had, however, anticipated a considerably more expanded level of effort during that time. Allowing for the budgetary restrictions, we consider our program to be well on schedule.

Elmar R. Reiter
Professor of Atmospheric Science
Principal Investigator

TABLE OF CONTENTS

	<u>Page</u>
TITLE PAGE	i
PREFACE	ii
TABLE OF CONTENTS	iii
LIST OF FIGURES	iv
LIST OF TABLES	vii
ACKNOWLEDGMENTS	ix
ABSTRACT	1
1 Scope of Work According to Research Proposal	2
2 Model Development	3
2.1 From Feedback-Control System to Adaptive System Identification	3
2.2 A Proposed Framework for Adaptive System Identification	4
2.3 Model Validation	6
2.4 1976-1977 Greeley Energy Consumption	12
2.5 Modelling Cheyenne, Wyoming	12
3 Input Data and Data Acquisition	14
3.1 Building Census	14
3.2 Summary of Greeley Weather	18
3.3 Cheyenne Weather	20
3.4 Metropolis Study	21
4 Effects of a Cold Winter on Energy Demand	24
4.1 The Weather Sensitivity of Residential Demands on Natural Gas Supplies	24
4.2 The Effects of January 1977	25
5 The Interannual Variability of the Ocean-Atmosphere System	28
6 Surface Temperature Variability Related to Large-Scale Flow	36
7 Executive Summary.	40
7.1 Energy Modelling	40
7.2 Statistical Data Sampling	40
7.3 Urban Climate Studies	41
7.4 The Interannual Variability of the Ocean-Atmosphere System	41
7.5 Effects of Large Scale Flow Patterns on Surface Temperatures Over the Eastern United States	41
REFERENCES	42
APPENDIX A - Development of the Heuristic Descriptive Polynomial Model	43
APPENDIX B - Thermal Modelling	48
APPENDIX C - Evidence of an Urban Heat Island in Greeley, Colorado	54
APPENDIX D - Data Used in Air-Sea Interaction Studies	63
REFERENCES TO APPENDICES	75

LIST OF FIGURES

		Page
Fig. 2.1	Feedback-control-system realization of the conversion of energy to space-conditioning needs.	3
Fig. 2.2	Alternate block diagram for conversion of energy to space-conditioning needs	4
Fig. 2.3	A conceptual input/output system identification block diagram	4
Fig. 2.4	The self-organized dynamic forecasting model with adaptive feedback, diagnostics, updating and re-evaluation mechanisms	5
Fig. 2.5	Locations of the seven Greeley weather stations and the structures that were individually validated during the winter of 1976-77	7
Fig. 2.6	Photograph of mobile home court which was validated for the winters of 1975-76 and 1976-77 .	8
Fig. 2.7	Comparison of the measured total daily and predicted space-heating gas use and the weather data used in validating the mobile home court during the winter of 1976-77	8
Fig. 2.8	Photograph of the Weld Hospital which was validated for the winters of 1975-76 and 1976-77 .	9
Fig. 2.9	Same as Fig. 2.7, except for Weld County Hospital.	9
Fig. 2.10	Photograph of the agricultural supply store which was validated for the winter of 1976-77 .	9
Fig. 2.11	Same as Fig. 2.7, except for the agricultural supply store	9
Fig. 2.12	Weather data at our seven Greeley stations for 7:00 A.M. following a clear night. Minimum temperature = 13.5°F. Maximum temperature = 67.0°F. Winds are less than 3 meters per second	10
Fig. 2.13	Photograph of the bank building which was validated for the winter of 1976-77.	10
Fig. 2.14	Comparison of the measured total daily and predicted space-heating gas consumption used in validating the bank building during the winter of 1976-77.	10
Fig. 2.15	Photograph of the apartment structure which was validated for the winter of 1976-77.	10
Fig. 2.16	Same as Fig. 2.7, except for the apartment building.	11
Fig. 2.17	Photograph of Greeley West High School which was validated for the winter of 1976-77	11
Fig. 2.18	Same as Fig. 2.7, except for Greeley West High School.	11
Fig. 2.19	Same as Fig. 2.7, except for the entire area of Greeley, Colorado.	12
Fig. 2.20 a,b,c	Comparison of the measured total daily and predicted space-heating natural gas consumption and the average daily weather data for Cheyenne, Wyoming during January (a), February (b) and March (c) 1977	13
Fig. 2.21	Comparison of the measured total daily and predicted space-heating natural gas consumption for F.E. Warren Air Force Base during February 1977.	13
Fig. 3.1	Map of Cheyenne, Wyoming. The dashed lines indicate the city boundaries; the square boxes represent our sectional boundaries. Also indicated is the topography and the location, denoted by crosses, of our weather stations.	14
Fig. 3.2 a,b,c	Number of residential structures in each age group as a function of twice the standard error of the average floor area for a 1%, 5% and 10% sample size, respectively	15
Fig. 3.3	Average square footage of the pre-1970 residential structures as a function of the average value of owner occupied units for 26 regions in Greeley and Cheyenne	18
Fig. 3.4	Map of Greeley, Colorado showing the locations of the nine meteorological stations	18
Fig. 3.5	Pattern of the temperature and wind variables as they are used in the physical model of Greeley.	19
Fig. 3.6	Climatological daily temperatures and daily mean temperatures during the winter of 1976-77 for Fort Collins. Positive or warm deviations are indicated by hatched areas.	20
Fig. 3.7	Wind roses for Stations #6 and #3 during the winter of 1976-77 in Cheyenne	20

	<u>Page</u>
Fig. 3.8	Mean bihourly temperatures for Stations #6 and #3 in Cheyenne during the winter of 1976-77 21
Fig. 4.1	Estimated net energy use in 1972. (FEA, 1975.) 24
Fig. 4.2	Domestic consumption, marketed production, domestic producer sales and imports of natural gas: (FEA, 1977.) 25
Fig. 4.3	Storage of natural gas. (FEA, 1977.) 25
Fig. 4.4	Oil heating degree days for January 1977 in terms of departures from normal (data from Wagner, 1977). 26
Fig. 4.5	Percent departures of January 1977 heating degree days from normal 26
Fig. 4.6	Percent departure of heating degree days during January 1977 from the normal of January 1941-1970. (FEA, 1977.) 26
Fig. 4.7	The weather-dependent part of energy demand (Eq. 4.1) extrapolated to 1970 census data on population 26
Fig. 4.8	The excess of the weather-dependent part of energy demand (Eq. 4.1) during January 1977 over that expected during a normal month of January 27
Fig. 5.1	Precipitation anomalies over the United States, winter 1976-77. Hatched regions indicate below normal precipitation, dotted regions above normal precipitation. (From "Mosaic" National Science Foundation, July/August 1977, after Namias.) 28
Fig. 5.2	Schematic diagram of sea-surface temperature anomalies over the North Pacific, leading to atmospheric circulation anomalies and to temperature anomalies over the western and eastern United States. (From "Mosaic" National Science Foundation, July/August 1977, after Namias.) 28
Fig. 5.3	Seven-month running mean of monthly departures from 15-year monthly means of SST for latitude bands indicated. Heavy dashed-dotted lines indicate least-squares linear or parabolic fit 29
Fig. 5.4	Seven-month running mean of sea-surface temperature anomalies ($^{\circ}\text{C}$) in the latitude band 40° - 50°N of the North Pacific, calculated with respect to the 1962-1976 monthly mean temperatures. Dots after 1962: data from Fleet Numerical Weather Center. Solid line between 1949 and 1962: data from Fisheries Research Board of Canada. Dots prior to 1962: data from National Oceanic and Atmospheric Administration (NOAA). 29
Fig. 5.5 a,b,c	Mean monthly isotherms of SST by 2°C intervals (8°C intervals are labelled) for June (a) 1963, (b) 1969, and (c) 1976. Isotherms over continents should be ignored; they appear solely for the purpose of computer plotting requirements 30
Fig. 5.6 a,b,c	Same as Fig. 5.5, except for July. 31
Fig. 5.7	Monthly departures of u-component (m/sec) from the "long-term" monthly means given (a) the u-component of the North Pacific trade winds at the ocean surface in the "box" 5°N - 19°N , 125°E - 95°W , heavy full line (land masses excluded) and (b) the u-component of the South Pacific trades in the "box" 1°S - 15°S , 125°E - 75°W , heavy dashed line, seven-month running averaging applied to data. Positive values indicate stronger-than-normal east wind. Parabolic least-square trends are given by thin, full and dashed lines. Vertical lines indicate January of each respective year. 31
Fig. 5.8	Schematic feedback system between atmospheric and oceanic large-scale circulation. 32
Fig. 5.9 a,b	Lag-correlation coefficients (ordinate) as a function of time-lag in months (abscissa) between the trade-wind v-component and SST anomalies in the (a) 30° - 40°N and (b) 40° - 50°N latitude bands. Dots in the lower portions of diagrams indicate significance of the correlations at better than the 50, 80, 90, 95 and 99 percent levels, respectively. 32
Fig. 5.10	Monthly departures from long-term monthly mean values (seven-month "low-pass" running-mean filter applied to anomaly data) of the following parameters: (1) Sea-surface temperatures ($^{\circ}\text{C}$), in the latitude belt 40° - 50°N , over the longitudinal extent of the Pacific at those latitudes. Linear least-squares trend indicated by heavy dashed line. This portion of the diagram is time-lagged against the other parameters by 20 months. (2) Northern (N.H., heavy solid line) and southern hemisphere (S.H., thin solid line) v-components (m/sec) of trade-winds in the "boxes" 5°N - 19°N , 125°E - 95°W and 1°S - 15°S , 125°E - 75°W . Stronger-than-normal flow towards the equator in each hemisphere is indicated by positive anomaly values. Parabolic least-square trends are indicated by heavy (N.H.) and light (S.H.) dashed lines. Letters "E" signify approximate dates of (continued)

	El Niño occurrences. (3) Curl of the zonal wind stress (arbitrary units) computed as the difference in $\frac{u^2}{f}$ between 13-15°N and 7-9°N, parabolic least squares trend indicated by heavy dashed line. (4) Sea-level differences (cm) across the North Equatorial Current in the western central Pacific (heavy line) and 12-month running mean (thin line); approximate copy of data from Wyrski (1974).	33
Fig. 5.11	Schematic diagram of feedback mechanisms involving oceanic and atmospheric anomalies in the Pacific region. Positive feedbacks are indicated by solid lines with arrows between "boxes", negative feedbacks by dotted lines and "N.F."	34
Fig. 5.12	Mean Pacific trade-wind v-component anomalies ($(V_{N.H.} + V_{S.H.})/2$ in m/sec, (solid line) and precipitation index for Line Islands, (dashed-dotted line). Seven-month smoothing applied to both data sets	34
Fig. 5.13	Line Island precipitation index for the years 1910 to 1975. Dots indicate monthly values, the heavy line stands for a 7-month running average	35
Fig. 6.1	Monthly mean temperature anomalies from the indicated states used to calculate C_1 , C_2 and C_3 , the temperature pattern coefficients	36
Fig. 6.2	The normalized pattern $r_{11}^2 S_{11}$ which represents the linear relationship between the mean surface-temperature pattern coefficient, C_2 and the monthly mean meridional wind, $\bar{v}$, at each point	37
Fig. 6.3	The normalized pattern $r_{12}^2 S_{12}$ which represents the linear relationship between the north-south gradient of the surface-temperature coefficient, C_2 , and the monthly mean meridional wind, $\bar{v}$, at each point	37
Fig. 6.4	The normalized pattern $r_{13}^2 S_{13}$ which represents the linear relationship between the east-west gradient of the surface-temperature coefficient, C_3 , and the monthly mean meridional wind, $\bar{v}$, at each point	37
Fig. 6.5	Observed mean temperature-pattern coefficient, C_1 , versus $\bar{v}$ pattern coefficient, B_1 . The least-squares linear fit is also plotted	38
Fig. 6.6	Observed north-south temperature-gradient-pattern coefficient, C_2 , versus $\bar{v}$ pattern coefficient, B_2 . The least-squares linear fit is also plotted	38
Fig. 6.7	Observed east-west temperature-gradient-pattern coefficient, C_3 , versus $\bar{v}$ pattern coefficient B_3 . The least-squares linear fit is also plotted	39
Fig. A.1	The GMDH Block Diagram	45
Fig. C.1	Daily average temperature of Greeley for the 81-day period	55
Fig. C.2	Daily average insolation of Greeley for the 81-day period	55
Fig. C.3	Average hourly wind speeds of the 6 stations for the 81-day period	56
Fig. C.4a	Percent frequency of wind direction by wind speed class for the Tower station during the 81-days for daytime	56
Fig. C.4b	Same as Fig. C.4a, except for nighttime	57
Fig. C.5	Percent frequency of wind direction for day (thick line) and night (thin line) at Station 1 for the 81-day period	57
Fig. C.6	Percent of observations when the wind speed at Station 5 is greater than (solid), less than (dashed-dots), and equal to (dashed) the wind speed at Station 4	58
Fig. C.7a	Temperature differences between Stations 5 and 6 by weather classes for the 81-day period	59
Fig. C.7b	Temperature differences between Stations 5 and 6 by weather classes for the 81-day period	59

	<u>Page</u>
Fig. C.7c	Temperature differences between Stations 2 and 1 by weather classes for the 81-day period 60
Fig. C.7d	Temperature differences between Stations 3 and 6 by weather classes for the 81-day period 60
Fig. C.7e	Temperature differences between Stations 4 and 5 by weather classes for the 81-day period 60
Fig. C.7f	Temperature differences between Stations 4 and 6 by weather classes for the 81-day period 61
Fig. C.8 a-e	Map of Greeley showing the average observed temperature patterns during: a) total 81-day period; b) weather class 1; c) weather class 2; d) weather class 3; e) weather class 4 62

LIST OF TABLES

Table 2.1	Characteristics of "Typical" 12-foot x 60-foot Mobile Home	8
Table 3.1	The average calculated residential floor area, total count and percent of count sampled for each section in Cheyenne	16
Table 3.2	The average square footage, count, and percent of total count for all building types during the winter of 1977 for Cheyenne, Wyoming	17
Table 3.3	An example of the meteorological input as used by the physical model for January 1, 1977	19
Table 3.4	Mean monthly air temperatures for the five stations in Cheyenne during the 1976-77 winter in degrees Centigrade	21
Table 4.1	Energy Consumption, November 1974	24
Table 4.2	Energy consumption by economic sector and primary source, November 1976	24
Table 4.3	Record and near-record low monthly mean temperatures observed during January 1977	25
Table 6.1	Statistical analysis of linear least-squares fit for temperature-pattern coefficients, C_i , calculated from mean v-component wind-pattern coefficients, B_i	39
Table 6.2	Percent variance explained by least-squares linear fit	39
Table C.1	National climatic center climatological data for Greeley, Colorado 1976-77	54
Table C.2	Weather classifications.	55
Table D.1a	Pacific sea surface temperatures, monthly mean values, °C, averaged from gridded data over the longitudinal extent of the Pacific and between 20°N and 30°N. (Original data, courtesy of Fleet Numerical Weather Central, Monterey, California.)	63
Table D.1b	Departures of the values shown in Table D.1a (20-30°N) from long-term monthly mean values	63
Table D.1c	Data of Table D.1b subjected to 7-month running-mean filter	63
Table D.2a	Similar to Table D.1a, except Pacific SST's in latitude band 30-40°N	64
Table D.2b	Similar to Table D.1b, except monthly SST anomalies, 30-40°N	64
Table D.2c	Similar to Table D.1c, except 7-month smoothed SST anomalies, 30-40°N	64
Table D.3a	Similar to Table D.1a, except Pacific SST's in latitude band 40-50°N	65
Table D.3b	Similar to Table D.1b, except monthly SST anomalies, 40-50°N	65
Table D.3c	Similar to Table D.1c, except 7-month smoothed SST anomalies, 40-50°N	65
Table D.4a	Similar to Table D.1a, except Pacific SST's in latitude band 50-60°N	66
Table D.4b	Similar to Table D.1b, except monthly SST anomalies, 50-60°N	66
Table D.4c	Similar to Table D.1c, except 7-month smoothed SST anomalies, 50-60°N	66
Table D.5a	Differences in monthly mean values of SST, °C, between 20-30°N and 40-50°N over the longitudinal extent of the Pacific, derived from Tables D.1a and D.3a.	67

	<u>Page</u>
Table D.5b	Departures of the values shown in Table D.5a from their long-term monthly means 67
Table D.5c	Data of Table D.5b subjected to 7-month running-mean filter 67
Table D.6a	Monthly mean heights (geopotential meters in excess of 1500 gpm) of the 850-mb surface at 20°N over the Pacific longitude sector, obtained from NMC data tapes, courtesy of NCAR . . . 68
Table D.6b	Departures of the values shown in Table D.6a from their long-term monthly mean values . . . 68
Table D.6c	Data of Table D.6b subjected to 7-month running-mean filter 68
Table D.7a	Monthly mean heights (geopotential meters in excess of 1000 gpm) of the 850-mb surface at 50°N over the Pacific longitude sector, obtained from NMC data tapes, courtesy of NCAR . . . 69
Table D.7b	Departures of the values shown in Table D.7a from their long-term monthly mean values . . . 69
Table D.7c	Data of Table D.7b subjected to 7-month running-mean filter 69
Table D.8a	Monthly mean heights (geopotential meters in excess of 9000 gpm) of the 300-mb surface at 20°N over the Pacific longitude sector, obtained from NMC data tapes, courtesy of NCAR . . . 70
Table D.8b	Departures of the values shown in Table D.8a from their long-term monthly mean values . . . 70
Table D.8c	Data of Table D.8b subjected to 7-month running-mean filter 70
Table D.9a	Monthly mean heights (geopotential meters in excess of 8000 gpm) of the 300-mb surface at 50°N over the Pacific longitude sector, obtained from NMC tapes, courtesy of NCAR 71
Table D.9b	Departures of the values shown in Table D.9a from their long-term monthly mean values . . . 71
Table D.9c	Data of Table D.9b subjected to 7-month running-mean filter 71
Table D.10a	Monthly mean thicknesses 300/850 mb (geopotential meters in excess of 7500 gpm) at 20°N over the Pacific longitude sector 72
Table D.10b	Departures of the values shown in Table D.10a from their long-term monthly mean value . . . 72
Table D.10c	Data of Table D.10b subjected to 7-month running-mean filter 72
Table D.11a	Monthly mean thickness 300/850 mb (geopotential meters in excess of 7000 gpm) at 50°N over the Pacific longitude sector 73
Table D.11b	Departures of the values shown in Table D.11a from their long-term monthly mean values . . . 73
Table D.11c	Data of Table D.11b subjected to 7-month running-mean filter 73
Table D.12a	Monthly mean values of thickness difference 300/850 mb (geopotential meters) between 20°N and 50°N over the Pacific longitude sector 74
Table D.12b	Departure of the values shown in Table D.12a from their long-term monthly mean values . . . 74
Table D.12c	Data of Table D.12b subjected to 7-month running-mean filter 74

ACKNOWLEDGMENTS

The atmospheric variability studies in this report were supported in part by National Science Foundation Grant No. ATM76-21017. That research was performed with the aid of sea-surface temperature data furnished by the U.S. Navy Fleet Numerical Weather Central, and of computer time made available by the National Center for Atmospheric Research. NCAR also provided most of the meteorological instrumentation installed in Greeley, Colorado, in Cheyenne, Wyoming and in a midwestern metropolis during the 1976-77 and 1977-78 winters. NCAR is supported by the Atmospheric Science Division of the National Science Foundation.

Again, we are indebted to Messrs. Raymond Fouts and Michael Erland of the Greeley Gas Company, to Weld County Assessor Herbert Hansen, to Thomas Rounds of the Weld County Planning Staff and to Glendale Cobb of the University of Northern Colorado for assistance in collecting data essential to our work on modelling the gas consumed in space heating by the city of Greeley, Colorado. We are similarly indebted to Messrs. Robert Larsen of Cheyenne Fuel, Light & Power Company, to Bruce Burbank of the Public Service Company of Colorado, to Robert Beebe of the Cheyenne National Weather Service Forecast Office, to Leo Breeden of the Laramie County School District No. 1, to John Dean of the Western High Plains Grasslands Experimental Station, to Howard Gallensky of Fort Warren AFB, and to the staff of the Laramie County Assessor's Office for assistance in acquiring the data needed to model the space-heating demand for natural gas in Cheyenne, Wyoming.

Cooperation has been magnificent from the utility companies, utility customers, and state, county and municipal officials in the midwestern metropolis which is the current primary target of our space-conditioning energy-consumption research. We look forward to explicitly acknowledging these contributions when our studies of that metropolis have progressed to the point where a meaningful report and usefulness evaluation thereof is possible. It must be appreciated that we cannot publish results applicable to a particular utility company or customer until those results have first been accepted by these parties.

THE EFFECTS OF ATMOSPHERIC VARIABILITY ON ENERGY UTILIZATION AND CONSERVATION

By

Elmar R. Reiter, Principal Investigator,
E. Dreiseitl, G.R. Johnson, H.H. Leong, B.C. Macdonald,
W.L. Somervell, Jr., A.M. Starr and K.O. Timbre

Atmospheric Science Department
Colorado State University
Fort Collins, Colorado

ABSTRACT

Our space-heating energy-consumption model for Greeley, Colorado for the winter of 1976-77 was within 98.9 percent of actual natural gas consumption for that city. Modelling of Cheyenne, Wyoming, including the testing of a new statistical scheme to develop the building census required by our energy consumption model, has progressed to the point where reliable natural gas consumption estimates can be made with our model for that community.

A detailed study of temperature and surface wind patterns in and near the city of Greeley, Colorado revealed that, at times, an urban heat island effect is present, in spite of the relatively small size of that town.

During the present grant period we examined various feedback mechanisms between the oceans and the atmosphere. Several of these mechanisms appear to be the cause of the interannual variability of the atmosphere's general circulation and of climatic changes on a time scale of several tens of years. Specifically we examined a recent cooling trend in the North Pacific north of 40°N, and sea-surface temperature fluctuations with an irregular periodicity of 2 to 4 years superimposed upon this trend. To advance regional long-range forecasting skills we correlated January temperature anomalies over the eastern United States with flow patterns over the U.S. and Canada.

1. SCOPE OF WORK ACCORDING TO RESEARCH PROPOSAL

The proposed scope of work listed in our research proposal dated April 1976 contains the following items:

- A. Proofreading Part 4 of "Atmospheric Transport Processes".
- B. Studies of Regional and Global Atmospheric Variability.
- C. Energy Consumption Modelling.

In April 1976 we had anticipated that Vol. 4 of "Atmospheric Transport Processes" (Radioactive Tracers) would be available in print by spring of 1977. Due to unforeseen scheduling problems in the editorial offices at Oak Ridge, Tennessee, this time frame has been slipped by one year. The galley proofs of this book have been received by now. The reading of page proofs and the preparation of authors' and subject indices still remain to be done.

The studies of regional and global atmospheric variability have progressed satisfactorily. A short summary of results is given in Chapters 5 and 6 of this report. Results are also reported in several papers which have been accepted for publication by various scientific journals (see listing at the end of this section).

The energy-consumption model was refined during the present grant period. Application to the 1976-77 heating season in Greeley, Colorado gave a calculated space-heating consumption of natural gas which was 98.9 percent of actual. Chapter 2 of this report summarizes the results of the Greeley study. Chapter 3 outlines a statistical approach for obtaining a building census. This approach has given very satisfactory results in Cheyenne, Wyoming.

The major findings of our energy modelling study were presented at the Spring AGU Meeting in Washington, D.C. on 31 May 1977. The following reports were given at that meeting.

Reiter, E.R., A Modelling Concept for Energy Utilization.

Johnson, G.R., A Physical Model for Calculating the Energy Needed to Space Heat a Community as a Function of Ambient Weather.

Somervell, W.L., Jr. and G.R. Johnson, Validation of Weather Effects on Space-Heating Energy Requirements.

Starr, Ann M., Building Census Input Data for Space Conditioning Energy Needs.

Dreiseitl, E. and E. R. Reiter, The Effect of Urban Climatology on Energy Requirements.

Sparling, E., Analysis of Various Socioeconomic Inducements to Improving Insulation Levels in Existing Residential and Commercial Buildings.

Macdonald, B.C., Large-Scale Weather Patterns and Their Effects on Energy Consumption.

Papers published during present grant period:

Reiter, E.R., The Interannual Variability of the Ocean-Atmosphere System. (Accepted by Journal of Atmospheric Science)

Reiter, E.R., Long-Term Wind Variability in the Tropical Pacific, Its Possible Causes and Effects. (Accepted by Monthly Weather Review)

Reiter, E.R., Another Year of Drought Ahead? ("Potato Grower of Idaho", Nov. 1977, pp. 6, 10, 12)

Reiter, E.R., On the Recent Cooling Trend in the North Pacific. (Submitted to Journal of Geophysical Research)

Reiter, E.R., G. Johnson, W. Somervell and E. Sparling, The Effects of Atmospheric Variability on Energy Utilization and Conservation. Paper presented at ERDA Workshop, Washington, D.C. Feb. 4, 1977.

McGuirk, James P., Fluctuations in the Atmosphere's Energy Cycle. From a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Environmental Research Paper No. 6. C00-1340-53.

Seigel, Anne D., Oceanic Latent and Sensible Heat Flux Variability and Air-Interaction. From a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science. Environmental Research Paper No. 7. C00-1340-54.

2. MODEL DEVELOPMENT

The major research effort of our team focused on the development and refinement of an energy consumption model for space heating that could be applied to communities, cities, and eventually whole regions of the United States. In the aftermath of the severe winter of 1976-77, which caused a major disruption of our national economy, such a modelling effort seemed to be particularly appropriate. Energy conservation measures which, under the ever increasing demand for foreign oil and natural gas, became more and more urgent, require careful economic planning instead of a haphazard and piecemeal approach that is potentially more harmful than good. Such planning should have the benefit of model tests which are of sufficient accuracy and reliability to provide a significant input into the decision-making process.

A variety of approaches are possible in assessing the energy requirements of a community. With respect to the development of an energy model, it should be noted that we have adopted two different views on methods of modelling the space-conditioning energy demand of a large community. The first is referred to as the large-scale deterministic method. In this procedure, the object is to decompose the system as much as possible. To implement this procedure, it is necessary to describe the physical relationships of heat loss or gain for the lowest components (each individual building) and calculate the energy consumption by small time steps. The individual buildings for each thermal classification are then lumped into the response representing the energy consumption for that building classification. Combining these responses from lower levels to higher levels eventually represents the output for the whole system. This approach has been used in our current physical simulation model, and we refer to it as an aggregated or lumped micromodel.

The information needed for a micromodel is very extensive. Detailed information on physical variables and economics as well as the social behavior of the building occupants are required. These data were gathered for Greeley, Colorado, by means of a detailed and exhaustive survey. A refinement in the input-data procedure was used for the city of Cheyenne, Wyoming. In the latter case, described in Section 3.1, a less detailed building census was generated by means of statistical sampling schemes and procedures. The purpose of these sampling schemes was to constrain the workload to a tractable level, consistent with model-information needs, for later application in modelling large metropolitan communities.

An alternative approach to the development of an energy model is the macromodel. In the macro approach, the model utilizes such socioeconomic factors as are available through the processing of census data and/or other data available within the community. Because of the incomplete nature of available information, estimates from the macromodel are always associated with error terms described by probabilistic statements. However, if per capita indices were available for a variety of communities and would indicate the existence of functional relationships (e.g. between income and per capita residential, office or industrial space) one could apply such relationships with some confidence to different communities.

The micro and macro approaches both have their merits and tradeoffs. There is no clear choice that justifies one over the other. The best approach is

probably a combination of these two modelling techniques, and this is the approach currently being used in the development of our physical-adaptive model.

2.1 FROM FEEDBACK-CONTROL SYSTEM TO ADAPTIVE SYSTEM IDENTIFICATION

The fundamental basis of modelling the space conditioning requirements for a community may be viewed as a feedback-control system. The purpose of the feedback loop is to achieve a simple goal -- driving the difference between the actual and the desired temperature inside the building to zero (target) within the next time interval, $t + \Delta t$, where Δt may be the minimum acceptable time lag. This conceptual feedback-control loop is illustrated in Fig. 2.1. The energy demand of a community may then be viewed as the result of a "regulator" which is responsible for the conversion of the available source of energy to space heating or cooling. We may think of the regulator as a resultant of the mixture between the physical mechanism, such as a furnace, reacting to the space heating/cooling conditions and to the human preferences of setting the level of the real mechanism, such as a thermostat. Such a regulator is not necessarily at an optimum for any particular criterion and may be inefficient for some circumstances. The output from the regulator is in turn an internal input to the system which then influences a new system's output and thus completes the feedback loop.

The actual output reflects the state of the system, which results from the specific present and some past (finite memory) inputs. It can be noted from Fig. 2.1 that in order to maintain or drive the system close to the target temperature for every time instant the regulator, and thus the whole system, must be acting continuously to cope with the changes of the input variables as well as their feedback. Because of this phenomenon, the system must be described in terms of a dynamic process.

The feedback-control system configuration of Fig. 2.1 can be equivalently represented as Fig. 2.2. The advantage of the latter configuration is that the

Fig. 2.1 Feedback-control-system realization of the conversion of energy to space-conditioning needs.

Fig. 2.2 Alternate block diagram for conversion of energy to space-conditioning needs.

output becomes the energy demand. From the point of view of data collection, this is advantageous for, although the energy demand at each time instant is not obtainable, the daily total consumption is available from utility companies. On the other hand, the difference between the actual temperature and the desired temperature inside the buildings is not routinely obtainable (although it is measurable and may be available for special types of buildings). Under the prevailing circumstances this temperature difference is treated as one of the unmeasurable internal states and can be replaced by some estimation. The solution to the energy-demand problem now becomes an identification problem of the feedback-control system, based on its input and output measurements as shown in Fig. 2.3. Furthermore, it is easy to see from Fig. 2.3 that the energy demand depends on (a) various characteristic functions of the system, (b) the input variables which are themselves functions with respect to time and (c) its own past observations at t , $t - \Delta t$, $t - 2\Delta t$, ... etc.

Assuming that this system is stationary and deterministic, conventional system analysis may be applied to find the transfer function of the system on the basis of the measurements of the input and output variables. If the structure of the characteristic functions of the system is known, optimization techniques may be applied to calibrate these parameters in an identification scheme. Based on a knowledge of the physical laws and the structural and thermal information for different types of individual buildings, it has been demonstrated (Reiter et al., 1976) that this physical model provides a reliable means to synthesize the energy consumption for space conditioning by a community.

But an important question is "To what extent can the system still be considered as a steady-state system within an acceptable range of errors?" For a relatively short duration, treating the community as a steady-state system implies that the parameters characterizing the system remain constant. This provides a logical ground for most prevailing modelling techniques which allow the use of observed data to estimate the necessary parameters of a model. Subsequently the model can be applied for simulating or predicting the events at different times. However, communities change with time. They change physically due to new structures being built, old buildings being torn down, people migrating, etc.; but also more subtly because of changing policies and regulations from the local or Federal governments, and the introduction of new technologies or products from

Fig. 2.3 A conceptual input/output system identification block diagram.

industries which gradually change the functions of various socio-economic sectors.

This suggests that, rather than formulating a "fixed, good-for-ever" model, it is more practical to have a systematic way of modelling, such that it is possible to estimate an optimum system description at time t , based on the knowledge up to t ; as time progresses, the model includes a mechanism to update itself, based on the arrival of new information necessary to cope with the evolution of the community.

Thus, the framework that is being developed is not a "one-shot" modelling technique but a continuous procedure which itself is a feedback-control process that exercises the learn-validate-optimize cycle. This approach is generally referred to as "adaptive system identification".

2.2 A PROPOSED FRAMEWORK FOR ADAPTIVE SYSTEM IDENTIFICATION

Adaptive system identification is necessary when one of the following situations is encountered:

1. The dynamics or the characteristics of the system are modified because of changes in the environment to which the system is applied -- uncertainty due to the environment;
2. The regulator in the feedback-control system generates random-control strategies -- uncertainty due to the regulator.
3. The stochastic nature of the input variable changes its course of occurrence -- uncertainty due to the change of probability distribution of the random input variable.

From the discussion in Section 2.1, a community inevitably exhibits the first two uncertainties as time progresses. The first kind of uncertainty is introduced when structures are added or eliminated. The second kind occurs when new policies or new living habits evolve. The third kind of uncertainty is not as prevalent as the first two, although it occurs whenever the stochastic process of an input variable becomes nonhomogeneous. It is not unusual for it to be misclassified as an extreme event of a homogeneous stochastic process. Usually long term evidence must

be accumulated or a careful hypothesis test must be designed for detection. An example of the third kind of uncertainty would be a change in the climate pattern of a region.

System identification may be defined as a process of extracting appropriate essential information from the target system in order to formulate a mathematical model within a specified class of systems to which the target system is equivalent on the basis of a certain specified index of performance. An adaptive system identification may then be defined as system identification that provides a means of continuously measuring the "goodness-of-fit" of the identified model versus the actual process at a given probability-significance level. An example of this process is the acceptance/rejection of new building modules. It also provides a means of automatically improving the parameters of the model when more information is available, or in reformulating the system description when the estimated response fails to satisfy the goodness-of-fit test upon comparison with the actual observations.*

With this conceptualization in mind, the structure shown in Fig. 2.3 is extended to an adaptive identification framework as shown in Fig. 2.4. Each major block (subsystem) is described below.

*This tentative definition is an analog to the definition of adaptive system given by W.D.T. Davies in his book, "System Identification for Self-Adaptive Control", John Wiley, 1970.

The "data-base" block represents the finite memory of the system, which draws upon the basic assumption that the behavior of the system can be traced from the past history of its inputs and corresponding outputs. For practical purposes, this is the place for storing and retrieving past and new input/output data for the system. These data serve as: (1) input data for the model upon program-control requests; (2) the essential information of the system to be used for "structural identification" in order to construct a better mathematical system description; and (3) information storage for "model updating", so that the current model may be improved or updated by the introduction of new data.

The "current-model" block is the set of mathematical representations which best describe the relationship between input and output under the criteria used by the "structural identification" or "model-updating" blocks. This set of descriptions is provided for mapping/transforming a selected input from the data base into the desired output, and/or to condense particular sample data into statistics to be used in the future by other blocks.

The "estimation" block actually executes the system descriptions that reside in the "current-model" block, to produce the estimate of the output upon request, for example, the simulation of last winter's energy consumption or the prediction of the energy demand for the next few days.

Fig. 2.4 The self-organized dynamic forecasting model with adaptive feedback, diagnostics, updating and re-evaluation mechanisms.

The "hypothesis-testing" block is used to detect the degree of lack-of-fit of the current model by using some specified *a priori* statistical hypothesis-testing procedure. The output of the "hypothesis-testing" block is a signal which is transmitted to the "controller" block, to indicate whether the testing statistics are significant or insignificant with respect to various probabilistic levels, say 90%, 95% or 99%. This statistical result is sufficient to confirm or disprove an existing model. But the important note is that one of two actions, either rejection or acceptance of the current model, will be signified to the controller.

The action of rejecting the current model will trigger the "structural identification" block to retrieve the essential data from the data base, to reevaluate and to construct a new set of mathematical representations for the system. If the action of the current model is accepted, the model-updating block may then retrieve the latest accumulated data from the data base. These data are used in the existing model to form a set of improved parameters for the same structural mathematical representation of the system. The resulting mathematical representation for either action will be used to replace the existing model and thus reside within the current-model block. The structural identification block of our program is the same block that has been used in the model-validation procedures; that is, the Group Method of Data Handling (GMDH) algorithm, (Gabor, et al., 1961; Ivakhnenko, 1971; Ivakhnenko, et al., 1974) which is discussed in more detail in Appendix A.

The model-updating block is operational and has been used to update the current model based on information from the data base. For example, by adding approximately 300 new buildings constructed since 1976, this program was used to update the space-heating model for simulating the Greeley, Colorado space-heating energy consumption during the winter of 1976-77.

The current physical model is for heating only, and can be used to predict or simulate the energy utilization for space heating (see Appendix B for a theoretical development of the model) in a community described by the data base. It should be noted that the framework of our space-conditioning model may be utilized for investigating almost any weather-sensitive demand for energy. All that is necessary is to define the physics for the specific application, and to appropriately expand the data base.

During the next phase, the hypothesis-testing algorithms will be developed, as will the controller decision-making block. This will complete the model as shown in Fig. 2.4 for energy consumed by space heating. In addition, work will begin on extending the physical model to include energy consumption for space cooling. The completion of this task will result in an entire model for the space-conditioning energy requirements of a specified city. The model can then be used to simulate the energy consumed in space conditioning in a major midwestern metropolis, as soon as the structural data base is compiled.

2.3 MODEL VALIDATION

In addition to the ongoing development of our modelling technique described in the two previous sections, the primary activities during the past year centered around the following five major tasks:

- i) The continued development of the modules required to model the western high plains small city of Greeley, Colorado.
- ii) The validation of specific modules that were constructed for the four building types whose short-term gas consumption data were available. Each building represents a particular structural type used in the building classification.
- iii) The application of the total model to predict the daily gas consumption for Greeley, Colorado, during the period 16 December 1976 through 6 March 1977.
- iv) The application of the total model to predict the daily gas consumption for Cheyenne, Wyoming, during the period 1 January 1976 through 20 March 1977. This is the first test case using a randomly sampled thermal data base rather than a detailed thermal data base as was utilized in the Greeley, Colorado, study.
- v) The package of the programs has been extended for use with either a complete building census such as the data base of Greeley, Colorado, or a partial building census/random sampling data base as was used for Cheyenne, Wyoming.

During this year, four new building modules have been validated in Greeley: a small one-story bank representative of many detached commercial structures; a farm-equipment store (in this case, an all-metal structure); a high school; and a modern two and one-half story apartment building. In addition, continuing tests were conducted on the previously validated mobile home park and the Weld County Hospital.

The model validation procedure consists of the following steps:

- 1) During the heating (or cooling) season, energy consumed by the buildings under investigation is recorded on a daily or more frequent basis.
- 2) The building age, physical dimensions, and the major materials that determine the structural thermal characteristics are obtained from one of the following: a) an on-site inspection; b) the plans for the building; or c) computerized city or county records.
- 3) A use pattern is estimated based on physical dimensions and occupant type (e.g., department store, restaurant, church, bank, industrial building, etc.)
- 4) The input data corresponding to 2) and 3) above are entered into program HEATLOAD, and a specialized thermal load-analysis subroutine (module) is generated for that building (see Appendix B of Reiter et al., 1976).
- 5) Meteorological data taken continuously on the building or in the near vicinity are then used as input data. The space-conditioning demand for energy is calculated in two-hour steps for the entire heating (cooling) season.

- 6) The actual energy consumption and the calculated space conditioning energy consumption are compared, and the residuals are calculated. If the results are acceptable (sum-of-square errors less than an *a priori* specified error criterion) the module is deemed validated.
- 7) If the sum-of-square error exceeds the error criterion, the actual energy consumption time series is processed through an adaptive learning algorithm (Group Method of Data Handling, Leong, 1975) which maintains the structural form of all equations used but reestimates the term coefficients. These resulting coefficients are analyzed to insure reasonableness of value; that is, they represent updated overall heat-transfer coefficients and use-pattern coefficients. The adaptive learning algorithm only uses a portion of the time series as the training-data set. The remaining portion of the time series is used as a testing set. The updated module is then used to calculate the energy consumption, and the procedure is repeated until the sum-square-error criterion is met (See Appendix A).

Figure 2.5 shows the locations of the seven Greeley weather stations and the structures that were used for validation during the winter of 1976-77. Each weather station consists of a thermograph recording continuous temperature data and/or wind instrumentation recording wind speed and direction. These data were analyzed as discussed in Section 3.2 and used as the meteorological input data for the model-validation phase. Before proceeding to the recently validated modules, it would be appropriate to first discuss two of the models which were validated last year, but for which new weather and energy-consumption data are now available.

The 265-unit mobile-home court is indicated on the Greeley map and a photograph of the court is shown in Fig. 2.6. Daily consumption data and weather information for this mobile-home park for the period 16 December 1976 through 6 March 1977 were obtained. Three mobile-home modules are used: the 12-foot width, the 14-foot width, and the dual 24-foot width configurations. The entire mobile court is simulated simultaneously using the actual weather observations. A comparison of the predicted and actual daily energy consumption for the winter is shown in Fig. 2.7, along with the actual weather observations. As can be seen, the agreement is quite good over most of this 81-day period.

Fig. 2.5 Locations of the seven Greeley weather stations and the structures that were individually validated during the winter of 1976-77.

Fig. 2.6 Photograph of mobile home court which was validated for the winters of 1975-76 and 1976-77.

Fig. 2.7 Comparison of the measured total daily and predicted space-heating gas use and the weather data used in validating the mobile home court during the winter of 1976-77.

On all of the succeeding validation figures, the measured or actual gas consumption is the solid line, whereas the computer-predicted energy consumption is represented by the dashed line.

Three expressions are now defined to characterize the error between the predicted and observed energy consumption data. The first is simply the running sum of the predicted consumption divided by the running sum of the observed consumption. This number will be referred to as "the seasonal error", that is, the comparison of the total seasonal predicted to the total seasonal measured energy consumption. Two error terms are used to characterize the daily differences. The first term will simply be referred to as "the daily error" and is the sum of the absolute value of the observed minus the predicted divided by the number

of days, divided by the mean of the observed gas consumption for the entire heating season. The third error term is defined as the square root of the sum of the square of the daily observed minus predicted gas consumption divided by the number of days, divided by the mean of the observed data; this is the conventional root-mean-square error or RMS error. Values of these errors will be presented for each of the validated buildings and the communities that are discussed in the following sections.

It is interesting to note that, in general, the model overpredicts consumption for this mobile-home park. This is particularly true during the holiday period of December and early January, when the model seems to grossly overpredict the energy consumption. However, note that the weather observations for this period indicate that it is one of the coldest periods during the 1976/77 winter. Let us assume that the predicted gas consumption information is reasonable for this severe period of time. Then the fact that the measured consumption is considerably less (80,000 cubic feet of natural gas per day) than calculated may indicate that the occupant or use pattern of the mobile-home park was drastically altered. This could be the result of two possible reasons: first, that the occupant loading of the mobile home park was increased during this period of time, i.e., the holiday period, and heating requirements were made up through increased occupancy; or, second, that the occupancy was decreased and perhaps thermostats were turned down during this period of time. Also, of course, if the occupancy is decreased, the infiltration losses in mobile homes can be substantially reduced. Therefore, it appears upon examination of this validation data that, except for this one anomalous period, the computed results are in good agreement with what was actually observed. The predicted seasonal gas consumption is 116% of actual. The daily error is 17.4% and the RMS error is 24.3%. The model used for this study was the same model that had been verified and the results were presented by Reiter, et al., 1976. For convenience, the characteristics of the mobile-home court are reproduced in Table 2.1.

Table 2.1 Characteristics of "Typical" 12-foot x 60-foot Mobile Home. (Note: 60-foot mobile homes are actually 56 feet in length, the 60-foot length is to the hitch.)

AREAS

Ceiling	672 ft ²
Walls	841
Skirt	408
Windows	75
Doors	36
Floor	672

COEFFICIENT OF TRANSMISSION:

Ceiling with R-30 insulation (required)	0.027
Walls with R-9 insulation	0.075
Single-glass window	1.13
Door	0.49
Door + metal storm door	0.197
Floor with R-9 insulation	0.079
Aluminum sheet	0.61

The second previous-year module to be retested is that for the Weld County Hospital. This building is a 1940-70 era structure for which the previous module-validation results were presented by Reiter, et al., 1976. Fig. 2.8 shows a photograph of this five-story, brick-and-glass building. Fig. 2.9 gives the test results of the module for the 1976-77 winter. As can be seen, during the 1976-77 winter the module appears to be overpredicting the energy consumption of the hospital. The inaccuracies seem to be most pronounced during the more severe weather conditions which occurred in late December and early January, see Fig. 2.9. As the winter progresses on to February and March, the predicted and observed energy consumptions are in good agreement with each other. Again, it is concluded that the module which was developed for this public building is still reasonably accurate for predicting the energy consumption of the structure. Considering the complex nature of the Weld County Hospital, it is notable that, even though the daily agreement is not close, the module seems to represent the energy-consumption trends of the building quite accurately. The predicted seasonal gas consumption is 107.9% of actual. The daily error is 9.3% and the RMS error is 10.5%. The module is a candidate for the adaptive algorithm at this point; but this work has not been performed to date. It will be undertaken

Fig. 2.8 Photograph of the Weld County Hospital which was validated for the winters of 1975-76 and 1976-77.

Fig. 2.9 Same as Fig. 2.7, except for Weld County Hospital.

early next year to see what sensitivity the coefficients exhibit in order to follow the observed energy-consumption data more closely.

The first new module to be validated was for the all-metal building, shown in Fig. 2.10, and located near the Cache La Poudre River. This structure houses a farm-implement sales business. The building is one story, 14-feet high, with a floor area of 45,840 square feet. Fig. 2.11 presents the computed versus the actual gas consumption for this structure, as generated from the HEATLOAD program. The agreement is generally quite good with a slight overprediction in the same period of time as shown previously. However, as the winter progresses, agreement becomes very good and overall the predicted energy is 109.8% of the actual, excluding the missing days of measured information. The daily error is 13.6% and the RMS is 17.4%. The weather data for this building is shown in the accompanying figure (Fig. 2.11).

Fig. 2.10 Photograph of the agricultural supply store which was validated for the winter of 1976-77.

Fig. 2.11 Same as Fig. 2.7, except for the agricultural supply store.

Fig. 2.12 Weather data at our seven Greeley stations for 7:00 A.M. following a clear night. Minimum temperature = 13.5°F . Maximum temperature = 67.0°F . Winds are less than 3 meters per second.

a consequence of a chinook event which took place to the west of Greeley during the early morning of the 21st. Warm air parcels were thereby advected over most of the stations. The two Poudre River Valley stations, Putnam and Winograd, however, remained protected in the cool drainage air and were not effected by the warm advection. As can be seen, the temperature differed by approximately 9°C among the different sites within the Greeley vicinity, with the coldest in-town temperature being recorded at the Winograd location which is near the building shown in Fig. 2.10. In general, the module as developed for this light industrial building was considered validated as generated from the HEATLOAD program. No tuning of the model was deemed necessary.

The second new building to be validated was a detached bank building located in the downtown area (see photograph, Fig. 2.13). This building is representative of detached low-rise commercial structures. The bank has an area of 2,500 square feet and is a one-story brick-and-glass structure. Three sides of the octagonal structure are glass walls. This constitutes a higher-than-normal use of glass for construction in this area. As can be seen in Fig. 2.14, the agreement for computed versus observed gas consumption in this structure is very good, and the overall agreement over the 81-day heating season is 98% of actual. The daily error is 9.4% and the RMS error is 11.9%. The weather data used in the module validation is the same as that shown in Fig. 2.11. Once again, the trends are all modelled very well and

Fig. 2.13 Photograph of the bank building which was validated for the winter of 1976-77.

Fig. 2.14 Comparison of the measured total daily and predicted space-heating gas consumption used in validating the bank building during the winter 1976-77.

it is assumed that the deviations may be primarily due to changes in use patterns rather than mis-applied thermal structural characteristics.

The third new structure to be validated was the modern two and one-half story apartment building shown in Fig. 2.15. This building is typical of multi-unit apartment buildings in the Colorado front-range area, that is, typical of communities such as Greeley, Colorado, and Cheyenne, Wyoming. It is a rather new structure and has a total of 12,000 heated square feet. The predicted energy consumption for this building is shown in Fig. 2.16 and, again, the agreement with observed data is very good, the overall agreement being 94.4% of observed, discounting the short period of time in early January during which observed data were not available. The daily error is 9.1% and the RMS error is 12.2%. All trends, again, are duplicated well by the model. Therefore this

Fig. 2.15 Photograph of the apartment structure which was validated for the winter of 1976-77.

Fig. 2.16 Same as Fig 2.7, except for the apartment building.

module was incorporated without adjustments into the library of modules for the overall program as constructed from program HEATLOAD. The weather data for this building are also shown in Fig. 2.16.

The fourth building to be validated was the Greeley West High School, shown in Fig. 2.17, a structure representative of fairly large public buildings, particularly of the elementary, junior-high and high-school types. The Greeley West High School is a one-story building of 110,800 square feet of floor space. It was built in 1963 and it is typical of flat-roof brick construction with almost no glass. In this case a systematic discrepancy between observed and predicted energy use provided a rather interesting result. As can be seen in Fig. 2.18 the agreement between the two energy consumption curves is very good except for the holiday period when the actual consumption is greater than was predicted. The primary reason for this is that the students occupying the building were not "removed" from the model during this period; they are removed on weekends. The students apparently contribute a fairly significant portion of

Fig. 2.17 Photograph of Greeley West High School which was validated for the winter of 1976-77.

Fig. 2.18 Same as Fig. 2.7 except for Greeley West High School.

the heat required to maintain the comfort level in this particular high school. As indicated by Fig. 2.18, the actual energy consumption is greater with the students absent than with the students present in the building. It is not known if the thermostats were set back during the vacation period. If they were not, then the School District should be informed of our computed results, so that energy savings could be realized. The predicted seasonal gas consumption for the High School is 93.1% of actual. The daily error is 10.6% and the RMS error is 14%. The accompanying weather data for this building are also shown in Fig. 2.18.

A fifth new module which was to have been added to the data bank of thermal modules was that for a detached restaurant, the Moot House. The module for this structure was completely unsuccessful, because evidently far more gas is consumed for cooking than is used for space conditioning. The building appears to require cooling nearly all year, because of this energy input from the nature of the business. No further work will be done with this module until we get a better understanding of the business-related energy consumption, which appears to be non-weather sensitive.

As of the current date, the modules which have been validated include single-family residential dwellings, mobile homes, small commercial detached structures, light industrial buildings, multi-story apartment dwellings, and large public buildings.

Modules to be validated in the near future include a museum, a high-rise post office, a laundry, a hangar, a federal office building and a VA hospital center, all located in Cheyenne, Wyoming. Upon successful modelling of the mix of the structural types occurring in Cheyenne, emphasis will shift to building types more representative of a large metropolis. The Greeley results indicate that all of the modules employed in the simulation of rural communities are quite adequate for calculating space-heating requirements for energy.

2.4 1976-1977 GREELEY ENERGY CONSUMPTION

Following incorporation of refinements represented by the four newly validated structures and the updating of the building census to reflect approximately 300 buildings constructed during the past year, the Greeley model was run for the 1976-77 winter. The results, shown in Fig. 2.19, were a computed seasonal consumption of natural gas for space heating which was 98.9% of actual consumption. It should be noted also, that the day-to-day differences were much smaller than those which our model produced during the 1975-76 winter, when periods of pronounced overprediction compensated partially for other periods with serious underpredictions. For Greeley, the calculated daily error is 6.0% and the RMS error is 7.5%. This compares with values of 7.6% and 9.1%, respectively, for the results obtained for the heating season of 1975/1976. Since the physical model was not changed (the newly validated modules needed no tuning and therefore are the same as last year) between these two runs, it is concluded that the expanded meteorological network has provided better resolution for the input weather data. The result is an improvement of about 1.5% in error using the seven meteorological stations of the three recording stations which we had available during 1975-76.

Fig. 2.19 Same as Fig. 2.7, except for the entire area of Greeley, Colorado.

2.5 MODELLING CHEYENNE, WYOMING

One of the principal modelling activities during this current contractual period was the prediction of natural gas consumed in space heating by the city of Cheyenne during the 1976-77 winter. Construction and size data for all commercial, industrial and public buildings have been extracted individually from assessor's files and/or site visits. Moreover, the energy consumption by F.E. Warren AFB has been monitored separately and therefore can be modelled separately. The quality of our Cheyenne space-heating computations is a reflection of the degree to which our statistical sampling methodology produces a valid thermal data base for residential structures. The

results, shown in Fig. 2.20a, b, c, for the three months of January, February, and March 1977, for the space-heating consumption of natural gas in Cheyenne are quite satisfactory. Over the 81-day period of simulation, the model predicted 97.8% of the actual consumption. The daily error was 8.3% and the RMS error was 10.2%. This is approximately a 2% higher

Fig. 2.20a,b,c Comparison of the measured total daily and predicted space-heating natural gas consumption and the average daily weather data for Cheyenne, Wyoming during January (a), February (b), and March (c) 1977.

error than found for Greeley. It would then seem that the sampling scheme is quite adequate to predict the energy consumption of a community.

As indicated, F.E. Warren AFB has been isolated from Cheyenne and sample results are shown in Fig. 2.21 for the month of February. Unfortunately, dates of the interruption periods have not yet been made available so that the results are incomplete. This work will be continued during the coming research period.

Fig. 2.21 Comparison of the measured total daily and predicted space-heating natural gas consumption for F.E. Warren Air Force Base during February 1977.

3. INPUT DATA AND DATA ACQUISITION

The calculation of the daily energy consumption of a community as a function of weather requires a detailed knowledge of the size, structural characteristics and use designation (habit patterns of occupants) of each building. For the city of Greeley, Colorado, a detailed building census was carried out on foot during the summer of 1975 to arrive at these required input data.

Obviously, as other metropolitan areas of considerably larger dimensions are being considered for energy consumption modelling a "foot census" of all structures is no longer feasible. Considerable efforts were expended, therefore, to develop a statistical sampling routine which lets us arrive at average building and occupant-habit characteristics with a minimum standard error between the estimated and actual characteristics. We were encouraged in this approach by the fact that most residential and commercial structures of recent design in the United States draw upon a rather limited choice of building materials and floor patterns. The philosophy of mass production, as it turned out, clearly worked in favor of our statistical sampling approach.

3.1 BUILDING CENSUS

The building census used to model natural gas consumed for space heating in Greeley, Colorado, during the 1976-77 winter includes the data from which our 1975-76 calculations were made (Reiter et al., 1976), plus those structures constructed since that survey. The new construction information was gathered from the Greeley assessor's files and consisted of 299 units, most of which were single-family detached dwellings.

To model the city of Cheyenne, Wyoming, a building census of the entire area, shown in Fig. 3.1, was required. Recognizing the need for a less arduous approach to census generation than that employed in Greeley, a statistical sampling methodology was developed. In this sampling scheme it is assumed that the required accuracy will vary according to whether the building type is residential, commercial, public or industrial. This assumption was deemed acceptable because the Greeley building census indicated that residential buildings represent over 90% of the total. Thus, in its present form, our sampling scheme applies only to single-family detached residences other than mobile homes. The physical description of the mobile homes was compiled through a telephone census of the major mobile home parks, where the managers were questioned on the size distribution of the homes. This gross sampling is thought to be sufficient because of the extreme homogeneity of mobile homes. The task of sampling the non-residential and apartment structures has not yet been undertaken, due to the difficulty of defining a suitable sampling scheme for such heterogeneous buildings. However, the omission of those structures from our sampling scheme was considered to be of little consequence, since they constitute only 10% of the total count.

Our statistical methodology has three fundamental procedures: (1) analysis of aerial photography; (2) assignment of an appropriate sample size; and (3) acquisition of the data sample which contains the proper building information.

Fig. 3.1 Map of Cheyenne, Wyoming. The dashed lines indicate the city boundaries; the square boxes represent our sectional boundaries. Also indicated is the topography and the location, denoted by crosses, of our weather stations.

3.1.1 ANALYSIS OF AERIAL PHOTOGRAPHY

The area to be modelled is first broken down into sections which (1) are congruent with characteristic temperature and wind patterns entering into the consumption model and (2) appear to be fairly homogeneous in their construction characteristics. In order that the meteorological analysis need not be completed prior to the building census, these sections must be small enough that within each the meteorological variables may be considered uniform. Thus far, we have used one square mile as the standard section size.

The buildings in each section are then classified according to their age group and use pattern, i.e., residential, commercial, public or industrial. The age of a building is important, since construction practices effecting its thermal efficiency vary according to whether it was built before 1940, between 1940 and 1970, or after 1970. The classifications according to use pattern, age group, and whether a high- or low-rise structure, are then used to establish the total count, or frame, on which the sampling is based.

3.1.2 ASSIGNMENT OF APPROPRIATE SAMPLE SIZE

In the modelling of Greeley, Colorado, where a census on foot of each individual building was performed, we found that it is sufficient to use the average dimension for each building type in a section. Since from the aerial analysis we obtained the number

of buildings and an approximation (e.g. from the size of trees in the yards) of the age group delineation of residential structures, we need only concentrate on determining the average space dimensions for each section.

Theoretically, to minimize the sampling requirements there must be some prior knowledge of certain properties of the population (Cochran, 1963) in each class of buildings. Since this information will not be available in most cities, a statistical technique was devised to define the proper sample size. Our approach is based upon the building data we obtained for Greeley, Colorado.

The average Greeley residential building dimension by age group was calculated over 13 square-mile sections for several different sample sizes using simple random sampling. The different sample sizes are calculated as percentages of the total number of residential buildings in each section. The sampling was performed 200 times in order to obtain a representative value for each sample size. The standard error of the average floor area for each sample size is calculated as:

$$S.E. = \sqrt{\frac{\sum_{i=1}^n (\bar{X}_i - \bar{X})^2}{n-1}}$$

where $\bar{X}_i$ is the average floor area from each random sample;

$\bar{X}$ is the mean of all random samples, $\bar{X}_i$; and

n is the number of random samples tested, which in our case is 200.

This formulation of the standard error is based upon the assumption of a normal distribution of the 200 events.

Upon examination of all of the 13 Greeley sections analyzed, the standard errors appeared to be a function of the total number of units in each age group. These functions are presented in Fig. 3.2a, b and c for 1%, 5% and 10% sample sizes, respectively, using a log-log scale. As can be seen from these diagrams, the standard errors show an inverse (log-log) relationship with the number of residences. The solid lines are the least-squares fit of the data points on a logarithmic scale, and the dashed lines represent one standard deviation from this line. The ordinate (y-axis) in all cases is twice the standard error, and thus represents a 95% probability confidence level.

It is from these three curves that we can establish statistically the proper sample size according to a predetermined tolerable error of the building dimensions. For example, if the tolerable error is 50 ft², there must be at least 500 residences for each age group in order to make a 1% sample suffice, or 200 to make do with a 5% sample, or 100 to allow a 10% sample. By assuming that the population of residences in Greeley is representative of other residential populations, we can apply this sample-sizing technique to other areas which we wish to model.

Preliminary sensitivity analyses of the physical model indicate that a uniform 10% error in the size of the buildings in Greeley would produce a 6% error in the predicted energy consumption. Knowing that the

Fig. 3.2a,b,c Number of residential structures in each age group as a function of twice the standard error of the average floor area for a 1%, 5% and 10% sample size, respectively.

average size of the buildings in Greeley is 1595 ft², we can say that an error of 50 ft² will produce an error in the gas consumption of 2%. It is therefore necessary to choose a sample size for which twice the standard error does not exceed 50 ft².

3.1.3 ACQUISITION OF DATA SAMPLE

Having determined the proper sample size for each square-mile section, a set of random numbers is applied to select the residences to be sampled. The proper building information is then collected by finding the selected residences in the county or city assessor's files and by recording this information. Complications may occur when a sampling of nonresidential buildings is attempted, due to the fact that only taxable structures are inventoried by the assessor.

3.1.4 APPLICATION OF SAMPLING TECHNIQUE TO CHEYENNE

The city of Cheyenne, Wyoming, was used as a testing site for our sampling technique. The area modelled, shown in Fig. 3.1, was defined in cooperation with Cheyenne Fuel, Light and Power Company to be compatible with their distribution area. This region consisted of F.E. Warren Air Force Base and 46 square-mile sections, many of which are sparsely populated. All building information for F.E. Warren Air Force Base was provided through the courtesy of the base commander. Recent aerial photographs of the distribution area were then broken down into sections and analyzed as discussed in Section 3.1.2.

In sections where the residential building counts are large enough to make sampling feasible, structures were randomly selected. Table 3.1 shows the count, the sample size, and average space dimensions of all residential structures, excluding mobile homes and apartments, for each of the 46 square-mile sections. The sample size is labelled 100% whenever there are too few structures in the section to make sampling feasible. In these sections the residential buildings are accounted for individually.

It can be demonstrated from Table 3.1 that 95% of these residential structures in the Cheyenne region are modelled using a 6% sample. The method used to verify the adequacy of the sampling is to see how the computed values of natural gas consumption (using both sampled and individual structural data for all types of buildings as input to the model described in the previous section) compare with the values measured by Cheyenne Fuel, Light and Power Company. The results of this comparison for the 80-day period over which our calculations were performed show a 2.2% error, which is close to the 2% error to be expected due to our sampling technique alone. This result encourages us to continue making use of our sampling technique in future community-modelling endeavors.

Table 3.2 summarizes the results of our building census for the entire Cheyenne area, including F.E. Warren Air Force Base, according to building use patterns. An increase in the size of single-family dwellings from pre-1940 to post-1970 is as apparent here as it was in Greeley. It should also be noted that residential structures make up 93% of the total Cheyenne count, which is similar to the 91.7% observed in Greeley.

TABLE 3.1

The average calculated residential floor area, total count and percent of count sampled for each section in Cheyenne.

Section #	Average Size	Total Count	Sample Size
1	1991	28	100%
2	1953	35	100%
3	1729	34	100%
4	1578	50	100%
5	1875	16	100%
6	1443	465	10%
7	1306	649	5%
8	1771	14	100%
9	1374	49	100%
10	1435	91	10%
11	1219	744	5%
12	1228	7	100%
13	1308	686	1%
14	1166	116	10%
15	1216	16	100%
16	1800	2	100%
17	1174	455	5%
18	1428	528	5%
19	1058	815	5%
20	0	0	
21	1189	607	10%
22	1210	100	10%
23	1160	39	100%
24	1038	459	10%
25	1470	998	5%
26	966	1108	5%
27	1166	1340	5%
28	1123	1251	1%
29	963	16	100%
30	0	0	
31	1006	8	100%
32	864	437	10%
33	833	721	10%
34	972	63	100%
35	0	0	
36	950	6	100%
37	1210	36	100%
38	993	626	5%
39	1215	145	100%
40	960	25	100%
41	1100	2	100%
42	1360	5	100%
43	1030	163	10%
44	858	72	10%
45	1358	14	100%
46	0	0	

TABLE 3.2

The average square footage, count and percent of total count for all building types during the winter of 1977 for Cheyenne, Wyoming.

Type	Average Size (Sq. ft.)	Count	% of Total Count
<u>Residential</u>			
Single-family dwellings			
Pre-1940	1196	3231	19.14
1940-1970	1097	8441	49.99
Post-1970	1506	1499	8.88
Duplexes	2549	322	1.91
Triplexes	1789	38	.23
Fourplexes	5262	17	.10
Sixplexes	7530	1	.006
Mobile Homes	821	1949	11.54
Apartments	7262	206	1.22
Total for Residential	1239	15704	93.01
<u>Commercial</u>			
Business, Sales	5346	267	1.58
Business, Services	5237	24	.14
Laundry	4336	14	.08
Bank	13296	7	.04
Cafes, Restaurants	4830	42	.25
Bowling, Pool Halls	14933	5	.03
Grocery, Food Stores	13309	15	.09
Offices	6705	169	1.00
Bars	4976	5	.03
Theaters	16348	4	.02
Private Buildings (Country Clubs, etc)	7223	6	.04
Department Stores	21362	5	.03
Motels, Hotels	6414	93	.55
Bakery	1344	1	.01
Ice Cream Stores	1678	5	.03
Greenhouse	2485	5	.03
Total for Commercial	6261	667	3.95
<u>Public Buildings</u>			
Church	5624	81	.48
Nursing Home	33970	4	.02
School, Grade-High	49707	37	.22
School, College	18725	16	.09
Government Buildings	12191	73	.43
Library	15638	3	.02
Fire Departments	4595	3	.02
Community Buildings	6205	9	.05
Hospital	34023	16	.09
Total for Public Buildings	17690	242	1.42
<u>Industrial</u>			
Auto Repairs	7876	14	.08
Auto Sales	7868	10	.06
Machine Shops	29090	4	.02
Warehouses	8124	109	.65
Gas Stations	1588	74	.44
Steel & Metal Company	3660	2	.01
Distributing Company	18520	1	.01
Train Station	10608	4	.02
General Storage	1713	11	.07
Garage	6568	24	.14
Manufacturing Company	17121	12	.07
Industrial Laundry	2014	3	.02
Asphalt	1435	3	.02
Total for Industrial	6527	271	1.61

3.1.5 AN ALTERNATIVE BUILDING CENSUS PROCEDURE

The sampling discussed above is adequate for generating an energy-model building census for a small rural community (50,000-75,000 population). It may even be satisfactory for determining the building census of a large metropolitan area; but if a model is to be developed which will accurately predict the space heating demand for energy for an entire state or nation, then we must look for a data base which is much broader in scope. It is for this reason that we have continued to investigate parameterization schemes and indirect indices. The methodology is based upon the establishment of economic parameters as indicators of structural building information. The data base presently being explored is the 1970 Census.

Despite their limitations, these data provide a systematic collection basis for the entire United States. To develop our parameterization scheme it is necessary to rely upon the building data we have collected in the past, and for this reason we have not yet been able to go as far in this development as we would have liked. We are, however, encouraged by our preliminary results.

The Greeley census-data files were available only for census tracts, which did not always correspond with the sections which we delineated for our building census. In order to compare these two data bases, weighted averages of our sections were combined in such a way as to conform to the established census tracts. For Cheyenne, the census data were available in block form which could easily be summed in such a way as to make them compatible with our square-mile sections.

Figure 3.3 compares the average dollar value (of both house and lot) of owner-occupied units obtained from U.S. Bureau of Census data with the average square footage of pre-1970 residences (excluding mobile homes and apartments) obtained from our building census for 11 census tracts in Greeley and 15 square-mile sections in Cheyenne. The solid line represents the least-squares fit of all 26-data points and the dashed lines show one standard deviation of fit. The combination of Cheyenne and Greeley data into this one curve is justified since the least-squares approximations for the two individually analyzed cities fall within one-standard deviation of the combined results. The R value in Fig. 3.3 of .79 is the correlation coefficient of these two variables. Such a relationship would then make it possible to substitute readily available U.S. Bureau of Census data for our desired structural size information. It can be foreseen that this particular relationship would probably not be accurate for different geographical areas, due to differences in the housing demand and in assessed valuation, and would need to be re-constructed for each region to be modelled. This task, however, would be far less demanding than a total building census for an entire region.

Fig. 3.3 Average square footage of the pre-1970 residential structures as a function of the average value of owner occupied units for 26 regions in Greeley and Cheyenne.

3.2 SUMMARY OF GREELEY WEATHER

During the 1975-76 winter, air temperatures measured with diverse instrumentation at five locations in and around Greeley were used in our investigation of weather sensitivity of energy consumed to heat individual buildings and the whole city. Subsequent analysis indicated that this data set was deficient for modelling the energy consumption of a city. Thus, during the 1976-77 winter, we recorded both temperature and wind with uniform instrumentation at eight chosen Greeley area sites. These locations were mainly selected for proximity to buildings to be used for module validations of the energy consumption model (hospital, high school, industrial building, mobile-home park etc.). The station locations are depicted on Fig. 3.4 and listed below.

Station #1 - PUTNAM. Situated in the Cache la Poudre River Valley less than 1 km to the south of the river and 3 meters higher in elevation. This rural site is located 4 km northwest of the city center.

Station #2 - WINOGRAD. An urban industrial site also situated in the Cache la Poudre River Valley about 4.5 km southeast of Station #1, near the northeast corner of the city limits.

Station #3 - MOOTHOUSE. Located in a residential area and sheltered to the west by a large garage. This urban site is 15 meters higher in elevation than Stations #1 and #2.

Station #4 - HOSPITAL. Situated on a northeast facing slope. This station is 100 meters west of the five-story Weld County Hospital.

Station #5 - HIGH SCHOOL WEST. Located on the ridge separating the two river valleys approximately 100 meters southwest of a one-story high school which is set in a rural surrounding.

Station #6 - MOBILE HOME. Located on a south facing slope, 1 km north of the South Platte River. Only temperature was recorded at this rural station.

Station #7 - DISPATCH TOWER. This site was chosen for the sole purpose of obtaining unobstructed wind measurements. The instruments were mounted 45 meters above ground on a radio dispatch tower.

Station #8 - UNC, University of Northern Colorado. Located on the eastern end of the ridge. This station's instruments, which include a solar radiometer, are placed on the roof of a three-story building.

Station #9 - CENTRAL CAMPUS. Located in a garden near some deciduous trees, on a northeast facing slope; only temperature was recorded at this station.

The north-south extent of the Greeley Gas Company service area is approximately 11 kilometers; the east-west extent is about 8 kilometers. The elevation range is 75 meters, with the lowest heights in the valleys of the Cache la Poudre and South Platte Rivers.

Air temperature was recorded continuously for 81 days, from 16 December 1976 until 6 March 1977, with hygrothermographs in standard Stephenson screens. All instruments were calibrated before and after the field measurements and checked daily during the 81-day period. This enabled us to obtain a continuous set of data and to correct for instrument errors. The temperature records were reduced to bihourly mean values.

GREELEY 1976-77 WEATHER STATIONS

Fig. 3.4 Map of Greeley, Colorado showing the locations of the nine meteorological stations.

Wind speeds and directions were measured at heights of 3 to 4.5 meters above ground at six of the stations, at a level of 45 meters at the Dispatch Tower, and at 18 meters at Ross Hall (on the roof of this 3-story building). These wind measurements were reduced to average hourly values. Each of the individual stations are examined in more detail in Appendix C. In addition, solar radiation data recorded by a pyronograph was provided by the University of Northern Colorado (UNC).

An example of the meteorological data as they are used for input into the energy model is shown in Table 3.3. The temperature, wind speed and solar radiation measurements are listed for one randomly selected 24-hour period. These data represent only point measurements and must be extended in our computer model so as to represent meteorological conditions in each section of Greeley. Fig. 3.5 presents the scheme by which the temperature and wind data are then distributed to fit the input demands of the energy model. This distribution scheme is developed with considerations of topography, land use and consultation with those who have had experience with the local meteorology of Greeley.

In a city, temperature variations can be attributed to different thermal properties of the various surface types and to topographical effects. The thermal properties govern the absorption, storage, and release of both solar and anthropogenic energy. For the city of Greeley, the major topographical features are the two river systems which surround the city on the north, east and south. An example of the influence of this topography are much cooler nighttime temperatures in the valleys (e.g. see Fig. 2.12). However, calculations of average winter temperatures at each of the stations, based on the 81-day sample, eliminated most of these local effects because of the varying weather conditions and resulted in averages which did not differ greatly from station to station. The average difference between the warmest urban station (Hospital) and the coldest rural station (Putnam) was only 1.4°C. Under well-defined weather conditions, e.g., on calm and clear

Fig. 3.5 Pattern of the temperature and wind variables as they are used in the physical model of Greeley.

evenings, temperature differences between the individual stations were observed to be as high as 5°C. This situation and others which could influence the accuracy of the energy-utilization model are discussed in Appendix C. Analysis of wind directions in Greeley shows two prevailing features, weak down-valley winds during nighttime and stronger upvalley winds during daytime.

The 1976-77 winter was characterized by two distinct weather conditions: cold temperatures and snow in the eastern United States and warm temperatures and drought in the western United States. A measure

TABLE 3.3

An example of the meteorological input as used by the physical model for January 1, 1977.

bihourly interval												
AIR TEMPERATURE	degree Fahrenheit											
	1	3	5	7	9	11	13	15	17	19	21	23
Station #9	13.0	8.5	6.0	5.0	8.0	13.5	20.5	20.5	16.0	12.0	9.0	7.5
#1	13.5	8.5	5.5	4.0	9.5	14.5	22.5	23.5	14.5	9.0	5.5	5.0
#3	13.0	8.5	6.0	4.0	7.0	11.0	19.0	22.0	18.0	12.0	8.0	6.5
#2	14.5	11.0	7.5	7.0	9.5	14.5	23.0	25.5	20.0	14.5	10.5	9.0
#4	14.0	9.5	7.0	6.0	8.5	13.5	19.5	22.0	16.5	12.5	9.5	8.0
#5	15.0	11.0	8.0	6.5	8.0	12.0	18.0	21.0	17.0	12.0	8.0	8.5
#6	11.5	8.0	4.5	3.0	7.5	11.5	18.5	20.0	14.5	10.5	6.5	5.5
WINDSPEED	miles per hour											
	1	3	5	7	9	11	13	15	17	19	21	23
#1	3.9	2.2	2.2	2.2	2.2	2.8	4.5	4.5	2.8	2.2	2.2	1.7
#3	3.9	3.9	3.4	2.8	2.2	2.8	3.4	2.8	1.1	1.1	1.1	1.1
#2	6.7	3.4	4.5	3.9	2.2	2.8	4.5	4.5	4.5	2.2	2.8	2.2
#4	5.6	5.6	5.6	4.5	3.4	2.8	4.5	5.0	4.5	2.2	2.8	2.2
#5	7.3	5.0	5.6	3.9	3.4	3.4	7.3	7.3	7.3	2.8	2.8	2.8
RADIATION	Langley per two hours											
	1	3	5	7	9	11	13	15	17	19	21	23
#8						23.0	48.0	78.0	44.0	4.0		

of the difference between this past winter and the long-term mean for Northern Colorado is provided by the comparison in Fig. 3.6 of the 60-year daily temperature means for Fort Collins, Colorado with the daily mean temperatures observed in Fort Collins during the 1976-77 winter. Comparable long-term climatological data are not available for Greeley, Colorado; however, temperatures in these two cities generally do not differ appreciably.

During most of the 1976-77 winter the mean circulation over North America consisted principally of a ridge near the West Coast and a trough in the East. Below-normal temperatures accompanied this trough over the eastern United States, and warm air associated with the ridge provided above-normal temperatures in the West. As can be seen in Fig. 3.6, above-normal temperatures occurred in Fort Collins during most of December.

An abrupt change in the mid tropospheric circulation took place during the last week of February when the strong eastern Pacific ridge finally broke down, allowing fast-moving storm systems to traverse the country. This change is also evident from a return to near normal temperatures in Ft. Collins for the remainder of the winter.

Fig. 3.6 Climatological daily temperatures and daily mean temperatures during the winter of 1976-77 for Fort Collins. Positive or warm deviations are indicated by hatched areas.

3.3 CHEYENNE WEATHER

Air temperature, wind speed and wind direction were measured at six different locations in the Cheyenne area during the 1976-77 winter season. The locations of these stations are shown in Fig. 3.1. We used methods similar to those already applied in Greeley to investigate how wind speed and air temperature varied across Cheyenne. The relative difference in altitude across the city is approximately 75 meters in both Greeley and Cheyenne, but greater steepness of slope is evident in Cheyenne. This city lies to the west of the lowest elevation of the Continental Divide and therefore lies in the channel of high mean wind

speeds. Whereas the mean wind speed for Greeley was 1.8 m/s, in Cheyenne an average wind speed of 3.6 m/s was observed during the 1976-77 winter. Due to the prevalence of high wind speeds in Cheyenne, we did not expect large temperature differences across the city.

The weather stations were established in areas near the buildings to be used for module validations. Only two of them were located in the downtown area of the city. Temperatures were recorded at all locations with thermographs placed in standard Stephenson screens. Wind speed and direction were measured at an elevation of 3 meters at four of the stations. At the National Weather Service Airport Station (# 3), the wind instruments are 9-meters above ground. Standard meteorological practice calls for wind observations above the level of surrounding obstructions to assure the measurement of flow characteristics of the planetary boundary layer. In our investigation we were more interested, however, to obtain wind data which affect the infiltration rate into buildings. Therefore, our instruments were placed at a fairly low level above ground representative of the average building height in the vicinity.

Station #6, outside of the built-up area, has the lowest terrain elevation of all our stations. This is reflected in its having the coldest average temperature of all our stations. It is situated in the eastern section of a WNW-ESE valley. To examine how the local topography might influence the dominant wind direction, wind roses for Stations 6 and 3 are plotted in Fig. 3.7. Indeed, we can see some channeling effects such that the most frequent wind direction is shifted from WNW at Station 3, which is not influenced by the valley, to W at Station 6. For both of these stations the most frequently observed wind directions are in the north-west quadrant, with almost no winds from the northeast to the southeast.

Station #4, located downtown, is sheltered to the east by the State Museum Building which quite drastically influences both wind speed and direction. Most of the large and multi-story buildings in Cheyenne, such as the State Capitol and an 8-story post office, are located within $\frac{1}{4}$ mile of this station. The average measured wind speed here is only 2.0 m/s, which is half the mean speed of all remaining stations.

Fig. 3.7 Wind roses for Stations #6 and #3 during the winter of 1976-77 in Cheyenne.

Station #5 is located south of the railroad tracks in the same valley as Station #6 and approximately three miles west of it. However, in contrast to Station #6, Station #5 is considered to be a downtown site. The mean temperature is the same as that recorded at Station #4, the other downtown station, as can be seen in Table 3.4.

Station #2 was set up at F.E. Warren Air Force Base, which is on the western outskirts of Cheyenne. No wind data were available and the temperature data was limited by frequent missing periods caused by instrument malfunctions.

Station #3, the National Weather Service Airport Station, is located north of the city center. Winds are measured at 9 meters, and temperatures at 1.9 meters. Much larger average wind speeds, 6.5 m/s, were measured at this best exposed higher station. However, whether this pronounced difference is due more to the instruments elevation of 9 meters high or to the improved sensor exposure has not yet been determined. The frequency distribution of wind directions at this station is shown in Fig. 3.7.

Station #1 is situated in the northwest portion of our observation network on a gently sloping ridge extending as far south as the downtown area. It was sheltered from northeast quadrant winds by the three-story Highway Department Building, but was exposed to the prevailing wind direction. The temperature observations of this station could not be used due to constant malfunctioning of the thermograph. The second highest average wind speeds, of 4.6 m/s, were observed at this well-exposed site.

TABLE 3.4

Mean monthly air temperatures for the five stations in Cheyenne during the 1976-77 winter in degrees Centigrade.

Temp.	Station #6	Station #4	Station #5	Station #2	Station #3
Jan.	-5.9	-4.6	-4.5	-4.5	-4.8
Feb.	-.1	.4	.8	.6	.3
Mar.	-1.1	-1.2	-1.3	-1.2	-1.2
Ave.	-2.6	-1.9	-1.9	-1.9	-2.1

A summary of the temperature observations collected in Cheyenne during winter 1976-77 are shown in Table 3.4. Fig. 3.8 depicts the observations averaged bihourly for a warm and cold station, #3 and #6, respectively. Considering the differences in topography and land use patterns in Cheyenne, we observe only small differences in the temperature distributions throughout the city. This can be attributed to a mixing of the lower layer of the atmosphere by the relatively high winds. The areal expansion of our station data to meet the model requirements was, therefore, easily developed, and consequently we have confidence in the validity of these data.

Fig. 3.8 Mean bihourly temperatures for Stations #6 and #3 in Cheyenne during the winter of 1976-77.

3.4 METROPOLIS STUDY

In view of successes achieved in the modelling of Greeley, Colorado and Cheyenne, Wyoming, the effort devoted to our study of a large midwestern metropolis has increased significantly. This study will constitute an increase approaching two orders of magnitude in the number and complexity of structures, but we feel that our modelling methodology has developed to the point where this task is a realistic undertaking.

Our work in the metropolitan area has not yet approached a state such that the cooperating utility companies and customers might assess the validity of our computations. Therefore, we may not yet identify by name this metropolitan area or the specific buildings under investigation. It will be recalled that at the beginning of our research efforts this seeming constraint was deemed an understandable and entirely acceptable measure, to ensure shielding of the cooperators from premature or unnecessary harassment. According to our agreement, prior to customer identification, the modelling should have reached an advanced stage of development, to eliminate inquiries regarding preliminary and possibly incorrect results. Also, each cooperator is entitled to an opportunity to withhold any procedural or indirect-cost data which might be construed as divulging business secrets.

The metropolis study is being conducted in separate but related tasks, as discussed below.

3.4.1 MODULE VALIDATION

In the metropolitan area under study, there are a number of building classifications which are typical of large communities but which were not encountered in either Greeley or Cheyenne. In order that our city-wide model might incorporate the more common or

important of these structural types, we are presently collecting the requisite data on the following:

1. A pre-1940 high-rise office building.
2. A 1940-70 vintage low-rise electronic manufacturing company.
3. A post-1970 high-rise office building.
4. A turn of the century low-rise department store.
5. A glass curtain-wall skyscraper of post-1970 vintage with offices and stores.
6. A post-1970 high-rise apartment building.
7. A 1940-70 high-rise apartment building.
8. A mixed vintage of about 30 University buildings consisting of office, classroom and dormitory structures.
9. A mixed vintage of five buildings containing a museum, school and arts center.
10. A pre-1940 low-rise post office building.
11. A pre-1940 high-rise post office building.
12. A pre-1940 high-rise office building.
13. A pre-1940 high-rise department store.
14. A pre-1940 high-rise communications and office building.
15. A 1940-70 high-rise office building.
16. A 1940-70 low-rise technical processing and office building.
17. A 1940-70 high-rise office building.
18. A pre-1940 high-rise hotel.
19. A 1940-70 high-rise hotel.
20. A 1940-70 high-rise hotel.
21. A post-70 low-rise motel.
22. A 1940-70 low-rise shopping mall.
23. A mixed vintage of more than 15 public schools, elementary through high school.
24. A 1940-70 low-rise hospital.
25. A 1940-70 low-rise nursing home.
26. A 1940-70 low-rise apartment building.
27. A 1940-70 low-rise apartment building.
28. A 1940-70 low-rise office.
29. A pre-1940 high-rise hospital complex.
30. A 1940-70 high-rise hospital complex.

For reasons of confidentiality more specific information concerning these buildings cannot be presented at the present time.

Determination of Physical Characteristics

Project personnel have personally visited buildings representative of each of the foregoing structural classes, and with the assistance of the building engineers obtained a sufficiently detailed description of shell, usage, infiltration, internal heat load, etc., characteristics for each so that their space-conditioning demands for energy might be calculated with reasonable accuracy.

Acquisition of Daily or More Frequent Fuel-Consumption Data

It will be obvious, that it is thanks to the willingness of the owners or managers of the buildings listed above to participate in our research that we will be able to validate our computer modules for these building types. Accurate knowledge of fuel consumption is essential, and the availability of these data entails either daily measurement by building employees of fuel consumed (oil, natural gas, propane, steam, coal, electricity) and/or the owner's authorization that the utility company may furnish such data to us. With intervals between fuel consumption observations longer than a day, it becomes progressively more difficult to verify the extent to which consumption amounts are due to weather severity.

To date, fuel-consumption data being collected are restricted mainly to the 1976-77 and 1977-78 winter (heating) seasons. However, arrangements have been made to acquire individual building energy-consumption data for the 1978 cooling (summer) season.

Measurement of Weather Conditions in the Vicinity of Module Structures

For the 1976-77 winter, we were able to sufficiently augment CSU weather instrumentation with equipment made available by the National Center for Atmospheric Research (NCAR), that the existing metro-area weather-station network could be increased by eight project sites. These installations were either in the immediate vicinity of, or actually upon, buildings for which the computer module is to be validated. Installations upon buildings, although undesirable, was necessary so as to minimize losses from vandalism or theft.

Installations of weather stations for the 1977-78 winter was again made possible by the loan of instrumentation from NCAR. These installations were primarily for the purpose of defining city-wide temperature and wind patterns, as discussed hereinafter; a number of the stations established were so sited that the data are expected to be satisfactory for module validations.

3.4.2 CITY-WIDE MODEL DEVELOPMENT AND VERIFICATION

As discussed previously (Reiter et al., 1976), it is rare that the corporate limits of a community coincide with a definable portion of a utility company's total service area for which daily sendout data are available. It is also unlikely that, in the case of large- or even medium size cities, the energy supplies are furnished by only a single utility company. Thus, in the metropolitan area under consideration, there are several different utility companies. Moreover, there are over 70 separate and distinct communities within the minimum service area for which the utility companies can provide daily natural gas and electricity sendouts. Although problems such as these increase the difficulty of model development, they are nevertheless realities which must be recognized and overcome if we are to successfully model those areas encompassing a very small fraction of the total land wherein the vast majority of the U.S. population is located.

Generation of Building Census

The progress from a detailed building census to one wherein the majority of the structures are deduced by a statistical sampling methodology is discussed in Section 3.1. Work to date in furtherance of such less arduous procedures for establishing a building census for our midwestern metropolis has included the acquisition of low-level aerial photography for the entire area. In addition, we are to receive photographic data of emitted nocturnal infrared radiation for the more densely populated regions of this city. We have also been in contact with the city and county assessors, and although it appears that the acquisition of assessor files may be limited to a less detailed summary for that part of the metropolitan area for which the files have been transformed to magnetic tape, we do expect to gain sufficient access to the assessor files for the other communities to satisfy our "building-visitation" requirements for taxable structures.

Acquisition of Daily Utility Sendout Data

Utility company cooperation has been outstanding, and we are assured of receiving daily gas, steam and electricity sendouts for the present winter and the coming summer for those regions within the overall metropolitan area which these companies are serving.

Determination of Weather Variations Within the Metropolitan Area

In the metropolis under study there are already many existing weather stations, both public and private. An examination of data for the 1976-77 winter indicated temperature differences of as large as 17°C between the inner city and the rural outskirts. This measured difference included some roof-top temperatures, but it did not yet reflect potential differences between city center and surroundings, which could have been even larger. We have to contend with wind and temperature variations due to topography, and with a pronounced variability in building density within the area, the effects of which are not too well defined in presently available meteorological data. We therefore concluded that for the 1977-78 winter season we should install the maximum possible number of weather stations, the number of which was dictated by the availability of instrumentation. 20 sites were chosen. Site locations could not be selected on the basis of a predetermined grid; but for the sake of minimizing theft and vandalism as well as time needed to make the selections, the selection was dependent upon the cooperation of utility companies, building supervisors and meteorological personnel participating in this research effort. Thanks to their cooperation we were able to locate sites where there would be a reasonable chance for minimizing equipment losses, and which provide a very good cross section of topographic and structural density differences.

4. EFFECTS OF A COLD WINTER ON ENERGY DEMAND

The energy consumption model for space heating requirements described in Chapters 2 and 3 will eventually be applied to large and densely populated regions of the United States. It will still take us some time to calibrate our model for such an application. This chapter describes a "first-guess" of energy demand during January 1977 over the eastern United States, using model parameters that were developed for Greeley, Colorado. In spite of the inadequacies of such a premature model application, some results significant for present and future energy policies could be obtained.

4.1 THE WEATHER SENSITIVITY OF RESIDENTIAL DEMANDS ON NATURAL GAS SUPPLIES

Fig. 4.1 Estimated net energy use in 1972. (FEA, 1975.)

Figure 4.1 shows the estimated net energy use in 1972 (F.E.A., 1975). According to this diagram the residential and commercial sector uses 31% of the total energy. Of this amount 2/3 (or 20% of the total) are consumed for space heating on an annual average basis. Table 4.1 shows that during November 1974 1/3 of the total energy consumed was in the form of natural gas (F.E.A., 1975). Under present consumption patterns (November, 1976), roughly 37 per cent of the natural gas produced on an annual basis is used by the residential and commercial sector (Table 4.2, F.E.A., 1977). Since the production and sales to interstate pipelines of natural gas has in the past been kept rather steady during the course of a year (Fig. 4.2, F.E.A., 1977) it is easily seen that underground storage (Fig. 4.3), and the industrial use of natural gas have been stabilizing factors in the utilization of this commodity. Interruptible industrial users served as a "buffer" to assure availability of gas for space heating under abnormally cold weather, and at the same time allow full disposal of the gas volume purchased by utility companies years ahead of time if mild weather prevailed.

TABLE 4.1

ENERGY CONSUMPTION, NOVEMBER 1974

Refined Petroleum Products	2.830×10^{15} BTU	48%
Natural Gas (Dry)	1.958×10^{15} BTU	33%
Coal	1.090×10^{15} BTU	19%
	5.878×10^{15} BTU	100%

TABLE 4.2

Energy Consumption by Economic Sector and Primary Source - November 1976

[Quadrillion (10^{15}) Btu]

SECTOR	PRIMARY ENERGY SOURCE					PRIMARY ENERGY CONSUMPTION
	Coal	Natural Gas (dry)	Petroleum	Hydroelectric	Nuclear	
Residential and Commercial	0.025	0.700	0.643	--	--	1.368
Industrial	0.330	0.931	0.586	0.003	--	1.850
Transportation	0.001	0.059	1.561	--	negligible	1.621
Electric Utilities	0.840	0.225	0.324	0.217	0.172	1.777
TOTAL	1.196	1.915	3.113	0.220	0.172	6.615

(FEA, 1977).

Fig. 4.2 Domestic consumption, marketed production, domestic producer sales and imports of natural gas. (FEA, 1977.)

Fig. 4.3 Storage of natural gas. (FEA, 1977.)

Present energy utilization plans foresee a restriction of natural gas use by industry. The space heating sector shown in Fig. 4.1 would benefit from such a decision by a stretching-out of natural gas reserves. The gas use by this sector, however, is highly weather dependent. We have to expect, therefore, that production and delivery henceforth -- contrary to Fig. 4.2 -- will undergo a marked seasonal variability and also a strong interannual variability as abnormal winter weather patterns evolve.

It is difficult to estimate the effects of a change in use strategy on the deregulated price of natural gas. If industry were to convert quickly to other energy forms, a temporary "glut" of gas might depress its market price. In the long run, however, production and demand will adjust to each other, and a rise in prices may have to absorb the risk factors to which producers, pipeline companies and utility companies, will be exposed due to a highly variable demand situation.

Under the proposed use strategy there are some new inherent risks for the home user of natural gas which will have to be studied in detail by models such as the one under development here and described in earlier chapters of this report. These risks can be described briefly as follows: In the past adequate supplies of gas to the space-heating sector were assured by 1) underground storage in reservoirs, 2) storage in the pipelines, 3) curtailment of interruptible customers, and 4) emergency purchases of gas from other than the customary sources. Item (3) constituted a considerable safety factor in the system under adverse weather conditions. It also helped to improve the profit margin of utility companies because interruptible customers pay less per unit volume of

gas than residential users. Item (4), for financial reasons, used to be the least popular alternative with utility companies.

Under the proposed use strategy we will assume that there are no longer any major interruptible customers (with the exception, perhaps, of fertilizer production). If that were the case, storage remains as the only "buffer" against excessive demand fluctuations. With full reservoirs and light demand, production of gas will have to be cut. When an adverse weather pattern moves into a heavily populated region (such as the eastern United States), excessive demand will cause depletion of the reservoirs. Gas production and transmission will have to increase abruptly, but it might take a week before the surge in production will be felt at the delivery points in the east.

4.2 THE EFFECTS OF JANUARY 1977

The last winter should have taught us a valuable lesson. It can serve as an example for the weather-caused variability in gas demand with which our delivery system will have to cope. Table 4.3 (Wagner, 1977) shows some of the temperature anomalies encountered in the east during January 1977. In Fig. 4.4 these anomalous January temperatures are interpreted in terms of oil-heating degree days. Fig. 4.5, containing the percent departures from normal January degree days, shows that over much of the populated east an excess natural gas demand for space heating of 30, even 50 per cent, during the record-setting month

TABLE 4.3

Record and near-record low monthly mean temperatures observed during January 1977

Station	Temperature (°F)	Anomaly (°F)	Remarks*
Topeka, Kans.	15.2	-12.8	2nd coldest Jan. (1940)
Tulsa, Okla.	26.9	- 9.7	5th coldest Jan. (1918)
Austin, Tex.	41.6	- 8.1	3rd coldest Jan. (1930)
Baton Rouge, La.	41.8	- 9.2	
Shreveport, La.	37.3	- 9.9	2nd coldest Jan. (1940)
Ft. Smith, Ark.	26.5	-12.5	3rd coldest Jan. (1918)
Springfield, Mo.	18.9	-14.0	3rd coldest Jan. (1940)
Columbia, Mo.	13.6	-15.7	Coldest month
St. Louis, Mo.	15.1	-16.2	
Jes Moines, Iowa	10.1	- 9.3	5th coldest Jan. (1912)
Dubuque, Iowa	3.4	-14.3	Coldest month
Waterloo, Iowa	-0.1	-16.4	Coldest month
Rochester, Minn.	-1.8	-14.7	2nd coldest Jan. (1912)
Minneapolis, Minn.	0.3	-11.9	2nd coldest Jan. (1912)
Madison, Wisc.	3.7	-13.1	Tied for 2nd coldest (1912)
Green Bay, Wisc.	3.1	-12.3	2nd coldest Jan. (1912)
Milwaukee, Wisc.	8.3	-11.1	2nd coldest Jan. (1912)
Detroit, Mich.	12.8	-11.8	
Rockford, Ill.	5.9	-14.3	2nd coldest Jan. (1912)
Moline, Ill.	8.2	-13.3	2nd coldest Jan. (1912)
Peoria, Ill.	8.5	-15.3	Coldest month
Springfield, Ill.	10.3	-16.4	Coldest month
Cairo, Ill.	22.4	-13.9	3rd coldest Jan. (1918)
Chicago, Ill. (Midway Airport)	10.1	-14.2	
Ft. Wayne, Ind.	9.2	-16.1	Coldest month
Indianapolis, Ind.	10.3	-17.6	
Evansville, Ind.	14.8	-17.8	Coldest month
Cincinnati, Ohio	12.0	-19.1	Coldest month
Columbus, Ohio	11.4	-17.0	Coldest month
Toledo, Ohio	9.6	-15.2	
Akron, Ohio	11.4	-14.9	Coldest month
Youngstown, Ohio	10.3	-15.4	Coldest month
Cleveland, Ohio	11.0	-15.9	Coldest month
Parkersburg, W. Va.	17.5	-15.4	
Elkins, W. Va.	15.0	-15.0	
Erie, Pa.	12.5	-12.6	Coldest month
Pittsburgh, Pa.	11.4	-16.7	Coldest month
Avoca, Pa.	15.0	-11.0	Coldest month
Philadelphia, Pa.	20.0	-12.3	Coldest month
Buffalo, N.Y.	13.8	- 9.9	
New York, N.Y. (Central Park Observatory)	22.1	-10.1	2nd coldest Jan. (1918)

(TABLE 4.3 continued)

Station	Temperature (°F)	Anomaly (°F)	Remarks*
Concord, N.H.	10.6	-10.0	Coldest month
Worcester, Mass.	16.2	- 7.4	2nd coldest Jan. (1970)
Trenton, N.J.	21.7	-10.4	2nd coldest Jan. (1918)
Wilmington, Del.	20.8	-11.2	
Washington, D.C.	25.4	-10.2	5th coldest Jan. (1918)
Lynchburg, Va.	23.0	-13.6	
Richmond, Va.	25.3	-12.2	
Cape Hatteras, N.C.	35.8	- 9.5	
Greensboro, N.C.	26.7	-12.0	
Charlotte, N.C.	30.1	-12.0	
Asheville, N.C.	24.8	-13.1	
Lexington, Ky.	17.8	-15.1	Coldest month
Louisville, Ky.	18.6	-14.7	Coldest month
Knoxville, Tenn.	27.2	-13.4	2nd coldest Jan. (1940)
Chattanooga, Tenn.	28.5	-11.7	
Nashville, Tenn.	24.5	-13.8	Coldest month
Jackson, Miss.	35.3	-11.8	2nd coldest Jan. (1940)
Columbia, S.C.	35.8	- 9.6	2nd coldest Jan. (1940)
Athens, Ga.	31.2	-12.2	Coldest month
Atlanta, Ga.	29.3	-13.1	
Augusta, Ga.	35.5	-10.3	
Savannah, Ga.	39.9	-10.0	
Rome, Ga.	28.9	-12.2	Coldest month
Tallahassee, Fla.	43.9	- 8.7	2nd coldest Jan. (1940)
Tampa, Fla.	51.2	- 9.2	
Ft. Myers, Fla.	55.9	- 7.6	
West Palm Beach, Fla.	58.5	- 7.0	Coldest month
Lakeland, Fla.	52.0	- 8.8	Coldest month

* All are coldest January on record except as otherwise indicated. When shown, a date indicates the year of the coldest January on record other than the current one.

(Wagner, 1977).

Fig. 4.4 Oil heating degree days for January 1977 in terms of departures from normal (data from Wagner, 1977).

Fig. 4.5 Percent departures of January 1977 heating degree days from normal.

of January 1977 had to be absorbed by the delivery system. Fig. 4.6 shows a similar anomaly pattern for the extended period July 1, 1976 to February 27, 1977 (F.E.A., 1977).

Note: Above normal heating degree days correspond to below normal temperatures.

Source: Department of Commerce-NOAA.

Fig. 4.6 Percent departure of heating degree days during January 1977 from the normal of January 1941-1970. (FEA, 1977.)

A formula derived from our energy demand model results predicts a daily per capita use of energy, B , for Greeley, Colorado (Reiter et al., 1976) according to the regression

$$B = (65 - \bar{T}) \times 4153 + 199479 \quad (\text{in BTU}) \quad (4.1)$$

$\bar{T}$ is the average daily temperature in °F. The last number in that equation constitutes the weather-invariant natural gas use for industry, water heating, etc. In a gross simplification we assume that the same weather-dependent use pattern is applicable over the eastern United States. Under this assumption, and with the 1970 population census data, the temperature-related part of the energy demand during January 1977 produced the pattern shown in Fig. 4.7, depicted in area segments of 1° latitude x 1° longitude. One should supplement the numbers shown in this diagram with the "weather-independent" base load which, due to curtailments and industrial conglomerations different from those in Greeley, Colorado, may differ drastically from the 199479 BTU per capita per day shown in Eq. 4.1. Our modelling efforts, which are described in more detail in Chapters 2 and 3, eventually will lead us to more accurate estimates than those provided in Fig. 4.7.

Fig. 4.7 The weather-dependent part of energy demand (Eq. 4.1) extrapolated to 1970 census data on population.

It should be pointed out that Fig. 4.7 depicts the energy demand for space heating, but not necessarily the actual energy consumption. Because of the closing of many industrial and commercial activities and the lowering of thermostat settings one should hope that the consumption (for which, at this time, we have no actual data) fell short of the demand projection in Fig. 4.7.

Fig. 4.8 shows the projected energy demand -- with the same assumption inherent in Fig. 4.7 -- in terms of demand in excess of a normal month of January. If the BTU units shown in this diagram are divided by 10^3 one arrives roughly at the equivalent excess natural gas demand in units of ft^3 ($1 \text{ ft}^3 = 0.283 \text{ m}^3$).

Fig. 4.8 The excess of the weather-dependent part of energy demand (Eq. 4.1) during January 1977 over that expected during a normal month of January.

It is quite obvious that, in the absence of interruptible industrial customers, the present purchasing system involving utility, pipeline and producing companies will have to be overhauled drastically. Storage capacities upon which utility companies can rely will have to be able to sustain extreme temperature conditions for at least as much time as is required to deliver additional gas from a surge in production in those gas fields which can be considered as potential supplies under stress conditions. A heavy burden of responsibility will fall on long-range weather forecasting. It will be incumbent upon the forecaster to recognize the development of abnormal weather regimes, their intensity, duration and areal extent. He will have to possess a thorough understanding of the economic implications of his forecasts. This requires a degree of specialized commitment which the National Weather Service under its present manpower restrictions might be hard-pressed to deliver. Also, the present state-of-the-art of long-range weather prediction leaves much to be desired. Under these circumstances one could foresee a rapidly developing demand for private meteorological consulting services whose specialized skills would provide a major input in the optimization of the energy industry, and would help assure the economic viability of that industry.

Since long-range forecasting is still very much in its infancy, there is a need for strong links -- providing a rapid technology transfer -- between industry, private service organizations, research institutions and government agencies.

5. THE INTERANNUAL VARIABILITY OF THE OCEAN-ATMOSPHERE SYSTEM

A possible connection between sea-surface temperature (SST) anomalies in the North Pacific and weather patterns over the United States has been pointed out by Namias (e.g., 1977). Such a connection seems to hold especially during fall and winter, providing us with a long-range forecasting tool for seasonal prediction. An example of such a forecast by Namias for the severe winter of 1976/77 is shown in Fig. 5.1. These forecasts were based on SST anomalies such as the ones illustrated in Fig. 5.2.

Fig. 5.1 Precipitation anomalies over the United States, winter 1976-77. Hatched regions indicate below normal precipitation, dotted regions above normal precipitation. (From "Mosaic" National Science Foundation, July/August 1977, after Namias.)

Fig. 5.2 Schematic diagram of sea-surface temperature anomalies over the North Pacific, leading to atmospheric circulation anomalies and to temperature anomalies over the western and eastern United States. (From "Mosaic" National Science Foundation, July/August 1977, after Namias.)

The possibilities of skilled long-range forecasts, especially of excessively severe or mild winters, through the study of SST patterns in the North Pacific motivated us to search for the causes of these SST anomalies. This search has been highly successful, indeed. In the following we present a short summary of research results which were submitted for publication to several scientific journals (Reiter, 1977a, b, c).

Figure 5.3 depicts SST anomalies*, averaged over four different latitude belts, and over the longitudinal extent of the North Pacific. Seasonal trends have been removed from these data by subtracting monthly averages for the period March 1962 through January 1977 from the latitudinally-averaged mean monthly SST's. In order to remove short-term fluctuations while retaining interseasonal persistence, a seven-month running-average calculation was performed on these monthly SST anomalies. The results are shown in Fig. 5.3 (also see Appendix D).

After elimination of short-term intraseasonal noise, two types of fluctuations in SST anomalies became obvious: (1) A long-term cooling trend appears in high latitudes, north of 40°N. (2) Fluctuations with an irregular periodicity of approximately 2 to 4 years are superimposed upon the long-term trends.

The long-term trend appeared to be almost linear during the past 15 years in the latitude belt 40-50°N. Farther north, between 50 and 60°N, there was an increase in temperature until about 1967. From thereon a declining trend prevailed. The latitude band 30-40°N showed virtually no long-term temperature trend, whereas the band 20-30°N showed a slight increase until approximately 1969 and a slight decreasing trend thereafter.

SST records, received from NOAA, from the Fleet Numerical Weather Central and from the Fisheries Research Board of Canada, show several trend reversals between 1900 and the present (Fig. 5.4). The recent long-term temperature decrease in the North Pacific also showed in a tightening of the meridional SST gradient in the region of the North Pacific Drift (Figs. 5.5, 5.6). Such a tightening of the temperature gradient would indicate a speeding up of the North Pacific gyre and, perhaps, the upwelling of cold water from below the oceanic surface layer in the region south of the Aleutian Islands. The speeding up of the Pacific gyre appears to coincide, at least qualitatively, with a modest increase in the zonal wind stress in the trade-wind regions of the Pacific reported by Wyrtki and Meyers (1975), and is also evident in the long term behavior of the trade-wind u-component over the North and South Pacific (Fig. 5.7). Thus, there appears to be a feedback mechanism operating between atmosphere and ocean which is illustrated schematically in Fig. 5.8.

Another feedback, involving the v-component of the trade winds, seems to be involved in the 2- to 4-year SST-anomaly fluctuations. A lag correlation

*SST data were received from the U.S. Navy Fleet Numerical Weather Central, Monterey, California.

Fig. 5.3 Seven-month running mean of monthly departures from 15-year monthly means of SST for latitude bands indicated. Heavy dashed-dotted lines indicate least-square linear or parabolic fit.

Fig. 5.4 Seven-month running mean of sea-surface temperature anomalies ($^{\circ}\text{C}$) in the latitude band 40° - 50°N of the North Pacific, calculated with respect to the 1962-1976 monthly mean temperatures. Dots after 1962: data from Fleet Numerical Weather Center. Solid line between 1949 and 1962: data from Fisheries Research Board of Canada. Dots prior to 1962: data from National Oceanic and Atmospheric Administration (NOAA).

Fig. 5.5a,b,c Mean monthly isotherms of SST by 2°C intervals (8°C intervals are labelled) for June (a) 1963, (b) 1969, and (c) 1976. Isotherms over continents should be ignored; they appear solely for the purpose of computer plotting requirements.

Fig. 5.6 Same as Fig. 5.5, except for July.

Fig. 5.7 Monthly departures of u-component (m/sec) from the "long-term" monthly means given (a) the u-component of the North Pacific trade winds at the ocean surface in the "box" $5^{\circ}\text{N} - 19^{\circ}\text{N}$, $125^{\circ}\text{E} - 95^{\circ}\text{W}$, heavy full line (land masses excluded) and (b) the u-component of the South Pacific trades in the "box" $1^{\circ}\text{S} - 15^{\circ}\text{S}$, $125^{\circ}\text{E} - 75^{\circ}\text{W}$, heavy dashed line, seven-month running averaging applied to data. Positive values indicate stronger-than-normal east wind. Parabolic least-square trends are given by thin, full and dashed lines. Vertical lines indicate January of each respective year.

Fig. 5.8 Schematic feedback system between atmospheric and oceanic large-scale circulation.

between the trade-wind v-component and SST anomalies in the 30-40°N, and 40-50°N latitude bands is illustrated in Fig. 5.9. Because of the heavy time and space smoothing involved in the data used for these correlation computations, we have to rule out the effects of traveling Rossby waves in the North Pacific Drift as causative factors for the SST anomalies. Figure 5.10 illustrates, as an example, the v-component anomalies in the Pacific trade-wind regions of the two hemispheres, the curl of the wind stress in the North Pacific trade-wind region, the sea level differences across the North Equatorial Current, and the time-lagged SST anomalies at 40-50°N.

Fig. 5.9 Lag-correlation coefficients (ordinate) as a function of time-lag in months (abscissa) between the trade-wind v-component and SST anomalies in the (a) 30 - 40°N and (b) 40 - 50°N latitude bands. Dots in the lower portions of diagrams indicate significance of the correlations at better than the 50, 80, 90, 95 and 99 percent levels, respectively.

The feedback mechanisms operating on these SST fluctuations are schematically described in Fig. 5.11. A large-scale control of the SST anomalies is involved through the wind stress-generated water transport in the Pacific current systems. Fluctuations in the trade-wind v-components seem to be mainly responsible. They also respond to meridional temperature and pressure gradients in extratropical latitudes, thereby providing an oscillatory feedback. Height gradients in the North Pacific, as indicators of storminess, might have local and short-lagged effects on SST anomalies which can disturb the 20-month lag of the large feedback loop indicated in Fig. 5.11. It is no coincidence that 20 months correspond to the average transition time of waters around the Pacific gyre from the tropics into middle latitudes.

A close correlation between precipitation in the Line Island region and the trade-wind v-components (Figs. 5.12 and comparing 5.13 to 5.4) suggest the existence of a self-enforcing feedback loop (see Fig. 5.11) that intensifies the tropical wind systems through the release of latent heat. A clue as to the mechanism which interrupts this feedback involving the hydrological cycle can be gained from the following pieces of evidence: (1) Each peak of the v-components shown in Fig. 5.12 heralds a stronger-than-average El Niño occurrence off the coasts of Peru and Ecuador. (2) Barnett (1977) showed that changes in the v-component correlated with SST anomalies in the Christmas Island region, so that interannual increases in v occurred with positive temperature anomalies, decreases in v with negative SST anomalies. According

Fig. 5.10 Monthly departures from long-term monthly mean values (seven-month "low-pass" running-mean filter applied to anomaly data) of the following parameters: (1) Sea-surface temperatures (°C), in the latitude belt 40°-50°N, over the longitudinal extent of the Pacific at those latitudes. Linear least-squares trend indicated by heavy dashed line. This portion of the diagram is time-lagged against the other parameters by 20 months. (2) Northern (N.H., heavy solid line) and southern hemisphere (S.H., thin solid line) v-components (m/sec) of trade-winds in the "boxes" 5°N - 19°N, 125°E - 95°W and 1°S - 15°S, 125°E - 75°W. Stronger-than-normal flow towards the equator in each hemisphere is indicated by positive anomaly values. Parabolic least-squares trends are indicated by heavy (N.H.) and light (S.H.) dashed lines. Letters "E" signify approximate dates of El Niño occurrences. (3) Curl of the zonal wind stress (arbitrary units) computed as the difference in $\left(\frac{u^2}{f}\right)$ between 13° - 15°N and 7° - 9°N, parabolic least squares trend indicated by heavy dashed line. (4) Sea-level differences (cm) across the North Equatorial Current in the western central Pacific (heavy line) and 12-month running mean (thin line); approximate copy of data from Wyrtki (1974).

Fig. 5.11 Schematic diagram of feedback mechanisms involving oceanic and atmospheric anomalies in the Pacific region. Positive feedbacks are indicated by solid lines with arrows between "boxes", negative feedbacks by dotted lines and "N.F."

Fig. 5.12 Mean Pacific trade-wind v-component anomalies $(v_{N.H.} + v_{S.H.})/2$ in m/sec, (solid line) and precipitation index for Line Islands, (dashed-dotted line). Seven-month smoothing applied to both data sets.

to Fig. 5.10 decreases in v are often coincident with peaks in the curl of the wind stress, signalling the upwelling of cold water.

* Thus, it appears that increases in the trade-wind v-component enhance the current systems of the equatorial Pacific, namely the North and South Equatorial Currents and the Equatorial Counter Current. The moisture transport from a warm ocean into the atmosphere is also enhanced with increasing wind speeds. According to Laevastu (1963)

$$LH = (0.26 + 0.077u) (0.98e_w - e_a) \frac{L}{10}$$

where LH = latent heat flux ($\text{cal cm}^{-2} \text{ day}^{-1}$)

u = wind speed at 10 m (m sec^{-1})

e_w = saturation vapor pressure of the sea surface (mb)

e_a = water vapor pressure of air at 10 m (mb)

L = latent heat of vaporization = 597.3 cal g^{-1}

If $(e_w - e_a)$ is negative, the term 0.26 is omitted.

With a drop of 1°C at temperatures prevailing in the equatorial Pacific, e_w decreases by approximately 6 percent. Upwelling of colder water, especially at the edge between the Equatorial Counter Current and the North Pacific Current, under an intensified current system (see Defant, 1961) might lessen the evaporation which feeds the precipitation in the ITCZ. Cold water might also be supplied by the upwelling off the continental west coasts. This upwelling would be enhanced with intensified trade-wind systems. Furthermore, extensive cloud cover in a well-developed ITCZ

(which coincides with strong trade-wind systems) might cut down on the radiation received by the ocean. Each of these processes might help to undermine the positive feedback with the hydrological cycle shown in Fig. 5.11, causing its eventual breakdown. As the feedback cycle collapses, the tradewind system weakens, leading to the El Niño episodes observed along the Peruvian coasts.

The cause-and-effect relationships between trade winds, evaporation, ITCZ intensity and SST anomalies in the tropical Pacific outlined above are still somewhat speculative in nature. They will be the subject of further investigation.

Fig. 5.13 Line Island precipitation index for the years 1910 to 1975. Dots indicate monthly values, the heavy line stands for a 7-month running average.

6. SURFACE TEMPERATURE VARIABILITY RELATED TO LARGE-SCALE FLOW

Long-range prediction of surface regional weather conditions poses difficult problems of pressure- and temperature-pattern definition and interpretation. Such simple methods as persistence or climatology of the regional patterns do not provide the desired accuracy. Furthermore, we are interested in features which occur on a larger, even hemispheric, scale.

The regional surface-temperature pattern over an area of concern may be represented as scalar coefficients and are related to the hemispheric mid-tropospheric flow patterns. Anomalies in the flow patterns might be related to anomalies in surface temperature. The first step in our predictive scheme, therefore, is to define mathematically the correlation between these two parameters or their anomalies.

Regional surface-temperature-anomaly patterns over the eastern United States may be examined over all scales of space and time averaging. In this study, we have restricted ourselves to examining January temperature anomalies for fourteen separate years (1957-1960, 1963-1972) in eight states in the eastern United States (from National Oceanic and Atmospheric Administration, 1957-1972). Temperature anomalies for stations in each of these states (shown in Fig. 6.1) are averaged to give a value for that state for each month. The "state" temperature anomalies are then used to calculate three coefficients which represent the temperature-anomaly patterns for the region for each month. The first coefficient, C_1 , represents the average of the temperature anomalies from all eight states; the second coefficient, C_2 , depicts the north-south gradient of anomalies; and the third, C_3 , represents the east-west gradient of the anomalies. The coefficient C_1 is calculated as a simple arithmetic mean of the eight temperatures while the "gradients", C_2 and C_3 , are calculated as follows:

Let $\vec{G}_2$ represent a vector with eight components, each representing the average latitude of the eight states ($g_{21}, g_{22}, \dots, g_{28}$). $\vec{G}_3$ is another vector describing their average longitude ($g_{31}, g_{32}, \dots, g_{38}$). We modify $\vec{G}_2$ and $\vec{G}_3$ by subtracting the average of the eight components ($\bar{g}_i$) from each component and by dividing by the magnitude of the resultant vector,

$$|\vec{G}_i| = (g_{i1}^2 + g_{i2}^2 + \dots + g_{i8}^2)^{1/2}.$$

We are left with two normalized eight-component vectors ($\vec{F}_i, i = 2, 3$) whose components are:

$$\gamma_{ij} = \frac{g_{ij} - \bar{g}_i}{|\vec{G}_i|}$$

so that

$$\vec{F}_i = (\gamma_{i1}, \gamma_{i2}, \dots, \gamma_{i8}).$$

Fig. 6.1 Monthly mean temperature anomalies from the indicated states used to calculate C_1 , C_2 , and C_3 , the temperature pattern coefficients.

Now let T_j represent the temperature anomaly of a given month in state j and

$$T_j = (T_1, T_2, \dots, T_8).$$

We compute C_2 and C_3 as the projection of the temperature-anomaly pattern $\vec{T}$ on the vectors $\vec{F}_2$ and $\vec{F}_3$, respectively, i.e., by computing the scalar product

$$C_i = \vec{T} \cdot \vec{F}_i.$$

The three values of C_i are used in our analysis to depict the monthly temperature-anomaly pattern over the eastern United States. They will be used as dependent variables in our predictive scheme, which will be developed in the future.

The second step in our approach is to relate statistically these coefficients, C_i , with some physically meaningful feature of the larger scale flow. It is the experience of many operational forecasters that the 500-mb flow field controls to a large extent the advection of air masses at the surface. Accordingly, we should expect that average surface temperatures in a region should be related to

the midtropospheric flow from sources of warmer or colder air masses. Over the eastern United States we might expect the mean temperature patterns to be related to the north-south component (the v-component) of 500-mb flow. We have examined some data in order to ascertain this relationship.

The geostrophic v-component at 500 mb is computed on a 5°-latitude x 5°-longitude grid from 30°N to 60°N and 77.5°W to 122.5°W from average height values taken from NMC analyses for the given months of January using a simple finite-difference scheme. The average values of v at point i , v_i ($i = 1, \dots, 70$), are then statistically related to the three sets of coefficients discussed above by using a least-squares fit of the data pairs made up by v_i ($i = 1, \dots, 70$) and C_j ($j = 1, 2, 3$) for each of the 14 years used in our investigation. A correlation coefficient between C_j and v_i , called r_{ij} , was calculated; the slope of the linear fit, S_{ij} , was also determined. Since the square of the correlation, the covariance, describes the percent of variance explained by the relationship and the slope of the least-squares fit line gives the change in C_j per unit change in v_i , the multiples of these two parameters $r_{ij}^2 S_{ij}$ should depict the relative influence of the v_i data on C_j for each of the 70 points. The product of these two values $r_{ij}^2 S_{ij}$ can thus be used to represent the patterns of v_i which most significantly affect C_j . These patterns are shown in Figs. 6.2, 6.3, and 6.4, for C_1 , C_2 , and C_3 .

Note that the v-component of the winds over the Mississippi Valley appears to dominate the average surface temperature over the eastern United States (Fig. 6.2). We would expect strong northerly winds (negative v-component values) to be associated with cold average temperatures (negative temperature anomaly) and southerly winds, or weaker northerlies, to be associated with warmer temperature anomalies.

Fig. 6.2 The normalized pattern $r_{i1}^2 S_{i1}$ which represents the linear relationship between the mean surface-temperature pattern coefficient, C_1 , and the monthly mean meridional wind, $\bar{v}$, at each point.

Fig. 6.3 The normalized pattern $r_{i2}^2 S_{i2}$ which represents the linear relationship between the north-south gradient of the surface-temperature coefficient, C_2 , and the monthly mean meridional wind, $\bar{v}$, at each point.

Fig. 6.4 The normalized pattern $r_{i3}^2 S_{i3}$ which represents the linear relationship between the east-west gradient of the surface-temperature coefficient, C_3 , and the monthly mean meridional wind, $\bar{v}$, at each point.

The coefficient of the north-south gradient pattern, C_2 , is related to the differences in temperature anomalies over the eight states in the north-to-south direction. A larger (positive) value of C_2 implies a cold anomaly in the northern states and a warm one in the southern states of the 8-state sample used in our investigation. The reverse is true for a small (negative) value of C_2 . Note from Fig. 6.3 that high values of C_2 are associated with the stronger northerly winds over most of North America above 45°N, especially over central and western Canada as well as the states of the Pacific Northwest. Over

the southwestern United States $\bar{v}$ and C_2 are positively correlated, so that one might expect warmer anomalies in the southeast with southerly winds over the southwest.

The coefficient of the east-west gradient pattern, C_3 , depicts the differences in temperature anomalies from east to west in the region investigated. A high value of C_3 implies cold anomalies on the east coast and warm anomalies along the Mississippi River Valley, while a low value of C_3 implies the opposite. As seen in Fig. 6.4, strong northerly (low or negative) values of $\bar{v}$ over the eastern United States are related to high values of the C_3 (colder along the Atlantic Seaboard), as one might expect. Strong northerly winds over the Rockies are related to a negative value of C_3 (colder over the Mississippi Valley).

It is, of course, always possible that in a statistical correlation such as this the results might be spurious and show relationships which do not physically exist. Indeed, in carrying out this analysis at 70 locations and using only 14 data pairs at each location, one could expect some highly correlated spurious relationships. However, the emergence of a consistent pattern for each one of these relationships gives us confidence that these relationships and the resulting derived patterns are physically real.

Now that we have developed patterns of the monthly average v-component over midlatitude North America which are related to three components of temperature-anomaly patterns in the eastern United States, it would be helpful to express the entire v-component pattern as a single scalar rather than a vector of 70 variables. To do this, we use the technique described above where we developed the coefficients C_2 and C_3 . Let $\vec{A}_i$ ($i = 1, 2, 3$) represent 70-component vectors which are extracted from the $\bar{v}$ data in either Figs. 6.2, 6.3, or 6.4, and which depict the winds associated with the respective temperature-anomaly patterns. Since these vectors have been normalized, the simple dot product of the actual average v-component pattern for any one month with $\vec{A}_i$ represents the projection of that month's wind pattern upon the derived vector $\vec{A}_i$. For each month, then, we can portray the mean v-component of the wind in terms of three scalars (B_i) which are in turn related to the temperature-anomaly patterns derived above. Thus we can develop a least-squares linear relationship in which C_i can be determined from the calculated values of B_i . Figs. 6.5, 6.6, and 6.7 show the scatter diagrams and the least-squares linear fit for the three relationships. The linear equations along with the standard error and the explained variance in percent of the total variance for the three relationships are shown in Table 6.1. With the given patterns and derived relationships we can use the predicted or analyzed monthly average v-component pattern for January to estimate the predicted or actual temperature patterns over the eastern United States. The statistics in Table 6.1 also allow us to assess the standard error of our estimate.

The results of these established relationships allow us to conclude that the original temperature anomalies for January can be explained, at least

Fig. 6.5 Observed mean temperature-pattern coefficient, C_1 , versus $\bar{v}$ pattern coefficient, B_1 . The least-squares linear fit is also plotted.

Fig. 6.6 Observed north-south temperature-gradient-pattern coefficient, C_2 , versus $\bar{v}$ pattern coefficient, B_2 . The least-squares linear fit is also plotted.

partially, by the standing-eddy flow patterns of the midtropospheric v-component for that month. Because Pacific sea-surface temperatures (SST) anomalies appear to be related to monthly temperature anomalies over the United States (e.g. Namias, 1974), it is natural to examine the relationship between the sea-surface temperatures and the hemispheric stationary wave patterns of the midtroposphere. Techniques identical to those described above were used to relate the mean monthly temperatures over the Pacific to the harmonic analysis of the 500-mb height fields (taken from NMC gridded data).

Fig. 6.7 Observed east-west temperature-gradient-pattern coefficient, C_3 , versus v pattern coefficient B_3 . The least-squares linear fit is also plotted.

TABLE 6.1

Statistical Analysis of Linear Least-Squares Fit for Temperature-Pattern Coefficients, C_i , Calculated from Mean v -Component Wind-Pattern Coefficients, B_i .

i	Temperature Pattern	Least Squares fit	Standard error (rms) C_i	Percent of Variance explained
1	Mean	$C_1 = 0.148B_1 - 0.130$	1.104	55.4
2	North-South Gradient	$C_2 = 0.136B_2 - 2.002$	2.154	45.5
3	East-West Gradient	$C_3 = 0.145B_3 - 0.334$	0.862	73.6

Mean January monthly 500-mb height maps were subjected to a zonal harmonic analysis at latitudes 30°N, 40°N and 50°N. The amplitude coefficients of the sine and cosine terms for wave numbers one through six are calculated at each latitude and used as the set of data to describe the monthly mean height pattern. Thus, there are thirty-six such coefficients for each month's height field for the ten months of January (1963 through 1972) used in this analysis. Sea-surface temperatures were taken from the monthly averages of daily SST's obtained from the U.S. Fleet Numerical Weather Central (Wolff et al., 1965). These data covered the northern hemisphere on a 63 by 63 grid, but we recomputed these values on a 5 by 5 latitude/longitude grid at 150 points over the North Pacific. Mean data for the same January months noted above are used.

We let D_{ij} represent the mean January ocean surface temperature for year i at point j ; and we let H_{ik} represent one of the thirty-six 500-mb height harmonic coefficients ($k=1, \dots, 36$) for the same month and year. We computed the correlation coefficient r_{jk} between each of the 150 points of ocean temperature data and each of the 36 height pattern coefficients using the ten years of available data. We also computed the slope of the least-squares linear fit of these data, s_{jk} , using the same ten years of data. The 150-point pattern of sea-surface temperatures which influence the 36 harmonic height coefficients was calculated, as before, by the product $(r_{jk})^2(s_{jk})$ at each of the points. This pattern can be represented by a 150-component vector, Q_k , independently for each of the 36-harmonic height coefficients. The dot product of the vector, Q_k , with a given 150-point observed monthly sea-surface temperature vector, Y_i , was then calculated.

$$R_{ik} = Y_i \cdot \frac{Q_k}{|Q_k|}$$

This dot product R_{ik} gives a scalar coefficient which was used to develop a linear relationship between the sea-surface temperature patterns and the k^{th} harmonic height coefficient, H_{ik} . We used a least-squares linear fit to estimate H_{ik} from the R_{ik} data. Table 6.2 shows the percentage of the variance in the hemispheric harmonic height data that can be described from the ocean surface-temperature data. Note that the variance in the height coefficients which can be explained by the ocean temperature-pattern coefficients is generally between 70% and 90%.

TABLE 6.2

Percent Variance Explained by Least-Squares Linear Fit.

HEIGHT PATTERN LAT. TERM	WAVENUMBER					
	1	2	3	4	5	6
30N Sin	81.94	92.92	82.89	88.45	74.98	81.32
30N Cos	82.44	75.95	75.93	62.02	79.98	66.61
40N Sin	73.32	86.03	87.19	80.34	78.29	83.24
40N Cos	75.40	75.95	80.21	79.92	73.95	72.92
50N Sin	78.16	72.77	84.63	79.01	77.93	78.67
50N Cos	81.50	77.36	86.22	71.46	82.85	85.79

7. EXECUTIVE SUMMARY

Our research efforts between 1 November 1976 and 31 October 1977 were centered mainly on:

1. A refinement of the space-heating energy consumption model whose application has been tested with data from the cities of Greeley, Colorado, and Cheyenne, Wyoming.

2. The development and testing of a statistical sampling technique which would allow the establishment of a building census without a "foot survey" of the city under investigation.

3. Detailed analysis of improved meteorological data for the cities of Greeley and Cheyenne to establish the urban climate characteristics that influence the energy demand of a city.

4. In-depth studies of the interannual variability of ocean surface temperatures, mainly in the North Pacific, and atmospheric parameters that appear to entail feedback mechanisms with the ocean.

5. Statistical studies of relationships between large-scale flow patterns over the eastern United States and surface temperature variability as it would influence energy demand.

The studies mentioned under Items 4 and 5 above are aimed at the development of long-range forecasting techniques to be applied to energy consumption projections, mainly for the cold season of the year. Items 1 to 3 deal with engineering applications of meteorological information to the problem of urban and regional energy consumption.

7.1 ENERGY MODELLING

We have combined two approaches in modelling the energy consumption of a community for space heating: A "lumped micro-model" was designed which estimates on an hourly basis the heat loss from different types of structures, and then "lumps" the losses from these structures into the aggregated loss from the whole community, i.e. the cities of Greeley, Colorado, or Cheyenne, Wyoming.

The second approach results in a "macro-model" and entails the utilization of socio-economic factors which are available from census data and/or assessors files. From such factors one can derive per capita indices (e.g. income, residential space, commercial space, etc.) which have a bearing on energy use. This modelling concept is still under development and will be refined as more data from micro-model applications to different communities become available.

During the present grant period the energy demands of several types of structures have been investigated in detail to validate our "micro-model" for such structures. In addition to the building types validated in our previous report (Reiter et al., 1976) we studied (a) an all-metal commercial building (farm-implement sales building); (b) a low-rise commercial building (bank); (c) a 2½-story apartment building and (d) a one-story high-school building. Daily energy-consumption data and bi-hourly weather data from the winter 1976/1977 were also used to re-check the model performance on some of the building types that have been dealt with in our previous report.

We noted that major discrepancies between the daily energy demand calculated by our model and the actual energy consumption obtained from daily meter readings could be explained by changes in the occupant habit patterns. These changes, had they been known to us *a priori*, could have been incorporated into the model to improve its performance. Specifically it was found that a mobile home used less energy than anticipated from Christmas until well into the first half of January. Presumably many of the residents were absent from their homes during that period. The Weld County Hospital also showed less energy use than anticipated, already starting before Christmas, presumably due to a decrease in the number of patients and/or in equipment use. On the other hand West Greeley High School required relatively more energy during the Christmas recess than during the regular school period. The absence of body heat and of heat generated by electric fixtures (taken into account by our model for weekends) was the probable cause for the observed discrepancy.

The model computations of the aggregated energy consumption for the winter 1976/77 and for the whole city of Greeley, Colorado, were 98.9% of the actual consumption. The improvements in our model results against the winter 1975/76 were mainly due to a better meteorological data base. In our opinion it does not suffice to consider one meteorological station (such as the Weather Bureau Airport Station) as representative for the meteorological parameters (mainly temperature and wind) that govern the heat loss from, or the heat gain by, buildings.

Our energy consumption model was also applied to the city of Cheyenne, Wyoming. The model predicted 97.8% of the actual energy use for the months of January, February and March 1977. The slightly larger error of our model is due to the fact that no detailed building census was taken in Cheyenne but a statistical sampling technique was employed instead.

7.2 STATISTICAL DATA SAMPLING

The detailed building census which was taken for Greeley, Colorado turned out to be highly reliable, but consumed more time than what we could afford to spend on other, even larger, communities. A statistical sampling technique was designed therefore, which relies on the following approach: (1) Aerial photography establishes those sub-sections of a city which are fairly homogeneous in terms of buildings construction characteristics. Buildings in each sub-section of the city are classified according to age and use pattern. (2) Data obtained from Greeley, Colorado, allowed us to determine the sample size required for each major building type to estimate the average building size within tolerable error limits. (3) The sample size required for each square-mile section of the city serves as input into a randomization scheme which calls out addresses of residences to be checked for their sizes from the assessor's files, until the required number of structures to be sampled is filled.

This sampling scheme was tested successfully in the city of Cheyenne, Wyoming. Because the number of commercial structures in each city section fell below the threshold value which would allow meaningful application of our randomization scheme, these structures still had to be surveyed individually.

7.3 URBAN CLIMATE STUDIES

Detailed weather information received from stations scattered throughout Greeley, Colorado and Cheyenne, Wyoming, allowed an analysis of urban effects on meteorological parameters. In Greeley relatively large temperature differences could be detected on many days between individual stations. These differences, to a large extent, were controlled by the city's topography. Cheyenne, on the other hand, on the average revealed smaller cross-city temperature differences because of the much windier climate which prevails there. The reduction of wind speed in the built-up area of town, as compared to the wind speeds given by the Weather Bureau station at the airport, is of great significance, however, when estimating the energy demand for space heating.

A preliminary estimate of the effects of a cold winter on energy consumption has been conducted using the per capita use of energy per degree day calculated for Greeley, Colorado, and applying it to the 1970 population census data for the eastern United States. Over wide regions of the country the energy demand during January 1977 was estimated to have been more than 50 percent higher than normal. In the metropolitan regions of Chicago and New York the excessive energy demand during that month and over an area 1° longitude $\times$ 1° latitude was of the order of 10^{13} Btu or 10^{10} cubic ft of natural gas.

7.4 THE INTERANNUAL VARIABILITY OF THE OCEAN-ATMOSPHERE SYSTEM

North Pacific sea-surface temperature data received for the period 1962-1976 indicate that a cooling trend prevailed in the latitude belt $40-50^\circ\text{N}$ since 1963, and in the latitude belt $50-60^\circ\text{N}$ since 1967. Since the turn of the century the North Pacific apparently has undergone several warming and cooling trends, but the accuracy of the available data does not suffice to establish the amplitudes of these trends with any reliability. Thus we do not know if the cold temperatures observed during summer 1976 (and held responsible by several scientists for the cold winter 1976/77 over the eastern United States) match, or fall short of, earlier cold periods around 1905 and 1925.

The recent cooling trend has led to a tightening of the oceanic meridional temperature gradient in the region of the Kuroshio and Oyashio. A similar tightening of the temperature gradient can be observed between Gulf Stream and Labrador Current in the Atlantic.

This long-term trend behavior of North Pacific SST's might possibly be tied by a feed-back mechanism to the intensity of the trade-winds in the tropical Pacific which have also undergone a marked secular trend.

Superimposed upon the long-term trends are shorter anomaly variations in North Pacific SST's. These appear to be caused, in part, by Ekman pumping forced by local atmospheric circulation systems in the North Pacific, but also by large-scale advection of water masses through the North-Equatorial and Kuroshio currents. Surges in this advection may be caused by observed surges of the trade-wind systems.

These trade-wind surges correlate very well with precipitation regimes in the equatorial Pacific, notably over the Line Islands. They also appear to

coincide with El Niño events off the coasts of Ecuador and Peru.

It is hoped that a better understanding of the causative factors influencing SST anomalies in the North Pacific might lead to powerful long-range forecasting tools.

7.5 EFFECTS OF LARGE SCALE FLOW PATTERNS ON SURFACE TEMPERATURES OVER THE EASTERN UNITED STATES

Since surface weather patterns are, to a large extent, controlled by advective processes in the middle troposphere, a successful attempt was made to correlate mean temperatures as well as zonal and meridional temperature gradients over the eastern United States with large-scale flow patterns at the 500-mb level over North America. The correlations which we found encouraged us to explore the possible forcing effect of sea-surface temperature anomalies, mainly in the North Pacific, on planetary wave patterns which, in turn, would influence the mid-tropospheric flow characteristics over North America. Preliminary results indicate that the forcing of atmospheric wave patterns by SST anomalies is significant. Forecasts of SST anomalies, therefore, might find useful applications for winter temperature forecasts for the eastern United States.

REFERENCES

- Barnett, T.P., 1977: The principle time and space scales of the Pacific trade wind fields. J. Atmos. Sci., Vol. 34, No.2, p. 221-236.
- Cochran, W.G., 1963: Sampling Techniques. John Wiley and Sons, Inc., New York, 413 pp.
- Davies, W.D.T., 1970: System Identification for Self-Adaptive Control. John Wiley, N.Y.
- Defant, A., 1961: Physical Oceanography, Vol. I and II. Macmillan Company, New York, 1327 pp.
- F.E.A., 1975: Monthly Energy Review, March 1975. Federal Energy Administration, National Energy Information Center, Washington, D.C., 65 pp.
- _____, 1977: Monthly Energy Review, March 1977, Federal Energy Administration, National Energy Information Center, Washington, D.C., 92 pp.
- Gabor, D., W.P.L. Wilby and R. Wordcock, 1961: A universal nonlinear filter, predictor and simulator which optimizes itself by the learning process. J. Inst. Elect. Engr., July, p. 422-438.
- Ivakhnenko, A.G., 1971: Polynomial theory of complex systems. IEEE, Transaction on Systems, Man and Cybernetics, Vol. SMC-1, No. 4, p. 364-378.
- _____, V.V. Shervashidze, O.I. Shelvd'ko, S.G. Patereu and N.A. Ivakhnenko, 1974: Discovery of physical laws by GMDH method with the absence-of-bias criterion. Soviet Automatic Control, Vol. 4, No. 2, p. 32-44.
- Laevastu, T., 1963: Energy Exchange in the North Pacific; Its Relations to Weather and Its Oceanographic Consequences. Part I - Formulas and Nomographs for Computations of Heat Exchange Components Over the Sea. Report No. 30, Hawaii Institute of Geophysics, Univ. of Hawaii, 10 pp.
- Leong, H.H., 1975: Using Recursive Regression Polynomials to Construct a System Description -- An Introduction to the GMDH Algorithm. M.S. Thesis, Statistics Dept., Colorado State Univ., Fort Collins, Colorado, 96 pp.
- Namias, J., 1974: Longevity of a coupled air-sea-continent system. J. Appl. Meteor., Vol. 102, p. 638-648.
- _____, 1977: Paper presented at Workshop on "Climate Response to Stratospheric Change". National Center for Atmospheric Research, Boulder, Colo., 7 June 1977.
- National Oceanic and Atmospheric Administration, 1957-1972: Climatological Data. National Summary. U.S. Dept. of Commerce. Government Printing Office, Washington, D.C.
- National Science Foundation "Mosaic", The Ocean Connection. Vol. 8, No. 4, July/August 1977, p. 35-41.
- Reiter, E.R., 1977a: The interannual variability of the ocean-atmosphere system. Accepted for publication by J. Atmos. Sci.
- _____, 1977b: Long-term wind variability in the tropical Pacific, its possible causes and effects. Accepted for publication by Monthly Weather Review.
- _____, 1977c: On the recent cooling trend in the North Pacific. Submitted to the Journal of Geophysical Review.
- _____, G.R. Johnson, W.L. Somervell, Jr., E.W. Sparling, E. Dreiseitl, B.C. Macdonald, J.P. McGuirk and A.M. Starr, 1976: The Effects of Atmospheric Variability on Energy Utilization and Conservation. Environmental Research Paper No. 5, Colo. State Univ., Fort Collins, Colo., 72 pp.
- Wagner, A.J., 1977: Weather and circulation of January 1977. The coldest month on record in the Ohio Valley. Mon. Wea. Rev., Vol. 105, No. 4, p. 553-560.
- Wolff, P.M., L.P. Carstensen and T. Laevastu, 1965: Analyses and Forecasting of Sea-Surface Temperature. Fleet Numerical Weather Facility. Tech. Note No. 8, Monterey, Calif., 48 pp.
- Wyrtki, K., 1974: Equatorial currents in the Pacific 1950 to 1970 and their relations to the trade winds. J. Phys. Oceanogr., Vol. 4, p. 372-380.
- _____, and G. Meyers, 1975: The Trade Wind Flow Over the Pacific Ocean. Reports No. HIG-75-1 and No. HIG-75-2 to National Science Foundation and Office of Naval Research, Hawaii Institute of Geophysics, Univ. of Hawaii, 42 pp.

APPENDIX A

DEVELOPMENT OF THE HEURISTIC DESCRIPTIVE POLYNOMIAL MODEL

Instead of searching for suitable differential equations to represent a system performance, A.G. Ivakhnenko has proposed an alternative approach termed the "Polynomial Description" of a system. The scheme is to construct an optimum polynomial description based on known input and output data. Such a scheme is called the "Grouped Method of Data Handling" or "GMDH".

Consider a non-linear system with a single output $Y(t)$ and S number of inputs $X_i(t)$, $i=1,2,\dots,S$. This system could be represented by the following equation

$$Y(t) = f[X_1(t), X_2(t), \dots, X_S(t)] \quad (A.1)$$

The problem is to determine the unknown structure $f(X_1, X_2, \dots, X_S)$ from the available past data.

Assuming the data to be a stationary random sequence, the Kolmogorov-Gabor polynomial for stationary stochastic process is used to determine the structure of $f(X_1, X_2, \dots, X_S)$. The polynomial takes the form of

$$Y = \beta_0 + \sum_i \beta_i X_i + \sum_{i,j} \beta_{ij} X_i X_j + \sum_{i,j,k} \beta_{ijk} X_i X_j X_k + \dots \quad (A.2)$$

If the number of variables is S , the first-order polynomial will contain $(S+1)$ terms, the second-order will have $(S+1)(S+2)/2!$ terms, the third-order $(S+1)(S+2)(S+3)/3!$ terms, etc. However, to determine the large number of coefficients in Eq. (A.2), a large amount of data and computation of high-dimensional matrices is required. For example, consider a fourth-order polynomial with four arguments X_1, X_2, X_3 and X_4 . The complete polynomial including terms of all powers and all covariations of arguments has 70 terms.

The complete polynomial is:

$$\begin{aligned} Y = & \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_1^2 + \beta_6 X_2^2 \\ & + \beta_7 X_3^2 + \beta_8 X_4^2 + \beta_9 X_1 X_2 + \beta_{10} X_1 X_3 + \beta_{11} X_1 X_4 \\ & + \beta_{12} X_2 X_3 + \beta_{13} X_2 X_4 + \beta_{14} X_3 X_4 + \beta_{15} X_1^3 + \beta_{16} X_2^3 \\ & + \beta_{17} X_3^3 + \beta_{18} X_4^3 + \beta_{19} X_1^2 X_2 + \beta_{20} X_1^2 X_3 \\ & + \beta_{21} X_1^2 X_4 + \beta_{22} X_2^2 X_1 + \beta_{23} X_2^2 X_3 + \beta_{24} X_2^2 X_4 \\ & + \beta_{25} X_3^2 X_1 + \beta_{26} X_3^2 X_2 + \beta_{27} X_3^2 X_4 + \beta_{28} X_4^2 X_1 \\ & + \beta_{29} X_4^2 X_2 + \beta_{30} X_4^2 X_3 + \beta_{31} X_1 X_2 X_3 + \beta_{32} X_1 X_2 X_4 \\ & + \beta_{33} X_1 X_3 X_4 + \beta_{34} X_2 X_3 X_4 + \beta_{35} X_1^4 + \beta_{36} X_2^4 \\ & + \beta_{37} X_3^4 + \beta_{38} X_4^4 + \beta_{39} X_1^2 X_2^2 + \beta_{40} X_1^2 X_3^2 + \end{aligned}$$

$$\begin{aligned} & + \beta_{41} X_1^2 X_4^2 + \beta_{42} X_2^2 X_3^2 + \beta_{43} X_2^2 X_4^2 + \beta_{44} X_3^2 X_4^2 \\ & + \beta_{45} X_1^3 X_2 + \beta_{46} X_1^3 X_3 + \beta_{47} X_1^3 X_4 + \beta_{48} X_1^2 X_2 X_3 \\ & + \beta_{49} X_1^2 X_2 X_4 + \beta_{50} X_1^2 X_3 X_4 + \beta_{51} X_2^3 X_1 + \beta_{52} X_2^2 X_1 X_3 \\ & + \beta_{53} X_2^2 X_1 X_4 + \beta_{54} X_2^3 X_3 + \beta_{55} X_2^3 X_4 + \beta_{56} X_2^2 X_3 X_4 \\ & + \beta_{57} X_3^2 X_1 X_2 + \beta_{58} X_3^3 X_1 + \beta_{59} X_3^3 X_2 + \beta_{60} X_3^3 X_4 \\ & + \beta_{61} X_3^2 X_1 X_4 + \beta_{62} X_3^2 X_2 X_4 + \beta_{63} X_4^2 X_1 X_2 \\ & + \beta_{64} X_4^2 X_1 X_3 + \beta_{65} X_4^3 X_1 + \beta_{66} X_4^2 X_2 X_3 + \beta_{67} X_4^3 X_2 \\ & + \beta_{68} X_4^3 X_3 + \beta_{69} X_1 X_2 X_3 X_4 \quad (A.3) \end{aligned}$$

To determine the coefficients by solving Gaussian normal equations, it would be necessary to invert matrices with dimension of 70 x 70 components, a very expensive task. To overcome this difficulty, Ivakhnenko proposed to break down the complete polynomial into several layers of partial polynomials each of which contains two or more of the input variables such that the complete polynomial could be reconstructed by back substitution from all the layers considered. The advantage of the Ivakhnenko proposal lies in the fact that by breaking down the complete polynomial into partial polynomials having fewer input variables results in equations with much smaller matrices, and thus the ill-conditioned matrix of the complete polynomial is replaced with smaller well-conditioned matrices. In addition, solving the coefficients of the partial polynomials requires many fewer data points than if the complete polynomial is used directly.

Applying Ivakhnenko's proposal to our previous example of a second-degree polynomial with four variables X_1, X_2, X_3 and X_4 , the partial polynomials for the combination of variables (X_1, X_2) and (X_3, X_4) are:

$$y_1 = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_1^2 + b_4 X_2^2 + b_5 X_1 X_2 \quad (A.4)$$

$$y_2 = c_0 + c_1 X_3 + c_2 X_4 + c_3 X_3^2 + c_4 X_4^2 + c_5 X_3 X_4 \quad (A.5)$$

and the complete polynomial is constructed from y_1 and y_2 as:

$$Y = d_0 + d_1 y_1 + d_2 y_2 + d_3 y_1^2 + d_4 y_2^2 + d_5 y_1 y_2 \quad (A.6)$$

In this case it is sufficient to solve three systems of equations each with a 6 x 6 matrix, instead of solving one system with a 70 x 70 matrix.

There are six ways in which two of the four variables X_1 , X_2 , X_3 and X_4 can be combined in a partial polynomial, and thus six partial polynomials would be constructed in the first layer. By passing the six partial polynomials to the next layer we would have 15 ways in which the six partial polynomials from the first layer could be combined, and the number of partial polynomials would keep increasing from one layer to the next.

The GMDH algorithm is performed in such manner that only variables and partial polynomials that satisfy certain chosen heuristic decisions or thresholds are passed from one layer to the next in order to obtain an optimum complete descriptive polynomial. The structure of the GMDH algorithm resembles the structure of a multilayered Perceptron*, where separating "useful" and "harmful" information by thresholds at each level of the solution is possible.

In summary, the GMDH algorithm used in this study is performed as follows. To obtain an optimum complete descriptive polynomial for a process with one output and S input variables, the GMDH algorithm breaks down the expected complete descriptive polynomial into sets of partial descriptive polynomials at several layers, with each partial polynomial carrying only a few of the total number of independent variables. Then from the available data the coefficients of each partial polynomial are estimated using the least squares method. A sum of squares error criterion is used to judge which polynomials will be passed from one layer to the next, where the sum of squares error for each partial polynomial is computed between the observations and the estimated polynomial. Observe that the available data are divided into training and testing sets where the training data are used to estimate the coefficients of the polynomials, and the testing data are used to compute the sum of squares errors; this is done so that overfitting the data is eliminated. This process is repeated from one layer to the next until a specified accuracy criterion is reached or until a specified number of layers is reached. Details of the exact algorithm are discussed below and shown schematically in Fig. A.1.

GMDH Algorithm

The GMDH algorithm could be separated into three stages:

1. Pre-GMDH stage -- at this stage the data are reduced and grouped for the GMDH stage. Also the order of the partial polynomials, and values of the various thresholds are assigned.
2. GMDH stage -- recursive estimation of the partial polynomials for all the layers is performed at this stage.

3. Post-GMDH stage -- depending on the results from the GMDH stage, two situations can occur:

- (a) Reconstruction of the complete descriptive polynomial if the assigned accuracy is reached.
- (b) If the assigned accuracy is not reached, readjust values of the thresholds and/or the partial polynomials and repeat the GMDH stage.

Pre-GMDH Stage:

In this stage the available data are processed and made ready for use in the GMDH stage. This includes reducing the data set to a workable number and dividing the data into training and testing sets. Also at this stage the order of the partial polynomials, the number of variables in each polynomial and the values for the various thresholds are assigned. These procedures are performed by the following steps:

Step 1. Reduce the data points to a workable number in such manner that the data chosen are representative of all possible outcomes of the process.

Step 2. Split the data into training and testing sets. The process of splitting the data is a heuristic process by which any criterion may be used to accomplish. But if no criterion is available, the following suggestion is recommended. Compute the distance defined below, Eq. A.7, for each data point and use data points with large distance values for the training set and data points with small distance values for the testing set. This is done so that the points that are farther away from the norms of the process are used to estimate the partial polynomials and the points with small distances are used to test the estimated polynomials to find how good they predict the norms of the process. A distance threshold θ_d defined below is used to determine which data points would belong to each set.

The distance for a data point is defined as follows:

$$D_n = \left[\left(\frac{Y(n) - \bar{Y}}{\bar{Y}} \right)^2 + \left(\frac{X_1(n) - \bar{X}_1}{\bar{X}_1} \right)^2 + \dots + \left(\frac{X_S(n) - \bar{X}_S}{\bar{X}_S} \right)^2 \right]^{\frac{1}{2}} \quad (A.7)$$

where,

$$\bar{X}_i = \frac{1}{N} \sum_{n=1}^N X_i(n) \quad (A.8)$$

and,

$$\bar{Y} = \frac{1}{N} \sum_{n=1}^N Y(n) \quad (A.9)$$

and N is the number of observations in the sample.

*The concept of the Perceptron is discussed by Frank Rosenblatt in his book Principles of Neurodynamics, where the Perceptron concept is used as a model for the brain. The perceptron is defined as a signal transmission network, in which signals are passed from one stage of the network to the next only if the input signal exceeds a given threshold.

Fig. A.1 The GMDH Block Diagram.

Step 3. Assign values for the following thresholds:

θ_d = distance threshold for separating the data points into training and testing sets. To determine the magnitude of θ_d it is recommended that first the distance for each data point be computed and, based on the results, the value of θ_d is selected.

θ_s = selection threshold for testing the Sum of Squares Error, SSE, to determine whether a partial polynomial is eligible to become an intermediate characteristic variable and passed on to the next layer. The magnitude of θ_s is taken as large as possible for the first layer to allow all the partial polynomials to pass to the second layer, and then for the second layer θ_s takes the value of the minimum SSE from the first layer such that the partial polynomials passing from the second layer to the third layer have to be better in terms of SSE than those polynomials passed from the first layer.

θ_r = correlation threshold for testing the correlation between a pair of characteristic variables to determine whether they can be combined to construct a partial polynomial. The magnitude of θ_r is selected close to unity.

θ_a = accuracy threshold for checking if the minimum SSE of a given layer has reached an optimum value which then means that an optimum solution is reached.

Step 4. Select the number of characteristic variables to be used in each partial polynomial. Usually, two will be used unless it is found that two are insufficient during the recursive estimation procedure.

Step 5. Select the order of the polynomial for the partial polynomials. Selection of the order of the polynomial is a heuristic decision, and if no information is available on the system, any order can be used as long as the following criterion is met. Note that the order of the polynomial is dependent on the quantity of the available data, since higher order polynomials have a larger number of coefficients and require more data to solve for those coefficients. Let K equal the order of the polynomial, N = size of sample, and P = number of coefficients in the polynomial. The value of K must be selected such that $P \leq N-1$. Usually it is recommended that the number (N-1-P) is kept as large as possible because the stability of the estimated coefficients will become sensitive when (N-1-P) is small.

GMDH Stage:

In this stage recursive estimation of the partial polynomials for all the layers is performed. This procedure involves several steps:

Step 1. As stated above each partial polynomial is usually constructed using a pair of the characteristic variables. To determine which variables can be combined to form a partial polynomial, the correlation coefficients between all possible combination of variables are computed at each layer. A correlation coefficient is defined between two variables X, and Y by:

$$r_{XY} = \frac{\sum_i (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_i (X_i - \bar{X})^2 \sum_i (Y_i - \bar{Y})^2}} \quad (A.10)$$

Variables whose correlation coefficients are smaller than the correlation threshold are combined to form a partial polynomial. The reason for doing this is that when the correlation coefficient between two variables approaches unity it means that the two variables are linearly correlated and carry almost the same information, i.e., there is no point in combining two variables that carry the same information in a partial polynomial. This problem becomes more evident as the number of layers increase.

Step 2. Once it is known which variables can be combined from Step 1, then all of the polynomials from all possible combination of variables are constructed as follows:

$$P_L^1(1,2) = P(X_1, X_2) \quad (A.11)$$

$$P_L^2(1,3) = P(X_1, X_3) \quad (A.12)$$

⋮

$$P_L^m(i,j) = P(X_i, X_j) \quad (A.13)$$

where $P_L^m(i,j)$ is the m^{th} partial polynomial of the L^{th} layer, with the characteristic variables X_i and X_j .

Step 3. Using the data from the training set, the coefficients for each partial polynomial constructed in Step 2 are estimated using the least squares method. For example let the selected pair of variables be,

$$\underline{X}_i^T = [X_i(1), X_i(2), \dots, X_i(TR)] \quad (A.14)$$

$$\underline{X}_j^T = [X_j(1), X_j(2), \dots, X_j(TR)] \quad (A.15)$$

and the dependent variable be,

$$\underline{Y}^T = [Y(1), Y(2), \dots, Y(TR)] \quad (A.16)$$

where TR is the number of data points in the training set. Consider solving for the m^{th} partial polynomial of the form

$$P_L^m(i,j) = \beta_0 + \beta_1 X_i + \beta_2 X_i^2 + \beta_3 X_j + \beta_4 X_j^2 + \beta_5 X_i X_j \quad (A.17)$$

Then the least squares method would be applied to estimate the unknown coefficients,

$$\underline{\beta}^T = [\beta_0, \beta_1, \dots, \beta_5] \quad (A.18)$$

as follow:

a. Perform a "directed" vector multiplication, *, as shown

$$\underline{X}_i * \underline{X}_i = \begin{bmatrix} x_i^2(1) \\ x_i^2(2) \\ \vdots \\ x_i^2(TR) \end{bmatrix}; \underline{X}_j * \underline{X}_j = \begin{bmatrix} x_j^2(1) \\ x_j^2(2) \\ \vdots \\ x_j^2(TR) \end{bmatrix};$$

$$\underline{X}_i * \underline{X}_j = \begin{bmatrix} x_i(1) x_j(1) \\ x_i(2) x_j(2) \\ \vdots \\ x_i(TR) x_j(TR) \end{bmatrix} \quad (A.19)$$

b. Obtain the matrix,

$$\underline{X} = [1, \underline{X}_i, \underline{X}_i * \underline{X}_i, \underline{X}_j, \underline{X}_j * \underline{X}_j, \underline{X}_i * \underline{X}_j]$$

c. Compute $\underline{X}^T \underline{X}$, $\underline{X}^T \underline{Y}$ and $(\underline{X}^T \underline{X})^{-1}$ to solve for the normal equation,

$$\underline{X}^T \underline{Y} = (\underline{X}^T \underline{X}) \underline{\beta} \quad (A.20)$$

and the solution for the normal equation becomes the estimated coefficients, as shown in Fig. A.1, for the partial polynomial, i.e.

$$\underline{\hat{\beta}} = (\underline{X}^T \underline{X})^{-1} (\underline{X}^T \underline{Y}) \quad (A.21)$$

d. From the current pair of characteristic variables $\underline{X}_i$ and $\underline{X}_j$ compute the estimated partial description values $\hat{Y}_m$ from:

$$\hat{Y}_m(t) = \hat{\beta}_0 + \hat{\beta}_1 x_i(t) + \hat{\beta}_2 x_i^2(t) + \hat{\beta}_3 x_j(t) + \hat{\beta}_4 x_j^2(t) + \hat{\beta}_5 x_i(t) x_j(t) \quad (A.22)$$

for $t = 1, 2, 3, \dots, TR$ with respect to the training set, and for $t = 1, 2, 3, \dots, TE$ with respect to the testing set.

Step 4. Compute the sum of squares error for each partial polynomial at the L^{th} layer using both the data from the training and testing sets such as,

$$SSE_m(\text{Train}) = \sum_{t=1}^{TR} [Y(t) - \hat{Y}_m(t)]^2 \quad (A.23)$$

$$SSE_m(\text{Test}) = \sum_{t=1}^{TE} [Y(t) - \hat{Y}_m(t)]^2 \quad (A.24)$$

and then arrange the partial polynomials in descending order according to their SSE from the testing set and compare the minimum SSE with the accuracy threshold θ_a . If the minimum SSE from the testing set is less

than θ_a , the optimum partial polynomial has been obtained and the scheme jumps to the Post-GMDH stage, otherwise proceed to the next step.

Step 5. If the scheme has reached a pre-assigned layer number or if the minimum SSE does not improve considerably, then the process is stopped and the scheme jumps to the Post-GMDH stage.

Step 6. If the scheme does not jump to the Post-GMDH stage from Step 5 and the minimum SSE is larger than θ_a , none of the estimated partial polynomials has satisfied the optimum criterion and another layer of partial descriptions is required. Set the value of θ_s equal to the minimum SSE and repeat Steps 1 through 6 while setting the values of the partial polynomials that are allowed to pass to the next layer to be the characteristic variables for the partial polynomials of the next layer.

Post-GMDH Stage:

Two situations may result from the GMDH stage

(1) The result from the GMDH stage satisfies the accuracy threshold θ_a , and an optimum solution has been reached. If this is the case, reconstruct the complete description polynomial from the optimized partial polynomials.

(2) The result from the GMDH stage does not satisfy θ_a . Then readjust the values of the thresholds and/or re-assign the order of the partial polynomials, and/or increase the number of characteristic variables in each or some of the partial polynomials and repeat the GMDH stage.

A computer program for this algorithm was written by Leong, 1975 to perform the steps of the GMDH stage discussed above, and a modified version of that program is used to estimate the performance of the systems considered in Chapter 2 of this report.

APPENDIX B

THERMAL MODELLING

Theoretical Model:

The heating (cooling) load is the amount of energy that is transferred from (to) the air in the building to (from) the surroundings and simultaneously added (removed) by the heating (cooling) equipment at any given time. To calculate this quantity directly requires a rather laborious solution of energy balance equations involving the air in each room of the building, surrounding walls, infiltrating and ventilating air, and internal energy sources. This approach would require simultaneously solving a large number of coupled non-linear differential equations, a tedious task.

A more simplified approach would be to consider a fictitious space that has the same dimensions as the building and is enclosed by four walls, a ceiling and floor, and having infiltrating air as well as normal internal energy sources.

The energy balance equations representing the thermal process taking place in the building are:

$$\rho' V_R C_{PR} \frac{dT_R}{dt} = \sum_{i=1}^6 A_i h_i (T_i - T_R) + \sum_{i=1}^6 A_i g_{i-R} (T_i^4 - T_R^4) + Q_{\text{gain}} + Q_{\text{inf}} + Q_{\text{app}} + Q_{\text{occ}}$$

$$\rho' V_1 C_{P1} \frac{dT_1}{dt} = A_1 h_1 (T_R - T_1) + A_1 g_{a-1} (T_A^4 - T_1^4) + \sum_{i=2}^6 A_1 g_{i-1} (T_i^4 - T_1^4) + A_1 h_0 (T_A - T_1) + A_1 g_{a-1} (T_A^4 - T_1^4) + Q_{\text{sol-1}}$$

$$\rho' V_2 C_{P2} \frac{dT_2}{dt} = A_2 h_2 (T_R - T_2) + A_2 g_{R-2} (T_R^4 - T_2^4) + \sum_{i=1, i \neq 2}^6 A_2 g_{i-2} (T_i^4 - T_2^4) + A_2 h_0 (T_A - T_2) + A_2 g_{a-2} (T_R^4 - T_2^4) + Q_{\text{sol-2}}$$

$$\rho' V_3 C_{P3} \frac{dT_3}{dt} = A_3 h_3 (T_R - T_3) + A_3 g_{R-3} (T_R^4 - T_3^4) + \sum_{i=1, i \neq 3}^6 A_3 g_{i-3} (T_i^4 - T_3^4) + A_3 h_0 (T_A - T_3) + A_3 g_{a-3} (T_A^4 - T_3^4) + Q_{\text{sol-3}}$$

$$\rho' V_4 C_{P4} \frac{dT_4}{dt} = A_4 h_4 (T_R - T_4) + A_4 g_{R-4} (T_R^4 - T_4^4) + \sum_{i=1, i \neq 4}^6 A_4 g_{i-4} (T_i^4 - T_4^4) + A_4 h_0 (T_A - T_4) + A_4 g_{a-4} (T_A^4 - T_4^4) + Q_{\text{sol-3}}$$

$$\rho' V_5 C_{P5} \frac{dT_5}{dt} = A_5 h_5 (T_R - T_5) + A_5 g_{R-5} (T_R^4 - T_5^4) + \sum_{i=1, i \neq 5}^6 A_5 g_{i-5} (T_i^4 - T_5^4) + A_5 h_0 (T_G - T_5)$$

$$\rho' V_6 C_{P6} \frac{dT_6}{dt} = A_6 h_6 (T_R - T_6) + A_6 g_{R-6} (T_R^4 - T_6^4) + \sum_{i=1}^5 A_6 g_{i-6} (T_i^4 - T_6^4) + A_6 h_{\text{ATT}} (T_{\text{ATT}} - T_6)$$

where

- Q_{gain} = rate of solar heat gained through windows and absorbed by the interior of the building;
- Q_{occ} = rate of heat gain from occupants;
- Q_{app} = rate of heat gain from light and appliances in the building;
- Q_{inf} = rate of heat loss by infiltrating outdoor air;
- Q_{sol} = rate of solar heat gained by the walls;
- T_R = the room air temperature;
- T_A = the ambient outdoor air temperature;
- T_G = the ground temperature;
- T_{ATT} = the attic temperature.

The h_i are the convective heat transfer coefficients between the air in the room and surface i . These coefficients could be determined from Lof et al., 1974. The term $\rho' V C_p$, where ρ' is the density, V the volume, and C_p the heat capacity, is known as the total capacitance of a material. A is the area of the surface i . g_{i-j} is the radiation heat transfer factor between two surfaces and is given by

$$g_{i-j} = \frac{\sigma}{(1-\epsilon_i)/\epsilon_i + 1/F_{ij} + (1-\epsilon_j)A_i/\epsilon_j A_j}$$

where σ is the Stefan-Boltzmann constant;

ϵ is the emissivity of the surface and

F_{ij} is the view factor between two surfaces and can be determined for specific configurations from Duffie and Beckman, 1974.

Simplified Model:

Obtaining an elaborate solution to the seven equations listed above requires a large amount of computer time, and the resulting accuracy from such a solution does not justify the number of computations involved due to the incompleteness of the thermal performance input data on the house.

A greatly simplified model is considered here for the computations of the heating and cooling loads of the building at any time. This model considers calculating separately the various thermal processes that take place in the fictitious space. Then the heating or cooling load is equated to the sum of these processes.

This model does not take into consideration the effect of thermal storage in the various structural elements of the building, i.e., the system is considered to be in the steady state condition. This assumption will be relaxed and lagged equations will be used in the structural identification phase.

Other assumptions considered in the model are:

- 1) There is a one-dimensional heat flow through walls, ceiling and floor.
- 2) The sky can be considered as a black body for long wave-length radiation at air temperature.
- 3) All surfaces are at uniform temperature.
- 4) Characteristic properties of building materials are independent of temperature.
- 5) Solar radiation flux is nonpolarized.
- 6) Glass is opaque to long wavelength radiation.

Further assumptions were considered for some of the thermal processes and will be discussed when the specific process is considered.

The equations used in this model to calculate the heating and cooling load of the building are developed below. The heating load at any time is given by:

$$Q_{load} = \sum_{\text{windows}} Q_{loss} + \sum_{\text{walls}} Q_{loss} + Q_{loss,c} + Q_{loss,f} + Q_{gain} + Q_{occ} + Q_{app} + Q_{inf} \quad (B.1)$$

where

Q_{load} = heating load of the building;

$\sum_{\text{windows}} Q_{loss}$ = sum of the rate of heat losses by conduction through all windows in the building;

$\sum_{\text{walls}} Q_{loss}$ = sum of the rate of heat losses by conduction through all walls and doors in the building;

$Q_{loss,c}$ = rate of heat loss by conduction through the ceiling;

$Q_{loss,f}$ = rate of heat loss by conduction through the floor;

The equations used to calculate the various thermal processes shown by Eq. (B.1) are developed as follows:

1) Rate of Heat Losses by Conduction

The rate of heat losses by conduction through any section of the building is given in general by the equation

$$Q_{loss} = AU (T_0 - T_i)$$

where

A = area of section involved;

U = overall heat transfer coefficient;

T_0 = exterior temperature adjacent to the section involved.

T_i = interior temperature adjacent to the section involved.

T_i in all of this work is taken as room air temperature T_R . U and T_0 take different values depending on the section of building under consideration as well as the material of the section. Analysis of the various sections of the building follow:

a) Above Grading Walls: Usually these walls form the basic walls for floors above the basement like the first floor, second floor, etc. Such walls are exposed directly to the outdoor air, and the exterior temperature for such walls is taken as the temperature of the exterior surface T_S . The rate of heat loss by conduction for these walls is then given by:

$$Q_{loss} = AU(T_S - T_R)$$

These walls are made from several materials that have different resistances to heat flow. The overall heat transfer coefficient U , is calculated from the equation

$$U = \frac{1}{\frac{1}{U_0} + \frac{1}{U_i}}$$

where U_0 and U_i are the exterior and interior heat transfer coefficients of the wall, respectively. The value of U_i is given by the equation

$$U_i = \frac{1}{\sum_i R_i}$$

where $\sum_i R_i$ is the sum of all the resistances of various components of the wall section including the

resistance between the interior wall and the room air. The value of U_0 is given by

$$U_0 = h_c + h_r$$

where

$$h_c = 32.7 + 13.68 V_w, \text{ [KJ/hr-m}^2 \text{ - } ^\circ\text{K]}$$

$$h_r = \epsilon \sigma (T_S^2 + T_A^2)(T_S + T_A). \text{ [KJ/hr-m}^2 \text{ - } ^\circ\text{K]}$$

where

$$V_w = \text{wind speed}$$

$$\epsilon = \text{emissivity}$$

$$\sigma = \text{Stefan-Boltzmann constant.}$$

T_S is exterior wall temperature, which is determined by writing energy balance equation for the wall section and solving for T_S . The energy balance equation for the wall section is given as

$$A h_c (T_A - T_S) + A h_r (T_A - T_S) + AU_i (T_R - T_S) + \alpha A H_T = 0, \quad (\text{B.2})$$

where

$$\alpha = \text{absorptivity}$$

$$H_T = \text{heat gain from solar radiation.}$$

and solving for T_S ,

$$T_S = \frac{(h_c + h_r) T_A + U_i T_R + \alpha H_T}{h_c + h_r + U_i}. \quad (\text{B.3})$$

Note that h_r appears in Eq. (B.2) and T_S appears in Eq. (B.3), which means we have to solve two simultaneous non-linear equations. An iterative procedure is used by assuming some value of T_S and solving for h_r , then computing T_S from Eq. (B.3). If the two values of T_S agree the procedure is stopped, otherwise set T_S equal to the value computed from Eq. (B.3) and proceed as outlined.

b) Basement Walls: These are usually made from concrete and are underground. The exterior temperature is taken as an average value of ground, T_G , and outdoor air, T_A , temperatures. This average temperature is assumed because no other data is available for the variation of temperature with soil depth for the location considered in this work. The equation for the rate of heat flow through basement walls is given by

$$Q_{\text{loss}} = AU \left[\frac{T_G + T_A}{2} - T_R \right]$$

where U is calculated from

$$U = \frac{1}{\sum_i R_i}$$

and $\sum_i R_i$ is the sum of the resistances of the components of the basement wall.

c) Basement Floor: Heat loss from the floor of the basement to the ground is calculated from

$$Q_{\text{loss},f} = AU (T_G - T_R)$$

where T_G is the ground temperature, and is taken here as the ground water temperature. The ground water temperature is assumed here as an estimate of the ground temperature because that is the best available estimate for this location.

d) Losses Through Ceiling: Most residential buildings have an attic on top of the building. The attic is usually used for nonliving purposes, and usually is unheated. Some attics are ventilated during the summer months taking advantage of natural cooling. If the building does not have an attic, then the heat loss is calculated from

$$Q_{\text{loss},c} = AU (T_A - T_{Rf}) \quad (\text{B.4})$$

where U is the overall heat transfer coefficient of the ceiling and T_{Rf} is the roof temperature. But if the building has an attic then the attic temperature should be used instead of the outdoor air temperature, and U is the same as above except it is necessary to adjust for the exterior convective coefficient. Thus, Eq. (B.4) becomes

$$Q_{\text{loss},c} = AU (T_{\text{ATT}} - T_{Rf})$$

An estimate of the attic temperature T_{ATT} is calculated as follows:

The roof as well as the attic walls are exposed to the outdoor air. An energy balance on the roof gives

$$A_{Rf} \alpha H_T + A_{Rf} U_3 (T_{\text{ATT}} - T_{Rf}) + A_{Rf} U_4 (T_A - T_{Rf}) = 0.$$

Solving for T_{Rf} yields

$$T_{Rf} = \frac{\alpha_{Rf} H_T + U_3 T_{\text{ATT}} + U_4 T_A}{U_3 + U_4}$$

The energy balance on the facing walls gives

$$A_w \alpha_w H_T U_5 (T_{\text{ATT}} - T_w) + A_w U_6 (T_A - T_w) = 0.$$

Solving for T_w yields

$$T_w = \frac{\alpha_w H_T U_5 + U_6 T_{\text{ATT}} + U_6 T_A}{U_5 + U_6}$$

The energy balance of the attic gives

$$A_{Rf}U_3 (T_{Rf} - T_{ATT}) + A_{W5} (T_W - T_{ATT}) + q_{inf}(T_A - T_{ATT}) = 0.$$

where

q_{inf} = the rate of infiltration in the attic

T_W = the attic wall temperatures.

Solving for T_{ATT} yields

$$T_{ATT} = \frac{A_{Rf}U_3 T_{Rf} + A_{W5} T_W + q_{inf} T_A}{A_{Rf}U_3 + A_{W5} + q_{inf}} \quad (B.5)$$

It is clear that an iterative procedure similar to the one discussed earlier is needed to determine the attic temperature. Note also that for a non-ventilated attic the value of q_{inf} is zero.

e) Losses through Windows: Losses by conduction through windows is given by the equation

$$Q_{loss} = AU (T_A - T_R) \quad (B.6)$$

The value of U for the window is calculated from

$$U = \frac{1}{\frac{N}{C \left[\frac{(T_g - T_A)}{N+f} \right]^{.33} + \frac{1}{h_w}} + \frac{\sigma(T_g^2 + T_A^2)(T_g + T_A)}{\frac{1}{\epsilon_p + .05N(1-\epsilon_p)} + \frac{2N+f-1}{\epsilon_g} - N}} \quad (B.7)$$

where

$$h_w = 5.7 + 3.8 V_w \quad (V_w \text{ is the wind speed})$$

$$f = (1 + .04 h_w + .0005 h_w^2) (1 + .91 N)$$

$$C = 365.9$$

$$N = \text{number of plates of glass in window}$$

$$\epsilon_g = \text{emissivity of the glass}$$

$$\epsilon_p = \text{emissivity of the room or drapery}$$

$$\sigma = \text{Stefan-Boltzmann constant}$$

The value of T_g , the temperature of the glass, is taken as an average value of room and outdoor air temperature, i.e.,

$$T_g = \frac{T_R + T_A}{2} \quad (B.8)$$

2) Rate of Heat Loss by Infiltration:

The rate of heat loss by infiltration includes both sensible and latent heat losses. The equation to estimate this quantity is given by

$$Q_{inf} = H_s + H_l \quad (B.9)$$

where H_s and H_l are sensible and latent heat loss respectively. The values of H_s and H_l are calculated from the equations

$$H_s = \dot{q} C_p \rho' (T_A - T_R) \quad (B.10)$$

$$H_l = \dot{q} \rho' (W_A - W_R) h_{fg} \quad (B.11)$$

where

$\dot{q}$ = volume of outdoor air entering the building;

ρ' = density of air at temperature T_A ;

C_p = specific heat of air at temperature T_A ;

W_A = humidity ratio of outdoor air;

W_R = humidity ratio of indoor air;

h_{fg} = latent heat of vapor at W_R .

The volume of air flow $\dot{q}$ into and out of a building depends on the magnitude of the pressure difference between the inside and outside of the structure and on the resistance to flow of air offered by openings in the building. The flow rate is given by the equation

$$\dot{q} = C \Delta P^n \quad (B.12)$$

where

C = proportionality constant;

n = exponent of flow, between $\frac{1}{2}$ and 1;

ΔP = pressure difference.

The pressure difference exerted on the building is caused by wind and by density differences between the inside and outside air. The effect of the difference in density is called the chimney or stack effect. Computation of these two pressure differences is obtained by the following relations:

a) Wind Forces: Air flow due to wind around and over a building creates regions in which the static pressure is either above or below the static pressure in the undisturbed air stream. In general, pressures are positive on the windward side resulting in inflow of air, and negative on the leeward side resulting in outflow of air. The magnitude of the pressure difference depends on both the magnitude of wind speed as well as on the direction from which the wind is blowing. Unfortunately it is very difficult to determine the effect of wind direction on the pressure difference due to lack of wind direction data and thus it is not considered in this work. The effect of wind speed on the pressure difference is obtained from the velocity head which is a function of wind speed and given by

$$P_v = 0.000482 V_w^2 \quad (B.13)$$

where

P_v = velocity head, (inches water gage);

V_w = wind speed, (miles per hour):

and the pressure difference due to wind is given by

$$\Delta P_w = 0.65 P_v \quad (B.14)$$

as discussed by the ASHRAE Handbook (1972).

The wind speed in Eq. (B.13) is taken as wind speed at half the height of the building. The relation between the wind speed at any height to the point where the actual measurement is taken, is given by

$$\frac{V_{h1}}{V_{h2}} = \left(\frac{h1}{h2}\right)^K \quad (B.15)$$

where

$K = .17$ for country type surroundings, and

$K = .45$ for city type surroundings.

b) Temperature Forces: When the temperature in a building or room is different from that outside, pressure differences between inside and outside occur as a result of differences in air density giving rise to the chimney or stack effect. The pressure difference due to temperature is expressed by

$$\Delta P_T = 0.52 P h' \left(\frac{1}{T_A} - \frac{1}{T_R} \right) \quad (B.16)$$

where

ΔP_T = pressure difference, (inches of water);

h' = height of building, (feet);

P = absolute pressure, (pounds per square inch).

Finally the total pressure difference ΔP appearing in Eq. (B.12) is the sum of the pressure differences due to wind and temperature, i.e.,

$$\Delta P = \Delta P_w + \Delta P_T \quad (B.17)$$

3) Rate of Solar Heat Gain by Windows:

The rate of solar heat gained through windows and absorbed by the interior of a building is a function of both the diffuse and beam solar radiation, and the heat gain is calculated from:

$$Q_{\text{gain}} = \sum_{\text{all windows}} A_{\text{window}} [(\tau\alpha)_{\text{eff},60} H_D + F_{\text{shade}} (\tau\alpha)_{\text{eff}} H_B] \quad (B.18)$$

where,

A_{window} = area of the window;

H_D = diffuse solar radiation incident on the window;

H_B = beam solar radiation incident on the window;

$(\tau\alpha)_{\text{eff},60}$ = effective transmittance-absorptance product for the window at 60 degrees angle of incidence of the diffuse solar radiation;

F_{shade} = shade factor which is the fraction of the total area of the window that is exposed to the beam radiation.

The angle for the incidence of the diffuse solar radiation is assumed to be an average of 60 degrees as suggested by Hottel and Woertz, 1942. The shade factor for each window is computed from shadow area equations developed to calculate the shadow cast over windows by overhangs and side fins as a function of the sun location and the window orientation. Development of the shadow area equations is discussed in detail by Tseng-Yao, 1968.

The beam and diffuse solar radiation incident on a surface depends on the surface orientation as well as on the time of day and day of the year. The value of H_B and H_D is calculated from the measured total solar radiation, H , on a horizontal surface following the work of Liu and Jordan, 1960. The two values are expressed by:

$$H_B = H_b R_b \quad (B.19)$$

$$H_D = H_d R_d + H R_r \quad (B.20)$$

where H_b and H_d are the beam and diffuse radiation on a horizontal surface respectively, and are calculated by:

$$H_d = H [1.0045 + 2.6313 K_t^3 - 3.522 K_t^2 + 0.04349 K_t] \quad (B.21)$$

$$H_b = H - H_d \quad (B.22)$$

where

$$K_t = \frac{H}{H_0} \quad (B.23)$$

and

$$H_0 = [1 + 0.033 \cos (360n'/365)] S_c \cos (\theta_z) \quad (B.24)$$

S_c is the solar constant, and n' is the day number of the year. The values of R_b , R_d , and R_r are expressed as

$$R_b = \cos (\theta_z) / \cos (\theta_t) \quad (B.25)$$

$$R_d = (1 + \cos(s))/2 \quad (B.26)$$

$$R_r = \rho_g (1 - \cos(s))/2 \quad (B.27)$$

where θ_t is the incidence angle of the solar radiation of the surface and θ_z is the special case of θ_t when the surface is vertical, i.e., south facing wall. s is the slope of the wall and is equal to 90° . ρ_g is the ground reflectivity and equal to 0.2 for the no snow condition and 0.7 for the snow condition.

4) Rate of Heat Gain from Occupants:

The rate of heat gain from occupants of a building is calculated using the ASHRAE Handbook (1972) approach. Heat released per occupant of a residence is assumed to be 237 KJ/hr (225 BTU/hr) of sensible heat. Then the total heat released by all the occupants is expressed as

$$Q_{occ} = 237 \times \text{number of occupants (KJ/hr)}. \text{ (B.28)}$$

5) Rate of Heat Gain from Lights and Appliances:

Heat gain from lights and appliances can be calculated from the rate of heat released by these appliances during the time they are in use. The rate of heat released by different appliances is given by the ASHRAE Handbook, 1972.

APPENDIX C

EVIDENCE OF AN URBAN HEAT ISLAND IN GREELEY, COLORADO

The urban heat island is defined as the area where observed temperatures, usually found in densely populated cities, exceed those in their immediate surroundings. This phenomenon of urban heat islands is most pronounced during nights with clear skies and calm wind conditions. Several methods have been employed to investigate the urban heat island. In Montreal, Oke and Maxwell (1975) have observed heat islands of over 10°C. Hutcheon et al., (1967) and Duckworth and Sandberg (1954) have documented that small cities with populations of 50,000 to 100,000 also contain heat islands of several degrees centigrade. Landsberg (1975) investigated the heat island effect by interpreting long-term meteorological records. He noticed an increase of several degrees centigrade in the temperature difference between the city of Colombia, Maryland, and its surroundings as the city's population increased 100-fold.

There are several physical differences between cities and rural areas that cause the development of the urban heat island. Urban surfaces are normally rougher than rural surfaces and are composed of materials of higher thermal capacities. The large quantity of anthropogenic heat sources found in cities can increase urban temperatures.

C.1 CLIMATOLOGICAL BASE

Greeley, Colorado, is situated on the high plains 34 km east of the front range of the Rocky Mountains. The average annual precipitation is 31 centimeters. In winter, the driest season, the weather is dominated by continental anticyclones. The average winter season maximum and minimum temperatures are 7.0°C and -10°C, respectively. The diurnal and seasonal temperature ranges are large, characteristic of interior continental regions.

The 1976-77 winter season in Greeley was warmer and drier than the climatological average (see Table C.1). The average diurnal temperature range in Greeley (during the four months shown) was nearly 18°C, from 10.1°C to -7.8°C. The average temperature for the four months was 2.6°C above the normal. The meteorological data from Stations #1 through #6 are investigated in this appendix. Wind measurements from the Tower, #7, are used as a reference for the free stream flow. Fig. C.1 shows the mean Greeley temperature averaged from the six station's temperature values for the entire 81-day period. The minimum daily temperature for the period was -14°C and occurred on January 8. As shown in Table C.1, the 1.75cm of precipitation recorded during the four months was only 40 percent of the climatic average. The daily precipitation in Greeley is shown in Fig. C.2 along with the daily insolation.

The surface temperatures and wind speeds and directions, measured at the six locations described in Section 3.2, allowed a detailed investigation of the local heat island. Temperature data of four different weather classes are investigated to determine the nature and variability of Greeley's heat island under the different conditions. The data are divided into the four combinations of high/low winds, and clear/cloudy skies listed in Table C.2. Periods of high winds are defined to be those in which the Tower

TABLE C.1

National Climatic Center Climatological Data for Greeley, Colorado 1976-77

Month	Average Maximum Temperature (°C)	Average Minimum Temperature (°C)	Average Temperature (°C)	Departure from Normal (°C)
December	9.9	-8.5	0.7	2.9
January	5.2	-11.9	-3.3	0.8
February	11.7	-5.6	3.1	4.4
March	13.7	-4.9	4.4	2.4
Average	10.1	-7.8	1.2	2.6

Month	Snow Sleet (cm)	Total Precipitation (cm)	Departure from Normal (cm)
December	3.6	0.30	-0.41
January	4.1	0.33	-0.56
February	T	T	-0.76
March	10.9	1.12	-0.79
Total	18.6	1.75	-2.52

station wind speed was in excess of 2 ms⁻¹, whereas low wind periods consist of data less than and equal to 2 ms⁻¹. Since no cloud cover data are gathered in Greeley, the clear/cloudy criteria are based on the examination of temperature and insolation profiles and cloud cover data obtained from the National Weather Service for Fort Collins, Colorado, 40km northwest of Greeley. If the clear/cloudy classification could not readily be determined from these criteria, the period in question was not assigned to a class.

C.2 GREELEY WINDS

The urban character of Greeley has a pronounced complex effect on the local winds, (Woo et al., 1976) as a result of the wind interacting with buildings. In general, vortex circulations can be formed. The rough surfaces of cities produce a frictional drag on the air that reduces wind speeds but increases turbulence. Local convective motions also result from thermal gradients due to the different heat capacities of buildings and the ground. In addition to urban surfaces and temperature gradients, topography and mesoscale weather patterns effect both the wind speed and direction.

Fig. C.1 Daily average temperature of Greeley for the 81-day period.

Fig. C.2 Daily average insolation of Greeley for the 81-day period.

TABLE C.2

Weather Classifications

Class	Description
1	Clear skies and high wind speeds
2	Clear skies and low wind speeds
3	Cloudy skies and low wind speeds
4	Cloudy skies and high wind speeds

Figure C.3 shows the hourly average wind speeds measured at each station for the entire 81-day period. Stations 1, 2, and 3 (Putnam, Winograd, and Moot House, respectively) all at low elevations have lighter winds than those stations located at higher elevations. Convective mixing during the day is responsible for the observed afternoon maximum. Figs. C.4a and C.4b show the daytime and nighttime wind roses, respectively, by wind speed class for the Tower station. The strong northwesterly wind direction is associated with frontal passages. The nighttime southwesterly wind direction indicates down-valley winds, whereas the daytime southeasterly flow indicates up-valley winds through the Cache La Poudre River Valley. Fig. C.5 illustrates this valley wind system as it is observed at Station 1, Putnam, located in the Cache La Poudre River Valley as can be seen in Fig. 3.4. The Putnam station lies in a section of the valley which has a east-west orientation. Westerly, down-valley flow can be observed at night, whereas the easterly up-valley flow during daytime is less frequently observed.

Chandler (1965) and Bornstein et al. (1972) demonstrated for London and New York, respectively, that the rural near-surface wind speeds are greater than the urban wind speeds under strong wind conditions, and that the opposite relationship holds true under light wind conditions. The critical point at which the urban-rural wind speed differences reversed was found by Chandler (1965) to equal $3-5 \text{ ms}^{-1}$, and by Bornstein et al. (1972) to be 4 ms^{-1} . The urban-induced acceleration of wind is thought to be caused by increased horizontal pressure gradients, a consequence of the urban heat island. Thus, with light wind conditions, the heat island effect more than compensates for the urban surface friction effect.

Urban-rural wind speed relationships are studied in Greeley by comparing the near-surface observations at Stations 4 and 5, Hospital and High School, respectively. The graph in Fig. C.6 shows the percentage of observations when the wind speed at Station 4 (urban) is less than, equal to and greater than the wind speed at Station 5 (rural). The wind speed at the tower station, the abscissa of the graph, is used to clarify the differences between the high and low wind speed periods in Greeley. When the winds are strong, the wind speed $U(5)$ is nearly always greater than the wind speed $U(4)$. When the tower station wind speeds are low, it is more common for the urban station (4) to be equal to or greater than the wind speed at the rural station (5). We can infer that the presence of greater frictional drag dominates the effects of the heat island at higher wind speeds. The critical point where the two plots, $U(5) > U(4)$ and $U(5) < U(4)$, cross lies between the tower wind speed of $2-3 \text{ ms}^{-1}$.

Fig. C.3 Average hourly wind speeds of the 6 stations for the 81-day period.

Fig. C.4a Percent frequency of wind direction by wind speed class for the tower station during the 81-days for daytime.

Fig. C.4b Same as Fig. C.4a except for nighttime.

Fig. C.5 Percent frequency of wind direction for day (thick line) and night (thin line) at Station 1 for the 81-day period.

Fig. C.6 Percent of observations when the wind speed at Station 5 is greater than (solid), less than (dots), and equal to (dash-dot) the wind speed at Station 4.

This speed is slightly less than the values found by Chandler (1965) and Bornstein (1968). However, this result is not inconsistent with their values since the magnitude of the heat island in Greeley is smaller than that observed in either London or New York.

C.3 GREELEY TEMPERATURES

In order to investigate the Greeley heat island effect, temperature differences between stations are calculated for each of the four weather classes, as shown in Table C.2. Temperature differences for several pairs of stations are shown in Fig. C.7a-f as a function of the time of day. Stations 1, 5, and 6, Putnam, High School, and Mobile Home, are located outside the city limits and are defined as rural stations. Stations 2, 3, and 4, Winograd, Moot House, and Hospital, are within the city limits and are defined as urban stations.

Fig. C.7a illustrates the temperature differences between rural Stations 5 and 6. The temperature differences are generally less than 1°C and Station 5 is nearly always warmer than Station 6. It is reasonable to assume that the topographical differences (Mobile Home - 1448 m; High School - 1472 m) contribute to the temperature pattern.

Fig. C.7b-f illustrate temperature differences between urban and rural sites. The most pronounced temperature differences are visible in Fig. C.7b, in which the temperature of Station 1 (rural) is subtracted from Station 4 (urban); (ΔT_{4-1}). The positive temperature difference observed between 1700 and 0900

M.S.T. in all four weather classes is believed to be caused by the local heat island. The largest values of ΔT_{4-1} occur between 2100 and 2300 M.S.T., although the variations of ΔT_{4-1} throughout the night are small. During the day, ΔT_{4-1} is negative, indicating

that the city is cooler than the rural area. The temperature differences between Stations 2 (urban) and 1 (rural) (both located in the river valley at the same terrain elevation) are plotted in Fig. C.7c. This figure contains, therefore, the most convincing evidence that a local heat island does indeed exist in Greeley. Again, positive temperature differences are present between 1700 and 0900 M.S.T. and largest in the early hours of the night. ΔT_{2-1} is negative

during the daytime hours for classes 2 and 3. The urban temperatures begin to exceed the rural temperatures just before sunset, and the temperature differences between urban and rural areas become largest within a few hours after sunset. Thereafter, they decrease gradually throughout the night. These figures clearly indicate that during calm and clear conditions (class 2) a positive temperature difference between our urban and rural stations is a dominant characteristic of all the curves during night. Theoretically, the urban heat island is best developed during calm and clear conditions, which is consistent with our results. These positive nocturnal temperature differences are then thought to be indicative of a local urban heat island in Greeley.

Differences between the urban and rural net infrared radiations contribute to the urban heat island effect (Fuggle and Oke, 1970) and are largest

Fig. C.7a Temperature differences between Stations 5 and 6 by weather classes for the 81-day period.

Fig. C.7b Temperature differences between Stations 4 and 1 by weather classes for the 81-day period.

Fig. C.7c Temperature differences between Stations 2 and 1 by weather classes for the 81-day period.

Fig. C.7d Temperature differences between Stations 3 and 6 by weather classes for the 81-day period.

Fig. C.7e Temperature differences between Stations 4 and 5 by weather classes for the 81-day period.

Fig. C.7f Temperature differences between Stations 4 and 6 by weather classes for the 81-day period.

on clear nights. As seen in Fig. C.7b, under clear skies at night ΔT_{4-1} is approximately 1°C greater than that observed under cloudy skies.

In Fig C.7b, under the conditions of high wind, class 1 (4), temperature differences between urban and rural areas are less than those observed under low wind conditions, class 2 (3), because the heat losses due to advective and turbulent transports from the urban area are greater under high wind conditions. The magnitude of ΔT_{4-1} for the low wind cases exceed the high wind cases within the same cloudiness class by approximately 0.5°C .

That the heat island effect is most clearly defined in classes 1 and 2 is also evident from maps constructed from the mean temperatures at each station for the four weather classifications. These maps along with one drawn from the average temperatures for the entire 81-day period are presented in Fig. C.8a-e.

From Fig. C.7b-f, it can be seen that daytime negative temperature differences are most pronounced under clear sky conditions. Figs. C.7d, e and f illustrate that these differences for class 1 days are greatest at 0900 M.S.T., approximately two hours after sunrise. However, in Fig. C.7b and c the maximum differences occur at 1300 M.S.T. This delay may be a consequence of the large magnitude of the nocturnal heat island, which is best developed in these two figures. Two possible explanations for the existence of these daytime negative temperature differences are topography and thermal diffusivity differences between the stations. It can be shown that the terrain elevations of the urban stations (with the exception of Winograd, #2) are all higher than those of the rural stations. The possibility exists that the negative temperature differences are caused by a greater mixing with cooler air at the higher stations (urban) while the lower stations (rural) are allowed to heat more rapidly and are exposed to a lesser amount of mixing with cool air.

It has been noted that there is a difference between the thermal conductivity in urban and rural surfaces. The higher conductivity (and therefore absorptivity) of the urban surfaces limits the amount of solar radiation which can be realized into sensible heat in the atmosphere; while the lower conductivity of the rural surfaces allows greater realization of sensible heat. These differences in conductivity would then contribute to the daytime negative temperature differences shown in Fig. C.7b-f.

To obtain an estimate of the production of anthropogenic heat, a derived relationship between the daily natural gas consumption and the average daily temperature in Greeley is used. According to Reiter et al., (1976), the average daily consumption of energy for Greeley can be approximated by

$$B = ((65 - \bar{T}) \cdot 4153 + 199479) \cdot 0.0122 \quad (C.1)$$

where B is the average daily consumption of energy (watts/capita), and $\bar{T}$ is the average daily temperature ($^{\circ}\text{F}$). For the 81-day period, the average daily temperature is 34.2°F . Therefore, B is 3994 watts/capita. The average population density of Greeley is $0.00118 \text{ persons/m}^2$, thus the average energy consumption from space heating is 4.7 watts/m^2 . According to Schewe (1975) the temperature inversion height during the night in the winter season is approximately 100m in this region. If all of the energy from the burning of natural gas in the city is converted to sensible heat and then stored in the lowest 100m of the atmosphere, the temperature of the layer would increase 1.8°C . Although the assumption that all of the natural gas used in Greeley for one day would stay in a box located over the city is probably not valid; there are many times during the night in winter when the wind speed was zero and an inversion was present. Under these atmospheric conditions it would seem acceptable to use such a box model in conjunction with some type of diffusion model to determine the effect of anthropogenic heat generation on the urban heat island. This type of model is presently in the development stage by our research group and results should be forthcoming within the next research period.

Fig. C.8a-e Map of Greeley showing the average observed temperature patterns during:
a) total 81-day period; b) weather class 1; c) weather class 2; d) weather class 3; e) weather class 4.

APPENDIX D

DATA USED IN AIR-SEA INTERACTION STUDIES

TABLE D.1a. Pacific sea surface temperatures, monthly mean values, °C, averaged from gridded data over the longitudinal extent of the Pacific and between 20°N and 30°N. (Original data, courtesy of Fleet Numerical Weather Central, Monterey, California.)

	1	2	3	4	5	6	7	8	9	10	11	12
1962			21.16	21.91	22.98	24.25	25.70	26.54	26.44	25.51	24.49	23.06
1963	21.57	20.92	20.95	21.66	23.09	24.54	25.52	26.19	26.73	26.01	24.82	23.73
1964	22.27	21.49	21.36	21.93	22.81	24.29	25.62	26.05	26.28	25.74	24.63	23.32
1965	21.89	21.35	21.25	21.51	22.76	(24.50)	(26.02)	26.69	26.61	25.62	24.70	23.32
1966	21.97	21.43	21.64	22.18	23.14	24.69	26.00	26.48	26.48	25.95	24.69	23.40
1967	22.25	21.60	21.59	22.05	23.23	24.63	25.85	26.47	26.88	26.25	25.17	23.35
1968	21.97	21.29	21.02	21.84	23.06	24.95	26.24	26.54	26.74	26.09	25.06	23.48
1969	22.19	21.77	21.56	22.18	23.44	24.67	25.71	26.21	26.40	25.89	24.58	23.25
1970	22.06	21.49	21.47	22.16	22.91	24.42	25.65	26.23	26.21	25.84	24.71	23.18
1971	21.84	21.26	21.19	22.01	22.10	24.03	25.92	26.43	26.44	25.81	24.54	23.05
1972	21.79	21.18	21.09	21.51	23.05	24.47	25.47	26.22	26.43	25.65	24.55	23.25
1973	22.13	21.59	21.64	22.38	23.31	24.54	25.66	26.29	26.44	25.93	24.79	23.35
1974	22.17	21.55	21.47	22.13	23.16	24.62	25.60	26.24	26.50	26.04	24.97	23.77
1975	22.26	21.51	21.57	21.98	23.04	24.60	25.74	25.94	26.23	25.78	24.57	23.24
1976	21.96	21.40	21.60	22.04	23.13	24.32	25.26	26.22	26.38	25.96	24.91	23.65
1977	22.35											
Σ	330.67	299.83	320.56	329.47	346.30	368.32	385.96	394.74	397.19	388.07	371.18	350.40
Mean	22.04	21.42	21.37	21.96	23.09	24.55	25.73	26.32	26.48	25.87	24.75	23.36
σ	.21	.20	.23	.24	.17	.19	.24	.20	.18	.19	.20	.21

TABLE D.1b. Departures of the values shown in Table 1a (20-30°N) from the long-term monthly mean values.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			-.21	-.05	-.11	-.30	-.03	.22	-.04	-.36	-.26	-.30
1963	-.47	-.50	-.42	-.30	-.00	-.01	-.21	-.13	.25	.14	.07	.37
1964	.23	.07	-.01	-.03	-.28	-.26	-.11	-.27	-.20	-.13	-.12	-.04
1965	-.15	-.07	-.12	-.45	-.33	-.05	.29	.37	.13	-.25	-.05	-.04
1966	-.07	.01	.27	.22	.05	.14	.27	.16	.00	.08	-.06	.04
1967	.21	.18	.22	.09	.14	.08	.12	.15	.40	.38	.42	-.01
1968	-.07	-.13	-.35	-.12	-.03	.40	.51	.22	.26	.22	.31	.12
1969	.15	.35	.19	.22	.35	.12	-.02	-.11	-.08	.02	-.17	-.11
1970	.02	.07	.10	.20	-.18	-.13	-.08	-.09	-.27	-.03	-.04	-.18
1971	-.20	-.16	-.18	.05	.10	.28	.19	.11	-.04	-.06	-.21	-.31
1972	-.25	-.24	-.28	-.45	-.04	-.08	-.26	-.10	-.05	-.22	-.20	.11
1973	.09	.17	.27	.42	.22	-.01	-.07	-.03	-.04	.06	.04	-.01
1974	.13	.13	.10	.17	.07	.07	-.13	-.08	.02	.17	.22	.41
1975	.22	.09	.20	.02	-.05	.05	.01	-.38	-.25	-.09	-.18	-.12
1976	-.08	-.02	.23	.08	.04	-.23	-.47	-.10	-.10	.09	.16	.29
1977	.31											

TABLE D.1c. Data of Table D.1b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1962						-.07	-.10	-.13	-.15	-.18	-.24	-.34
1963	-.37	-.32	-.29	-.27	-.22	-.12	-.04	.02	.07	.10	.14	.16
1964	.12	.06	.01	-.06	-.13	-.17	-.18	-.20	-.16	-.15	-.14	-.12
1965	-.15	-.18	-.17	-.13	-.05	-.02	-.04	.02	.06	.05	.01	.00
1966	.01	.06	.08	.13	.16	.16	.13	.09	.09	.10	.09	.10
1967	.11	.12	.14	.15	.14	.17	.19	.24	.22	.20	.16	.09
1968	.02	-.04	-.04	.03	.07	.13	.21	.27	.29	.26	.23	.23
1969	.22	.24	.21	.19	.16	.10	.07	.02	-.05	-.06	-.05	-.02
1970	.02	-.01	.00	.00	-.02	-.06	-.08	-.12	-.12	-.13	-.14	-.15
1971	-.11	-.09	-.04	.01	.06	.07	.09	.05	-.01	-.08	-.14	-.20
1972	-.26	-.25	-.24	-.23	-.21	-.18	-.17	-.14	-.15	-.12	-.06	-.01
1973	.06	.12	.15	.16	.14	.11	.08	.02	-.01	.01	.04	.06
1974	.09	.09	.09	.08	.05	.03	.04	.05	.10	.12	.15	.19
1975	.19	.16	.13	.08	-.01	-.06	-.10	-.13	-.14	-.16	-.16	-.07
1976	-.03	-.01	-.01	-.06	-.07	-.08	-.10	-.09	-.05	.03		

TABLE D.2a. Similar to Table D.1a, except Pacific SST's in latitude band 30-40°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			15.08	15.61	16.65	19.02	21.24	23.84	23.62	21.85	19.42	17.47
1963	15.72	14.88	14.75	15.18	17.05	19.31	21.76	23.45	23.41	21.72	19.57	17.69
1964	15.83	14.92	15.03	15.67	16.87	18.52	21.63	23.57	23.37	21.73	19.66	17.74
1965	16.30	15.23	14.99	15.30	16.48	(18.27)	(21.50)	23.56	22.97	21.23	19.28	17.44
1966	15.95	14.96	14.97	15.27	16.73	18.55	21.33	23.05	23.28	21.87	19.74	17.71
1967	16.19	15.45	15.34	15.56	16.95	18.79	21.58	23.86	24.21	22.31	20.09	17.98
1968	16.16	15.24	14.71	15.27	16.64	18.68	21.19	23.60	23.45	21.57	19.44	17.38
1969	16.05	15.42	15.00	15.57	16.80	18.44	21.26	22.86	23.13	21.24	19.00	17.12
1970	15.57	14.64	14.39	15.21	16.62	18.56	21.49	23.70	23.50	21.79	19.64	17.66
1971	16.17	15.22	14.99	15.64	16.81	19.09	22.05	23.70	23.44	21.68	19.67	17.76
1972	16.26	15.48	15.30	15.65	17.16	18.93	21.60	23.34	23.17	21.48	19.54	17.55
1973	16.07	15.28	15.13	15.69	17.10	19.01	21.53	23.35	23.47	21.72	19.66	17.68
1974	16.11	15.31	15.01	15.44	16.70	18.72	21.25	23.21	23.30	21.61	19.40	17.63
1975	16.16	15.35	15.16	15.69	17.08	18.85	21.54	23.39	23.09	21.64	19.54	17.71
1976	16.12	15.35	15.37	15.70	16.87	18.87	21.26	22.95	23.08	21.32	19.40	17.54
1977	15.67											
$\bar{x}$	240.33	212.73	225.22	232.45	252.51	281.61	322.21	351.44	350.49	324.76	293.05	264.06
Mean	16.02	15.20	15.01	15.50	16.83	18.77	21.48	23.43	23.37	21.65	19.54	17.60
σ	.22	.24	.25	.19	.20	.27	.23	.30	.29	.26	.22	.19

TABLE D.2b. Similar to Table D.1b, except monthly SST anomalies, 30-40°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			.07	.11	-.18	.25	-.24	.41	.25	.20	-.12	-.13
1963	-.30	-.32	-.26	-.32	.22	.54	.28	.03	.04	.07	.03	.09
1964	-.19	-.28	.02	.17	.04	-.25	.15	.14	.00	.08	.12	.14
1965	.28	.03	-.02	-.20	-.35	-.50	.02	.13	-.40	-.42	-.26	-.16
1966	-.07	-.24	-.04	-.23	-.10	-.22	-.15	-.38	-.09	.22	.20	.11
1967	.17	.25	.33	.06	.12	.02	.10	.43	.84	.66	.55	.38
1968	.14	.04	-.30	-.23	-.19	-.09	-.29	.17	.08	-.08	-.10	-.22
1969	.03	.22	-.01	.07	-.03	-.33	-.22	-.57	-.24	-.41	-.54	-.48
1970	-.45	-.56	-.62	-.29	-.21	-.21	.01	.27	.13	.14	.10	.06
1971	.15	.02	-.02	.14	-.02	.32	.57	.27	.07	.03	.13	.16
1972	.24	.28	.29	.15	.33	.16	.12	-.09	-.20	-.17	.00	-.05
1973	.05	.08	.12	.19	.27	.24	.05	-.08	.10	.07	.12	.08
1974	.09	.11	.00	-.06	-.13	-.05	-.23	-.22	-.07	-.04	-.14	.03
1975	.14	.15	.15	.19	.25	.08	.06	-.04	-.28	-.01	.00	.11
1976	.10	.15	.36	.20	.04	.10	-.22	-.48	-.29	-.33	-.14	-.06
1977	-.35											

TABLE D.2c. Similar to Table D.1c, except 7-month smoothed SST anomalies, 30-40°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962						.10	.11	.08	.09	.01	.00	-.10
1963	-.18	-.18	-.08	-.02	.02	.08	.12	.17	.15	.05	-.03	-.03
1964	-.01	-.02	-.06	-.05	.00	.04	.05	.04	.05	.13	.11	.09
1965	.06	.00	-.09	-.11	-.13	-.19	-.25	-.25	-.23	-.17	-.20	-.23
1966	-.20	-.16	-.15	-.15	-.19	-.17	-.14	-.07	-.04	.01	.07	.17
1967	.19	.18	.15	.15	.19	.27	.32	.39	.43	.44	.43	.33
1968	.18	.06	-.04	-.13	-.13	-.12	-.09	-.07	-.08	-.06	.01	-.01
1969	-.01	-.01	-.04	-.04	-.12	-.19	-.25	-.33	-.40	-.42	-.46	-.47
1970	-.48	-.45	-.40	-.33	-.23	-.13	-.02	.03	.07	.12	.12	.08
1971	.08	.06	.09	.17	.18	.19	.20	.20	.22	.21	.17	.17
1972	.18	.23	.23	.22	.18	.11	.04	.02	-.03	-.05	-.05	-.02
1973	.03	.09	.13	.14	.12	.13	.12	.11	.08	.06	.07	.08
1974	.06	.03	.01	-.04	-.08	-.11	-.11	-.13	-.10	-.08	-.02	.03
1975	-.07	-.11	-.14	-.15	-.12	-.06	.04	.01	-.01	-.01	.00	.06
1976	.13	.14	.15	.10	.02	-.04	-.14	-.19	-.20	-.27		

TABLE D.3a. Similar to Table D.1a, except Pacific SST's in latitude band 40-50°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			7.33	7.91	8.68	11.06	13.78	16.25	16.20	13.59	10.80	9.05
1963	8.32	8.07	8.01	8.06	10.19	10.82	14.13	16.97	15.86	13.53	10.77	9.28
1964	7.72	8.22	6.82	6.95	8.63	10.32	12.64	15.36	15.24	13.00	11.09	9.41
1965	8.05	7.34	7.33	7.60	8.23	(10.20)	(12.75)	15.63	15.40	13.53	11.13	9.04
1966	7.92	7.02	6.84	7.15	8.15	10.07	12.39	15.34	15.24	13.52	11.40	9.45
1967	7.88	7.32	7.08	7.26	8.75	11.03	14.09	17.10	16.05	13.36	10.89	8.99
1968	7.95	7.58	7.32	7.52	8.86	10.70	12.79	15.29	15.02	13.41	11.01	9.06
1969	8.06	7.23	6.79	7.00	7.94	9.65	12.64	15.83	15.76	12.80	10.73	8.68
1970	7.33	6.91	6.68	6.98	8.15	9.78	12.33	15.31	15.66	14.01	11.65	9.59
1971	8.11	7.71	7.24	7.35	8.02	9.84	13.04	15.28	14.58	12.98	11.02	9.21
1972	7.70	7.29	7.19	7.52	8.61	10.39	12.78	15.50	15.72	13.88	11.05	9.29
1973	7.83	7.19	6.94	7.08	8.09	9.65	12.23	15.17	14.98	13.24	10.92	8.83
1974	7.80	7.36	6.94	7.27	8.06	9.68	12.48	15.11	15.46	13.53	10.54	8.70
1975	7.62	6.92	6.63	7.03	8.00	9.71	12.51	15.05	15.47	13.37	10.52	8.94
1976	7.58	7.02	6.69	6.72	7.60	9.69	11.85	13.78	14.16	12.35	10.23	8.59
1977	7.36											
$\bar{x}$	117.23	103.16	105.83	109.40	125.96	152.59	192.43	232.97	220.80	200.10	163.75	136.11
Mean	7.82	7.07	7.06	7.29	8.40	10.17	12.83	15.53	15.39	13.34	10.92	9.07
σ	.26	.39	.35	.36	.60	.50	.65	.77	.53	.41	.34	.29

TABLE D.3b. Similar to Table D.1b, except monthly SST anomalies, 40-50°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			.27	.62	.28	.89	.95	.72	.81	.25	-.12	-.02
1963	.50	.70	.95	.77	1.79	.65	1.30	1.44	.47	.19	-.15	.21
1964	-.10	.85	-.24	-.34	.23	.15	-.19	-.17	-.15	-.34	.17	.34
1965	.23	-.03	.27	.31	-.17	.03	-.08	.10	.01	.19	.21	-.03
1966	.10	-.35	-.22	-.14	-.25	-.10	-.44	-.19	-.15	.18	.48	.38
1967	.06	-.05	.02	-.03	.35	.86	1.26	1.57	.66	.02	-.03	-.08
1968	.13	.19	.26	.23	.46	.53	-.04	-.24	-.37	.07	.09	-.01
1969	.24	-.14	-.27	-.29	-.46	-.52	-.19	.30	.37	-.54	-.19	-.39
1970	-.49	-.46	-.38	-.31	-.25	-.39	-.50	-.22	.27	.67	.73	.52
1971	.29	.34	.18	.06	-.38	-.33	.21	-.25	-.61	-.36	.10	.14
1972	-.12	-.08	.13	.23	.21	.22	-.05	-.03	.33	.54	.13	.22
1973	.01	-.18	-.12	-.21	-.31	-.52	-.60	-.36	-.41	-.10	.00	-.24
1974	-.02	-.01	-.12	-.02	-.34	-.49	-.35	-.42	.07	.19	-.38	-.37
1975	-.20	-.45	-.43	-.26	-.40	-.46	-.32	-.48	.08	.03	-.40	-.13
1976	-.24	-.35	-.37	-.57	-.80	-.48	-.98	-1.75	-1.23	-.99	-.69	-.48
1977	-.46											

TABLE D.3c. Similar to Table D.1c, except 7-month smoothed SST anomalies, 40-50°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962						.65	.65	.54	.50	.44	.41	.44
1963	.43	.65	.76	.95	1.09	1.05	.94	.81	.59	.48	.42	.18
1964	.06	.07	.11	.05	.04	-.10	-.12	-.04	-.03	-.02	.01	.07
1965	.14	.16	.14	.08	.06	.07	.06	.04	.06	.07	.03	-.01
1966	-.03	-.10	-.14	-.20	-.24	-.21	-.16	-.07	.02	.05	.10	.13
1967	.15	.17	.23	.35	.57	.67	.67	.67	.61	.50	.35	.16
1968	.10	.17	.25	.25	.20	.12	.09	.07	.00	-.04	-.05	-.06
1969	-.04	-.12	-.21	-.23	-.22	-.15	-.19	-.18	-.17	-.16	-.20	-.30
1970	-.39	-.35	-.38	-.40	-.36	-.25	-.10	.04	.15	.25	.37	.43
1971	.40	.25	.10	.05	-.02	-.19	-.27	-.26	-.19	-.16	-.20	-.14
1972	.01	.09	.10	.08	.09	.15	.21	.19	.19	.16	.15	.13
1973	.06	.07	.16	.28	.33	.36	.36	.33	.32	.25	.16	.13
1974	-.07	-.11	-.18	-.19	-.25	-.24	-.19	-.75	-.26	-.21	-.22	-.22
1975	-.27	-.36	-.37	-.36	-.40	-.32	-.26	-.28	-.24	-.21	-.21	-.20
1976	-.29	-.41	-.42	-.54	-.76	-.88	-.97	-.99	-.94	-.94		

TABLE D.4a. Similar to Table D.1a, except Pacific SST's in latitude band 50-60°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			3.23	3.98	4.92	7.03	9.27	10.87	10.45	7.58	5.77	4.32
1963	3.83	3.63	4.01	3.76	5.19	6.61	8.93	10.48	10.63	8.75	6.04	4.77
1964	4.14	4.14	3.80	3.55	4.30	6.93	8.83	10.25	9.89	8.13	6.22	5.04
1965	4.16	3.40	3.95	4.06	4.72	(7.35)	(9.28)	10.75	11.14	9.08	7.10	5.40
1966	4.51	4.02	3.56	3.62	4.41	6.62	8.86	10.72	10.51	8.58	6.43	5.37
1967	4.32	3.86	3.31	3.79	5.29	7.47	10.15	12.07	11.10	8.93	6.71	4.74
1968	4.00	3.56	3.44	3.60	4.92	7.25	9.54	10.94	10.49	8.19	6.16	4.73
1969	3.93	3.36	2.95	3.41	4.38	6.71	9.69	11.63	11.08	9.26	6.89	5.22
1970	4.37	3.68	3.80	3.94	4.82	6.69	8.75	10.13	10.44	9.17	7.03	5.52
1971	4.23	3.39	3.11	3.21	4.10	5.62	8.19	10.20	9.50	8.02	6.15	4.76
1972	3.81	3.10	2.79	3.18	4.12	5.85	8.70	10.88	10.42	8.39	6.37	4.94
1973	3.87	3.29	3.19	3.42	4.11	6.12	8.72	10.31	10.02	8.25	6.31	4.85
1974	4.04	3.39	2.99	3.26	4.42	6.71	9.39	11.26	11.24	8.99	6.32	4.76
1975	3.40	2.95	2.33	2.58	3.57	5.78	8.37	10.38	10.39	8.38	5.93	4.37
1976	3.67	3.03	2.73	2.90	3.96	6.07	8.70	10.46	9.72	8.13	6.00	4.98
1977	3.93											
$\bar{x}$	60.21	48.80	49.19	52.26	67.23	98.81	135.37	161.33	157.03	127.83	95.43	73.77
Mean	4.01	3.49	3.28	3.48	4.48	6.59	9.02	10.76	10.47	8.52	6.36	4.92
σ	.28	.34	.47	.40	.47	.56	.50	.63	.51	.48	.39	.34

TABLE D.4b. Similar to Table D.1b, except monthly SST anomalies, 50-60°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962						.24	.11	-.04	-.19	-.28	-.30	-.21
1963	-.17	.07	.16	.23	.22	.22	.15	.06	-.06	-.05	.06	.17
1964	.16	.10	.20	.19	.10	-.08	-.21	-.24	-.19	-.22	-.21	-.04
1965	.13	.22	.35	.37	.34	.45	.44	.46	.49	.46	.50	.54
1966	.46	.37	.27	.18	.10	.03	.00	-.01	.06	.10	.18	.19
1967	.23	.34	.45	.55	.69	.73	.78	.79	.65	.52	.37	.20
1968	.13	.14	.18	.28	.31	.30	.23	.18	.09	-.01	-.10	-.18
1969	-.19	-.16	-.11	.01	.15	.25	.41	.49	.55	.58	.51	.46
1970	.44	.39	.32	.24	.10	.07	.09	.12	.16	.17	.20	.26
1971	.23	.08	-.15	-.36	-.47	-.59	-.64	-.63	-.60	-.49	-.43	-.42
1972	-.32	-.30	-.38	-.40	-.35	-.31	-.25	-.21	-.16	-.07	-.05	-.08
1973	-.08	-.12	-.19	-.23	-.28	-.31	-.34	-.34	-.29	-.22	-.19	-.17
1974	-.14	-.11	-.08	-.02	.05	.17	.28	.30	.29	.19	.06	-.15
1975	-.39	-.59	-.70	-.77	-.73	-.67	-.55	-.49	-.43	-.37	-.34	-.36
1976	-.44	-.49	-.50	-.47	-.46	-.51	-.48	-.45	-.37	-.31		

TABLE D.4c. Similar to Table D.1c, except 7-month smoothed SST anomalies, 50-60°N.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			-.05	.50	.44	.44	.25	.11	-.01	-.94	-.59	-.60
1963	-.18	.14	.73	.28	.71	.02	-.09	-.28	.16	.23	-.32	-.15
1964	.13	.65	.52	.07	-.18	.34	-.19	-.51	-.58	-.39	-.14	.12
1965	.15	-.09	.67	.58	.24	.76	.26	-.01	.67	.56	.74	.48
1966	.50	.53	.28	.14	-.07	.03	-.16	-.04	.04	.06	.07	.45
1967	.31	.37	.03	.31	.81	.88	1.13	1.31	.63	.41	.35	-.18
1968	-.01	.07	.16	.12	.44	.66	.52	.18	.02	-.33	-.20	-.19
1969	-.08	-.13	-.33	-.07	-.10	.12	.67	.87	.61	.74	.53	.30
1970	.36	.19	.52	.46	.34	.10	-.27	-.63	-.03	.65	.67	.60
1971	.22	-.10	-.17	-.27	-.38	-.97	-.83	-.56	-.97	-.50	-.21	-.16
1972	-.20	-.39	-.49	-.30	-.36	-.74	-.32	.12	-.05	-.13	.01	.02
1973	-.14	-.20	-.09	-.06	-.37	-.47	-.30	-.45	-.45	-.27	-.05	-.07
1974	.03	-.10	-.29	-.22	-.06	.12	.37	.50	.77	.47	-.04	-.16
1975	-.61	-.54	-.95	-.90	-.91	-.81	-.65	-.38	-.08	-.14	-.43	-.55
1976	-.34	-.46	-.55	-.58	-.52	-.52	-.32	-.30	-.75	-.39	-.36	.06
1977	-.08											

TABLE D.5a. Differences in monthly mean values of SST, °C, between 20-30°N and 40-50°N over the longitudinal extent of the Pacific, derived from Tables D.1a and D.3a.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			13.83	14.00	14.30	13.19	11.92	10.29	10.24	11.92	14.69	14.01
1963	13.25	12.85	12.94	13.60	12.90	13.72	11.39	9.22	10.87	12.48	14.05	14.45
1964	14.55	13.27	14.54	14.98	14.18	13.97	12.90	10.69	11.04	12.74	13.54	13.91
1965	13.84	14.01	13.92	13.91	14.53	(14.30)	(13.27)	11.06	11.21	12.09	13.57	14.28
1966	14.05	14.41	14.80	15.03	14.99	14.62	13.61	11.14	11.24	12.43	14.29	13.95
1967	14.37	14.28	14.51	14.79	14.48	13.60	11.76	9.37	10.83	12.89	14.28	14.36
1968	14.02	13.73	13.70	14.32	14.20	14.25	13.45	11.25	11.72	12.68	14.05	14.42
1969	14.13	14.54	14.77	15.18	15.50	15.02	13.07	10.38	10.64	13.09	13.85	14.57
1970	14.73	14.58	14.79	15.18	14.76	14.64	13.32	10.92	10.55	11.83	13.06	13.59
1971	13.73	13.55	13.95	14.66	15.17	14.99	12.88	11.15	11.86	12.83	13.52	13.84
1972	14.09	13.89	13.90	13.99	14.44	14.08	12.69	10.72	10.71	11.77	13.50	13.96
1973	14.30	14.40	14.70	15.30	15.22	14.89	13.43	11.12	11.46	12.69	13.87	14.52
1974	14.37	14.19	14.53	14.86	15.10	14.94	13.12	11.13	11.04	12.61	14.43	15.07
1975	14.64	14.59	14.94	14.95	15.04	14.09	13.23	10.89	10.76	12.41	14.05	14.30
1976	14.38	14.38	14.91	15.32	15.53	14.63	13.41	12.44	12.22	13.61	14.68	15.06
1977	14.99											
Σ	213.44	196.67	314.72	420.07	220.34	215.73	193.53	161.77	166.39	187.97	207.43	214.29
Mean	14.23	14.05	14.32	14.67	14.69	14.30	12.99	10.78	11.09	12.53	13.83	14.29
σ	.42	.51	.56	.54	.65	.55	.66	.75	.52	.48	.42	.41

TABLE D.5b. Departures of the values shown in Table D.5a from their long-term monthly means.

	1	2	3	4	5	6	7	8	9	10	11	12
1962			-.49	-.67	-.39	-1.19	-.98	-.49	-.85	-.61	-.14	-.28
1963	-.98	-1.20	-1.38	-1.07	-1.79	-.66	-1.51	-1.56	-.22	-.05	.22	.16
1964	.32	-.78	.22	.31	-.51	-.41	.08	-.09	-.05	.21	-.29	-.38
1965	-.39	-.04	-.40	-.76	-.16	-.09	.37	-.28	.12	-.44	-.26	-.01
1966	-.18	.36	.48	.36	.30	.24	.71	.36	.15	-.10	-.54	-.34
1967	.14	.23	.19	.12	-.21	-.78	-1.14	-1.41	-.26	.36	.45	.07
1968	-.21	-.32	-.62	-.35	-.49	-.13	.55	.47	.63	.15	.27	.13
1969	-.10	.49	.45	.51	.01	.64	.17	-.40	-.45	.56	.02	.28
1970	.50	.53	.47	.51	.07	.26	.42	.14	-.54	-.70	-.77	-.70
1971	-.50	-.50	-.37	-.01	.48	.61	-.02	.37	.77	.30	-.31	-.45
1972	-.14	-.16	-.42	-.68	-.25	-.30	-.21	-.06	-.38	-.76	-.33	-.33
1973	.07	.35	.38	.63	.53	.51	.53	.34	.37	.16	.04	.23
1974	.14	.14	.21	.19	.41	.56	.22	.35	-.05	-.02	.60	.78
1975	.41	.54	.62	.28	.35	.51	.33	.11	-.33	-.12	.22	.01
1976	.15	.33	.59	.65	.84	.25	.51	1.66	1.13	1.08	.85	.77
1977	.76											

TABLE D.5c. Data of Table D.5b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1962						-.72	-.74	-.66	-.65	-.62	-.65	-.78
1963	-.81	-.98	-1.05	-1.23	-1.31	-1.17	-.98	-.80	-.52	-.38	-.27	-.02
1964	.06	-.01	-.10	-.11	-.17	-.06	-.07	-.15	-.13	-.13	-.15	-.19
1965	-.29	-.35	-.32	-.21	-.11	-.09	-.10	-.02	-.00	-.02	-.02	.01
1966	.04	.15	.22	.22	.40	.37	.29	.16	.07	.05	-.01	-.04
1967	-.04	-.06	-.09	-.21	-.43	-.50	-.47	-.43	-.39	-.31	-.19	-.08
1968	-.09	-.21	-.29	-.22	-.13	.01	.12	.20	.29	.29	.28	.28
1969	.26	.36	.42	.42	.38	.25	.26	.19	.12	.10	.15	.27
1970	.41	.34	.37	.39	.34	.19	.02	-.16	-.27	-.38	-.51	-.58
1971	-.51	-.34	-.14	-.04	.08	.26	.36	.31	.18	.07	.05	-.06
1972	-.27	-.34	-.34	-.31	-.30	-.33	-.38	-.33	-.34	-.29	-.21	-.14
1973	.00	.19	.31	.43	.47	.47	.44	.35	.31	.26	.20	.18
1974	.16	.19	.27	.27	.30	.27	.24	.30	.35	.33	.37	.41
1975	.46	.51	.50	.43	.39	.27	.18	.15	.10	.05	.05	.12
1976	.26	.40	.40	.47	.69	.80	.87	.90	.89	.97		

TABLE D.6a. Monthly mean heights (geopotential meters in excess of 1500 gpm) of the 850-mb surface at 20°N over the Pacific longitude sector, obtained from NMC data tapes, courtesy of NCAR.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	4.89	27.13	28.97	34.25	39.29	34.64	28.48	26.16	22.61	15.48	37.43	33.01
1964	43.02	39.18	35.16	40.08	24.26	29.20	25.91	16.27	18.44	26.42	19.99	22.69
1965	17.08	20.32	31.39	33.10	29.00	36.95	26.99	20.73	12.80	21.19	27.87	32.42
1966	38.17	31.03	33.75	32.23	32.51	43.37	27.72	17.93	15.42	23.57	24.02	37.04
1967	41.16	39.21	32.55	33.11	29.85	24.44	18.63	20.60	4.24	24.24	31.74	33.51
1968	23.27	22.54	43.78	29.68	27.66	38.22	29.24	23.31	8.27	17.10	37.06	26.38
1969	18.94	32.58	44.56	46.43	36.09	33.98	34.35	25.13	15.12	23.18	26.03	43.08
1970	34.60	42.50	41.81	47.10	35.21	37.49	30.66	19.88	20.90	22.27	27.84	35.06
1971	15.74	31.76	33.41	30.15	33.06	37.47	23.36	19.11	15.29	27.51	29.33	25.45
1972	18.06	19.31	21.99	29.13	28.17	22.04	7.77	15.95	17.17	20.77	43.28	35.69
1973	35.96	41.83	49.33	50.33	42.72	41.82	35.68	33.63	43.08	33.07	34.51	39.35
1974	24.71	34.24	31.68	41.49	34.20	24.45	29.03	16.49	22.52	34.55	25.16	38.86
1975	35.62	39.14	33.79	38.76	27.08	33.90	26.23	19.94	22.45	30.83	29.45	31.38
1976	19.08	24.08	24.54	33.67	32.88	26.55	29.15	31.38	20.30	37.91	37.28	29.98
Mean	26.45	31.78	34.77	37.11	32.28	33.18	26.66	21.89	18.47	25.58	30.79	33.14
σ	11.12	7.75	7.42	6.74	4.87	6.52	6.61	5.27	8.60	6.32	6.18	5.50

TABLE D.6b. Departures of the values shown in Table D.6a from their long-term monthly mean values.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	-21.56	-4.65	-5.80	-2.86	7.01	1.46	1.82	4.27	4.14	-10.10	6.64	-1.13
1964	16.57	7.40	-3.39	2.97	-8.02	-3.98	-7.75	-5.62	-0.03	-8.64	-10.80	-10.45
1965	-9.37	-11.46	-3.38	-4.01	-3.28	3.77	.33	-1.16	-5.67	-4.39	-2.92	-7.72
1966	11.72	-7.75	-1.02	-4.88	.23	10.19	1.06	-3.96	-3.05	-2.01	-6.77	3.90
1967	14.71	7.43	-2.22	-4.00	-2.43	-8.74	-8.03	-1.29	-14.23	-1.34	.95	.37
1968	-3.18	-9.24	9.01	-7.43	-4.62	5.04	2.58	1.42	-10.20	-8.48	6.27	-6.76
1969	-7.51	.80	9.79	9.32	3.81	.80	7.69	3.24	-3.35	-2.40	-4.76	9.94
1970	8.15	10.72	7.04	9.99	2.93	4.31	4.00	-2.01	2.43	-3.31	-2.95	1.92
1971	-10.71	-.02	-1.36	-6.96	.78	4.29	-3.30	-2.78	-3.18	1.93	-1.46	-7.69
1972	-8.39	-12.47	-12.78	-7.98	-4.11	-11.14	-18.89	-5.94	-1.30	-4.81	12.49	2.55
1973	9.51	10.05	14.56	13.22	10.44	8.64	9.02	11.74	24.61	7.49	3.72	6.21
1974	-1.74	2.46	-3.09	4.38	1.92	-8.73	2.37	-5.40	4.05	8.97	-5.63	5.72
1975	9.17	7.36	-.98	1.65	-5.20	-.72	-.43	-1.95	3.98	5.25	-1.34	-1.76
1976	-7.37	-7.70	-10.23	-3.44	.60	-6.63	2.49	9.49	1.83	12.33	6.49	-3.16

TABLE D.6c. Data of Table D.6b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1963				-3.51	1.79	1.43	.82	2.18	1.16	3.32	4.11	3.56
1964	3.39	3.69	2.17	2.08	-1.09	-2.15	-2.08	-4.05	-4.40	-5.17	-6.70	-6.36
1965	-6.94	-7.54	-5.45	-3.91	-2.74	-1.91	-2.06	-1.90	-1.54	-.40	-.56	-.54
1966	-.42	-.24	2.11	2.36	.12	-.20	-.36	-.62	-.09	.55	1.46	1.71
1967	1.58	1.52	1.24	-.47	-2.75	-5.85	-5.72	-5.02	-4.62	-3.82	-3.99	-2.52
1968	-1.55	-2.02	-1.44	-1.12	-.46	-.60	-3.10	-1.14	-1.45	-3.24	-3.49	-2.30
1969	.49	2.25	1.46	3.53	5.06	4.47	2.73	.72	1.59	2.64	3.08	3.62
1970	5.53	6.29	7.58	6.73	5.28	4.10	2.62	.77	.63	-1.52	-2.09	-2.00
1971	-3.34	-2.76	-1.72	-2.47	-1.34	-1.79	-1.32	-.53	-1.74	-3.55	-4.86	-6.29
1972	-6.98	-7.84	-9.22	-10.82	-10.47	-8.88	-7.74	-4.81	-3.86	-.91	3.22	6.15
1973	8.22	10.40	9.85	10.78	11.10	13.18	12.17	10.81	10.20	8.72	7.78	5.67
1974	2.78	1.98	.21	-.35	-.87	-.64	1.08	-.35	.19	2.75	3.46	4.09
1975	3.75	1.73	2.63	1.76	1.67	-.32	.57	.15	.64	-.52	-1.56	-2.74
1976	-3.80	-4.46	-5.22	-4.61	-2.20	-.84	2.38	3.80	3.26			

TABLE D.7a. Monthly mean heights (geopotential meters in excess of 1000 gpm) of the 850-mb surface of 50°N over the Pacific longitude sector, obtained from NMC data tapes, courtesy of NCAR.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	301.31	304.28	410.08	419.96	391.47	428.41	483.22	481.96	381.92	399.02	348.25	268.96
1964	276.11	322.38	369.05	420.70	481.41	418.31	429.14	445.65	426.50	418.19	376.07	367.99
1965	300.15	301.37	345.33	408.00	404.13	398.43	467.52	456.71	455.38	380.67	369.98	348.05
1966	244.86	321.90	340.96	382.76	416.72	416.85	458.61	456.59	383.10	434.66	407.51	281.69
1967	296.68	293.68	385.89	446.70	449.91	431.54	487.19	437.33	387.61	360.80	349.58	339.79
1968	357.94	280.88	336.33	404.24	441.68	439.42	429.34	450.02	473.14	391.25	314.70	373.48
1969	353.14	286.17	336.05	335.85	371.82	404.29	484.76	473.56	400.14	370.36	351.59	232.95
1970	317.76	257.38	290.30	388.00	419.35	428.63	446.88	473.60	429.35	417.95	412.61	324.73
1971	379.11	322.99	311.75	366.92	394.97	409.92	462.15	456.66	441.02	433.92	353.77	365.31
1972	357.09	346.99	356.58	443.78	391.83	417.52	464.57	442.32	452.76	427.94	324.91	339.75
1973	319.45	288.96	309.12	392.04	382.40	421.76	464.25	475.33	432.39	426.83	394.20	258.00
1974	338.90	313.80	313.99	348.56	386.48	447.29	468.97	458.55	461.01	388.03	334.32	283.52
1975	338.83	310.45	371.09	419.27	395.79	460.08	466.88	475.43	472.47	405.37	374.16	314.54
1976	266.52	347.97	353.93	364.01	388.92	459.51	430.07	437.31	425.22	385.77	322.87	282.93
Mean	317.10	307.09	345.03	395.77	408.35	427.28	460.83	460.07	430.14	402.91	359.61	312.94
σ	37.58	24.16	31.51	32.49	29.45	18.25	18.24	13.36	30.65	23.34	29.80	43.36

TABLE D.7b. Departures of the values shown in Table D.7a from their long-term monthly mean values.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	-16.39	-2.81	65.05	24.19	-16.88	1.13	22.39	21.89	-48.22	-3.89	-11.36	-43.98
1964	-41.59	15.29	24.02	24.93	73.06	-8.97	-31.69	-14.42	-3.64	15.28	16.46	55.05
1965	-17.55	-5.72	.30	12.23	-4.22	-28.85	6.69	-3.36	25.24	-22.24	10.37	35.11
1966	-72.84	14.81	-4.07	-13.01	8.37	-10.43	-2.22	-3.48	-47.04	31.75	47.90	-31.25
1967	-21.02	-13.41	40.86	50.93	41.56	4.26	26.36	-22.74	-42.53	-42.11	-10.03	26.35
1968	40.24	-26.21	-8.70	8.47	33.33	12.14	-31.49	-10.05	43.00	-11.66	-44.91	60.54
1969	35.44	-20.92	-8.98	-59.92	-36.53	-22.99	23.93	13.49	-30.00	-32.55	-8.02	-79.99
1970	.06	-49.71	-54.73	-7.77	11.00	1.35	-13.95	13.53	-.79	15.04	53.00	11.79
1971	61.41	15.90	-33.28	-28.85	-13.38	-17.36	1.32	-3.41	10.68	31.01	-5.84	52.37
1972	39.39	39.90	11.55	48.01	-16.52	-9.76	3.74	-17.75	22.62	25.03	-34.70	26.81
1973	1.75	-18.13	-35.91	-3.73	-25.95	-5.52	3.42	15.26	2.25	23.92	34.59	-54.94
1974	21.20	6.71	-31.04	-47.21	-21.87	20.01	8.14	-1.52	30.87	-14.88	-25.29	-29.42
1975	21.13	3.36	26.06	23.50	-12.56	32.80	6.05	15.36	42.33	2.46	14.55	1.60
1976	-51.18	40.88	8.90	-31.76	-19.43	32.23	-22.76	-2.76	-4.92	-17.14	-36.74	-30.01

TABLE D.7c. Data of Table D.7b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1963				10.95	16.42	9.94	.09	-4.99	-8.86	-14.97	-15.98	-15.68
1964	-5.23	5.77	6.11	7.86	11.75	9.04	7.79	6.50	4.01	2.78	6.49	8.60
1965	10.86	8.08	1.60	-5.30	-3.28	1.15	-2.07	-2.24	3.28	-3.00	-1.84	-1.95
1966	-7.41	-3.04	-6.01	-11.34	-1.43	-10.27	-5.15	3.55	-2.11	-3.62	-5.22	1.11
1967	15.11	16.51	10.28	18.51	18.26	14.10	2.25	-6.46	-8.63	-3.49	-11.00	-9.00
1968	-1.71	9.06	12.23	3.97	-3.22	6.67	6.25	-1.38	2.51	5.84	7.35	7.50
1969	-7.20	-10.75	-7.62	-12.85	-15.99	-17.29	-20.65	-13.24	-19.45	-16.15	-26.67	-36.42
1970	-33.24	-27.02	-25.68	-16.25	-14.33	-7.34	2.63	11.31	11.42	20.00	24.27	17.58
1971	13.57	9.51	-.54	-2.03	-11.29	-12.01	-2.83	.46	9.85	17.96	23.47	25.61
1972	30.91	24.12	23.56	16.62	8.45	5.98	7.91	-3.91	2.28	3.93	.80	-1.79
1973	-5.55	-12.84	-8.67	-12.01	-10.08	-7.17	1.38	6.85	2.71	6.53	7.00	.38
1974	-6.68	-13.22	-15.31	-6.29	-9.54	-6.09	-3.78	-.65	-1.73	-1.57	-2.25	1.69
1975	.64	.97	9.27	14.33	13.51	19.08	15.71	14.43	16.45	4.45	9.42	8.51
1976	-2.08	-5.21	-2.68	-6.16	.76	-5.79	-9.51	-10.22	-11.73			

TABLE D.8a. Monthly mean heights (geopotential meters in excess of 9000 gpm) of the 300-mb surface at 20°N over the Pacific longitude sector, obtained from NMC data tapes, courtesy of NCAR.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	581.50	621.39	600.14	611.37	637.97	669.50	657.98	666.91	683.49	660.16	656.09	657.17
1964	624.51	613.31	601.28	603.32	642.27	680.59	682.89	680.95	676.98	664.60	635.31	623.80
1965	622.45	589.55	606.43	621.01	653.20	686.47	664.95	679.62	682.62	673.04	656.53	642.22
1966	654.64	627.44	637.88	647.53	668.94	703.14	689.93	691.72	684.33	674.04	657.48	657.01
1967	648.91	616.59	613.08	620.91	663.94	687.52	681.89	686.35	679.99	679.96	650.04	625.88
1968	619.88	632.33	634.26	620.75	662.65	690.50	683.30	698.12	671.98	678.65	685.91	645.70
1969	609.91	618.63	623.03	649.78	682.91	714.27	699.04	697.83	697.43	683.52	654.89	678.88
1970	636.19	664.83	634.88	649.20	659.55	692.50	694.11	685.76	670.49	662.53	645.29	628.20
1971	590.01	612.93	632.12	617.45	645.23	666.04	668.54	663.18	664.89	649.37	633.21	589.42
1972	576.25	567.17	597.49	593.11	653.36	688.26	669.04	679.06	677.06	679.79	676.24	641.13
1973	639.41	626.08	640.34	640.61	657.01	691.42	694.93	674.82	696.60	671.37	659.96	654.50
1974	599.20	606.19	604.34	625.63	640.84	660.46	675.65	679.45	667.96	674.77	636.08	654.13
1975	629.68	613.88	605.29	611.77	631.79	672.35	651.29	674.41	668.58	672.49	643.79	610.90
1976	584.89	564.28	577.55	609.13	644.77	658.45	676.98	675.46	681.36	677.94	667.31	644.65
Mean	615.53	612.47	614.87	622.97	653.17	682.82	677.89	680.97	678.84	671.59	654.15	639.54
σ	24.75	24.82	18.31	17.12	13.33	15.45	13.78	9.32	9.55	9.04	14.75	21.66

TABLE D.8b. Departures of the values shown in Table D.8a from their long-term monthly mean values.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	-34.03	8.92	-14.73	-11.60	-15.20	-13.32	-19.91	-14.06	4.65	-11.43	1.94	17.63
1964	8.98	.84	-13.59	-19.65	-10.90	-2.23	5.00	-.02	-1.86	-6.99	-18.84	-15.74
1965	6.92	-22.92	-8.44	-1.96	.03	3.65	-12.94	-1.35	3.78	1.45	2.38	2.68
1966	39.11	14.97	23.01	24.56	15.77	20.32	12.04	10.75	5.49	2.45	3.33	17.47
1967	33.38	4.12	-1.79	-2.06	10.77	4.70	4.00	5.38	1.15	8.37	-4.11	-13.66
1968	4.35	19.86	19.39	-2.22	9.48	7.68	5.41	17.15	-6.86	7.06	31.76	6.16
1969	-5.62	6.16	8.16	26.81	29.74	31.45	21.15	16.86	18.59	11.93	.74	39.34
1970	20.66	52.36	20.01	26.23	6.38	9.68	16.22	4.79	-8.35	-9.06	-8.86	-11.34
1971	-25.52	.46	17.25	-5.52	-7.94	-16.78	-9.35	-17.79	-13.95	-22.22	-20.94	-50.12
1972	-39.28	-45.30	-17.38	-29.86	.19	3.44	-8.85	-1.91	-1.78	8.20	22.09	1.59
1973	23.88	13.61	25.47	17.64	3.84	8.60	17.04	-6.15	17.76	-.22	5.81	14.96
1974	-16.33	-6.28	-10.53	2.66	-12.33	-22.36	-2.24	-1.52	-10.88	3.18	-18.07	14.59
1975	14.15	1.41	-9.58	-11.20	-21.38	-10.47	-26.60	-6.56	-10.26	.90	-10.36	-28.64
1976	-30.64	-68.19	-37.32	-13.84	-8.40	-24.37	-.91	-5.51	2.52	6.35	13.16	5.11

TABLE D.8c. Data of Table D.8b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1963				-14.27	-11.41	-12.02	-11.55	-9.62	-4.93	-1.74	1.22	1.29
1964	-2.18	-2.11	-2.70	-4.51	-5.79	-6.18	-5.24	-5.12	-5.81	-4.50	-8.49	-9.70
1965	-9.71	-8.71	-5.49	-5.09	-6.28	-2.46	-1.05	-.43	-.05	5.02	9.00	12.48
1966	15.45	17.50	20.06	21.40	17.35	15.99	13.05	10.02	10.26	12.13	11.00	9.21
1967	8.13	9.32	9.51	7.59	3.59	3.16	4.62	4.32	.83	.78	3.05	5.05
1968	4.57	4.73	6.41	9.14	10.96	7.15	5.39	10.24	9.77	7.87	7.97	6.69
1969	11.50	14.74	14.69	16.84	20.05	21.82	22.36	18.64	20.01	18.47	22.93	23.38
1970	24.47	23.67	24.95	21.65	19.38	10.71	6.56	1.54	-.99	-6.02	-8.27	-6.49
1971	-6.08	-5.92	-7.06	-6.77	-5.67	-7.73	-13.36	-15.57	-21.59	-24.81	-29.94	-29.88
1972	-32.16	-28.96	-25.47	-19.58	-14.24	-8.02	-4.37	3.05	3.25	6.17	9.38	13.29
1973	16.07	15.45	13.52	15.73	11.44	12.03	8.36	6.67	8.26	4.70	1.36	.74
1974	-1.42	-3.15	-7.17	-9.63	-7.51	-8.17	-6.21	-9.17	-5.33	-.11	.41	-.74
1975	-.79	-4.30	-3.21	-9.10	-12.05	-13.72	-12.22	-12.10	-13.14	-16.02	-19.11	-23.50
1976	-24.01	-25.34	-27.34	-23.38	-19.79	-12.55	-6.31	-2.45	-.52			

TABLE D.11a. Monthly mean thickness 300/850 mb (geopotential meters in excess of 7000 gpm) at 50°N over the Pacific longitude sector.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	524.35	415.95	494.68	550.86	649.09	755.39	933.05	923.01	746.43	609.16	490.56	319.70
1964	347.29	327.77	450.47	522.79	695.23	754.18	884.13	911.17	757.51	592.38	495.79	449.52
1965	407.06	419.68	447.00	560.88	631.98	709.74	888.25	901.84	815.14	616.09	484.37	434.19
1966	379.30	367.80	430.19	504.52	677.85	700.80	916.57	919.11	771.71	632.08	551.43	424.46
1967	324.33	355.44	483.58	577.43	694.28	764.89	956.00	904.96	741.30	575.04	475.07	481.90
1968	460.31	409.84	432.65	525.82	651.72	697.78	865.60	885.74	759.32	688.08	444.94	469.86
1969	382.76	354.56	405.07	488.00	626.26	767.16	910.77	934.10	761.03	586.74	489.98	327.49
1970	355.61	343.16	386.05	503.54	651.33	749.51	903.17	954.72	791.73	646.48	568.47	415.50
1971	465.30	386.05	379.23	469.66	569.54	768.85	892.23	885.40	770.98	641.45	488.72	456.67
1972	406.04	428.77	466.07	562.44	660.28	770.89	888.70	904.57	811.38	646.46	458.11	436.96
1973	403.62	358.96	441.94	501.59	608.44	705.51	936.38	932.24	746.21	657.89	584.54	407.70
1974	516.25	417.00	447.51	497.22	602.42	743.40	854.45	927.23	810.46	603.97	452.09	352.49
1975	405.48	394.04	421.39	537.96	635.65	783.47	886.24	918.28	787.95	632.26	538.76	421.53
1976	416.20	403.23	434.17	481.86	616.24	760.43	834.79	842.45	740.14	610.91	478.46	433.34
Mean	413.85	384.45	437.71	520.33	640.74	744.86	896.45	910.34	772.24	624.21	500.09	420.74
σ	57.19	31.54	31.96	32.15	34.22	27.88	31.68	26.15	25.78	29.69	42.03	41.42

TABLE D.11b. Departures of the values shown in Table D.11a from their long-term monthly mean values.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	110.50	31.50	56.97	30.53	8.35	10.53	36.60	12.67	-25.81	-15.05	-9.53	-41.04
1964	-66.56	-56.68	20.76	2.46	54.49	9.32	-12.32	.83	-14.73	-31.83	-4.30	28.78
1965	-6.79	35.23	9.29	40.55	-8.76	-35.12	-8.20	-8.50	42.90	-8.12	-15.72	13.45
1966	-34.55	-16.65	-7.52	-15.81	37.11	-44.06	20.12	8.77	-.53	7.87	51.34	3.72
1967	-87.52	-29.01	45.87	57.10	53.54	20.03	59.55	-5.38	-30.94	-49.17	-25.02	60.26
1968	46.46	25.39	-5.06	5.49	10.98	-47.08	-30.85	-24.60	-12.92	63.87	-55.15	49.12
1969	-31.09	-29.89	-32.64	-32.33	-14.48	18.30	14.32	23.76	-11.21	-37.47	-10.11	-93.25
1970	-58.24	-41.29	-51.66	-16.79	10.59	4.65	6.72	44.38	19.49	22.27	68.38	-5.24
1971	51.45	1.60	-58.48	-50.67	-71.20	23.99	-4.22	-74.94	-1.26	17.24	-11.37	35.93
1972	-7.81	44.32	28.36	42.11	19.54	26.03	-7.75	-5.77	39.14	22.25	-41.98	16.22
1973	-10.23	-25.49	4.23	-18.74	-32.30	-39.35	39.93	21.90	-26.03	33.68	84.45	-13.04
1974	102.40	32.55	9.80	-23.11	-38.32	-1.46	-42.00	16.89	38.22	-20.24	-48.00	-68.25
1975	-8.37	9.59	-16.32	17.63	-5.09	38.61	-10.21	7.94	15.71	8.05	38.67	.79
1976	2.35	18.78	-3.54	-38.47	-24.50	15.57	-61.66	-67.89	-32.10	-13.30	-21.63	12.60

TABLE D.11c. Data of Table D.11b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1963				40.71	26.74	18.55	8.26	2.54	-4.52	-15.53	-28.86	-27.70
1964	-23.66	-13.73	-11.04	-6.93	2.69	8.69	1.17	.21	-3.46	-5.77	1.03	2.24
1965	10.13	13.43	9.03	3.74	3.50	4.59	2.11	-5.93	-2.76	-2.68	-3.88	-3.74
1966	-12.13	-5.67	-9.72	-8.77	-2.88	-.27	1.92	11.52	6.75	.25	-6.77	-1.47
1967	6.77	13.29	8.82	16.79	28.81	28.54	14.96	3.23	4.19	7.97	3.09	3.13
1968	8.34	16.93	13.78	.76	-9.39	-14.86	-5.02	-13.68	-8.23	-5.95	-5.81	-6.96
1969	-9.73	-20.92	-10.43	-15.40	-7.57	-4.90	-5.59	-2.41	-13.67	-24.60	-32.54	-43.32
1970	-44.12	-37.25	-35.14	-20.86	-6.20	2.48	13.04	25.21	22.95	29.64	28.90	14.21
1971	4.19	-9.17	-15.51	-15.36	-26.27	-26.68	-15.87	-10.25	5.05	.51	7.44	15.06
1972	21.25	21.58	26.93	20.69	20.98	20.24	19.36	7.35	6.88	1.70	-.84	.59
1973	-7.68	-15.47	-15.09	-11.71	-7.12	-7.19	-2.99	11.75	14.51	34.76	33.70	31.97
1974	32.39	22.10	9.83	5.69	-6.52	-5.71	-10.00	-13.56	-17.83	-18.82	-11.45	-16.20
1975	-19.14	-16.97	-4.60	3.69	6.02	6.90	10.38	13.38	14.22	9.04	13.18	11.54
1976	3.80	-.85	-4.15	-13.07	-23.10	-30.37	-31.76	-29.36	-24.06			

TABLE D.12a. Monthly mean values of thickness difference 300/850 mb (geopotential meters) between 20°N and 50°N over the Pacific longitude sector.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	552.26	678.31	576.49	526.26	449.59	379.47	196.45	217.74	414.45	535.52	628.10	744.46
1964	734.20	746.36	607.65	-540.45	422.78	397.21	272.85	253.51	401.03	545.80	619.53	651.59
1965	698.31	649.55	628.04	527.03	492.22	439.78	249.71	257.05	354.68	535.76	644.29	675.61
1966	737.17	728.61	673.94	610.78	458.58	458.97	245.64	254.68	397.20	518.39	582.03	695.51
1967	783.42	721.94	596.95	510.37	439.81	398.19	207.26	260.79	434.45	580.68	643.23	611.37
1968	636.30	699.95	657.83	565.25	483.27	454.50	288.46	289.07	404.39	473.47	703.91	649.46
1969	708.21	731.49	673.40	615.35	520.56	417.13	253.92	238.60	421.28	573.60	638.88	808.31
1970	745.98	779.18	707.02	598.56	474.01	405.50	260.28	211.16	357.86	493.78	548.98	677.64
1971	608.97	695.12	719.48	617.64	542.63	359.72	252.95	258.67	378.62	480.41	615.16	607.30
1972	652.15	619.09	609.43	501.54	464.91	393.33	272.57	258.54	348.51	512.56	674.85	668.48
1973	699.83	725.29	649.07	588.69	505.85	444.09	222.87	208.95	407.31	480.41	540.91	707.45
1974	558.24	654.95	625.15	586.92	504.22	392.61	292.17	235.73	334.98	536.25	658.83	762.78
1975	688.58	680.70	650.11	535.05	469.06	354.98	238.82	236.19	358.18	509.40	575.58	657.99
1976	647.61	636.97	618.84	593.60	495.65	371.47	313.04	301.63	420.92	529.13	651.57	681.33
Mean	675.23	696.25	642.39	665.54	480.22	404.78	294.19	210.74	388.13	521.80	623.28	685.66
n	66.73	64.01	39.80	39.49	31.49	32.70	31.22	25.79	30.83	31.81	45.27	53.72

TABLE D.12b. Departure of the values shown in Table D.12a from their long-term monthly mean values.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	-122.97	-17.94	-65.90	-39.28	-30.63	-25.31	-58.34	-31.00	26.32	13.72	4.82	58.80
1964	58.97	50.11	-34.74	-25.09	-57.44	-7.57	18.06	4.77	12.90	24.00	-3.75	-34.07
1965	23.08	-46.70	-14.35	-38.51	12.00	35.00	-5.08	8.31	-33.45	13.96	21.01	-10.05
1966	61.94	32.36	31.55	45.24	-21.64	54.19	-9.15	5.94	9.07	-3.41	-41.25	9.85
1967	108.19	25.69	-45.44	-55.17	-40.41	-6.59	-47.53	12.05	46.32	58.88	19.95	-74.29
1968	-38.93	3.70	15.44	-29	3.05	49.72	33.67	40.33	16.26	-48.33	80.63	-36.20
1969	32.98	35.24	31.01	49.81	40.34	12.35	-0.87	-10.14	33.16	51.80	15.60	122.65
1970	70.75	82.93	64.63	33.02	-6.21	.72	5.49	-37.58	-30.27	-28.02	-74.30	-8.02
1971	-66.26	-1.13	77.09	52.10	62.41	-45.06	-1.84	9.93	-9.51	-41.39	-8.12	-78.36
1972	-73.04	-77.16	-32.96	-64.00	-15.31	-11.45	17.78	9.80	-39.62	-9.24	51.57	-17.18
1973	24.60	29.04	6.68	23.15	25.63	39.31	-31.92	-39.19	19.10	-41.39	-82.37	21.79
1974	-116.99	-41.30	-17.24	21.38	24.00	-12.17	37.38	-13.01	-53.15	14.45	35.55	77.12
1975	13.35	-15.55	7.72	-30.49	-11.16	-49.80	-15.97	-12.55	-29.95	-12.40	-47.70	-27.67
1976	-25.62	-59.28	-23.55	28.06	15.43	-33.31	58.25	52.89	32.79	7.33	28.29	-4.33

TABLE D.12c. Data of Table D.12b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1963				-51.48	-38.34	-32.02	-20.65	-14.35	-1.57	10.47	25.96	25.43
1964	18.08	7.92	6.15	.33	-7.41	-12.73	-4.34	-1.29	2.05	6.43	-2.82	-5.56
1965	-12.90	-14.61	-9.08	-4.94	-7.05	-5.15	-1.11	7.39	4.24	8.09	13.44	16.76
1966	28.00	22.92	27.66	27.78	19.78	16.46	11.46	-8.9	3.61	11.32	16.30	8.96
1967	-2.22	-5.51	-5.55	-8.75	-22.49	-19.54	-4.64	6.10	1.26	-3.36	3.95	4.44
1968	-2.22	-10.20	-5.94	9.48	20.80	22.60	13.49	25.05	19.44	17.05	17.27	15.94
1969	20.73	33.40	23.65	28.69	22.53	22.24	25.21	20.32	24.08	40.42	52.39	63.07
1970	63.05	54.77	52.64	35.90	20.43	4.26	-8.98	-24.31	-24.57	-34.14	-35.08	-18.70
1971	-6.93	5.98	10.16	11.04	21.93	20.73	3.81	-4.80	-24.91	-21.77	-32.53	-38.65
1972	-46.44	-42.71	-43.19	-29.45	-24.76	-19.39	-16.01	.50	.24	5.39	7.00	6.55
1973	15.52	20.50	18.75	16.64	7.44	6.03	-8.3	-15.91	-16.46	-38.78	-40.12	-36.90
1974	-36.59	-27.25	-17.22	-14.99	-14	-1.83	2.70	4.72	12.31	15.96	8.39	11.36
1975	14.59	10.93	-1.26	-14.56	-18.26	-20.31	-23.19	-25.65	-28.01	-24.55	-30.74	-32.31
1976	-24.02	-20.05	-17.99	-5.72	5.50	18.65	23.05	23.10	20.27			

TABLE D.9a. Monthly mean heights (geopotential meters in excess of 8000 gpm) of the 300-mb surface at 50°N over the Pacific longitude sector, obtained from NMC tapes, courtesy of NCAR.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	825.66	720.23	904.76	970.82	1040.56	1183.80	1416.27	1404.97	1128.35	1008.18	838.81	648.66
1964	623.40	650.15	827.52	943.49	1176.64	1172.49	1313.27	1356.82	1184.01	1010.57	871.86	817.61
1965	707.21	721.05	792.33	968.08	1036.11	1108.17	1355.77	1358.55	1270.52	996.76	854.35	782.24
1966	624.16	689.70	771.15	887.28	1094.57	1117.65	1375.18	1375.70	1154.81	1066.74	958.94	706.15
1967	621.01	649.12	869.47	1024.13	1144.19	1196.43	1443.19	1342.29	1128.91	935.84	824.65	820.29
1968	818.25	690.72	768.98	930.06	1093.40	1137.20	1294.94	1335.76	1232.46	1007.33	759.64	843.34
1969	735.90	640.73	741.12	823.85	998.08	1167.45	1395.53	1407.66	1161.17	957.10	841.57	560.44
1970	673.37	600.54	676.35	891.54	1070.68	1178.14	1350.05	1428.32	1221.08	1064.43	981.08	740.23
1971	844.41	709.04	690.98	836.58	964.51	1178.77	1354.38	1342.06	1212.00	1075.37	842.49	821.98
1972	763.13	775.76	822.65	1006.22	1052.11	1188.41	1353.27	1346.89	1264.06	1074.40	783.02	776.71
1973	723.07	647.92	751.06	893.63	990.84	1127.27	1400.63	1398.57	1178.60	1084.72	978.74	665.70
1974	855.15	730.80	761.50	845.78	988.90	1190.69	1323.38	1385.78	1271.47	992.00	786.41	636.01
1975	744.31	704.49	792.48	957.23	1031.44	1243.55	1353.12	1393.71	1260.42	1037.63	912.92	736.07
1976	682.72	751.20	788.10	845.87	1005.16	1219.94	1272.86	1299.76	1165.36	996.68	801.33	716.27
Mean	731.55	691.53	782.75	916.10	1049.09	1172.14	1357.27	1369.77	1202.37	1021.98	859.70	733.69
σ	79.03	46.78	59.45	62.60	59.21	36.95	45.29	34.01	50.04	44.66	70.06	80.66

TABLE D.9b. Departures of the values shown in Table D.9a from their long-term monthly mean values.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	94.11	28.70	122.01	54.72	-8.53	11.66	59.00	35.20	-74.02	-13.80	-20.89	-85.03
1964	-108.15	-41.38	44.77	27.39	127.55	.35	-44.00	-12.95	-18.36	-11.41	12.16	83.92
1965	-24.34	29.52	9.58	52.78	-12.98	-63.97	-1.50	-11.22	68.15	-25.22	-5.35	48.55
1966	-107.39	-1.83	-11.60	-28.82	45.48	-54.49	17.91	5.93	-47.56	44.76	99.24	-27.54
1967	-110.54	-42.41	86.72	108.03	95.10	24.29	85.92	-27.48	-73.46	-86.14	-35.05	86.60
1968	86.70	-.81	-13.77	13.96	44.31	-34.94	-62.33	-34.01	30.09	-14.65	-100.06	109.65
1969	4.35	-50.80	-41.63	-92.25	-51.01	-4.69	38.26	37.89	-41.20	-64.88	-18.13	-173.25
1970	-58.18	-90.99	-106.40	-24.56	21.59	6.00	-7.22	58.55	18.71	42.45	121.38	6.54
1971	112.86	17.51	-91.77	-79.52	-84.58	6.63	-2.89	-27.71	9.63	53.39	-17.21	88.29
1972	31.58	84.23	39.90	90.12	3.02	16.27	-4.00	-22.88	61.69	52.42	-76.68	43.02
1973	-8.48	-43.61	-31.69	-22.47	-58.25	-44.87	43.36	28.80	-23.77	62.74	119.04	-67.99
1974	123.60	39.27	-21.25	-70.32	-60.19	18.55	-33.89	16.01	69.10	-29.98	-73.29	-97.68
1975	12.76	12.96	9.73	41.13	-17.65	71.41	-4.15	23.94	58.05	15.65	53.22	2.38
1976	-48.83	59.67	5.35	-70.23	-43.93	47.80	-84.41	-70.01	-37.01	-25.30	-58.37	-17.42

TABLE D.9c. Data of Table D.9b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1963				51.67	43.25	28.58	9.18	-1.63	-12.55	-29.67	-44.01	-42.64
1964	-28.16	-7.96	-4.93	.93	14.53	17.82	9.80	7.62	1.39	-2.14	8.36	11.58
1965	21.74	21.52	10.64	-1.56	.32	5.83	.86	-7.44	1.35	-4.85	-4.90	-4.96
1966	-18.81	-8.71	-15.73	-20.11	-3.92	-10.45	-2.40	15.90	5.46	-2.54	-11.16	.38
1967	22.61	29.80	19.09	35.30	47.17	42.73	18.04	-2.40	-3.62	5.30	-7.09	-5.13
1968	7.36	25.99	26.01	4.73	-12.51	-8.10	-8.22	-24.51	-15.18	-9.57	-7.92	-9.01
1969	-26.48	-31.68	-18.05	-28.25	-23.46	-22.09	-25.41	-14.82	-32.29	-39.93	-58.39	-79.00
1970	-76.63	-64.27	-60.83	-37.11	-20.43	-4.76	16.50	37.35	35.20	50.47	54.00	32.53
1971	18.49	.35	-16.05	-17.39	-37.48	-38.60	-17.86	-8.96	15.73	19.30	31.74	41.40
1972	52.90	45.70	50.49	37.30	29.52	26.30	28.09	4.26	9.98	6.44	.78	-4.48
1973	-12.50	-28.31	-23.76	-23.72	-18.39	-15.56	-2.07	18.15	16.76	40.83	40.24	33.09
1974	26.44	8.88	-5.48	-.60	-15.97	-11.71	-12.96	-13.38	-18.74	-19.57	-12.87	-13.77
1975	-17.77	-16.01	4.67	18.03	19.62	26.07	26.91	28.64	31.50	14.32	23.44	20.78
1976	2.46	-6.05	-6.83	-19.23	-22.25	-36.06	-40.44	-38.75	-34.96			

TABLE D.10a. Monthly mean thicknesses 300/850 mb (geopotential meters in excess of 7500 gpm) at 20°N over the Pacific longitude sector.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	576.61	594.26	571.17	577.12	598.68	634.86	629.50	640.75	660.88	644.68	618.66	624.16
1964	581.49	574.13	566.12	563.24	618.01	651.39	656.98	664.68	658.54	638.18	615.32	601.11
1965	605.37	569.23	575.04	587.91	624.20	649.52	637.96	658.89	669.82	651.85	628.66	609.80
1966	616.47	596.41	604.13	615.30	636.43	659.77	662.21	673.79	668.91	650.47	633.46	619.97
1967	607.75	577.38	580.53	587.80	634.09	663.08	663.26	665.75	675.75	655.72	618.30	592.37
1968	596.61	609.79	590.48	591.07	634.99	652.28	654.06	674.81	663.71	661.55	648.85	619.32
1969	590.97	586.05	578.47	603.35	646.82	680.29	664.69	672.70	682.31	660.34	628.86	635.80
1970	601.59	622.33	593.07	602.10	625.34	655.01	663.45	665.88	649.59	640.26	617.45	593.14
1971	574.27	581.17	598.71	587.30	612.17	628.57	645.18	644.07	649.60	621.86	603.88	563.97
1972	558.19	547.86	575.50	563.98	625.19	664.22	661.27	663.11	659.89	659.02	632.96	605.44
1973	603.45	584.25	591.01	590.28	614.29	649.60	659.25	641.19	653.52	638.30	625.45	615.15
1974	574.49	571.95	572.66	584.14	606.64	636.01	646.62	662.96	645.44	640.22	610.92	615.27
1975	594.06	574.74	571.50	573.01	604.71	638.45	625.06	654.47	646.13	641.66	614.34	579.52
1976	565.81	540.20	553.01	575.46	611.89	631.90	647.83	644.08	661.06	640.03	630.03	614.67
Mean	589.07	580.70	580.10	585.86	620.96	649.64	651.24	659.08	660.37	646.01	623.37	606.41
σ	16.80	20.82	13.38	14.23	13.37	14.05	12.55	11.74	10.69	10.66	11.06	18.30

TABLE D.10b. Departures of the values shown in Table D.10a from their long-term monthly mean values.

	1	2	3	4	5	6	7	8	9	10	11	12
1963	-12.45	13.56	-8.93	-8.74	-22.28	-14.78	-21.74	-18.33	.51	-1.33	-4.71	17.75
1964	-7.57	-6.57	-13.98	-22.62	-2.95	1.75	5.74	5.60	-1.83	-7.83	-8.05	-5.30
1965	16.31	-11.47	-5.06	2.05	3.24	-.12	-13.28	-.19	9.45	5.84	5.29	3.39
1966	27.41	15.71	24.03	29.44	15.47	10.13	10.97	14.71	8.54	4.46	10.09	13.56
1967	18.69	-3.32	.43	1.94	13.13	13.44	12.02	6.67	15.38	9.71	-5.07	-14.04
1968	7.55	29.09	10.38	5.21	14.03	2.64	2.82	15.73	3.34	15.54	25.48	12.91
1969	1.91	5.35	-1.63	17.49	25.86	30.65	13.45	13.62	21.94	14.33	5.49	29.39
1970	12.53	41.63	12.97	16.24	4.38	5.37	12.21	6.80	-10.78	-5.75	-5.92	-13.27
1971	-14.79	.47	18.61	1.44	-8.79	-21.07	-6.06	-15.01	-10.77	-24.15	-19.49	-42.44
1972	-30.87	-32.84	-4.60	-21.88	4.23	14.58	10.03	4.03	-.48	13.01	9.59	-.97
1973	14.39	3.55	10.91	4.42	-6.67	-.04	8.01	-17.89	-6.85	-7.71	2.08	8.74
1974	-14.57	-8.75	-7.44	-1.72	-14.32	-13.63	-4.62	3.88	-14.93	-5.79	-12.45	8.86
1975	5.00	-5.96	-8.60	-12.85	-16.25	-11.19	-26.18	-4.61	-14.24	-4.35	-9.03	-26.89
1976	-23.25	-40.50	-27.09	-10.40	-9.07	-17.74	-3.41	-15.00	.69	-5.98	6.66	8.26

TABLE D.10c. Data of Table D.10b subjected to 7-month running-mean filter.

	1	2	3	4	5	6	7	8	9	10	11	12
1963				-10.77	-11.61	-13.48	-12.39	-11.81	-6.09	-5.06	-2.89	-2.27
1964	-5.59	-5.82	-4.89	-6.61	-4.73	-4.05	-3.17	-1.08	-1.42	.66	-1.80	-3.32
1965	-2.77	-1.19	-.06	-1.20	-3.56	-.57	.99	1.46	1.48	5.42	9.56	13.02
1966	15.86	17.24	17.93	19.01	17.20	16.18	13.38	10.63	10.35	11.57	9.53	7.49
1967	6.54	7.78	8.26	8.04	6.32	8.99	10.32	9.33	5.44	4.60	7.04	7.57
1968	6.11	6.73	7.83	10.24	11.41	7.73	8.46	11.37	11.21	11.10	11.47	8.99
1969	11.00	12.47	13.21	13.29	14.96	17.33	19.61	17.91	18.41	15.82	19.85	19.75
1970	18.93	17.51	17.49	15.04	14.22	6.73	4.06	.90	-1.62	-4.50	-6.18	-4.49
1971	-2.75	-3.19	-5.35	-4.32	-4.35	-5.96	-12.07	-15.05	-19.86	-21.26	-25.08	-23.59
1972	-25.19	-21.14	-16.27	-8.77	-3.79	.84	3.35	7.86	7.11	7.09	6.16	7.14
1973	7.83	5.02	3.65	4.93	.32	-1.17	-3.83	-4.15	-1.95	-4.03	-6.42	-4.93
1974	-4.21	-5.15	-7.39	-9.30	-6.67	-7.55	-7.31	-8.84	-5.53	-2.86	-3.06	-4.84
1975	-4.55	-6.04	-5.86	-10.87	12.24	-13.43	-12.82	-12.26	-13.78	-15.51	-17.55	-20.76
1976	-20.23	-20.90	-22.14	-18.79	-17.61	-11.73	-8.71	-6.26	-3.79			

REFERENCES TO APPENDICES

- American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1972: Handbook of Fundamentals. ASHRAE, New York, N.Y.
- Bornstein, R.D., A. Lorenzen, and D. Johnson, 1972: Recent observations of urban effects on winds and temperatures in and around New York City. Preprints Conf. Urban Environ. Second Conf. Biometeorol., Amer. Meteor. Soc., p. 28-33.
- Chandler, T.J., 1965: The Climate of London. Hutchinson and Co., 292 pp.
- Duckworth, F.S. and J.S. Sandberg, 1954: The effect of cities upon horizontal and vertical temperature gradients. Bull. Amer. Meteor. Soc., Vol. 35, p. 198-207.
- Duffie, J.A. and W.A. Beckman, 1974: Solar Energy Thermal Processes. Wiley, N.Y.
- Fuggle, R.F. and T.K. Oke, 1970: Infra-red flux divergence and the urban heat island. Urban Climates, Tech. Note No. 108, World Meteorological Organization, Geneva, p. 70-78.
- Hottel, H.C. and B.B. Woertz, 1942: Performance of flat plate solar heat collection. Transactions American Society of Mechanical Engineers. Vol. 64, No. 3.
- Hutcheon, R.J., R.H. Johnson, W.P. Lowry, C.H. Black, and D. Hadley, 1967: Observations of the urban heat island in a small city. Bull. Amer. Meteor. Soc., Vol. 48, p. 7-10.
- Ivakhnenko, A.G. and V.G., Vata, 1967: Cybernetics and Forecasting Techniques. American Elsevier, New York.
- Landsberg, H.E., 1975: Atmospheric Changes in a Growing Community (The Colombia, Maryland Experience). Inst. Fluid Dyn. Appl. Math., Univ. of Maryland, Tech. Note BN 823, 54 pp.
- Leong, H.H., 1975: Using Recursive Regression Polynomials to Construct a System Description -- An Introduction to the GMDH Algorithm. M.S. Thesis, Statistics Dept., Colorado State Univ., Fort Collins, Colorado, 96 pp.
- Liu, B.Y.H. and R.C. Jordan, 1960: The interrelationship and characteristic distribution of direct, diffuse and total radiation. Solar Energy. Vol. 4, No. 3.
- Lof, G., J. Ward, D. Ward, C. Smith, 1974: Design and construction of a residential solar heating and cooling system. Colorado State University, Solar energy application lab. Fort Collins, Colorado.
- Oke, T.R., and G.B. Maxwell, 1975: Urban heat island dynamics in Montreal and Vancouver. Atmospheric Environment, Vol. 9, p. 191-200.
- Reiter, E.R., G.R. Johnson, W.L. Somervell, Jr., E.W. Sparling, E. Dreiseitl, B.C. Macdonald, J.P. McGuirk, and A.M. Starr, 1976: The Effects of Atmospheric Variability on Energy Utilization and Conservation. Environ. Research Paper No. 5, Colo. State Univ., Fort Collins, Colo., 72 pp.
- Rosenblatt, F., 1962: Principles of Neurodynamics: Perceptrons and the Theory of Brain Mechanisms. Startan Book, Washington, D.C.
- Schewe, G.J., 1975: A Climatology of Inversions. Atmospheric Sci. Paper No. 238, Dept. of Atmos. Sci., Colo. State Univ., Fort Collins, Colo., 103 pp.
- Solar Energy Lab, 1975: A transient simulation program - TRNSYS. University of Wisconsin, Madison, Wisconsin.
- Tseng-Yao, S., 1968: Shadow area equation for window overhangs and side fins and their application in computer calculations. ASHRAE Transactions. Vol. 74, No. 1.
- Woo, H.G.C., J.A. Peterka, and J.E. Cermak, 1976: Wind Tunnel Measurements in the Wakes of Structures. Contract NAS-8-29583. Colorado State Univ., Fort Collins, Colorado.

Auth Elmar R. Reiter, et al.

THE EFFECTS OF ATMOSPHERIC VARIABILITY ON
ENERGY UTILIZATION AND CONSERVATION

Colorado State University
Department of Atmospheric Science

Environmental Research Paper No. 14
February 1978. 75 pp.

U.S. Department of Energy
Grant No. EY-76-5-02-1340 A002

C00-1340-56

Our space-heating energy-consumption model for Greeley, Colorado for the winter of 1976-77 was within 98.9 percent of actual natural gas consumption for that city. Modelling of Cheyenne, Wyoming, including the testing of a new statistical scheme to develop the building census required by our energy consumption model, has progressed to the point where reliable natural gas consumption estimates can be made with our model for that community.

A detailed study of temperature and surface wind patterns in and near the city of Greeley, Colorado revealed that, at times, an urban

Subject Headings:

Atmospheric Variability
Weather Effects
Energy Consumption
Air-Sea Interactions
Energy Modelling

Author: Elmar R. Reiter, et al.

THE EFFECTS OF ATMOSPHERIC VARIABILITY ON
ENERGY UTILIZATION AND CONSERVATION

Colorado State University
Department of Atmospheric Science

Environmental Research Paper No. 14
February 1978. 75 pp.

U.S. Department of Energy
Grant No. EY-76-5-02-1340 A002

C00-1340-56

Our space-heating energy-consumption model for Greeley, Colorado for the winter of 1976-77 was within 98.9 percent of actual natural gas consumption for that city. Modelling of Cheyenne, Wyoming, including the testing of a new statistical scheme to develop the building census required by our energy consumption model, has progressed to the point where reliable natural gas consumption estimates can be made with our model for that community.

A detailed study of temperature and surface wind patterns in and near the city of Greeley, Colorado revealed that, at times, an urban

Subject Headings:

Atmospheric Variability
Weather Effects
Energy Consumption
Air-Sea Interactions
Energy Modelling

Author: Elmar R. Reiter, et al.

THE EFFECTS OF ATMOSPHERIC VARIABILITY ON
ENERGY UTILIZATION AND CONSERVATION

Colorado State University
Department of Atmospheric Science

Environmental Research Paper No. 14
February 1978. 75 pp.

U.S. Department of Energy
Grant No. EY-76-5-02-1340 A002

C00-1340-56

Our space-heating energy-consumption model for Greeley, Colorado for the winter of 1976-77 was within 98.9 percent of actual natural gas consumption for that city. Modelling of Cheyenne, Wyoming, including the testing of a new statistical scheme to develop the building census required by our energy consumption model, has progressed to the point where reliable natural gas consumption estimates can be made with our model for that community.

A detailed study of temperature and surface wind patterns in and near the city of Greeley, Colorado revealed that, at times, an urban

Subject Headings:

Atmospheric Variability
Weather Effects
Energy Consumption
Air-Sea Interactions
Energy Modelling

Author: Elmar R. Reiter, et al.

THE EFFECTS OF ATMOSPHERIC VARIABILITY ON
ENERGY UTILIZATION AND CONSERVATION

Colorado State University
Department of Atmospheric Science

Environmental Research Paper No. 14
February 1978. 75 pp.

U.S. Department of Energy
Grant No. EY-76-5-02-1340 A002

C00-1340-56

Our space-heating energy-consumption model for Greeley, Colorado for the winter of 1976-77 was within 98.9 percent of actual natural gas consumption for that city. Modelling of Cheyenne, Wyoming, including the testing of a new statistical scheme to develop the building census required by our energy consumption model, has progressed to the point where reliable natural gas consumption estimates can be made with our model for that community.

A detailed study of temperature and surface wind patterns in and near the city of Greeley, Colorado revealed that, at times, an urban

Subject Headings:

Atmospheric Variability
Weather Effects
Energy Consumption
Air-Sea Interactions
Energy Modelling

heat island effect is present, in spite of the relatively small size of that town.

During the present grant period we examined various feedback mechanisms between the oceans and the atmosphere. Several of these mechanisms appear to be the cause of the interannual variability of the atmosphere's general circulation and of climatic changes on a time scale of several tens of years. Specifically we examined a recent cooling trend in the North Pacific north of 40°N, and sea-surface temperature fluctuations with an irregular periodicity of 2 to 4 years superimposed upon this trend. To advance regional long-range forecasting skills we correlated January temperature anomalies over the eastern United States with flow patterns over the U.S. and Canada.

heat island effect is present, in spite of the relatively small size of that town.

During the present grant period we examined various feedback mechanisms between the oceans and the atmosphere. Several of these mechanisms appear to be the cause of the interannual variability of the atmosphere's general circulation and of climatic changes on a time scale of several tens of years. Specifically we examined a recent cooling trend in the North Pacific north of 40°N, and sea-surface temperature fluctuations with an irregular periodicity of 2 to 4 years superimposed upon this trend. To advance regional long-range forecasting skills we correlated January temperature anomalies over the eastern United States with flow patterns over the U.S. and Canada.

heat island effect is present, in spite of the relatively small size of that town.

During the present grant period we examined various feedback mechanisms between the oceans and the atmosphere. Several of these mechanisms appear to be the cause of the interannual variability of the atmosphere's general circulation and of climatic changes on a time scale of several tens of years. Specifically we examined a recent cooling trend in the North Pacific north of 40°N, and sea-surface temperature fluctuations with an irregular periodicity of 2 to 4 years superimposed upon this trend. To advance regional long-range forecasting skills we correlated January temperature anomalies over the eastern United States with flow patterns over the U.S. and Canada.

heat island effect is present, in spite of the relatively small size of that town.

During the present grant period we examined various feedback mechanisms between the oceans and the atmosphere. Several of these mechanisms appear to be the cause of the interannual variability of the atmosphere's general circulation and of climatic changes on a time scale of several tens of years. Specifically we examined a recent cooling trend in the North Pacific north of 40°N, and sea-surface temperature fluctuations with an irregular periodicity of 2 to 4 years superimposed upon this trend. To advance regional long-range forecasting skills we correlated January temperature anomalies over the eastern United States with flow patterns over the U.S. and Canada.

PREVIOUSLY PUBLISHED ENVIRONMENTAL RESEARCH PAPERS

- No. 1 On the Variability of Hemispheric Scale Energy Parameters, by J.P. McGuirk, E.R. Reiter and A.M. Barbieri, January 1975.
- No. 2 On Determining Vertical Wind Velocities from Eole Constant-Density Balloon Data, by Robert M. Banta, June 1975.
- No. 3 Atmospheric Eddy Transports and Their Efficiencies, by Srinivasan Srivatsangam, January 1976.
- No. 4 Interannual Variations and Regional Effects of Hemispheric Parameters, by Ann M. Starr (née Barbieri), July 1976.
- No. 5 The Effects of Atmospheric Variability on Energy Utilization and Conservation, by E.R. Reiter et al., November 1976.
- No. 6 Fluctuations in the Atmosphere's Energy Cycle, by James P. McGuirk, March 1977.
- No. 7 Oceanic Latent and Sensible Heat Flux Variability and Air-Interaction, by Anne D. Seigel, April 1977.
- No. 8 Observations of Stratospheric Thermal Structure from Satellites, by Thomas J. Kleespies, May 1977.
- No. 9 Effects of Coal Mine Drainage on Macroinvertebrates of Trout Creek, Colorado, by Steven P. Canton and James V. Ward, April 1977.
- No. 10 Potential Effects of Oil Shale Extraction and Processing Activities on Macroinvertebrates of Piceance and Black Sulphur Creeks, Colorado, by Lawrence J. Gray and James V. Ward, April 1977.
- No. 11 Modeling Atmospheric Dispersion of Lead Particulates From a Highway, by Paul C. Katen, July 1977.
- No. 12 Residence Time of Atmospheric Pollutants and Long-Range Transport, by Teizi Henmi, Elmar R. Reiter and Roger Edson, July 1977.
- No. 13 Quasi-Periodicities of Atmospheric Circulation and Their Application to Long-Range Weather Prediction, by S. Srivatsangam, Chi-Nan Hsiao, and Elmar R. Reiter, November 1977.