J2.13 SYNOPTIC AND MESOSCALE PATTERN ASSOICATED WITH SUPER-COOLED LIQUID WATER CONTENT OVER THE MEDICINE BOW AND SIERRA MADRE MOUNTAINS

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ABSTRACT

Snowpack in the Western high mountains during the winter and the attendant spring runoff provides needed water to lower elevations. Agriculture, recreation, water supply, and hydro-electric power are but a few of the users of this renewable resource. Snowpack becomes even more critical over the Intermountain West during the moderate to extreme drought conditions reported by NOAA's Climate Prediction Center (CPC). Although Snowpack telemetry (SNOTEL) sites within the Medicine Bow and Sierra Madre Mountain ranges initially recorded snow water equivalents (SWE's) nearly 130% of average by February 2006, much of the Intermountain West remained below seasonal normals. Cloud seeding technology for enhanced snowpack may be beneficial for long-term water management. The Wyoming Weather Modification Pilot Project is a five-year cloud seeding program contracted by the Wyoming Water Development Commission. The program contains a cloud seeding phase with snowpack and runoff evaluations within weather patterns that would produce the snowfall over the mountains. It is more important in cloud seeding operations to find synoptic and mesoscale conditions that produce the greatest amount of super-cooled liquid water in clouds than the conditions that produce the greatest snowfall. This study is the initial step in examining the synoptic and mesoscale patterns over the Medicine Bow and Sierra Madre Mountains with the intent of identifying ideal seeding conditions. A future study will compare snowfall rates with WSR-88D Doppler radar reflectivity over the Medicine Bow and Sierra Madre Mountain ranges

1. INTRODUCTION

The presence of super-cooled liquid water (SLW) is essential for cloud seeding operations. Although there are a variety of related factors that will either hinder or contribute to cloud seeding efforts, knowing the synoptic or mesoscale weather patterns that will yield the highest SLW content provides the first step in the cloud seeding process. Many studies have examined the local effects on SLW in the Sierra Nevada Mountains (Heggli et al., 1983; Heggli and Rauber, 1988), the Tushar Mountains in southwest Utah (Long et al., 1990), the Cascade Mountains in Washington (Hobbs, 1975), the northern Colorado Rockies (Rauber et al., 1986; Rauber and Grant, 1986), and the San Juan Mountains in southwest Colorado (Cooper and Marwitz, 1980). Two prominent features were the location of the 700 hPa trough and orographic effects.

Rauber et al. (1986) examined the SLW content during pre- and post-frontal systems and found higher SLW content nearly 7 to 10 hours after the frontal passage. They attributed this to the time difference related to the deteriorating convective condition which results in shallow clouds with warmer tops. However, the Heggli and Rauber (1988) study found larger regions of SLW content were associated with immediate post-frontal passage. Rauber and Grant (1986a and b) also studied the orographic effects over the Park Range located in the northern Colorado Rockies. They found that the highest SLW content was located directly upwind of the mountain crest due to strong orographic forcing and the SLW content rapidly decreased on the leeward side in the descending motion. In the same study they also found that the increased SLW production near the ridge line was associated with strong barrier wind speeds.

This preliminary study will examine the synoptic and mesoscale features that may yield the highest SLW contents for the Medicine Bow and Sierra Madre Mountain ranges. Section 2 will discuss the data used in the examination. A brief description of three events with the flight data are discussed in section 3. A summary of the results and possible future work will be noted in section 4.

2. DATA USED

The Wyoming Weather Modification Pilot Project (referred as WWMPP throughout the paper) includes the Wind River Range located in the Riverton forecast area of the National Weather Service (NWS) and the Medicine Bow and Sierra Madre Mountain ranges (shown as points A and B, respectively in Fig. 1) located in the Cheyenne forecast area of the NWS. For this paper, the synoptic and mesocale focus will be in the Medicine Bow and Sierra Madre Mountain ranges.

The maximum elevation for the Medicine Bow and Sierra Madre Mountains are 6 km and 4 km respectively. Data used to examine synoptic and

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mesoscale features comprised an array of datasets. GOES satellite imagery included visible and infrared data; National Center for Environmental Prediction (NCEP) Eta Model data on the 212 grid, using three hourly intervals and initialization analysis at 1800 UTC for February 14th and 2nd events, and at 0600 UTC for the March 1st event. Sounding data examined using the Eta model for sites C14, KLAR, and KCYS in the BUFKIT program shown in Figure 1.

Aircraft measurements are provided by the National Center for Atmospheric Research (NCAR) Research Application Laboratory (RAL). A Piper Cheyenne aircraft, owned by Weather Modification Incorporated, conducted cloud physics research flights during the winter and early spring months of the 2006 water year. All of the flight tracks are at 14,000 ft due to flight restrictions requiring aircraft to maintain 2000 ft separation with the highest terrain. Droplet concentration measurements were taken by a Particle Measuring Systems Forward Scattering Spectrometer Probe (FSSP). Refer to Pinnick et al. (1981) or Rauber and Grant (1986) to read more about the FSSP instrument. For errors associated with the FSSP measurements refer to Cerni (1983). Particles larger than 25 μm are measured by the Two-Dimensional Cloud Optical Array Spectrometer (2DC). In glaciated clouds, many of these particles are ice. Rauber and Heggli (1988) describe the response of the 2DC probe in a mixed-phase cloud.

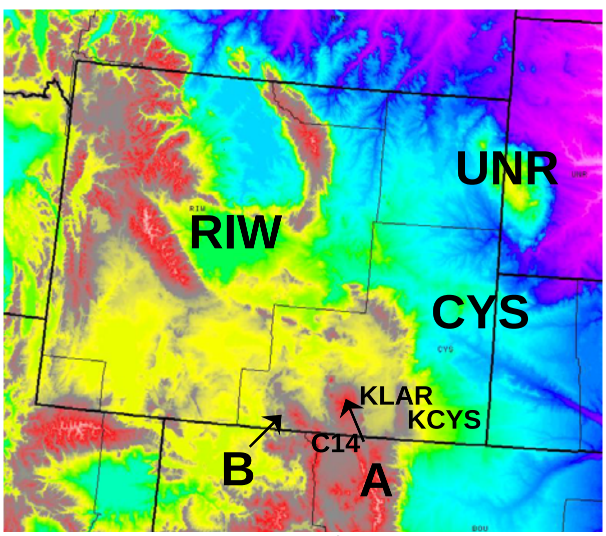

Figure 1: Topographic map of Wyoming with the area forecast responsibility of the National Weather Service Cheyenne (CYS) shown in red. Point A and B indicate the Medicine Bow and Sierra Madre Mountain ranges, respectively.

3. CASE STUDIES

In this preliminary study, six of the 27 flight tracks were examined for their synoptic and mesoscale patterns. Six events were examined closely and revealed a reoccurring pattern showing a correlation between the SLW content and the location of the 700 hPa trough. This paper will focus on three events that occurred on February 2nd, 14th, and March 1st during the winter of 2006.

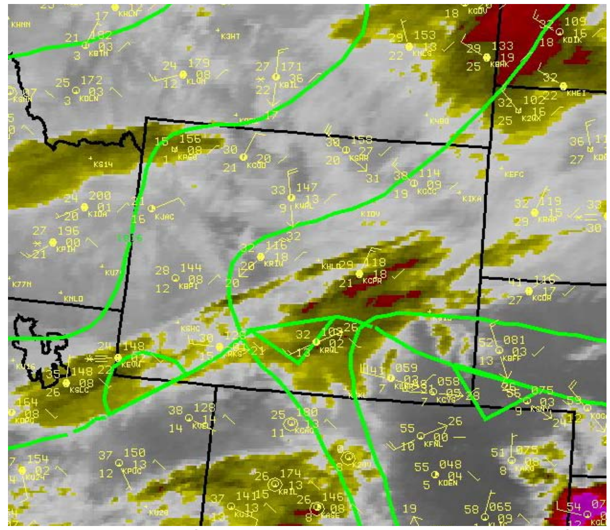

Figure 2: Infrared satellite imagery, surface observations, and NCEP surface and pressure analysis (green lines) are shown at 1800 UTC on February 14, 2006.

3.1. *February 14, 2006*

At 1800 UTC, an upper-level shortwave trough was moving across eastern Montana ahead of a developing low over the west coast at 500 hPa. At the surface, a closed low developed over northeast Colorado that slowly moved towards the Texas and Okalahoma panhandles by 2300 UTC. The IR satellite imagery at 1800 UTC (Fig. 2) shows the surface cold front extending from Salt Lake City (SLC), Utah and through northeast Wyoming to the Nebraska Panhandle with frontal movement to the southeast across Wyoming. The surface observations at Casper (CPR) indicate frontal passage with north to northeast winds at 15 knots. The cold front is near Rawlins (RWL) with southwest winds at 15knots. By 1900 UTC, the cold front is still located between RWL and CPR and remained there until after 2300 UTC. Surface observations indicated rising pressure between 1900 and 2300 UTC at CPR, while the pressure continued to drop at RWL between 1900 and 2100 UTC and then remained steady between 2100 and 2300 UTC. The surface winds indicated frontal passage at CPR with north to northeast winds at 15 to 20 knots, while RWL observations show southwest winds at 15 to 20 knots. Although the southwest flow along and prior to the frontal passage provided the optimal direction for cloud seeding over the target area, the location of the 700 hPa trough proved to be extremely important for the SLW content.

The 700 hPa trough was oriented southwest to northeast across Wyoming in the 1800 UTC initial analyses from the Eta model. The three-hour forecast indicated little movement of the trough by 2100 UTC. As shown in other studies with pre-700 hPa passage

(Rauber et al., 1986), lower SLW content was observed across both the Medicine Bow and Sierra Madre Mountain ranges. Measurements were taken between 2045 UTC on February 14th and 0006 UTC on February 15th. Temperatures ranged between -17 to -13°C at flight level. The cloud droplet concentrations ranged from 600 to 800 cm^{-3} with a derived SLW content of 0.3 gm^{-3} and median volume diameters around 10 μm.

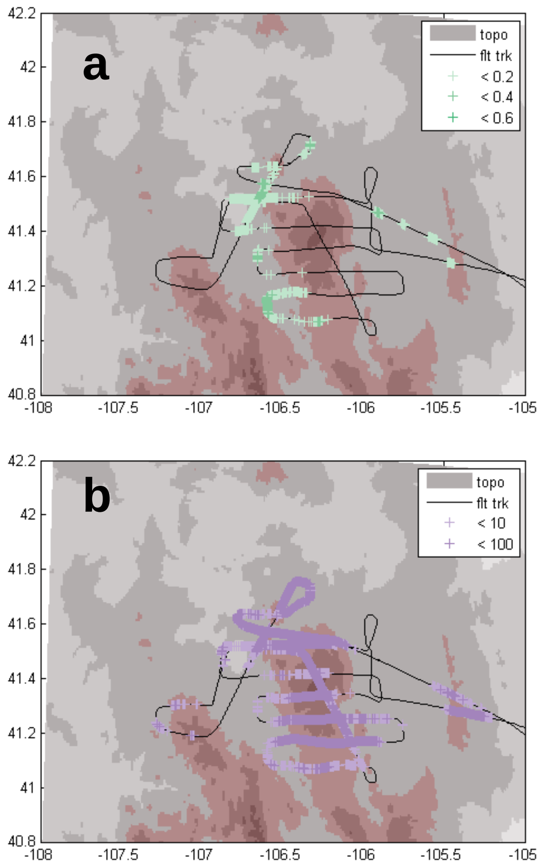

Figure 3: Flight track from 20:45 UTC to 23:50 UTC on February 14, 2006 (black line) with a) FSSP liquid water content plotted when FSSP concentration is greater than 50 cm^{-3} (green marks) and b) 2DC total concentration implying ice concentration (purple marks).

These high droplet concentrations with low liquid water are indicative of a polluted air mass and are not consistent with other studies. The Heggli et al. (1983) study over the Sierra Nevada Mountains showed that SLW content rarely exceeded 0.2 gm^{-3} in pre-trough conditions. Also, in the several years of work examining the SLW over the northern Colorado Rockies and Park Range, Rauber and Grant (1986b) found the average droplet concentrations rarely exceeded 300 cm^{-3} with many storms not exceeding 150 cm^{-3}. Politovich and Vali (1983) found average droplet concentrations of 250 to 350 cm^{-3} over Elk Mountain which is the northern most peak of the Medicine Bow Mountain range. They stated that it was typical of the wintertime mid-continental systems that are unpolluted (i.e., with low cloud condensation nuclei [CCN] concentrations). As seen in Figure 3, the flight track indicates the SLW content was found significantly upwind of the Medicine Bow Mountains with ice clouds spreading across the entire range. There appears to be a consistent deck of ice particles measured by the 2DC probe with concentrations varying from 10 to 30 L^{-1} outside of the liquid core and 0 to 5 L^{-1} in the cloud droplet core.

3.2. *March 1, 2006*

This event was driven by another upper-level shortwave trough moving across central Montana and north-central Wyoming on March 1, 2006. Although both the March 1st and February 14th events had shortwave features moving across Montana, March 1st had a much stronger upper level jet of 110 knots based on an initial analysis of the 0600 UTC Eta model. The surface low was moving west into central Montana and north-central Wyoming by 1200 UTC with an associated cold front moving west across Wyoming. The cold front extended northward between Rock Springs (RKS) and RWL through CPR and Gillette (GCC) by 0300 UTC. Figure 4 shows the cold front across far southeast Wyoming between Laramie (LAR) and Cheyenne (CYS) at 0600 UTC. Surface winds at RWL switched to west-northwest at 30 knots with gusts to 35 knots. The cold front then continued west across the Nebraska panhandle and northeast Colorado through 0900 UTC.

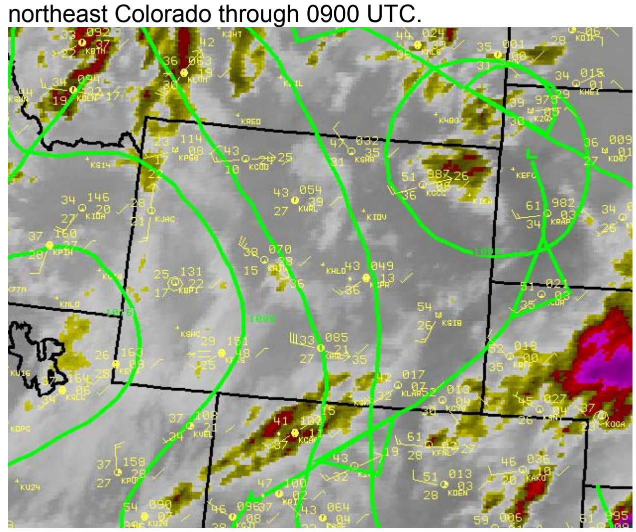

Figure 4: Infrared satellite imagery, surface observations, and NCEP surface and pressure analysis (green lines) are shown at 0600 UTC on March 1, 2006.

The 700 hPa trough was located across eastern Wyoming by the 0600 UTC initial analysis from the Eta model and moved into the Nebraska panhandle and northeast Colorado by 0900 UTC based on the 0600 UTC Eta model three-hour forecast. Thus the 700 hPa trough was passing across the target area when the flight measurements were taken. These events have been shown (Rauber et al., 1986) to provide reasonable concentrations of SLW content, but not necessarily the highest SLW contents. The Heggli et al. (1983) study over the Sierra Nevada Mountains showed that SLW content is maximized nearly 7 to 10 hours after the 700 hPa trough passage.

The flight track from this event showed temperatures ranging from -13 to -10°C at flight level. The droplet concentration was 100 to 200 cm^{-3} with a derived SLW content of 0.2 to 0.45 gm^{-3}. The median volume diameters were around 17 to 20 μm. These microphysical measurements are suggestive of a cleaner air regime. The flight track also indicates SLW content was again found to be on the upwind side of the Medicine Bow Mountain range with ice clouds spreading across the entire range (Fig. 5). Ice concentrations, as indicated by the 2DC, vary from 20 to 120 L^{-1} outside the liquid cloud core and 0 to 5 L^{-1} in the cloud droplet core. Given the location of the SLW content, the mesoscale features for this event appear to be more orographically driven. Politovich and Vali (1983) noted that the most common orographic clouds formed over Elk Mountain in Wyoming after passage of an upper level disturbance or shortwave.

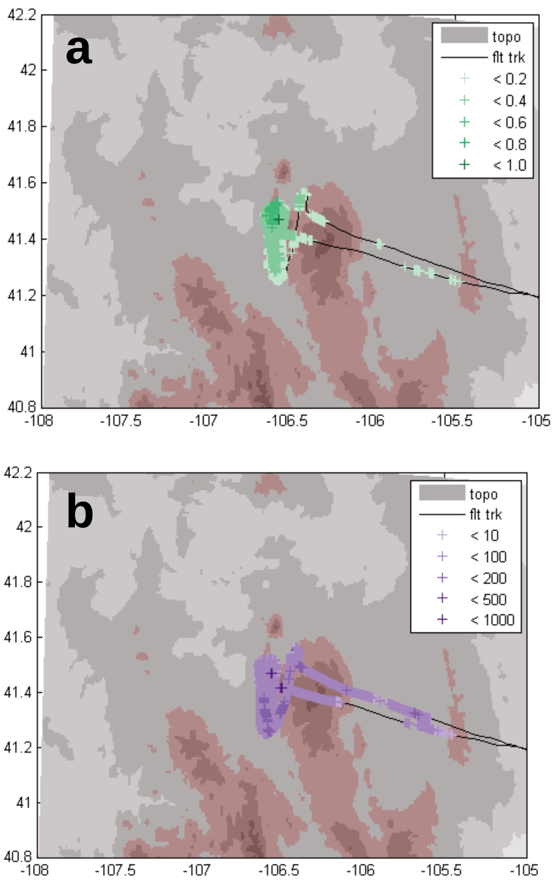

Figure 5: As in Figure 3 but for flight track from 06:12 to 09:18 UTC March 1, 2006.

3.3. *February 2, 2006*

This event was different from the previous two cases examined in that a back door cold front moved across eastern Wyoming after 0000 UTC on February 3, 2006. At 500 hPa, a shortwave was sliding across central North Dakota that extended southward through northeast Colorado. The upper level winds at 200 to 350 hPa showed a 120 knot jet moving across southeast Idaho and into western Wyoming in the 0000 UTC initial analysis field on February 2, 2006. At the surface, a low pressure system was sliding southward into the Midwest with the associated cold front moving southward across South Dakota and extending back into northeast Wyoming and central Montana at 2100 UTC. Figure 6 shows the observations and infrared satellite imagery at 2100 UTC with strong north to northwest winds across Wyoming.

The 700 hPa trough extended from southwest North Dakota to southwest Wyoming based on an initial analysis of the 1800 UTC Eta model. The three-hour forecast at 2100 UTC showed that the trough had moved southeast and was located across central North Dakota through northeast Colorado. Thus the 700 hPa trough had already moved through the target area, but only within an hour or two of the aircraft measurements. Although this does not correspond to the 7 to 10 hour difference that Rauber and Grant (1986a) found, Heggli and Rauber (1988) stated in a later study that the largest most sustained regions of SLW content were associated with the immediate post-frontal trough. The flight track began 2141 UTC on February 2, 2006 through 00:01 UTC on February 3, 2006. The recorded temperatures were between -13 to -10°C at flight level. Droplet concentration was measured at 300 to 400 cm^{-3} with derived a SLW content of 0.6 to 1.0 gm^{-3}. The median volume diameters were around 15 to 16 μm, which correlates to a relatively clean air regime. Figure 7 shows the flight track that indicated SLW content and ice was found upwind and over the peaks of the Medicine Bow Mountains. In most penetrations, the total concentrations were 20 L^{-1}. However, there were two passes where the total concentration increased to 100 L^{-1}. This was accompanied by a decrease of total droplet concentration around 200 cm^{-3} and SLW content to 0.35 gm^{-3}.

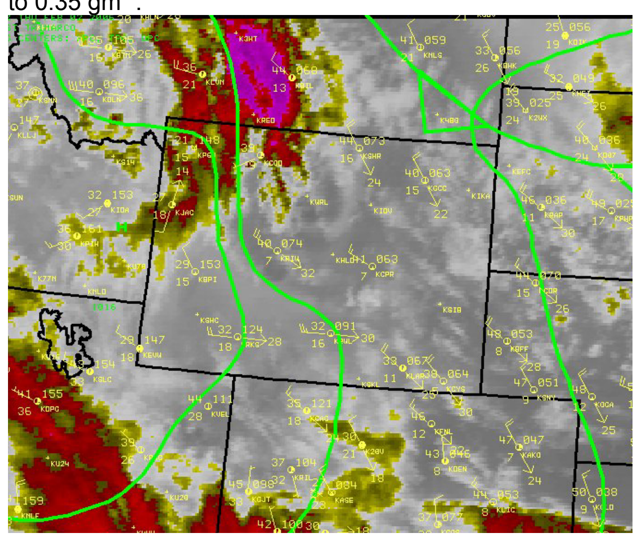

Figure 6: Infrared satellite imagery, surface observations, and NCEP surface and pressure analysis (green lines) are shown at 2200 UTC on February 2, 2006.

4. SUMMARY

This WWMPP is a five-year program that will determine if the cloud seeding process is beneficial to Wyoming. The success of the program will be measured by the snowpack each year from which runoff can be estimated. It is hoped that cloud seeding will increase snowpack and runoff by 10 to 20% per year with the cloud seeding operations. Snowpack received during the winter months and the attendant spring runoff provides needed water to lower elevations for activities such as agriculture, recreation, water supply, etc. Although the cloud seeding process is not designed to mitigate the drought across the Intermountain West or the Midwest states, it poses some benefits during the drier winter seasons. The 2006 water year for the Medicine Bow and Sierra Madre Mountain ranges proved to be near normal to slightly above normal in recorded snow water equivalents and below normal in spring runoff. The 2007 water year has begun and at this time the Climate Prediction Center has indicated the early onset of a weak to moderate El Niño. During a moderate to strong El Niño period, the subtropical jet strengthens and the dominant winter storm track shifts across the southern part of the United States. For Wyoming this would suggest a drier than normal weather pattern for the winter months. Future research related to this study will evaluate the effects of the potentially drier winter season of 2007 in relation to the production of SLW and impacts on cloud seeding operations.

In this preliminary study, three winter events were examined to determine a correlation between synoptic or mesoscale feature and high amounts of SLW. It was found that the most prominent feature in the events was the location of the 700 hPa trough. This was similar to findings by Rauber and Grant (1986) and Heggli and Rauber (1988). However, there was not a 7 to 10 hour difference between highest SLW content as seen by Rauber and Grant (1986).

This examination is the first step in finding optimal conditions for cloud seeding operations. We will continue to collect and examine the synoptic and mesoscale features over the next couple years to build an extensive climatology of the area. Future studies will also include comparisons of snowfall rates with WSR-88D Doppler radar reflectivity over the Medicine Bow and Sierra Madre Mountain ranges.

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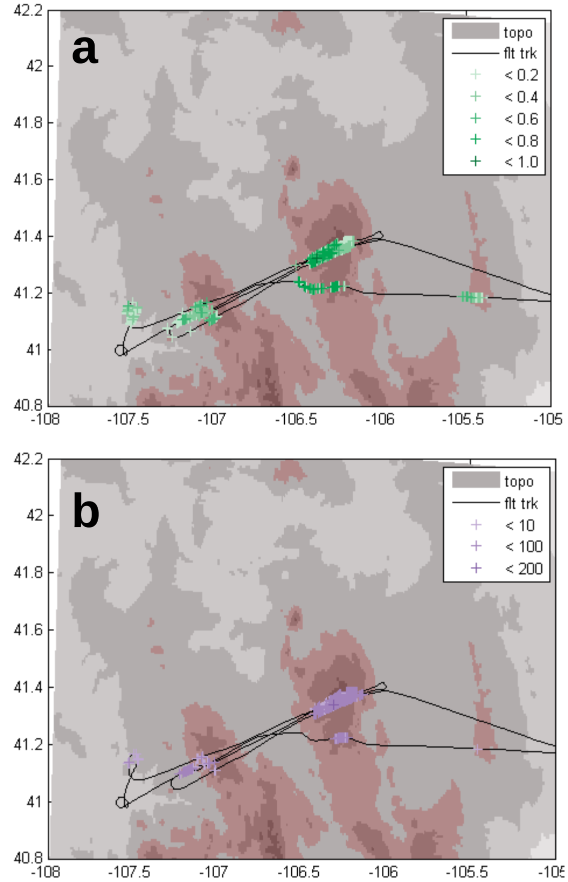

Figure 7: As in Figure 3 but for flight track from 0612 to 0918 UTC March 1, 2006.

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