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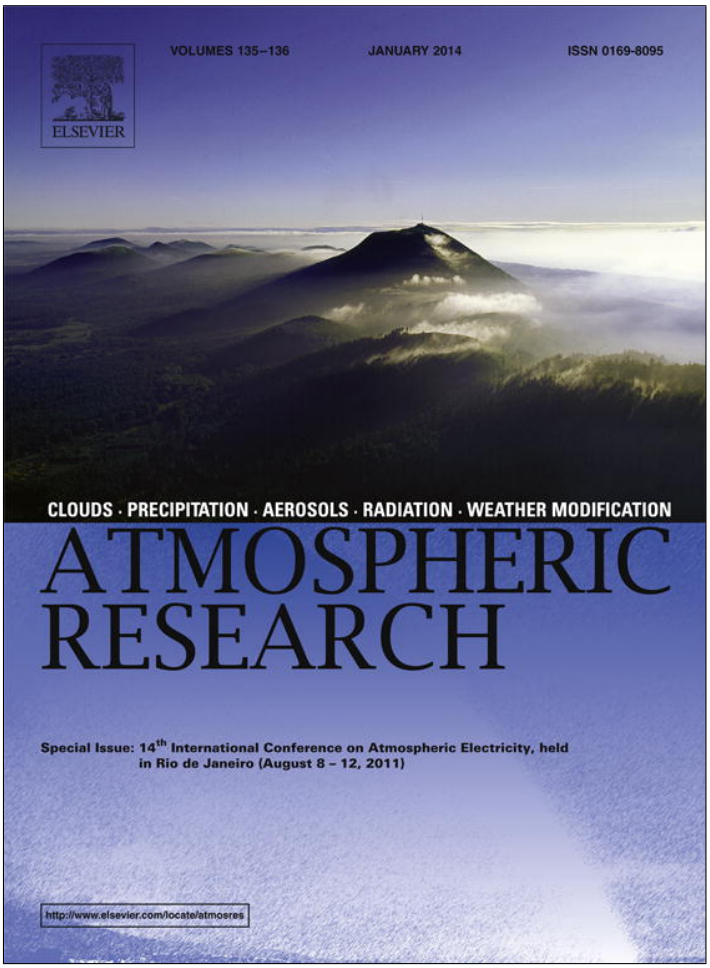

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Extra area effects of cloud seeding — An updated assessment ☆

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ABSTRACT

This paper examines the commonly-held hypothesis that cloud seeding reduces precipitation in regions adjacent to seeding target areas, sometimes referred to as "downwind" but more correctly referred to as "extra area" effects ("the robbing Peter to pay Paul" hypothesis). The overall concept in the potential creation of extra area effects from seeding is illustrated with respect to the hydrologic cycle, which includes both dynamical and microphysical processes. For the first time, results were synthesized from five operational and research weather modification experiments, including winter orographic snowpack enhancement and summer experiments to enhance rainfall. One of the most surprising aspects of these results is that extra area seeding effects on precipitation appear to be uniformly positive (5–15% increases, perhaps greater for some convective systems) for both winter and summer seeding projects examined in this paper. The spatial extent of the positive extra area seeding effects may extend to a couple hundred kilometers for winter orographic seeding projects and summer convective seeding projects (such as North Dakota, Texas, Thailand). Both microphysical and dynamical effects of seeding appear to be contributors to these extra area effects. Future work needs to incorporate larger data sets from some of the larger more sustained projects with advanced cloud models and tracer experiments.

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1. Introduction

Examined in this paper is the answer to a frequently asked question, "do increases in target area precipitation amounts from seeded cloud systems mean there will be less precipitation falling in areas located beyond the intended target areas"? Popular intuitive belief suggests that such seeding decreases precipitation that should otherwise have fallen without cloud seeding (i.e., "robs Peter"), and the rain goes to benefit someone else (i.e., goes to "pay Paul"). Actual seeding activities to increase precipitation that generally indicate an increase in precipitation amounts in target areas also generally indicate an increase beyond the intended target areas (e.g., Langmuir, 1950; Hobbs and Radke, 1973; Brown et al., 1975; Mulvey, 1977; Brown et al., 1978; Long, 2001; Solak et al., 2003; Griffith et al., 2005; Wise, 2005). Hence, cloud seeding typically benefits both "Peter" and "Paul". However, the database is still small enough to retain some doubt regarding the validity of such positive extra area seeding effects. Consequently, the Weather Modification Association (WMA) and the American Society of Civil Engineers (ASCE) held a jointly-sponsored, international workshop to scrutinize evidence currently available to address this frequently asked question at its 2012 annual meeting held in Las Vegas, Nevada on April 27, 2012.

A better understanding of "extra area" effects will also lend itself to improved understanding and modeling of the global water balance. In that subsequent connection, the National Research Council, NRC (2003) suggests that the effects of cloud seeding could be viewed as a means to alter natural hydrological cycles by increasing the number of times atmospheric water is recycled at the earth's surface, and not just as a means for increasing the local precipitation. The following sections highlight some topical background and recent evidence that cloud seeding increases precipitation in the intended target areas and beyond.

2. Background

Typical cloud seeding efforts focus on increasing the precipitation efficiency in seeded (or treated) cloud systems, compared to unseeded natural clouds, such that their precipitation falls within a pre-determined area, often referred to as the target area. This paper defines a cloud as a population of cloud droplets and interstitial cloud nuclei (i.e., located between the cloud drops) surrounded by the atmosphere. Contrary to popular belief, seeding operations generally do not involve treating every cloud or cloud system that passes overhead. A seeded cloud or cloud system contains potentially enhanced dynamic effects or microphysical effects, which generally increase the amount of precipitation, and is typically mobile, implying its precipitation will likely fall over an extended ground area. The seeded precipitation could conceivably fall beyond the boundaries of the target area. The seeding-induced precipitation that falls beyond the target area boundaries is often referred to as an "extra area" effect. Seeding effects have primarily been estimated by relating observed precipitation amounts in the target area during seeded periods with similar observations in control regions or in selected non-seeded control clouds. An exception is found in the design of the Santa Barbara II, phases I and II randomized research program which included specific "extra area" of effects observational and analysis components. In the French hail prevention project, the effect of ground seeding is observed on the hailpad network at a distance corresponding to an 80 min hailstorm travel from the silver iodide generators (Dessens and Fraile, 2000). This travel time corresponds to nearly 60 km for the most severe storms which move at a mean velocity of 12.2 m/s (Berthet et al., 2013). Observed precipitation amounts may be based on surface measurements and/or on estimated precipitation amounts derived from weather radar returns. In winter programs, control regions are selected to have similar precipitation climatologies, elevations and exposures as the target area(s). These control regions are not part of the seeding operations nor are they influenced by the operations, and consequently, represent the 'natural' state. In summer programs, weather radar returns for natural clouds that exhibit similar characteristics to clouds selected for seeding prior to their being seeded are selected for comparison as the seeded and non-seeded control clouds move into areas beyond the intended target area. For example, Wise (2005) determined downwind and control regions by observing radar-derived storm track data. He found a possible positive target and "extra area" effect from non-randomized seeding over western North Dakota during summertime (June, July, August) under southwesterly windflow. The most common method used to quantify "extra area" effects is the a-posteriori historical target/control regression technique (Dennis, 1980) or adaptation thereof (e.g., Griffith et al., 1978, 1980; Gabriel and Petrondas, 1983; Woodley and Solak, 1990; Woodley and Rosenfeld, 2004). Great caution should be used with this technique, as historical target control ratios cannot be assumed constant with time, due to climatic fluctuations, land use changes, or other long-term perturbations.

A National Science Foundation sponsored workshop on "extra area" effects of weather modification was conducted in August 1977 (Brown et al., 1978). They reported; *the "better quality" evidence available from mostly a-posteriori analyses of randomized seeding programs suggested that precipitation changes in extended areas tended to be similar in sign (i.e., increases or decreases) and roughly the same magnitude as those in the primary "target area". The extended effects appeared to be detectable at distances of a few hundred kilometers from the seeding source. There was little evidence available to support that seeding to increase rainfall in one area deprived another area of its normal rainfall. The extended-area effect appeared to be a continuum from the nucleating source to the final observed effect in most cases. It was considered likely that more than one physical mechanism might produce changes in precipitation patterns in extended areas: 1) the transport of particles (either ice crystals or silver iodide nuclei) from a seeded volume well removed from the intended area of effect or 2) a seeding induced dynamic effect in the intended target area which may affect other areas. There were field*

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measurements and observations of both ice crystals and ice nuclei reported to be transported over 100 km from a seeding source. They also reported the need for more data since their data base was statistically too small to more definitely report on extra-area effects. The Las Vegas 2012 WMA/ASCE workshop presentations and discussions reaffirmed many of Brown et al.'s (1978) findings.

Recent technological advances in measurement system capabilities enable comprehensive water budget measurements for seeded systems and advanced techniques to yield a more accurate quantification of the answer to our question. Such examples are polarimetric radar rainfall measurements and high resolution model predictions of precipitation, which can serve as a control against the actually measured seeded precipitation in a randomized scheme. Such measurements and simulations are useful since "extra area" effects are dependent on cloud systems and their inherent dynamics. The detection of "extra area" effects due to cloud seeding depends generally on how well dynamical and ensuing microphysical effects (sometimes referred to as dynamic and static effects) are characterized during the "extra area" transport of the seeding material. It is imperative that representative, finer than cloud-system-scale measurements be used to quantify "extra area", or any, effects due to cloud seeding; statistical representativeness notwithstanding. These effects are functions of a complex set of processes and their interactions which influence the following factors among others: (i) persistence and effectiveness of seeding material, (ii) dispersion (transport and diffusion), (iii) seeding agent concentration, (iv) background cloud microstructure (hydrometeors and nuclei), and (v) the air-mass characteristics (e.g., state parameters, gas, solid and aqueous phase composition) in which the cloud was formed (e.g., Rosenfeld and Woodley, 2003; Rosenfeld et al., 2005; Bell et al., 2008).

Transport and dispersion of seeding material may be verified using tracer measurements (e.g., SF_6), ice nuclei and ice crystal concentration, trace chemical analyses (e.g., indium, silver) of snow samples, and trajectory models. In the case of winter orographic clouds, analyses suggest that seeding effects are detectable in the target area and as far as a few hundred kilometers beyond the target area, with nearly all such studies indicating an increase in precipitation (e.g., Silverman, 2001).

The second phase of the Florida Area Cumulus Experiment (FACE-2) investigated the question of extended-area seeding effect (Meitin et al., 1984), using geosynchronous, infrared satellite imagery and the Griffith–Woodley (G–W) rain estimation technique (Griffith et al., 1978, 1980; Woodley et al., 1982, 1983). The G–W technique (Griffith et al., 1978, 1980) was derived in South Florida by calibrating infrared images using rain gauge and radar observations to produce an empirical, diagnostic (a posteriori), satellite rain estimation technique. Gauge, radar and satellite rain estimates were made for the FACE target area over South Florida. All daily rainfall estimates were composited in two ways: 1) in the original fixed coordinate system and 2) in a relative coordinate system that rotates the research area as a function of wind direction. After compositing, apparent seeding effects were examined as a function of space and time. The results indicated more rainfall (in the mean) on seed than on no seed days, both in and downwind of the target but lesser rainfall upwind of the target. All differences (averaging +20% downwind and −10% upwind) were spatially confined to within 200 km of the center of the FACE target and temporally to the 8 h period following initial treatment.

Numerical models have become increasingly proficient at simulating cloud processes and the effects of seeding (e.g., Meyers et al., 1995; Caro et al., 2004; Curic et al., 2007; Chen and Xiao, 2010; Saleeby et al., 2011; Xue et al., 2013a, 2013b). Some case studies have taken advantage of field measurements, such as tracers for targeting and plume dispersion as well as fine-scale precipitation data, for comparison and validation of numerical model output, particularly for orographic systems over complex terrain (e.g., Bruintjes et al., 1995; Xue et al., submitted for publication). However, there is still a need for realistic (i.e., validated) modeling studies over a range of seeding scenarios in order to convincingly document "extra-area" effects relying solely on model results. Consequently, while recognizing the importance and progress in the ability of numerical models to simulate relevant cloud processes, this paper focuses on measurement-based evidence of "extra-area" effects from cloud seeding activities.

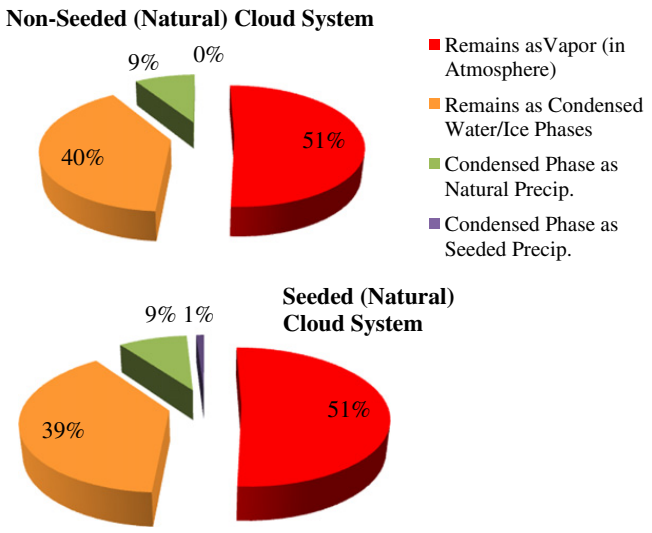

Fig. 1. Conceptual water budget for natural cloud system that yields precipitation compared to a conservative equivalent for a seeded natural cloud system that yields precipitation. Values are derived from thermodynamic diagrams, soundings during winter orographic storms and from Braham (1952).

3. Conceptual model

The WMA-ASCE sponsored Las Vegas workshop participants considered the hypothesis that cloud seeding to increase

Table 1
Summary of "extra area" indications.
Adapted from Solak et al. (2003).

Distance from target (km)	No. of sites	Ratio observed (O)/predicted (P) precipitation	Precipitation difference (dp)	Correlation (r)
Target	27	1.14	35.31 mm	0.97
0–40	6	1.12	8.89 mm	0.90
40–80	1	1.42	12.45 mm	0.59
80–120	1	1.19	8.13 mm	0.82
120–160	2	1.16	8.89 mm	0.75
160–200	4	1.06	6.35 mm	0.88
200–240	3	0.98	−2.29 mm	0.83

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precipitation (rainfall, or snowfall) benefits the intended target areas as well as areas located beyond the intended target area(s). As the discussions matured, the group formulated a conceptual model of the "extra area" effect due to cloud seeding. It assumed the existence of an atmospheric water balance, such as that explained for the hydrologic cycle described in Trenberth et al. (2007), wherein a total column moisture flux is generally balanced by evapo-transpiration and evaporation, precipitation, and atmospheric moisture storage, at any given time. From Trenberth et al. (2007), approximately 35% of the atmospheric water vapor over land masses originates from evaporation off the earth's ocean surfaces, whereas 65% of the atmospheric water vapor over land originates from evapo-transpiration over land surfaces. This atmospheric water vapor reservoir is involved in producing precipitation, and any increases in precipitation through cloud seeding over an intended target area or also over "extra area" adjacent to the intended target area. There are likely to be many variations in the global hydrologic cycle water reservoir estimate when viewed on local to regional scales. Even though, large amounts of water vapor pass over the U.S. every day, not all of it condenses out and forms precipitation, especially on a local scale. For example, Reed et al. (1997) estimated that the average annual through-flux (1973–1994) of atmospheric moisture over Texas is 7788 mm while the annual precipitation is 720 mm, indicating that about 9% of the moisture passing over Texas (annually) falls as precipitation. This implies that some water vapor and condensate remain during and following precipitation. Their exact amounts depend on a number of variables, including thermodynamic profiles (e.g., Braham, 1952; Gamache and Houze, 1983; Chong and Hauser, 1989; Tao et al., 1993; Gao and Li, 2008; Trenberth et al., 2007; Li et al., 2011).

Seeding operations designed to enhance the efficiency of the precipitation process (i.e., the conversion of the vapor to precipitation) produce about 5–15% additional precipitation in certain seeded target areas (e.g., American Society of Civil Engineers—ASCE, 2004). If we assume the Reed et al. example as representative of a typical non-seeded precipitating system, and assume a 10% enhancement in the efficiency of the precipitation process due to cloud seeding, then 9% of the 'moisture that passes over Texas falls as precipitation' without seeding could become 10% of the 'moisture that passes over Texas falls as precipitation'. Seeded-enhanced precipitation processes persist longer (perhaps up to 8 h based on evidence provided earlier), thereby increasing the amount of precipitation and its ground coverage as this system moves. Fig. 1 depicts this basic concept.

4. Evidence

There have been three noteworthy precipitation enhancement projects (Cases 1–3) dedicated to addressing the hypothesis according to the Las Vegas workshop and they are summarized in the following.

4.1. Case 1

Solak et al. (2003) used the a-posteriori historical target/control regression approach to provide quantitative estimates of extra area effects from a large, long-term, ground-based winter

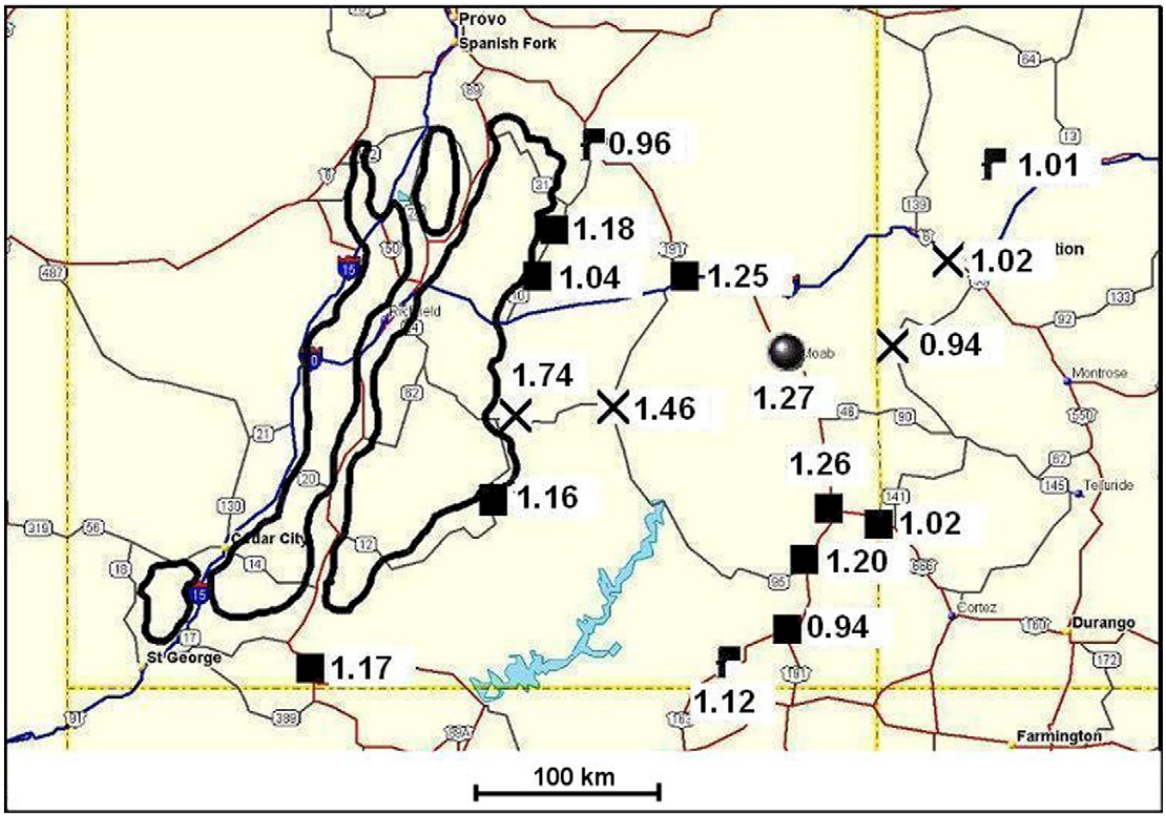

Fig. 2. Ratios of extra area observed/predicted precipitation amounts for 34 seeded winter seasons in Utah. Thick black outlines designate seeding target areas. Extra area site symbols indicate corresponding correlation coefficient: square = greater than or equal to ≥0.80; flag = 070–0.79; ball = 0.60–0.69; and × < 0.60.

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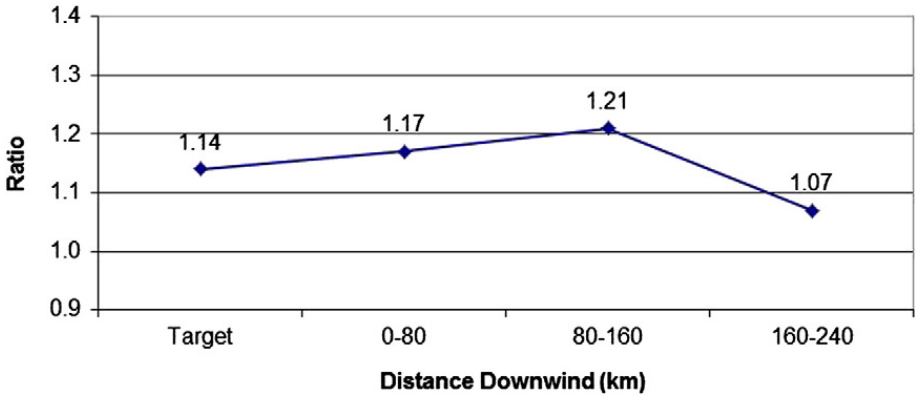

Fig. 3. Average observed overpredicted precipitation ratios for 80-km "extra-area" distance bands (34 winter seasons).

(cold season) operational cloud seeding program being conducted in central and southern Utah (Griffith et al., 2009). They used the regression method, with regression equations developed from non-seeded historical periods to estimate natural precipitation for each extra area precipitation site during 25 seeded seasons. These seeded seasons were comprised of the 1974–2002 water years but excluding the 1984–1987 water years which were not seeded. Observed "extra area" precipitation during the seeded periods was compared with regression-based predictions for these "extra areas". The observed/predicted precipitation (O/P) ratios and the mean observed minus the mean predicted differences in precipitation (dp) are provided in Table 1. An observed overpredicted ratio >1.0 would indicate a potential increase based on the regression equation output. The complete 17 extra-target area group of sites has an average O/P ratio of 1.08, suggesting average extra area precipitation increases of about 8%. The O/P values were similar for the target and extra areas. The estimated dp values indicate that amounts of additional precipitation in the extra areas are considerably less than in the target, but they are all positive out to 200 km. Their results provided evidence of target and "extra area" increases in precipitation, with an apparent 160–200 km limit to the extra area increases. The 160–200 km limit is consistent with observations of extra area transport of the AgI ice forming nuclei or ice crystals (e.g., Brown et al., 1978).

North American Weather Consultants staff extended the work of Solak et al. (2003) through 2011 providing an "extra area" database that encompasses 34 seeded winter seasons. Ten control sites, spread across eastern Nevada, western Utah and northern Arizona, were used in the analysis (i.e., Ely NV, McGill NV, Pioche NV, Ruby Lake NV, Callao UT, Grand Canyon National Park AZ, Flagstaff AZ, Seligman AZ, Williams AZ, Wupatki National Monument AZ). Fig. 2 provides a graphic representation of the combined results for the 34 seeded seasons at several precipitation sites located east of the intended target areas. The thick black outlines designate the intended target areas. Different symbols are used in Fig. 2 to indicate ranges of correlation coefficients from the regression equations. They found a 14% average increase in target areas, a 14% average increase 0–120 km east of the target area and a 5% average

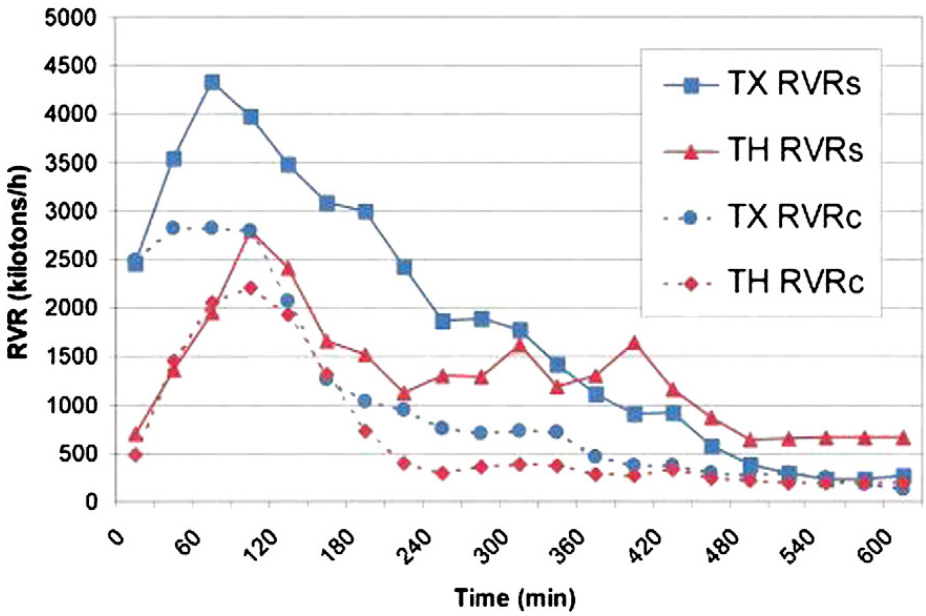

Fig. 4. Time plots of seeded (S) and matched control (C) units mean rain-volume rate (RVR) in the Texas (TX) High Plains program (out, 2-h match). The Thai S and C plots were obtained from its randomized seeding effort. Thus the RVR plots for the Texas operational seedings can be compared to those generated from the randomized seeding in Thailand.
From Woodley and Rosenfeld (2004).

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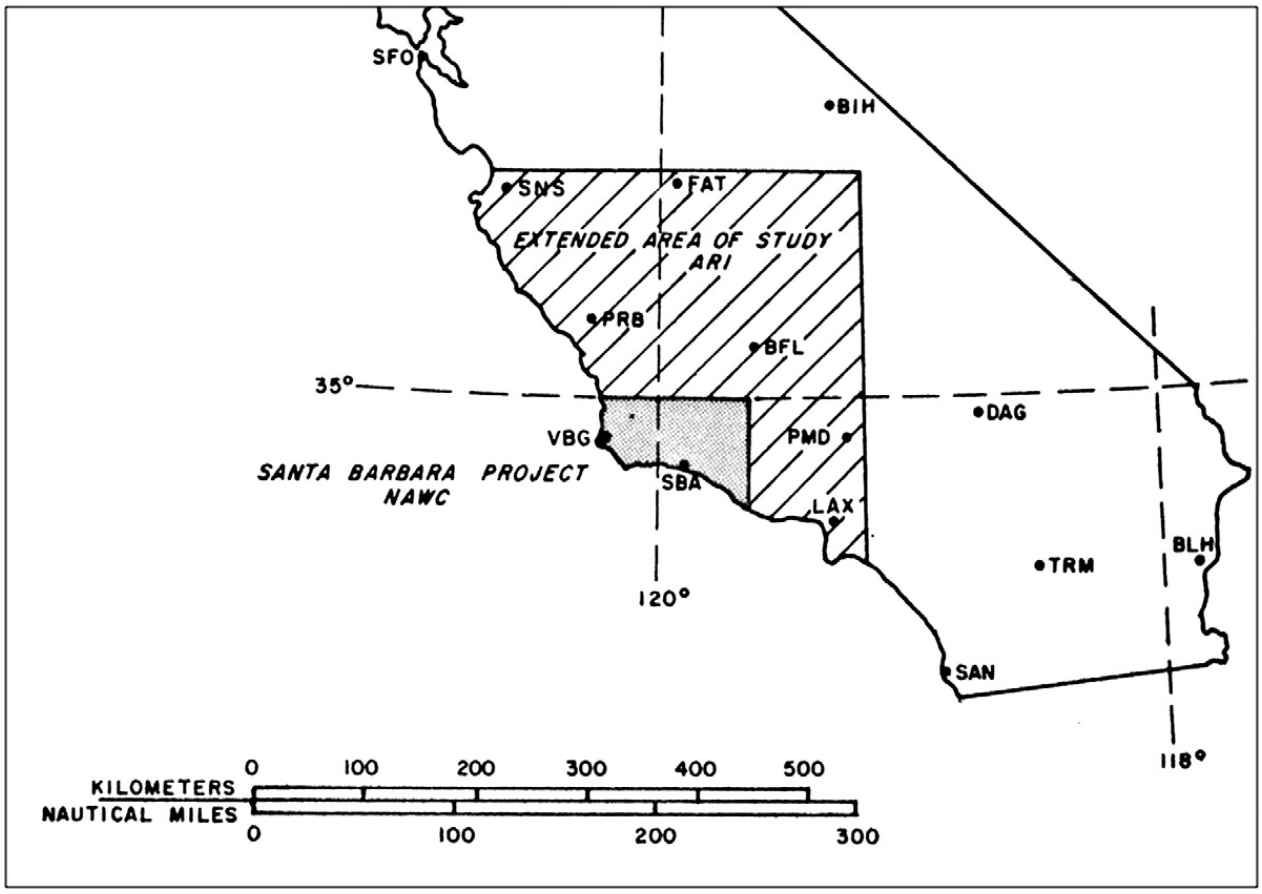

Fig. 5. Santa Barbara II, phases I and II, project areas.

increase 120–240 km east of the target area over the entire 34 season database (Fig. 3). They confirmed positive seeding effects in the target area and out to 160 km east of the target area that had the same sign and similar magnitude (percentage-wise). Even though the indicated percentage increases were similar for target and "extra area", the estimated precipitation amounts were smaller in the "extra area" due to their more arid characteristics. There was also a gradient in the estimated seeding effect as a function of extra area distance, consistent with relevant physical principles (e.g., reduced seeding agent concentrations, timing of growth and fallout of artificially generated snowflakes).

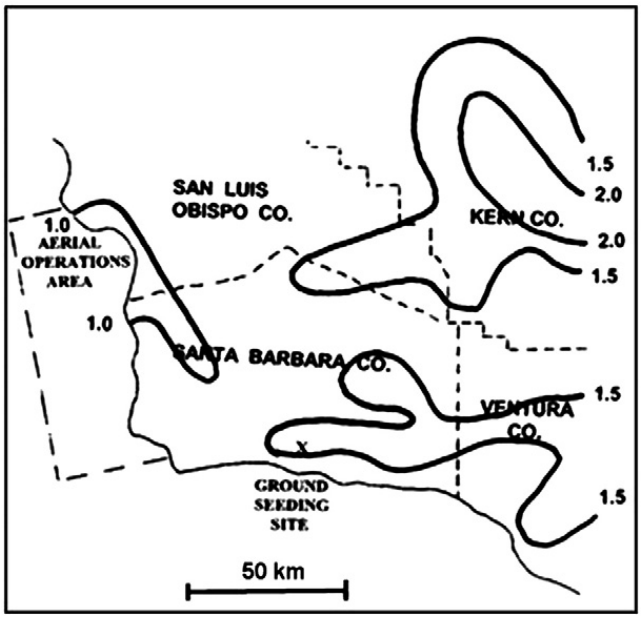

Fig. 6. Seed/no-seed ratios of convection band precipitation, Santa Barbara II phase I, ground-based seeding. The × symbol represents the location of the ground seeding site.

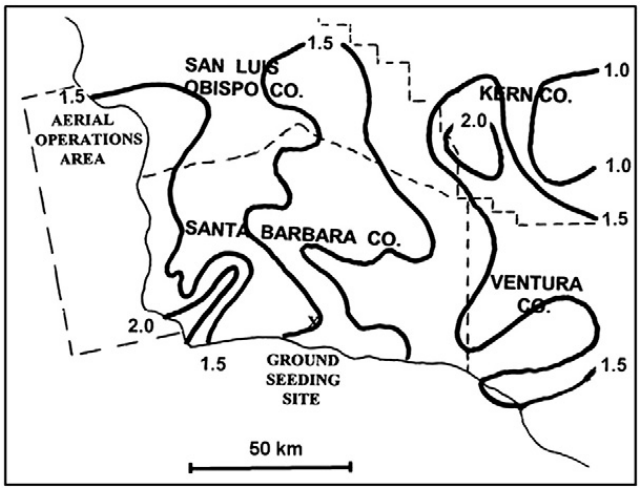

Fig. 7. Seed/no-seed ratios of convection band precipitation, Santa Barbara II phase II, airborne seeding. The × symbol represents the location of the ground seeding site used in phase I for comparison purposes.

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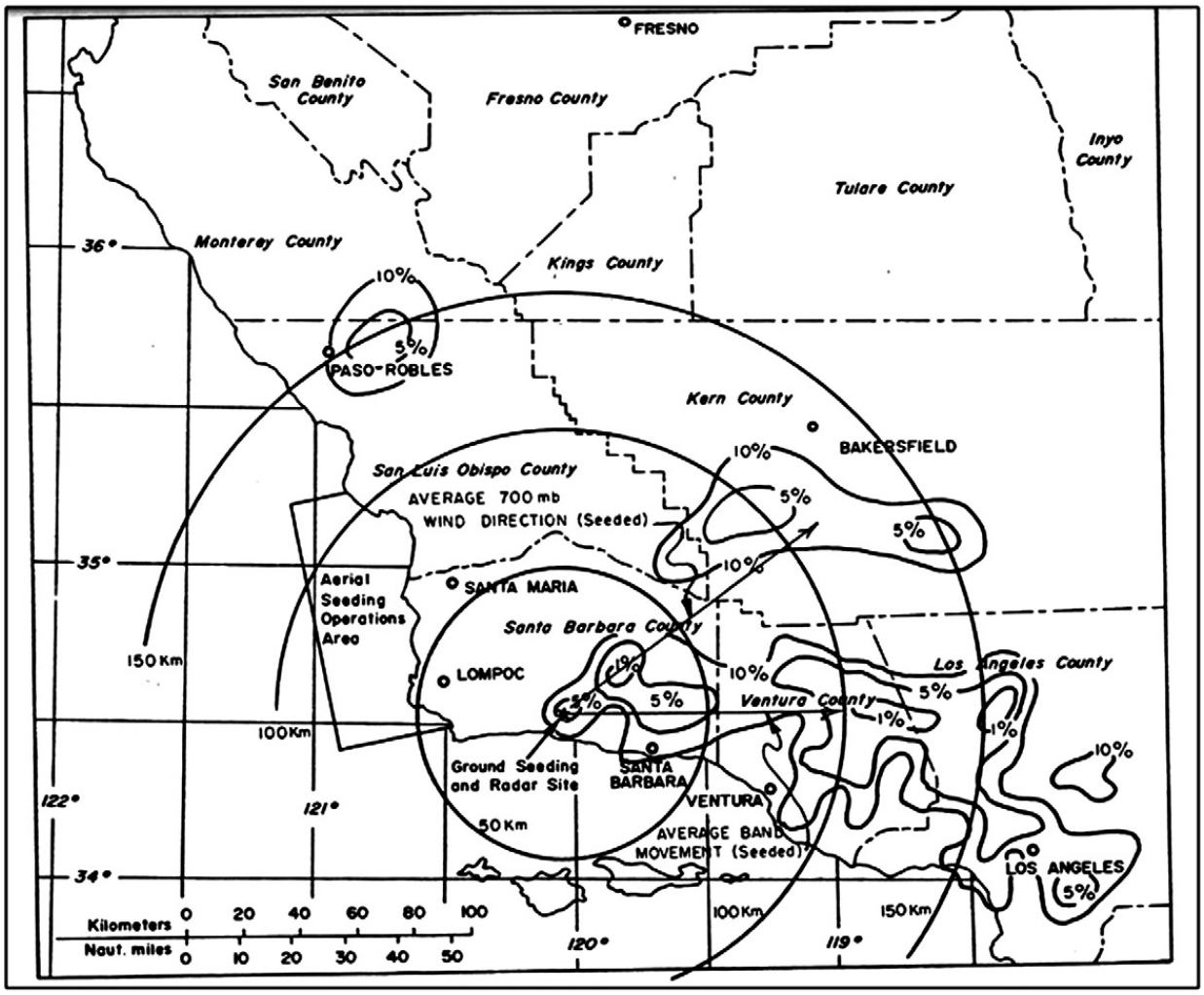

Fig. 8. Comparison of 700 mb wind direction and convective band movement with areas of high statistical significance with convective band seed/no-seed precipitation ratios, Santa Barbara II, phase I, ground-based seeding. Star represents a ground seeding site.

4.2. Case 2

For the evaluation of operational cloud seeding programs employing dynamic seeding concepts, a method for the objective evaluation of short-term, nonrandomized operational convective cloud seeding projects on a floating-target-area basis was developed and tested (Woodley and Rosenfeld, 2004). This was done in the context of the operational cloud seeding projects of Texas. The computer-based method makes use of the WSR-88D mosaic radar data to define fields of circular (25-km radius) floating-target analysis units with lifetimes from the first echo to the disappearance of all echoes and then superimposing the track and seeding actions of the project seeder aircraft onto the unit fields to define seeded (S) and non-seeded (NS) analysis units. Objective criteria (quantified in Woodley and Rosenfeld, 2004) are used to identify "control" matches for each of the seed units from the archive. To minimize potential contamination by seeding, no matching is allowed for any control unit if its perimeter came within 25 km of the perimeter of a seed unit during its lifetime.

The methodology was used to evaluate seeding effects in the High Plains Underground Water Conservation District (HP) and Edwards Aquifer Authority (EA) programs during the 1999, 2000, and 2001 (EA only) seasons. Objective unit matches were selected from within and outside each operational target within 12, 6, 3, and 2 h of the time on a given day that seeding of a particular unit took place. These were done to determine whether selection biases and the diurnal convective cycle confounded the results. Matches were also drawn from within and outside each fixed target using the entire archive of days on which seeding was done. Although the statistical significance of the results was calculated, the resulting probability (P) values were used solely to determine the relative strength of the various findings, because significance tests are valid only for a priori hypotheses.

The apparent effect of seeding in both programs was large — even after determining the effect of selection biases and accounting for the diurnal convective cycle. The most conservative and credible estimates of seeding effects were obtained from control matches drawn from outside the operational target within 2 h of the time that each unit was seeded initially. Under these circumstances, the percentage increase exceeds 50% and the volumetric increment was greater than 3000 acre-feet (3700 kt) per unit with strong P-value support (i.e., 0.0001) in both HP and EA programs. This is in good agreement with the apparent percentage effects of seeding for the randomized Texas and Thailand cloud-seeding programs, which were 43% in Texas and ranged between 48% and 92% in Thailand. In the EA program

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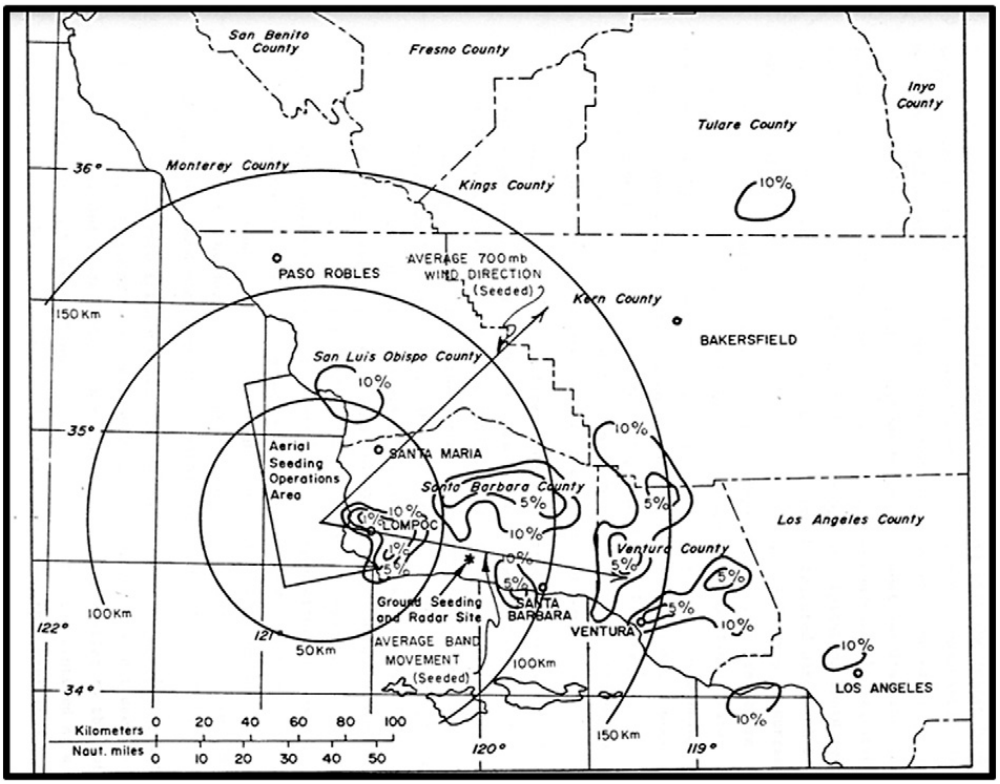

Fig. 9. Comparison of 700 mb wind direction and convective band movement with areas of high statistical significance with convective band seed/no-seed precipitation ratios, Santa Barbara II, phase II, airborne seeding. Star represents the ground seeding site used in phase I for comparison purposes.

25% of the seeded rain volumes fell outside the fixed target downwind in the 8 h period of evaluation. In the EA program 34% of the seeded rain volume fell outside the target in the same 8 h period of evaluation. As with the FACE randomized seeding, these results indicate that rainfall is increased downwind of the seeding activity, primarily as the seeded clouds move out of the target downwind.

Plots of the mean S and C rain volume rates (RVR) versus time for the HP operational program are provided in Fig. 4 (blue lines). The matching C values were obtained from outside the operational target within 2 h of the initial seeding in each unit. Included also in Fig. 4 are comparable S and NS plots from the Thai randomized glaciogenic cloud-seeding program (Woodley et al., 2003a, 2003b). The plots are surprisingly similar considering the Texas plots were generated for an operational seeding program while those for Thailand were obtained for its randomized cloud seeding program. Both S and C plots peak at about 60 to 90 min after initial unit seeding. Note also the mean S RVR values exceed the mean C values out to 8 h after initial seeding in both programs. This protracted effect of seeding explains why so much of the S rainfall was observed to fall outside the fixed target area in which seeding was conducted.

All of these results and their *P*-value support after partitioning gave even stronger indications of positive seeding effects. Although the results of these and other analyses described herein make a strong case for enhanced rainfall by the operational seeding programs within the S units and downwind of the fixed target, such operational programs must not be viewed as substitutes for randomized seeding efforts that are conducted in conjunction with realistic cloud modeling and are followed by replication, preferably by independent groups for maximum credibility.

4.3. Case 3

Griffith et al. (2005) examined the results of both research and operational cloud seeding activities conducted in Santa Barbara County, California since 1950. A randomized research program, known as Santa Barbara II, was conducted in the Santa Barbara area in two phases during the 1967–1973 winter seasons. Phase I involved single site, ground-based silver iodide flare seeding of "convection bands" that were embedded in stratiform storms. Earlier research had indicated that these bands contained supercooled liquid water and would present good cloud seeding targets of opportunity. Phase II (1971–1974) involved airborne seeding of convection bands with flights typically conducted off the west coast of the county. The primary project area was essentially Santa Barbara County. Fig. 5 provides the location of the primary and extended areas of study. An interesting aspect concerning the design of Santa Barbara II was that the design included a component directed at attempting to identify any extra area seeding effects. As a consequence, analyses from this program looking at such potential extra area effects were a-priori, not a-posteriori in nature. These analyses indicated the presence of extended seeding effects at distances of a few hundred kilometers beyond the intended target area and insight into the possible mechanisms causing changes in precipitation patterns in these extended areas (Figs. 6–9). These analyses identified a primary seeding zone (i.e., within ~50 km of the seeding source), a second area (about 100 km from the seeding source) and a third area (about 100 to 150 km from the seeding source) shown by three different radii in Figs. 8 and 9, which provide graphical representations of these results. All three areas had statistically significant indications of augmented precipitation during the Santa Barbara II research

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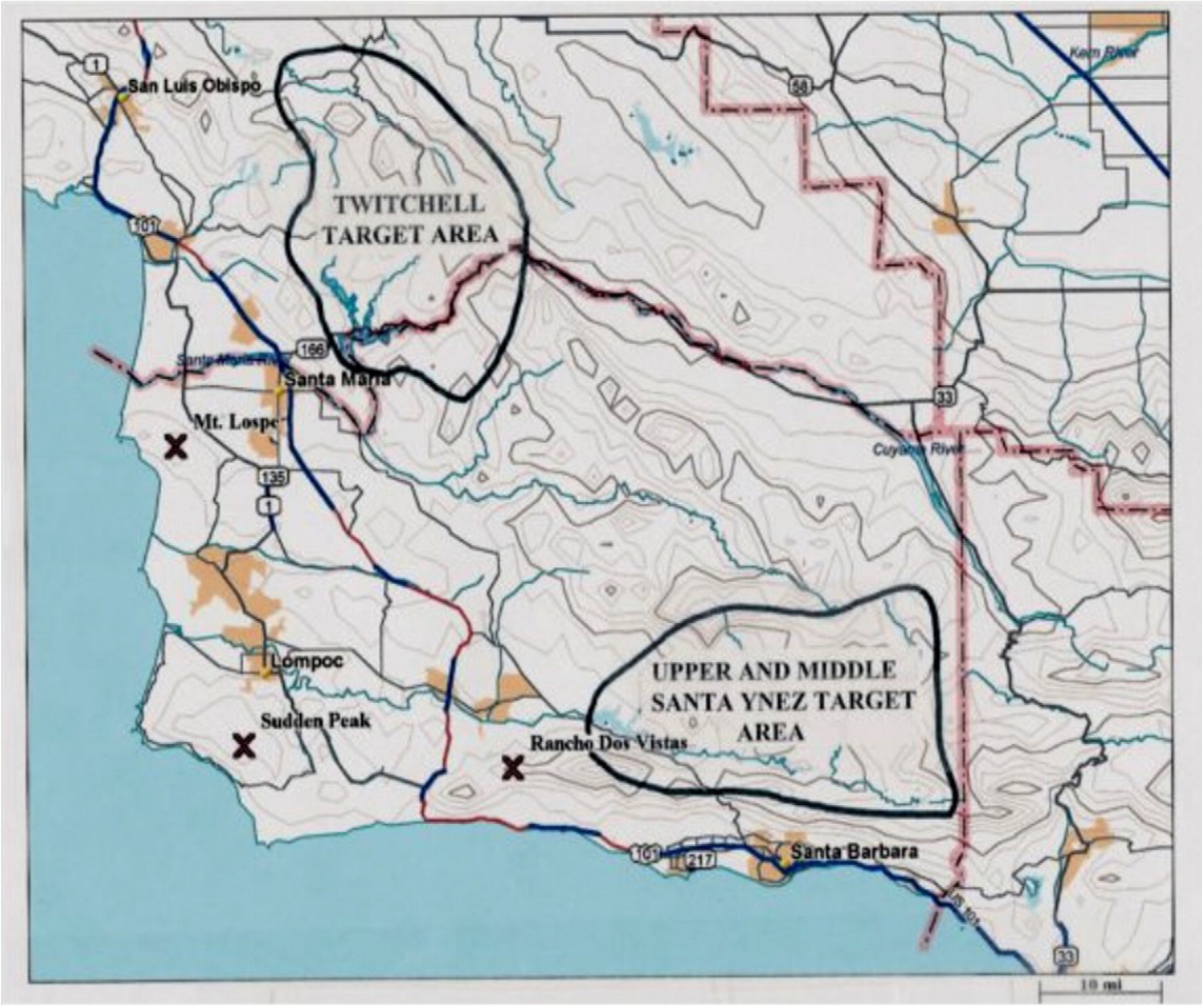

Fig. 10. Target areas for recent operational cloud seeding projects in Santa Barbara County. The ×'s represent ground seeding sites.

study. Referring to Figs. 8 and 9, the second area was aligned according to the 700 mb flow, and the augmented rain in this "extra area" region was probably caused by a direct transport of either silver iodide nuclei or very small ice particles. The third area was aligned more with the movement of the rain bands to the right of the mean winds and the augmented rain in this "extra area" region was probably due to "mesoscale dynamics". These results support the concept that both static and dynamic effects may occur (especially in convective type clouds) due to seeding and further that extra area effects may not always be directly "downwind" of the target area, thus the more correct phrase "extra area effects" came into being.

An operational non-randomized seeding program was initiated in 1981 due to dry conditions. The Santa Barbara II research program served as the basis for the design of this program. This operational seeding program, which has been primarily focused in Santa Barbara County, encompassed two primary target watersheds, Twitchell and the Upper and Middle Santa Ynez (Fig. 10). No historical target/control evaluations of these operational programs have been attempted since there are no upwind ground based precipitation control sites available; oceans both west and south of Santa Barbara County.

5. Summary

One of the most surprising aspects of the Las Vegas 2012 WMA/ASCE workshop presentations and additional studies examined is that "extra area" seeding effects appear to be uniformly positive (5–15% increases, perhaps larger for some convective systems) for both winter and summer seeding projects. These results run counter to widely held misconceptions over the years and to previous NAS/NRC assessments (e.g., Garstang et al., 2005). We suggest that this is because previous reports on "extra area" effects were limited only to randomized cloud seeding experimental results, many of which had limited duration and sample size, or inadequate gauge/radar coverage. The spatial extent of the positive "extra area" seeding effects may extend to a couple hundred kilometers. Both microphysical (static) and dynamical (dynamic) effects of seeding appear to be contributors to these "extra area" effects.

The results described in this paper, summarized in Table 2, make a strong case for enhanced precipitation, or a direct seeding effect, in "extra area" regions from the conduct of seeding programs. They did not reveal regional impacts to the water balance, nor to the natural precipitation on a regional scale. This suggests that cloud seeding would not dry up the

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Table 2
Summary of experimental cases.

Experiment name	Seeding period	Type of experimental units	Number of experimental units	Randomization	Method of evaluation scheme	Indicated effect (% at specified distance downwind of target or at time following seeding)	Reference
Central-Southern Utah (Case 1)	1974–2002, excluding 1984–1987	Season (Dec.–Mar.)	25 seasons	No	Historical target control, ground based precipitation	+14 (target-T) +12 (T + 40 km) +42 (40–80 km) +19 (80–120 km) +16 (120–160 km) + 6 (160–200 km) −2 (200–240 km)	Solak et al. (2003)
Central-Southern Utah (Case 1)	1974–2002, excluding 1984–1987	Season (Dec.–Mar.)	34 seasons	No	Historical target control, ground based precipitation	+14 (target-T) +17 (T + 80 km) +21 (80–160 km) +7 (160–240 km)	WMA/ASCE 2012 Las Vegas workshop
HP (Case 2)	1999–2000	Cells (25 km radius)-radar	635	No	Radar selected controls	+82 (2 h) +62 (3 h) +77 (6 h) +53 (12 h)	Woodley and Rosenfeld (2004)
EA (Case 2)	1999–2001	Cells-radar	306	No	Radar selected controls	+104 (2 h) +84 (3 h) +80 (6 h) +59 (12 h)	Woodley and Rosenfeld (2004)
Santa Barbara II, phase I, ground (Case 3)	1967–1971 winter seasons	Convection bands	56 seed, 51 not-seeded	Yes	Ground observations of band precipitation	+50 (0–50 km) +50–+100 (50–100 km) +50 (100–150 km)	Griffith et al. (2005)
Santa Barbara II, phase II air borne (Case 3)	1971–1974 winter seasons	Convection bands	18 seed, 27 not-seeded	Yes	Ground observations of band precipitation	+50 (0–50 km) +50–+100 (50–100 km) +50–+100 (100–150 km)	Griffith et al. (2005)

atmosphere or lead to summer drought, contrary to a popular belief. Cloud seeding typically benefits both "Peter" and "Paul".

The results should be verified and strengthened by randomized seeding efforts that are conducted in conjunction with realistic high-resolution cloud modeling that can simulate cloud seeding and transport of seeding agents, tracer studies, and confirmatory physical measurements. The National Research Council, NRC (2003) report supports these conclusions, suggesting that the question about extended area effects likely will become better defined and understood as more is learned about the global water balance and as new tools enable the cloud scientist to better understand clouds and their response to seeding.

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References

American Society of Civil Engineers—ASCE, 2004. Standard Practice for the Design and Operation of Precipitation Enhancement Projects, Reston, VA (100 pp.).

Bell, T.L., Rosenfeld, D., Kim, K.-M., Yoo, J.-M., Lee, M.-I., Hahnenberger, M., 2008. Midweek increase in U.S. summer rain and storm heights suggests air pollution invigorates rainstorms. J. Geophys. Res. 113, 001–009.

Berthet, C., Wesolek, E., Dessens, J., Sanchez, J.L., 2013. Extreme hail day climatology in Southwestern France. Atmos. Res. 123, 139–150.

Braham, R.R., 1952. The water and energy budgets of the thunderstorm and their relation to thunderstorm development. J. Meteorol. 9 (4), 227–242.

Brown, K.J., Thompson, J.R., Elliott, R.D., 1975. Large scale effects of cloud seeding. Aerometric Research Inc. Report No. 72-2 to U.S. Dept. of Interior, Bureau of Reclamation.

Brown, K.J., Elliott, R.D., Elliott, R.D., 1978. Transactions of Workshop on Extra Area Effects of Weather Modification. North American Weather Consultants Executive Summary Report No. 78-42A submitted to the National Science Foundation.

Bruintjes, R.T., Clark, T.L., Hall, W.D., 1995. The dispersion of tracer plumes in mountainous regions of Central Arizona: comparisons between observations and modeling results. J. Appl. Meteorol. 34, 971–988.

Caro, D., Wobrock, W., Flossmann, A.I., Chaumerliac, N., 2004. A two-moment parameterization of aerosol nucleation and impaction scavenging for a warm cloud micro-physics: description and results from a two-dimensional simulation. Atmos. Res. 70, 171–208.

Chen, B., Xiao, H., 2010. Silver iodide seeding impact on the microphysics and dynamics of convective clouds in the high plains. Atmos. Res. 96, 186–207.

Chong, M., Hauser, D., 1989. A tropical squall line observed during the CORT 81 experiment in West Africa. Part II: water budget. Mon. Weather Rev. 117 (4), 728–744 (0027–0644).

Curic, M., Janc, D., Vuckovic, V., 2007. Cloud seeding impact on precipitation as revealed by cloud-resolving mesoscale model. Meteorol. Atmos. Phys. 95, 179–193.

Dessens, J., Fraile, R., 2000. The effect of silver iodide seeding on hailstone size distributions. J. Weather Modif. 32, 26–30.

Gabriel, K.R., Petrondas, D., 1983. On using historical comparisons in evaluating cloud seeding operations. J. Appl. Meteorol. 22, 626–631.

Gamache, J.F., Houze Jr., R.A., 1983. Water budget of a mesoscale convective system in the tropics. J. Atmos. Sci. 40, 1835–1850.

Gao, Shouling, Li, Xiaofen, 2008. Cloud-resolving Modeling of Convective Processes. Springer, New York (210 pp.).

Garstang, M., Bruintjes, R., Serafin, R., Orville, H., Boe, B., Cotton, W., Warburton, J.A., (May) 2005. Weather modification—finding common ground. Bull. Am. Meteorol. Soc. 86, 647–655.

Griffith, C.G., Woodley, W.L., Grube, P.G., Martin, D.W., Stout, J., Sikdar, D.N., 1978. Rain estimation from geosynchronous satellite imagery — visible and infrared studies. Mon. Weather Rev. 106, 1152–1171.

Griffith, C.G., Woodley, W.L., Grube, P.G., Martin, D.W., Stout, J., Sikdar, D.N., Augustine, J.A., 1980. Estimation of convective summertime rainfall in

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the United States High Plains from thermal infrared, geostationary satellite data. Final Report to the Water and Power Resources Service, vol. 2 (Dept. of Interior, Boulder, Colorado 72 pp.).

Griffith, D.A., Solak, M.E., Almy, R.D., Gibbs, D., 2005. The Santa Barbara Cloud Seeding Project in Southern California, summary of results and their implications. J. Weather Modif. 37, 21–27.

Griffith, D.A., Solak, M.E., Yorty, D.P., 2009. 30+ seasons of operational cloud seeding in Utah. J. Weather Modif. 41, 23–37.

Hobbs, P.V., Radke, L.F., 1973. Redistribution of snowfall across a mountain range by artificial seeding— a case study. Science 181, 1043–1045.

Langmuir, I., 1950. Control of precipitation from cumulus clouds by various techniques. Science 112, 35–41.

Li, X., Shen, X., Liu, J., 2011. A partitioning analysis of tropical rainfall based on cloud budget. Atmos. Res. 102, 444–451.

Long, A.B., 2001. Review of downwind extra-area effects of precipitation enhancement. J. Weather Modif. 33, 24–45.

Meitin, J.G., Woodley, W.L., Flueck, J.A., 1984. Exploration of extended-area treatment effects in FACE-2 using satellite imagery. J. Climate Appl. Meteorol. 23, 63–83.

Meyers, M.P., DeMott, P.J., Cotton, W.R., 1995. A comparison of seeded and nonseeded orographic cloud simulations with an explicit cloud model. J. Appl. Meteorol. 34, 834–846.

Mulvey, G.J., 1977. Physical mechanisms for extra-area effects from weather modification. Atmos. Sci. Paper, 276. Dept. of Atmos. Sci., Colorado State Univ, Fort Collins, CO 138.

National Research Council, NRC, 2003. Critical Issues in Weather Modification Research Report. National Academies Press, Washington, DC (See www.nap.edu/openbook/0309090539/html/R1.html; last accessed 08/09/2013, 123 pp + 8 plates).

Reed, S.M., Maidment, D.R., Patoux, J., 1997. CRWR online report 97-1: spatial water balance of Texas. Report Submitted to Texas Water Resources Institute and the U.S. Geological Survey under Project 5903. (http://www.crwr.utexas.edu/reports/1997/rpt97-1/SECT2.HTM).

Rosenfeld, D., Woodley, W.L., 2003. Closing the 50-year circle: from cloud seeding to space and back to climate change through precipitation physics. Chapter 6 of "Cloud systems, hurricanes, and the Tropical Rainfall Measuring Mission (TRMM)". In: Tao, Wei-Kuo, Adler, Robert (Eds.), Meteorol. Monographs, 51. AMS, pp. 59–80 (234 pp.).

Rosenfeld, D., Xing, Yu., Dai, Jin, 2005. Satellite retrieved microstructure of AgI seeding tracks in supercooled layer clouds. J. Appl. Meteorol. 44, 760–767.

Saleeby, S.M., Cotton, W.R., Fuller, J.D., 2011. The cumulative impact of cloud droplet nucleating aerosols on orographic snowfall in Colorado. J. Appl. Meteorol. Climatol. 50, 604–625.

Silverman, B.A., 2001. A critical assessment of glaciogenic seeding of convective clouds for rainfall enhancement. Bull. Am. Meteorol. Soc. 82, 903–923.

Solak, M.E., Yorty, D.P., Griffith, D.A., 2003. Estimations of downwind cloud seeding effects in Utah. J. Weather Modif. 35, 52–58.

Tao, W.K., Simpson, J., Sui, C.H., Ferrier, B., Lang, S., Scala, J., Chou, M.D., Pickering, K., 1993. Heating, moisture and water budgets of tropical and midlatitude squall lines: comparisons and sensitivity to longwave radiation. J. Atmos. Sci. 50, 673–690.

Trenberth, K.E., Smith, L., Qian, T., Dai, A., Fasullo, J., 2007. Estimates of the global water budget and its annual cycle using observational and model data. J. Hydrometeorol. Spec. Sect. 8, 758–769.

Wise, E.A., 2005. Precipitation Evaluation of the North Dakota Cloud Modification Project (NDCMP). (MS Thesis) University North Dakota, Grand Forks, ND (63 pp.).

Woodley, W.L., Rosenfeld, D., 2004. The development and testing of a new method to evaluate the operational cloud-seeding programs in Texas. J. Appl. Meteorol. 43, 249–263.

Woodley, W.L., Solak, M.E., 1990. Results of operational seeding over the watershed of San Angelo, Texas. J. Weather Modif. 22, 30–42.

Woodley, W.L., Jordan, J., Simpson, J., Biondini, R., Flueck, J., Barnston, A., 1982. Rainfall results of the Florida Area Cumulus Experiment, 1970–1976. J. Appl. Meteorol. 21, 139–164.

Woodley, W.L., Barnston, A.J., Flueck, J.A., Biondini, R., 1983. The Florida Area Cumulus Experiment's second phase (FACE-2), part II: replicated and confirmatory analyses. J. Climate Appl. Meteorol. 22, 1529–1540.

Woodley, W.L., Rosenfeld, D., Silverman, B.A., 2003a. Results of on-top glaciogenic cloud seeding in Thailand: part I, the demonstration experiment. J. Appl. Meteorol. 42, 920–938.

Woodley, W.L., Rosenfeld, D., Silverman, B.A., 2003b. Results of on-top glaciogenic cloud seeding in Thailand: part II, exploratory analyses. J. Appl. Meteorol. 42, 939–951.

Xue, L., Hashimoto, A., Murakami, M., Rasmussen, R., Tessendorf, S., Breed, D., Parkinson, S., Holbrook, P., Blestrud, D., 2013a. AgI cloud seeding effects as seen in WRF simulations. Part I: model description and idealized 2D sensitivity tests. J. Appl. Meteorol. Climatol. 52, 1433–1457.

Xue, L., Tessendorf, S., Nelson, E., Rasmussen, R., Breed, D., Parkinson, S., Holbrook, P., Blestrud, D., 2013b. AgI cloud seeding effects as seen in WRF simulations. Part II: 3D real case simulations and sensitivity tests. J. Appl. Meteorol. Climatol. 52, 1458–1476.

Xue, L., Chu, X., Rasmussen, R., Breed, D., Boe, B., Geerts, B., 2013. The dispersion of silver iodide particles from ground-based generators over complex terrain. Part 2: WRF large-eddy simulations vs. observations. J. Appl. Meteorol. Climatol. (submitted for publication).