HIPLEX-1: Statistical Evaluation

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ABSTRACT

Results of statistical analyses for HIPLEX-1, a randomized cloud seeding experiment, are presented. The analyses are based principally on multi-response permutation procedures (MRPP) as specified before the HIPLEX-1 experiment was initiated. Even though the sample sizes are very small, due in part to the premature termination of this experiment, the three primary response variables measured in the first five minutes following treatment indicate pronounced differences in the development of ice crystals between nonseeded and seeded events. However, the response variables measured more than five minutes after treatment generally do not indicate obvious differences in the subsequent development of precipitation between nonseeded and seeded events. This lack of difference is a possible consequence of 1) lack of a seeding effect, 2) inadequacies in the physical hypothesis, or 3) the small sample sizes. Consequently, only the initial steps in the HIPLEX-1 physical hypothesis could be confirmed in this evaluation of the experiment.

1. Introduction

The primary statistical results and interpretations of HIPLEX-1, a randomized summertime cumulus cloud seeding experiment, are presented in this paper. Elsewhere in this issue, the experimental design, physical hypothesis, and response variables are described in detail by Smith *et al.* (1984) and the physical interpretations are considered by Cooper and Lawson (1984). The purpose of this paper is to evaluate statistically the chain of events prescribed by the physical hypothesis.

The statistical procedures are described in Section 2 and preliminary sample size estimates are explained in Section 3. Section 4 presents the empirical results of this study, and discussion and conclusions are given in Section 5.

2. Statistical procedures

The statistical analyses in this paper are based on multiresponse permutation procedures (MRPP). While complete descriptions and theoretical topics related to MRPP are given elsewhere (Brockwell *et al.*, 1982; Mielke, 1978, 1979; Mielke *et al.*, 1976, 1981a,b, 1982; O'Reilly and Mielke, 1980), a brief description is given here. Let

$$\Omega = \{\omega_1, \ldots, \omega_N\}$$

be a finite population of N objects (e.g., cumulus clouds), let

$$\mathbf{x}'_I = (x_{1I}, \ldots, x_{rI})$$

denote r commensurate response measurements for object ω_I ($I = 1, \ldots, N$) of a point in the r-dimensional Euclidean data space, let

$$\Delta_{I,J} = [\sum_{k=1}^{r} (x_{kI} - x_{kJ})^2]^{1/2}$$

be the Euclidean distance between points associated with objects ω_I and ω_J in r-space, and let $S_1, \ldots, S_g$ denote an exhaustive partitioning of the N objects comprising Ω into g disjoint groups. In cloud seeding experiments like HIPLEX-1, there will usually be two groups (seeded and nonseeded experimental units) so that $g = 2$. The choice of Euclidean distance yields an

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analysis space which is congruent to the data space being investigated (Mielke and Berry, 1983; Mielke *et al.*, 1982). Then the MRPP statistic used in this study is given by

$$\delta = \sum_{i=1}^{g} \left(\frac{n_i}{N}\right) \xi_i,$$

where $n_i \geqslant 2$ is the number of objects in group S_i $(i = 1, \ldots, g)$,

$$N = \sum_{i=1}^{g} n_i,$$

$$\xi_i = \binom{n_i}{2}^{-1} \sum_{I<J} \Delta_{I,J} \psi_i(\omega_I) \psi_i(\omega_J)$$

is the average between-object distance for all objects within group S_i $(i = 1, \ldots, g)$, $\sum_{I<J}$ is the sum over all I and J such that $1 \leqslant I < J \leqslant N$, and $\psi_i(\omega_I)$ is 1 if ω_I belongs to S_i and 0 otherwise $(i = 1, \ldots, g; I = 1, \ldots, N)$. The underlying permutation distribution of δ (the null hypothesis) assigns equal probabilities to the

$$M = N!\left(\prod_{i=1}^{g} n_i!\right)^{-1}$$

possible allocations of the N objects to the g groups. Since small values of δ imply a concentration of response measurements within at least some of the g groups, the null hypothesis is rejected when the observed value of δ is small. The exact P-value (i.e., the probability under the null hypothesis of a value of δ being as or more extreme than the observed value of δ) is the proportion of all M values of δ which are equal to or less than the observed value of δ. Berry (1982) has developed an efficient algorithm for calculating exact P-values; it is practical for values of M up to 20 000. Efficient and accurate moment approximation procedures exist for calculating P-values for large values of M (Mielke, 1979; Mielke *et al.*, 1976, 1981a, 1982). It should be noted that when a single response variable is analyzed, then MRPP is a univariate analysis procedure. However, the term MRPP will designate both univariate and multivariate analyses in this paper.

3. Preliminary sample size estimates

Because the power characteristics of permutation tests, such as the MRPP, are highly dependent upon both the actual distribution and the hypothesized alternative in question, it is important that reasonable approximations be obtainable for both these entities. To this end, a simulation program was designed to yield power-characteristic results and sample size estimates for HIPLEX-1. The data base for this simulation consisted of measurements on CIC5, TFPI, and PIC8 collected on 35 clouds (11 of which were seeded) as part of the calibration seeding trials during the summer of 1978 and prior to the actual experiment. Appendix E of the design document (Bureau of Reclamation, 1979) provides details of the data set. From this data base, four sets of random samples (N = 50, 100, 150, and 200) were drawn with replacement.

For analyses involving more than a single response variate (i.e., joint effects), the investigator must insure that the response measurements are commensurate, i.e., the sample ranges of the different response variates must be equalized. Let the kth response measurement for a seeded case be represented by x_{kjS} $(k = 1, \ldots, r$ and $j = 1, \ldots, n_S)$; similarly, let the kth response measurement for a nonseeded case be represented by x_{kjNS} $(k = 1, \ldots, r$ and $j = 1, \ldots, n_{NS})$. Seeded and nonseeded variates of the kth response measurement are respectively denoted by

$$\left.\begin{aligned} y_{kjS} &= b_{kNS}(a_{kS} + c_{kS}x_{kjS}) \\ y_{kjNS} &= b_{kNS}(x_{kjNS}) \end{aligned}\right\},$$

where b_{kNS} is a commensuration adjustment, a_{kS} is a location adjustment, and c_{kS} is a scale adjustment for the kth response measurement. In this way, the input for the MRPP simulation program was generated; values for a_{kS}, b_{kNS}, and c_{kS} for CIC5, TFPI, and PIC8 are given in Table 1. Response variables CIC5, TFPI, and PIC8 were considered most important at the time. The definitions of 1) all primary and secondary response variables and 2) the final test statistics are given in Table 2. Values of b_{kNS} were based on the observed ranges. Since prior information on a_{kS} and c_{kS} did not exist, these initial values were based on a concensus judgment by the HIPLEX-1 investigators.

Given the specified adjustments of Table 1, the results of the MRPP computer simulation, using the four sets of random samples (N = 50, 100, 150, and 200) with $n_S = n_{NS} = N/2$, indicated that 50–150 test cases of a given class of cloud (25–75 each of seeded and nonseeded clouds in a given class) would be required to reject the null hypothesis with α = 0.10, where α is the probability of a type-I statistical error. Unfortunately, because 1) the summer of 1980 was extremely dry in eastern Montana, 2) HIPLEX-1 was pre-empted by the Cooperative Convective Precipitation Experiment (CCOPE) in the summer of 1981, and 3) the funding for HIPLEX-1 was suddenly ter-

TABLE 1. Specified changes associated with the location adjustment a_{kS}, the commensuration adjustment b_{kNS}, and the scale adjustment c_{kS} of the three response variates CIC5, TFPI, and PIC8.

Response variate	Adjustment		
	a_{kS}	b_{kNS}	c_{kS}
CIC5	5.0	1.0	1.0
TFPI	0.0	2.4	0.6
PIC8	0.2	16.0	1.0

TABLE 2. Primary and secondary response variables and final test statistics.

Primary response variables:		
1	CIC2	Cloud ice concentration, 2 min after treatment
2	CIC5	Cloud ice concentration, 5 min after treatment
3	CCR5	Concentration of crystals rimed, 5 min after treatment
4	PIC8	Precipitating ice number concentration, 8 min after treatment
5	MVD8	Mean volume diameter of precipitating ice particles, 8 min after treatment
6	AWC8	Average liquid water concentration, 8 min after treatment
7	TFPI	Time to first precipitating ice (particles with diameters $\geqslant$ 0.6 mm in concentrations > 0.1 L^{-1})
8	TFE	Time to first SWR-75 radar echo (15 dBZ)
9a	TIPA	Time to initial precipitation at +10°C level, aircraft measurement
9b	TIPR	Time to initial precipitation at +10°C level, SWR-75 radar (15 dBZ)
10a	RERC	Radar-estimated rainfall at +10°C level, using a constant *Z*–*R* relationship
10b	AER	Aircraft-estimated rainfall at +10°C level
Secondary response variables:		
1	FCC5	Fraction of crystals which are columnar, 5 min after treatment
2	M2EA	Maximum area of the 20-dBZ echo
3	M3EA	Maximum area of the 30-dBZ echo
4	D2EC	Time duration of the 20-dBZ echo
5	D3EC	Time duration of the 30-dBZ echo
6	MAXZ	Maximum radar reflectivity factor
7	TIPB	Time to initial precipitation at cloud base (15-dBZ echo on SWR-75 radar)
Final test statistics:		
1a	PCPA	Proportion of experimental units that precipitate, based on TIPA
1b	PCPR	Proportion of experimental units that precipitate, based on TIPR
2a	AVRA	Average volume of precipitation per experimental unit, based on AER
2b	AVRC	Average volume of precipitation per experimental unit, based on RERC

minated in early 1982, only 20 total cases were available for analysis, with 7 cases of Class A-1 clouds (4 seeded and 3 nonseeded) and 13 cases of Class B clouds (8 seeded and 5 nonseeded). (Table 3 presents the cloud selection criteria for A-1, A-2 and B clouds in HIPLEX-1.) Consequently, the sample sizes were insufficient to achieve the stated objectives of HIPLEX-1. In particular, a large *P*-value suggests that either 1) there exists no obvious effects, or 2) the effects were sufficiently small that the small sample sizes precluded any chance of detecting the effect. Furthermore, a small *P*-value in the present context suggests that either 1) a very strong effect was detected, or 2) a bad break in the randomization scheme occurred, i.e., a type-I statistical error.

4. Empirical results

The HIPLEX-1 primary and secondary response variables are listed in Tables 4 and 5, respectively. Table 6 and Figs. 1 and 2 present univariate MRPP comparisons of nonseeded and seeded experimental units for the HIPLEX-1 primary response variables

TABLE 3. Cloud selection criteria for HIPLEX-1.

A *Class A-1 cloud criteria:*

1 Average cloud liquid water concentration greater than 0.5 g m^{-3} over approximately a 1-km-long cloud region determined by 10 s of flight at approximately 100 m s^{-1} (AWC0)[a]
2 Average ice-crystal concentration[b] less than 1.0 L^{-1} in the 1-km-long (10 s of flight) cloud region of maximum average liquid water concentration (AIC0)
3 Maximum ice-crystal concentration[b] less than 5.0 L^{-1} for any 1-km-long (10 s of flight) cloud region (defined by FSSP liquid water concentration greater than 0.01 g m^{-3}) during the test pass (MIC0)
4 Vertical air velocity greater than −1.0 m s^{-1} in the region defined by item 1, but if the vertical velocity is greater than 10.0 m s^{-1} and the buoyancy is greater than 1°C, reject the candidate (VVL0 and BOY0)
5 Length of the test penetration more than 2 and less than 8 km as defined by an FSSP liquid water concentration greater than 0.01 g m^{-3} (LPN0)
6 No radar echo detectable on the aircraft weather radar (RFL0)
7 Cloud-top temperature lower than −6°C but higher than −12°C (CTT0)
8 Cloud-base temperature higher than 0°C (CBT0)
9 Minimum separation between the current test cloud and previous test clouds greater than 15 km to insure the meteorological independence of the clouds (DBC0)

B *Class A-2 cloud criteria:*

1 Items A1 to A9 above
2 An average wind direction between the surface and 800 mb from 250 to 040° true (AWD0)
3 A 30-mb-thick stable layer present with its base between 0 and −10°C and its top temperature at least 1.5°C higher than the temperature extrapolated from the base of the layer to the top using pseudoadiabatic ascent (DTC0)
4 A 10°C dewpoint depression present somewhere within the 30-mb layer of B3 above (DPD0)

C *Class B cloud criteria:*

1 Items A1–A3, A5, A6, A8, and A9 above[c]
2 Cloud-top temperature lower than −6°C but higher than −20°C (CTT0)
3 Vertical air velocity greater than −1.0 m s^{-1} in the region defined by item A1, but no other vertical velocity or buoyancy restrictions (VVL0 and BOY0)

[a] Symbols in parentheses indicate the names assigned to the variables in the computer programs.
[b] Measured by the depolarization signal from the PMS 2D-C probe, not the regular 2D-C image data. Although the depolarization signal is believed to indicate only about 25% of the actual ice-crystal concentration, it was used because the image data include spurious images that could not be rejected in real time.
[c] Clouds that failed to meet criteria A4 and A7 for Class A were then evaluated as candidates for Class B.

TABLE 4. HIPLEX-1 primary response variables.

Test case	Date	Treatment time (CUT)	Cloud class	(S/NS)	CIC2 (L^{-1})	CIC5 (L^{-1})	CCR5 (L^{-1})	PIC8 (L^{-1})	MVD8 (mm)	AWC8 ($g\ m^{-3}$)	TFPI (s)	TFE (s)	TIPA (s)	TIPR (s)	AER ($mm\ km^2$)	RERC ($mm\ km^2$)
1	21 Jun 79	213301	B	NS	0.266	0.106	0.16	0.023	1.178	0.083	727	1106	2400[d]	2400[d]	0.185	0.000
2	22 Jun 79	201503	B	S	29.440	12.699	3.40	0.060	1.590	0.069	497	1500	1893	1804	0.392	0.071
3	22 Jun 79	222314	A-1	NS	0[a]	0.000	0.00	0.000	0.600[d]	0.000	1020[d]	2400[d]	2400[d]	2400[b]	0.000	0.000[b]
4	11 Jul 79	204036	B	S	1.236[c]	4.628	4.18	0.041	1.272	0.007	291	2269	2400[d]	2400[d]	0.000	0.000
5	11 Jul 79	212749	B	NS	0.769	0.466	0.15	0.045	1.219	0.000	53	859	1558	859	0.152	0.012
6	12 Jul 79	190124	A-1	S	11.204	0.583	0.00	0.013	0.966	0.059	680	2400[d]	2400[d]	2400[d]	0.000	0.000
7	16 Jul 79	183422	A-1	NS	0.070	0.000	0.00	0.000	0.600[d]	0.000	1020[d]	827	1916	2400[b]	2.578	0.000[b]
8	16 Jul 79	205308	B	S	0[a]	0.000	0.00	0.000	0.600[d]	0.000	1020[d]	2400[d]	2400[d]	2400[d]	0.000	0.000
9	22 Jul 79	211433	B	S	29.326	60.025	161.	0.030	1.061	0.040	1020[d]	796	1547	1479	9.400	3.767
10	23 Jul 79	200230	A-1	S	3.159	0.019	11.2	0.000	0.600[d]	0.000	659	492	1242	2400[b]	0.001	0.000[b]
11	24 Jul 79	193556	B	NS	0.037	0.143	0.00	0.014	1.249	0.002	1020[d]	2400[d]	2400[d]	2400[d]	0.000	0.000
12	24 Jul 79	203348	B	S	66.423	21.953	41.2	0.049	0.932	0.043	481	2400[d]	2400[d]	2400[c]	0.036	0.000[c]
13	16 May 80	202556	B	S	8.811	2.281	0.00	0.002	1.223	0.083	830	1357	2400[d]	2400[c]	0.014	0.000[c]
14	16 May 80	211718	B	S	1.703	4.287	23.0	0.107	1.653	0.090	197	426	1348	2400[c]	2.742	0.000[c]
15	7 Jun 80	212533	A-1	S	1.004	2.112	2.26	0.235	1.045	0.045	438	1026	2376	2400[b]	0.126	0.000[b]
16	16 Jun 80	180617	A-1	NS	0.000	0.000	0.00	0.002	1.116	0.013	1020[d]	2400[d]	2400[d]	2400[b]	0.059	0.000[b]
17	2 Jul 80	184901	B	NS	0.137	0.067	0.00	0.019	0.891	0.066	1020[d]	2400[d]	1394	2400[d]	0.000	0.000
18	2 Jul 80	201033	B	NS	0.052	8.242	3.77	0.051	0.918	0.064	462	1592	2400[d]	2400[c]	0.000	0.000[c]
19	2 Jul 80	215852	A-1	S	33.240	89.87	280.	0.009	0.964	0.004	676	1710	1922	2400[b]	0.182	0.000[b]
20	15 Jul 80	194209	B	S	3.857	51.40	15.8	0.047	1.677	0.072	1020[d]	566	883	2400[c]	1.925	0.000[c]

[a] No cloud present at pass altitude.
[b] Median for Type A-1 cases used as default value.
[c] Median for Type B cases used as default value.
[d] Default value specified in design document.

TABLE 5. HIPLEX-1 secondary response variables.

Test case	Date	Treatment time (CUT)	Cloud class	(S/NS)	FCC5	M2EA (km²)	M3EA (km²)	D2EC (s)	D3EC (s)	MAXZ (dBZ)	TIPB (s)	RERL[d] (mm km²)	RERB[d] (mm km²)	Echo range (km)	Echo azimuth (deg)
1	21 Jun 79	213301	B	NS	0	0.00	0.00	0	0	16.1	1106	0	0	47	339
2	22 Jun 79	201503	B	S	0.875	2.27	0.00	720	0	24.9	1658	0.066	0.117	35	334
3	22 Jun 79	222314	A-1	NS	0.830[a]	0.00	0.00	0	0	14.9[c]	2400[c]	0	0	—	—
4	11 Jul 79	204036	B	S	0.030	0.00	0.00	0	0	17.2	2269	0	0	52	294
5	11 Jul 79	212749	B	NS	0	0.00	0.00	0	0	16.6	859	0	0.012	25	66
6	12 Jul 79	190124	A-1	S	0	0.00	0.00	0	0	14.9[c]	2400[c]	0	0	—	—
7	16 Jul 79	183422	A-1	NS	0.830[a]	11.96	4.02	1260	360	34.6	827	1.627	1.627	73	81
8	16 Jul 79	205308	B	S	0.266[b]	0.00	0.00	0	0	14.9[c]	2400[c]	0	0	—	—
9	22 Jul 79	211433	B	S	0.824	39.97	13.53	1440	720	36.5	946	7.228	3.767	120	64
10	23 Jul 79	200230	A-1	S	0.806	0.00	0.00	0	0	19.2	2400[c]	0	0	112	46
11	24 Jul 79	193556	B	NS	0.266[b]	0.00	0.00	0	0	14.9[c]	2400[c]	0	0	—	—
12	24 Jul 79	203348	B	S	0.590	0.00	0.00	0	0	14.9[c]	2400[c]	0	0	—	—
13	16 May 80	202556	B	S	0.266[b]	2.30	0.00	360	0	22.0	1529	0	0.075	74	331
14	16 May 80	211718	B	S	0.581	12.58	0.00	1260	0	27.9	2400[c]	1.256	[e]	136	321
15	7 Jun 80	212533	A-1	S	0.854	1.98	0.00	180	0	20.6	2400[c]	0.013	[e]	110	204
16	16 Jun 80	180617	A-1	NS	0.830[a]	0.00	0.00	0	0	14.9[c]	2400[c]	0	0	—	—
17	2 Jul 80	184901	B	NS	0.250	0.00	0.00	0	0	14.9[c]	2400[c]	0	0	—	—
18	2 Jul 80	201033	B	NS	0.282	6.00	0.00	540	0	24.8	2400[c]	0.108	[e]	110	64
19	2 Jul 80	215852	A-1	S	1.000	0.00	0.00	0	0	19.6	2083	0.071	0.035	114	78
20	15 Jul 80	194209	B	S	0.026	2.38	0.00	360	0	21.6	2400[c]	0	0	136	20

[a] Median for Type A-1 cases used as default value.
[b] Median for Type B cases used as default value.
[c] Default value specified in design.
[d] Variable not specified in design document.
[e] Beam center above cloud base at lowest tilt.

TABLE 6. Summary of univariate MRPP *P*-values for HIPLEX-1 primary response variables.

Response variable	Class A-1 clouds (3 NS, 4 S)		Class B clouds (5 NS, 8 S)		Class A-1 and B clouds (8 NS, 12 S)	
	Raw data	Ranks	Raw data	Ranks	Raw data	Ranks
CIC2	0.057	0.029	0.0396	0.0109	0.00939	0.00034
CIC5	0.057	0.029	0.0793	0.0637	0.0382	0.0114
CCR5	0.257	0.143	0.0653	0.102	0.0438	0.0173
PIC8	0.143	0.229	0.428	0.523	0.289	0.460
MVD8	0.400	0.429	0.278	0.249	0.267	0.195
AWC8	0.343	0.314	0.922	0.832	0.405	0.467
TFPI	0.029	0.029	1.000	1.000	0.227	0.178
TFE	0.486	0.600	0.761	0.598	0.505	0.375
TIPA	0.743	0.600	0.864	0.810	0.622	0.441
TIPR	(1.000)*	(1.000)*	0.838	0.887	0.814	0.770
AER	1.000	1.000	0.110	0.196	0.578	0.529
RERC	(1.000)*	(1.000)*	0.487	0.674	0.334	0.712

* Parentheses indicate situations for which all the values of the response variable were equal, so that no separation between seeded and nonseeded cases can be determined.

CIC2, CIC5, CCR5, PIC8, MVD8, AWC8, TFPI, TFE, TIPA, TIPR, AER, and RERC. The listed order of the previously listed primary response variables corresponds to the chain of events prescribed by the physical hypothesis (Smith *et al.,* 1984).

In order to mitigate the potential effect of a relatively few extreme values, the individual response variables were coded as rank order values from below, i.e., the *N* response variable values were converted to integers from 1 to *N* in correspondence with their observed magnitudes. The rank order values associated with any two response variables are commensurate with one another by virtue of their construction, i.e., each response variable is rescaled from 1 to *N*. On the other

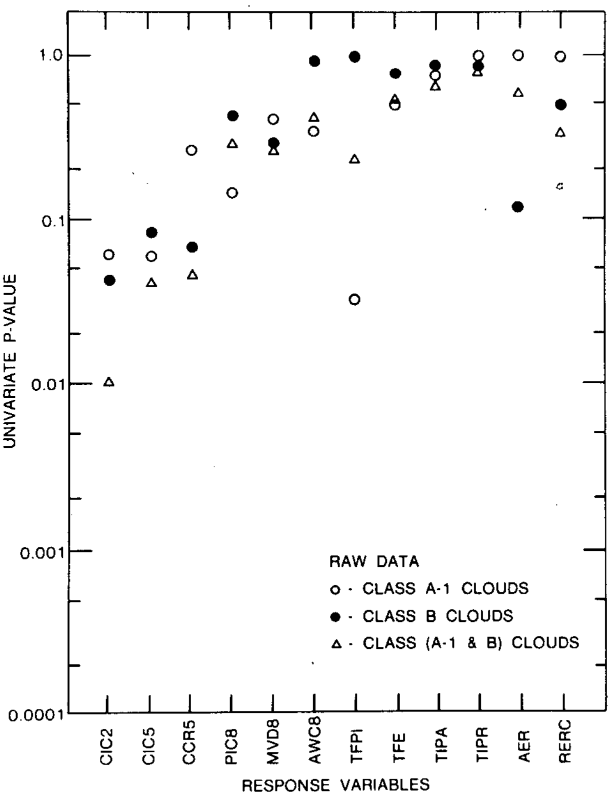

FIG. 1. Logarithmic scaled univariate *P*-values based on MRPP with raw data for primary response variables.

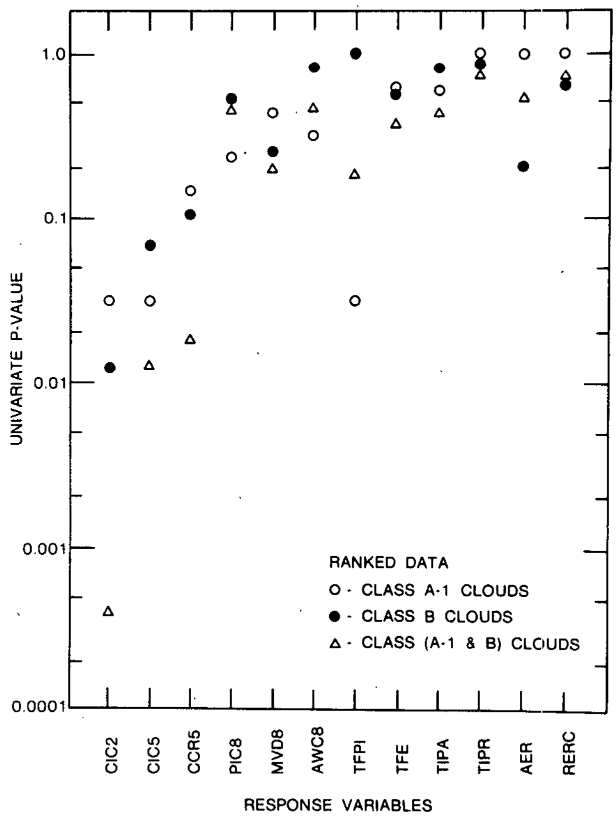

FIG. 2. As in Fig. 1, but with ranked data.

hand, the individual response variable raw values were made commensurate with one another by rescaling from 0 to 1, i.e., dividing the difference between an individual observed value and the minimum value by the difference between the maximum and minimum values.

The MRPP *P*-values based on raw and rank order response variable values are presented separately for Class A-1 clouds, Class B clouds, and pooled A-1 and B clouds. Such pooling was not discussed in the HIPLEX-1 design, but has been effected for exploratory analysis mainly because of the small sample sizes available.

Exact *P*-values are presented for the A-1 clouds ($M = 35$) and B clouds ($M = 1287$), whereas approximate *P*-values are presented for the pooled A-1 and B clouds ($M = 125\,970$). The smallest possible *P*-value for a category is $1/M$; in particular, for Class A-1 clouds ($M = 35$), the smallest possible *P*-value is $1/35 \approx 0.029$. [If Case 16 is deleted because of the selection error discussed in Section 6 of Smith *et al.* (1984), then the remaining sample of four seeded and two nonseeded Class A-1 clouds would have yielded $M = 15$ with the smallest possible *P*-value being $1/15 \approx 0.067$.] The MRPP are analogous to two-sided tests: thus a *P*-value of 1.0 indicates no separation of the response variables for the experimental units of the two groups in *r*-space, while a small *P*-value suggests a separation between the two groups.

The only primary response variables indicating consistent differences (larger values for seeded cases) are CIC2, CIC5, and CCR5. These are the three response variables associated with the development of ice crystals in the clouds during the first 5-min interval following treatment (i.e., a "placebo" or a dry ice seeding). Even for CCR5 in the A-1 clouds (for which the physical hypothesis was developed) the seeding "signature" is not strong. The reason that the rank tests for the first 5-min period responses yielded stronger results than the tests based on raw data is that the contributions of a few large raw data measurements (in response variables which apparently have long-tail distributions) are subdued. A strong indication of accelerated formation of precipitation, due to seeding, also appears in the TFPI for the Class A-1 clouds (*P*-value is 0.029). There are a few other instances suggesting possible effects, for example PIC8 for Class A-1 clouds or AER for Class B clouds, but the *P*-values are not small enough to be regarded as significant (a possible consequence of the small sample sizes). However, in all cases except AWC8 (where the values were very small), the directions (despite the small sample sizes) are consistent with those suggested by the HIPLEX-1 physical hypotheses.

Table 7 and Figs. 3 and 4 present progressive multivariate comparisons of nonseeded and seeded experimental units for the HIPLEX-1 primary response variables; the order in which the response variables are added corresponds to the chain of events described by the physical hypothesis. Thus, each successive *P*-value in a column of Table 7 is a measure of the separation of the two subgroups (nonseeded and seeded) in an *r*-space where *r* equals the number of response variables included up to that point. Figure 5 illustrates the "perfect" separation (*P*-value is 0.029) of the Class A-1 nonseeded and seeded subgroups in the ranked data 3-space (CIC2, CIC5, CCR5). The *P*-values in the bottom row provide an evaluation of the degree to which seeded clouds of a particular class are distinct from nonseeded clouds in a 12-dimensional space representing all 12 of the response variables. Thus, the Class B seeded clouds may be said to differ from the Class B nonseeded clouds, considering rank-ordered response variables, with a *P*-value of 0.170.

The univariate values presented in Table 6 help show which response variables are responsible for most of the difference. The multivariate sequence in Table 7 helps show how far down the chain of events in the physical hypothesis marked differences can be traced. The *P*-values of Table 7 become substantially larger

TABLE 7. Summary of multivariate MRPP *P*-values for HIPLEX-1 primary response variables.

Variables CIC2 thru:	Class A-1 clouds (3 NS, 4 S)		Class B clouds (5 NS, 8 S)		Class A-1 and B clouds (8 NS, 12 S)	
	Raw data	Ranks	Raw data	Ranks	Raw data	Ranks
CIC2	0.057	0.029	0.0396	0.0109	0.00939	0.00034
CIC5	0.057	0.029	0.0365	0.0124	0.0118	0.00123
CCR5	0.057	0.029	0.0295	0.0225	0.0108	0.00174
PIC8	0.057	0.029	0.0365	0.0412	0.00553	0.00306
MVD8	0.371	0.057	0.0412	0.0319	0.0201	0.00483
AWC8	0.257	0.086	0.162	0.0427	0.0930	0.00810
TFPI	0.114	0.029	0.353	0.0793	0.0678	0.00820
TFE	0.114	0.029	0.439	0.103	0.112	0.0104
TIPA	0.171	0.029	0.549	0.121	0.145	0.0126
TIPR	0.171	0.029	0.637	0.143	0.161	0.0141
AER	0.171	0.029	0.594	0.148	0.168	0.0198
RERC	0.171	0.029	0.607	0.170	0.169	0.0221

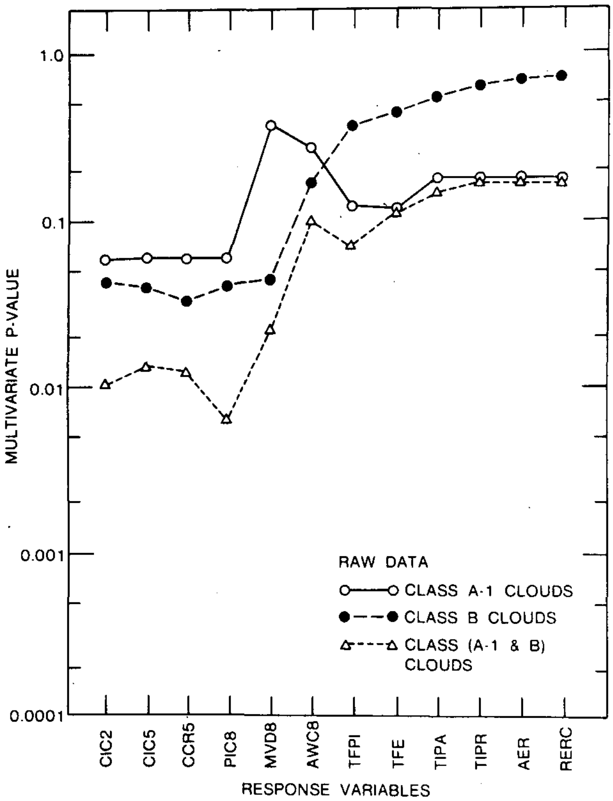

FIG. 3. Logarithmic scaled multivariate *P*-values based on MRPP with commensurate raw data for primary response variables.

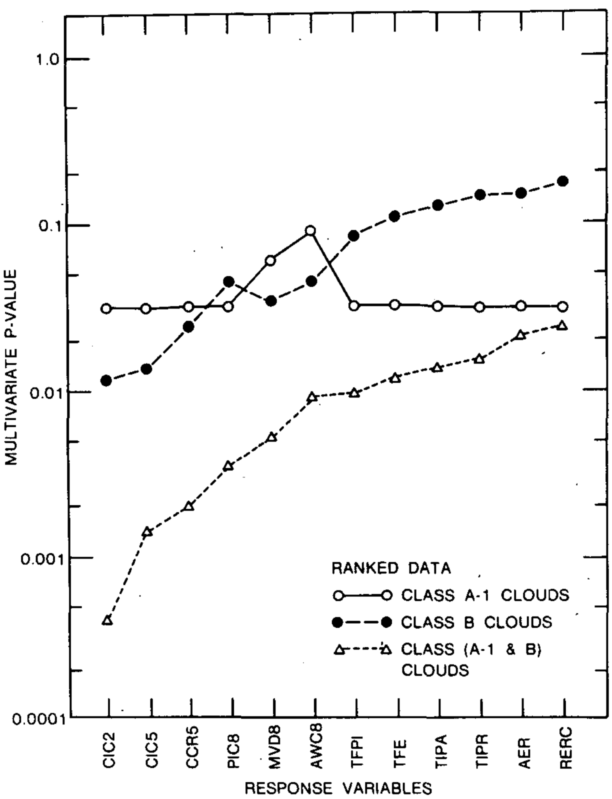

FIG. 4. As in Fig. 3, but with ranked data.

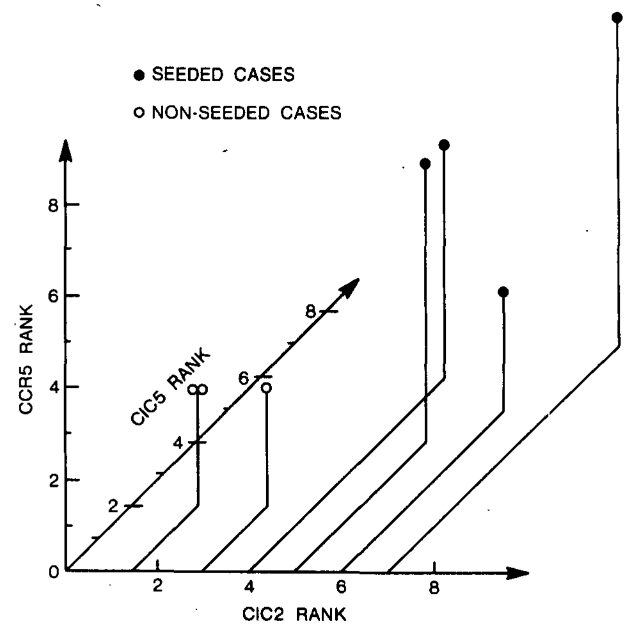

FIG. 5. Illustration of the separation of points for the Class A-1 clouds in ranked-data 3-space.

(for most of the cases) with the addition of one or another of the response variables measured at about 8 min after treatment. This observation is consistent with the results of the univariate comparisons given in Table 6.

These results are suggestive of a seeding effect discernible through the development of the ice crystal plume up to about 5 min after treatment. They also give an indication that the seeding effects in the chain of events in the HIPLEX-1 physical hypothesis could not be followed past the development of the initial ice crystal plume. It seems reasonable to inquire whether the subsequent differences considered together are significant. Table 8 presents multivariate comparisons of the "post-5-min" primary response variables (PIC8 through RERC). The high *P*-values indicate no obvious differences between the nonseeded and seeded experimental units for those response variables intended to monitor the subsequent development of precipitation.

Univariate comparisons between nonseeded and seeded experimental units are presented in Table 9 for two secondary response variables (FCC5 and MAXZ). The *P*-values indicate no obvious differences between

TABLE 8. PIC8 through RERC multivariate MRPP *P*-values for "post-5-minute" response variables.

Cloud class	Values	*P*-value
A-1	Raw data	0.257
A-1	Ranks	0.286
B	Raw data	0.880
B	Ranks	0.768
A-1 and B	Raw data	0.528
A-1 and B	Ranks	0.584

TABLE 9. Univariate *P*-values for secondary response variables FCC5 and MAXZ.

Cloud class	Values	*P*-value FCC5	*P*-value MAXZ
A-1	Raw data	0.200	0.486
A-1	Ranks	0.200	0.657
B	Raw data	0.117	0.203
B	Ranks	0.159	0.225
A-1 and B	Raw data	0.653	0.321
A-1 and B	Ranks	0.660	0.205

the nonseeded and seeded experimental units for either of these response variables. In fact, none of the secondary response variables indicated any obvious differences between nonseeded and seeded experimental units.

The point estimates and exact one-sided *P*-values associated with the final test statistics PCPA (based on TIPA), PCPR (based on TIPR), AVRA (based on AER), and AVRC (based on RERC) are given in Table 10. Even though some of the seeded to nonseeded rainfall ratios are either extremely small or extremely large, these results may not be important because none of the corresponding *P*-values (except that for the AVRA rain ratio associated with Class B clouds) is very small and/or the sample sizes are also very small. In addition, the rain ratio for both Class A-1 and Class B clouds is dominated by a single case, and 11 of the 17 zero values associated with the average rain amounts determined from RERC are due to default decisions. The corresponding results for AVRC must be interpreted with these points in mind. The AER univariate *P*-values (Table 6) and the AVRA *P*-values (Table 10) suggest an increase in precipitation due to seeding for Class B clouds, even though much of the details of the mechanism in the physical hypothesis and the locations and times of observations are open to question.

5. Discussion and conclusions

The differences found between nonseeded and seeded experimental unit responses during the first 5-min period following the seeding treatment (*viz.*, CIC2, CIC5, and CCR5) were substantial. Thus, a strong inference can be drawn that the HIPLEX-1 seeding treatments succeeded in producing ice crystal plumes more rapidly than they would have appeared naturally.

The *P*-values for the multivariate responses in Figs. 3 and 4 are roughly monotonically increasing, especially beyond the initial 5-min period. This fact suggests that the strong results for the initial 5-min period following the treatment are increasingly diluted by the addition of the subsequent responses specified by the physical hypothesis. The experiment was therefore not successful in following the chain of events through the subsequent development of earlier and increased precipitation in the seeded clouds. However, there was some evidence of earlier precipitation in one type of cloud (Class A-1) and of increased precipitation in another type (Class B).

It should be emphasized that the sample sizes of this experiment are extremely small (7 Class A-1 clouds, 13 Class B clouds, and no Class A-2 clouds) due to the premature termination of the experiment. Therefore, it cannot be determined whether the absence of significant differences after the 5-min mark is due to the lack of a seeding effect, inadequacies in the physical hypothesis, or the small sample sizes. Besides the small sample sizes, possible reasons for the lack of significant differences in responses beyond the initial 5-min period include the lack of conditions conducive to further growth of the artificial precipitation embryos. Cooper and Lawson (1984) investigate this possibility. They find that many of the clouds treated had very short lifetimes, which prevented the formation of precipitation in them and thus precluded significant statistical results for the post 5-min variables.

TABLE 10. Point estimates and exact one-sided *P*-values involving PCPA (based on TIPA), PCPR (based on TIPR), AVRA (based on AER), and AVRC (based on RERC).

Measure		Class A-1 Clouds S		Class A-1 Clouds NS	Class B Clouds S		Class B Clouds NS	Class A-1 and B Clouds S		Class A-1 and B Clouds NS
PCPA	Proportion with rain	3/4		1/3	4/8		2/5	7/12		3/8
	Exact *P*-value		0.371			0.587			0.325	
PCPR	Proportion with rain	0/4		0/3	2/8		1/5	2/12		1/8
	Exact *P*-value		1.00			0.685			0.656	
AVRA	Average rain (mm km^2)	0.077		0.879	1.81		0.067	1.23		0.372
	Ratio (S/NS)		0.088			26.9			3.32	
	Exact *P*-value		0.714			0.078			0.237	
AVRC	Average rain (mm km^2)	0.00		0.00	0.480		0.0024	0.320		0.0015
	Ratio (S/NS)		—			200			213	
	Exact *P*-value		1.00			0.359			0.347	

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