Factor Separation in Numerical Simulations

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ABSTRACT

A simple method is developed for computing the interactions among various factors influencing the atmospheric circulations. It is shown how numerical simulations can be utilized to obtain the pure contribution of any factor to any predicted field, as well as the contributions due to the mutual interactions among two or more factors. The mathematical basis for n factors is developed, and it is shown that 2^n simulations are required for the separation of the contributions and their possible interactions. The method is demonstrated with two central factors, the topography and surface fluxes, and their effect on the rainfall distribution for a cyclone evolution in the Mediterranean.

1. Introduction

Numerical models provide a powerful tool for atmospheric research. One of the most common ways of utilizing a model is by performing sensitivity experiments. Their purpose is to isolate the effect of different factors on certain atmospheric fields in one or more case studies. Factors that have been tested in sensitivity studies include, for example, surface sensible and latent heat fluxes, latent heat release, horizontal and vertical resolution, sea surface temperatures, horizontal diffusion, surface stress, initial and boundary conditions, topography, surface moisture, atmospheric stability, and radiation. These sensitivity studies are performed either with real-data case studies or with idealized atmospheric situations.

Sensitivity studies often evaluate the influence of only one factor like topography (McGinley and Goerss 1986; Tibaldi et al. 1980; Dell'Osso 1984), but many investigations test several factors and try to estimate their relative importance. One common method of evaluating the contribution of a specific factor is by analyzing the difference fields between a control run and a simulation where this factor is switched off. Although the difference map is, in general, more illustrative than the presentation of the two individual simulations, the latter approach has been used in many studies (e.g., Uccellini et al. 1987; Mullen and Baumhafner 1988; Kuo and Low-Nam 1990; Leslie et al. 1987; Tibaldi et al. 1980; Lannici et al. 1987; Mesinger and Strickler 1982).

Presentation of a map showing the difference between two simulations is also a common procedure (Mailhot and Chouinard 1989; Kenney and Smith 1983; Chang et al. 1982, 1984; McGinley and Goerss 1986; Benjamin and Carlson 1986; Chen et al. 1983; Orlansky and Katzfey 1987; Zack and Kaplan 1987; Maddox et al. 1981; Alpert and Neumann 1984). It will be shown, however, that the difference map for two simulations, when more than two factors are considered, does not have a simple meaning and in fact may be quite misleading.

Suppose that the effects of two factors are investigated: the topography and the surface fluxes. Three simulations are performed (as in many of the aforementioned studies): CON, the control simulation; NOT, the no-terrain simulation; and NOF, the no-fluxes simulation. What is the meaning of the difference between the simulated fields of CON and NOT? It shows the effect of the topography but also of the joint effect (interaction) of topography with fluxes because both effects vanish when the terrain is switched off. In the same way, the difference between CON and NOF includes the effects of both the fluxes and the interaction between fluxes and topography. If the interaction factor is not isolated, the difference maps CON − NOT and CON − NOF cannot then be simply interpreted, as is commonly attempted.

Although the aforementioned interactions between factors are usually neglected, their significant role in some cases has been pointed out (e.g., Uccellini et al. 1987; Mailhot and Chouinard 1989). To the best of our knowledge, no sensitivity studies have yet been

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proposed to isolate these interaction factors. The method presented in this paper shows a consistent and quite simple approach for isolating the resulting fields due to any interactions among factors, as well as that due to the pure factors, using linear combinations of a number of simulations.

2. The proposed method for two factors

The value of any predicted field f depends on the initial and boundary conditions, as well as the model itself. If a continuous change is made in any factor ψ (e.g., terrain), the resulting field f (e.g., accumulated rainfall) will in general change in a continuous manner as well. This can be mathematically formulated as follows. Let the factor ψ be multiplied by a changing coefficient c so that

$$\psi(c) = c\psi, \quad 0 \leqslant c \leqslant 1. \tag{1}$$

The resulting field f is a continuous function of c:

$$f = f(c), \tag{2}$$

so that $f(1)$ is the value of f in the control simulation and $f(0)$ is the value of f in the simulation where the factor ψ is omitted. In the notation to follow, f_0 and f_1 are used for $f(0)$ and $f(1)$, respectively.

It is always possible to decompose any function $f(c)$ into a constant part, $\hat{f}_0$, which is independent of c, and a c-dependent component, $\hat{f}(c)$, such that $\hat{f}(0) = 0$. In this simple example,

$$\hat{f}_0 = f_0 \tag{3}$$

and

$$\hat{f}(c) = f(c) - f_0. \tag{4}$$

It is important to understand the meaning of $\hat{f}_0$ and $\hat{f}_1$, the latter being a short form for $\hat{f}(1)$. The term $\hat{f}_1$ represents that fraction of f that is induced by the factor ψ, while $\hat{f}_0$ is the remaining part that does not depend on the factor ψ. In order to get $\hat{f}_0$ and $\hat{f}_1$, two simulations must be performed, one with factor ψ included (control) that results in f_1 and the other with ψ excluded that results in f_0:

$$f_1 = \hat{f}_0 + \hat{f}_1, \tag{5}$$

$$f_0 = \hat{f}_0. \tag{6}$$

Solution of the above equations for $\hat{f}$ in terms of the output field f yields

$$\hat{f}_0 = f_0 \tag{7}$$

$$\text{and } \hat{f}_1 = f_1 - f_0. \tag{8}$$

Equation (8) shows that subtraction of the field f_0 (factor ψ excluded) from field f_1 (control run) results in that part of f that is solely induced by the factor ψ. This is how the method works for a single factor, and exemplifies the more general rule that will be developed next. Some of the aforementioned studies have indeed applied the difference method [i.e., (7) and (8)] for the purpose of isolating the contribution due to a single factor.

3. Generalization of the method for *n* factors

Let the field f now depend on n factors ψ_i, where $i = 1, 2, \cdots, n$. Each factor is multiplied by a coefficient c_i, where

$$f = f(c_1, c_2, c_3, \cdots, c_n). \tag{9}$$

The function f can be decomposed (e.g., through a Taylor series expansion) as follows:

$$\begin{aligned} f(c_1, c_2, \cdots, c_n) = \hat{f}_0 + \sum_{i=1}^{n} \hat{f}_i(c_i) \\ + \sum_{i,j=1,2}^{n-1,n} \hat{f}_{ij}(c_i, c_j) + \sum_{i,j,k=1,2,3}^{n-2,n-1,n} \hat{f}_{ijk}(c_i, c_j, c_k) \\ + \cdots + \hat{f}_{123\cdots n}(c_1, c_2, c_3, \cdots, c_n). \end{aligned} \tag{10}$$

Here $\sum_{i,j=1,2}^{n-1,n}$ is a sum on all sorted pairs, and $\sum_{i,j,k=1,2,3}^{n-2,n-1,n}$ is a sum on all sorted trios and so on. Each function $\hat{f}_{ijk..}(c_i, c_j, c_k, \ldots)$ becomes identically zero if any of its variables c_i are zero. Using a notation in which f_{ij} is the value of f in a simulation with $c_i = c_j = 1$ while all the rest of the coefficients are zero and setting c_i ($i = 1, 2, \cdots, n$) to either 1 or 0 in (10) yields

$$f_0 \equiv f(0, 0, 0, \cdots, 0) = \hat{f}_0, \tag{11}$$

$$f_i = \hat{f}_i + \hat{f}_0, \tag{12}$$

$$f_{ij} = \hat{f}_{ij} + \hat{f}_i + \hat{f}_j + \hat{f}_0, \tag{13}$$

$$f_{ijk} = \hat{f}_{ijk} + \hat{f}_{ij} + \hat{f}_{jk} + \hat{f}_{ik} + \hat{f}_i + \hat{f}_j + \hat{f}_k + \hat{f}_0, \tag{14}$$

$$\begin{aligned} f_{123\cdots n} = \hat{f}_{123\cdots n} + \cdots + \sum_{i,j,k=1,2,3}^{n-2,n-1,n} \hat{f}_{ijk} \\ + \sum_{i,j=1,2}^{n-1,n} \hat{f}_{ij} + \sum_{i=1}^{n} \hat{f}_i + \hat{f}_0. \end{aligned} \tag{15}$$

Equations (11)–(15) contain

$$\binom{n}{0}, \binom{n}{1}, \binom{n}{2}, \cdots, \binom{n}{n}$$

equations, respectively. Here $\hat{f}_{ij}$ is a short form for $\hat{f}_{ij}(1, 1)$, and the same applies for all other terms. Equations (11)–(15) consist of 2^n equations for 2^n unknowns $\hat{f}_0, \hat{f}_1, \ldots, \hat{f}_n, \hat{f}_{12}, \ldots, \hat{f}_{n-1,n}, \ldots, \hat{f}_{123\cdots n}$. This set of equations is solved by recursive elimination of $\hat{f}_i$ from (12), then $\hat{f}_{ij}$ from (13), and so forth. The general solution then becomes

$$\hat{f}_{i_1 i_2 i_3 \cdots i_l} = \sum_{m=0}^{l} (-1)^{l-m} \Big(\sum_{j_1, j_2, j_3, \cdots, j_m = i_1, i_2, \cdots, i_m}^{i_{l-m+1}, i_{l-m+2}, \cdots, i_l} f_{j_1 j_2 j_3 \cdots j_m} \Big), \tag{16}$$

where the sum $\sum_{j_1, j_2, j_3, \cdots, j_m = i_1, i_2, \cdots, i_m}^{i_{l-m+1}, i_{l-m+2}, \cdots, i_l}$ is over all groups of m sorted indices $j_1, j_2, j_3, \ldots, j_m$ chosen from l indices $i_1, i_2, i_3, \ldots, i_l$, where $0 \leqslant l \leqslant n$. For example, in the case of three factors, (16) yields eight (2^n) equations:

$$\hat{f}_0 = f_0, \tag{17}$$

$$\hat{f}_1 = f_1 - f_0, \tag{18}$$

$$\hat{f}_2 = f_2 - f_0, \tag{19}$$

$$\hat{f}_3 = f_3 - f_0, \tag{20}$$

$$\hat{f}_{12} = f_{12} - (f_1 + f_2) + f_0, \tag{21}$$

$$\hat{f}_{13} = f_{13} - (f_1 + f_3) + f_0, \tag{22}$$

$$\hat{f}_{23} = f_{23} - (f_2 + f_3) + f_0, \tag{23}$$

$$\hat{f}_{123} = f_{123} - (f_{12} + f_{13} + f_{23}) + (f_1 + f_2 + f_3) - f_0. \tag{24}$$

Obviously, in this example with three factors, eight simulations are necessary for the complete solution. The result would then be not only the factors' separation for $\hat{f}_1, \hat{f}_2, \hat{f}_3$, but also all the possible combinations of these factors, that is, $\hat{f}_{12}, \hat{f}_{23}, \hat{f}_{13}, \hat{f}_{123}$. The factor $\hat{f}_{123}$, for instance, is the contribution due to the pure triple interaction among the three factors under evaluation. A full description of the notation is found in the Appendix. In the following section, the above method is illustrated in a study of the effects of terrain and surface fluxes on precipitation in an eastern Mediterranean (EM) winter cyclone.

4. An example for the application of the method for Mediterranean cyclogenesis

In Fig. 1, the simulation domain and the model topography are illustrated. Figures 2a–d show the surface pressure development of a winter storm in the EM, starting on the 0000 UTC 5 January 1987 with a 12-h interval. The cyclone that originated in the western Mediterranean moved eastward towards the island of Cyprus. The present case can be considered as a typical cyclone for the area, where the phenomenon is referred to by local forecasters as a "Cyprus low" (Alpert et al. 1990; Stein and Alpert 1991). Such a "Cyprus low"

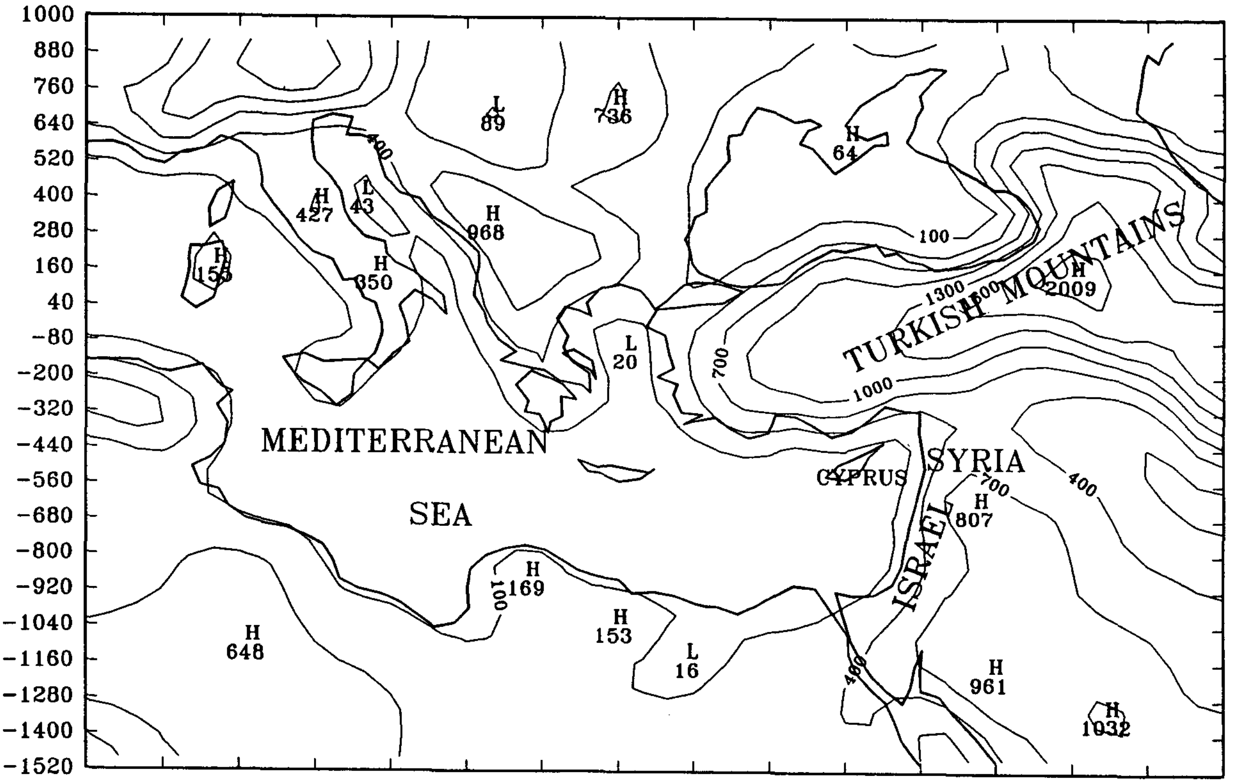

FIG. 1. Simulation domain and the model topography with a contour interval of 300 m. Horizontal east–west and south–north scale (km) is given. Some geographic areas are indicated.

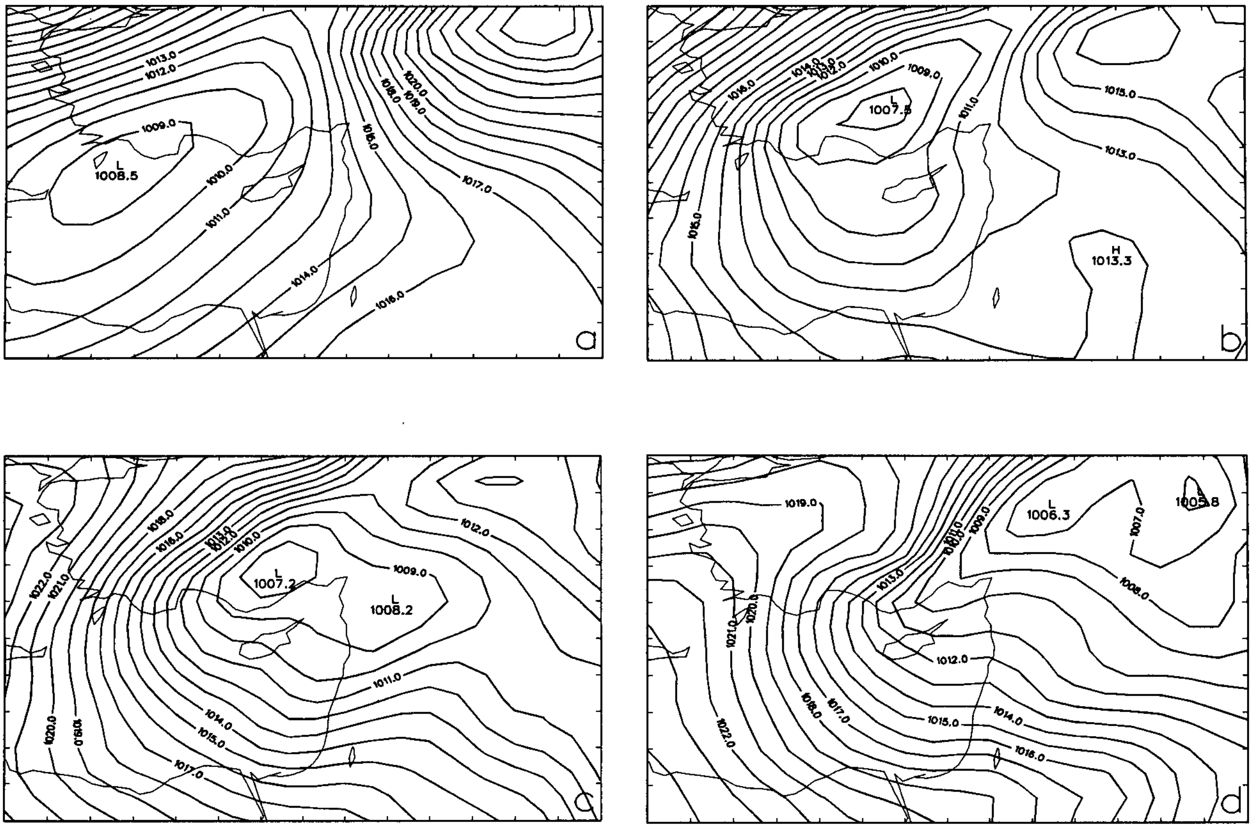

FIG. 2. The control run simulated surface pressure maps for: (a) 0000 UTC 5 January; (b) 1200 UTC 5 January; (c) 0000 UTC 6 January; and (d) 1200 UTC 6 January. Run is based on the ECMWF initialized analysis for the 0000 UTC 5 January and shows the surface development of a winter storm in the EM. Contour interval is 1 hPa.

contributes, on the average, approximately 10% of the annual precipitation in the coastal area of the EM (i.e., about 50 mm). The surface cyclone was associated with an upper-level deep cold trough extending from Europe towards the EM (not shown). By 1200 UTC 6 January 1987, the cyclone moved quickly out of the region as its center reached 36°E.

For the initialization and lateral boundary conditions, the ECMWF initialized analyses with 2.5° horizontal resolution were used by interpolating the data to the mesoscale grid interval of 80 km. The same dataset is used for the model initialization with the flat-terrain simulation. Numerical simulations for the 36-h integration were initialized at 0000 UTC 5 January and were made using the Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model version 4 (MM4). The MM4 model is described in detail by Anthes et al. (1987). The model was run on the EM domain 20°–50°N, 0°–55°E with a mesh of 31 × 46 × 16 grid points. For a model time step of 120 s, a total of approximately 2 CPU hours on an IBM RS/6000 workstation was needed for a 36-h run.

In order to study the effects of terrain (first factor) and the surface heat fluxes (second factor) on the precipitation in this case study, four (2^2) simulations were performed: a control simulation (f_{12}), a simulation with flat terrain (f_2), a simulation without surface fluxes (f_1), and a simulation without terrain and without fluxes (f_0). The total 36-h rainfall in each of these simulations is shown in Figs. 3a–d, respectively.

The method developed in the previous sections is used to isolate the rainfall induced by terrain ($\hat{f}_1$), the rainfall induced by surface fluxes ($\hat{f}_2$), the interaction rainfall contribution due to terrain and fluxes ($\hat{f}_{12}$), and the rainfall unrelated to either terrain or fluxes ($\hat{f}_0$). Equation (16) then yields

$$\hat{f}_0 = f_0, \tag{25}$$

$$\hat{f}_1 = f_1 - f_0, \tag{26}$$

$$\hat{f}_2 = f_2 - f_0, \tag{27}$$

$$\hat{f}_{12} = f_{12} - (f_1 + f_2) + f_0. \tag{28}$$

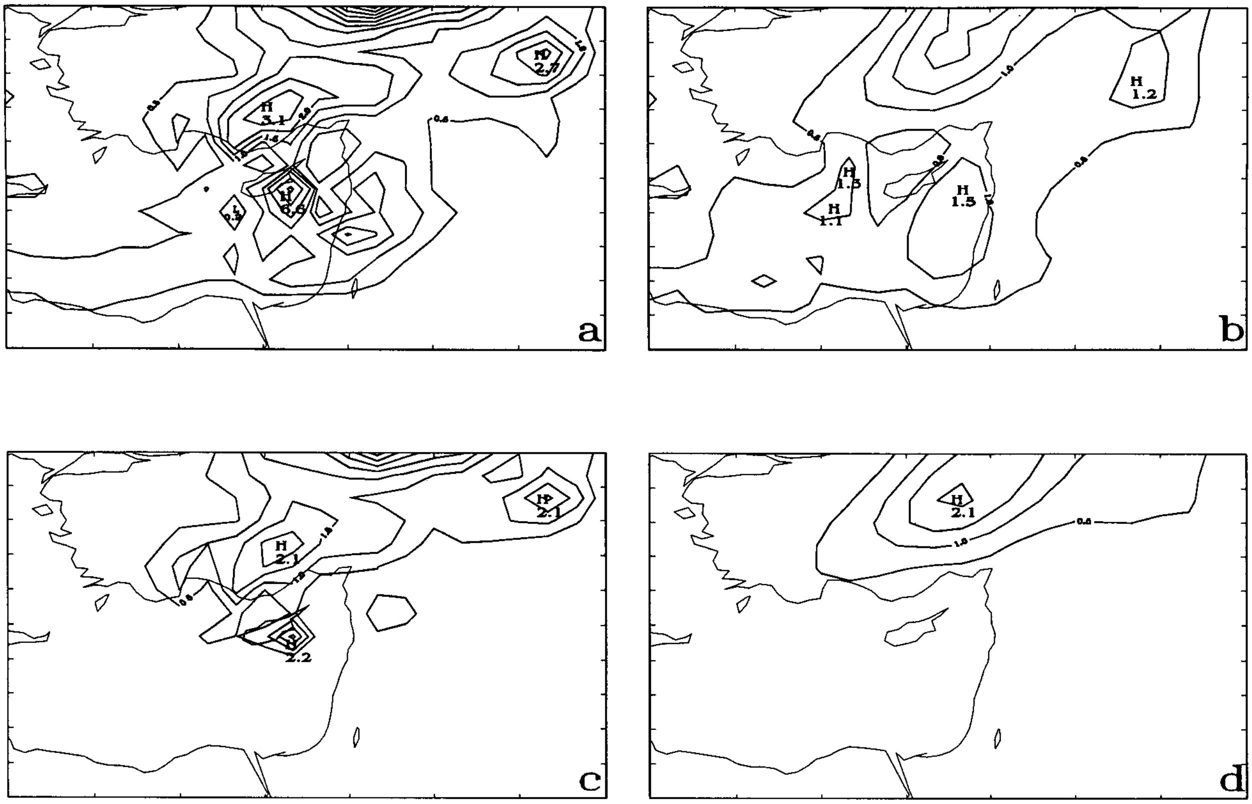

FIG. 3. The total 36-h rainfall in each of the following simulations. (a) Control simulation with both factors on (f_{12}); (b) simulation with flat topography (f_2); (c) simulation without surface fluxes (f_1); (d) simulation with flat terrain and without fluxes (f_0). Contour interval is 0.5 cm.

Figures 4a–d show the fields of $\hat{f}_0$, $\hat{f}_1$, $\hat{f}_2$, and $\hat{f}_{12}$ as calculated from (25) to (28), respectively.

It is quite evident from Fig. 4c that the primary influence of the surface fluxes on precipitation amounts is the enhancement of rainfall over the Mediterranean sea and its coast to the east. The main effect of the topography (Fig. 4b) is the enhancement of rain over the Turkish mountains and in a very localized area near Cyprus. It is not surprising that the topographical contributions include quite large areas of negative rainfall contribution, whereas the fluxes induce mostly positive values.

The joint effect of topography and fluxes is reflected in the additional enhancement of rainfall over the southeast lee area of the Turkish mountains, in the localization of the rain near Cyprus, and in the rainfall strip at the central coastal area to the east (Fig. 4d). It is interesting to note that most of the rainfall in northern Israel and southern Syria is due to the interaction contribution between fluxes and topography, not due to any of the two factors alone.

The information revealed above is interesting and surprising in some aspects. A few questions arise, like what is the dynamical explanation of the local precipitation maximum near Cyprus or the decrease of rainfall over the sea at distances of about 50–100 km to the west of the coast in Fig. 4d. Obtaining the net effect of each factor facilitates the understanding of mesoscale mechanisms influencing the local weather. A more detailed study of cyclogenesis in the Mediterranean, applying this method for a few case studies, will be presented in a forthcoming paper (Stein and Alpert 1993).

5. Discussion

Here a few examples of sensitivity studies chosen from other papers will be briefly shown to illustrate the advantages of the present approach. These examples are all characterized by the following: 1) the study of at least two factors (not including changes in the model parameterizations and initial datasets); 2) the performance of a number of experiments that switch off some of the factors; and 3) the estimation of the effect of certain factors by comparing various experiments. As will be shown, most of the works have not considered the interaction factors. This led to an improper comparison among the various contributions. In particular, quantitative conclusions thus become difficult.

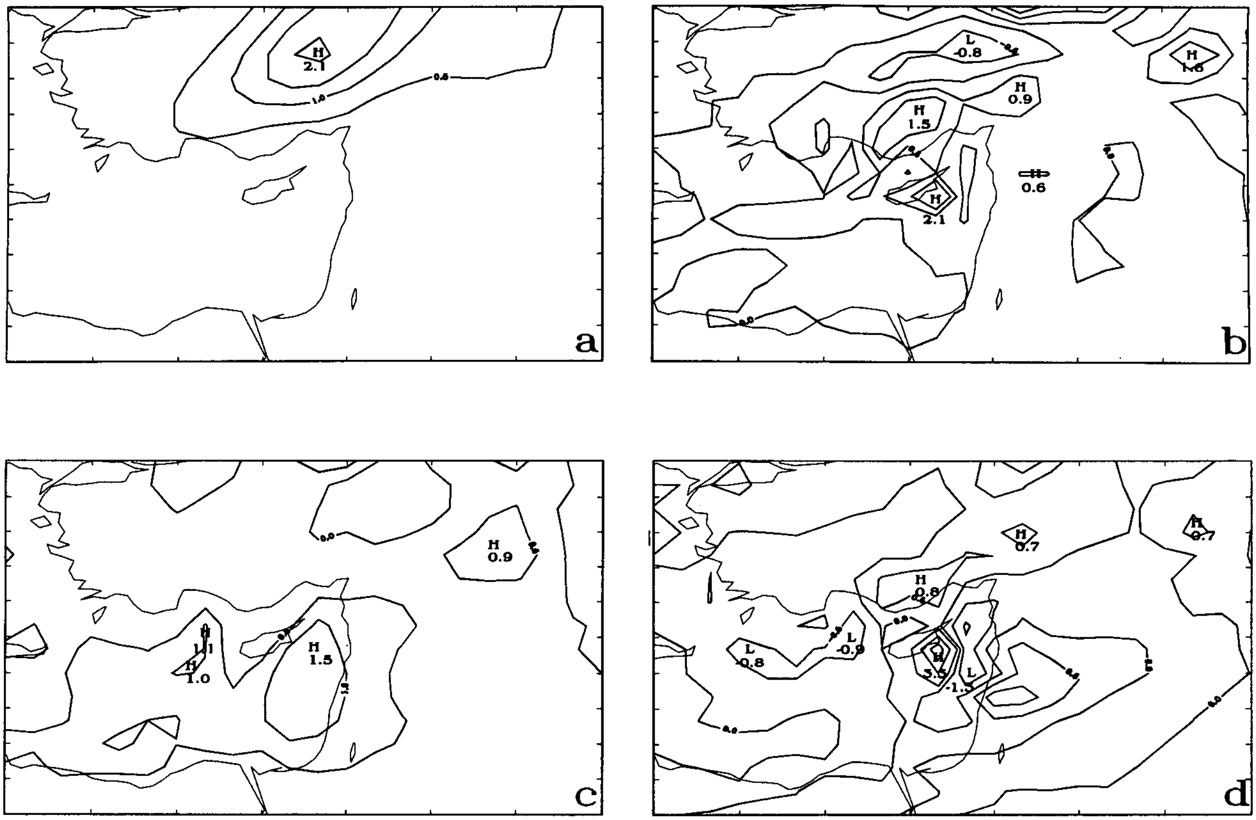

FIG. 4. (a) Rainfall unrelated to either topography or surface fluxes ($\hat{f}_0$); (b) rainfall induced by terrain ($\hat{f}_1$); (c) rainfall induced by surface fluxes ($\hat{f}_2$); (d) rainfall induced by the interaction between topography and fluxes ($\hat{f}_{12}$). Contour interval is 0.5 cm.

a. Example 1

Anthes et al. (1983) study the effects of the following three factors on explosive cyclone development: 1) the sensible heat flux; 2) evaporation; and 3) the latent heating. In the basic model configuration (90-km grid with supplementary data), three experiments were performed: all factors are switched off (f_0); factors 1 and 2 are switched off (f_3); all factors operate (f_{123}). These correspond to experiment 2, 3, and 4, respectively, in Anthes et al. (1983).

The effect of the surface fluxes (factors 1 and 2, i.e., $\hat{f}_1 + \hat{f}_2$) was deduced by comparing experiments 4 and 3. Experiment 4, however, consists of the following factors and interactions:

$$f_{123} = \hat{f}_0 + \hat{f}_1 + \hat{f}_2 + \hat{f}_3 + \hat{f}_{12} + \hat{f}_{13} + \hat{f}_{23} + \hat{f}_{123}, \quad (29)$$

while in experiment 3, $f_3 = \hat{f}_0 + \hat{f}_3$. Consequently, the difference between the two simulations yields

$$f_{123} - f_3 = \hat{f}_1 + \hat{f}_2 + \hat{f}_{12} + \hat{f}_{13} + \hat{f}_{23} + \hat{f}_{123}. \quad (30)$$

Indeed, the first two factors are the sensible heat flux and the evaporation contributions, but in addition there are four interaction terms. Hence, the pure effect of the sensible heat flux and the evaporation have not been isolated.

b. Example 2

Nuss and Anthes (1987; NA henceforth) studied the sensitivity of an idealized cyclone to the effects of latent heat release, surface heat flux, and surface evaporation, as well as to the horizontal temperature gradient and static stability. The physical factors tested were 1) the surface heat flux and 2) the latent heat release. The following experiments were performed: control (experiment 1), no fluxes (experiment 2), and no moisture (experiment 3). These correspond to f_{12}, f_2, and f_1 in our notation.

Nuss and Anthes (1987) deduced the effect of the surface heat fluxes ($\hat{f}_1$ due to factor 1) by comparing experiments 1 and 2. Since $f_{12} = \hat{f}_0 + \hat{f}_1 + \hat{f}_2 + \hat{f}_{12}$ and $f_2 = \hat{f}_0 + \hat{f}_2$, the difference between the two simulations yields

$$f_{12} - f_2 = \hat{f}_1 + \hat{f}_{12}. \tag{31}$$

Hence, the comparison of experiments 1 and 2 includes $\hat{f}_{12}$, the interaction between the two factors, in addition to $\hat{f}_1$, the pure effect of surface heat fluxes. Similarly, NA deduced the effect of latent heat release by comparing experiments 3 and 1. But here the difference between experiment 1 and experiment 3 includes the interaction term $\hat{f}_{12}$ in addition to $\hat{f}_2$, the pure effect of latent release.

c. *Example 3*

Kuo and Reed (1988; KR henceforth) evaluate the effects of some physical processes on storm development. These included 1) the surface fluxes, 2) surface friction, and 3) latent heat release. The following experiments were performed: control (experiment 1); surface fluxes switched off (experiment 2); latent heat release switched off (experiment 4); latent heat release and surface fluxes switched off (experiment 5); and latent heat release, surface fluxes, and surface friction switched off (experiment 6). They correspond to f_{123}, f_{23}, f_{12}, f_2, and f_0 in our notation.

Again, KR deduced the effect of surface fluxes ($\hat{f}_1$ due to factor 1) from comparison of experiment 2 and experiment 1. But the difference between experiment 1 and experiment 2 is

$$f_{123} - f_{23} = \hat{f}_1 + \hat{f}_{12} + \hat{f}_{13} + \hat{f}_{123}, \tag{32}$$

which indeed includes the effect of surface fluxes $\hat{f}_1$ but also three interaction terms. Similarly, the effect of latent heat release ($\hat{f}_3$ due to factor 3) was deduced from comparison of experiment 4 and experiment 1, but the difference between experiment 1 and experiment 4 is given by

$$f_{123} - f_{12} = \hat{f}_3 + \hat{f}_{13} + \hat{f}_{23} + \hat{f}_{123}, \tag{33}$$

which includes $\hat{f}_3$ and three interaction terms.

In general, it is expected that as the number of active factors increases, the role of $\hat{f}_0$ will accordingly diminish. Ideally, if all the possible factors are studied, $\hat{f}_0$ will be zero. Consequently, the separation of the effect of any chosen factor really means the isolation from all other tested factors and not from the rest of the factors that remain hidden in $\hat{f}_0$. For instance, in our example, the field $\hat{f}_1$ shown in Fig. 4b includes the contributions due to the interactions of the topography with untested factors like surface friction or latent heat release. It does not, however, include the interaction with the other chosen factors, that is, surface heat fluxes. Hence, the two factors under test can be properly compared.

Regarding the number of relevant factors in a particular problem, the investigator will frequently have a reasonably good estimate for the dominant factors in a particular case. Basically, the factor separation could be applied several times with varying factors. Obviously, this may involve a considerable computational effort. Another approach may be to include a large number of potential factors but restrict the interactions being resolved to the lower order ones. For instance, with ten factors, instead of performing $2^{10} = 1024$ simulations, only $56 = (n, 0) + (n, 1) + (n, 2)$ are needed to obtain double interactions only. At this stage, the dominant factors are identified, and a more complete factor separation may then be performed.

Another question relates to the applicability of the method once the useful limit of predictability is reached. We believe that at this limit the method is probably not meaningful because the errors will be large, particularly with the higher-order interactions where several simulations are involved.

6. Conclusions

A consistent approach for calculating the contributions of various physical processes, as well as their mutual interactions, is suggested. It is illustrated on the mesoscale (basically, the method is independent of any scale), with a case of cyclogenesis over the Mediterranean. The method enables a quantitative isolation of the effects due to certain factors and can guide researchers to the necessary experiments. This is particularly crucial when comparing the relative magnitudes of different physical processes. If the synergistic contributions are not calculated and separated, the comparison among factors may be misleading, especially when the synergistic effect is not negligible.

It seems that in the atmosphere, the nonlinear interactions are quite often not negligible. Uccellini et al. (1987), for instance, suggest that "the rapid development phase of extratropical cyclones is dependent not on the processes, but on a synergistic interaction among them." The method presented here uncovers the synergistic nonlinear contributions by separating them from the "pure" processes. Obviously, pure here, as well as elsewhere in the paper, is in the relative sense meaning that the effect due to one factor is separated from the other chosen factors. For instance, in the aforementioned example, the pure terrain effect is due to the mechanical mountainous forcing, while the terrain-fluxes contribution is due to the thermal mountain effect. As illustrated, the synergistic rainfall contribution exceeds that of the pure processes (terrain or surface fluxes) over a domain consisting of parts of Syria, Lebanon, and Israel.

Using the method presented in this work can help in studying the effects of local factors like terrain, land–sea differences, land-use, snow cover, air–sea interaction, sea surface temperature, urban areas, air pollution, etc. The net effects of the aforementioned factors on rainfall, cloud cover, and air temperatures are crucial in many studies and over the whole range of atmospheric scales. In addition, the atmospheric circulations induced by each factor separately or by the interaction among two or more factors are essential for the better understanding of the various mechanisms in dynamical systems.

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APPENDIX

Notation

ψ, ψ_i—factors influencing atmospheric circulation (e.g., topography, SST, etc.)
f—a field predicted by the simulation
$\hat{f}$—factor-separated f: transformation
c, c_i—multiplication constant for the factor in the simulation
$f_0 \equiv f(0, 0, 0, \cdots)$—predicted field when all factors are zero
$f_1 \equiv f(1, 0, 0, \cdots)$—predicted field when the first factor is fully on, while all others are switched off
$f(c_1, c_2, \ldots, c_n)$—value of the predicted field as a function of the coefficients c_i
$\hat{f}(c_i, c_j, \ldots, c_k)$—part of the predicted field dependent only on the coefficients $c_i, c_j, \ldots, c_k$
$\hat{f}_0 = \hat{f}(0, 0, 0, \cdots)$—part of the predicted field independent of the factors
$\hat{f}(c)$—part of the predicted field that depends solely on the factor ψ with a c coefficient
$\hat{f}_1 \equiv \hat{f}(1) \equiv \hat{f}(c = 1)$—part of the predicted field when only factor number 1 is fully switched on
$\hat{f}_{ijk\ldots}(c_i, c_j, c_k, \ldots)$—part of the predicted field dependent solely on combination of factors $\psi_i, \psi_j, \psi_k, \ldots,$ with corresponding coefficients $c_i, c_j, c_k \ldots$
$f_{ijk\ldots}$—value of the predicted field where only factors $i, j, k, \ldots$ are on
$\hat{f}_{ijk\ldots}$—a short form for $\hat{f}_{ijk\ldots}(1, 1, 1, \ldots)$

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