

Evaluation of Climate Change Using Numerical Models

R. A. Pielke

Cooperative Institute for Research in the Atmosphere
and

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

1 Abstract

This short paper discusses two approaches to permit the interpolation of GCM model results down to local scales. The first approach uses a synoptic classification of GCM output to construct dominant large scale weather scenarios from which local scale model simulations can be performed. The second approach links the GCM model output to two-way multiple interactive numerical model grids which telescope down to the local scale. The local scale models in both cases include detailed terrain, and vegetation and soil representations of the area. Vegetation changes due to climate change can assist in the estimation as to whether alterations in the biosphere can mitigate climate change perturbations (i.e., the Lovelock Gaia hypothesis).

2 Introduction

Climate global circulation models (GCMs) have been effective at focusing attention on potential long-term changes in global climate (e.g., see the Schlesinger et al., 1985 excellent review). Unfortunately, however, these models have not yet attained sufficient spatial resolution to target specific geographic areas, nor have they included a number of important physical feedback mechanisms.

This short paper discusses two approaches to permit the interpolation of GCM model results down to local scales. The first approach uses a synoptic classification of GCM output to construct dominant large scale weather scenarios from which local scale model simulations can be performed. The second approach links the GCM model output to two-way multiple interactive numerical model grids which telescope down to the local scale. The local scale models in both cases include detailed terrain, and vegetation and soil representations of the area. Vegetation changes due to climate change obtained from ecosystem models can assist in the estimation as to whether alterations in the biosphere can mitigate climate change perturbations (i.e., the Lovelock Gaia hypothesis; Lovelock, 1979).

The final section of the paper lists several physical mechanisms which need to be added to GCM simulations before the model results could be accepted as definitive. Also discussed are additional tests which need to be performed to demonstrate the credibility of the GCMs.

3 Synoptic Classification Using GCM Output

Pielke et al. (1987) discussed a procedure to type synoptic weather using conventional large scale weather analyses. Illustrated in Figure 1¹,

¹Figure 1 and Tables 1 and 2 are reproduced from Pielke et al. (1987).

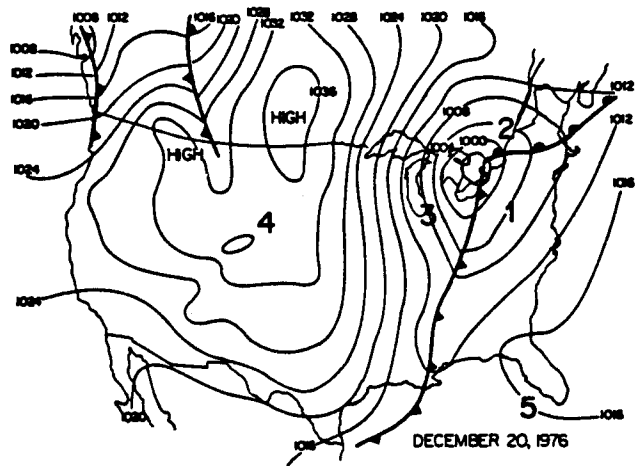
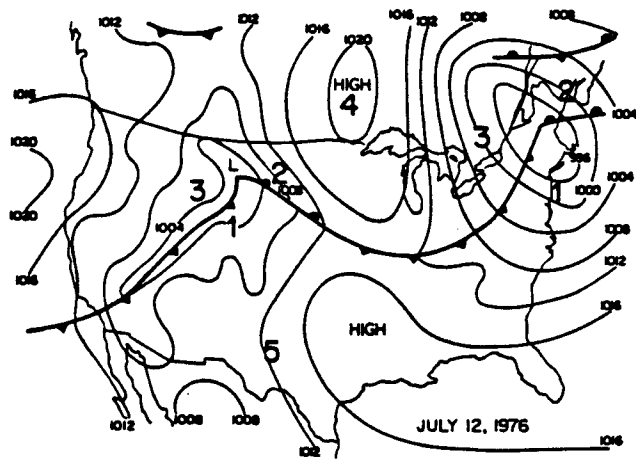


Figure 1. Synoptic classification scheme illustrating typical (a) summer and (b) winter patterns.

the dominant zones within major midlatitude weather systems are identified. Table 1¹ and 2¹ summarize major attributes of each synoptic category. Several investigations have used this synoptic categorization to analyze local climatology. In Yu and Pielke (1986), for example, the frequency and duration of these synoptic classes for a five-year period between October and May in southern Utah were determined as part of an air quality study. Pielke et al. (1986) have used these synoptic categories, and subclasses related to surface synoptic geostrophic wind speed and direction within each category, to estimate worst case air pollution dispersion situations over southern Florida. Garstang et al. (1980), and Lindsey (1980), where this synoptic classification procedure was first introduced, determined the daily frequency of the different synoptic categories for a 10-year period along the Atlantic and Gulf coasts of the United States. Lindsey and Glantz (1984, 1986) used this approach to characterize local meteorology at nuclear facilities. Snow (1981) applied the synoptic classification scheme to determine representative cases to integrate a mesoscale meteorological model in order to estimate wind energy potential for regions along the Gulf of Mexico and Atlantic coasts of the United States. It was found for that study that only three integrations for each site of the mesoscale model were needed to characterize the wind energy available. Recently Stocker and Pielke (1987) have added two categories (corresponding to the monsoon trough and eastern side of the subtropical ridge) for application to the western United States.

Pielke et al. (1987) discussed the application of this synoptic classification scheme to define frequency of occurrence of major weather features as related to the polar front, and to use the frequency of times a location is poleward of the front to meteorologically define seasons. An example of the use of this technique was presented using 10 years of data from the Atlantic and Gulf coasts of the United States. While the frequency of the specific types of major synoptic weather features vary with latitude, the meteorological definitions of season was found to be comparatively invariant with latitude (differing by no more than a month) for this geographic area. Using a meteorological definition, the average winter occurs from late October or early November to late March or early April in the geographic region studied. Summer is from late May to early June until late August or late September. Changes in climatic conditions do not occur as just a gradual change in temperature or in the amount of precipitation but rather in the frequency with which a given region is subjected to the dominant synoptic systems. The net result of the aggregation of synoptic systems yields climate. If the aggregation changes, climate changes. Thus by using GCM model output and typing the weather categories in a climate change scenario, representative cases within each scenario can be used to integrate a numerical mesoscale model in order to assess local long-term weather changes due to GCM simulated large scale climate changes.

With the finest spatial resolution of about 2° x 2° (222 km x 222 km) in GCM models, it is impossible to adequately resolve features with a scale of 4Δx or smaller (i.e., 888 km x 888 km), as discussed in Pielke (1984, Chapter 10) and elsewhere. Therefore, it will be impossible to properly simulate local climate effects due to only information from a GCM simulation of a change in climate. Using the synoptic classification approach, however, it will be possible to integrate down to local scales using the

¹Figure 1 and Tables 1 and 2 are reproduced from Pielke et al. (1987).

Table 1. Synoptic classification scheme (from Pielke, 1982; modified from Lindsey, 1980).

Category	Air mass	Reason for categorization*
1	<i>mT</i>	<i>In the warm sector of an extratropical cyclone. In this region the thickness and vorticity advection is weak with little curvature to the surface isobars. There is limited low level convergence with an upper level ridge tending to produce subsidence. Southerly low-level winds are typical</i>
2	<i>mT/cP, mT/cA, mP/cA</i>	<i>Ahead of the warm front in the region of cyclonic curvature to the surface isobars. Warm air advecting upslope over the cold air stabilizes the thermal stratification, while positive vorticity advection and low-level frictional convergence can add to the vertical lifting. Because of the warm advection, the geostrophic winds veer with height. Low-level winds are generally north-easterly through south-easterly</i>
3	<i>cP; cA</i>	<i>Behind the cold front in the region of cyclonic curvature to the surface isobars. Positive vorticity advection and negative thermal advection dominate, with the resultant cooling causing strong boundary layer mixing. The resulting thermal stratification in the lower troposphere is neutral, or even slightly, superadiabatic. Gusty winds are usually associated with this sector of an extratropical cyclone. Because of the cold advection, the geostrophic winds back with height. Low-level winds are generally from the north-east through south-west</i>
4	<i>cP; cA</i>	<i>Under a polar high in a region of anticyclonic curvature to the surface isobars. Negative vorticity advection, weak negative thermal advection and low-level frictional divergence usually occur, producing boundary layer subsidence. Because of relatively cool air aloft, the thermal stratification is only slightly stabilized during the day, despite the subsidence. At night, however, the relatively weak surface pressure gradient associated with this category causes very stable layers near the ground on clear nights due to long-wave radiational cooling. The low-level geostrophic winds are usually light to moderate varying slowly from north-westerly to south-easterly as the ridge progresses eastward past a fixed location</i>
5	<i>mT</i>	<i>In the vicinity of a subtropical ridge where the vorticity and thickness advection, and the horizontal pressure gradient at all levels are weak. The large upper-level ridge, along with the anticyclonically curved low level pressure field, produces weak but persistent subsidence. This sinking causes a stabilization of the atmosphere throughout the troposphere. Low-level winds over the eastern United States associated with these systems tend to blow from the south-east through south-west</i>

* This discussion applies to northern hemisphere.

Table 2. Overview of meteorological aspects of the 5 synoptic categories illustrated in Figure 1 which can be directly obtained from synoptic surface analysis (northern hemisphere) (adapted from Forbes and Pielke, 1985 and Pielke et al., 1986).

Category Characteristics	Category 1	2	3	4	5
Category Class	mT: In the warm sector of an extratropical cyclone	mT/cP, mT/cA, mP/cA: Ahead of the warm front in the region of cyclonic curvature at the surface	cP, cA: Behind the cold front in the region of cyclonic curvature to the surface isobars	cP, cA: Under a polar high in a region of anticyclonic curvature at the surface	mT: In the vicinity and west of a subtropical ridge
Surface winds	Birk SW surface winds	Light to moderate SE to ENE surface winds	Strong NE to SW surface winds	Light and variable winds	Light SE to SW winds
Vertical motions	Weakening synoptic descent as the cold front approaches	Synoptic ascent due to warm advection and negative vorticity advection aloft becomes positive vorticity advection aloft closer to low center, resulting in enhanced vertical motion	Synoptic ascent due to positive vorticity advection aloft (in this region this ascent more than compensates for the descent due to cold advection)	Synoptic descent (due to warm advection and/or negative vorticity advection aloft)	Synoptic subsidence (descending branch of the Hadley cell). Descent becomes stronger as you approach the ridge axis
Temperature advection Inversion	Little temperature advection at the surface Weak synoptic subsidence inversion caps planetary boundary layer	Warm advection above the frontal inversion Boundary layer capped by frontal inversion	Cold advection at the surface Deep planetary boundary layer	Weak temperature advection at the surface Synoptic subsidence inversion and/or warm advection aloft create an inversion which caps the planetary boundary layer	Weak temperature advection at the surface Synoptic subsidence inversion
Diurnal variation in boundary-layer stability	Moderate diurnal variability in the boundary-layer stability	Little diurnal variability in boundary-layer stability because of cloud cover	Little diurnal variability in the boundary-layer stability because of strong winds and destabilizing of boundary layer by cold advection	In the absence of snow cover, because of clear skies and light winds, there is large diurnal variability in boundary-layer stability	Moderate diurnal variability in boundary-layer stability
Diurnal variation in surface layer stability	Moderately unstable surface layer during the day Moderately stable surface layer during the night	Stably stratified surface layer day and night	Near neutral surface layer day and night	Weakly to moderately unstable surface layer during the day unless snow cover present or low Sun angle, in which case surface layer tends to be stably stratified. Very stable surface layer at night	Moderately to strongly unstable surface layer during the day. Moderately to strongly stable surface layer during the night
Humidity near the surface	Often humid in relative and absolute sense	Often dry in absolute sense, but humid in relative sense	Dry in the absolute sense; usually dry in the relative sense	Dry in the absolute sense, humid in the relative sense at night/dry in relative sense during the day except when ground is snow-covered	Humid in relative and absolute sense
Cloud cover	Clear to partly cloudy skies except near squall lines	Mostly cloudy to cloudy	Clear to scattered or broken shallow to medium depth convective clouds	Clear except tendency for fog at night	Day: scattered fair weather cumulus Night: clear (except near the mesoscale systems listed below)
Dominant mesoscale systems	Squall lines	Embedded lines of convection	Forced airflow over rough terrain systems: lake effect storms	Mountain-valley flows, land-sea breezes, urban circulations (thermally-forced systems)	Mountain-valley flows, land-sea breezes, urban circulations (thermally-forced systems)
Precipitation types	Organized lines of convective precipitation	Often stable cloud types and precipitation. Overcast in general	Medium to shallow depth convective clouds, showery precipitation	No precipitation	Shallow low convective clouds with deeper convective clouds and precipitation organized by thermally forced mesoscale systems such as listed above
Ventilation	Moderate to good ventilation	Poor ventilation of low level (i.e. below frontal inversion) emissions	Excellent ventilation	Night or snow-covered ground: poor ventilation Day: poor to moderate ventilation	Day: moderate to good ventilation Night: moderate to poor ventilation
Deposition	Dry deposition except wet deposition in showers	Dominated by wet deposition	Dry deposition except in showers	Dry deposition	Dry deposition except wet deposition in showers and thunderstorms
Transport	Long range	Long range above inversion	Long range	More local as you approach the centre of the polar high	More local as you approach the centre of the subtropical high

synoptic categories and a physically sophisticated mesoscale meteorological model. Such a modeling approach has the advantage of being able to represent terrain features which do not currently occur in a region, such as glaciers, snowfields, and different types of vegetation. In addition, GCM predictions of prevailing wind flows different from those found currently could be realistically represented since the model is based on fundamental physical concepts. Greenhouse gas effects could similarly be included.

In summary, GCM model output can be quantitatively evaluated in terms of synoptic categories. Using grid point data from the GCMs the following quantities can be used to define categories (illustrated here for midlatitudes):

- Category 1:

- cyclonic 1000 mb height curvature; negligible 500 mb vorticity advection; and negligible 700 and 850 mb temperature advection; equatorward of polar front

- Category 2a:

- cyclonic 1000 mb height curvature; positive 700 and 850 mb temperature advection; negative 500 mb vorticity advection; poleward of polar front

- Category 2b:

- cyclonic 1000 mb height curvature; positive 700 and 850 mb temperature advection; positive 500 mb vorticity advection; poleward of polar front

- Category 3:

- cyclonic 1000 mb height curvature; negative 700 and 850 mb temperature advection; positive 500 mb vorticity advection; poleward of polar front

- Category 4a:

- anticyclonic 1000 mb height curvature; negative 700 and 850 mb temperature advection; negative 500 mb vorticity advection; poleward of polar front

- Category 4b:

- anticyclonic 1000 mb height curvature; positive 700 mb and 800 mb temperature advection; negative 500 mb vorticity advection; poleward of polar front

- Category 5:

- anticyclonic 1000 mb height curvature; equatorward of polar front; west side of a subtropical ridge's north-south axis

- Category 6:
 - anticyclonic 1000 mb height curvature; equatorward of polar front; east side of a subtropical ridge's north-south axis
- Category 7:
 - cyclonic 1000 mb height curvature; equatorward of polar front

Within each category, average wind speed and direction, average temperature and moisture soundings, and their standard deviations would be used to set up the initial conditions for the mesoscale meteorological model.

To obtain the synoptic categories, the GCM models must be integrated with seasonal cycles in order to provide the most accurate climate estimates. The integration of GCM models for many days with frozen external forcing in order to obtain "equilibrium conditions" is unrealistic. The real atmosphere is not in equilibrium since the solar input changes continuously throughout the year.

4 Telescoping Nested Grids

The use of GCM model output to provide boundary conditions for a regional-mesoscale nested grid model is an effective technique to link climate changes from a global model to what is expected to occur on a local scale. Such nested models are becoming state-of-the-art. One such example is the Regional Atmosphere Mesoscale Model (RAMS) reported most recently in Cotton et al. (1987) where the nested approach was applied on the large eddy simulation scale. Cram and Pielke (1987) describe a one-way nested version of RAMS used to link National Meteorological Center (NMC) analyses on a large scale to a regional-mesoscale nested grid simulation of a major snowstorm in Colorado.

This approach has the advantage of being able to include detailed terrain, vegetation characteristics, and details of glaciation, if present, which are necessarily lacking in the GCM model because of its lack of resolution. The mesoscale model can even be linked to an ecosystem model in order to investigate the interaction between local climate and the biosphere. Local summer snowfield effects on the surface energy budget can also be included if they develop in the local scale model. Such snowfields will have a major effect on local climate because of changes in albedo that result.

The cost of a nested model simulation for several hundred years is greater than that of the GCM alone but is feasible with state-of-the-art supercomputers. An example of a grid which could be applied to simulate the grassland-forest boundary in the central United States is presented as Figure 2.

A statistical model correlation between GCM output and local weather cannot be applied for general climatic change since a regression model can only be expected to be accurate for the same range of input-output conditions for which it was developed. Even for that case, the model should be tested against an independent data set. When the input parameters fall outside of the data used to construct the regression, nonlinear effects can cause the regression estimate to be in serious error. Thus for future

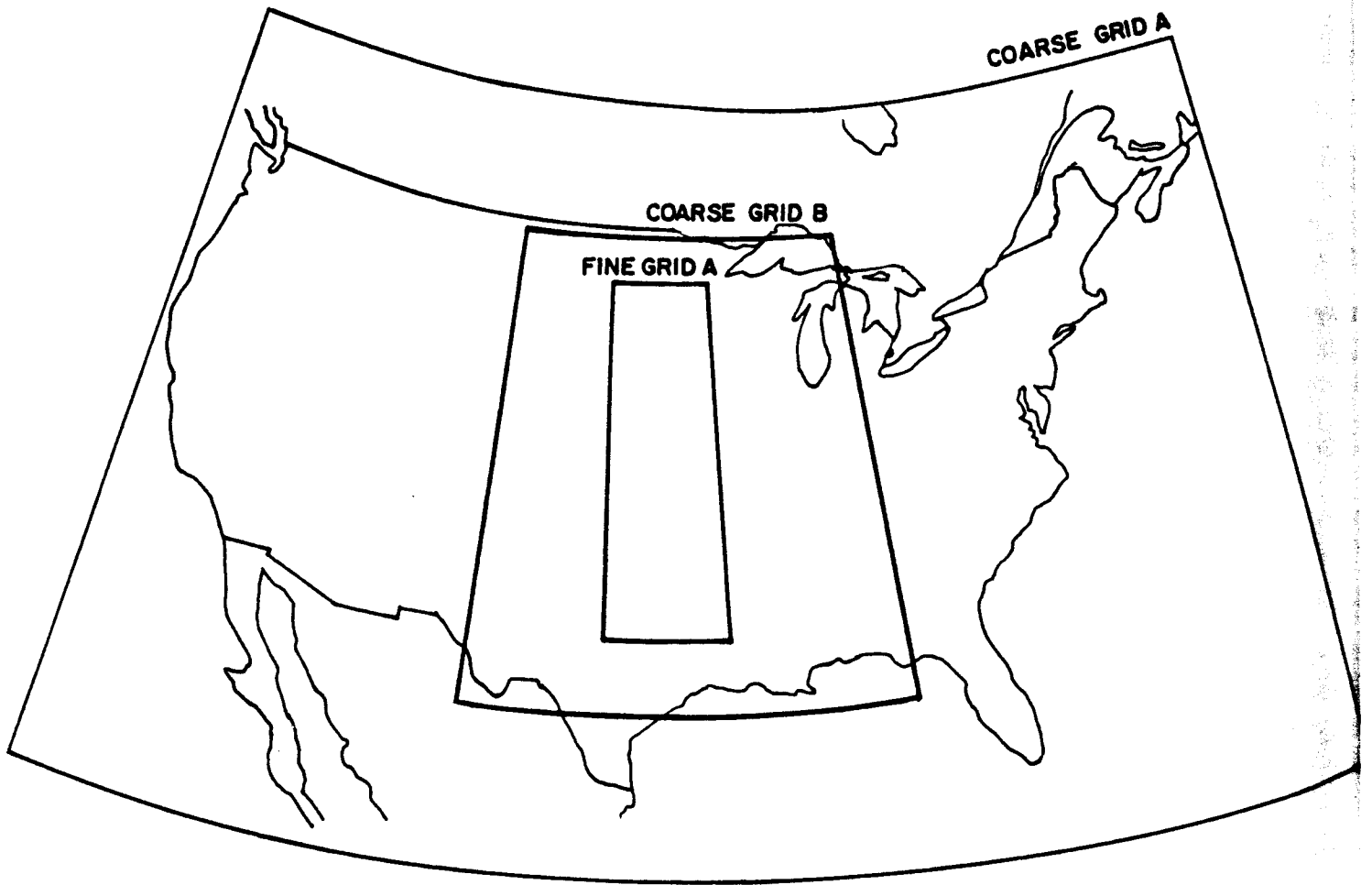


Figure 2. Illustration of telescoping interactive grid nests used to simulate prairie-deciduous forest boundary in the central United States. Boundary conditions for coarse grid A comes from a GCM simulation.

climate scenarios since no data, of course, exists such a model is likely to be insufficient since no analog is available to correctly construct such a tool.

Similarly, objective analysis models which obtain output from a GCM model are able to provide efficient estimates of the effect of complex topography on winds only for very restricted atmospheric conditions (see Pielke, 1985). Only a dynamically complete meteorological model such as RAMS is able to represent the complex interactions between the surface and the overlying atmosphere.

5 Missing Physical Feedback Mechanisms in GCMs

The influence of a number of physical processes in GCMs makes interpretation of their results tentative. Such models, for example, do not represent changes in the average earth's albedo due to anthropogenic aerosol pollution which can alter the albedo of the atmosphere directly, or when the aerosols are entrained into cloud droplets. A greater concentration of aerosols which serve as cloud condensation nuclei can make the clouds colloiddally more stable, thereby allowing the clouds to persist longer, thus contributing to a larger planetary albedo for short wave radiation.

The dynamic accuracy of GCM models have not been adequately tested. Such models need to be used to predict short-term weather changes since skill at such forecasts is essential if the models are to demonstrate a numerical fidelity in simulating wave-wave interactions. If GCMs have insufficient spatial resolution or physics to forecast weather as accurately as current operational weather numerical weather prediction models, what confidence should be placed on their skill at predicting long-term climate change? Long-term climate is made up of a cumulation of day-to-day weather.

6 Summary

This short paper discusses two approaches to permit the interpolation of GCM model results down to local scales. The first approach uses a synoptic classification of GCM output to construct dominant large scale weather scenarios from which local scale model simulations can be performed. The second approach links the GCM model output to two-way multiple interactive numerical model grids which telescope down to the local scale. The local scale models in both cases include detailed terrain, and vegetation and soil representations of the area. Vegetation changes due to climate change can assist in the estimation as to whether alterations in the biosphere can mitigate climate change perturbations (i.e., the Lovelock Gaia hypothesis).

7 Acknowledgements

The author acknowledges the support of Doug Wesley in obtaining Figure 2 used in this paper. The opportunity to present these views was facilitated by the goal of CIRA Director Tom Vonder Haar to permit an effective exchange of ideas at annual CIRA workshops. Dallas McDonald is thanked for completing her normal outstanding editorial preparation of the paper. Support for the typing of the paper was provided by NSF grant #ATM-3616662.

8 References

- Cotton, W. R., R. A. Pielke, C. Chen, M. G. Hadfield, C. J. Tremback, and R. L. Walko, 1987: Large eddy simulations of plume transport and dispersion over flat and hilly terrain. Final Report, EPRI Contract No. 1630-25, September, Electric Power Research Institute, Inc., Palo Alto, California, 60 pp. + Appendices.
- Cram, J. M. and R. A. Pielke, 1987: The importance of synoptic forcing and mesoscale terrain to a numerical simulation of an orographically-induced system. Proceedings of the 3rd AMS Conference on Mesoscale Processes, August 21-26, 1987. Vancouver, British Columbia, Canada, 118-119.
- Garstang, M., S. Nnaji, R. A. Pielke, J. Gusdorf, C. Lindsey, J. W. Snow, 1980: Coastal zone wind energy, Part 1. Synoptic and mesoscale controls and distributions of coastal wind energy. DOE Contract DE-AS06-76ET-20274, March 1980.
- Lindsey, C. G., 1980: Analysis of coastal wind energy regimes. M.S. Thesis, University of Virginia, June 1980.
- Lindsey, C. G. and C. S. Glantz, 1984: A method to characterize local meteorology for air pollution studies and emergency response needs. Reprint, AMS Fourth Joint Conference on Application of Air Pollution Meteorology, 16-19 October 1984, Portland, Oregon, 260-263.
- Lindsey, C. G. and C. S. Glantz, 1986: A method to characterize local meteorology at nuclear facilities for application to emergency response needs. Report prepared for the U.S. Nuclear Regulatory Commission, NUREG/CR-3882 PNL-5155, 53 pp.
- Lovelock, J. E., 1979: A New Look at Life on Earth, Oxford University Press, 175 pp.
- Pielke, R. A., 1984: Mesoscale Meteorological Modeling, Academic Press, New York, NY, 612 pp.
- Pielke, R. A., 1985: The use of mesoscale numerical models to assess wind distribution and boundary layer structure in complex terrain. Bound. Layer Meteor., 31, 217-231.
- Pielke, R. A., M. Garstang, C. Lindsey and J. Gusdorf, 1987: Use of a synoptic classification scheme to define seasons. Theor. Appl. Climatol., 38, 57-68.
- Pielke, R. A., R. W. Arritt, M. Segal, M. D. Moran and R. T. McNider, 1987: Mesoscale numerical modeling of pollutant transport in complex terrain. Bound.-Layer Meteor. (in press).
- Schlesinger, M. E. and J. F. B. Mitchell, 1987: Model projections of the equilibrium climatic response to increased carbon dioxide. Rev. Geophys., 25, 760-798.
- Snow, J. W., 1981: Coastal zone wind power assessment. Ph.D. Dissertation, Department of Environmental Sciences, University of Virginia, 244 pp.

Stocker, R. A. and R. A. Pielke, 1987: A synoptic classification of air mass, wind direction, and wind speed for the western United States (1980-1984). (In preparation).

Yu, C-H. and R. A. Pielke, 1986: Mesoscale air quality under stagnant synoptic cold season conditions in the Lake Powell area. Atmos. Environ., 20, 1751-1762.