THE EFFECTS OF ATMOSPHERIC VARIABILITY ON
ENERGY UTILIZATION AND CONSERVATION

Summary of Research Conducted Between
1 November 1976 and 31 July 1977

by

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Again, we are indebted to Messrs. Raymond Fouts and Michael Erland of the Greeley Gas Company, Weld County Assessor Herbert Hansen, Thomas Rounds of the Weld County Planning Staff and 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, Bruce Burbank of Public Service Company of Colorado, Robert Beebe of the Cheyenne National Weather Service Forecast Office, Leo Breeden of Laramie County School District No. 1, John Dean of the Western High Plains Grasslands Experimental Station, Howard Gallensky of Fort Warren AFB, and the staff of the Laramie County Assessor's Office for assistance in acquiring the data needed to model the space-heating demand for 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 utility evaluation thereof

is possible. It will be appreciated that we cannot publish results applicable to a particular utility or utility customer until those results have first been accepted by that cooperator.

ABSTRACT

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.

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, is under way.

1.0 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 of 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 slipped by one year. More than half of 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 Section 2 of this report. Results are also being reported in several papers which have been submitted for publication to 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 an agreement within 98.9 percent with actual natural gas consumption. Section 3 of this progress report summarizes the results of the Greeley study. It also outlines a statistical approach to obtain a building census. This approach is presently being tested in Cheyenne, Wyoming.

Drs. Gearold Johnson and Elmar R. Reiter reported the major findings of our energy modelling study during 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. (Submitted to Journal of Atmospheric Science)

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

Reiter, E.R., Another Year of Drought Ahead? (Submitted to "Potato Grower of Idaho" and "The Sugar Producer")

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.

The Principal Investigator was on sabbatical leave during academic year 1976-77, and hence was relieved of all teaching and other departmental responsibilities. Thus, although the project was charged for $2\frac{1}{2}$ month of his time between 1 November 1976 and 31 July 1977, he actually was able to devote 4 months to the project. The Principal Investigator expects to devote an additional month to this project during the three months remaining in the current term.

2. ATMOSPHERIC VARIABILITY AND LONG-RANGE FORECASTING STUDIES

2.1 Ocean-Atmosphere Feedback Mechanisms

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. Examples of such a forecast by Namias for the severe winter of 1976/77 are shown in Fig. 1. These forecasts were based on SST anomalies such as the ones illustrated in Fig. 2.

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 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. 3.

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

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

Figure 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.)

Figure 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.)

Figure 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.

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, show several trend reversals between 1900 and the present (Fig. 4). There is a qualitative match between these long-term oceanic temperature variations and precipitation in the U.S. midwest (see e.g., the precipitation record for Columbia, Mo., published by the Committee on Climate and Weather, 1976). It has been pointed out recently by several authors that a "double sunspot cycle" of 22 years' periodicity underlies the major drought occurrences in the midwest. In the light of preliminary evidence from SST anomalies over the North Pacific, we most seriously question the contention that the sunspot cycle causes droughts. It is very difficult to see how a phenomenon with as little amplitude in energy variation as the double sunspot cycle could cause as large an energy variation as is observed in the North Pacific. Possible SST and drought correlations will be the subject of further study.

The recent long-term temperature decrease in the North Pacific was caused by a tightening of the meridional SST gradient into first one (by 1969), then two oceanic frontal zones (Figs. 5, 6, 7). 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,

Figure 4. Monthly sea surface temperature anomalies, ($^{\circ}\text{C}$), North Pacific 40-50 $^{\circ}\text{N}$ for the period 1900 - 1976 (last two digits of years labeled along abscissa). A linear 7-month running average filter has been applied to the data.

(a)

Figure 5. Mean monthly isotherms of SST by 1°C intervals (5°C intervals marked by heavier lines) for (a) May, (b) June, and (c) July 1963. Heavy dashed-dotted lines indicate discontinuities in meridional temperature gradients.

(b)

Figure 5 (continued)

(c)

Figure 5 (continued)

(a)

Figure 6. Same as Fig. 3, except for 1969.

(b)

Figure 6 (continued)

(c)

Figure 6 (continued)

Figure 7. Same as Fig. 3, except for 1976.

(b)

Figure 7 (continued)

(c)

Figure 7 (continued)

with a modest increase in the zonal wind stress in the trade-wind regions of the Pacific reported by Wyrtki and Meyers (1975). Thus, there appears to be a feedback mechanism operating between atmosphere and ocean which is illustrated schematically in Fig. 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 between the trade-wind v component and SST anomalies in the $40\text{--}50^{\circ}\text{N}$ latitude band is illustrated in Fig. 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 10 illustrates, as an example, the v component anomalies in the Pacific trade-wind regions of the two hemispheres and the time-lagged SST anomalies at $40\text{--}50^{\circ}\text{N}$.

The feedback mechanisms operating on these SST fluctuations are schematically described in Fig. 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. 11. It is no coincidence that 20 months correspond to the 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. 12 and 13) suggest the existence of a self-enforcing feedback loop (see Fig. 11) that intensifies the tropical

Figure 8. Schematic feedback system between atmospheric and oceanic large-scale circulation.

Figure 9. Lag correlation between the v component of the trade winds in the North Pacific and the SST anomalies in the Pacific latitude band $40-50^{\circ}N$. The dashed line makes use of monthly anomaly data, the solid line uses the seven-month-smoothed anomaly data. The dot diagram at the bottom indicates significance levels of the dashed and the solid curves (plotted with respect to a dashed or solid base line). Significance levels are indicated for 50%, 80%, 90% and 95% respectively.

Figure 10. SST anomalies from 15-year monthly means, seven-month time-smoothed ($^{\circ}\text{C}$, upper curve) in the latitude band $40\text{--}50^{\circ}\text{N}$ of the Pacific. Dashed-dotted lines indicate trends of maximum, mean, and minimum anomalies. Lower curves: v component anomalies of trade-wind circulation, m/sec, positive values indicate equatorward flow. Solid lines: average v component in box $5^{\circ}\text{N}\text{--}19^{\circ}\text{N}$, $125^{\circ}\text{E}\text{--}95^{\circ}\text{W}$; dotted line: $1^{\circ}\text{S}\text{--}15^{\circ}\text{S}$, $125^{\circ}\text{E}\text{--}75^{\circ}\text{W}$; shaded area marks difference between the two curves. The SST anomaly curve is time-lagged by 20 months against the v component curves. (Note: The slight discrepancies between the SST anomalies depicted in this diagram and those shown in Fig. 3 are due to the use of different smoothing techniques. The anomalies shown in this diagram were derived by averaging grid point values falling into the respective latitude band whereas the anomalies shown in Fig. 3 were derived by transposing grid point values to 5° -latitude-longitude intersection points.)

Figure 10

Figure 11. Schematic flow-diagram of feed-back mechanisms between mid-latitude sea-surface temperature (SST) anomalies, atmospheric meridional temperature and height gradients, trade-wind circulation and large-scale water transport in the North Pacific. (Solid lines with arrows indicate amplifying [positive] feedback, dashed line symbolizes damping [negative] feedback.) (For explanation see text.)

Figure 12. Anomalies from 20-year monthly mean rainfall index for the Line Islands (dashed line, scale on left side of diagram) and average v component departure (positive for winds blowing towards the equator) of the trade winds in the North and South Pacific (solid line, scale in m/sec on right side of diagram). The vertical lines in the coordinate grid pertain to January of each year. Seven-month running averaging has been applied to the monthly departure values.

Figure 13. Correlation between the Line Island precipitation index departures from the monthly mean values 1956-1975, and the monthly values of the average of the two curves of the northern and southern hemisphere v components (positive towards the equator) in the Pacific trade-wind region. The regression for the data from 1963 to 1972 can be expressed as Line Island Rain Index = $82.913 \frac{v_{N.H.} + v_{S.H.}}{2} - 0.732$ if the wind speeds are given in m/sec.

The standard deviation of the ten years of monthly departures from normal of the combined v component data is $\sigma_v = 0.196$ m/sec, the standard deviation for the Line Island precipitation index for the same ten years is $\sigma_{p.I.} = 18.533$. The correlation coefficient between the two sets of data is $R = 0.8786$.

Figure 13.

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. 12 coincides with 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.

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 (Warsh, 1973)

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

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

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 (Laevastu, 1963).

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. 11, causing its eventual breakdown. As the feedback cycle collapses, the trade-wind 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.

2.2 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 a component correlated to the hemispheric midtropospheric 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. Temperature anomalies for stations

in each state (shown in Fig. 14) 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 pattern 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. These "gradients" 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 dividing by the magnitude of the resultant vector,....

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

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

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

so that

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

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 $\vec{T}_2$ and $\vec{T}_3$, respectively, i.e., by computing the scalar product

$$C_j = \vec{T} \cdot \vec{T}_i.$$

Figure 14. Monthly mean temperature anomalies from the indicated states were used to calculate C_1 , C_2 , and C_3 , the temperature-pattern coefficients.

The three values of C_j are used in our analysis to depict the 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_j , with some physically meaningful feature of the larger-scale flow. It is the experience of many operational forecasters, that the 500-mb flow field directs 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 ($i = 1, 70$), 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 $\gamma_{ij}^2 S_{ij}$ 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 $\gamma_{ij}^2 S_{ij}$ can thus be used to represent the patterns of v_i which most significantly affects C_{ji} . These patterns are shown in Figs. 15, 16, and 17, 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. 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.

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. 16 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 our region. 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. 17, strong northerly (low or negative) values of $\bar{v}$ over the eastern United States are related to high

Figure 15. The normalized pattern $r_{i_2}^2 s_{i_1}$ 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. See text for details.

Figure 16. The normalized pattern $r_{i_2}^2 s_{i_2}$ which represents the linear relationship between the north-south gradient of surface-temperature coefficient, C_2 , and the monthly mean meridional wind $\bar{v}$ at each point. See text for details.

Figure 17. The normalized pattern $r_{i_3}^2 s_{i_3}$ which represents the linear relationship between the east-west gradient of surface-temperature coefficient, C_3 , and the monthly mean meridional wind $\bar{v}$, at each point. See text for details.

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_1 , C_2 , and C_3 . Let $\vec{A}_i$ ($i = 1, 2, 3$) represent 70-component vectors extracted from the $\bar{v}$ data in either Figs. 15, 16, or 17 to represent 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 . Figures 18, 19, and 20 show the scatter

Figure 18. Observed mean temperature-pattern coefficient (C_1) versus $\bar{v}$ pattern coefficient (B_1). The least-squares linear fit is also plotted.

Figure 19. Observed north-south temperature-gradient-pattern coefficient C_2 versus $\bar{v}$ pattern coefficient B_2 . The least-squares linear fit is also plotted.

Figure 20. Observed east-west temperature-gradient-pattern coefficient (C_3) versus $\bar{v}$ pattern coefficient B_3 . The least-squares linear fit is also plotted.

diagrams and the least-squares linear fit for the three relationships. The linear equations along with the standard error and the percent of explained variance for the three relationships are shown in Table 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 1 also allow us to assess the standard error of our estimate.

The results of these established relationships allow us to conclude that the regional temperature anomalies for January can be explained at least partially from the standing-eddy flow patterns of the midtropospheric v component for that month. Further research during this contract period will assess the importance of the u component, or westerly winds, of the monthly standing eddies. During the next contract period, we plan to investigate the influence of the North Pacific sea-surface-temperature anomaly patterns upon the development of standing waves over North America. After meaningful connections between these features are established, we will begin to develop a predictive scheme which will allow us to forecast surface-temperature anomalies over the eastern United States from the sea-surface-temperature anomaly patterns.

In addition to these correlations we plan to examine the influence of both the size of the hemispheric cold pool and the three-week cycle of hemispheric energy parameters (McGuirk & Reiter, 1976) upon the relationships we have derived.

Table 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

3.0 PHYSICAL MODEL OF SPACE-CONDITIONING ENERGY CONSUMPTION

During the current grant period, primary modelling emphasis has been directed at:

- (1) validating additional building thermal classifications from data acquired in Greeley, Colorado, Cheyenne, Wyoming and a mid-western metropolis;
- (2) calculating the energy consumed by Greeley for space heating during the 1976-1977 winter;
- (3) continued development of the structure of the computer program for investigating weather-sensitive demands for energy;
- (4) developing a statistical technique for generating residential building censuses, for application first to the city of Cheyenne;
- (5) conducting meteorological studies of Greeley, Cheyenne and the midwestern metropolis, to more accurately define wind and temperature variations across these cities and to better understand their urban heat islands; and
- (6) readying the Cheyenne data in anticipation of calculating the space-heating energy consumed by that city during the 1976-1977 winter.

3.1 Validation of Building Modules

In this contract period to date, four more Greeley modules have been validated: a small one-story bank representative of many detached commercial structures; an industrial building (in this case, an all-metal structure); a high school representative of a low-rise public building; and a modern 3-story brick apartment building. Additional validations were conducted on the mobile-home park and the Weld County Hospital.

The module-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 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, and the space-conditioning demand for energy is calculated in two-hour steps for the entire heating season.

(6) The actual energy consumption and the calculated space-conditioning energy consumption are compared and the residuals are determined. If the results are acceptable (sum-of-square errors less than *a priori* 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 algorithm [Gabor et al., 1961; Ivakhnenko, 1971; Ivakhnenko et al., 1974; Leong, 1975]) which maintains the structural form of all equations used but reestimates the term coefficients. These resulting coefficients are analyzed to ensure reasonableness of value (i.e., they represent updated overall heat-transfer coefficients or use-pattern coefficients). The adaptive learning algorithm only uses a portion of the time series as a 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-of-square error criterion is met.

Figures 21 and 22 present preliminary validation results for the bank and the high school. These modules represent the current models for detached commercial and modern public buildings.

Validations to be carried out during the remainder of this contract year include a museum, high-rise post office, laundry, hangar, federal office building and VA hospital center in Cheyenne, Wyoming. Upon satisfaction of the mix of structural types needed to model Cheyenne, emphasis will shift to building types more representative of a large metropolis. In this regard, 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.

3.2 1976-1977 Greeley Energy Consumption

Following incorporation of refinements represented by the five newly validated structures and updating of the building census to reflect the 300-odd buildings constructed during the past year, the Greeley model was run for the 1976-77 winter. The results, shown in Fig. 23, were computed space-heating consumption of natural gas which was 98.9% of actual. It should be noted also, that the day-to-day differences were much smaller than those which occurred during the 1975-76 winter, when periods of pronounced overprediction compensated partially for other periods with serious underpredictions.

3.3 Model Development

With respect to development of the energy model, it should be noted that there are two opposing 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 for the lowest components

Figure 21. Comparison of measured total daily with calculated space-heating gas use for low-rise commercial buildings. 16 December 1976 to 6 March 1977. Greeley, Colorado.

Figure 22. Comparison of measured total daily with calculated space-heating gas use for a low-rise high school 16 December 1976 to 6 March 1977. Greeley, Colorado.

Figure 23. Comparison of measured total daily and predicted space-heating gas use with weather, Greeley, Colorado, 16 December 1976 to 6 March 1977.

(each individual building) and calculate the energy consumption for 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 level 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. A refinement in the input-data procedure is currently being used for the city of Cheyenne. In the latter case, described in the next section, a less detailed building census is generated by means of statistical sampling schemes and procedures rather than a physical survey. The purpose is to constrain the workload to a tractable level, consistent with model-information needs, for later use in 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 socioeconomic data available within the community. Because of the incomplete knowledge and the limited amount of available information, estimates from the macromodel are always associated with error terms described by probabilistic statements. However, if derived per capita indices were understood for once, and not just determined by mechanical calculations, there is reason to believe that we could apply modifications thereof with confidence to different communities. We are therefore now investi-

grating the possibility of jointly studying Pittsburgh, Pennsylvania with a Carnegie-Mellon University group having a strong interest in the impact of weather upon the socioeconomic consequences of energy nonavailability.

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.

Figure 24 illustrates the block structure of the physical-adaptive model. Each major block (subsystem) is described below. The "data Base" block represents the finite memory of the system, which is a 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," allowing the model to be improved or updated by the introduction of new data.

The "reconstruction" 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.

The "hypothesis testing" block is used to detect the degree or 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

Figure 24. The self-organized dynamic forecasting model with adaptive feedback, diagnostics, updating and re-evaluation mechanisms.

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 prove 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 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 algorithm.

The model-updating block is currently operational and has been used to update the current model based on information from the data base. For example, by adding the 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 model is for heating only, and can be used to predict or simulate the energy utilization for space heating 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 that 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. 24 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 by a major midwestern metropolis, as soon as the structural data base is compiled.

3.4 Building Census

We recognized the need for a less arduous approach to the generation of a census of the buildings within a community, than that employed in Greeley, Colorado. The methodology developed for determining less detailed descriptions of the buildings in Cheyenne, Wyoming, uses a statistical sampling scheme wherein it is assumed that the required degree of accuracy will vary according to whether the buildings are residential, commercial, public or industrial. It will be recalled (Reiter et al., 1976), that even though in Greeley the nonresidential buildings represent less than 10% of the total building count, they consumed more than 40% of the natural gas consumed for space conditioning.

In its present form, our sampling scheme applies only to residential structures other than mobile homes and apartment buildings. This restriction has been imposed because of the pronounced heterogeneity of nonresidential structures. However, once verified for the relatively homogeneous residential structures, the procedure will be extended to nonresidential buildings.

Our statistical methodology has three fundamental procedures:

(1) Analysis of aerial photography; (2) Assignment of an appropriate sample size according to the homogeneity of an area; and (3) Acquisition of the data sample which contains the proper building information.

(1) STEP I: Analysis of aerial photography.

The first step in the analysis is to divide the area to be surveyed into sections which will have physical continuity with weather patterns which occur in that area. In order that the meteorological analysis need not be completed before the building census is started, the sections are defined so as to be small enough that the meteorological variables may be considered constant throughout each section. Here, we define each section to be one square mile.

The buildings in each section are then classified according to their age group and use pattern, i.e., residential, commercial, public or industrial. The delineations according to use pattern and age group are then used to establish the total count, or frame, on which the sampling is based.

(2) STEP II: Assignment of Appropriate Sample Size

In modelling Greeley, we found that it is sufficient to use the average space dimensions of each building type and age group in a section. This is important for minimizing the sample size.

Theoretically, to minimize the sampling size there must be some prior knowledge of certain properties of the population. Since for Cheyenne this information is not available to us at this time, we devised an analytical approach to defining the proper sample size. Our approach is based upon the building data we obtained for Greeley, Colorado, where a total census of the area was performed.

In this approach, the average Greeley, Colorado residential building dimension by each age group was calculated over 13 square-mile sections

for several different sample sizes using simple random sampling. The different sample sizes were calculated as percentages of the total number of residential buildings in each section.

Figure 25 is an example of this calculation for one of these Greeley sections. The dark solid lines represent the true average floor size. The light lines show the composite results of taking each sample 200 times. The numbers to the right of each curve are the standard error of the average floor area for each respective sample size.

The standard error is calculated as:

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

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.

This formulation of the standard error is based upon the assumption of a normal distribution, which is observed upon examining the 200 observations which make up Fig. 25. Also noted on Fig. 25 is the total number of residences in each of the different age groups.

Upon examination of all of the 13 Greeley sections analyzed, it was observed that the standard errors appeared to be a function of the total number of units in each age group. The functions observed are shown in Figs. 26, 27 and 28 for 1%, 5% and 10% sample sizes, respectively, and show an inverse log-log relationship. The solid lines are the least-squares fit of the data points, and the dashed lines represent one standard deviation of this line. The ordinate (y - axis) in all cases is in actuality twice the standard error, so as to represent a 95% probability confidence level.

Figure 25. Average floor sizes, in square feet, for each age classification for one square mile section in Greeley, Colorado as a function of sample size. The dark lines represent the true average floor sizes and the numbers to the right of each curve are the standard errors of the mean for each respective sample size.

Figure 26. Number of residential structures in each age group as a function of twice the standard error of the average floor area for a 1% sample size for 13 sections in Greeley, Colorado. The solid line is the least-squares fit of the data points and the dashed lines are one standard deviation of the least squares fit.

Figure 27. Same as Figure 26, except for a 5% sample size.

Figure 28. Same as Figure 26, except for a 10% sample size.

It is from these three curves that we analytically established the proper sample size according to a predetermined tolerable error of the building dimensions. For example, if the tolerable error is 50 ft^2 , there must be at least 500 residences for each age group to be able to take a 1% sample, or 200 to take a 5% sample, or 100 to take a 10% sample. By assuming that the population of residences in Greeley is representative of other residential populations, we are applying this sample-sizing technique to the generation of a building census for Cheyenne.

Preliminary sensitivity analyses of the physical model indicate that a uniform 10% error in the size of the buildings in Greeley would have produced a 6% error in the predicted energy consumption. Knowing that the average size of the buildings in Greeley is 1595 ft^2 , we can say that an error of 50 ft^2 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 ft^2 . In the sampling of residential buildings we have used this 50 ft^2 error as our upper bound.

(3) STEP III: Acquisition of Data Sample.

Having determined the proper sample size for each square-mile section, a set of random numbers is applied to each 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 recording this information. The use of the Cheyenne assessor's files for residential type buildings has thus far been quite successful. However, complications may occur when a sampling of nonresidential buildings is attempted, due to the fact that only taxable structures are inventoried by the assessors.

3.5 Meteorological Analyses

Because of difficulties experienced in defining the Greeley, Colorado, urban heat island during the 1975-76 winter, we established 7 additional weather stations around the city from 16 December 1976 to 6 March 1977. The locations of these stations and of the two stations maintained by the University of Northern Colorado are shown in Fig. 29, wherein the plotted winds and temperatures are fairly typical of the clear-sky patterns experienced near sunrise. For example, it will be quite evident that on this occasion (and generally throughout the winter) the lower minimum temperatures occurred at the lower elevations, as is to be expected. It should be noted, that the specific Greeley station locations indicated in Fig. 29 were based upon locations proximate to building types high on the priority list for module validation -- rather than any meteorological factor.

In our study of Greeley 1976-77 winter wind and temperature patterns, we have been far more successful than previously in defining an urban heat island of the approximate magnitude and in the location which research elsewhere would have suggested for this community. The distinction between the radiative and thermal characteristics of urban versus rural areas is quite apparent in the temperature differences observed, particularly during the evening hours. In fact, we believe that we are able to detect evidence that part of the difference is due to the release of anthropogenic heat. We are therefore attempting to develop a modified Gaussian diffusion model for diffusing the anthropogenic heat into the planetary boundary layer over a city.

In our 1976-77 Cheyenne analyses, on the other hand, owing to the greater average wind speed and the arrangement of the city, it has been more difficult to detect and define the urban heat island. This analytical

0700T, 21 FEB 1977

Figure 29. Map showing location of weather stations in vicinity of Greeley, Colorado, just west of the junction of South Platte and Cache La Poudre Rivers. Weather data plotted for 7:00 A.M. following a clear night. Minimum Temp = 13.5°F. Maximum temp. = 67.0°F. Winds less than 3 MPS.

problem has been aggravated by the installation at the 6 Cheyenne locations shown in Fig. 30 (again selected primarily on the basis of high-priority building validations) of the poorest of the meteorological instrumentation available to us. Notwithstanding, we are hopeful that following detailed examination we will be able to distinguish between temperature differences due to topography and those caused by the urban heat island.

We have not yet commenced analysis of the weather data collected for the 8 project stations installed during the 1976-77 winter at the midwestern metropolis. At this time, these data are primarily for the validation of structures representative of large cities and not for city-wide-energy-consumption calculations. However, in preliminary examinations of project and the routinely available weather data, temperature differences as large as 17°C between city center and outskirts have appeared. It is not yet suggested that such differences are due entirely to an urban heat island, for the reason that equipment security dictated that we mount much of our instrumentation on the buildings to be validated. Hence, it is possible that the warmer temperatures reflect the transmission of heat through building walls and roofs.

In view of the far greater complexity and the relative immensity of many metropolitan structures and the large temperature differences observed during the 1976-77 winter, we are again installing a number of wind and temperature sensors (obtained from the National Center for Atmospheric Research) throughout the midwestern metropolis for the forthcoming winter. However, whereas funding limitations necessitated dependence upon cooperative building owners/superintendents/engineers last winter, with some losses in data quality and continuity, for the 1977-78 winter arrangements will be made for weekly maintenance visits to each of the planned 25 stations by a project agent.

Figure 30. Map showing location of weather stations in vicinity of Cheyenne, Wyoming. Municipal boundary indicated by dashed lines. Thin solid lines are terrain height contours. Heavy solid line is one square mile grid.

3.6 Modelling Cheyenne, Wyoming

The principal modelling activity during the remainder of the current contractual period will be prediction of natural gas consumed in space heating of the city of Cheyenne during the 1976-77 winter. All commercial, industrial and public buildings have been censused individually from assessor's files and/or site visits. Moreover, Fort Warren AFB has been isolated and is being separately modelled. Therefore, the goodness of our Cheyenne space-heating computations will be a reflection of the degree to which our statistical sampling methodology produces a valid thermal data base for residential structures.

If the sampling procedures are effective, then coupled with the validated modules it would appear that the first steps have been taken to the modelling of any community with tractable input-data requirements. In our future work these procedures will be refined and documented.

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